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Declaration

I declare that all the unreferred work described in this thesis is entirely my own, and no portion of the work contained in this thesis has been submitted in support of an application for another degree or qualification of this or any other university or institute of learning.

SIGNED: Michael Munphy

Michael J. Murphy

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Planar Sputter Magnetron Technology

Abstract

In order to contextualise the main work a general overview of surface engineering technology is given. There follows a detailed account of current state of play in sputter magnetron design, the coatings which can be grown and their properties.

Next the magnetic field surrounding a two dimensional magnet is described. This allows a check on the subsequent derivation of an equation in integral form which in principle enables the calculation of the magnetic field associated with any simple (usually one ferromagnetic component) magnetron whose geometry may be regarded as being two dimensional. The equation is arrived at using conformal mapping techniques. It is used to find analytic expressions for the magnetic stream function and the magnetic field for the 'standard' rectangular magnetron geometry. General behaviour of sputter magnetrons as a function of magnetic field is discussed. Theoretical results are given for a commercial planar magnetron and these are supported by experiment. The results are used to calculate the effective potential well as seen by electrons in the vicinity of this device. Some device characterisation is included.

Theory, design, construction and performance of a magnetron system based on the Penning geometry is described. This apparatus is referred to as the Dimag. It is retrofitted to an existing high vacuum facility. This system is then used to produce Carbon Nitride coatings with approximately 39 atomic percent Nitrogen incorporation.

Chapter 1 - Introduction

Subject of thesis

Broadly speaking this thesis is concerned with magnetron sputtering technology. The focus is on the design of planar sputter magnetron coating apparatus. This is set in the context of hard/novel coatings deposition.

What is magnetron sputtering?

Sputtering can be defined as the ejection of atoms from a solid following momentum exchange due to ion impact. Magnetron sputtering is where magnetic fields are used to enhance the sputtering rate. It is the most versatile vapour phase coating technology and is a key operation in many industrial manufacturing processes.

Why is it necessary to use coatings?

- a) When bulk component material properties are not compatible with optimum surface requirements.
- b) The application per se is such that very fine materials tailoring is required such as in electronic device fabrication or fundamental scientific studies.

Why Use Hard Coatings ?

Hard coatings can revolutionise the performance of certain contacting components by virtue of the following advantages:

- a) Reduced friction may imply lower contacting forces, less heat generated, lower machine power and less adhesive wear.
- b) A hard surface means less abrasive wear

Coatings do not work where the substrate is brittle or excessive loads cause plastic deformation of the bulk material.

Principle Objectives:

- Development of a general integral equation which completely describes the magnetic field for any 2-D magnetron subject to some minor restrictions.
- Use of the above mentioned integral equation to find an analytic solution for what may be referred to as the standard rectangular sputter magnetron geometry.
- Application of the analytic solution mentioned above to a 'real world' magnetron geometry (Teer Coatings Services, Hartlebury, UK) and experimental confirmation of the result.
- Theory, design construction and some characterisation of a planar sputter magnetron source based on the Penning geometry. This is referred to as the Dimag source.
- Growth of Carbon Nitride coatings with a high atomic percentage Nitrogen incorporation

Chapter 2 - A Practical Overview of Surface Coatings Technology

I. Introduction

The phrase "surface coatings technology" sounds very impressive. It conjures up images of technological sophistication far beyond the purview of your average man in the street. This can be misleading. Painting, for example, is a mundane yet important surface coating technique. It serves a decorative function and is often used to prevent corrosion. Methods for its application whether by using brush (garden gates), roller (ceilings and walls) or spray gun (motor vehicles) are very familiar. Other only marginally less familiar examples of surface coating include electroplating (chrome plating is widespread from hydraulic pistons to balustrades), vitreous enameling (as on cooking pot exteriors), evaporation (aluminising mirrors) and anodising (for aesthetic effect and corrosion protection of aluminium). Furthermore many of the concepts which are applied in these techniques such as applying a paint primer followed by an overcoat are also relevant to high tech scenarios where so called interlayers may be used to give good adhesion and the overcoat has the desired surface properties of aesthetic effect, hardness, low friction, thermal flow resistance or whatever. Therefore in considering the more complex areas of surface engineering it is often helpful to relate back to these techniques. The remainder of this chapter is intended to provide a general introduction to the field of hard/novel surface coatings technology and thereby to place magnetron sputtering in context. It is divided up as follows. Section II gives a brief account of hard facing coatings technology. Section III briefly describes liquid phase coating technology. Section IV describes deposition from the vapour phase in general terms. Section V gives an account of the most pertinent Chemical Vapour Deposition techniques. Section VI gives an account of important Physical Vapour Deposition techniques. Magnetron sputtering is included in this category. Section VII describes the operating 'mechosystem'. Section VIII is the conclusion.

II. Hard facing coating technologies



Table 2.1: Hard facing coating techniques

These divide into three major categories¹, i.e. thermal spraying, welding and cladding. The most important point to note about these methods is that the deposits tend to be quite thick being typically on the order of 0.1 to 5mm. They find application where there is severe erosive or abrasive wear. Examples include weld cladding of undersea valves and abrasive slurry pipes. They can also be used for corrosion resistance applications. Spray coatings may be used on precision components such as print rollers to build-up worn or mismachined parts. These must subsequently be machined back to size. A more detailed account of hard facing is given in the book by Bhushan and Gupta¹.

III. Liquid phase coating technologies

Electroplating, electroless plating and anodising are the best known technologies for liquid phase deposition of hard coatings. The anodising however is mainly used for corrosion resistance and aesthetic appeal. Electroplated chrome is a widely used product from gramophone heads to balustrades to motor vehicle trim. Electroplated nickel is widely used as an undercoat for gold coatings in order to give shininess and hardness. A measure of the importance of the technique is that it has been estimated



Figure 2.1: A brass tube which has been electrolessly coated with Nickel. The tube has been cut away in sections. It can be seen that the Nickel coating extends right up the tube length.

that the total electroplating industry in the United States is worth several billion dollars². Electroless deposition is popular because it enables coating deposition onto plastics, it gives good thickness uniformity and the capability to down tubes and blind holes. **Figure 2.1** shows a photograph of u-shaped brass tube which has been given an electroless nickel coat. It can be seen that the coating has covered the entire length of the tube. Again a more detailed account of these techniques is given in the book by Bhushan and Gupta¹.

IV. Coating deposition from the vapour phase



 Table 2.2: Classification of vapour phase deposition techniques

Table 2.2 gives a classification of vapour deposition¹ techniques. As can be seen these can be divided into three categories, i.e. Chemical Vapour Deposition, Physical Vapour Deposition and the hybrid Physical-Chemical Vapour Deposition. Here is not the place for an exhaustive description. Instead this overview is confined to those vapour deposition techniques which are commercially successful in the production of hard coatings. Such PVD techniques include cathodic arc evaporation, magnetron sputtering, low voltage electron beam evaporation and triode ion plating. Of the CVD techniques conventional thermally assisted CVD is the linchpin technology but mention will be made of Hot Filament Assisted CVD which is used commercially³ in the production of diamond coatings. Hybrid techniques will not be considered though it is worth noting that they are of crucial importance in the electronics industry.

V. Chemical Vapour Deposition (CVD)

Chemical Vapour Deposition (CVD) of hard, wear resistant coatings such as Titanium Carbide or Titanium Nitride to enhance the performance of cemented carbide cutting tools was introduced in the late 1960's. Since then new applications for the procedure have been found and CVD coatings are now routinely applied to cold work parts such as trim dies, punches, thread roll dies etc. Their general characteristics are given overleaf. **Table 2.3** gives an idea of the benefits to be obtained from CVD⁴ coatings.



Figure 2.2: Schematic of Thermally Assisted Chemical Vapour Deposition⁴

Thermally Assisted CVD

Thermally Assisted Chemical Vapour Deposition is the standard CVD technique used for depositing coatings on tools. See Figure 2.2.

The method is to introduce a gas mixture into a reactor in which the tools to be coated are heated to about 1000 C. The gaseous atmosphere envelops them. A chemical reaction takes place on the surface of the parts yielding a solid material. Examples of such reactions are:

$$TiCl_4(g) + CH_4(g) \rightarrow TiC(s) + 4HCl(g)$$

$$2AlCl_3(g) + 3CO_2 + 3H_2(g) \rightarrow Al_2O_3(g) + 6HCl(g) + 3CO(g)$$

$$2TiCl_4(g) + N_2(g) + 4H_2(g) \rightarrow 2TiN(s) + 8HCl(g)$$

2.5

Points to note about CVD

1) As far as coating of carbide and steel is concerned CVD processes take place at temperatures around the 1000 C mark. Substrates must be able to withstand these temperatures. A consequence of this is that certain tools specified to high tolerance cannot be coated using this technique. For tool steels a post deposition in-vacuum heat treatment is necessary to harden the material.

2) In CVD a gaseous atmosphere envelops the part and reacts on its surface to deposit a coating. Complex geometries, tubes and blind holes can be coated.

3) The range of coatings is limited by the chemical reactions which are allowed and the availability and cost of suitable precursor gases.

4) These processes use and exhaust toxic gases which must be neutralised.

5) The technique tends to round an edge thus making it less sharp.

6) CVD coatings have tensile stresses owing to the thermal mismatch between substrate and coating.

7) From the process point of view surface preparation such as cleaning and low surface roughness are not as critical as for PVD. However for optimum tool performance low roughness is required and post polishing is recommended.

8) CVD coatings have a relatively large grained microstructure and are rougher than PVD coatings.

9) When coating carbides any corners must be honed in order to achieve good adhesion. In addition CVD coating temperatures cause carbon atoms to migrate from the substrate material and bond with the titanium. This layer of carbon deficiency in the substrate which is referred to as the eta phase is very brittle and can lead to premature tool failure.

Part	AISI Grade	CVD Coating	Application	Uncoated Pieces Machined or Operations Before Resharpening	Coated Pieces Machined or Operations Before Resharpening
Trim Die	M2	TiN	Cold Heading S.S. hex head bolts	10 000	40 000
Punch	CPM T15	TiN	Cold Heading AISI 8630 Steel Sockets	20 000	40 000
Class C Hob	M3-2	TiN	Hobbing AISI 4630 Steel Gears	1500	4500
Thread Roll Die	D2	TiC	Rolling Threads on Low Carbon Steel Bolts	500 000	2 000 000
13 mm Pine Tan	M2	TiN	Tapping Holes in Gray Iron	3 000	9 000
Tipe Tup					
8 mm Drill	M7	TiN	Drilling Low Carbon Steel	1 000	4 000
Form Tool	T15	TiC	Screw Machine Application	4950	23 000
Cutoff Tool	M2	TiN	Cutting Low Carbon Steel	150	1 000
Wiping Ring	D2	TiN	Forming Transmission Parts	5 000	40 000

 Table 2.3: Performance of CVD coatings in typical applications⁴

As can be seen toxic materials such as Titanium Tetrachloride and Hydrogen Chloride are used and exhausted respectively. So it is necessary to pass the output gases to a chemical neutraliser before exhausting to the atmosphere.

Within Ireland conventional CVD for hard coating deposition is performed only by Hi-Life Tools in Shannon.

Hot Filament Assisted CVD

One of the most remarkable features of vapour deposition technology is the capability to produce materials which from a thermodynamic standpoint simply should not form at the temperatures and pressures used. Nowhere is this more clearly highlighted than in the case of diamond coating deposition. Traditionally industrial diamond has been produced at high temperatures and extreme pressures. Nowadays using hot filament assisted CVD it is possible to produce diamond coatings at below atmospheric pressure at around 900C. A schematic³ of an industrial apparatus used at CemeCon Gmbh is given as Figure 2.3. The key to depositing diamond as opposed to graphite is the introduction of a hydrogen to methane gas flow ratio of about 100 to 1. This is necessary because the hydrogen preferentially etches the graphitic sp^2 bonds in favour of the sp³ diamond bonding. Thermionic electrons from the tungsten filaments used are also thought to assist in the process. Commercially it is possible to coat carbide inserts (containing less than 6% Cobalt) and most standard cutting tools. Note that high solubility of carbon in iron means that diamond is not suitable for cutting ferrous materials. Machining tests at Trinity College Dublin support claims by CemeCon that their diamond coatings can outperform Polycrystalline Diamond in machining of abrasive materials such as Metal Matrix Composites. The probable reason for this is that there is no weakening binder phase within the diamond coating as there is between the PCD grains. At any rate the point is made that due to the far from thermodynamic equilibrium nature of the vapour growth process a once exotic material is readily available. This theme of the use of vapour techniques to produce new and unexpected coating types is particularly relevant to Chapter 7 where preliminary work on Carbon Nitride materials will be described.



Figure 2.3: An apparatus³ for hot filament assisted deposition of diamond

VI. Physical Vapour Deposition (PVD)

Although the hard CVD coatings have been very effective on cemented carbide cutting tools, it is difficult to transfer the technology to tool and die steels because the high (typically 800 to 1100C) CVD coating temperature anneals the steel. CVD coated steel tooling could be re-heat treated but for precision tooling the distortion from heat treatment would leave the tool out of tolerance. This is elegantly summarised in **Table 2.4** from Sandvik.

This has led to the evolution of an industry since about 1980 for depositing hard coatings by low temperature PVD techniques. This is the time that the Mitsubishi company of Japan first introduced their Titanium Nitride coated gear cutting hobs. Features of PVD technology are described overleaf. As mentioned earlier there are four basic types of equipment⁵ in use today and these are now discussed.

Low Voltage Electron Beam Evaporation

The low voltage electron beam evaporation process is used by Balzers. In this process an electric beam or arc is produced in an ionisation chamber as illustrated. The beam is attracted to a crucible containing the source material which is usually titanium. The titanium is consequently melted and vapourised. A reactive gas is introduced into the vacuum chamber. This gas reacts first on the surface of the substrates and then on the surface of the growing film. The roughly 100 Volt beam produces a high degree of ionisation of the evaporated metal and the reactive gas within the chamber. A negative

Dim	IT4	ITS	пе	177	ITS	179	IT 10	П11	IT 12	1713	IT14
1-3	-	_ 5	7	9	TA	25	40	60	100	140	250
3-6	4	-6	-	12	18	30	48	75	120	180	300
6-10	4	6	-	15	22	36	58	490	150	220	360
10-18	5	8	11	TR	28	43	370	10	180	270	430
18-30	6	9	13	21	23	(DER	84	130	210	330	520
30-50	7	11	16	25	39	62	100	160	250	460	620
50-80	8	13	19	30	46	74	120	190	300	540	740
80-120	10	15	22	35	1)54	87	140	220	350	630	840
120-180	12	18	25	40	63	100	160	250	400	720	1000
180-250	14	20	29	46	72	115	185	890	250	810	1150
250-315	16	23	32	52	81	130	210	320	520	890	1300
315-400	18	25	36	57	89	140	230	3,60	570	970	1400
400-500	20	27	40	63	97	155	250	400	620	1900	1550

TOLERANCE RANGE MICRONS

Table 2.4: When the tool tolerance lies in region 1 which is the region of tightest tolerance then CVD coatings cannot be used. When the tolerance lies in region 2 CVD can be used but only with great care. Furthermore a good quality powder metallurgy produced steel must be used. In regions 3 and 4 CVD coatings are allowed and the steel need only be of the finest quality if the required tool hardness is above about 57 and 62HRc respectively. The table is from literature produced by Sandvik.

Points to Note about PVD

1) PVD is a low temperature < 550 C technology. This is important for production of tools within tight tolerances.

2) A plasma or an ion beam gun is used to obtain ion bombardment of the growing film. This improves coating density and quality. Ion bombardment may allow the formation of novel materials such as amorphous carbon hydrogen.

3) PVD deposition techniques are 'line of sight'. This has two important consequences:

a) Tubes or blind holes with a depth to width ratio greater than one cannot be coated.

b) Complex shaped samples have to be manipulated in front of the vapour sources in order to get all round coverage. Alternatively a number of vapour sources can be strategically placed with respect to the substrate.

4) Virtually any solid material can be deposited. The magnetron sputtering technique is particularly valuable in this regard.

5) PVD is an environmentally friendly technology. It may eventually compete with electroplating.

6) PVD allows a sharp edge condition to be retained.

7) Hard PVD coatings have very high internal compressive stress which often limits coating thickness. A benefit of these stresses is that fatigue cracking is delayed.

8) Substrate preparation such as cleaning and low surface roughness are especially critical in PVD.

9) PVD coatings have a very fine grained structure which reduces the risk of cracking and leaves a smoother finish.



Figure 2.4: A low voltage electron beam evaporation unit⁶ from Balzers

substrate voltage induces the ions to bombard the growing film promoting densification and consequently better mechanical properties. This process can produce both TiN and TiCN. However it is not used for newer alloy coatings such as TiAlN. This is because the electron beam causes the aluminium portion of a TiAl source to evaporate faster than the titanium resulting in a poor quality inconsistant coating. Even when separate aluminium and titanium sources are used it is difficult to produce a uniform coating with this technology.

Low voltage electron beam systems are limited to relatively small inserts or tools measuring no more than a few inches. If the distance metal atoms must travel is too great the deposition rate falls too low to be practical.

Triode High Voltage Electron Beam

For larger tools or a larger volume of tools, the triode high voltage electron beam process might be used. This process makes use of equipment produced exclusively by Tec Vac in the UK. In this case a high voltage electron beam gun evaporates the source material. The process can achieve high evaporation rates but its 10000 Volt beam ionises little of the evaporant as it comes off the sources. To increase the level



Figure 2.5: Schematic⁶ of triode high voltage electron beam evaporation

of ionisation, a triode system injects electrons into the system from a hot filiment source. These electrons collide with and ionise evaporant and reactive gas atoms gas atoms.

Because the high voltage system yields higher evaporation rates, it can handle larger tools than the low voltage system can. Also the triode system gives the operator some control over the degree of ionisation which is a critical process parameter. Like the low voltage system it is used to deposit TiN and TiCN but not TiAlN.

Cathodic Arc Evaporation

Cathodic Arc Evaporation using random or steered arcs can be used to deposit TiAlN. Companies which use this technique include Multi-Arc Scientific Coatings and Hauzer Vac Tec. This process strikes an electric arc on several solid targets. The arc dances around on the surface of the targets and flash evaporates the material directly from solid to vapour. As the evaporant passes through the arc it becomes ionised. The cathodic arc process produces the highest degree of ionisation of the 4 main PVD processes.



Figure 2.6: Schematic of an arc evaporation system⁷

The cathodic arc process is used to produce TiAlN coatings because it develops such a high level of energy that it can evaporate aluminium and titanium at roughly the same rate. The cathodic arc process can also produce a very thin zone, 200 to 300 Angstroms thick on the substrate surface where the coatings and substrate materials are intermixed. No other PVD process produces this intermixed zone. Some manufacturers believe that it provides better tool performance in stamping and punching applications.

A drawback of the arc process though is that it produces liquid droplets or macroparticles of metal, 1 to 15 um in size, during evaporation of the target material. The macroparticles form because the arc acts as a very intense localised heat source producing a tiny amount of molten metal as well as metal vapour. The molten metal forms small droplets that can be trapped in the growing film on the substrate. This usually doesn't cause a problem with tool coatings.

Modifications to the cathodic arc system can reduce the number of droplets getting into the film. In steered arc systems, a magnetic field steers the arc across the target surface and reduces the dwell time at any given point. This significantly cuts down on the number of macroparticles.

Magnetron Sputtering

The magnetron sputtering process can be used to produce any PVD coating. In this process, multiple cathodes produce a plasma of inert gas ions which knock (or sputter) atoms out of the source material. Metallic atoms from the source material are deposited on the surface of the substrate where they combine with the reactive gas to form the coating. The outer magnets of the sputtering cathodes have been made stronger with respect to the inner magnets. This causes the field lines from one magnetron to link up with those of its neighbour to form a closed field geometry as illustrated in Figure 2.7. This traps the fast secondary electrons that escape from the cathode surface and forces them to undergo ionising collisions with inert gas atoms away from the cathode surface. In this way a dense secondary plasma forms in the region where the substrates are placed. This plasma causes ion bombardment of the growing film. The system shown in Figure 2.7 is from Teer Coatings. It is noted that designs based on this geometry but combining arc and magnetron technology are being sold by Hauzer under the name Arc Bond Sputtering (ABS). The idea is that ABS combines the good adhesion of arc technology with the advantages of magnetron sputtering.



Figure 2.7: A closed field sputter magnetron coating system⁸

2.15

VII. The tool mechosystem

It is critical to understand that the coating must not be viewed in isolation as some kind of add-on. Rather it must be seen as a single variable in a process which has many other interdependent factors such as substrate material (as highlighted in the last section), substrate hardness, substrate geometry, surface finish, the materials with which the coated component will interact in service, machine operating parameters etc.

Substrate Hardness

A D2 form tool, normally hardened to 60-62 HRc for improved wear, breaks in service. A hardness of 58HRc is sufficient for the coated tool. The hard coating provides wear resistance and the tool has greater toughness to resist cracking.

Substrate Geometry

An example given earlier is that of cemented carbide inserts. Here the cutting edge must be radiused in order to prevent corner breakage.

Surface Finish

Good surface finish leads to lower friction between tool and workpiece. This is of obvious advantage in applications ranging from extrusion to metal cutting.

Materials with which the coated tool will interact

An example is the forming of Titanium using a Titanium Nitride coated tool. Chemical interaction between tool and workpiece causes tool failure due to adhesive wear. Lubricants could also affect coating performance.

Machine Operating Parameters

It is well known that in order to achieve the best performance from Titanium Nitride metal cutting tools it is necessary to roughly double the cutting speed. At standard cutting speeds there is no significant difference in performance.

A good example⁶ of interdependence in the tool mechosystem is the coating of twist drills. In the first instance consideration must be given to the tool material, surface roughness and coating type. It is then found that increases in productivity can only be achieved on a machine that is able to work at appropriate high speeds and feed rates without vibrations. With the greater productivity it is necessary to remove more chips, i.e. the twist drill flute must be designed correspondingly. Holes are smoother.

Application	Benefits
Cutting	Increased Tool Life. Larger Chip
	Volume. Reduced Cutting Forces.
	Reduced Downtime. More Regrinds
	Possible. Smoother Workpiece Surfaces.
Punching	Increased Tool Life. Smoother Cuts
	Without Burrs so Less Finishing.
	Reduced Cold Welding. More Regrinds
	Possible. Perforation Distances May Be
	Shorter Than Material Thickness.
Aluminium and Zinc Die Casting	Less Adhesive Wear
Forming	Increased Tool Life. Improved Behaviour
	of the Material Being Formed. Easier
	Workpiece Ejection. Smoother
	Workpiece Surface.
Plastics Processing	Increased Tool Life. Easier Mould
	Release. Low Tendency Towards
	Deposits in the Mould so Less
	Expenditure for Cleaning and
	Repolishing. Improved Flowability of the
	Plastic Material. Less machine downtime.
	Shorter cycle times.
Precision Contacting Components	Increased Life. Reduced Friction gives
	Smoother Contact. In Emergency May be
	Able to Run for Short Periods Without
	Lubricant.

Table 2.5: Benefits Associated with PVD Coating (Information from Balzers)

Coating /	Deposition	Deposition	Micro -	Coating	Maximum	Coating
Treatments /	Technique	Temp. (°C)	hardness at	Thickness	Service	Colour
Substrates			25 °C	(um)	Temp. (°C)	
			(HV 0.05)			
TiN	PVD	300 - 500	2300	1 - 5	600	gold - yellow
TiCN	PVD	300 - 500	3000	1 - 5	400	blue - gray
WC/C or TiC/C	PVD	< 250	1000	1 - 4	300	black - gray
CrN	PVD	< 500	1800	1 - 15	700	silver - gray
TiAIN/TiNAIO	PVD	< 500	3300	1 - 5	800	
Poly. Diamond	CVD	~ 800	10000	3 - 5	600	gray - clear
TiC / TiN	CVD	~ 1050	3000	5 - 8	600	yellow
VC	Toyota Diff.	~ 1000	2900			grey - brown
Nitrided Steel	Diffusion	< 500	1100	N/A		Sub-surface
						white layer
Hard Chrome	Electoplate	40 - 70	1100	2.5 to 500	400 +	silver - gray
a - Diamond	PVD	< 250	~ 8000			
Cold work steel	N/A	N/A	750	N/A	< T.T.	N/A
High speed steel	N/A	N/A	900	N/A	< T.T.	N/A
Powder	N/A	N/A	900	N/A	900 +	N/A
Metallurgy steel						
Cemented	N/A	N/A	1700	N/A		N/A
Carbide						

 Table 2.6: Properties of Various Hard Coating / Diffusion Treatments and Substrates

2.18

VIII. Conclusion

A general macroscopic overview of hard coatings technology and its applications has been given. This has served to introduce the field, to highlight the differences between CVD and PVD and to illustrate the interdependencies within the coating mechosystem. This has all been from a very practical viewpoint. Chapter 3 will concentrate more on the detail of coating deposition with a particular eye to magnetron sputtering.

References

- 2.1) B. Bhushan and B.K. Gupta, "Handbook of Tribology Materials, Coatings and Surface Treatments", McGraw Hill (1991).
- 2.2) Kirk and Othmer (Eds), "Encyclopaedia of Chemical Technology Fourth Edition" Vol 9, pg 279 (1995).
- 2.3) T. Leyendecker, O. Lemmer, S. Esser and M. Frank, in Eds: A. Feldman, Y. Tzeng, W.A. Yarborough, M. Yoshikawa and M. Murakawa, "Third Intl. Conf. On Applications of Diamond Films and Related Materials", (1995).
- 2.4) C. Wick, J.T. Benedict and R.F. Veilleux Eds: "Tool and Manufacturing Engineers Handbook - Fourth Edition" Vol 1, pg 24-1 (1983).
- 2.5) W. Sproul, *Cutting Tool Engineering*, February pg 52 (1994).
- 2.6) J. Vogal in Hans K. Pulker (Eds) "Wear and Corrosion Resistant Coatings by CVD and PVD", Expert Verlag, pg 165 (1989).
- 2.7) K.S. Fancey and A. Matthews in D.S. Rickerby and A. Matthews Eds: *"Advanced Surface Coatings: a Handbook of Surface Engineering"*, Blackie & Son Ltd. pg 142 (1991).
- 2.8) D.P. Monaghan, D.G. Teer, K.C. Laing, I. Efeoglu and R.D. Arnell, Surface and Coatings Technology, 59 pg 21 (1993).

Chapter 3 - Sputter Technology and Coating Growth

I. Introduction

In the last chapter an overview of surface coatings technology is given. This concentrates on techniques which are commercially important. It also highlights the differences between PVD and CVD and discusses interdependencies in the tool mechosystem. It is a macroscopic overview where the coating is assumed to perform as specified. The purpose of this section by contrast is to discuss the nity grity of magnetron sputtering (which is the main subject of this thesis) and coating growth. It is noted that most of the general remarks pertaining to film growth are also applicable to other PVD techniques. Section II describes the fundamentals of sputtering. Section II discusses diode sputtering. Section IV details planar magnetron sputtering. Section V deals with initial thin film growth stages. Section VI deals with subsequent growth. Section VII discusses adhesion. Section VIII discusses stress in the coating. Section IX is the conclusion.

II. Fundamentals of Sputtering

Sputtering can be defined as the ejection of atoms from a solid following momentum exchange due to ion impact. The solid upon which the ions impact is called the *target*. An inert impacting gas is generally used because it will not react with the target surface. There are five inert gases, He, Ne, Ar, Kr, Xe which could be considered. Argon is usually chosen as the result of a trade-off. It is reasonably inexpensive yet the ions are large enough to give acceptable sputtering rates. The mechanism of sputtering is that the ion impinges on one or more target atoms inducing a collision cascade within the target. The resultant distribution of momentum vectors is such that one or more sputtered atoms may be produced. In a small percentage of cases an atomic cluster may be formed. It is noted that ions are neutralised by field emission shortly before impact. Furthermore depending on the relative mass of target atoms and

bombarding ions significant numbers of ions may be reflected as energetic neutrals. Alternatively the ions may be implanted into the target surface. In the text that follows all impacting ions are assumed to evolve from a *glow discharge plasma* source (See **Appendix 3.1**).

Sputter Yield

With the assumption of normal incidence onto a flat polycrystalline material an expression for the sputter yield, that is the number of target atoms emitted per incident ion, is given by¹⁻³

S=constant.
$$\varepsilon \frac{E}{U} \alpha (\frac{M_t}{M_i})$$

The yield depends directly on the energy transfer function ε . The term $\alpha(M_t / M_i)$ is a near-linear function of M_t / M_i , E is the kinetic energy of the incident ion and U is the heat of sublimation of the target material. It is noted that $\varepsilon \alpha$ does not vary greatly from one material to the next. The primary material sensitive factor is the heat of sublimation and this only has a first order dependence. So most materials have sputter yields within an order of magnitude of one another. This universality is what makes sputtering the process of choice for many applications³. It is in contrast to evaporation where the rate can differ by several orders of magnitude. Sputter yields for selected elements under 500eV Argon bombardment are C = 0.12, Ti = 0.51, Al = 1.05, Cu = 2.35 and Ag = 3.12.

Secondary Electrons

Secondary electrons are emitted from a target as a consequence of bombardment. They are emitted with low energy (a few eV) but are accelerated down the potential hill of the sheath to the negative glow. In doing this they accumulate kinetic energy which in the absence of collisions may correspond to the discharge potential. The *secondary electron yield* γ is defined as the number of electrons emitted per incident ion. A typical value for metals would be 0.1. These particles are critical in D.C. diodes as they sustain the plasma density. They do this because they have an energy corresponding to some fraction of the very high discharge energy and thus can cause

multiple ionisations before becoming thermalised. The condition for maintenance of the discharge is therefore that each secondary electron should be capable of producing at least $1/\gamma$ ionisations. Secondary electrons may also affect thin film growth by bombarding the growing structure but discussion of this will be held over till later.

Other Effects

Emission of visible, u.v. and X-ray radiations as well as desorption of species from the target may occur. In the target itself several other processes can occur including amorphisation, implantation, compound formation, cascade generation, localised heating and the creation of point and lattice defects. A diagram by Mattox⁴ illustrates most of these effects. See **Figure 3.1**.

Sputtering of Compound Targets

So far it has been more or less implicit that the target is an elemental metal. However compound targets can also be sputtered. What is more the growing coating will have the same composition as the target provided, the target is maintained sufficiently cool to avoid diffusion of constituents, the target does not decompose, reactive contaminants are not present, the gas phase transport of the components is the same, and the sticking coefficients for the components on the substrate are the same. It should be noted though that initially element(s) of the compound target with the highest sputtering yield will preferentially evolve. This leaves an altered layer on the target surface containing predominantly low yield element(s). It is essential that diffusion of high yield material from the bulk does not replenish this altered layer if the film composition is to reflect that of the target.

Reactive Sputtering

This will be treated in more detail in Chapter 5. Suffice to say here that this technique introduces a reactive gas to the sputtering system to enable growth of compound films. Titanium Nitride is by far the most successful and widely deposited example of such a coating.

3.3



Figure 3.1: Schematic⁴ of the effects on the surface and the subsurface region due to bombardment by energetic species. Surface effects include (i) desorption of weakly bonded surface species (ii) ejection of secondary electrons (iii) reflection of the energetic species as high energy neutrals (iv) sputter ejection ("physical sputtering") of surface atoms by momentum transfer through collision cascades (v) sputtering and redeposition of sputtered species by collisions in the gas phase, by ionisation and acceleration back to the surface (vi) enhanced surface mobilities of atoms on the surface (vii) enhanced chemical reaction of adsorbed species on the surface to produced condensed species (reactive deposition) or volatile species (reactive ion etching). Subsurface effects include (i) the impinging particles may be physically implanted (ii) the collision cascades cause displacement of lattice atoms and the creation of lattice defects (iii) surface species may be recoil implanted into the subsurface lattice (iv) mobile species may be trapped at lattice defects (v) much of the particle kinetic energy is converted into heat.

III. Diode Sputtering

In this simple arrangement a target is located within a vacuum chamber and biased negatively. The chamber is evacuated to high vacuum and then backfilled with an inert gas. The target is negatively biased and a glow discharge plasma is ignited. It is noted that the nature of the plasma is such that virtually the entire discharge potential is dropped from the plate to a distance several millimetres away. This region is referred to as the cathode sheath. Those parts of the target where a discharge is not desirable are shielded. Positively charged Argon ions in the glow diffuse to the target vicinity, see a large negative sheath potential and are accelerated to impact on the target causing sputtering as previously discussed. These sputtered target atoms may then find their way to the substrates to form a coating. Typical operating parameters are a pressure of 10^{-1} mbar, a potential of 1000 - 5000 Volts, a current density of 1 mA cm⁻² and a (very slow) deposition rate of 40nm per minute. **Figure 3.2** illustrates the idea.



Figure 3.2: Representation³ of the plasma in a diode sputtering source

IV. Planar Magnetron Sputtering

The first planar magnetron sputtering system was described by Chapin⁵ in 1974. The importance of the work lies in the high sputter rates which are achievable with his device as compared with ordinary diode sputtering. Even today, 22 years on, the fundamentals of the original design are unchanged. Furthermore, basic concerns expressed in the original paper are still topical. Examples are the poor target utilisation inherent in the technique and arcing on the target surface.

There have been considerable advances however and amongst these have been the use of a feedback mechanism for closed loop control of reactive sputtering processes (See Chapter 5), the development of unbalanced magnetrons (See Chapter 4) and the relatively recent appreciation of the advantages of closed magnetic field multiple magnetron configurations for coating three dimensional parts (See Chapter 2).

The standard magnetron geometry is similar to that of a diode arrangement but with a magnetic circuit located behind the target such that magnetic field lines form as shown in **Figure 3.3**⁶. The parallel component of magnetic field above the target surface should be in the range $0.02 - 0.05 \text{ T}^5$. The magnetic and electric fields then conspire to form an electron trap along a racetrack in the vicinity of the target. This increases the plasma density hence the number of ions bombarding the target per second, hence the sputtering rate and so the deposition rate. The target potential for a magnetron is typically in the range 300-700Volts negative with respect to ground. The cathode current density is typically 20mA cm⁻². Operating pressures are typically in the 1-20 mbar range. Growths on the order of 1um per minute are routine for metal coatings.

Furthermore the low operating pressure in magnetron sputtering means that redeposition of sputtered materials back onto the target is less likely. This is another factor which acts to increase deposition rate. The main deposition rate limiting factors in magnetron sputtering are the thermal conductance of the target, the efficiency of the water cooling, the melting point of the target material and the target sputtering yield.



Figure 3.3: Schematic⁶ of a circular and a rectangular magnetron. The combination of electric and magnetic fields encourages electron drift in the directions indicated. The paths are closed in the form of a racetrack. This is to force electrons to circulate in front of the cathode. High plasma densities result.

Yet another advantage of magnetron sputtering is that sputtered atoms are less likely to lose energy in collisions. This implies greater activation of the growing film which leads to denser coatings. Contrarywise a carefully designed magnetron can minimise ion bombardment by comparison with a diode. This is important when coating thermally sensitive substrates. With all these advantages it is easy to see why magnetron sputtering has completely supplanted the d.c. diode growth method.

In typical operation the vacuum chamber is evacuated to high vacuum. It is then backfilled with an inert gas (usually Argon) to a pressure in the 0.5 to 30 mtorr range. The magnetron is then ignited at very low power and the substrate biased several hundred volts negative. Thus a magnetron assisted d.c. etch of the substrate takes place. This could last for as long as believed necessary to get it clean. Next the substate bias is reduced, speaking in absolute terms, to less than 200Volts negative. The magnetron power is increased and a dense glow discharge is initiated. The power supply unit should have good arc suppression capabilities for high power operation. It should also have a ramp up capability to minimise thermal shock to sensitive targets. The glow forms a racetrack above the target and material is sputtered from this region onto the substrate. The bias on the substrate acts to increase ion bombardment energy and so densify the coating. By introducing controlled amounts of a reactive gas it is possible to obtain compound coatings in the manner indicated in the reactive sputtering section. Upon completion of the growth the substrates should be allowed to cool before being exposed to atmosphere. Spallation of the coating may occur otherwise.

V. Initial stages of Coating Growth

Imagine following an atom from a coating stream down onto the surface of a substrate. The atom will impart most of its energy to the substrate lattice. It may stick immediately to the substrate surface at the point of impact. It may move around (surface diffusion) during which time it could be resputtered, evaporated, or simply find an energetically favourable site and remain there. Finally it may diffuse into the bulk of the coating. Temperature is the important parameter in determining which of these phenomena is observed.



(c)

Figure 3.4: Electron⁷ micrographs of silver island films (a) without ion bombardment; (b) with weak ion bombardment; (c) with strong ion bombardment.

Initial growth of a solid film on a substrate is primarily dependent upon the relative values of the adatom-adatom and adatom-substrate (cohesive and adhesive) interaction energies. There are three classifiable growth modes. Island or Volmer-Weber growth is characterised by nucleation and growth of adatom islands on the substrate surface. This occurs when the cohesive energy to the first order exceeds the adhesive energy. Islands may only become stable after reaching a critical size. Layer or Frank-van der Merve growth occurs when the adhesive energy is greater than the cohesive energy so that the initial atoms form a complete monolayer before forming a second and so on.
Such growth is contingent upon the decreases in binding energy being monotonic towards the bulk crystal value. Intermediate layer-plus-island or Stransky-Krastinoff growth is when island growth dominates after a few monolayers.

Effect of Ion Bombardment on Initial Growth Stages

Ion bombardment of the substrate may cause increased surface diffusion by excitation of surface phonons and may lead to impact induced break up of nucleation clusters of less than some critical size. Above this size islands may be stable because the arrival of adatoms more than compensates for the destructive ion break-up. See Figure 3.4. Computer simulations may be helpful in understanding these effects.

Finally note that in general these growth mechanisms are of greater relevance to techniques such as Molecular Beam Epitaxy (MBE) which have much lower atom arrival rates at the substrate than magnetron sputtering so a pseudo equilibrium condition can be brought about. In MBE ion bombardment has been used successfully to produce epitaxial coatings at temperatures lower than those normally associated with epitaxial growth. Ultra-high vacuum, low supersaturation, high surface diffusion and lattice matching between the deposited film and the crystalline substrate are all necessary for epitaxial growth⁸. Magnetron sputtering by contrast is generally a far from equilibrium technique and metastable structures are the order of the day.

VI. Subsequent Growth - Structure Zone Models

Zone models provide a qualitative understanding of coating structure. The initial model was described by Movchan and Demchischin⁹ in 1969. This was based on results they had obtained for thick (0.3-2mm) coatings of Ti, Ni, W, ZrO_2 and Al_2O_3 deposited by evaporation. The typical dimensional scale of the structural features described is of order 0.1-1.0 um. The zone model highlights the importance of adatom mobility in determining film structure. It uses the temperature of the film during deposition normalised to its bulk melting point (i.e. T/T_m) as the parameter describing thermally induced mobility. The resulting classic diagram is illustrated in **Figure 3.5**. This shows three structural zones.





Zone 1 where $T/T_m < 0.3$ consists of tapered grains with domed tops. These grains have voided boundaries. Mechanically the coating is hard but laterally weak. The internal structure of the grains is poorly defined with a high dislocation density. The grain diameter increases with T/T_m which is an indication of limited surface diffusion. Electrical resistivities may be orders of magnitude higher than in the bulk material due to oxidation at the open boundaries.

Zone 2 where $(0.3 < T/T_m < 0.5)$ also has a columnar microstructure but here the grain boundaries are well defined. Dislocations are usually confined to these boundary regions. As before grain diameter increases with T/T_m and may extend through the coating thickness for high T/T_m . Metallic properties are similar to cast metals.

Zone 3 where $(T/T_m < 1)$ has an equiaxed structure due to bulk diffusion. Again the grain size increases with T/T_m . For metallic deposits properties are similar to fully annealed bulk metals.

In 1974 the model of Movchan and Demchischin was extended by Thornton¹⁰ to include magnetron sputter deposited films. This was done by adding an extra axis to the original zone diagram to take account of the effects of sputtering gas pressure. Thornton also recognised the existence of an additional transition zone between zones

1 and 2 consisting of poorly defined fibrous grains with sufficiently strong grain boundaries to give respectable mechanical properties. This he called Zone T. The Zone T structure has been defined by Craig and Harding¹¹ as the limiting form of the Zone 1 structure at zero T/T_m on infinitely smooth substrates. The Thornton structure zone diagram is illustrated in **Figure 3.6**.



Figure 3.6: Structural Zone Model¹⁰ for sputtered metal coatings

Zone 1 with its open grain boundaries results when adatom diffusion is insufficient to overcome the effects of surface shadowing. Shadowing induces open boundaries because high points on the surface receive more coating flux than valleys. It is caused by surface roughness which can result from the shapes of the initial nucleii, from preferential nucleation at substrate inhomogeneities, from substrate roughness and preferential growth¹². This effect is exacerbated when there is a significant oblique component in the coating flux. At higher pressures the oblique component is enhanced by collisions. It is also present when coating 3-D parts.



Figure 3.7: Cross section¹² showing Zone 1 boundary formation in sputtered cobalt alloy at low points on a rough substrate

The zone 1/T structure was first modelled by Henderson, Brodsky and Chaudhari¹³. They treated the coating atoms as hard spheres impacting at a 45 degree angle which were allowed to relax only to the nearest "pocket" where they could make contact with previously deposited spheres. Dirks and Leamy¹⁴ performed similar tests for normal and oblique incidence. Interestingly when two impacting species of different size were used to simulate binary alloy deposition the number of voids increased. Both sets of results highlight a tendency for columns to lean toward the incident flux. They also indicate a coating density which is substantially less than that observed by experiment. This led to the suspicion that the columns might be an artifact of the low coating density. So Kim. Henderson and Chaudhari¹⁵ performed a simulation in which the sticking coefficient was less than unity. The result was a dense coating with retention of the columnar orientation. The columns were more difficult to identify visually. However, a plot of the distribution in directions of the contacting pairs shows that this model yields an even higher degree of structural anisotropy than the lower density deposits. This is taken to be a Zone T structure. The important role of adatom mobility in formation of this structure is clear.

The models mentioned above suggest that Zone 1 structures have a voided sponge-like inter and intra granular anatomy. Support for this is an observation by Westwood¹⁶ of an inverse relationship between film density and sputter gas pressure in platinum films. In addition TEM studies by Nakahara¹⁷⁻²⁰ and colleagues and also Fabis²¹ indicate large numbers ($10^{10} - 10^{12}$ cm⁻²) of small (10 - 50Å) voids in sputtered, evaporated and electroplated films. Voiding was most pronounced near the substrate surface.

With regard to Zone 2 Thornton defines it as that region of the structure zone diagram where adatom surface diffusion effects dominate. He makes partial use of a model developed by Van der Drift²². See Figure 3.8.

This Figure shows schematics of crystal growth under various extreme conditions. Fig 3.8a shows the effect of zero surface diffusion and zero condensation coefficient. The coating flux is normal with some side scattering to avoid one dimensional crystals. The orientation of the initial nucleii is preserved. The structure is Zone T. Figure 3.8b illustrates the case of zero surface diffusion and a condensation coefficient which

3.12

depends on the substrate crystallographic surface. Here the crystal face which receives the most coating flux grows out of existence. The resulting structure is Zone 1. Figure 3.8c illustrates the case of infinite surface diffusion. The growth flux is redistributed so there is no dependence on condensation coefficient. The growth rate is assumed to be the same on all crystal planes. The direction of fastest growth is from the centre to the farthest point on the crystal. This is a dense columnar Zone 2 structure. Figure 3.8d is similar to Figure 3.8c except that periodic renucleation is allowed. The columnar structure is still evident.



Figure 3.8: Two dimensional growth structures constructed for several extreme cases of adatom surface diffusion. (a) Zero surface diffusion, unity condensation coefficient. (b) Zero surface diffusion, condensation coefficient dependent on crystallographic surface (c) Infinite surface diffusion (d) Infinite surface diffusion with periodic renucleation.

Zone 3 is defined as the region of the zone diagram where bulk diffusion has a dominant influence on the coating microstructure. Spontaneous nucleation coupled with the bulk diffusion allows for an equiaxed grain structure of a type commonly observed when the homologous temperature is greater than ~ 0.5 . Occasionally open boundaries are observed¹².

Energetic Ion & Neutral Bombardment and Coating Structure

Energetic particle bombardment is commonly used to modify coating structure during low temperature in-vacuum deposition. Its effects were highlighted by Mattox²³ in the context of ion plating. In the magnetron sputtering technique energetic ions and neutrals may all impinge on the surface of a film as it is growing. Neutrals give up momentum and energy as do ions which also give up their charge. The major effects of all this are to increase adatom mobility, to cause sputtering from and perhaps redeposition back onto the growing film and to cause preferential erosion of roughness peaks. This means that atoms are more likely to find energetically favourable sites on the growing surface. The consequence is that changes in average grain size, the degree or direction of orientation, film stress, film density and the number of voids are observed. A commonly encountered example is the use of bombardment to effect a Zone T instead of a Zone 1 coating microstructure. Thornton¹⁰ found that for copper at low T/T_m the suppression of open boundaries required an ion bombardment flux adequate to resputter a significant proportion of the incident coating flux (i.e. 30 -60%) and that this magnitude increased with the magnitude of incident surface irregularities. A structure zone diagram due to Messier et al^{24,25} which illustrates the combined effects of substrate bias voltage and substrate temperature on the grain structure of sputtered metal film is given in Figure 3.9.

Theoretical support, based on molecular dynamic calculations, for these experimental results has been given by Muller²⁶ who found that a) ion bombardment during growth removes overhanging atoms and causes void regions to remain open until filled by new depositing atoms b) sputtered atoms are redeposited mainly in voids c) ions induce surface diffusion (diffusion distance is a few interatomic spacings), local heating,

collapse of voids and recrystallisation. Two snapshots are given which illustrate the densification effect. See Figure 3.10.

Both ion energy and ion neutral flux ratio are critical parameters if full packing density is to be achieved. When film packing density is low the microstructure will be sensitive to increases in bombarding ion energy. This effect fades as the regime of fully dense films is reached. The effect of ion neutral ratio on packing density for ion energies of 10eV and 50eV is illustrated²⁷ in **Figure 3.11**. The effect of ion energy at fixed ion to neutral is shown²⁷ in **Figure 3.12**. Rohde²⁸ makes the point that the ion to neutral ratio is nearly constant for a given system geometry, gas species and cathode material. Simply increasing the discharge current does nothing as the neutral deposition rate will increase correspondingly. So to achieve a greater range of bombardment levels some means of independently controlling the ion current density is required. A graphic illustration of the effect of ion bombardment on a Titanium Nitride coating is given by Bull and Rickerby²⁹. See **Figure 3.13**.



Figure 3.9: Structure Zone Diagram of Messier et al²⁴



Figure 3.10: Structural evolution at the surface of a Nickel film during the impact of 100eV Argon ions²⁷



Figure 3.11: Packing density²⁷ as a function of the ion to atom flux ratio, j_I/j_A , for Argon ion energies of E = 10 eV and E = 50 eV



Figure 3.12: Packing density²⁷ versus Argon ion energy, E, for a fixed ion to atom flux ratio of, $j_I/j_A = 0.16$



Figure 3.13: SEM pictures of an (a) unbiased and (b) -60V biased Titanium Nitride coating deposited onto a Stainless Steel substrate by magnetron sputtering.

VII. Adhesion

Introduction

The ASTM defines adhesion as the "condition in which two surfaces are held together by either valence forces or mechanical anchoring or by both together". Adhesion is dependent on substrate cleanliness, topology, roughness, composition, microstructure and coating stress.

Classification

Adhesion is often classified into five distinct types depending on the microstructure of the coating substrate interface. This is illustrated in **Figure 3.14**. However it should be noted that most interfaces comprise a superposition of more than one of these.

Mechanical anchoring is found on rough surfaces. The coating material impinges onto the substrate and 'keys' into it. This type of adhesion is particularly important in thermal and plasma spraying where surfaces to be coated are usually grit blasted.

Abrupt interfaces are characterised by an abrupt transition from the film material to the substrate material. The transition region has a thickness in the range 2-5Å. An example is gold on NaCl. Interfaces of this type form when no diffusion occurs, there is little chemical reaction, and the substrate surface is dense and smooth.

Chemical bonding interfaces are characterised by a constant chemical composition across several atomic layers. They result from chemical reactions between film and substrate atoms.

Diffusion interface layers can be formed when there is at least partial solubility (interdiffusion) between the substrate and film materials. They are usually encountered in high temperature CVD coatings. The interphase material formed may be brittle, have Kirkendall voids, and develop stress induced microcracks. Voids are especially likely when diffusion rates of film and substrate materials are different.

Pseudo-diffusion interface layers are formed by ion implantation into the substrate with subsequent film growth. By contrast with diffusion interface layers they can form from materials which do not mutually diffuse. The 'solubility' may be enhanced by point defects and stress gradients created during substrate bombardment.



Figure 3.14: Classification of the various modes of adhesion after Hintermann³⁰

Improving Adhesion

1) Substrate cleaning is important in obtaining good adhesion of the coating. If the substrate isn't clean then inconsistant results are likely. Furthermore porosity, colour variation and failure in application are more probable.

Typical treatments are substrate dependent but might involve a vapour degrease to get rid of organic contaminants and an alkaline or acid rinse to get rid of inorganic contaminants. There would also be intermediate water rinses. Ultrasonic baths are often used. Where the substrate is rough a mild grit blast is used. It is noted that there is currently a trend away from organic vapour degreasing because of the environmental ozone depletion capability of the freons released. Unquestionably it will soon be phased out altogether.

2) The substrate can be sputter cleaned to reveal a fresh substrate surface. In situ r.f plasma etching of the substrate is preferable to d.c. since the former can etch away any remaining insulating contaminants. In the case of compound substrates preferential sputtering may reveal a more receptive surface chemistry.

3) A good strategy for improving adhesion is to use an interlayer. The interlayer should bond well to the substrate and the subsequent layer. Multiple and graded interlayers are often used in vacuum technologies. An example is the low temperature \sim 300C deposition of Titanium Nitride. Here a Titanium 'primer' is used. This leads to the more general point that for good adhesion the compatibility of the coating and substrate must be considered.

VIII. Film Stress

Stress is commonly observed in PVD coatings due to the low deposition temperatures. It often causes delamination from the substrate in the form of buckling, spallation or cracking into platelets. It has two components.

Thermal stress is due to the thermal mismatch between coating and substrate. It is given by the equation

$$\sigma_{\rm th} = {\rm E}_{\rm f}(\alpha_{\rm f} - \alpha_{\rm s})({\rm T}_{\rm s} - {\rm T}_{\rm a})$$

where E_f is the Youngs modulus, α_f and α_s are the average coefficients of thermal expansion for the film and substrate, T_s is the substrate temperature during deposition and T_s is the temperature during measurement. The stress is tensile when $\alpha_f > \alpha_s$. It can be larger than the yield strength of the film.

Intrinsic stress arises from the microstructure of the coating. It occurs due to the energy and flux of bombarding particles, or 'atomic peening', during the growth



Figure 3.15: A stress pattern in an amorphous carbon hydrogen film deposited by PECVD. The sin wave can be observed under the microscope as it extends across the coating. Atmospheric humidity and light from the microscope appear to exacerbate the situation leading to more rapid coating failure.

process. It may be tensile or compressive generally going from the former condition to the latter with increasing coating density. It is often greater than the yield strength of the coating. It may relax at low temperatures (T/T_m in the range 0.1 to 0.3 where T_m is the melting point of the coating). This is known as recovery. At higher T/T_m (0.3-0.5), the stresses are relaxed by the recrystallisation of the strained grains into new strain free grains³¹. We will return to the topic of process effects on stress later. **Figure 3.15** provides a good illustration of buckling failure due to compressive intrinsic stress in an amorphous carbon hydrogen coating grown by PECVD in a methane plasma. Here sinusoidal stress patterns propagate from an initiation site(s). Then additional buckles branch in directions normal to the sinusoidal paths thus forming a regular network. This pattern often begins to form when the sample is taken outside the vacuum chamber. High humidity accelerates the effect.

Stress in a film will cause a thin (say < 0.1mm) substrate to bend. For a circular disc this bending can be used as an indication of stress according to the well known³² formula

$$\sigma = \frac{4\mathrm{d}}{\mathrm{D}^2} \frac{\mathrm{E}_{\mathrm{s}}}{3(1-\nu)} \frac{\mathrm{t}_{\mathrm{s}}^2}{\mathrm{t}_{\mathrm{f}}^2}$$

where D is the disc diameter, d is the deflection, t_s and t_f are substrate and film thickness respectively, E_s is the Young's modulus of the substrate and ν is Poissons ratio. The deflection (d) can be measured using an optical microscope. So the stress can be estimated.

IX. Conclusion

A review of magnetron sputtering and a detailed description of important issues concerning the coatings which can be produced has been presented.

Introduction

Magnetron sputtering and many of the various vacuum coating technologies described depend for their functionality on the use of plasma environments. Therefore it makes sense at this point to describe this fourth state of matter in the context of in vacuo film growth.

A plasma can be defined as a gas which is to some extent ionised. It can be categorised according to two parameters, the free electron density, usually referred to as the plasma density, and the kinetic energy of the electrons, or electron temperature. Both electron and ion species may individually be in thermodynamic equilibrium, i.e. obey Maxwell-Boltzmann statistics, but the system as a whole does not. The kinetic temperature of the ions\neutrals will be much less than the electron temperature because of the greater mass of the former. A consequence is that the electrons may be regarded as moving rapidly against a stationary cold ion background.

Plasmas are created and sustained by judicious arrangement of electric and magnetic fields. We start by considering single charged particle motion in the presence of such fields. In the case of very low pressure plasmas, where the mean free path between collisions is large, such descriptions are perfectly adequate.

Individual Charged Particle Motion in Electric and Magnetic Fields

In order to simplify understanding of process plasmas the motion of individual particles in the absence of collective or simple diffusion effects is first considered. Here the particles will obey the equation of motion

$$\frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t} = \frac{\mathrm{e}}{\mathrm{m}} \left(\mathbf{E} + \mathbf{v} \times \mathbf{B} \right)$$

where E is the electric field, v the particle velocity, B the magnetic field and m the particle mass. The electric field term represents a simple acceleration. An examination of the velocity\magnetic field term indicates that particles tend to follow field lines while also orbiting around the lines. Therefore the described trajectory tends to be helical.

Another way of viewing this motion is in terms of drifts^{33,34}. For instance in mutually perpendicular E & B fields a particle will drift with velocity

$$\mathbf{v}_{\mathrm{E}\times\mathrm{B}} = \frac{\mathbf{E}\times\mathbf{B}}{\mathbf{B}^2}$$

A particle with velocity v at right angles to the B-field will yield a similar v x B drift

$$\mathbf{v}_{\mathbf{v}\times\mathbf{B}} = \mathbf{q}\cdot\mathbf{v}\times\mathbf{B}$$

A particle exposed to a magnetic field gradient ∇B will drift in a direction perpendicular both to the gradient and the magnetic field directions. This occurs because the cyclotron radius will be smaller on the high field side of the orbit than on the low field side. The velocity is given by

$$\mathbf{v}_{\mathbf{B}\times\nabla_{\perp}\mathbf{B}} = \frac{\mathbf{r}_{\mathbf{c}}\,\mathbf{v}_{\perp}}{2}\frac{\mathbf{B}\times\nabla_{\perp}\mathbf{B}}{\mathbf{B}^{2}}$$

where r_c is the radius at which a charged particle orbits a magnetic field line.

A particle travelling along a curved field line will experience a centripetal force. This causes a motion given by

$$\mathbf{v}_{\mathrm{R}\times\mathrm{B}} = \frac{\mathbf{v}_{\parallel}^{2}}{\mathbf{R}\boldsymbol{\omega}_{c}} \frac{\mathbf{R}\times\mathbf{B}}{\mathbf{B}\mathbf{R}}$$

where R is the radius of curvature of the field line, v_{\parallel} is the velocity along the field line and w_c the frequency of revolution about the field line. The motion is perpendicular both to the field and its direction of curvature.

Yet another type of drift is known as magnetic mirroring. This occurs under adiabatic conditions.

Then the magnetic moment μ given by

$$\mu = \frac{W_{\perp}}{B} = \frac{m v_{\perp}^2}{2B}$$

is invariant between collisions. $W_{\!\!\perp}$ is the perpendicular energy of the particle. The expression for $v_{\!_{\|}}$ is

$$v_{\parallel} = \sqrt{(2(W - \mu B)/2)}$$

where W is the constant total kinetic energy of the particle.

With increasing magnetic field it can be seen that v_{\parallel} will eventually equal zero and then go negative, i.e. the particle is reflected. If at the initial particle position the field is B_o and if at the position of reflection the field is B_m then at B_o , $\mu = W_{\perp}/B_o$ and at B_m , $\mu = W/B_m$. The latter equation results because at the point of reflection $W = W_{\perp}$. Then the condition for mirroring is

$$\frac{B_e}{B_m} = \frac{v_\perp^2}{v^2} = \sin^2 \theta = \frac{1}{R}$$

where θ is the pitch angle of the helix at $B = B_0$, and R is defined as the mirror ratio. Particles with pitch angles greater than θ will be reflected while the remainder will have too much parallel velocity and are not reflected. These equations will resurface again when magnetrons are discussed in more detail. Next we move on to discuss diffusion effects which become important as plasma pressure is increased.

Many Particle Motion - Diffusion

If it is desired to take diffusion into account then the situation becomes more complicated. This is due to the various types of collisional interaction that may occur. A selection of those relevant to magnetron discharges is

(1)
$$e + X \rightarrow X^* + e$$
 (10) $e + X \rightarrow X^- + hv$

(2)
$$e + X^* \rightarrow X^{**} + e$$
 (11) $X^- + h\nu \rightarrow e + X$

(3)
$$e + X^* \rightarrow X + e$$
 (12) $e + YZ^+ \rightarrow Y + Z^*$

- (4) $e + X \rightarrow X^+ + e + e$ (13) $X + Y^+ \rightarrow X^+ + Y$
- (5) $e + X^* \rightarrow X^+ + e + e$ (14) $X^- + Y^+ \rightarrow XY$
- (6) $e + e + X^+ \rightarrow X + e$ (15) $X^* + Y \rightarrow X + Y^*$
- (7) $e + YZ \rightarrow e + Y^+ + Z^-$ (16) $X^* + Y \rightarrow X + Y + K.E.$
- (8) $e + YZ \rightarrow e + Y + Z$ (17) $X^* + Z \rightarrow X + Z^+ + e$
- (9) $e + YZ \rightarrow Y + Z^-$ (18) $e + X \rightarrow X^{++}e^+e^-$

where e, X or Y or Z, X*, X**, X+ represent electrons, atoms, excited atoms, doubly excited atoms, ions and doubly charged ions respectively. The processes are referred to by the names electron collisional excitation (1), (2), superelastic collision of an excited atom and electron (3), electron collisional ionisation (4), (5), collisional

recombination (6), dissociation & ionisation (7), (8), (9), radiative attachment (10), photo-detachment (11), dissociative recombination (12), charge transfer (13), ion-ion recombination (14), excitation exchange (15), (16), Penning ionisation (17). Of these the most important interactions are (1) and (4).

The scenario raises an obvious question. Why don't the ions and electrons all recombine to form a neutral gas again? The reason is that the heat of neutralisation cannot be dissipated in such a way as to conserve energy and momentum. This can only happen during rare three body collisions or at a surface. Consequently vacuum chamber fixtures are set at a remove from the plasma environment.

The complexity of this environment compared to the gaseous one is evident from the interactions listed above. In a monatomic gas the collision mean free path is given simply by

$$\lambda = \frac{1}{\sqrt{2} n 4 \pi a^2}$$

on the assumption that the atoms are hard spheres with radius a. In a plasma there are myriad different reactions all having their own differential velocity dependent cross sections. So any calculation of the mean free path must take these different interactions into account. In general such calculations necessitate a fast computer.

Nonetheless one equation which is worth mentioning is the Langevin equation

$$\frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t} = \frac{\mathrm{e}}{\mathrm{m}} \left(\mathbf{E} + \mathbf{v} \times \mathbf{B} \right) - \mathrm{m}\,\mathrm{v}\,\upsilon_{\mathrm{m}}$$

where $v_m = n \sigma(v) v$ is the collision frequency for momentum transfer from electrons to background ions and neutrals. It is the simplest model to include interactions between particles in a plasma.

Collective Diffusion³⁵

A singular feature of plasmas in comparison to ordinary gases is the collective behaviour which may be exhibited. Such behavior is a result of long range forces. These are Coulombic in nature. They can be significant because for a given solid angle the volume of plasma subtended by another plasma volume increases with distance according to a cubed law whereas the Coulomb force decreases according to a squared law. Another way of looking at this is as follows.

An isolated charge in the plasma will tend to electrostatically drag opposite charges to its vicinity. This has the effect of shielding the field due to the original charge. This shielded potential may be derived using thermodynamics and Poissons equation. The expression is given by

$$V(r) = \frac{Q}{4\pi\varepsilon_o r} \cdot e^{-r/\lambda_D}$$

where Q represents the isolated charge, r the field point, ε_0 the permittivity of free space, and the characteristic Debye shielding distance is given by

$$\lambda_{\rm D} = \sqrt{\frac{{\rm k} {\rm T_e} \varepsilon_o}{{\rm ne}^2}} = 743 \sqrt{\frac{{\rm T_e}}{{\rm n}}} {\rm cm}$$

where k is the Boltzmann constant, n the electron number density, T_e is the electron temperature and e is the electronic charge.

The numerical value of $\lambda_{\rm D}$ provides an important criterion for deciding whether collective effects are to be expected. If the plasma dimension is small compared with $\lambda_{\rm D}$ then shielding will not be significant and ordinary interparticle collisions such as those listed above will result. Conversely if $\lambda_{\rm D}$ is much less than the plasma dimension a collision may involve not only the test charge but also its surrounding 'cloud' of charge. Taking reasonable values for a magnetron plasma, i.e. electron temperature equal to 5eV and charge number density equal to 10¹⁰ per cm³, we get $\lambda_{\rm D} = 0.017$ cm. This is small compared to a typical laboratory plasma dimension of the order of 10 cm. So by

this indicator collective effects are to be expected in magnetron plasmas. Another important plasma parameter is the characteristic plasma frequency. This is an indication of the time the plasma needs to respond to an applied field. For electrons it is given by

$$\omega_{\rm p} = 5.64 \times 10^4 \times \sqrt{n \, (\rm cm^{-3})}$$

Collective effects are highly complex. Highly sophisticated computer aided treatments are required. These have not to date been attempted in the literature. So these phenomena will not be gone into here. It turns out that a good understanding of magnetron sputtering plasmas can be achieved without invoking them.

References

3.1) P. Sigmund, Phys. Rev. 17, 396, (1980).

1.1

- 3.2) P. Sigmund, J. Vac. Sci. & Tech. 184, 383, (1969).
- 3.3) J.F. Thornton in R.F. Bunshah (Ed) "Deposition Technologies for Films and Coatings", Noyes Publications, pg 170 et seq. (1982).
- 3.4) D.M. Mattox, J. Vac. Sci. & Tech. A 7 (3) 1105 (1989).
- 3.5) J.S. Chapin, U.S. Patent 4,166,018 (1979).
- 3.6) S.M. Rossnagel in J.L. Vossen and W.L. Kern (Eds), "Thin Film Processes II"
 Academic Press, pg. 11 et seq, (1991)
- 3.7) M. Marinov, Thin Solid Films, 46 pg 267 (1977).
- S. Xu, L. Evans, D.I. Flynn, and C. En, "*Thin Solid Films*", 238 pg 54 (1994).
- 3.9) B.A. Movchan and A.V. Demchischin, *Phys. Met. Metallog.* 28 pg 83 (1969).
- 3.10) J.A. Thornton, J. Vac. Sci. & Tech. 11 pg 666 (1974).
- 3.11) S. Craig and G.L. Harding, J. Vac. Sci. & Tech. 19, pg 205 (1981).
- 3.12) J.A. Thornton in R.A. Huggins, R.H. Bube and R.W. Roberts (Eds) "Annual Reviews of Materials Science" Vol 7 pg 239 (1977)
- J. Henderson, M. H. Brodsky and P. Chaudhari, Appl. Phys. Letts. 25, pg 641 (1974).
- 3.14) A. G. Dirks and H. J. Leamy Thin Solid Films 47, pg 219 (1977).

- 3.15) S. Kim, D. J. Henderson and P. Chaudhari 47, pg 155 (1977).
- 3.16) W. D. Westwood, J. Vac. Sci. & Tech. 11, pg 466 (1974).
- 3.17) J.R. Loyld and S. Nakahara, J. Vac. Sci. & Tech. 14 pg 655 (1977).
- 3.18) A. Staudinger and S. Nakahara, Thin Solid Films 45, pg 125 (1977).
- 3.19) S. Nakahara, Thin Solid Films 45, pg 421 (1977).
- 3.20) S. Nakahara, K Kuwahara and A Nishimura, *Thin Solid Films* 72 pg 297 (1980).
- 3.21) F. M. Fabis, Thin Solid Films 128 pg 57 (1985).
- 3.22) A. Van Der Drift, Philips Res. Rpt. 22, pg 267 (1967).
- 3.23) D.M. Mattox in R.F. Bunshah, "Deposition Technologies for Films and Coatings", Noyes Publications pg 244 (1982).
- 3.24) R. Messier, A. P. Giri and R. A. Roy, J. Vac. Sci. & Tech. A2 pg 500 (1984).
- 3.25) R. Messier and J.E. Yehoda, J. Appl. Phys. 58 (10) pg 3739 (1985).
- 3.26) K.-H. Muller, Phys. Rev. B 35 pg 7906 (1987)
- 3.27) K.-H. Muller in J.J. Cuomo, S.M. Rossnagel and H.R. Kaufman (Eds), *"Handbook of Ion Beam Processing Technology"*, Noyes Publications, pg 241
 et seq, (1989).
- 3.28) S.L. Rohde in M.H. Francombe and J.L. Vossen (Eds), "*Plasma Sources for Thin Film Deposition and Etching*", Academic Press, pg 235 et seq (1994).

- 3.29) S.J. Bull and D.S. Rickerby in D.Dowson, C.M. Taylor and M. Godet (Eds),"Mechanics of Coatings", Elsevier, pg 339, (1990).
- 3.30) H.E. Hintermann in Hans K. Pulker (Ed), "Wear and Corrosion Resistant Coatings by CVD and PVD", Expert Verlag, pg 56 (1989).
- 3.31) J.A. Thornton & D.W. Hoffman, Thin Solid Films, 171 pg 5 (1989).
- 3.32) L. Maissel and K. Glang, "Handbook of Thin Film Technology", McGraw Hill (1970).
- 3.33) J.L. Cecchi in S.M. Rossnagel, J.J. Cuomo and W.D. Westwood (Eds),
 "Handbook of Plasma Processing Technology", Noyes Publications, pg 14 et seq (1990).
- 3.34) J.A. Thornton and A.S. Penfold in J.L. Vossen and W.L. Kern (Eds), "Thin Film Processes", Academic Press pg 82 (1978).
- 3.35) F.F. Chen, "Introduction to Plasma Physics", Plenum N.Y. (1974).

Chapter 4 - The Magnetic Field in Sputter Magnetrons

I. Introduction

In this section a general description of the magnetic field in two dimensional rectangular sputter magnetrons is given. An equation in integral form is given which in principle enables the calculation of the magnetic field associated with any simple magnetron whose geometry may be regarded as being two dimensional. The equation is arrived at using conformal mapping techniques. It should facilitate theoretical analyses of magnetron operation. It will also be useful to the thin film researcher faced with designing a magnetron system. There are limitations on the materials that can be used and on the magnetic geometry but these are not unduly restrictive. In Chapter 5 the results are used to describe the field in the vicinity of a commercial planar magnetron manufactured by Teer Coating Services Ltd. in Hartlebury, UK.

In Section II the general assumptions which are implicit throughout the calculations are outlined. In Section III the magnetic stream function (field lines) and magnetic flux density in the vicinity of one or more infinite rectangular cylindrical magnets is described with the assumption that there are no ferromagnetic materials present. These results are later used to support the main calculation since they represent a particular limiting case. Section IV serves as an introduction to calculations involving ferromagnetics. Section V describes the main calculation and gives a completely general description of the magnetic field in the vicinity of a magnetic circuit comprising a single arbitrarily shaped two dimensional ferromagnetic and any number of magnets. Since magnetrons are very often made up of a single ferromagnetic plus magnets arrangement the calculation is directly relevant. Section VI simplifies the last result to give an exact description of the magnetic field in the vicinity of what may be referred to as the 'standard' rectangular sputter magnetron geometry. Section VII discusses variations on the standard geometry. Section VIII deals with the issue of unbalance in sputter magnetrons. Section IX is the conclusion.

II. Assumptions Regarding Magnets and Ferromagnetics

The following assumptions apply throughout

- All magnets are treated as being uniformly magnetised with locked-in magnetisation.
- 2) Magnet permeability is assumed equal to that of free space.
- All ferromagnetic material is treated as being infinitely permeable. This assumption is considered in more detail in Section IV.

The operating range of a permanent magnet lies on the demagnetisation curve in the second quadrant of the hysteresis loop. Characteristic demagnetisation curves for various magnetic materials are shown in **Figure 4.1**.

Generally speaking AlNiCo magnets have a high remanent field but low coercivity. In contrast ferrites have reasonable coercivity but relatively low remanent field. Rare earth Samarium Cobalt and Neodymium Iron Boron magnets have high remanance together with high coercivity. These magnets have demagnetisation curves that are linear over a large range with a B to H ratio close to the permeability of air μ_{o} . Substantial reverse fields are necessary to drive the magnet into the non-linear region. The magnet is uniformly magnetised throughout its volume. This combination of properties allows these magnets to be treated as if they have an effective magnetic charge density at either pole with an air gap in between. Thus, calculation of the magnetic field at a point outside these magnets becomes a matter of integrating over the sheet surface charge at both poles. Also the superposition principle applies such that contributions to the field at a point from various magnets may be added vectorially to yield the total field. Bonded rare earths and some ferrites may be similarly treated but they demagnetise more easily¹.



Figure 4.1: Characteristic demagnetisation curves for various magnetic materials (1, AlNiCo; 2, anisotropic barium ferrite; 3, bonded SmCo; 4, SmCo; 5, NdFeB)

III. Magnetic Field for an Infinite Rectangular Cylindrical Magnet

In this section we will work in the complex z-plane. So when a point charge is being discussed what is meant is the charge per unit length q of an infinite (i.e. long enough so that end effects can be neglected) uniform line of charge. The field due to such a point monopole is given by¹

Field=V+iA =
$$\frac{q}{2\pi} \cdot \ln(z - z_o)$$
 [4.1]

where V is the scaler potential and A the stream function. Also $z_0=x_0+iy_0$ and z=x+iy are the source and field points respectively.

For an infinite uniformly magnetised bar magnet of rectangular cross-section the contributions to the total magnetic field from the lines of monopoles corresponding to the north and south poles must be calculated by integrating along the lines and then adding the two results vectorially. The geometry is illustrated in **Figure 4.2**. This depicts the magnet with top pole (tp) terminating at points $z_1=(x_1,y_1)$ and $z_2=(x_2,y_2)$ and with bottom pole (bp) terminating at points $z_3=(x_3,y_3)$ and $z_4=(x_4,y_4)$. The vector sum of the contributions from both poles adds to give the resultant magnetic field.



Figure 4.2: The Calculation Geometry

Note also that $q = \sqrt{B_{rem}}$. So for the top pole

$$w_{1} = \frac{q}{2\pi} \int_{Z_{1}}^{Z_{2}} \ln(z - z_{0}) \cdot q \cdot dz_{0} = \frac{B_{rem}}{2\pi} \int_{Z_{1}}^{Z_{2}} \ln(z - z_{0}) \cdot dz_{0}$$
 [4.2]

Let $Z=z-z_0$, then $dZ=-dz_0$

Also, $Z_1 = (x - x_1) + i(y - y_1) = p_1 + iq_1$ and $Z_2 = (x - x_2) + i(y - y_2) = p_2 + iq_2$

$$w_{1} = -\frac{B_{rem}}{2\pi} \int_{Z_{1}}^{Z_{2}} \ln(Z) dZ \qquad [4.3]$$

Integrating by parts,

$$w_{1} = -\frac{B_{rem}}{2\pi} \left[Z \cdot \ln(Z) - Z \right]_{Z_{1}}^{Z_{2}}$$
[4.4]

and expanding,

$$\mathbf{w}_{1} = -\frac{\mathbf{B}_{\text{ream}}}{2\pi} \left[\mathbf{Z} \cdot \left[\frac{1}{2} \ln(\mathbf{p}^{2} + \mathbf{q}^{2}) + i \operatorname{Atn}\left(\frac{\mathbf{q}}{\mathbf{p}}\right) \right] - \mathbf{Z} \right]_{Z_{1}}^{Z_{2}}$$
[4.5]

Note that it is critical to be aware of the quadrant in which a coordinate point lies when calculating the arctan function.

$$\mathbf{w}_{tp} = -\frac{\mathbf{B}_{rem}}{2\pi} \begin{bmatrix} \left[\frac{1}{2}\mathbf{p}\cdot\ln\left[\mathbf{p}^{2}+\mathbf{q}^{2}\right]-\mathbf{q}\cdot\operatorname{Atn}\left(\frac{\mathbf{q}}{\mathbf{p}}\right)-\mathbf{p}\right]+\\ i\left[\frac{1}{2}\mathbf{q}\cdot\ln\left[\mathbf{p}^{2}+\mathbf{q}^{2}\right]+\mathbf{p}\cdot\operatorname{Atn}\left(\frac{\mathbf{q}}{\mathbf{p}}\right)-\mathbf{q}\end{bmatrix} \end{bmatrix}_{Z_{1}=p_{1}+iq_{1}}^{Z_{2}=p_{2}+iq_{2}}$$
[4.6]

Defining $Z_3 = (x - x_3) + (y - y_3) = p_3 + iq_3$ and $Z_4 = (x - x_4) + (y - y_4) = p_4 + iq_4$ gives a corresponding expression for the bottom pole of the magnet,

$$w_{bp} = -\frac{B_{sem}}{2\pi} \begin{bmatrix} \frac{1}{2} p \cdot \ln[p^2 + q^2] - q \cdot Atn\left(\frac{q}{p}\right) - p \end{bmatrix} + \begin{bmatrix} z_{q^2 p_{q^2} + iq_{q^2}} \\ i\left[\frac{1}{2} q \cdot \ln[p^2 + q^2] + p \cdot Atn\left(\frac{q}{p}\right) - q \end{bmatrix} \end{bmatrix}_{Z_3 = p_3 + iq_3}^{Z_4 = p_q + iq_q}$$
[4.7]

and calculating the resultant contribution from both sides $w = w_{tp} - w_{bp}$ we have,

$$\mathbf{w} = -\frac{\mathbf{B}_{\text{rem}}}{2\pi} \left\{ \left[\frac{1}{2} \mathbf{p} \cdot \ln\left[\mathbf{p}^{2} + \mathbf{q}^{2}\right] - \mathbf{q} \cdot \operatorname{Atn}\left(\frac{\mathbf{q}}{\mathbf{p}}\right) - \mathbf{p} \right]_{Z_{1}}^{Z_{2}} - \left[\frac{1}{2} \mathbf{p} \cdot \ln\left[\mathbf{p}^{2} + \mathbf{q}^{2}\right] - \mathbf{q} \cdot \operatorname{Atn}\left(\frac{\mathbf{q}}{\mathbf{p}}\right) - \mathbf{p} \right]_{Z_{3}}^{Z_{4}} + \mathbf{i} \left[\frac{1}{2} \mathbf{q} \cdot \ln\left[\mathbf{p}^{2} + \mathbf{q}^{2}\right] + \mathbf{p} \cdot \operatorname{Atn}\left(\frac{\mathbf{q}}{\mathbf{p}}\right) - \mathbf{q} \right]_{Z_{1}}^{Z_{2}} - \mathbf{i} \left[\frac{1}{2} \mathbf{q} \cdot \ln\left[\mathbf{p}^{2} + \mathbf{q}^{2}\right] + \mathbf{p} \cdot \operatorname{Atn}\left(\frac{\mathbf{q}}{\mathbf{p}}\right) - \mathbf{q} \right]_{Z_{1}}^{Z_{4}} \right\}$$

$$(4.8)$$

The magnetic scaler potential is therefore given by

$$V = -\frac{B_{\text{norm}}}{2\pi} \left\{ \left[\frac{1}{2} p_2 \cdot \ln\left[p_2^2 + q_2^2\right] - q_2 \cdot \operatorname{Atn}\left(\frac{q_2}{p_2}\right) - p_2 \right] - \left[\frac{1}{2} p_1 \cdot \ln\left[p_1^2 + q_2^2\right] - q_1 \cdot \operatorname{Atn}\left(\frac{q_1}{p_1}\right) - p_1 \right] - \left[\frac{1}{2} p_4 \cdot \ln\left[p_4^2 + q_4^2\right] - q_4 \cdot \operatorname{Atn}\left(\frac{q_4}{p_4}\right) - p_4 \right] - \left[\frac{1}{2} p_3 \cdot \ln\left[p_3^2 + q_3^2\right] - q_3 \cdot \operatorname{Atn}\left(\frac{q_3}{p_3}\right) - p_3 \right] \right\}$$

$$(4.9)$$

and the magnetic stream function A is given by

$$A = -\frac{B_{rem}}{2\pi} \cdot \left\{ \left[\frac{1}{2} q_2 \cdot \ln\left[p_2^2 + q_2^2\right] + p_2 \cdot Atn\left(\frac{q_2}{p_2}\right) - q_2 \right] - \left[\frac{1}{2} q_1 \cdot \ln\left[p_1^2 + q_1^2\right] + p_1 \cdot Atn\left(\frac{q_1}{p_1}\right) - q_1 \right] - \left[\frac{1}{2} q_4 \cdot \ln\left[p_4^2 + q_4^2\right] + p_4 \cdot Atn\left(\frac{q_4}{p_4}\right) - q_4 \right] + \left[\frac{1}{2} q_3 \cdot \ln\left[p_3^2 + q_3^2\right] + p_3 \cdot Atn\left(\frac{q_3}{p_3}\right) - q_3 \right] \right\}$$

$$(4.10)$$

If we now fix the coordinates such that the magnet is centred around the origin then we can write that $p_2=p_4=x-x_0$ and $p_1=p_3=x+x_0$ and also $q_1=q_2=y-y_0$ and $q_3=q_4=y+y_0$ so the field expression becomes

$$A = -\frac{B_{rem}}{2\pi} \cdot \left\{ \left[\frac{1}{2} (y - y_0) \cdot \ln \left[(x - x_0)^2 + (y - y_0)^2 \right] + (x - x_0) \cdot Atn \left(\frac{(y - y_0)}{(x - x_0)} \right) \right] - \left[\frac{1}{2} (y - y_0) \cdot \ln \left[(x + x_0)^2 + (y - y_0)^2 \right] + (x + x_0) \cdot Atn \left(\frac{(y - y_0)}{(x + x_0)} \right) \right] - \left[\frac{1}{2} (y + y_0) \cdot \ln \left[(x - x_0)^2 + (y + y_0)^2 \right] + (x - x_0) \cdot Atn \left(\frac{(y + y_0)}{(x - x_0)} \right) \right] + \left[\frac{1}{2} (y + y_0) \cdot \ln \left[(x + x_0)^2 + (y + y_0)^2 \right] + (x + x_0) \cdot Atn \left(\frac{(y + y_0)}{(x - x_0)} \right) \right] \right\}$$

$$(4.11)$$

The expressions for A are of interest for the following reason. Note B is the magnetic flux density.

$$\mathbf{B} = \mathbf{CurlA} = \begin{vmatrix} \hat{\mathbf{x}} & \hat{\mathbf{y}} \\ \frac{\partial \mathbf{A}}{\partial \mathbf{x}} & \frac{\partial \mathbf{A}}{\partial \mathbf{y}} \end{vmatrix} = \frac{\partial \mathbf{A}}{\partial \mathbf{y}} \hat{\mathbf{x}} - \frac{\partial \mathbf{A}}{\partial \mathbf{x}} \hat{\mathbf{y}}$$
[4.12]

and

$$\frac{dy}{dx} = \frac{B_y}{B_x} = -\frac{\partial A/\partial x}{\partial A/\partial y}$$
[4.13]

so cross-multiplying

$$\frac{\partial A}{\partial x} \cdot dx + \frac{\partial A}{\partial y} \cdot dy = dA = 0$$
 [4.14]

which implies that lines of constant A are the magnetic field lines.

Also of interest is the magnitude of B and its components B_x , B_y .

$$B_x = -\frac{\partial V}{\partial x}$$
 & $B_y = -\frac{\partial V}{\partial y}$ [4.15]

 \overline{B} the complex conjugate of B can be written as

$$\overline{\mathbf{B}} = \mathbf{B}_{\mathbf{x}} - \mathbf{i}\mathbf{B}_{\mathbf{y}} = -\frac{\partial \mathbf{V}}{\partial \mathbf{x}} + \mathbf{i}\frac{\partial \mathbf{V}}{\partial y}$$
[4.16]

which, in conjunction with the Cauchy-Riemann equations,

$$\frac{\partial V}{\partial x} = \frac{\partial A}{\partial y}; \qquad \frac{\partial V}{\partial y} = -\frac{\partial A}{\partial x}$$
 [4.17]

gives

$$\overline{\mathbf{B}} = \mathbf{B}_{\mathbf{x}} - \mathbf{i}\mathbf{B}_{\mathbf{y}} = -\frac{\partial \mathbf{V}}{\partial \mathbf{x}} - \mathbf{i} \quad \frac{\partial \mathbf{A}}{\partial \mathbf{x}} = -\frac{\mathbf{d}\mathbf{w}}{\mathbf{d}\mathbf{z}}$$
[4.18]

which implies that

$$\left|\mathbf{B}\right| = \left|\frac{\mathrm{dw}}{\mathrm{dz}}\right| = \sqrt{\mathbf{B}_{x}^{2} + \mathbf{B}_{y}^{2}}$$
[4.19]

Now for our particular example we can find B, B_x , B_y as follows

$$\mathbf{w} = \mathbf{w}_{\rm up} - \mathbf{w}_{\rm bp} = -\frac{\mathbf{B}_{\rm mm}}{2\pi} \left\{ \left[Z \cdot \ln(Z) - Z \right]_{Z_1}^{Z_2} - \left[Z \cdot \ln(Z) - Z \right]_{Z_3}^{Z_4} \right\}$$
 [4.20]

Taking w_{tp},

$$\frac{\mathrm{d}\mathbf{w}_{\mathrm{tp}}}{\mathrm{d}\mathbf{z}} = -\frac{\mathbf{B}_{\mathrm{rem}}}{2\pi} \ln \left[\frac{\mathbf{Z}_2}{\mathbf{Z}_1}\right]$$
[4.21]

$$\frac{\mathrm{d}w_{tp}}{\mathrm{d}z} = -\frac{\mathrm{B}_{rem}}{2\pi} \left[\frac{1}{2} \ln \left[(\mathbf{x} - \mathbf{x}_0)^2 + (\mathbf{y} - \mathbf{y}_0)^2 \right] + i \mathrm{Atn} \left(\frac{\mathbf{y} - \mathbf{y}_0}{\mathbf{x} - \mathbf{x}_0} \right) - \left[\frac{1}{2} \ln \left[(\mathbf{x} + \mathbf{x}_0)^2 + (\mathbf{y} - \mathbf{y}_0)^2 \right] + i \mathrm{Atn} \left(\frac{\mathbf{y} - \mathbf{y}_0}{\mathbf{x} + \mathbf{x}_0} \right) \right] \right]$$
[4.22]

and similarly for $w_{\mbox{\tiny bp}}$ we have

$$\frac{dw_{bp}}{dz} = -\frac{B_{rem}}{2\pi} \left[\frac{1}{2} ln \left[(x - x_0)^2 + (y + y_0)^2 \right] + iAtn \left(\frac{y + y_0}{x - x_0} \right) - \left[\frac{1}{2} ln \left[(x + x_0)^2 + (y + y_0)^2 \right] + iAtn \left(\frac{y + y_0}{x + x_0} \right) \right] \right]$$
[4.23]

$$\frac{\mathrm{d}w}{\mathrm{d}z} = -\frac{\mathrm{B}_{\mathrm{rem}}}{2\pi} \left[\frac{1}{2} \ln \left[\frac{\left[\left(\mathbf{x} - \mathbf{x}_{0} \right)^{2} + \left(\mathbf{y} - \mathbf{y}_{0} \right)^{2} \right]}{\left[\left(\mathbf{x} + \mathbf{x}_{0} \right)^{2} + \left(\mathbf{y} - \mathbf{y}_{0} \right)^{2} \right]} \right] \right] + i \left[\operatorname{Atn} \left(\frac{\mathbf{y} - \mathbf{y}_{0}}{\mathbf{x} - \mathbf{x}_{0}} \right) - \operatorname{Atn} \left(\frac{\mathbf{y} - \mathbf{y}_{0}}{\mathbf{x} + \mathbf{x}_{0}} \right) \right] \right] - \left[\frac{1}{2} \ln \left[\frac{\left[\left(\mathbf{x} - \mathbf{x}_{0} \right)^{2} + \left(\mathbf{y} + \mathbf{y}_{0} \right)^{2} \right]}{\left[\left(\mathbf{x} + \mathbf{x}_{0} \right)^{2} + \left(\mathbf{y} + \mathbf{y}_{0} \right)^{2} \right]} \right] \right] + i \left[\operatorname{Atn} \left(\frac{\mathbf{y} + \mathbf{y}_{0}}{\mathbf{x} - \mathbf{x}_{0}} \right) - \operatorname{Atn} \left(\frac{\mathbf{y} + \mathbf{y}_{0}}{\mathbf{x} + \mathbf{x}_{0}} \right) \right] \right] = - \left(\mathrm{B}_{\mathbf{x}} + \mathrm{i} \mathrm{B}_{\mathbf{y}} \right)$$

$$= - \left(\mathrm{B}_{\mathbf{x}} + \mathrm{i} \mathrm{B}_{\mathbf{y}} \right)$$

$$(4.24)$$

Which expression provides a complete description of the magnetic field due to a 2-D rectangular magnet which is symmetric with respect to the origin of the z-plane. The results are used to support the calculations of the next section. If a number of magnets are present then the superposition principle applies and the resultant field is the vector sum of the individual contributions.

IV. 2-D Magnetic Fields due to a Combination of Magnets and Ferromagnetics

While the preceding discussion describes the Laplacian fields due to a superposition of 2-D magnets it takes no account of the ferromagnetics which are invariably used in magnetron design. These materials are incorporated for a variety of reasons. They provide a return path for the magnetic flux, enhance the magnetomotive force of the magnets and whether by accident or design they affect the shape of the field lines.

In the analysis to follow it is assumed that all ferromagnetic material is infinitely permeable. This commonly used approximation is discussed in the book by Binns and Lawrenson¹. The essential facts are that the assumption will be very accurate even when the relative permeability drops to the region of 100. Another reason for good accuracy is that the effect of less than infinite permeability will diminish with distance from the ferromagnetic. Since the magnetron geometry is almost invariably such that the region of the field of interest is separated from the ferromagnetic by a distance equal to that of the target thickness plus the magnet thickness there is another reason to expect good accuracy.

When considering magnetostatic fields in the presence of ferromagnetics it is again necessary to work in the complex plane. Conformal mapping techniques are used. These methods are well described in textbooks¹.

V. Calculating the Field due to Magnets in the Vicinity of and in Contact with an Arbitrary Finite Ferromagnetic Polygon

Consider two complex planes, t=u+iv and z=x+iy. The upper half of the t-plane can be conformally mapped¹ onto a region exterior to any finite polygon in the z-plane. The Schwartz-Christoffel equation which describes this transformation is given by

$$\frac{dz}{dt} = S (t^{2} + 1)^{-2} (t - a)^{(\alpha/\pi) - 1} (t - b)^{(\beta/\pi) - 1} \dots$$
[4.25]

where S is a constant scaling factor. All other parameters are indicated in Figure 4.3. Note once again that when a point charge is being discussed, what is meant is the charge per unit



Figure 4.3: A representation of the effect of the Schwartz-Christoffel mapping of the upper half of the complex t-plane into the region exterior to a polygon with a magnet attached. AB corresponds to EF and CD is the image of AB through the u-axis. The points a,b,c,d are determined by the dimensions of the polygon and α,β,χ,δ are the external angles of the polygon.
length q of an infinite i.e. long enough so that end effects can be neglected, uniform line of charge. The magnetic potential field due to such a charge in the z-plane is described by Equation [4.1]. (Note that throughout this work the zero subscript will be used to indicate source as opposed to field points).

The initial interest is in finding an expression for the magnetic field due to a single magnet with one pole in full contact with an arbitrary infinitely permeable finite ferromagnetic polygon. The extention to multiple magnet geometries is a straightforward superposition of contributions from the individual magnets. Thus the calculation naturally splits into two parts.

a) Magnetic Pole in Contact with the Polygon

The pole contacting the polygonal plate effectively gives it a magnetic charge. Flux leaving the plate goes to infinity. However the nature of Equation [4.25] is such that infinity in the z-plane corresponds to a finite point(s) in the t-plane. The total magnetic charge in the t-plane will then be equal and opposite to that on the plate. Since the real axis of the t-plane is equipotential, we can use the method of images to calculate the resulting field in the upper half of the t-plane. This is related to the field in the z-plane via Equation [4.25].

b) Magnetic Pole not in Contact with the Polygon

i) The pole is equal and opposite to the one considered previously. This implies that the sink at infinity is also equal and opposite to its counterpart of the last section. So when we translate this into the t-plane the two contributions superimpose and we have a cancellation. Likewise the images will also cancel. Therefore there will be no net contribution to the field arising from the considerations of section (a) or this first part of section (b).

It is also clear that if neither one of the two poles of the magnet is in contact with the plate then there will also be a cancellation. These results are a natural consequence of the dipole manifestation of the magnetic field (i.e. Div $\mathbf{B} = 0$).

ii) What is also necessary is to understand the distribution of charge in the t-plane that will yield the correct z-plane distribution under the Schwartz-Christoffel mapping. To get this we consider the fixed infinitesimal charge dQ that gets transferred from a small interval in one plane to a small interval in the other. For the z-plane

$$dQ = \lambda_z \cdot dz_o \qquad [4.26]$$

and for the t-plane

$$dQ = \lambda_t \cdot dt_o \qquad [4.27]$$

where λ_t , λ_z are the line densities of charge in the t and z planes respectively. We can therefore write

$$\lambda_{t} = \lambda_{z} \frac{\mathrm{d}z_{o}}{\mathrm{d}t_{o}}$$
[4.28]

The differential term can be found using Equation [4.25] and λ_z is a given constant. Hence an expression for λ_t is, in principle, always available.

It is necessary to find the field due to this line of density λ_t in order that it may be transformed to give the z-plane solution. The problem is reasonably straightforward because the principle of deformation of path², which is a consequence of the Cauchy-Goursat theorem, implies that integration of a complex function of position only depends on the limits of integration and not on the path followed. So the shape of the distribution in the t-plane can be completely ignored. We can therefore write an expression for the field solution to the non-contact portion of the problem for the t-plane field.

$$F = F_{t} - F_{timage} = \frac{q}{2\pi} \left(\int_{A}^{B} \lambda_{t} \ln(t - t_{o}) - \int_{C}^{D} \lambda_{t} \ln(t - t_{o}) \right) \cdot dt_{o}$$
 [4.29]

This general equation gives a complete description of the field in the t-plane due to a single magnet in contact with an arbitrary finite ferromagnetic polygon in the z-plane. Using Equation [4.25] the functions t(z) and $t_o(z_o)$ may be derived and substituted into Equation [4.28]. Also λ_t is expressed in terms of z using Equation [4.28]

$$F = \frac{q\lambda_z}{2\pi} \cdot \left(\int_{E}^{F} Ln[t(z) - t_o(z_o)] - \int_{G}^{H} Ln[t(z) - t_o(z_o)] \right) \cdot dz_o$$
[4.30]

If these functions t(z) and $t_o(z_o)$ can be expressed analytically then a closed form expression for the field in the z-plane may result. However with the notable exception of the finite thin backing plate discussed in the next section it is generally not possible to find t(z) or $t_o(z_o)$ explicitly. In addition the integral takes more steps to derive when Equation [4.30] is used for the problem of the line segment backing plate. Therefore in order to get a solution it is probably best to use Equation [4.29] to calculate the field in the t-plane and then transform into the z-plane using the known Schwartz-Christoffel relationship. This latter equation is therefore rewritten according to the superposition principle to accomodate the situation where there is more than one free magnetic pole.

$$F = \sum_{1}^{\text{Number of Free}} F_{t} - F_{timage} = \sum_{1}^{\text{Number of Free}} \frac{q}{2\pi} \left(\int_{A}^{B} \lambda_{t} \ln(t - t_{o}) - \int_{C}^{D} \lambda_{t} \ln(t - t_{o}) \right) dt_{a} \qquad [4.31]$$

Finally it should be pointed out that the integrals which result when considering ferromagnetic polygons which are in any way complex are not easily calculable. This is a drawback with the technique.

A diagram illustrating a selection of problems which should be solvable is given as **Figure 4.4**. The use of a ferromagnetic shaping pole instead of a magnet as shown in Figure 4.4b is sometimes encountered^{3,4}. This serves to highly unbalance the magnetron. Another interesting geometry for which the calculations could be specified is that of two magnetrons facing each other in a closed field configuration. The way to do this is to regard the pole pieces of each magnetron as extending back infinitely far as indicated. Then the poles will join at infinity forming a construction which for the purposes of conformal mapping calculations can be regarded as a single ferromagnetic polygon. The Schwarz-Christoffel transformation for such a geometry⁵ is given in integral form by

$$z = S \int_0^t \sqrt{(1 - t^2)(k^2 - t^2)} dt + B$$
 [4.32]



Figure 4.4: A selection of magnetrons the magnetic fields for which should be calculable using the derived equations. (a) is the 'standard' 2-D sputter magnetron with rectangular backing plate (b) is an unbalanced magnetron in which the centre magnet has been replaced by a ferromagnetic pole piece (c) is a dual magnetron arrangement which, for the purposes of obtaining a description of the magnetic field, is probably best imagined as having backing plates stretching off to infinity as indicated by the arrows

with



Figure 4.5: An appropriate Schwartz-Christoffel Transformation for calculating the field in the vicinity of a closed field dual magnetron arrangement

where the constants a,b and k are defined in Figure 4.5, B is a constant of integration, k' is the square root of $(1-k^2)$ and the symbols K and E represent the complete elliptic integrals of the first and second kind. The conventions used for calculating these integrals will be explained in detail in Chapter 6.

VI. Magnetic Field for a 'Standard' 2-D Magnetron

Having considered the general theory a specific example is chosen to illustrate its application. In particular the magnetic field in the vicinity of what may be described as the 'standard' 2-D planar magnetron is examined. See **Figure 4.6**. With the sole extra unforced but vastly simplifying approximation that the backing plate is a line segment rather than a rectangle it is possible to obtain an *analytic* result. No significant consequential error is expected for the region of interest in the case at hand.

The calculation geometry is illustrated in **Figure 4.7**. In order to obtain an analytic solution the assumption that the backing plate is a line segment rather than a rectangle is introduced. Otherwise the geometry is the same as in Figure 4.6. This assumption is also effectively

[4.33]



Figure 4.6: Schematic of a 'standard' two dimensional rectangular magnetron geometry. The magnets are sandwiched between the sputtering target and ferromagnetic backing plate. The arrows indicate the orientation of the magnetization vector.



Figure 4.7: (a) The calculation geometry. This is the same as that indicated in Figure 4.5 except that the backing plate is assumed to have zero thickness. For the purposes of this illustration c, the half width of the backing plate, is taken as 50mm and the height of the magnets is 6mm. (b) The monopole lines in the upper half of the t-plane correspond to those poles of the magnets in (a) that are not in contact with the backing plate. They have complex line monopole densities λ_t . Their images are shown in the lower half of the tplane. forced since the necessary computational machinery to deal with equations that result from more complex geometries have yet to be developed. However no significant error is expected for the region of interest in the case at hand.

More formally we note that by 'standard' magnetron geometry what is meant is that there are only four variables affecting the shape of the magnetic field and one extra, B_{rem} , affecting the magnitude of magnetic field. These are

- a) The distance from the centre of the magnetron to the outer side of the outer magnet
- b) The distance from the centre of the magnetron to the inner side of the outer magnet
- c) The distance from the centre to the outer side of the inner magnet
- d) The height of the magnets

Of course, in operation factors such as the target plate material, target plate thickness and the proximity of the substrate should be taken into account as these all affect film quality. It is noted in passing that with the word radius substituted for width in (a-c) the above definition also holds for the 'standard' circular magnetron geometry.

The concern then is in finding a solution for the problem as it appears in the z-plane. In order to do this we have to find the Schwartz-Christoffel equation for the transformation from the upper half of the t-plane to the z-plane.

Consider only the line sequent (in practice a thin plate of infinite extent into and out of the page) in Figure 4.7. It lies along the real axis of the z-plane between the points c and -c. Also the origin of the t-plane corresponds to the point z=c and the limits of the real axis with z=-c. The exterior angle of the polygon at z=c is 2π so using the Schwartz-Christoffel transformation of Equation 1 we can write¹

$$\frac{\mathrm{d}z}{\mathrm{d}t} = \mathrm{S}\frac{\mathrm{t}}{\left(\mathrm{t}^2 + 1\right)^2}$$
[4.34]

Integrating we find

$$z = -\frac{S}{2(t^2 + 1)} + k$$
 [4.35]

from which the values of S and k may be derived by substitution of the corresponding values of z and t. Hence k = -c and S = -4c so we have

$$\frac{dz}{dt} = \frac{-4ct}{\left(t^2 + 1\right)^2}$$
[4.36]

and so in its most simple form the transformation relating the z and t planes is given by

$$z = c \left[\frac{1 - t^2}{1 + t^2} \right]$$
[4.37]

where c is the half width of the backing plate. The inverse function t(z) can also be found. It is given by

$$t = \pm \sqrt{\frac{c-z}{c+z}}$$
 [4.38]

If z is in the upper half of the z-plane then the minus part of the sign is used else the plus is used.

We can use equations [4.28] and [4.29] to write down the solution in the t-plane, i.e.,

$$F_{t} = \frac{q}{2\pi} \int_{A}^{B} q \frac{dz_{0}}{dt_{0}} Ln(t-t_{0}) \cdot dt_{0} - \frac{q}{2\pi} \int_{C}^{D} q \frac{dz_{0}}{dt_{0}} Ln(t-t_{0}) \cdot dt_{0}$$
 [4.39]

or, in more simplified form,

$$F_{t} = -\frac{2cB_{rem}}{\pi} \int_{A}^{B} \frac{t_{o} Ln(t-t_{o})}{(t_{o}^{2}+1)^{2}} \cdot dt_{o} + \frac{2cB_{rem}}{\pi} \int_{C}^{D} \frac{t_{o} Ln(t-t_{o})}{(t_{o}^{2}+1)^{2}} \cdot dt_{o}$$
[4.40]

where we have taken $\lambda_z \cdot q = q^2 = B_{rem}$ the remanant field of the magnets. This can be simplified (see Appendix 4.1) to give

$$F_{t} = \frac{cB_{rem}}{\pi} \left(\frac{Ln(t-t_{0})}{(t_{0}^{2}+1)} - \frac{Ln(t-t_{0})}{(t^{2}+1)} + \frac{t \cdot Atn(t_{0})}{(t^{2}+1)} + \frac{1}{2} \frac{Ln(t_{0}^{2}+1)}{(t^{2}+1)} \right) \Big|_{t_{0}=A}^{t_{0}=B}$$
$$- \frac{cB_{rem}}{\pi} \left(\frac{Ln(t-t_{0})}{(t_{0}^{2}+1)} - \frac{Ln(t-t_{0})}{(t^{2}+1)} + \frac{t \cdot Atn(t_{0})}{(t^{2}+1)} + \frac{1}{2} \frac{Ln(t_{0}^{2}+1)}{(t^{2}+1)} \right) \Big|_{t_{0}=C}^{t_{0}=B}$$
[4.41]

There are a number of points to note about this last expression. First of all the terms of the form $t^{2}+1$ which appears in the denominator of all the terms of Equation [4.41] can, with the use of Equation [4.38], be simplified as follows

$$t^{2} + 1 = \frac{c - z}{c + z} + 1 = \frac{2c}{c + z}$$
 [4.42]

A second point to note is that the last terms within the two pairs of brackets of Equation [4.41] can be further simplified as follows

$$\frac{1}{2} \frac{\text{Ln}(t_0^2 + 1)}{(t^2 + 1)} = \frac{1}{2} \frac{c + z}{2c} \text{Ln}\left(\frac{2c}{c + z_0}\right) = \frac{1}{2} \frac{c + z}{2c} \left[\text{Ln}(2c) - \text{Ln}(c + z_0)\right]$$
[4.43]

Now when the limits of integration i.e. A and B or C and D are applied any constant terms will vanish. So we may substitute for the original term as follows

$$\frac{1}{2} \frac{\mathrm{Ln}(\mathbf{t}_0^2 + 1)}{(\mathbf{t}^2 + 1)} = -\frac{1}{2} \left(\frac{\mathbf{c} + \mathbf{z}}{2\mathbf{c}} \right) \mathrm{Ln}(\mathbf{c} + \mathbf{z}_0)$$
[4.44]

and again using Equation [4.38] to substitute for the variable t we have

$$F_{z} = \frac{B_{rem}}{2\pi} \left[(z_{0} - z) \cdot Ln \left(s \cdot \sqrt{\frac{c - z}{c + z}} - s_{0} \cdot \sqrt{\frac{c - z_{0}}{c + z_{0}}} \right) + s \cdot \sqrt{c^{2} - z^{2}} Atn \left[s_{0} \cdot \sqrt{\frac{c - z_{0}}{c + z_{0}}} \right] - \frac{c + z}{2} \cdot Ln(c + z_{0}) \right] \Big|_{z_{0} = E}^{z_{0} = E}$$
$$-\frac{B_{rem}}{2\pi} \left[(z_{0} - z) \cdot Ln \left(s \cdot \sqrt{\frac{c - z}{c + z}} - s_{0} \cdot \sqrt{\frac{c - z_{0}}{c + z_{0}}} \right) + s \cdot \sqrt{c^{2} - z^{2}} Atn \left[s_{0} \cdot \sqrt{\frac{c - z_{0}}{c + z_{0}}} \right] - \frac{c + z}{2} \cdot Ln(c + z_{0}) \right] \Big|_{z_{0} = G}^{z_{0} = H}$$
[4.45]

which is the expression for the potential field in the z-plane. The imaginary part of Equation [4.45] yields the stream function A and lines of constant A are the magnetic field lines. Note s, s_o represent the \pm sign. However for the magnet geometry described here the minus sign is the correct choice for both s and s_o . Next the limits of integration are applied. Because the geometry is always symmetric with respect to the y-axis E, F, G and H can be written as $-x_o + iy_o$, $x_o + iy_o$, $-x_o - iy_o$, and $x_o - iy_o$ respectively. The points E and F correspond to the end points of the line segment that is the top pole of the magnet. Upon translation of the points E and F into the t-plane they each form a mirror image through the u-axis which is terminated at the points C and D. These image points when translated back into the z-plane are denoted as G and H. Under these conditions the equation simplifies considerably because the arctangent term vanishes and we are left with the simpler form

$$F_{z} = \frac{B_{rem}}{2\pi} \left[(z_{0} - z) \cdot Ln \left(s \cdot \sqrt{\frac{c - z}{c + z}} - s_{0} \cdot \sqrt{\frac{c - z_{0}}{c + z_{0}}} \right) - \frac{c + z}{2} \cdot Ln(c + z_{0}) \right]_{z_{0} = -x_{0} + iy_{0}}^{z_{0} = -x_{0} + iy_{0}} \\ - \frac{B_{rem}}{2\pi} \left[(z_{0} - z) \cdot Ln \left(s \cdot \sqrt{\frac{c - z}{c + z}} - s_{0} \cdot \sqrt{\frac{c - z_{0}}{c + z_{0}}} \right) - \frac{c + z}{2} \cdot Ln(c + z_{0}) \right]_{z_{0} = -x_{0} - iy_{0}}^{z_{0} = -x_{0} - iy_{0}}$$
[4.46]

The imaginary part of the previous equation is all that is of interest as far as calculating the magnetic field lines is concerned. While it is possible to work from equation [4.46], and indeed the examples given later on in this chapter are derived from equation [4.46], it would be nice to have a non-complex expression for the field lines. This will make the results more accessible by avoiding the necessity for a reasonable understanding of complex number theory. The procedure is somewhat tedious and is bordered off from the rest of the text. First of all though we make some definitions.

For ease of reference it is noted that by De Moivre's Theorem the root of an arbitrary complex number a+ib is

$$\sqrt{a + ib} = \sqrt[4]{\left(a^{2} + b^{2}\right)} \left(\cos\left(\frac{\operatorname{Arg}(a + ib)}{2}\right) + i\operatorname{Sin}\left(\frac{\operatorname{Arg}(a + ib)}{2}\right) \right)$$
$$= \sqrt[4]{\left(a^{2} + b^{2}\right)} \left(\cos\left(\frac{\operatorname{Atn}(b/a)}{2}\right) + i\operatorname{Sin}\left(\frac{\operatorname{Atn}(b/a)}{2}\right) \right)$$
[4.47]

As previously we take z = x + iy & zo = xo + iyo. To start consider the equation.

$$k = \frac{(c-z)}{(c+z)} = \left(\frac{c^2 - x^2 - y^2}{(c+x)^2 + y^2}\right) - i\left(\frac{2cy}{(c+x)^2 + y^2}\right) = A + iB \qquad [4.48]$$

Next consider the square root of k

$$\sqrt{k} = \left(\sqrt[4]{\left(\frac{(c-x)^2 + y^2}{(c+x)^2 + y^2}\right)} \cos\left(\frac{1}{2}\operatorname{Arg}\frac{(c-x-iy)}{(c+x+iy)}\right) \right) + i\left(\sqrt{\left(\frac{(c-x)^2 + y^2}{(c+x)^2 + y^2}\right)} \sin\left(\frac{1}{2}\operatorname{Arg}\frac{(c-x-iy)}{(c+x+iy)}\right) \right)$$

$$(4.49)$$

which in terms of an Arctan function may be written

$$\sqrt{k} = \left(\sqrt{\left(\frac{(c-x)^2 + y^2}{(c+x)^2 + y^2}\right)} \cos\left(-\frac{1}{2}Atn\left(\frac{2cy}{c^2 - x^2 - y^2}\right)\right) \right) + \left(\sqrt{\left(\frac{(c-x)^2 + y^2}{(c+x)^2 + y^2}\right)} \sin\left(-\frac{1}{2}Atn\left(\frac{2cy}{c^2 - x^2 - y^2}\right)\right) \right) \right)$$

$$(4.50)$$

So as to get a more shorthand notation we write

$$\sqrt{k} = C + iD \& \sqrt{k_0} = C_0 + iD_0$$
 [4.51]

Now consider the two terms of equation [4.45]

Term I

$$(\mathbf{z}_0 - \mathbf{z}) \cdot \mathbf{Ln} \left(\mathbf{s} \cdot \sqrt{\frac{\mathbf{c} - \mathbf{z}}{\mathbf{c} + \mathbf{z}}} - \mathbf{s}_0 \cdot \sqrt{\frac{\mathbf{c} - \mathbf{z}_0}{\mathbf{c} + \mathbf{z}_0}} \right) = (\mathbf{z}_0 - \mathbf{z}) \mathbf{Ln} \left(\mathbf{s} \sqrt{\mathbf{k}} - \mathbf{s}_0 \sqrt{\mathbf{k}_0} \right) =$$

$$\left(\left(\mathbf{x}_{0} - \mathbf{x} \right) + \mathbf{i} \left(\mathbf{y}_{0} - \mathbf{y} \right) \right) \left[0.5 \mathrm{Ln} \left(\left(\mathbf{s} \cdot \mathbf{C} - \mathbf{s}_{0} \cdot \mathbf{C}_{0} \right)^{2} + \left(\mathbf{s} \cdot \mathbf{D} - \mathbf{s}_{0} \cdot \mathbf{D}_{0} \right)^{2} \right) + i \operatorname{Arg} \left(\left(\mathbf{s} \cdot \mathbf{C} - \mathbf{s}_{0} \cdot \mathbf{C}_{0} \right) + \mathbf{i} \left(\mathbf{s} \cdot \mathbf{D} - \mathbf{s}_{0} \cdot \mathbf{D}_{0} \right) \right) \right]$$

$$\left[4.52 \right]$$

Taking $s_{,s_0} = -1$ as before and dealing with the Logarithmic and Arctan terms separately and in expanded form, we can write

$$0.5((x_0 - x) + i(y_0 - y)) \left\{ Ln((C_0 - C)^2 + (D_0 - D)^2) \Big|_{-x_0 + iy_0}^{x_0 + iy_0} - Ln((C_0 - C)^2 + (D_0 - D)^2) \Big|_{-x_0 - iy_0}^{x_0 - iy_0} \right\}$$

[4.53]

$$i((x_0 - x) + i(y_0 - y)) \Big\{ Arg((C_0 - C) + i(D_0 - D)) \Big|_{-x_0 + iy_0}^{x_0 + iy_0} - Arg((C_0 - C) + i(D_0 - D)) \Big|_{-x_0 - iy_0}^{x_0 - iy_0} \Big\}$$

[4.54]

Using the notation

$$Amp_{0} = \sqrt{\left(\frac{(c-x_{0})^{2} + y_{0}^{2}}{(c+x_{0})^{2} + y_{0}^{2}}\right)} \quad \& \quad Amp = \sqrt{\left(\frac{(c-x)^{2} + y^{2}}{(c+x)^{2} + y^{2}}\right)}$$
[4.55]

and

$$\Psi_0 = \left(\frac{1}{2}\operatorname{Arg}\frac{(\mathbf{c} - \mathbf{x}_0 - i\mathbf{y}_0)}{(\mathbf{c} + \mathbf{x}_0 + i\mathbf{y}_0)}\right) \quad \& \quad \Psi = \left(\frac{1}{2}\operatorname{Arg}\frac{(\mathbf{c} - \mathbf{x} - i\mathbf{y})}{(\mathbf{c} + \mathbf{x} + i\mathbf{y})}\right)$$

or

$$\Psi_0 = \left(\frac{1}{2}\operatorname{Atn} \frac{-2\operatorname{cy}_0}{\operatorname{c}^2 - \operatorname{x}_0^2 - \operatorname{y}_0^2}\right) \quad \& \quad \Psi = \left(\frac{1}{2}\operatorname{Atn} \frac{-2\operatorname{cy}}{\operatorname{c}^2 - \operatorname{x}^2 - \operatorname{y}^2}\right)$$

and

$$\Theta = \left(\frac{2\mathrm{cy}}{\mathrm{c}^2 - \mathrm{x}^2 - \mathrm{y}^2}\right)$$
[4.57]

[4.56]

we have

w=V+iA=

$$-(y_{0} - y)Atn\left(\frac{(Amp_{0} \cdot Sin(\Psi_{0}) - Amp \cdot Sin(\Psi))}{(Amp_{0} \cdot Cos(\Psi_{0}) - Amp \cdot Cos(\Psi))}\right) + (y_{0} - y)Atn\left(\frac{((1/Amp_{0}) \cdot Sin(\Psi_{0}) - Amp \cdot Sin(\Psi))}{((1/Amp_{0}) \cdot Cos(\Psi_{0}) - Amp \cdot Cos(\Psi))}\right) + (-y_{0} - y)Atn\left(\frac{(-Amp_{0} \cdot Sin(\Psi_{0}) - Amp \cdot Sin(\Psi))}{(Amp_{0} \cdot Cos(\Psi_{0}) - Amp \cdot Cos(\Psi))}\right) - (-y_{0} - y)Atn\left(\frac{(-(1/Amp_{0}) \cdot Sin(\Psi_{0}) - Amp \cdot Sin(\Psi))}{((1/Amp_{0}) \cdot Cos(\Psi_{0}) - Amp \cdot Cos(\Psi))}\right) - (-y_{0} - y)Atn\left(\frac{(-(1/Amp_{0}) \cdot Sin(\Psi_{0}) - Amp \cdot Sin(\Psi))}{((1/Amp_{0}) \cdot Cos(\Psi_{0}) - Amp \cdot Cos(\Psi))}\right)$$

$$\begin{split} i \cdot 0.5 \cdot (\mathbf{y}_{0} - \mathbf{y}) \mathrm{Ln} \Big[\left(\mathrm{Amp}_{0} \cdot \mathrm{Cos}(\Psi_{0}) - \mathrm{Amp} \cdot \mathrm{Cos}(\Psi) \right)^{2} + \left(\mathrm{Amp}_{0} \cdot \mathrm{Sin}(\Psi_{0}) - \mathrm{Amp} \cdot \mathrm{Sin}(\Psi) \right)^{2} \Big] - \\ i \cdot 0.5 \cdot (\mathbf{y}_{0} - \mathbf{y}) \mathrm{Ln} \Big[\left((1/\mathrm{Amp}_{0}) \cdot \mathrm{Cos}(\Psi_{0}) - \mathrm{Amp} \cdot \mathrm{Cos}(\Psi) \right)^{2} + \left((1/\mathrm{Amp}_{0}) \cdot \mathrm{Sin}(\Psi_{0}) - \mathrm{Amp} \cdot \mathrm{Sin}(\Psi) \right)^{2} \Big] - \\ i \cdot 0.5 \cdot (-\mathbf{y}_{0} - \mathbf{y}) \mathrm{Ln} \Big[\left(\mathrm{Amp}_{0} \cdot \mathrm{Cos}(\Psi_{0}) - \mathrm{Amp} \cdot \mathrm{Cos}(\Psi) \right)^{2} + \left(-\mathrm{Amp}_{0} \cdot \mathrm{Sin}(\Psi_{0}) - \mathrm{Amp} \cdot \mathrm{Sin}(\Psi) \right)^{2} \Big] + \\ i \cdot 0.5 \cdot (-\mathbf{y}_{0} - \mathbf{y}) \mathrm{Ln} \Big[\left((1/\mathrm{Amp}_{0}) \cdot \mathrm{Cos}(\Psi_{0}) - \mathrm{Amp} \cdot \mathrm{Cos}(\Psi) \right)^{2} + \left(-(1/\mathrm{Amp}_{0}) \cdot \mathrm{Sin}(\Psi_{0}) - \mathrm{Amp} \cdot \mathrm{Sin}(\Psi) \right)^{2} \Big] \\ i (\mathbf{x}_{0} - \mathbf{x}) \mathrm{Arg} \Big(\left(\mathrm{Amp}_{0} \cdot \mathrm{Cos}(\Psi_{0}) - \mathrm{Amp} \cdot \mathrm{Cos}(\Psi) \right) + i \left(\mathrm{Amp}_{0} \cdot \mathrm{Sin}(\Psi_{0}) - \mathrm{Amp} \cdot \mathrm{Sin}(\Psi) \right) \Big) - \\ i (-\mathbf{x}_{0} - \mathbf{x}) \mathrm{Arg} \Big(\left((1/\mathrm{Amp}_{0}) \cdot \mathrm{Cos}(\Psi_{0}) - \mathrm{Amp} \cdot \mathrm{Cos}(\Psi) \right) + i \left((1/\mathrm{Amp}_{0}) \cdot \mathrm{Sin}(\Psi_{0}) - \mathrm{Amp} \cdot \mathrm{Sin}(\Psi) \right) \Big) - \\ i (\mathbf{x}_{0} - \mathbf{x}) \mathrm{Arg} \Big(\left(\mathrm{Amp}_{0} \cdot \mathrm{Cos}(\Psi_{0}) - \mathrm{Amp} \cdot \mathrm{Cos}(\Psi) \right) + i \left((1/\mathrm{Amp}_{0}) \cdot \mathrm{Sin}(\Psi_{0}) - \mathrm{Amp} \cdot \mathrm{Sin}(\Psi) \right) \Big) + \\ i (-\mathbf{x}_{0} - \mathbf{x}) \mathrm{Arg} \Big(\left((1/\mathrm{Amp}_{0}) \cdot \mathrm{Cos}(\Psi_{0}) - \mathrm{Amp} \cdot \mathrm{Cos}(\Psi) \right) + i \left(-\mathrm{Amp}_{0} \cdot \mathrm{Sin}(\Psi_{0}) - \mathrm{Amp} \cdot \mathrm{Sin}(\Psi) \right) \Big) + \\ i (-\mathbf{x}_{0} - \mathbf{x}) \mathrm{Arg} \Big((1/\mathrm{Amp}_{0}) \cdot \mathrm{Cos}(\Psi_{0}) - \mathrm{Amp} \cdot \mathrm{Cos}(\Psi) + i \left(-\mathrm{Amp}_{0} \cdot \mathrm{Sin}(\Psi_{0}) - \mathrm{Amp} \cdot \mathrm{Sin}(\Psi) \right) \Big) + \\ i (-\mathbf{x}_{0} - \mathbf{x}) \mathrm{Arg} \Big((1/\mathrm{Amp}_{0}) \cdot \mathrm{Cos}(\Psi_{0}) - \mathrm{Amp} \cdot \mathrm{Cos}(\Psi) + i \left(-\mathrm{Amp}_{0} \cdot \mathrm{Sin}(\Psi_{0}) - \mathrm{Amp} \cdot \mathrm{Sin}(\Psi) \right) \Big) + \\ i (-\mathbf{x}_{0} - \mathbf{x}) \mathrm{Arg} \Big((1/\mathrm{Amp}_{0}) \cdot \mathrm{Cos}(\Psi_{0}) - \mathrm{Amp} \cdot \mathrm{Cos}(\Psi) + i \left(-\mathrm{Amp}_{0} \cdot \mathrm{Sin}(\Psi_{0}) - \mathrm{Amp} \cdot \mathrm{Sin}(\Psi) \right) \Big) + \\ \\ i (-\mathbf{x}_{0} - \mathbf{x}) \mathrm{Arg} \Big((1/\mathrm{Amp}_{0}) \cdot \mathrm{Cos}(\Psi_{0}) - \mathrm{Amp} \cdot \mathrm{Cos}(\Psi) + i \left(-\mathrm{Amp}_{0} \cdot \mathrm{Sin}(\Psi_{0}) - \mathrm{Amp} \cdot \mathrm{Sin}(\Psi) \right) \Big) + \\ \\ i (-\mathbf{x}_{0} - \mathbf{x}) \mathrm{Arg} \Big((1/\mathrm{Amp}_{0}) \cdot \mathrm{Cos}(\Psi_{0}) - \mathrm{Amp} \cdot \mathrm{Cos}(\Psi) + i \left(-\mathrm{Amp}_{0} \cdot \mathrm{Sin}(\Psi_{0}) - \mathrm{Amp} \cdot \mathrm{Sin}(\Psi) \right) \Big) + \\ \\ i (-\mathbf{x}_{$$

Concentrating only on the stream function A, that is to say the imaginary part of the previous expression, this can be simplified further to give iA =

$$i(\mathbf{y}_{0}-\mathbf{y})Ln\left[\frac{Amp_{0}^{2}+Amp^{2}-2Amp_{0}\cdot Amp\cdot Cos(\Lambda)}{(1/Amp_{0}^{2})+Amp^{2}-2(Amp/Amp_{0})\cdot Cos(\Lambda)}\right]$$

$$i(-y_0 - y)Ln\left[\frac{(1 / Amp_0^2) + Amp^2 - 2(Amp / Amp_0) \cdot Cos(\Omega)}{Amp_0^2 + Amp^2 - 2Amp_0 \cdot Amp \cdot Cos(\Omega)}\right]$$

$$i(x_{0} - x)Arg\left(\frac{\left(Amp_{0} \cdot Cos(\Psi_{0}) - Amp \cdot Cos(\Psi)\right) + i\left(Amp_{0} \cdot Sin(\Psi_{0}) - Amp \cdot Sin(\Psi)\right)}{\left(Amp_{0} \cdot Cos(\Psi_{0}) - Amp \cdot Cos(\Psi)\right) + i\left(-Amp_{0} \cdot Sin(\Psi_{0}) - Amp \cdot Sin(\Psi)\right)}\right) + i\left(Amp_{0} \cdot Sin(\Psi_{0}) - Amp \cdot Sin(\Psi)\right) + i\left($$

$$i(-x_{0}-x)Arg\left(\frac{\left((1/Amp_{0})\cdot Cos(\Psi_{0})-Amp\cdot Cos(\Psi)\right)+i\left(-(1/Amp_{0})\cdot Sin(\Psi_{0})-Amp\cdot Sin(\Psi)\right)}{\left((1/Amp_{0})\cdot Cos(\Psi_{0})-Amp\cdot Cos(\Psi)\right)+i\left((1/Amp_{0})\cdot Sin(\Psi_{0})-Amp\cdot Sin(\Psi)\right)}\right)$$

where $\Lambda = \Psi_0 + \Psi$ and $\Omega = \Psi_0 - \Psi$ [4.59]

Finally it is noted that when the Limit of this expression is taken as c maps onto infinity the result reduces to

$$A = -\frac{B_{\text{rem}}}{2\pi} \cdot \left\{ \left[\frac{1}{2} (y - y_0) \cdot \ln \left[(x - x_0)^2 + (y - y_0)^2 \right] + (x - x_0) \cdot \operatorname{Atn} \left(\frac{(y - y_0)}{(x - x_0)} \right) \right] \right. \\ \left. - \left[\frac{1}{2} (y - y_0) \cdot \ln \left[(x + x_0)^2 + (y - y_0)^2 \right] + (x + x_0) \cdot \operatorname{Atn} \left(\frac{(y - y_0)}{(x + x_0)} \right) \right] \right] \\ \left. - \left[\frac{1}{2} (y + y_0) \cdot \ln \left[(x - x_0)^2 + (y + y_0)^2 \right] + (x - x_0) \cdot \operatorname{Atn} \left(\frac{(y + y_0)}{(x - x_0)} \right) \right] \right] \right. \\ \left. + \left[\frac{1}{2} (y + y_0) \cdot \ln \left[(x + x_0)^2 + (y + y_0)^2 \right] + (x + x_0) \cdot \operatorname{Atn} \left(\frac{(y + y_0)}{(x + x_0)} \right) \right] \right] \right\}$$

$$\left. \left. \left[\frac{1}{2} (y + y_0) \cdot \ln \left[(x + x_0)^2 + (y + y_0)^2 \right] + (x + x_0) \cdot \operatorname{Atn} \left(\frac{(y + y_0)}{(x + x_0)} \right) \right] \right] \right\}$$

$$\left. \left. \left[\frac{1}{2} (y + y_0) \cdot \ln \left[(x + x_0)^2 + (y + y_0)^2 \right] \right] \right] \right\}$$

$$\left. \left. \left[\frac{1}{2} (y + y_0) \cdot \ln \left[(x + x_0)^2 + (y + y_0)^2 \right] \right] \right] \right\}$$

$$\left. \left[\frac{1}{2} (y + y_0) \cdot \ln \left[(x + x_0)^2 + (y + y_0)^2 \right] \right] \right] \right\}$$

$$\left. \left[\frac{1}{2} (y + y_0) \cdot \ln \left[(x + x_0)^2 + (y + y_0)^2 \right] \right] \right] \right\}$$

$$\left. \left[\frac{1}{2} (y + y_0) \cdot \ln \left[(x + x_0)^2 + (y + y_0)^2 \right] \right] \right] \right\}$$

$$\left. \left[\frac{1}{2} (y + y_0) \cdot \ln \left[(x + x_0)^2 + (y + y_0)^2 \right] \right] \right] \right\}$$

$$\left. \left[\frac{1}{2} (y + y_0) \cdot \ln \left[(x + x_0)^2 + (y + y_0)^2 \right] \right] \right] \left[\frac{1}{2} (y + y_0) \cdot \ln \left[(x + x_0)^2 + (y + y_0)^2 \right] \right] \right]$$

which is identical to Equation [4.11] which was derived for a magnet located symmetrically about the origin. That is to say that as the backing plate becomes infinitely wide the field due to the magnet resting on the backing plate becomes equivalent to that of a magnet of twice its length without the backing plate. This result depends on the method of images and is illustrated schematically in **Figure 4.8**.



Figure 4.8: The left hand portion of this diagram illustrates a magnet resting against an infinitely permeable plate of infinite extent. By the Method of Images it can be seen that this geometry is identical to when the plate is removed and another identical magnet attached to our original. This latter magnet is outlined in grey.

Term II

This term is straightforward and may be dealt with as follows, i.e.

$$\frac{\mathbf{c}+\mathbf{z}}{2} \left[\mathbf{Ln}(\mathbf{c}+\mathbf{z}_{\theta}) \Big|_{\mathbf{z}_{\theta}=-\mathbf{x}_{\theta}+\mathbf{i}\mathbf{y}_{\theta}}^{\mathbf{z}_{\theta}=-\mathbf{x}_{\theta}+\mathbf{i}\mathbf{y}_{\theta}} - \mathbf{Ln}(\mathbf{c}+\mathbf{z}_{\theta}) \Big|_{\mathbf{z}_{\theta}=-\mathbf{x}_{\theta}-\mathbf{i}\mathbf{y}_{\theta}}^{\mathbf{z}_{\theta}=-\mathbf{x}_{\theta}-\mathbf{i}\mathbf{y}_{\theta}} \right]$$
[4.61]

which can be expanded to give

$$\frac{c+z}{2} \cdot \begin{bmatrix} \left(\frac{1}{2} Ln((c+x_0)^2 + y_0^2) + iArg(c+x_0 + iy_0)\right) \\ -\left(\frac{1}{2} Ln((c-x_0)^2 + y_0^2) + iArg(c-x_0 + iy_0)\right) \\ -\left(\frac{1}{2} Ln((c+x_0)^2 + y_0^2) + iArg(c+x_0 - iy_0)\right) \\ +\left(\frac{1}{2} Ln((c-x_0)^2 + y_0^2) + iArg(c-x_0 - iy_0)\right) \end{bmatrix}$$
[4.62]

The logarithmic terms cancel and again noting that

$$Arg(a+ib) = -Arg(a-ib)$$
 [4.63]

we are left with

$$i(c+z)[Arg(c+x_0+iy_0)-Arg(c-x_0+iy_0)]$$
 [4.64]

which can be written in real and imaginary form as

$$-\mathbf{y} \cdot \left[\operatorname{Atn}\left(\frac{\mathbf{y}_{0}}{\mathbf{c} + \mathbf{x}_{0}}\right) - \operatorname{Atn}\left(\frac{\mathbf{y}_{0}}{\mathbf{c} - \mathbf{x}_{0}}\right) \right] + \mathbf{i}(\mathbf{c} + \mathbf{x}) \left[\operatorname{Atn}\left(\frac{\mathbf{y}_{0}}{\mathbf{c} + \mathbf{x}_{0}}\right) - \operatorname{Atn}\left(\frac{\mathbf{y}_{0}}{\mathbf{c} - \mathbf{x}_{0}}\right) \right]$$
[4.65]

or

$$-y \cdot \left[Atn\left(\frac{h}{c+w}\right) - Atn\left(\frac{h}{c-w}\right)\right] + i(c+x) \left[Atn\left(\frac{h}{c+w}\right) - Atn\left(\frac{h}{c-w}\right)\right]$$
[4.66]

where h and w are the height and half width of the magnet respectively. In computing the formula account must be taken of the quadrant in which the Arctan function lies.

It is noted that the Arctan terms may be combined as follows

$$\left[\operatorname{Atn}\left(\frac{h}{c+w}\right) - \operatorname{Atn}\left(\frac{h}{c-w}\right)\right] = \operatorname{Atn}\left(\frac{\frac{h}{c+w} - \frac{h}{c-w}}{1 + \frac{h}{c+w} \cdot \frac{h}{c-w}}\right) = \operatorname{Atn}\left(\frac{-2wh}{c^2 - w^2 + h^2}\right) \quad [4.67]$$

So Equation [4.66] can be simplified to yield

$$y \cdot \operatorname{Atn}\left(\frac{2wh}{c^2 - w^2 + h^2}\right) + i(c + x) \cdot \operatorname{Atn}\left(\frac{-2wh}{c^2 - w^2 + h^2}\right)$$
[4.68]

It should also be noted that

$$\lim_{c \to \infty} \left\{ i(c+z) \cdot \operatorname{Atn}\left(\frac{-2wh}{c^2 - w^2 + h^2}\right) \right\} = 0$$
[4.69]

which is to be expected. By combining the results from Term I and Term II the non-complex expression for A is given by

$$\frac{B_{\text{nem}}}{2\pi} \left\{ (y_0 - y) Ln \left[\frac{Amp_0^2 + Amp^2 - 2Amp_0 \cdot Amp \cdot Cos(\Lambda)}{(1 / Amp_0^2) + Amp^2 - 2(Amp / Amp_0) \cdot Cos(\Lambda)} \right] + \right.$$

$$(-y_{0} - y) Ln \left[\frac{(1 / Amp_{0}^{2}) + Amp^{2} - 2(Amp / Amp_{0}) \cdot Cos(\Omega)}{Amp_{0}^{2} + Amp^{2} - 2Amp_{0} \cdot Amp \cdot Cos(\Omega)} \right] +$$

$$(\mathbf{x}_{0} - \mathbf{x})\operatorname{Arg}\left(\frac{(\operatorname{Amp}_{0} \cdot \operatorname{Cos}(\Psi_{0}) - \operatorname{Amp} \cdot \operatorname{Cos}(\Psi)) + i(\operatorname{Amp}_{0} \cdot \operatorname{Sin}(\Psi_{0}) - \operatorname{Amp} \cdot \operatorname{Sin}(\Psi))}{(\operatorname{Amp}_{0} \cdot \operatorname{Cos}(\Psi_{0}) - \operatorname{Amp} \cdot \operatorname{Cos}(\Psi)) + i(-\operatorname{Amp}_{0} \cdot \operatorname{Sin}(\Psi_{0}) - \operatorname{Amp} \cdot \operatorname{Sin}(\Psi))}\right) + i(\operatorname{Amp}_{0} \cdot \operatorname{Sin}(\Psi_{0}) - \operatorname{Amp} \cdot \operatorname{Sin}(\Psi))$$

$$(-\mathbf{x}_{0}-\mathbf{x})\operatorname{Arg}\left(\frac{\left((1/\operatorname{Amp}_{0})\cdot\operatorname{Cos}(\Psi_{0})-\operatorname{Amp}\cdot\operatorname{Cos}(\Psi)\right)+i\left(-(1/\operatorname{Amp}_{0})\cdot\operatorname{Sin}(\Psi_{0})-\operatorname{Amp}\cdot\operatorname{Sin}(\Psi)\right)}{\left((1/\operatorname{Amp}_{0})\cdot\operatorname{Cos}(\Psi_{0})-\operatorname{Amp}\cdot\operatorname{Cos}(\Psi)\right)+i\left((1/\operatorname{Amp}_{0})\cdot\operatorname{Sin}(\Psi_{0})-\operatorname{Amp}\cdot\operatorname{Sin}(\Psi)\right)}\right)+$$

$$\left(c+x\right)\cdot Atn\left(\frac{-2wh}{c^{2}-w^{2}+h^{2}}\right)\right\}$$
[4.70]

Now the magnetic field \mathbf{B} can be described. Since¹

$$\overline{\mathbf{B}} = -\frac{\mathrm{dF}_z}{\mathrm{d}z}$$
[4.71]

where \overline{B} is the complex conjugate of **B**. Thus we have in terms of z.

$$\overline{\mathbf{B}} = \frac{B_{rem}}{4\pi} \left[\frac{\frac{2c(z_0 - z)}{(c + z)^2}}{s\sqrt{\frac{c - z}{c + z}} \cdot \left(s \cdot \sqrt{\frac{c - z}{c + z}} - s_0 \cdot \sqrt{\frac{c - z_0}{c + z_0}}\right) + 2Ln\left(s \cdot \sqrt{\frac{c - z}{c + z}} - s_0 \cdot \sqrt{\frac{c - z_0}{c + z_0}}\right) \right. \\ \left. + Ln[c + z_0] \right]_{z_0 = E}^{z_0 = F}$$

$$\left. - \frac{B_{rem}}{4\pi} \left[\frac{\frac{2c(z_0 - z)}{(c + z)^2}}{s\sqrt{\frac{c - z}{c + z}} \cdot \left(s \cdot \sqrt{\frac{c - z}{c + z}} - s_0 \cdot \sqrt{\frac{c - z_0}{c + z_0}}\right)} + 2Ln\left(s \cdot \sqrt{\frac{c - z}{c + z}} - s_0 \cdot \sqrt{\frac{c - z_0}{c + z_0}}\right) \right. \\ \left. + Ln[c + z_0] \right]_{z_0 = H}^{z_0 = H}$$

$$\left. + Ln[c + z_0] \right]_{z_0 = H}^{z_0 = H}$$

$$\left. \left. 4.72 \right]$$

which equation can be used to calculate the components and absolute magnitude of magnetic field.

If it is desired to once again explicitly separate out the components into real and imaginary parts then assuming a rectangular magnet centred around the y-axis the procedure is as follows.

The following values are assigned to the variables A and B.

II
$$\mathbf{A} = (\operatorname{Amp}_{0} \cdot \operatorname{Cos}(\Psi_{0}) - \operatorname{Amp} \cdot \operatorname{Cos}(\Psi)) \quad \& \quad \mathbf{B} = (\operatorname{Amp}_{0} \cdot \operatorname{Sin}(\Psi_{0}) + \operatorname{Amp} \cdot \operatorname{Sin}(\Psi))$$

$$\mathbf{I} \qquad \mathbf{A} = \left((1 / \operatorname{Amp}_{0}) \cdot \operatorname{Cos}(\Psi_{0}) - \operatorname{Amp} \cdot \operatorname{Cos}(\Psi) \right) \quad \& \quad \mathbf{B} = \left((1 / \operatorname{Amp}_{0}) \cdot \operatorname{Sin}(\Psi_{0}) + \operatorname{Amp} \cdot \operatorname{Sin}(\Psi) \right)$$

$$\mathbf{IV} \qquad \mathbf{A} = \left(\operatorname{Amp}_{0} \cdot \operatorname{Cos}(\Psi_{0}) - \operatorname{Amp} \cdot \operatorname{Cos}(\Psi)\right) \quad \& \quad \mathbf{B} = \left(-\operatorname{Amp}_{0} \cdot \operatorname{Sin}(\Psi_{0}) + \operatorname{Amp} \cdot \operatorname{Sin}(\Psi)\right)$$

III
$$A = ((1 / Amp_0) \cdot Cos(\Psi_0) - Amp \cdot Cos(\Psi)) \& B = (-(1 / Amp_0) \cdot Sin(\Psi_0) + Amp \cdot Sin(\Psi))$$

Neglecting for the moment the $B_{rem}/2\pi$ factor we can differentiate the imaginary part of Equation [4.58] with respect to y in order to get the B_x component of magnetic field. Since the equations are of similar construction we need only differentiate one Logarithmic and one Arctan term so as to get a general form. The result is

$$-0.5 \cdot Ln(A^2 + B^2) +$$

$$\left\{0.5 \cdot (-y+y_0) \left\{2A \left[-\frac{\left(\left(\frac{-2y(Amp^4-1)}{(c+x)^2+y^2}\right)Cos\Psi\right)}{(4Amp^3)} + \frac{\left(Amp\left(\Theta^2 + \frac{2c}{c^2-x^2-y^2}\right)Sin\Psi\right)}{(2(1+\Theta^2))}\right] + \frac{(2(1+\Theta^2))}{(2(1+\Theta^2))}\right\}\right\}$$

$$2B\left[\frac{\left(\left(\frac{-2y(\operatorname{Amp}^{4}-1)}{(c+x)^{2}+y^{2}}\right)\operatorname{Sin}\Psi\right)}{(4\operatorname{Amp}^{3})}+\frac{\left(\operatorname{Amp}\left(\Theta^{2}+\frac{2c}{c^{2}-x^{2}-y^{2}}\right)\operatorname{Cos}\Psi\right)}{(2(1+\Theta^{2}))}\right]\right]}{(2(1+\Theta^{2}))}$$

$$\left\{\left(-x+x_{0}\right)\left\{-\frac{B}{A^{2}}\left(\frac{\left(\frac{2y(\operatorname{Amp}^{4}-1)}{(c+x)^{2}+y^{2}}\operatorname{Cos}\Psi\right)}{4\operatorname{Amp}^{3}}+\frac{\left(\operatorname{Amp}\left(\frac{4cy^{2}}{(c^{2}-x^{2}-y^{2})^{2}}+\frac{2c}{c^{2}-x^{2}-y^{2}}\right)\operatorname{Sin}\Psi\right)}{2(1+\Theta^{2})}\right)+\left(\frac{\left(\operatorname{Amp}\left(\frac{4cy^{2}}{(c^{2}-x^{2}-y^{2})^{2}}+\frac{2c}{c^{2}-x^{2}-y^{2}}\right)\operatorname{Cos}\Psi\right)}{2(1+\Theta^{2})}+\frac{\left(\frac{-2y(\operatorname{Amp}^{4}-1)}{(c+x)^{2}+y^{2}}\operatorname{Sin}\Psi\right)}{4\operatorname{Amp}^{3}}\right)\right\}/A\right\}-\frac{A^{2}}{A^{2}+B^{2}}$$

$$\left(\frac{4cy^{2}}{(c^{2}-x^{2}-y^{2})^{2}}+\frac{2c}{c^{2}-x^{2}-y^{2}}\operatorname{Cos}\Psi}{2(1+\Theta^{2})}+\frac{\left(\frac{-2y(\operatorname{Amp}^{4}-1)}{(c+x)^{2}+y^{2}}\operatorname{Sin}\Psi\right)}{4\operatorname{Amp}^{3}}\right)\right\}/A\right\}$$

The expression for the B_x component of magnetic field is therefore given by calculating this last result for the four separate pairs of values of A and B above and applying the formula

$$B_{x} = \frac{B_{rem}}{2\pi} (II - I - IV + III)$$
[4.74]

The scenario is similar for the B_y component except that now we differentiate the imaginary part of Equation [4.58] with respect to x. The general result is

$$\left\{ 0.5 \cdot \left(-y + y_{0}\right) \left\{ 2A \left[-\frac{\left(\left(\frac{-2(c+x)Amp^{4} - 2(c-x)}{(c+x)^{2} + y^{2}} \right) Cos\Psi \right)}{(4Amp^{3})} + \frac{(\Theta \cdot x \cdot Amp \cdot Sin\Psi)}{(1+\Theta^{2})} \right] + 2B \left[-\frac{\left(\left(\frac{-2(c+x)Amp^{4} - 2(c-x)}{(c+x)^{2} + y^{2}} \right) Sin\Psi \right)}{(4Amp^{3})} + \frac{(\Theta \cdot x \cdot Amp \cdot Cos\Psi)}{(1+\Theta^{2})} \right] \right\} \right] \left\{ -\frac{(A^{2} + B^{2})}{(A^{2} + B^{2})} \right\}$$

$$-Atn\left(\frac{B}{A}\right)+ \left\{ \left(-x+x_{0}\right)\left\{-B\left(\frac{\left(\frac{2(c+x)Amp^{4}}{((c+x)^{2}+y^{2})}+\frac{2(c-x)}{((c+x)^{2}+y^{2})}\right)Cos\Psi}{4Amp^{3}}+\frac{2cxy\cdot Amp\cdot Sin\Psi}{(c^{2}-x^{2}-y^{2})^{2}(1+\Theta^{2})}\right)+ \frac{1}{A}\left(\frac{\left(\frac{-2(c+x)Amp^{4}}{((c+x)^{2}+y^{2})}+\frac{-2(c-x)}{((c+x)^{2}+y^{2})}\right)Sin\Psi}{4Amp^{3}}+\frac{2cxy\cdot Amp\cdot Cos\Psi}{(c^{2}-x^{2}-y^{2})^{2}(1+\Theta^{2})}\right)\right\} / \left(1+\frac{B^{2}}{A^{2}}\right)\right\}$$

$$\left[4.75\right]$$

The expression for the B_y component of magnetic field is therefore given by calculating this last result for the four separate pairs of values of A and B above and applying the formula

$$B_{y} = \frac{B_{rom}}{2\pi} (II - I - IV + III)$$
[4.76]

Thus the objective of obtaining non-complex expressions for the components of magnetic field has been achieved.

VII Graphing the Magnetic Field for Different Magnetron Geometries

Equations [4.45] and [4.72] were used to produce contour maps of the magnetic field parameters for different magnetron geometries where the line segment backing plate assumption is appropriate. These were programmed into Mathematica, a maths oriented programming language. The code is given as **Appendices 4.2 and 4.3**. It should be noted that as given it is overlong and it should not be difficult to produce a more streamlined version. Indeed this has been done but the result has not been tested comprehensively.

Figures 4.9(a-d) illustrate the magnetic field lines, lines of constant B_x and B_y components and lines of constant magnitude of magnetic field B, respectively for a magnetron geometry where the inner magnet has a width of 10 mm and the outer magnets have a width of 15 mm. The inter magnet gap is 30 mm. All magnets are assumed to have equal magnetisation. The field line diagram is qualitatively similar to others published in the literature⁶. B_x and B_y diagrams are a useful aid to magnetron design as the magnitude of the former is important in the vicinity of the target while the magnitude of the latter is critical in determining the degree of ion bombardment at the substrate and the optimum substrate target distance.

In Figure 4.10 the field line diagram for a magnetron in which the central magnet has been removed altogether is illustrated. Analogous geometries have been considered before in the literature⁴. As can be seen from the shape of the lines the null point has moved closer to the magnetron so this magnetron is more unbalanced than when there is a central magnet present. Also the field lines are not shaped in the sense that there is no inner magnet to direct them.

It is common enough practise to achieve an unbalance in a magnetron by using a low strength magnet in the centre. In **Figure 4.11** the field line diagram for a magnetron in which the remanant field of the outer magnet is double that of the inner is shown. By comparison with the diagram of Figure 4.9a it can be seen that the null point has moved closer to the magnets and the degree of unbalance has been increased.

In Figure 4.12 the value of B_{rem} for the inner magnet has been doubled. As can be seen this has restored the magnetron to a state where it is much less unbalanced than in Figure 4.9a. The null point has moved out beyond the range of that portion of the y-axis indicated in the figure.

Figure 4.13a and **Figure 4.13b** show the magnetic field lines and lines of constant magnetic field for a magnetron in which there are two racetracks. This type of design is encountered in larger commercial systems and its inclusion helps to highlight the generality of the results and their applicability to various magnetron designs.



Figure 4.9a: The magnetic field lines for a 'standard' sputter magnetron design. Note that if the magnets all have the same value of B_{rem} , the shape of the field lines is purely dependent on magnetron geometry.



Figure 4.9b: Lines of constant absolute magnitude of Bx component of magnetic field for a 'standard' sputter magnetron design. If the magnets all have the same value of B_{rem} , the shape of the lines is purely dependent on magnetron geometry.



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Figure 4.9c: Lines of constant absolute magnitude of By component of magnetic field for a 'standard' sputter magnetron design. If the magnets all have the same value of B_{rem}, the shape of the lines is purely dependent on magnetron geometry.



Figure 4.9d: Lines of constant absolute magnitude of magnetic field for a 'standard' sputter magnetron design. If the magnets all have the same value of B_{rem} , the shape of the lines is purely dependent on magnetron geometry.



Figure 4.10: Magnetic field lines for a 'standard' magnetron where the central magnet has been removed.



Figure 4.11: Magnetic field lines for a sputter magnetron where Brem of the outer magnet is twice that of the inner.



Figure 4.12: Magnetic field lines for a sputter magnetron where Brem of the outer magnet is half that of the inner. Interestingly the field lines in this design are close to horizontal in the region above what would be the target surface.



Figure 4.13a: Magnetic field lines for a double racetrack sputter magnetron. Devices such as this are found in large industrial vacuum coating apparatus.



Figure 4.13b: Lines of constant magnitude of magnetic field for a double racetrack sputter magnetron.

VIII Sputter Magnetrons - A Matter of Unbalance

The primary consideration in designing a sputter magnetron for hard coating deposition is the shape of the magnetic field in front of the magnetron target. As described by Window and Savvides⁶ the circuit can be designed such that flux leaks inwardly towards the substrate. Such a design constrains more electrons than would otherwise have been the case to find their way to the substrate thereby increasing plasma density in the vicinity of the substrate and hence ion bombardment of the substrate. This is important for production of dense coatings. The alternative is to arrange the design such that flux leaks away from the substrate. This can be used where the substrate or coating is sensitive to damage by excessive heat input. Irrespective of the direction of the field lines the magnetron is said to be unbalanced. Window and Savvides referred to these two types as type II and type I. Here the more descriptive terms "inwardly unbalanced" and "outwardly unbalanced" are preferred. We shall primarily be concerned with the former. Both types are pictured in Figure 4.14. Here the unbalance has been achieved by using tall magnets and by making the outer magnet wider with respect to the inner for the inwardly unbalanced magnetron and by making the inner wider with respect to the outer for the outwardly unbalanced magnetron. It is noted in passing that a completely balanced magnetron design is not achievable and that all magnetrons will to a greater or lesser extent be unbalanced.

Speaking purely in the context of the inwardly unbalanced magnetron it is possible to develop an intuition for its degree of unbalance. This is done by first observing that there is a point of zero magnetic field, referred to as the null point, along the central axis of such a magnetron. The proximity of this point to the magnets is suggested as an indicator of degree of unbalance and is called the null point position. For normal magnetron operation the null point should be much closer to the magnets than the substrate onto which the coating is to be deposited. This is necessary in order to allow the leaked flux to impinge directly on the substrate. A plot of null point position versus magnet height for outer magnet widths of 10, 15, 20 and 25 mm is given in **Figure 4.15**. Note that the inner magnet width is fixed at 10mm and gap width is fixed at 30mm. The first obvious thing to note from Figure 4.15 is that as the magnet height increases the null point position moves closer to the magnetron and hence the degree of unbalance is increased. This result is qualitatively independent of the outer magnet width and



Figure 4.14: (a) An inwardly and (b) outwardly unbalanced sputter magnetron. The unbalance is achieved by changing the width of the inner magnet relative to the outer.



Figure 4.15: Perpendicular distance from the magnets to the null point as a function of the height of the magnets for different outer magnet widths. Inner magnet width = 10mm and gap width = 30mm.

is entirely to be expected. This is because as the magnet height is increased the contribution of the rear poles of the magnets to the total magnetic field in front of the magnets is diminished. With regard to Figure 4.15 it is also noted that for the 10mm width outer magnet the null point position decreases which is to say the degree of unbalance increases more rapidly with magnet height than is the case for when the outer magnet width is 15, 20 or 25mm. On a practical note it can be said that if one were designing a magnetron on the lines of the geometry indicated in Figure 4.15 there would be little to be gained in terms of unbalancing the magnetron by increasing the magnet width above 15mm as long as the magnets are taller than about 20mm high.

Figure 4.16 illustrates a plot of null point position versus magnet height for different intermagnet spacings. The inner and outer magnet widths are fixed at 10 and 15mm respectively. Once again it is clear that as the magnet height increases so too does the degree of unbalance of the magnetron. Not surprisingly it can be seen that as the intermagnet spacing increases the degree of unbalance decreases. This decrease is accelerated as the magnet gap becomes increasingly large. On a practical note it can clearly be seen why unbalanced magnetrons usually have a small gap spacing. For a magnet height of 5mm a gap greater than 20mm results in the null point being further than 100mm away from the magnets and therefore outside what would be considered a typical substrate-magnet distance. By increasing the height of the magnets it is possible to redress this situation but cost and space considerations may make very tall magnets undesirable.

Finally with regard to the notion of the degree of unbalance of a magnetron it is important to appreciate that the above discussion is concerned solely with the shape of the magnetic field. It says nothing about the remanent field of the magnets. This latter parameter is crucial because it determines the strength of the magnetic field in the vicinity of the substrate and therefore the ability of the field to constrain electrons to run along the field lines. A minimum field of 1mT at the substate surface is recommended. Futhermore the magnitude of the B_x component of magnetic field at the target surface is crucial to magnetron operation and should lie in the range 30-50mT. The actual value will be determined by the value of the remanent field as much as by the magnet circuit geometry. Other issues are that target utilisation will




decrease as degree of unbalance increases. If target cost is likely to be a significant factor then a trade off between cost and degree of unbalance may be desirable.

IX Conclusion

A general expression for the magnetic field due to any number of magnets in the vicinity of or in contact with a finite ferromagnetic polygon of arbitrary shape and dimension has been derived. It has been shown to be useful in deriving an analytic solution for the magnetic field in a 'standard' rectangular magnetron which is assumed to be infinitely long. Extension to much more complicated 2-dimensional designs is possible. The work provides a tool for obtaining an accurate, quantitative, and, sometimes completely analytic understanding of the magnetic fields in practical magnetron systems.

Appendix 4.1

A detailed working out of the solution to Equation [4.39] is given.

$$\int \frac{\mathbf{t}_{o} \cdot \mathrm{Ln}[\mathbf{t} - \mathbf{t}_{o}]}{\left(\mathbf{t}_{o}^{2} + 1\right)^{2}} \cdot d\mathbf{t}_{o} = -0.5 \cdot \left(\frac{1}{\mathbf{t}_{o}^{2} + 1}\right) \cdot \mathrm{Ln}[\mathbf{t} - \mathbf{t}_{o}] - 0.5 \cdot \int \left(\frac{1}{\mathbf{t}_{o}^{2} + 1}\right) \cdot \left(\frac{1}{\mathbf{t} - \mathbf{t}_{o}}\right) \cdot d\mathbf{t}_{o}$$

Next the integral on the right hand side of the above equation is worked through. To do this we write

$$\frac{1}{(t-t_{o})(t_{o}^{2}+1)} = \frac{A}{t-t_{o}} + \frac{Bt_{o}+C}{t_{o}^{2}+1}$$

:.
$$1 = A(t_0^2 + 1) + (Bt_0 + C)(t - t_0)$$

By putting t_0 =t an expression for A can be found. By equating coefficients B and C can be found. The results are

$$A = B = \frac{1}{t^2 + 1}; \quad C = \frac{t}{t^2 + 1}$$

The integral of Equation [4.39] can thus be written as

$$\int \left[\frac{1}{(t^2 + 1)(t - t_0)} + \frac{t + t_0}{(t^2 + 1)(t_0^2 + 1)} \right] dt_0$$

which is easily integrable so the complete solution can be written as

$$\int \frac{t_{o} \cdot Ln(t - t_{o})}{\left(t_{o}^{2} + 1\right)^{2}} \cdot dt_{o} = -\frac{1}{2} \cdot \frac{Ln(t - t_{o})}{\left(t_{o}^{2} + 1\right)} + \frac{1}{2} \cdot \frac{Ln(t - t_{o})}{\left(t^{2} + 1\right)} - \frac{1}{2} \cdot \frac{t \cdot Atn(t_{o})}{\left(t^{2} + 1\right)} - \frac{1}{4} \cdot \frac{Ln(t_{o}^{2} + 1)}{\left(t^{2} + 1\right)}$$

and used in the main analysis.

Appendix 4.2

PROGRAM NO. 1 MAGNETIC FIELD LINES

- **REM** A program to calculate the magnetic field lines in a standard sputter magnetron
- REM s is a constant used solely to try and avoid confusion with signs. c is the half width of the magnetron.
- **REM** z is the field point in question. (x,Iy) are its coordinates.
- REM brem is the remanant magnetic field of the magnet in question
- **REM** mh represents the magnet height
- **REM** mw is the distance from the centre of the magnetron to the outer side of the magnetic pole in question

brem = 1; c = 50; z = x + I y; mh =6; mw = 49.99;

```
z1 = -mw + mh I;
z2 = mw + mh I;
z3 = -mw - mh I;
z4 = mw - mh I;
```

k1 = -N[Sqrt[(c-z1)/(c+z1)]]; k2 = -N[Sqrt[(c-z2)/(c+z2)]]; k3 = -N[Sqrt[(c-z3)/(c+z3)]]; k4 = -N[Sqrt[(c-z4)/(c+z4)]]; k = -((c-z)/(c+z))^.5;

```
cz1 = N[c+z1];
cz2 = N[c+z2];
cz3 = N[c+z3];
cz4 = N[c+z4];
```

- + I ArcTan[Im[tl4]/Re[tl4]]))];
- $v4 = -(c^2 z^2)^{.5} N[(I .5 (0.5 Log[(Re[tl4])^2 + (Im[tl4])^2])^{.5}]$
- + I ArcTan[Im[tl3]/Re[tl3]]))];
- $v3 = -(c^2 z^2)^{.5} N[(I .5 (0.5 Log[(Re[tl3])^2 + (Im[tl3])^2])^{.5}]$
- + I ArcTan[Im[tl2]/Re[tl2]]))];
- $v2 = -(c^2 z^2)^{.5} N[(I .5 (0.5 Log[(Re[tl2])^2 + (Im[tl2])^2])^{.5}]$
- + I ArcTan[Im[tl1]/Re[tl1]]))];
- $v1 = -(c^2 z^2)^{.5} N[(I .5 (0.5 Log[(Re[t1])^2 + (Im[t1])^2])^{.5}]$
- tl4 = N[(I+k4)/(I-k4)];
- tI3 = N[(I+k3)/(I-k3)];
- tl2 = N[(I+k2)/(I-k2)];
- tl1 = N[(I+k1)/(I-k1)];
- u1 = (z1-z) N[(0.5 Log[(Re[kk1])^2 + (Im[kk1])^2] + I ArcTan[Im[kk1] / Re[kk1]])]; u2 = (z2-z) N[(0.5 Log[(Re[kk2])^2 + (Im[kk2])^2] + I ArcTan[Im[kk2] / Re[kk2]])]; u3 = (z3-z) N[(0.5 Log[(Re[kk3])^2 + (Im[kk3])^2] + I ArcTan[Im[kk3] / Re[kk3]])]; u4 = (z4-z) N[(0.5 Log[(Re[kk4])^2 + (Im[kk4])^2] + I ArcTan[Im[kk4] / Re[kk4]])];
- kk1 = N[k k1]; kk2 = N[k - k2]; kk3 = N[k - k3];kk4 = N[k - k4];

```
w1 = -.5 (c+z) N[(0.5 Log[(Re[cz1])^2 + (Im[cz1])^2] + I

ArcTan[Im[cz1]/Re[cz1]])];

w2 = -.5 (c+z) N[(0.5 Log[(Re[cz2])^2 + (Im[cz2])^2] + I

ArcTan[Im[cz2]/Re[cz2]])];

w3 = -.5 (c+z) N[(0.5 Log[(Re[cz3])^2 + (Im[cz3])^2] + I

ArcTan[Im[cz3]/Re[cz3]])];

w4 = -.5 (c+z) N[(0.5 Log[(Re[cz4])^2 + (Im[cz4])^2] + I

ArcTan[Im[cz4]/Re[cz4]])];
```

.

r1 = N[u1 + v1 + w1]; r2 = N[u2 + v2 + w2]; r3 = N[u3 + v3 + w3];r4 = N[u4 + v4 + w4];

1.00

mw = 35;

z1 = -mw + mh I; z2 = mw + mh I; z3 = -mw - mh I; z4 = mw - mh I;

k1 = -N[Sqrt[(c-z1)/(c+z1)]]; k2 = -N[Sqrt[(c-z2)/(c+z2)]]; k3 = -N[Sqrt[(c-z3)/(c+z3)]]; k4 = -N[Sqrt[(c-z4)/(c+z4)]]; k = -((c-z)/(c+z))^.5;

kk1 = N[k - k1]; kk2 = N[k - k2]; kk3 = N[k - k3];kk4 = N[k - k4];

```
u1 = (z1-z) N[(0.5 Log[(Re[kk1])^2 + (Im[kk1])^2]
+ I ArcTan[Im[kk1] / Re[kk1]])];
u2 = (z2-z) N[(0.5 Log[(Re[kk2])^2 + (Im[kk2])^2]
+ I ArcTan[Im[kk2] / Re[kk2]])];
u3 = (z3-z) N[(0.5 Log[(Re[kk3])^2 + (Im[kk3])^2]
+ I ArcTan[Im[kk3] / Re[kk3]])];
u4 = (z4-z) N[(0.5 Log[(Re[kk4])^2 + (Im[kk4])^2]
+ I ArcTan[Im[kk4] / Re[kk4]])];
```

tl1 = N[(I+k1)/(I-k1)]; tl2 = N[(I+k2)/(I-k2)]; tl3 = N[(I+k3)/(I-k3)];tl4 = N[(I+k4)/(I-k4)];

```
v1 = -(c^{2} - z^{2})^{.5} N[(I.5 (0.5 Log[(Re[t1])^{2} + (Im[t1])^{2}] + I ArcTan[Im[t1]/Re[t1]]))];
v2 = -(c^{2} - z^{2})^{.5} N[(I.5 (0.5 Log[(Re[t12])^{2} + (Im[t12])^{2}] + I ArcTan[Im[t12]/Re[t12]]))];
v3 = -(c^{2} - z^{2})^{.5} N[(I.5 (0.5 Log[(Re[t13])^{2} + (Im[t13])^{2}] + I ArcTan[Im[t13]/Re[t13]]))];
v4 = -(c^{2} - z^{2})^{.5} N[(I.5 (0.5 Log[(Re[t14])^{2} + (Im[t14])^{2}] + I ArcTan[Im[t14]/Re[t14]])];
```

```
cz1 = N[c+z1];
cz2 = N[c+z2];
cz3 = N[c+z3];
cz4 = N[c+z4];
```

```
w1 = - .5 (c+z) N[(0.5 Log[(Re[cz1])<sup>2</sup> + (Im[cz1])<sup>2</sup>] + I
ArcTan[Im[cz1]/Re[cz1]])];
w2 = - .5 (c+z) N[(0.5 Log[(Re[cz2])<sup>2</sup> + (Im[cz2])<sup>2</sup>] + I
ArcTan[Im[cz2]/Re[cz2]])];
```

```
+ I ArcTan[Im[kk2] / Re[kk2]])];
u3 = (z3-z) N[(0.5 Log](Re[kk3])^2 + (Im[kk3])^2]
+ I ArcTan[Im[kk3] / Re[kk3]])];
u4 = (z4-z) N[(0.5 Log[(Re[kk4])^2 + (Im[kk4])^2]
+ I ArcTan[Im[kk4] / Re[kk4]])];
```

```
tl1 = N[(I+k1)/(I-k1)];

tl2 = N[(I+k2)/(I-k2)];

tl3 = N[(I+k3)/(I-k3)];

tl4 = N[(I+k4)/(I-k4)];
```

```
v1 = -(c^{2} - z^{2})^{.5} N[(I .5 (0.5 Log[(Re[tl1])^{2} + (Im[tl1])^{2}] + I ArcTan[Im[tl1]/Re[tl1]]))];
v2 = -(c^{2} - z^{2})^{.5} N[(I .5 (0.5 Log[(Re[tl2])^{2} + (Im[tl2])^{2}] + I ArcTan[Im[tl2]/Re[tl2]]))];
v3 = -(c^{2} - z^{2})^{.5} N[(I .5 (0.5 Log[(Re[tl3])^{2} + (Im[tl3])^{2}] + I ArcTan[Im[tl3]/Re[tl3]]))];
v4 = -(c^{2} - z^{2})^{.5} N[(I .5 (0.5 Log[(Re[tl4])^{2} + (Im[tl4])^{2}] + I ArcTan[Im[tl4]/Re[tl4]]))];
```

cz1 = N[c+z1]; cz2 = N[c+z2]; cz3 = N[c+z3]; cz4 = N[c+z4];

```
w1 = - .5 (c+z) N[(0.5 Log[(Re[cz1])^2 + (Im[cz1])^2] + I
ArcTan[Im[cz1]/Re[cz1]])];
w2 = - .5 (c+z) N[(0.5 Log[(Re[cz2])^2 + (Im[cz2])^2] + I
ArcTan[Im[cz2]/Re[cz2]])];
w3 = - .5 (c+z) N[(0.5 Log[(Re[cz3])^2 + (Im[cz3])^2] + I
ArcTan[Im[cz3]/Re[cz3]])];
w4 = - .5 (c+z) N[(0.5 Log[(Re[cz4])^2 + (Im[cz4])^2] + I
ArcTan[Im[cz4]/Re[cz4]])];
```

r9 = N[u1 + v1 + w1]; r10 = N[u2 + v2 + w2]; r11 = N[u3 + v3 + w3];r12 = N[u4 + v4 + w4];

ContourPlot[Evaluate[(brem/(4 N[Pi])) (N[Im[r2]-Im[r1]+Im[r3] -Im[r4]-(Im[r6]-Im[r5]+Im[r7]-Im[r8])-(Im[r10]-Im[r9]+Im[r11] -Im[r12])])], {x, 0, 70}, {y, 1, 200}, Epilog -> {GrayLevel[0], Thickness[.008], Line[{{0, -.4}, {50, -.4}}], GrayLevel[1], Rectangle[{0, .2}, {50, 6}], GrayLevel[0], Thickness[.004], Line[{{35, 0.2}, {50, 6}, {50, 0.2}, {35, 0.2}}], Line[{{0, .2}, {5, .2}, {5, 6}, {0, 6}}]}, Contours -> {-.1, -.2, -.3, -.4, -.5, -.6, -.7, -.8, -.9, -.904, -.906, -.908, -.910}, ContourStyle -> Thickness[.006],

AspectRatio -> 2.857, ContourShading -> False, PlotPoints -> 90]

PROGRAM NO. 2 TOTAL MAGNETIC FIELD

- REM This program evaluates the total magnetic field for the standard sputter magnetron.
- REM s is a constant used solely to try and avoid confusion with signs. c is the half width of the magnetron.
- REM z is the field point in question. (x,ly) are its coordinates.
- REM brem is the remanant magnetic field of the magnet in question
- REM mh represents the magnet height
- REM mw is the distance from the centre of the magnetron to the outer side of the magnetic pole in question

brem = 1; c = 50; z = x + I y; mh =6; mw = 49.99;

```
z1 = -mw + mh I;
z2 = mw + mh I;
z3 = -mw - mh I;
z4 = mw - mh I;
```

```
k1 = -N[Sqrt[(c-z1)/(c+z1)]];
k2 = -N[Sqrt[(c-z2)/(c+z2)]];
k3 = -N[Sqrt[(c-z3)/(c+z3)]];
k4 = -N[Sqrt[(c-z4)/(c+z4)]];
k = -((c-z)/(c+z))^.5;
```

```
kk1 = N[k - k1];

kk2 = N[k - k2];

kk3 = N[k - k3];
```

kk4 = N[k - k4];

```
u1 = 2 N[(0.5 Log[(Re[kk1])<sup>2</sup> + (Im[kk1])<sup>2</sup>]
+ I ArcTan[Im[kk1] / Re[kk1]])];
u2 = 2 N[(0.5 Log[(Re[kk2])<sup>2</sup> + (Im[kk2])<sup>2</sup>]
+ I ArcTan[Im[kk2] / Re[kk2]])];
u3 = 2 N[(0.5 Log[(Re[kk3])<sup>2</sup> + (Im[kk3])<sup>2</sup>]
+ I ArcTan[Im[kk3] / Re[kk3]])];
u4 = 2 N[(0.5 Log[(Re[kk4])<sup>2</sup> + (Im[kk4])<sup>2</sup>]
+ I ArcTan[Im[kk4] / Re[kk4]])];
```

tl1 = N[(I+k1)/(I-k1)]; tl2 = N[(I+k2)/(I-k2)]; tl3 = N[(I+k3)/(I-k3)];tl4 = N[(I+k4)/(I-k4)];

cz1 = N[c+z1]; cz2 = N[c+z2]; cz3 = N[c+z3]; cz4 = N[c+z4];

```
w1 = N[(0.5 Log[(Re[cz1])^2 + (Im[cz1])^2] + I ArcTan[Im[cz1]/Re[cz1]])];

w2 = N[(0.5 Log[(Re[cz2])^2 + (Im[cz2])^2] + I ArcTan[Im[cz2]/Re[cz2]])];

w3 = N[(0.5 Log[(Re[cz3])^2 + (Im[cz3])^2] + I ArcTan[Im[cz3]/Re[cz3]])];

w4 = N[(0.5 Log[(Re[cz4])^2 + (Im[cz4])^2] + I ArcTan[Im[cz4]/Re[cz4]])];
```

 $\begin{aligned} x1 &= N[2 \ c \ (z1-z) \ ((c+z)^{-2}) \ ((k \ kk1)^{-1})]; \\ x2 &= N[2 \ c \ (z2-z) \ ((c+z)^{-2}) \ ((k \ kk2)^{-1})]; \\ x3 &= N[2 \ c \ (z3-z) \ ((c+z)^{-2}) \ ((k \ kk3)^{-1})]; \\ x4 &= N[2 \ c \ (z4-z) \ ((c+z)^{-2}) \ ((k \ kk4)^{-1})]; \end{aligned}$

r1 = N[u1 + w1 + x1];

r2 = N[u2 + w2 + x2]; r3 = N[u3 + w3 + x3];r4 = N[u4 + w4 + x4];

mw = 35;

z1 = -mw + mh I; z2 = mw + mh I; z3 = -mw - mh I;z4 = mw - mh I;

k1 = -N[Sqrt[(c-z1)/(c+z1)]]; k2 = -N[Sqrt[(c-z2)/(c+z2)]]; k3 = -N[Sqrt[(c-z3)/(c+z3)]]; k4 = -N[Sqrt[(c-z4)/(c+z4)]]; k = -((c-z)/(c+z))^.5;

kk1 = N[k - k1]; kk2 = N[k - k2]; kk3 = N[k - k3];kk4 = N[k - k4];

u1 = 2 N[(0.5 Log[(Re[kk1])^2 + (Im[kk1])^2] + I ArcTan[Im[kk1] / Re[kk1]])]; u2 = 2 N[(0.5 Log[(Re[kk2])^2 + (Im[kk2])^2] + I ArcTan[Im[kk2] / Re[kk2]])]; u3 = 2 N[(0.5 Log[(Re[kk3])^2 + (Im[kk3])^2] + I ArcTan[Im[kk3] / Re[kk3]])]; u4 = 2 N[(0.5 Log[(Re[kk4])^2 + (Im[kk4])^2] + I ArcTan[Im[kk4] / Re[kk4]])]; tl1 = N[(I+k1)/(I-k1)]; tl2 = N[(I+k2)/(I-k2)]; tl3 = N[(I+k3)/(I-k3)];tl4 = N[(I+k4)/(I-k4)];

```
cz1 = N[c+z1];
cz2 = N[c+z2];
cz3 = N[c+z3];
cz4 = N[c+z4];
```

 $w1 = N[(0.5 \text{ Log}[(\text{Re}[\text{cz1}])^2 + (\text{Im}[\text{cz1}])^2] + I \operatorname{ArcTan}[\text{Im}[\text{cz1}]/\text{Re}[\text{cz1}]])];$ $w2 = N[(0.5 \text{ Log}[(\text{Re}[\text{cz2}])^2 + (\text{Im}[\text{cz2}])^2] + I \operatorname{ArcTan}[\text{Im}[\text{cz2}]/\text{Re}[\text{cz2}]])];$ $w3 = N[(0.5 \text{ Log}[(\text{Re}[\text{cz3}])^2 + (\text{Im}[\text{cz3}])^2] + I \operatorname{ArcTan}[\text{Im}[\text{cz3}]/\text{Re}[\text{cz3}]])];$ $w4 = N[(0.5 \text{ Log}[(\text{Re}[\text{cz4}])^2 + (\text{Im}[\text{cz4}])^2] + I \operatorname{ArcTan}[\text{Im}[\text{cz4}]/\text{Re}[\text{cz4}]])];$

 $x1 = N[2 c (z1-z) ((c+z)^{-2}) ((k kk1)^{-1})];$ $x2 = N[2 c (z2-z) ((c+z)^{-2}) ((k kk2)^{-1})];$ $x3 = N[2 c (z3-z) ((c+z)^{-2}) ((k kk3)^{-1})];$ $x4 = N[2 c (z4-z) ((c+z)^{-2}) ((k kk4)^{-1})];$

r5 = N[u1 + w1 + x1]; r6 = N[u2 + w2 + x2]; r7 = N[u3 + w3 + x3];r8 = N[u4 + w4 + x4];

mw = 5;

z1 = -mw + mh I; z2 = mw + mh I; z3 = -mw - mh I; z4 = mw - mh I; k1 = -N[Sqrt[(c-z1)/(c+z1)]]; k2 = -N[Sqrt[(c-z2)/(c+z2)]]; k3 = -N[Sqrt[(c-z3)/(c+z3)]]; k4 = -N[Sqrt[(c-z4)/(c+z4)]]; k = -((c-z)/(c+z))^.5;

kk1 = N[k - k1]; kk2 = N[k - k2]; kk3 = N[k - k3];kk4 = N[k - k4];

u1 = 2 N[(0.5 Log[(Re[kk1])² + (Im[kk1])²] + I ArcTan[Im[kk1] / Re[kk1]])]; u2 = 2 N[(0.5 Log[(Re[kk2])² + (Im[kk2])²] + I ArcTan[Im[kk2] / Re[kk2]])]; u3 = 2 N[(0.5 Log[(Re[kk3])² + (Im[kk3])²] + I ArcTan[Im[kk3] / Re[kk3]])]; u4 = 2 N[(0.5 Log[(Re[kk4])² + (Im[kk4])²] + I ArcTan[Im[kk4] / Re[kk4]])];

tl1 = N[(I+k1)/(I-k1)]; tl2 = N[(I+k2)/(I-k2)]; tl3 = N[(I+k3)/(I-k3)];tl4 = N[(I+k4)/(I-k4)];

cz1 = N[c+z1]; cz2 = N[c+z2]; cz3 = N[c+z3]; cz4 = N[c+z4];

 $w1 = N[(0.5 Log[(Re[cz1])^2 + (Im[cz1])^2] + I ArcTan[Im[cz1]/Re[cz1]])];$

```
w2 = N[(0.5 \text{ Log}[(\text{Re}[\text{cz2}])^2 + (\text{Im}[\text{cz2}])^2] + I \operatorname{ArcTan}[\text{Im}[\text{cz2}]/\text{Re}[\text{cz2}]])];
w3 = N[(0.5 \text{ Log}[(\text{Re}[\text{cz3}])^2 + (\text{Im}[\text{cz3}])^2] + I \operatorname{ArcTan}[\text{Im}[\text{cz3}]/\text{Re}[\text{cz3}]])];
w4 = N[(0.5 \text{ Log}[(\text{Re}[\text{cz4}])^2 + (\text{Im}[\text{cz4}])^2] + I \operatorname{ArcTan}[\text{Im}[\text{cz4}]/\text{Re}[\text{cz4}]])];
```

```
 x1 = N[2 c (z1-z) ((c+z)^{-2}) ((k kk1)^{-1})]; 
 x2 = N[2 c (z2-z) ((c+z)^{-2}) ((k kk2)^{-1})]; 
 x3 = N[2 c (z3-z) ((c+z)^{-2}) ((k kk3)^{-1})]; 
 x4 = N[2 c (z4-z) ((c+z)^{-2}) ((k kk4)^{-1})];
```

```
r9 = N[u1 + w1 + x1];

r10 = N[u2 + w2 + x2];

r11 = N[u3 + w3 + x3];

r12 = N[u4 + w4 + x4];
```

```
ContourPlot[Evaluate[Abs[(brem/(4 N[Pi])) ((N[Re[r2]-Re[r1]+Re[r3]-Re[r4]]-
N[Re[r6]-Re[r5]+Re[r7]-Re[r8]]-N[Re[r10]-Re[r9]
+Re[r11]-Re[r12]])^2 + (N[Im[r2]-Im[r1]+Im[r3]
-Im[r4]]-N[Im[r6]-Im[r5]+Im[r7]-Im[r8]]-N[Im[r10]-Im[r9]
+Im[r11]-Im[r12]])^2)^.5]], {x, 0, 70}, {y, 1, 200},
ContourShading -> False, PlotPoints -> 90,
Epilog ->
{GrayLevel[0], Thickness[.008], Line[{{0, -.4}, {50, -.4}}],
GrayLevel[1],
Rectangle[{0, .2}, {5, 6}], Rectangle[{35, .2}, {50, 6}], GrayLevel[0],
Thickness[.004],
Line[{{0, .2}, {5, .2}, {5, 6}, {0, 6}, {50, 0.2}, {35, 0.2}],
Line[{{0, .2}, {5, .2}, {5, 6}, {0, 6}]},
AspectRatio -> 2.857,
ContourStyle -> {Thickness[.006]},
```

```
Contours -> {.07, .06, .05, .04, .03, .02, .01, .001, .0001}]
```

References

- 4.1) K.J. Binns and P.J. Lawrenson, Analysis and Computation of Electric and Magnetic Field Problems, Pergammon Press 1963.
- 4.2) Erwin Kreyzig, Advanced Engineering Mathematics (Fifth Edn.), John Wiley & Sons (1983)
- 4.3) M.S. Wong, W.D. Sproul and S.L. Rohde, Surf. Coat. Technol., 49 (1991) 121.
- 4.4) B. Window and G.L. Harding, J. Vac. Sci. & Tech. A., 10 (1992) 3300.
- 4.5) E. Durand "Electrostatique" Volume 2, Masson, Paris (1964)
- 4.6) B. Window and N. Savvides, J. Vac. Sci. & Tech. A., 4 (1986) 453.

Chapter 5 - The Teer Magnetron

I. Introduction

The sputter magnetrons at the Dublin City University (DCU) were purchased from Teer Coating Services Ltd in the UK. So there is an obvious interest in gaining a better understanding of these devices and also in applying the magnetic field theory of the previous chapter. Section II describes the vacuum system. Section III describes the physical characteristics of the Teer magnetron. Section IV applies the theoretical results obtained in Chapter 4 to the Teer magnet geometry and gives an experimental verification of the results. Section V shows how to calculate the potential energy well for secondary electrons in the vicinity of the sputter target. Section VI discusses the target erosion track. Section VII describes the V-I characteristics for the magnetron. Section VIII describes the factors affecting optical emission from the plasma. Section IX gives an account of the Titanium target poisoning effect when Nitrogen is added to the Argon plasma. Section X is the conclusion.

II. The vacuum system

The vacuum system housing the magnetrons is as illustrated in Figure 5.1. A rotary pump Varian SS - 700 is used for roughing out the main chamber and backing of the Varian VHS 6 (2400 litres/s air) oil diffusion pump. The rotary pump exhaust is piped to an oil mist filter and PVC tubing as illustrated. The reason for this filtering is that the oil mist, which occurs when large gas volumes are being pumped, may be injurious to health and is a pollutant. A foreline trap (Varian Model 345) is used in series in the rotary pumping line to protect against backstreaming oil from the conventionally lubricated pump. This trap also sorbs water vapour providing lower roughing pressures and a generally cleaner system. A Pirani gauge is used to monitor pressure in this line. Next the line branches into two flexible stainless steel couplings one of which leads to the roughing valve with the other leading to the backing valve. The







14.

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1.4

Figure 5.3:

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Schematic of the pump & valve control unit, the automatic r.f. matching control unit, the 0.6kW Glassman PSU, the three 5kW MDX magnetron PSUs and the 1.2kW r.f. PSU.



Figure 5.4: Control panel and power supplies for the high vacuum system.

couplings have to be flexible to isolate the main apparatus from rotary pump vibrations. The backing valve is directly connected to the diffusion pump and has two After the rotary pump is turned on the backing valve is opened to allow functions. pumping of the diffusion pump volume. Next, having first made sure that water is being supplied to its cooling pipes, the diffusion pump is turned on. Fifteen minutes is allowed for the silicone based diffusion pump oil to heat up. Once heated the oil evaporates up a capped chimney within the pump. The only way for the oil to escape is through downwardly directed jet assemblies. This steam of downwardly directed oil acts to push gases towards the diffusion pump exhaust thereby giving a pumping action. The oil cools on the diffusion pump walls and drips back into the heated reservoir at the chimney base and the process repeats. In operation once the oil is heated the next thing is that the backing valve is closed and the roughing valve which is directly connected to the vacuum chamber is opened so that the rotary pump can evacuate the chamber volume to below the maximum diffusion pump operating pressure of about 3 x 10^{-1} mbar as monitored by a second Pirani gauge connected to the chamber base plate. Once a pressure below this value has been achieved the roughing valve is closed and the backing valve opened once more. The next action is to open up the VAT gate valve which connects the diffusion pump to the main vacuum chamber. This valve has the useful feature that it can be set for an intermediate position on a scale of 0,1...10 where 0 corresponds to the valve being fully closed and 10 corresponds to the valve being fully open. This gives control of the effective pumping speed. The diffusion pump now acts to evacuate the chamber to high vacuum with the rotary pump removing diffusion pump exhaust gases. The chamber pressure is capable of attaining an ultimate vacuum of 1.10⁻⁸ mbar as read from the Penning high vacuum gauge. This gauge is shown attached to the curved wall of the chamber. Note that the output from all pressure gauges is fed to an Edwards 1005 digital pressure meter. Note also that all the valves are pneumatically actuated. The chamber is 603mm in diameter and 610mm high with four large rectangular ports at right angles to one another. These are either blanked off or fitted with a Teer magnetron. (The chamber design is based on that used by Teer Coating Services Ltd. UK for a four magnetron closed field magnetron array). Only two magnetrons /blanking plates are visible in Figure 5.1. The chamber also has a magnetron port built into the top plate. It is opened by using a chain block attached to the top plate to raise and lower either the top plate or more usually the top plate together with the main curved body of the chamber. This is illustrated in the photograph of **Figure 5.2**. Additional features include viewports, gas inlets and other feedthroughs. For clarity only the essential feedthroughs are illustrated. With regard to the gas inlets these may be blanked or fed via mass flow controllers from high purity gas bottles. In the illustration high purity Argon and Nitrogen are the gases which are connected. **Figure 5.3** shows the power supplies which are available. These are three MDX 5kW d.c. PSUs, a Glassman high voltage (1000V) low current (600mA max) PSU, one Advanced Energy r.f. PSU with matching unit and an electrical control box for electrical switching of the pumps and actuating the valve solenoids. **Figure 5.4** is a photograph of these units.

III. Physical description of the magnetron

Figure 5.5a is a photograph of the Teer magnetron. This is the side that in operation would face into the vacuum chamber. In order to reveal part of the magnetic circuit the target has been unscrewed from the aluminium body. Where there is contact with cooling water the aluminium has been black anodised for corrosion resistance. Elsewhere the anodise is applied for reasons of aesthetics. The magnets used are ferrites of remanant field $B_{rem} = 0.37$ T. The outer magnet width is 15mm, the intermagnet gap is 27.5mm and the inner magnet width is 10mm. The magnet length is 290mm. The inter-magnet gap at the ends of the magnetron is 20mm. The first layer of magnets is 6mm high. The second layer of magnets cannot be seen but is located directly beneath the visible first layer and is 25mm high. The reason for the double layer of magnets is that the designer wants to force water cool the target and also to avoid any cooling water short circuit. The magnets are slightly corroded and a design improvement would be to encapsulate them so as to prevent their corrosion due to cooling water circulation. This measure would also provide for a better degree of mechanical protection for the brittle magnets. The backing plate which forms the final part of the magnetic circuit is made from mild steel and is 10mm thick. See Figure 5.5b. Furthermore Figure 5.6 shows a two-dimensional schematic of the design. Figure 5.5b also shows that the bolts used to attach the magnetron to the vacuum



(a)



(b)



chamber are electrically isolated since they pass through Teflon bushes. In operation the main magnetron body is sealed against, and electrically isolated from, the vacuum chamber via a nylon flange with an o-ring on either side. Cooling water enters and exits through two brass feedthroughs bolted onto the backing plate. These are clearly visible in Figure 5.5b. In operation the water impinges directly onto the back of the target. This is often important as the maximum operational power is a sensitive function of cooling efficiency. An earth shield (not shown) suitably positioned within the vacuum chamber prevents sputtering of the screws.

IV. Magnetic field calculations

With regard to calculating the magnetic field the methodology is exactly the same as for the 'standard' sputter magnetron except that because there are two layers of magnets there are nine free (not contacting a ferromagnetic) magnetic poles to be taken into account.

The z-plane and t-plane geometries are pictured in Figure 5.6. Figures 5.7 - 5.10 show the magnetic field lines, the absolute magnitude of the B_x component of magnetic field, the absolute magnitude of the B_y component of magnetic field and the absolute magnitude of total magnetic field as calculated for the Teer magnetron.

Figure 5.11 is a superposition of the theoretical results and the spread of iron filings which resulted when the filings were scattered onto a piece of paper supported perpendicularly to the centre of the magnetron across the minor section of the racetrack.

With reference to Chapter 4 the magnetron is highly unbalanced in the sense that the null point is just 56mm from the target surface. A look at the 0.1mT contour in Figure 5.10 highlights nicely the null point position. Another point to make is that the B_x component of magnetic field at the target surface, as illustrated in Figure 5.8, lies in the range 30 to 50mT often cited as the operating range for sputter magnetrons.



Figure 5.6: The upper diagram is a schematic of the Teer magnetron. For calculation purposes this is regarded as being in the z-plane. The monopole lines in the upper half of the t-plane correspond to those poles of the magnets which are not in contact with the backing plate. Their images are shown in the lower half of the t-plane. The symbols S and N refer to south and north poles.



Figure 5.7: The field lines encountered moving from left to right across the top pole of the outer magnet are 0, -0.2, -0.4, -0.6, -0.8, -1.0, -1.1, -1.12, -1.14, -1.16, -1.18, -1.2 and -1.52 T mm.



Figure 5.8: Moving from left to right across the top pole of the outer magnet the lines of constant magnitude of B_x encountered are 70, 60, 50, 40, 30, 20, 10, 1, 0.1, 0.1, 1, 10, 20, 30, 40, 50, 60 and 70 mT.



Figure 5.9: The lines of constant B_y are 70, 50, 30, 10, 3, 1, 0.9 and 0.7 mT, moving along an axis perpendicular to the top pole of the outer magnet. Moving along the y-axis the values encountered are70, 50, 30, 10, 3, 1, 0.9, 0.7, 0.5, 0.5, 0.7 and 0.9 mT.



Figure 5.10: An illustration of the lines of constant magnitude of magnetic field (B) in front of a 10mm thick target mounted on the Teer magnetron. The lines are 70, 60, 50, 40, 30, 20, 10, 1, and 0.1 mT.



Figure 5.11: The diagram shows a superposition of a field line diagram as obtained theoretically and experimentally. Agreement is generally good. Any discrepancy is probably due to the fact that the magnetron is only 29cm long and so the two dimensional approximation is not perfectly valid in this case.

V. Effective energy well for secondary electrons

On a theoretical note it is interesting to develop an intuition for the region surrounding the magnetron which an electron of given energy emitted from a certain point on the target can access. This is done by considering the Hamiltonian motion of the particle in an effective potential well in a manner described by Schmidt¹ and by Wendt² et al and also by Sheridan et al³. Following Schmidt for a two dimensional geometry the non-relativistic Lagrangian of a particle in an electromagnetic field is given by

$$L = K.E. - P.E. = \frac{1}{2}mv^2 + q(A.v) - qV$$

The Hamiltonian is obtained from the Lagrangian by

$$=P_i\dot{Q}_i - L$$

where P_i is the canonical momentum, defined as

 $P_i = \partial L / \partial \dot{Q}_i$

 Q_i is the canonical coordinate, the dots denote time derivatives, and the summation convention for common indices is again adopted. The equations of motion are obtained from the canonical equations

 $\dot{Q}_i = \partial H / \partial P_i$

and

 $\dot{\mathbf{P}}_{i} = -\partial \mathbf{H} / \partial \mathbf{Q}_{i}$

If H does not depend on the coordinate Q_k then

 $\dot{P}_{k} = 0$

yielding P_k as a constant of the motion. Q_k is called a cyclic or ignorable coordinate.

For fields with planar symmetry (e.g. $\partial/\partial Q_3 = 0$ for every field quantity), we introduce Cartesian coordinates as canonicals. The velocity vector is now $v_i = \dot{Q}_i$ and the Lagrangian becomes

$$\mathbf{L} = \mathbf{I}_2 \mathbf{m} \dot{\mathbf{Q}}_i \dot{\mathbf{Q}}_i + \mathbf{q} \mathbf{A}_i \dot{\mathbf{Q}}_i - \mathbf{q} \mathbf{V}$$

while the canonical momentum becomes

$$P_i = m \dot{Q}_i + q A_i;$$
 $\dot{Q}_i = (P_i - q A_i)/m$

For the Hamiltonian the \dot{Q}_i 's have to be expressed in terms of the P_i 's. Therefore,

$$H = P_{i} \frac{P_{i} - qA_{i}}{m} - \frac{(P_{i} - qA_{i})(P_{i} - qA_{i})}{2m} - \frac{qA_{i}(P_{i} - qA_{i})}{m} + qV = \frac{(P_{i} - qA_{i})^{2}}{2m} + qV$$

If one of the coordinates (e.g. i=3) is cyclic we can write the previous expression in the form

$$H = \frac{(P_1 - qA_1)^2}{2m} + \frac{(P_2 - qA_2)^2}{2m} + \psi$$

where

$$\psi = \frac{\left(\mathbf{P}_3 - \mathbf{q}\mathbf{A}_3\right)^2}{2\mathbf{m}} + \mathbf{q}\mathbf{V}$$

is the effective potential, a known space-time function, because P_3 is a constant. The equations of motion, as derived from the expression for H reduce to those of two dimensional motion in the magnetic field defined by A_1 and A_2 with effective potential ψ .

Now in the case of a magnetron such as the Teer magnetron where the geometry can be approximated as being two dimensional one coordinate, say the z-coordinate, is a cyclic coordinate. So

$$\mathbf{P}_3 = \mathbf{m}\mathbf{v}_3 + \mathbf{q}\mathbf{A}_3$$

is a constant of the motion. The value of P₃ for an electron is equal to its value at the point of origin of the electron at the cathode plate corresponding to (x1,y1). This is because secondary electrons are usually emitted with a kinetic energy in the 1-4eV range so the initial velocity v₃ is close to zero and P₃ = $qA_3(x1,y1)$. The expression for the effective potential can now be rewritten as

$$\psi = \frac{e^2 (A_z(x, y) - A_z(x_1, y_1))}{2m}$$

and using Equation 4.46 to substitute for A it is possible to calculate the effective potential well.

This has been done for 500eV secondary electrons emitted at distances of x=0, 2.5, 5, 23, 40 and 42.5mm from the centre of the target in the Teer magnetron. The result is illustrated in Figure 5.12a. As expected electrons emitted at x=0 can travel along the magnetic field lines, which are effectively perpendicular to the target surface at that point, and escape from the magnetic trap. Only 2.5mm away from the centre there is a different story. As before the trap is defined by the white area of Figure 5.12b. The dark areas are forbidden. Moving out to 5mm for Figure 5.12c we see that the area which is accessible to the electron has shrunk and also moved closer to the target. At 23mm, a distance which corresponds to the area of deepest erosion on the magnetron target, the area available to the electron has shrunk tremendously and is now right up against the target. See Figure 5.12d. If the area were to get much smaller the electrons could never maximise their energy in falling down the full plasma sheath potential. This would lead to a less efficient discharge since the number of ionisations which a given electron would be capable of initiating would be reduced. This is consistent with the observation by many researchers that the magnetron effect only works up to a maximum B_x of about 50mT in front of the target. It is furthermore possible to imagine that the stage is reached where the secondary electrons cannot be ejected at all from the target due to the confining effects of the magnetic field. Moving on to 40mm as shown in Figure 5.12e we see a potential well which is roughly comparable to that produced at the 5mm point. It is noted that this point is directly in



Figure 5.12: These diagrams illustrate the effective potential well as seen by electrons emitted from a 10mm thick target mounted on the Teer magnetron. The emission points x = 0, 2.5, 5, 23, 40 and 42.5 mmcorrespond to (a), (b), (c), (d), (e) and (f). The dark areas are forbidden to electrons of energy less than 500eV.

line with the centre of the outer magnet. Finally we move out to 42.5 mm. See Figure 5.12f. This shows that as for 0mm the electron is free to escape from the magnetic trap. However it is constrained to do this in a way that directs it towards a region where a substrate could be located. So the unbalance acts to direct electrons to the substrate increasing the degree of ionisation and hence the ion bombardment there.

VI. The erosion track

The erosion pattern of the Teer magnetron has been graphed in **Figure 5.13**. A milling machine with a point attachment was used to take the measurements. The graph shows that the greatest erosion depth occurs at a distance of roughly 23mm from the centre of the target.

This is in accordance with Figure 5.9 which shows that the contour $B_y=0$ will intersect the target surface at approximately this distance. Since many researchers^{2,3} have commented that this is where maximum erosion occurs we have a further proof of the accuracy of the theory. So it can be pointed out that theoretical knowledge of the contour $B_y=0$ is useful because it makes it easy to predict the point of deepest erosion for a given target thickness.

Using the Hamiltonian approximation and assuming the secondary electrons to be evenly distributed over energetically accessible areas and estimating these areas at half the discharge voltage to allow for loss of energy due to collisions Wendt² et al arrived at an expression in the form of a Fredholm integral equation of the second kind which describes the flux of ions incident at a point (x,y) due to a secondary electron emitted from (x1,y1). Their expression is

$$j_i(x) = \gamma N \int_{x_1} \frac{Lh(x, x_1)}{A(x_1)} j_i(x_1) dx_1$$

where γ is the secondary electron emission coefficient, N is the number of ion electron pairs created in the plasma by each energetic electron, L is the length in the z-direction


Figure 5.13: An illustration of the erosion curve for a 10mm thick titanium target mounted on the Teer magnetron

that is being considered, h(x,x1) is the distance between the two y-values that bound the motion for a given x and A(x1) is the area available to an electron emitted from the target at x1. They fitted the results to experimental data and obtained reasonable agreement. Later Sheridan et al³ carried out a full scale simulation of the magnetron plasma and more accurately fitted the results to their target erosion profile.

VII. The V-I curve

The V-I curve for the device is given in **Figure 5.14**. This roughly satisfies the relation $I=kV^n$ where I is the current (Amps), V is the voltage (Volts), k is a proportionality constant and n is another constant. Using a least squares fit on a logarithmic plot it was found that $n \approx 7$ at a pressure of $3.5.10^{-3}$ mbar. k was then -41. This is precisely in the middle of the range 5-9 given by Thornton⁴ as being characteristic of sputter magnetron devices.

VIII. Emission intensity for a particular electron transition

In order to monitor and control reactive processes in the magnetron system a fibre optic bundle is sometimes used to guide radiation from the plasma to a monochromator. The output from the monochromator is transduced to an electrical signal which in turn is fed to a fast acting piezoelectric valve which controls the flow of reactive gas into the chamber. If the monitoring system is fixed on an emission line for the target metal then the feedback control will react so as to sustain a constant emission intensity. This constant intensity should correspond to that which is required for obtaining stoichiometric compound coatings. The requirement for this kind of monitoring will be more fully explained in the section dealing with target poisoning.

It is noted that the emission intensity I for a particular inter-atomic energy level transition is a complex function of the number density of sputtered atoms N, the probability of a particular neutral to become excited to a state i per unit time P_i and the probability that it will relax to a given state j per unit time T_{ij} . The emission intensity I for a particular spectral line as seen by the detection system is given by



Figure 5.14: The Voltage-Current characteristic for the Teer magnetron at a pressure of 3.5 10⁻³ mbar.



Figure 5.15: Intensity of the Ti 454nm optical emission line as a function of magnetron current at 3.5 10⁻³ mbar.

I=N P_i T_{ij} g

where g is the fraction of photons emitted at this wavelength which are collected by the fibre bundle.

A plot of the optical emission from Titanium at 454nm against magnetron discharge current yields the curve of **Figure 5.15**. The results were quickly taken as the maximum current used is well above the recommended 6 Amps and there was a fear of overheating. The measured intensity is a very complex function of the sputtering conditions, geometry and target material.

IX. Target poisoning during reactive sputtering

The titanium target was sputtered in an argon discharge. It is noted that the gate valve between the diffusion pump and the vacuum chamber was open to 0.4 of its maximum. The magnetron discharge current was 8 Amps. The initial pressure was 3.0×10^{-3} mbar. Nitrogen flow was initiated and gradually increased. The rate of increase is slow so that steady state conditions apply. The sputtering rate follows the path described by data corresponding to the blackened circles in **Figure 5.16**. Clearly the curve undergoes a sharp reduction in the region of flow =12 SCCM/s (x1.4). The reason for this is that the flow of reactive gas has become sufficiently great that sputtering from the target is no longer sufficient to preserve the fresh Titanium metal surface. A Titanium Nitride layer is formed on the target. This has a relatively low sputtering yield and the sputtering rate goes down. The chemical reaction at the target surface is often referred to as poisoning.

Next the Nitrogen flow is gradually reduced back to zero. See the data circles with a white background in Figure 5.16. The sputtering rate follows a different path. The reason for this path, as opposed to the previous one, is as follows. Significantly less flow of nitrogen is required to sustain the titanium nitride layer than was needed to create it. So the transition from compound sputtering mode to metal sputtering mode to occurs at lower flow values than the transition from metal sputtering mode to



Figure 5.16: Diagram illustrating the hysteresis curve which results from the poisoning effect of nitrogen on a titanium target during sputtering as the nitrogen flow is increased. The magnetron was run at 8 Amps and the vacuum chamber gate valve is open to 0.4 of its maximum.

compound sputtering mode. That is to say, a hysteresis effect is observed. It is an important feature of reactive sputtering processes.

Figure 5.17 is obtained as follows. An optical monochromator set to monitor a Titanium emission peak receives a signal from a fibre optic cable. The cable is pointed towards the magnetron plasma. The signal from the plasma is transduced into an electrical signal which is proportional to the intensity of the light and hence the concentration of Titanium present. This signal is fed back to a fast acting flow control valve which acts to correct any deviation from a preset value by altering the flow of nitrogen into the chamber so in turn altering the Titanium peak intensity. As this preset value (effectively optical emission on the graph) is reduced the flow of nitrogen going into the chamber increases rapidly at first as the substrate is poisoned. Next the target is about to be poisoned as in Figure 5.16. However the controller acts to reduce the flow of Nitrogen into the chamber thereby preventing this from happening. This continues until a point is reached at which the gettering capability of the target is completely lost and the flow must increase again. This point corresponds to the bottom of the Z-shaped curve of Figure 5.17.

Figure 5.18 shows a curve taken as for Figure 5.17 except when the pump gate valve is fully opened. The hysteresis effect has disappeared. Here the high throughput ensures that even with the substrate poisoned the pump carries away sufficient reactive gas to prevent sudden target poisoning. A slight increase in gas flow is therefore necessary to completely poison the target.

The input mass flow of reactive gas is gettered by five mechanisms⁵. Two of these, which relate to adsorption onto compound surfaces at the target and substrate are slight. The sticking coefficient for nitrogen adsorption onto these surfaces (α_n) is much less than the sticking coefficient (α_m) for nitrogen on titanium. The three important remaining mechanisms are the pumps, that fraction $(1-\Theta_t)$ of the target surface (A_t) which is unreacted and that fraction $(1-\Theta_c)$ of the substrate surface (A_c) which is unreacted. There is no gettering in the gas phase because such two body



Figure 5.17: The 'hysteresis' effect when the nitrogen flow is under feedback control at magnetron current of 8 Amps and the vacuum chamber gate valve open to 0.4 of its maximum.



Figure 5.18: The hysteresis effect vanishes when the magnetron current is 8 Amps and the vacuum chamber gate valve is fully open.

collisions do not allow for conservation of energy and momentum. So reactions only take place at surfaces.

Figure 5.19 illustrates these three gettering mechanisms. With increasing p_N the growing film is initially primarily responsible for gettering. Once the film has become saturated with nitrogen its gettering capability is limited by the arrival rate of fresh metal. However the target too becomes saturated thus curtailing metal supply. So the contribution of the film fades away since all the nitride is formed at the target surface.



Figure 5.19: Calculated curves for the target pump q_t , the receiver pump q_c , and the vacuum pump q_s vs partial pressure of the reactive gas⁶.

X. Conclusions

Selected characteristics of the Teer magnetron and its operation in the large vacuum system at DCU have been investigated. An accurate analytic description of the magnetic fields in the vicinity of the magnetron has been given. The theory has been supported with a simple experiment. A proof of the utility of the results is that they are currently being used (possibly in conjunction with Finite Element Analysis) by BNFL and the University of Salford as part of a large scale research project the focus of which is to investigate the use of Teer magnetron technology for development of coatings relevant to the nuclear industry. An account of the effective magnetic potential well trapping the electrons in the vicinity of the target has been given.

References

- 5.1) George Schmidt, "Physics of High Temperature Plasmas" 2nd Edn. Academic Press pg 30 (1979).
- 5.2) A.E. Wendt, M.A. Lieberman and H. Meuth, J. Vac. Sci. Technol. A, 6(3) pg 1827 (1988).
- 5.3) T.E. Sheridan, M.J. Goeckner and J. Goree, J. Vac. Sci. Technol. A, 8(1) pg 30 (1990)
- 5.4) J.F. Thornton in R.F. Bunshah (Ed) "Deposition Technologies for Films and Coatings", Noyes Publications, pg 201 (1982).
- 5.5) S. Berg, H.-O. Blom, M. Moradi and C. Nender, J. Vac. Sci. Technol. A, 7(3) pg 1225 (1989).
- 5.6) T. Larsson, H.-O. Blom, C. Nender and S. Berg, J. Vac. Sci. Technol. A, 6(3) pg 1832 (1988).

Chapter 6 - The Dimag: A Sputtering Source Based on the Penning Geometry

I. Introduction

So far this study has concentrated on gaining an understanding of conventional sputter magnetron geometries with particular emphasis being placed on the Teer magnetron. Hereafter the focus is on an unconventional sputter source based on the Penning discharge. A Penning¹ source is one in which two opposing cathodes have a magnetic field perpendicular to the cathode surfaces. Secondary electrons emitted during sputtering are in the main constrained to reside within the volume between the cathodes. So an intense discharge which is sustainable down to low pressures can be ignited.

The motivation for studying this kind of geometry is a belief that low pressure ($<1.10^{-3}$ mbar) high intensity discharges represent a way forward for magnetron sputtering technology. This chapter gives an account of the theory, design, construction and preliminary testing of a Penning type sputtering source which is referred to as the Dimag.

The idea to build the Dimag source came from a review article by Harper² in which he describes the use of a double cathode arrangement to extract an ion beam. Subsequently it was found that Naoe et al³⁻⁹ and Window et al^{10,11} have both explored sputtering systems based on this geometry.

Naoe et al first published the apparatus shown³ in Figure 6.1a in 1980. Their motivation for using this device was the need to achieve reasonable deposition rates from a ferromagnetic target material. For adequate ferromagnetic deposition rates in conventional magnetrons it is necessary to use very strong magnets to saturate the target

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thereby reducing its permeablility and/or use a very thin target. Such measures enable the establishment of a suitably strong transverse magnetic field component B_x above the target surface. By constructing a Penning type source Naoe et al circumvented this difficulty since the plasma discharge in this device depends solely on the perpendicular B_y component of magnetic field for confinement. Later⁴⁻⁷ they went on to sputter ferromagnetic materials using a permanent magnet design. One variation is shown in **Figure 6.1b**. The advantage with this source is that there is better target utilisation. The magnetic field is much weaker mostly because of the greater inter-magnet distance of 14cm. This was not a serious concern because at 10-15mT it is still sufficient to confine secondary electrons and prevent substrate overheating. This was important to Naoe et al because their early work³⁻⁶ aimed to deposit onto plastic polyimide film substrates with an eye to recording media applications. Maximum deposition rates were an impressive 0.4um per minute. The lowest working pressure mentioned³ is 3.10^{-3} mbar.



Figure 6.1: (a) Schematic of the original Penning apparatus from Naoe et al. This used a solenoid to produce the magnetic field. (b) Schematic of a later version of the Penning source of Naoe et al. Here a ring of permanent magnets have replaced the solenoid. This arrangement gives better target utilisation.

Window et al^{10,11} on the other hand were not especially interested in particular coating types but instead wanted to produce enhanced ion bombardment at the substrate while maintaining the high deposition rate of the conventional sputter magnetron. In their own words the aim was to produce "an intense plasma which extends well away from the cathode surface and close to the substrate surface". In a paper which is a precursor to their work on the unbalanced magnetron¹¹ they managed to create a source which was capable of providing 0.4 ions per deposited atom at a substrate distance of 72mm. See



Figure 6.2: Schematic of the Penning deposition system designed by Window et al. The conical cathodes are used to direct the flux in the direction of the substrate.

Figure 6.2. This compares with conventional magnetrons which have on the order of 0.1 ions per deposited atom under the same conditions.

The early investigations by Naoe et al³⁻⁶ are solely concerned with the deposition of Later⁷⁻⁹ investigations concentrate primarily on alternating ferromagnetic materials. current discharges with a view to high rate deposition of aluminium oxides. So the notion of the Penning discharge geometry as an alternative to the conventional sputter magnetron was not pursued. The work of Window et al was carried out on a device with very small (2 to 16mm) intercathode spacing. Furthermore the reported maximum discharge power is about 420 Watts, the lowest reported operating pressure is 5.10⁻³ mbar and the magnetic field used for deposition was 42mT. The Dimag as we will see allows for discharge powers up to at least an order of magnitude higher, sustainable plasma pressures down to at least two orders of magnitude lower and features magnetic field strengths up to ten times greater than those used in the apparatus of Window et al. The only limitation to working at even higher powers and lower pressures is the lack of a sufficiently high voltage high current power supply unit. Thus the Dimag is operating in a completely different regime to the device described by Window et al. Another point which should be addressed is one made by Rohde¹² in a review of unbalanced magnetron sputtering. This is to the effect that the scale-up potential for this type of system is quite low since the target substrate distances must be quite small in order to achieve high deposition rates. While it is true that the deposition rate from a Penning source will fall away rapidly with distance this is also true of the commercially very successful Balzers low voltage electron beam evaporation technique. Indeed it may be that with further development the Penning device could be developed into a sputtering analogue of that This would have the advantage that it should be possible to deposit apparatus. stoichiometrically controlled TiAlN coatings by sputtering from TiAl targets whereas this is not possible using evaporation. A further support for the possible upscaling of the Penning source stems from an earlier paper by Window et al in which they suggest that the source could be used effectively in strip roll coating¹⁰.

The rest of the chapter is organised as follows. Section II describes the theory used to calculate the magnetic field present in the Dimag source. Graphical results are presented for different inter magnet spacings. Section III describes the magnetic potential well. The degree of electron and ion confinement is illustrated and discussed. Section IV gives an account of the physical construction of the Dimag and its installation into the vacuum chamber described in Chapter 5. Section V describes preliminary experiments using titanium sputter targets. Section VI is the conclusion.

II. Magnetic fields in the Dimag source

In order to design the source it was first decided to get an indication of the magnetic field which exists within the device. This is done by slightly adapting equations given by Durand¹³. These describe the magnetic flux, the radial component of magnetic field and the axial component of magnetic field for a single pole of a cylindrical magnet. The expression for the flux is given by

$$F(\mathbf{R}, \mathbf{z}) = \frac{M}{4\pi} \left\{ 1 + \frac{\varepsilon}{2} \left(1 - \varepsilon^* \right) \left(\frac{\mathbf{R}^2}{\mathbf{a}^2} - 1 \right) \right\} -$$

$$\frac{\mathrm{aB}_{\mathrm{rem}}}{\pi} \frac{\mathbf{R} \cdot (\mathbf{z} - \mathbf{z}_0)}{\mathbf{r}_1} \left\{ \frac{1}{\mathrm{m}} (\mathbf{K}(\mathbf{m}) - \mathbf{E}(\mathbf{m})) + \left(\frac{1}{\mathrm{n}} - 1\right) (\mathbf{K}(\mathbf{m}) - \mathrm{Pi}(\mathbf{n}, \mathbf{m})) \right\}$$
[6.1]

The expression for the radial component of magnetic field is given by

$$B_{r}(R, z) = \frac{B_{rem}}{2\pi} \frac{r_{1}}{R} \left\{ \left(1 - \frac{m}{2}\right) (K(m) - E(m)) \right\}$$
[6.2]

The expression for the z-component of magnetic field is given by

$$B_{z}(\mathbf{R},z) = \frac{B_{rem}}{4\pi} \left\{ \varepsilon \cdot \left(1 - \varepsilon^{*}\right)\pi + \frac{2(z - z_{0})}{r_{1}} \left[\varepsilon^{*} \cdot \sqrt{1 - n} \cdot \operatorname{Pi}(n,m) - K(m)\right] \right\}$$
[6.3]

The total magnetic field is given by

$$\mathbf{B} = \sqrt{\mathbf{B}_{r}^{2} + \mathbf{B}_{z}^{2}}$$
 [6.4]

where B_{rem} is the remanant magnetic field of the magnets, a is the radius of the cylindrical magnet, (R,z) are the coordinates of the field points in question, M is the total magnetic charge at the magnet pole given by $M=2\pi a^2 B_{rem}$,

$$\varepsilon = \begin{cases} -1 & \text{if } z - z_0 < 0 \\ 0 & \text{if } z - z_0 = 0 \\ 1 & \text{if } z - z_0 > 0 \end{cases} \qquad \qquad \varepsilon^* = \begin{cases} -1 & \text{if } R < a \\ 0 & \text{if } R = a \\ 1 & \text{if } R > a \end{cases} \qquad [6.5]$$

the complete elliptic integrals of the first, second and third kinds are defined as

$$K(m) = \int_0^{\frac{\pi}{2}} (1 - m \cdot \sin^2 \omega)^{-\frac{1}{2}} d\omega \qquad [6.6]$$

$$E(m) = \int_0^{\frac{\pi}{2}} (1 - m \cdot \sin^2 \omega)^{\frac{1}{2}} d\omega$$
 [6.7]

$$Pi(n,m) = \int_{0}^{\frac{\pi}{2}} (1 - n \cdot \sin^{2} \omega)^{-1} (1 - m \cdot \sin^{2} \omega)^{-\frac{1}{2}} d\omega \qquad [6.8]$$

and

$$m = \frac{4a \cdot R}{r_1^2}, n = \frac{4a \cdot R}{(a+R)^2}, r_1 = \sqrt{(a+R)^2 + (z-z_0)^2} \qquad [6.9]$$

The equations assume that the disc is centred about the z-axis at a particular z-coordinate z_0 . Standard assumptions relating to the types of magnets for which the equation will be valid are as described in the beginning of Chapter 4.

The diagrams given in **Figures 6.3 to 6.6** illustrate the calculated magnetic flux lines, the B_r component, the B_z component and the total magnetic field for inter-magnet spacings of 5, 10, 15 and 20cm. The magnetic field is very intense. When the magnets are 5cm apart the minimum axial magnetic field is about 0.32T while at 20cm apart the field is still a respectable 0.025T. This is due to the use of powerful Neodymium Iron Boron magnets.

III. Effective energy well for electrons and ions in the Dimag plasma

The methodology for calculating the effective potential well for energetic electrons/ions in the Dimag is similar to that discussed in Chapter 5 except that here there is a cylindrically symmetric sputtering system. The expression for the effective potential is given by

$$\psi = \frac{\mathrm{e}^{2} \left(\mathrm{A}_{\theta}(\mathbf{r}, \mathbf{z}) - \mathrm{A}_{\theta}(\mathbf{r}_{1}, \mathbf{z}_{1}) \right)}{2\mathrm{mr}^{2}}$$
 [6.10]

where

$$A_{\theta} = \frac{F(r, z)}{2\pi r}$$
 [6.11]

Where (r,z) is the field point, (r_1,z_1) is taken as the birthplace of the particle and A_{θ} is the only relevant component of the vector potential.

Since electron and ion confinement will shortly be considered it is worth noting that with a constant magnetic field it is the e and m terms which determine how well particles are confined. Since the mass of an ion is much greater than that of an electron the effective potential well is not so high. So ions need less energy than electrons in order to escape. The other term which influences confinement is the e^2 term. Examination of Equation



Figure 6.3: (a) The magnetic flux for an intermagnet spacing of 5cm. Lines encountered in going clockwise from the point (0, -0.025) are $\{-0.02, -0.04, \dots, -0.20 \text{ Wb } (x10^{-3})\}.$

(b) The radial component of magnetic field for an intermagnet spacing of 5cm. Lines encountered in going along a magnet surface from the point (0.025, -0.025) to the point (0, -0.025) are $B_r = \{0.24, 0.20, \dots, 0.04, 0.032, \dots, 0.008 \text{ T}\}.$

(c) The axial component of magnetic field for an intermagnet spacing of 5cm. Lines encountered in going clockwise from the point (0, -0.025) are $B_z = \{0.4, 0.35, \dots, 0.1, 0.09, \dots, 0.01 T\}$.

(d) The absolute magnitude of magnetic field for an intermagnet spacing of 5cm. Lines encountered in going clockwise from the point (0, -0.025) are $B = \{0.5, 0.45, \dots, 0.1, 0.09, \dots, 0.01 T\}$.



Figure 6.4: (a) The magnetic flux for an intermagnet spacing of 10cm. Lines encountered in going clockwise from the point (0, -0.05) are {-0.02, -0.04,, -0.20 times 10⁻³ Wb}:-

(b) The radial component of magnetic field for an intermagnet spacing of 10cm. Lines encountered in going along a magnet surface from the point (0.025, -0.05) to the point (0, -0.05) are $B_r = \{0.24, 0.20, \dots, 0.04, 0.032, \dots, 0.008 \text{ T}\}.$



Figure 6.4: (c) The axial component of magnetic field for an intermagnet spacing of 10cm. Lines encountered in going clockwise from the point (0, -0.05) are $B_2 = \{0.4, 0.35, \dots, 0.1, 0.09, \dots, 0.01 \text{ T}\}$.

(d) The absolute magnitude of magnetic field for an intermagnet spacing of 10cm. Lines encountered in going clockwise from the point (0, -0.05) are B = $\{0.5, 0.45, \dots, 0.1, 0.09, \dots, 0.01 \text{ T}\}$.





(b) The radial component of magnetic field for an intermagnet spacing of 15cm. Lines encountered in going along a magnet surface from the point (0.025, -0.075) to the point (0, -0.075) are $B_r = \{0.24, 0.20, \dots, 0.04, 0.032, \dots, 0.008 \text{ T}\}.$





(d) The absolute magnitude of magnetic field for an intermagnet spacing of 15cm. Lines encountered in going clockwise from the point (0.01, -0.075) are $B = \{0.5, 0.45, \dots, 0.1, 0.09, \dots, 0.01 T\}$.





(b) The radial component of magnetic field for an intermagnet spacing of 20cm. Lines encountered in going along a magnet surface from the point (0.025, -0.1) to the point (0, -0.1) are $B_r = \{0.24, 0.20, \dots, 0.04, 0.032, \dots, 0.008\}$.



Figure 6.6: (c) The axial component of magnetic field for an intermagnet spacing of 20cm. Lines encountered in going clockwise from the point (0.01, -0.1) are $B_z = \{0.4, 0.35, \dots, 0.1, 0.09, \dots, 0.01 T\}$.

(d) The absolute magnitude of magnetic field for an intermagnet spacing of 20cm. Lines encountered in going clockwise from the point (0.01, -0.1) are $B = \{0.5, 0.45, \dots, 0.1, 0.09, \dots, 0.01 T\}$.



Figure 6.7: The effective potential well as seen by a 1500eV electron located just in front of the target in a Dimag source. The inter-magnet spacing is taken at 14cm and the inter-target spacing is 10cm. The diagrams (a-c) correspond with an electron being initially located at 10mm, 22.5mm and 50mm radii respectively.



Figure 6.8: The effective potential well as seen by a 10eV C⁺⁺ ion located just in front of the target in a Dimag source. The inter-magnet spacing is taken at 14cm and the inter-target spacing is 10cm. The diagrams (a-d) correspond to the ion being located at 0.5, 1.0, 1.5 and 2.0cm radii respectively.

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Figure 6.9: The effective potential well as seen by a 10eV Ar⁺⁺ ion located just in front of the target in a Dimag source. The inter-magnet spacing is taken at 7.5cm and the inter-target spacing is 5cm. The diagrams (a-d) correspond to the ion being located at 0.5, 1.0, 1.5 and 2.0cm radii respectively.



Figure 6.10: The effective potential well as seen by a 10eV Ti⁺⁺ ion located just in front of the target in a Dimag source. The inter-magnet spacing is taken at 7.5cm and the inter-target spacing is 5cm. The diagrams (a-d) correspond to the ion being located at 0.5, 1.0, 1.5, and 2.0cm radii respectively.



Figure 6.11: The effective potential well as seen by a 10eV Cu⁺⁺ ion located just in front of the target in a Dimag source. The inter-magnet spacing is taken at 7.5cm and the inter-target spacing is 5cm. The diagrams (a-d) correspond to the ion being located at 0.5, 1.0, 1.5 and 2.0cm radii respectively.

6.10 reveals that a doubly charged ion will see an effective potential well four times deeper than a singly charged ion of the same mass. Furthermore it can be seen that for example confining a Ti^{++} ion is identical to confining a C^{+} ion and that confining a 40eV C^{++} ion is equivalent to confining a 10eV Ti^{++} ion. This is because Titanium has four times the mass of Carbon. It should be noted of course that unlike electrons the ions can be reabsorbed at the cathodes. A description of various particle confinements in the Dimag is now given.

Figure 6.7(a-c) shows the result obtained when the inter-target spacing is 10cm. The secondary electrons are assumed to have 1500eV energy. This value was chosen because it is close to the maximum used in the experiments which will be described later. It can be seen that irrespective of their birthplace at the target surface whether it is at r=10mm, r=22.5mm (which corresponds to the edge of the magnet beneath the target) or r=50mm (which is twice the magnet radius) the electrons are still confined. At the former two radii the electrons are contained within a narrow convex lense shaped region. Even much higher energy electrons will not escape far beyond these regions. At r=50mm the convex area is noticably larger and extends up to 12cm out from the central axis. This is well beyond the target radius of 6cm but is consistant with the bulging shape of the plasma glow when the Dimag is in operation. It is also what one might intuitively expect judging by the shape of the magnetic field lines.

Figure 6.8(a-d) shows that even with an inter-target distance of 10cm which corresponds to a 14cm magnet spacing it is possible to obtain magnetic ion entrapment of 10eV C⁺⁺ ions that are assumed to come into existance immediately in front of a target. It can be seen that in general the ions can access a much broader area than can the electrons. Taking the birthplace of the ion at 0.5, 1.0, 1.5 and 2.0mm radii it can be seen from (a-d) that the area increases until at 2.0mm birthplace radius the ion can escape from the plasma by means other than colliding with the negatively biased target surface. **Figure 6.9(a-d)** shows the effective potential well as seen by 10eV Ar⁺⁺ ions. This time the inter-target distance is taken at 5cm since these ions are too heavy to be confined when the targets are 10cm apart. Once again the Figures (a-d) correspond to birthplace radii of 0.5, 1.0, 1.5 and 2.0mm. The Ar⁺⁺ ions are confined except for when the birthplace radius is 2.0mm. **Figure 6.10(a-d)** shows diagrams similar to those of Figure 6.3(a-d) except that this time the ions are 10eV Ti^{++} ions. Since the mass of this ion is a little greater than that of the Argon ion it is to be expected that the degree of confinement would be somewhat less. This can be seen to be the case with a greater area of accessibility in (a-c) and the ions being able more easily to escape the well in (d). Finally **Figure 6.11(a-d)** is again similar to Figures 6.3(a-d) and 6.4(a-d) except that now Cu^{++} ions are considered. These are heavier than the Titanium ions and will be more poorly confined. This is most noticable in (c) with r=1.5mm where the Copper ions are permitted to escape the potential well and in (d) where the outer energy barrier has disappeared altogether.

IV. Practical Design Considerations

The Dimag body is illustrated in Figure 6.12. The full Dimag source is pictured within the vacuum chamber in Figure 6.13. These schematics are complimented by the photographs of Figure 6.14(a-b) and Figure 6.15(a-b) which show various views of the source. Practical design considerations were:

1: Dimag Body Geometry

It was decided to opt for a circular (as opposed to rectangular) magnetron body geometry. The factors of price, availability of large diameter aluminium tube and ease of machining bar/tube all influenced this decision.

2: Issues regarding the magnets

Rectangular magnets were initially considered. These could probably be incorporated in other prototypes were the Dimag ever to be disassembled. On the other hand it is easier to model azimuthally symmetric as opposed to 3-D rectangular geometries. Designing a 2-D source was always out of the question from a cost point of view. So it was decided to use cylindrical magnets.

In order to optimise the chances of successful ignition at low pressures and to help enable the production of intense discharges the most powerful permanent magnets available were used. These are rare earth NdFeB magnets with a remanent field of 1.1T. The magnets are of a grade which can be cycled up to about 100 degrees Celcius and back to room temperature without permanently affecting the magnetisation. Five magnets are used in each Dimag body. These magnets are 5cm in diameter and 2.5cm high. They are stacked to form a cylinder 15cm high and located behind the target and water cooling cavity in each Dimag body as illustrated. The choice of 5cm diameter magnets is the outcome of a compromise between the high cost of magnet material and the desire to have a decent volume of plasma discharge. The cylinder is made very long in order to maximise the magnet field strength in the plasma region and also to try and ensure good electron and perhaps ion entrapment at a reasonable radial distance from the Dimag central axis. In other words once again the intention is to maximise the plasma volume. With regard to the magnets it is noted that they corrode easily in warm water. For this reason they were coated with a thick layer of rust prevention paint as insurance against a water leak. Ideally they would be placed in a separate housing of their own.

The magnetic field produced at the target surface or in the plasma region can be changed in a number of ways

- a) The target thickness can be altered with a corresponding change in magnetic field at the target surface
- b) The distance between the target and the magnets can be changed by moving the magnets within the Dimag body. Practically this only requires changing the height of the magnet supports. The magnetic field both at the target surface and in the plasma volume will be changed.
- c) The set of 5 magnets could be reduced to 4 or 3 or 2 or 1 in each Dimag body. There is a practical difficulty in that it is very difficult to prise the magnets loose once they are together. However this does offer a means of varying the magnetic field both in the plasma volume and at the target surface.

- d) The Dimag spacing could be altered. This leaves the magnetic field at the target surface unchanged but does change the plasma volume and the magnetic field within the plasma volume. In the current apparatus this change is easily effected by the nut and screw crossbar arrangement of Figure 6.13.
- e) A combination of (a), (b), (c) or (d) could be used. The mathematics for calculating the resulting magnetic field will always be identical to that given in the theory section.

3: Deciding on the Dimag body and hence target diameter

The Dimag body diameter was effectively defined by the magnet size. Sufficient space had to be left between the magnets and the inner wall of the Dimag to allow for cooling water tubes and the power supply cable and connector. An overall target diameter of 12cm was therefore chosen. This diameter is a standard among a number of target suppliers and so is readily available in a variety of materials. The standard thickness is 6mm though other thicknesses are available. The Dimag is deliberately designed to accomodate almost any target thickness though in the first instance a 6mm thick target was preferred. This choice is the outcome of a compromise between the desire to get the maximum possible magnetic field on the target surface on the one hand and the need to get some reasonable target utilisation on the other. Obviously too thin a target would also present the danger of the target bursting in operation and water leaking through and flooding the vacuum chamber and pumps.

4: The water cooling cavity plate

It was easy to decide on direct water cooling of the target because the better the target cooling efficiency the higher the discharge intensity which can be achieved.

The material through which the target cooling water flows must not be aluminium because aluminium corrodes rapidly in such an environment. So 316 Stainless Steel was chosen. It is possible that copper would have been a better choice since it would aid in conducting heat from the target and was available. Nonetheless the stainless steel worked very well. Molybdenum was not considered because of the cost.

Deciding on the depth of the cooling cavity was difficult. It was felt that if the cavity were made too narrow then target cooling might not be adequate. Furthermore water flow might be inhibited. On the other hand it was desired to ensure that the magnetic field in the plasma volume was as strong as possible. So the water channel should not be too wide as this would have the effect of removing the magnets further back from the target. Basically it was guessed that a 3mm deep cavity would allow for good forced water cooling if the water were under sufficient pressure. So the water cooling cavity plate was machined up. Connectors for the water tubes were brazed onto the back of the plate. The water inlet and outlet tubes were then fitted to the connectors . The assembly was then tested by installing the o-ring and placing a piece of perspex over the cavity in place of where the target would be during Dimag operation. This allowed viewing of the water flow as the pressure was increased. At low water pressures turbulence was observed and the water did not appear to make even contact with the back of the perspex. As the water pressure was increased the contact appeared much more even. This gave confidence that the assembly would act to efficiently cool the target.

A final point to note is that the power supply connector was welded onto the back of the cooling cavity plate. This connector is a 6mm screw with the head removed. Two nuts were then used to sandwich an eyelet connector to which the insulated power supply cable was attached as shown in Figure 6.12. This gave a good firm connection which is important from a safety viewpoint.

5: The aluminium mid-section of the Dimag body

The target and water cooling cavity are mounted onto an aluminium tube. This tube houses the magnet assembly. Aluminium was chosen over stainless steel because it is cheap, easily machinable and lightweight.

6: The target, the water cooling cavity plate and the aluminium mid-section

These were bolted together using hexagonal flat head stainless steel screws. Stainless steel screws are used throughout as they do not corrode and are non-magnetic. It is noted that each screw hole was vented by a 1mm hole drilled into the aluminium body at right angles to the screw hole. Viton O-rings were used to seal the target to the cooling cavity plate and the cavity plate to the aluminium mid-section. Viton was chosen due to its superior heat resistance by comparison with nitrile rubber o-rings which, due to their lower cost, were used elsewhere.

7: The Teflon electrical insulator

Since the PSU connection is at the water cooling cavity plate, the target, the plate and the aluminium body are all electrically live during operation. It is necessary to isolate these regions from ground. This is done using a teflon insulating ring as illustrated. This has a central hole to allow passage of water and PSU cables. The use of a Teflon insulator is a carry over from an earlier design in which the material was placed in close proximity to the target. Hence heat resistance was a consideration. In the final design incarnation a nylon material would be a better choice due to its relative toughness and lower cost. The Teflon despite tending to flex a little was nonetheless adequate to the task.

8: The stainless steel base plate and support tube of the Dimag body

The base plate of the Dimag body is made of stainless steel. This is to allow for TIG welding of the support tube to the body. It is important that the weld be leaktight, be on the vacuum side of the device, that the steel not be allowed to overheat during welding (when localised deterioration to a hydrogen permeable mild steel microstructure would result) and that the tube connect perpendicularly with the magnetron body. The tube and base plate assembly is connected to the aluminium mid-section of the Dimag body via the insulating Teflon annulus. The stainless steel screws cannot be allowed to make contact with the base plate since the aluminium is live and the base plate is grounded. So in order to prevent a conducting pathway Nylon bushes are used as illustrated. Furthermore in order to prevent any possibility of the screw heads shorting to the grounded aluminium
base plate in which they are housed the heads are covered with a flexible polyethylene cap. The caps are punctured to avoid air entrapment.

9: The grounded aluminium shielding

In order to avoid the possibility of plasmas forming in regions other than in front of the target it was necessary to provide for a grounded shielding to surround the Dimag body. To this end an aluminium base plate was attached to the stainless steel base plate. An aluminium tube was next mounted on top of this aluminium base plate in order to shield the curved surface area of the Dimag body. It is noted that another function of this tube is to shield against the possibility that the curved side of the Teflon annulus might get coated and thereby provide an electrical short between the live aluminium mid-section of the Dimag body and the grounded steel base plate. Once again it is noted that all screw holes were vented from the side.

10: The stainless steel ground shield

It was also considered necessary to use a stainless steel ground shield which extended some distance over the target surface. Stainless steel was chosen because the temperatures in the region were expected to be too high for aluminium. (Experience shows that this is certainly the case as an aluminium substate holder melted on one occasion). One reason is to prevent sputtering of the stainless steel screws used to clamp the target to the Dimag body. Another reason is to provide a physical barrier against flakes of metal from the targets finding their way into the 4mm gap between the grounded aluminium shielding and the live part of the Dimag body and lodging there thus causing a short. This is obviously more of a threat in the lower Dimag body.

After some experimentation it turned out that the S.S. ground shield was interfering with the plasma to the extent that extinction pressures up to one order of magnitude lower could be obtained when it is removed. For this reason the S.S. ground shield was dispensed with after the initial run of experiments to be described in this chapter. Rutherford Backscattering results to be described in detail later indicate that iron



Figure 6.12: The body of the lower half of the Dimag source



Figure 6.13: The Dimag source within the vacuum chamber



Figure 6.13: A photograph of the Dimag source within the vacuum chamber





Figure 6.14: (a) The thread and nut crossbar arrangement for raising and lowering the upper Dimag body (b) the upper Dimag body photographed within the vacuum chamber





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Figure 6.15: (a) The upper Dimag body pictured without the ground shield (b) the lower Dimag body pictured without the ground shield

contamination is less than 5 atomic percent for Carbon Nitride films. With regard to flakes lodging between ground and the electrically live Dimag body it was found that occasional preventative cleaning was sufficient to eliminate this concern.

11: The Wilson Seals

In order to allow for the linear movement of the Dimag as shown in Figure 6.13 it is necessary that the support tubes pass through Wilson seals. This is fairly standard with orings being forced to expand and grip the tubes. One singular feature however is the very long Wilson seal used for the lower Dimag body. The reason for this is to minimise any tendency the body has towards toppling by gripping the support tube at two widely spaced points. As it turned out the body was always supported within the chamber but the feature will be useful if it is required to move the two sources with respect to a constant centre point. The force due to atmospheric pressure with which each Dimag body is being pushed into the vacuum chamber is calculated to be about 58 Newtons which is equivalent to lifting a 6kg weight. The weight of each Dimag body must also be taken into account. There is also an attractive force due to the magnets which will act to pull both sources into the chamber. In the case of the lower Dimag body the push due to atmospheric pressure will be largely counteracted by the weight of the body. So ignoring the effect of the magnets (reasonable when they are spaced by more than a few centimetres) the net force acts to push the body out of the chamber. In the case of the upper Dimag body the forces due to atmospheric pressure and gravity conspire to push the body into the chamber. So it is essential that this be well supported. Such support and also linear movement of the upper body within the chamber is enabled by the use of a thread and crossbar arrangement as illustrated. A similar facility was provided for the lower source but it was not used throughout this work and is not illustrated.

12. Fibre Optic Viewport

A fibre optic viewport was positioned so as to monitor and/or control the plasma. The fibre optic cable collects light from the Penning discharge and transports it to a Digitwin



Figure 6.16: Voltage - Current Characteristics for Inter-Target Distances of 75, 100, 125 and 150mm at 1.10⁻² mbar

optical emission spectrometer where its characteristics are automatically examined to given an indication of the species present.

V. Initial Characterisation

This section outlines the results obtained from some initial experiments using a Titanium target. The main interest was to get some intuition about the behaviour of the device. Note that during this part of the work the stainless steel ground shields were still in place. So the lowest sustainable pressure was about 2.10^{-4} mbar and the lowest realistic working pressure was about 6.10^{-4} mbar.

I-V Characteristics

As a first step towards characterising the device the voltage - current characteristics were measured for inter-target distances of 75, 100, 125 and 150mm. (A check was done to see if the discharge could be ignited at 200mm which is close to the maximum inter-target spacing within the chamber. There was no difficulty at the only pressure checked which was 4.10^{-3} mbar). These measurements were carried out at pressures of 8.10^{-4} , 4.10^{-3} and 1.10^{-2} mbar as read on the Penning gauge. The setup is similar to that of Figure 6.13 except that there is no substrate holder.

The procedure is that the chamber is first evacuated to $\sim 2.10^{-6}$ mbar and then backfilled with Argon to the operating pressure. The targets were set a fixed distance apart by moving the upper Dimag body relative to the stationary lower device. The PSU was operated in constant current mode with the current being increased in steps of 0.1Amps. The corresponding target voltage was noted at each step. Measurements were stopped when either the current reached 5 Amps or the PSU could no longer reach the current setpoint. The 5 Amps limit was self-imposed since there was no desire to risk overheating the target. Significantly higher currents could probably be achieved as there was no noticable heat reddening of the target surface as indicated by Window et al¹¹. Another







Figure 6.18: Voltage - Current Characteristics for Inter-Target Distances of 75, 100, 125 and 150mm at 8.10⁻⁴ mbar

limitation to achieving higher currents, especially at larger target separation is the maximum voltage the PSU can attain.

Figure 6.16 shows the results obtained for a pressure of 1.10^{-2} mbar. The discharge requires a relatively low ignition voltage of between 600 and 700V depending on the intertarget spacing. As the current setpoint is increased the voltage drops precipitously to a minium after which it starts to gently rise again. The lowest operating voltage of the device can be seen here to be about 490V for 75mm separation at 2Amps setpoint. At 125 and 150mm spacings the voltage limit of the PSU then in use was reached. At 100 and 75mm spacings significantly greater currents than the self-imposed 5Amp limit could have been obtained. It is noted that the plasma tended to undergo mode changes and these are reflected in the voltage glitches which occur in the I-V curves. It is also conceivable that these could have been due to internal arcing within the device.

Figure 6.17 shows the results obtained for a pressure of 4.10^{-3} mbar. This is a typical operating pressure for a conventional sputter magnetron. The ignition voltage now lies in the range 800-850V. A voltage glitch occurs in the 75mm curve but the other curves are reasonably uniform. The position of the minimum regularly occurs at a lower setpoint current the farther the targets are apart. **Figure 6.18** shows the results obtained for a pressure of 8.10^{-4} mbar. Ignition voltages are highest and they are spread over a large range. The discharge is much more prone to voltage glitches. Of interest is the fact that at 75mm and 100mm the discharge power is limited solely by the 5.0kW available from the PSU.

Bias Current Characteristics

In order to get further insight into the plasma behaviour the bias current to a 2cm diameter probe as a function of negative probe bias was examined at probe distances of approximately 5cm, 11cm and 14cm from the Dimag axis and with a fixed inter-target distance of 7.5cm. This was done at pressures of 4.10^{-3} and 8.10^{-2} mbar and currents of 2 and 4 Amps. An exception is the 5cm distance where interference of the substrate with the

plasma prevented ignition at the lower pressure. Note that the stainless steel ground shield was in place during these measurements.

Figure 6.19 shows the curves obtained at 5cm distance. Here the probe is fairly well immersed in the main discharge. The self-bias of the probe is -3.8 and -3.56 Volts for currents of 2 and 4 Amps respectively. As can be seen doubling the discharge current from 2 to 4 Amps appears to slightly more than double the bias current to the probe. To take an example the current density to the probe for a discharge current of 4 Amps and a bias voltage of 50 Volts is 110 mAmps/cm².

Figure 6.20 shows the curves obtained at 11cm distance. The self biases of the probe at 2 and 4 Amps discharge currents are -2.33 and -3.37 Volts at 4.10^{-3} mbar and -4.07 and -4.62 Volts at 8.10^{-4} mbar. There is little difference in the characteristics at the different pressures with the 4.10^{-3} mbar discharge giving slightly higher bias current than the 8.10^{-2} mbar discharge. By comparison with the example taken for Figure 7.19 a 50 Volt bias results in a current flux to the probe of 64 mAmps/cm².when discharge current is 4 Amps and pressure is 4.10^{-3} mbar. Again doubling the discharge current roughly doubles the bias current at fixed bias voltage.

Figure 6.21 shows the curves obtained at 14cm distance. The self biases of the probe at 2 and 4 Amps discharge currents are +0.213 and +0.26 Volts at 4.10^{-3} mbar and +0.36 and +0.52 Volts at 8.10^{-4} mbar. This positive bias is similar to that reported by Window et al for their outwardly unbalanced magnetron where the magnetic field lines directed electrons away from their centrally located probe. An interpretation from the quantum well diagrams given earlier (See Figure 6.7(a-c)) is that the electrons are so tightly confined that they cannot easily find their way to a distance 14cm from the plasma. There is again little difference in the characteristics at the different pressures. However it is noticable, most particularly with the 2 Amp discharge which shall be taken as an example, that at a bias voltage of approximately 108 Volts the bias current goes from being greater at 4.10^{-3} mbar to being greater at 8.10^{-4} mbar. By comparison with the example taken for



Figure 6.19: The bias current to a 2cm diameter disk as a function of applied negative bias voltage. The measurements were performed at discharge currents Id of 2 and 4 Amps at a pressure of 4.10⁻³ mbar. The distance of the probe from the Dimag axis is 5cm.

.



Figure 6.20: The bias current to a 2cm diameter disk as a function of applied negative bias voltage. The measurements were performed at discharge currents Id of 2 and 4 Amps at pressures of 4.10^{-3} and 8.10^{-2} mbar. The distance of the probe from the Dimag axis is 11cm.

6.40



Figure 6.21: The bias current to a 2cm diameter disk as a function of applied negative bias voltage. The measurements were performed at discharge currents Id of 2 and 4 Amps pressures of 4.10⁻³ and 8.10⁻² mbar. The distance of the probe from the Dimag axis is 14cm.

Figure 6.19 a -50 Volt bias results in a current flux to the probe of 29 mAmps/cm². Again doubling the discharge current roughly doubles the bias current at fixed bias voltage.

Target Poisoning During Reactive Sputtering

As part of the effort to gain an understanding and intuition for the behaviour of the Dimag source it was decided to examine the poisoning characteristics of the target as has been done for the Teer magnetron. Initial Argon pressure was always 3.10⁻³ mbar.

Figure 6.22 shows a Titanium peak and absolute target voltage as a function of Nitrogen flow. The diffusion pump is fully open and the discharge current is fixed at 3 Amps. A feature of the curve obtained for Titanium peak as a function of Nitrogen flow is that there is no hint whatsoever of a hysteresis effect. This is not surprising in view of the small target area and the size of the pump. A curious feature occurs for a Nitrogen flow of 42 SCCM/s. The output voltage from the monochromator which corresponds to Titanium peak height rises rapidly. It is very odd that the Titanium peak should rise while the Nitrogen concentration is increased. One explanation that has been thought of is that extra emission lines may be overlapping the Ti peak and these suddenly start making a contribution to the signal. This is unsatisfactory for several reasons. Why is there a simultaneous sharp increase in system pressure and discharge voltage? Wouldn't such an effect be more gradual? A speculation is that some kind of reverse hysteresis effect is occuring. That is to say that assuming the initial fall-off in Ti signal to be due to target poisoning and sputtering of TiN then through some unknown mechanism the target has been depoisoned. This hypothesis could be further tested by using a feedback control to see if a hysteresis effect can be identified. Unfortunately this cannot easily be done using instrumentation available at DCU. It would be helpful to understand what might cause the 'reverse hysteresis'. A speculation as to the underlying cause is that it could be the result of target temperature. That is to say that as the flow of nitrogen is increased it can be seen that the discharge voltage also increases. Since the current is constant this means that the power input to the target is increasing. So unless the cooling is unbelievably



Figure 6.22: The diagram illustrates the drop in Titanium emission and the corresponding increase in discharge voltage as a function of increasing Nitrogen flow for Titanium targets. The magnetron current is 3 Amps. The diffusion pump gate valve was fully open.

efficient it is likely that the surface of the target is getting significantly hotter. At some point a temperature may be reached where the 'reverse hysteresis' comes into play ultimately causing the compound target to lose its nitrogen.

Figure 6.23 compares the Titanium peak as a function of nitrogen flow for discharge currents of 3 and 4 amps with the gate valve fully open. Both curves are consistant with plenty of excess pumping capacity and therefore no sign of a normal hysteresis effect. This is only to be expected as is the fact that at the higher discharge current the rate of decline of Titanium signal is lower. It is also interesting to see that whereas the 3 Amp curve simply falls before undergoing a dramatic rise at 42 SCCM/s as just discussed, the 4 Amp curve falls slowly (probably indicating only partial target poisoning), then at 38 SCCM/s it starts to rise gently before undergoing a dramatic rise at 64 SCCM/s. This gentle rise could be another indication of the depoisoning of the sputter target. It is very curious that this depoisoning (if that is indeed what is happening) returns the Titanium peak to 7/8 of its original value when there was no nitrogen present at all. It is further noted that this diagram contradicts the idea of a temperature induced depoisoning effect. This is because this might be expected to first effect the 4 Amp (higher current implies higher temperature) curve as opposed to the 3 Amp curve. As can be seen the opposite is the case.

The measurements graphed in **Figure 6.24** are similar to those of Figure 6.22 except that here the diffusion pump gate valve was set at 2/5 of the fully open position. The rate of incline is relatively steep indicating that we are closer to a hysteresis condition than before. This is entirely to be expected since the pumping throughput has been reduced. Interestingly there is a tendency for the Titanium peak to increase very gradually with nitrogen flow after the flow rate of 14 SCCM/s has been reached. The dramatic rise in Titanium peak value, so visible in the other graphs, was not encountered within the flow range explored in these results.



Figure 6.23: The diagram illustrates the drop in Titanium 454 nm emission as a function of increasing Nitrogen flow for a Titanium target. The magnetron currents are 3 and 4 Amps. The diffusion pump gate valve was fully open.



Figure 6.24: The diagram illustrates the drop in Titanium emission and the corresponding increase in discharge voltage as a function of increasing Nitrogen flow for Titanium targets. The magnetron current is 3 Amps. The diffusion pump gate valve was 2/5 open.

Target Erosion

The target erosion profile is illustrated in **Figure 6.25**. This is characteristic of the kind of profile to be expected from a Penning discharge. That is to say the erosion profile is concentrated in the centre of the target. **Figure 6.26a,b** are photographs of the target condition when close to being used up. It can be seen that target utilisation is poor (this was never a particular design concern and can be readily improved if necessary). Interestingly the surface of the target where erosion was most intense has the look of a surface which has been arced. It appears as though some localised melting has occured.

Additional Remarks

During the experiments described in this section it became clear that the aim of achieving low pressure operation had not been achieved. It was decided that the stainless steel ground shields might be interfering with the plasma to a significant extent. So, as mentioned earlier, these were removed and the discharge ignited. The improvement was dramatic and **the plasma is sustainable down to 3.10⁻⁵ mbar**. There is little doubt that with a PSU capable of sustaining higher voltages the pressures which are obtainable could be reduced still further. In addition whereas before it had been impossible to ignite a stable plasma at 5cm inter-target spacing this now causes no difficulties. A V-I curve and a plot of plasma conductance as a function of discharge current is given as **Figure 6.27**. Plasma conductance increases linearly with discharge current.

Conclusions

Theory, design and construction details have been presented for a sputtering source based on the Penning geometry. Basic characterisations have been performed using a Titanium target. It has been shown that the source is capable of operation at pressures down to 3.10^{-5} mbar.



Figure 6.25: The target erosion profile across one of the targets in the Dimag source



(a)



(b)



Figure 6.27: The V-I curve for a Copper target with the earth shield removed. It can also be seen that the conductance of the plasma increases linearly with current.

6.50

Appendix 6.1

PROGRAM NO. 1 MAGNETIC FLUX LINES FOR A DIMAG SOURCE

REM A program to calculate the magnetic flux lines in a Dimag source;

REM All magnets are assumed to have the same radius a;

REM The magnet geometry is assumed to be axisymmetric;

REM sig is the remanant magnetic field of the magnet in question. For the NdFeB magnets currently in use this is 1.1Tesla;

REM zp1,zp2,zp3,zp4 are the coordinates of the z-plane in which the four magnetic poles of the Dimag are situated;

REM z is the axial field ordinate;

REM cr is the radial field ordinate;

REM q and c are constants;

REM ep1..ep4 and epp1..epp4 are constants whose values depend on the relative position of the pole in question and the field point;

REM n is a variable which only depends on the radial field ordinate cr;

REM m1..m4 and r1..r4 are variables whose value depends on both cr and z;

REM flux1..flux4 represent the contribution to the flux from the four magnetic

poles The resultant gives the total flux at the field point in question;

a = .025; zp1 = .1; r1 = ((z-zp1)^2 + (a + cr)^2)^(1/2); sig = 1.1; q = N[Pi] a^2 sig; c = q/(4 N[Pi]); ep1 = Which[z < zp1, -1, z > zp1, 1, True, 0];

```
epp1 = Which[cr<a, -1, cr>a, 1, True, 0];

m1 = (4 a cr) / ((z - zp1)^2 + (a + cr)^2);

n = (4 a cr) / (a + cr)^2;

j1a = EllipticK[m1];

j2a = EllipticE[m1];

j3a = If[cr == a, 0, EllipticPi[n,m1]];

flux1 = c (1 + ((ep1)/2)(1 - epp1)((cr^2/a^2)-1)) - ((a sig)/(N[Pi]))(cr (z - zp1) / r1)(m1^{-1} (j1a - j2a) + ((n^{-1})-1) (j1a - j3a));
```

. . .

zp2 = -zp1; $r2 = ((z-zp2)^{2} + (a + cr)^{2})^{(1/2)};$ ep2 = Which[z < zp2, -1, z > zp2, 1, True, 0]; epp2 = Which[cr<a, -1, cr>a, 1, True, 0]; $m2 = (4 a cr) / ((z - zp2)^{2} + (a + cr)^{2});$ j1b = EllipticK[m2]; j2b = EllipticE[m2]; j3b = If[cr == a, 0, EllipticPi[n,m2]]; $flux2 = c (1 + (ep2/2)(1 - epp2)((cr^{2}/a^{2})-1)) - ((a sig)/(N[Pi]))(cr (z - zp2) / r2)(m2^{-1} (j1b - j2b) + ((n^{-1})-1) (j1b - j3b));$

$$zp3 = zp1 + .125;$$

 $r3 = ((z-zp3)^2 + (a + cr)^2)^(1/2);$
 $ep3 = Which[z < zp3, -1, z > zp3, 1, True, 0];$
 $epp3 = Which[cra, 1, True, 0];$
 $m3 = (4 a cr) / ((z - zp3)^2 + (a + cr)^2);$
 $j1c = EllipticK[m3];$
 $j2c = EllipticE[m3];$

```
j3c = If[cr == a, 0, EllipticPi[n,m3]];

flux3 = c (1 + ((ep3)/2)(1 - epp3)((cr^2/a^2)-1)) - ((a sig)/(N[Pi]))(cr (z - zp3) / r3)(m3^-1 (j1c - j2c) + ((n^-1)-1) (j1c - j3c));

zp4 = -zp3;

r4 = ((z-zp4)^2 + (a + cr)^2)^{(1/2)};

ep4 = Which[z < zp4, -1, z > zp4, 1, True, 0];

ep4 = Which[cr<a, -1, cr>a, 1, True, 0];

m4 = (4 a cr) / ((z - zp4)^2 + (a + cr)^2);

j1d = EllipticK[m4];

j2d = EllipticE[m4];

j3d = If[cr == a, 0, EllipticPi[n,m4]];

flux4 = c (1 + ((ep4)/2)(1 - epp4)((cr^2/a^2)-1)) - ((a sig)/(N[Pi]))(cr (z - zp4) / r4)(m4^-1 (j1d - j2d) + ((n^-1)-1) (j1d - j3d));
```

mm = Table[N[1000 (flux1 - flux2 - flux3 + flux4)], {z, -zp1 +.001, zp1 - .001, .002}, {cr, .001, .075, .002}];

ListContourPlot[mm, MeshRange -> {{0, .075}, {-zp1, zp1}}, ContourShading -> False, AspectRatio -> (2 zp1)/(3 a), ContourStyle -> {{Thickness[.006]}}, Contours -> {-.002, -.004, -.006, -.008, -.01, -.02, -.04, -.06, -.08, -.1, -.12, -.14, -.16, -.18, -.2}, Epilog -> {Thickness[.01], Line[{{0, zp1},{a, zp1}}], Line[{{0, -zp1},{a, -zp1}}]}]

PROGRAM NO. 2 TOTAL MAGNETIC FIELD FOR A DIMAG SOURCE

REM A program to calculate the magnetic flux density B in a Dimag source;

REM All magnets are assumed to be axisymmetric and to have the same radius a; REM sig is the remanant magnetic field of the magnet in question. For the NdFeB magnets currently in use this is 1.1Tesla;

REM zp1,zp2,zp3,zp4 are the coordinates of the z-plane in which the four magnetic poles of the Dimag are situated;

REM z is the axial field ordinate. cr is the radial field ordinate;

REM con and muo are constants;

REM ep1..ep4 and epp1..epp4 are constants whose values depend on the relative position of the pole in question and the field point (cr,z);

REM n is a variable depending on the radial field ordinate cr when the magnet radius a is constant;

REM m1..m4 and r1..r4 are variables whose value depends on both cr and z; REM brad1..brad4 and bzed1..bzed4 are the contributions of the respective magnetic poles to the radial and axial magnetic field at a field point (cr,z). The resultant gives the total radial and axial component at the point in question;

```
a = .025;

zp1 = .025;

r1 = ((z-zp1)^2 + (a + cr)^2)^(1/2);

muo = 4 N[Pi] 10^-7;

sig = 1.1;

con = sig /(4 N[Pi]);

ep1 = Which[z < zp1, -1, z > zp1, 1, True, 0];

ep1 = Which[cr<a, -1, cr>a, 1, True, 0];

m1 = (4 a cr) / ((z - zp1)^2 + (a + cr)^2);

n = (4 a cr) / (a + cr)^2;

j1a = EllipticK[m1];
```

```
j2a = EllipticE[m1];
j3a = If[cr == a, 0, EllipticPi[n,m1]];
bzed1 = If[z == zp1, con (ep1 (1 - epp1) N[Pi]),
con (ep1 (1 - epp1) N[Pi] +
(2 (z-zp1) / r1) (epp1 ((1 - n)^(1/2)) j3a - j1a))];
brad1 = (sig/(2 N[Pi])) (r1/cr) ((1 - 0.5 m1)j1a - j2a);
```

```
zp2 = -zp1;

r2 = ((z-zp2)^{2} + (a + cr)^{2})^{(1/2)};

ep2 = Which[z < zp2, -1, z > zp2, 1, True, 0];

epp2 = Which[cr<a, -1, cr>a, 1, True, 0];

m2 = (4 a cr) / ((z - zp2)^{2} + (a + cr)^{2});

n = (4 a cr) / (a + cr)^{2};

j1b = EllipticK[m2];

j2b = EllipticE[m2];

j3b = If[cr == a, 0, EllipticPi[n,m2]];

bzed2 = If[z == zp2, con (ep2 (1 - epp2) N[Pi]),

con (ep2 (1 - epp2) N[Pi] +

(2 (z-zp2) / r2) (epp2 (((1 - n)^{(1/2)}) j3b - j1b))];

brad2 = (sig/(2 N[Pi])) (r2/cr) (((1 - 0.5 m2)j1b - j2b);
```

```
zp3 = zp1 + .125;

r3 = ((z-zp3)^2 + (a + cr)^2)^(1/2);

ep3 = Which[z < zp3, -1, z > zp3, 1, True, 0];

epp3 = Which[cr<a, -1, cr>a, 1, True, 0];

m3 = (4 a cr) / ((z - zp3)^2 + (a + cr)^2);

n = (4 a cr) / (a + cr)^2;

j1c = EllipticK[m3];

j2c = EllipticE[m3];

j3c = If[cr == a, 0, EllipticPi[n,m3]];
```

```
bzed3 = If[z == zp3, con (ep3 (1 - epp3) N[Pi]),
con (ep3 (1 - epp3) N[Pi] +
(2 (z-zp3) / r3) (epp3 ((1 - n)^(1/2)) j3c - j1c))];
brad3 = (sig/(2 N[Pi])) (r3/cr) ((1 - 0.5 m3)j1c - j2c);
```

zp4 = -zp3; $r4 = ((z-zp4)^2 + (a + cr)^2)^{(1/2)};$ ep4 = Which[z < zp4, -1, z > zp4, 1, True, 0]; epp4 = Which[cr<a, -1, cr>a, 1, True, 0]; $m4 = (4 a cr) / ((z - zp4)^2 + (a + cr)^2);$ $n = (4 a cr) / (a + cr)^2;$ j1d = EllipticK[m4]; j2d = EllipticE[m4]; j3d = If[cr == a, 0, EllipticPi[n,m4]]; bzed4 = If[z == zp4, con (ep4 (1 - epp4) N[Pi]), con (ep4 (1 - epp4) N[Pi] + $(2 (z-zp4) / r4) (epp4 (((1 - n)^{(1/2)}) j3d - j1d))];$ brad4 = (sig/(2 N[Pi])) (r4/cr) (((1 - 0.5 m4)j1d - j2d);

mm = Table[N[Abs[((bzed1 - bzed2 - bzed3 + bzed4)^2 + (brad1 - brad2 - brad3 + brad4)^2)^(1/2)]], {z, -zp1 +.001, zp1 - .001, .001}, {cr, .001, .075, .001}];

ListContourPlot[mm, MeshRange -> {{0, .075}, {-zp1, zp1}}, ContourShading -> False, AspectRatio -> (2 zp1)/(3 a), ContourStyle -> {{Thickness[.006]}}, Contours -> {.5, .45, .4, .35, .3, .25, .2, .15, .1, .09, .08, .07, .06, .05, .04, .03, .02, .01}, Epilog -> {Thickness[.01], Line[{{0, zp1},{a, zp1}}], Line[{{0, -zp1},{a, -zp1}}]}]

References

- 6.1) P.M. Penning, Physica 3, 873 (1936).
- 6.2) J.M.E. Harper in Kern and Vossen (Eds), "*Thin Film Processes*", Academic Press, pg. 178 (1978).
- 6.3) M. Naoe, S. Yamanaka and Y. Hoshi, *IEEE Trans. Magn.* Vol. Mag-16, 5, (1980)
 pg. 646.
- 6.4) S. Kadokura and M. Naoe, *IEEE Trans. Magn.* Vol. Mag-18, 6, (1982) pg. 1113.
- 6.5) S. Kadokura, T. Tomie and M. Naoe, *IEEE Trans. Magn.* Vol. Mag-17, 6, (1981)
 pg. 3175.
- 6.6) Y. Hoshi, M. Kojima, M. Naoe and S. Yamanaka, *IEEE Trans. Magn.* Vol. Mag-18, 6, (1982) pg. 1433.
- 6.7) M. Matsuoka, Y. Hoshi, and M. Naoe, J. Vac. Sci. & Tech. A5, 52 (1987)
- 6.8) M. Matsuoka, Y. Hoshi and M.Naoe, J. Appl. Phys. 60, 2096 (1986).
- 6.9) M. Matsuoka and M. Ono, Appl. Phys. Letts., 53, 2025 (1988).
- 6.10) B. Window and F. Sharples, J. Vac. Sci. & Tech. A 3, 10 (1985).
- 6.11) B. Window, F. Sharples and N. Savvides, J. Vac. Sci. & Tech. A 3, 2368 (1985).
- 6.12) S.L Rohde in M.H. Francombe and J.L. Vossen (Eds), "Physics of Thin Films -Plasma Sources for Thin Film Deposition and Etching" Academic Press (1994).

6.13) E. Durand "Electrostatique" Volume 2, Masson, Paris. pg. 251 (1964).

Chapter 7 - Carbon Nitride Coatings

I. Introduction

One of the primary motivations for constructing the Dimag source was the hope that routine operation of a sputtering system at high discharge intensities would yield new and interesting coatings. This 'leap of faith' has been rewarded to a modest extent by results obtained from investigations made into Carbon Nitride coatings.

II. Overview

The aim of this section is to give an overview of developments in Carbon Nitride technology. For a more detailed account the review by Marton et al¹ is excellent. **Section III** describes the deposition parameters used for the production of carbon nitride by the Dimag. **Section IV** describes and interprets the results obtained from tests carried out on the coatings which were produced. **Section V** is the conclusion.

In 1989 Liu and Cohen² suggested that a Carbon-Nitrogen analogue of the β -Si₃N₄ structure, i.e. β -C₃N₄, is stable and has a bulk modulus comparable to that of diamond. A diagram illustrating the structure for β -Si₃N₄ is given as **Figure 7.1**. Later³ the same authors gave confidence to their hypothesis by accurately estimating the well-known electronic and structural properties of the β -Si₃N₄ compound and applying similar methodologies to the proposed β -C₃N₄. Table 7.1 gives theoretical and experimental values for the bulk moduluii of various materials. Furthermore it is thought that even if β -C₃N₄ does not exist, and there are some theoretical results⁴ to suggest that a defect zinc blende or a rhombohedral graphite-like material could have a thermodynamic stability close to that of β -C₃N₄, then other interesting Carbon-Nitrogen compounds may be found.

Material	Bulk Modulus (Mbar)	Bulk Modulus (Mbar)
	(Calc)	(Expt)
Diamond	4.35	4.43
β-C ₃ N ₄	4.27	
c-BN	3.69	3.67
β-Si ₃ N ₄	2.65	2.56

 Table 7.1: Calculated and experimental bulk modulii for various materials

This theoretical work has led to a flurry of activity to try and produce Carbon Nitride in the laboratory. Shock wave compression and pyrolysis of high nitrogen content precursors such as C_5N and C_3N_4 have been used⁽³⁻⁷⁾ but these have only succeeded in producing an amorphous sp² and sp bonded structure.



Figure 7.1: Structure of β -Si₃N₄ in the a-b plane¹. In β -C₃N₄, C atoms replace Si atoms. The c axis is normal to the page. Half of the atoms shown are located in the z=-c/4 plane and the other half are in the z=c/4 plane. The structure consists of buckled hexagonal rings arranged parallel to the z-axis, forming walls of large equilateral hexagonal cylinders (as in the centre) and of smaller elongated hexagonal cylinders. The parallelogram illustrates the unit cell.

All other attempts use thin film deposition techniques such as r.f. sputtering⁽⁸⁻¹³⁾, r.f. glow discharge deposition⁽¹⁴⁻¹⁵⁾, d.c. magnetron sputtering⁽¹⁶⁻²⁰⁾, electron cyclotron

resonance (ECR) plasma deposition²¹, laser ablation (in conjunction with nitrogen plasma or ion beam) ⁽²²⁻²⁶⁾, plasma decomposition²⁷, PECVD²⁸, IBAD⁽²⁹⁻³²⁾, N⁺ ion implantation in graphite or diamondlike carbon⁽³³⁻³⁶⁾ and mass separated N⁺ and C⁺ ion beams⁽³⁷⁻⁴¹⁾.

III Deposition of Carbon Nitride using the Dimag

It was decided to see if the Dimag is capable of producing interesting carbon nitride In particular the interest lay in seeing how much nitrogen could be coatings. incorporated into a carbon nitride coating grown using a Dimag source. To this end two graphite targets with copper backing plates were fitted to the source. The Dimag was then arranged so that these targets were 10cm apart (corresponding to the magnets being roughly 14cm apart) and the glow ignited in the usual way. After a process of trial and error it was found that operating with the substrates located about 13cm from the Dimag axis gave reasonable results for hard carbon growth. This location was therefore used in subsequent carbon nitride growths. Most of these sputter growths were carried out in 100% nitrogen gas at a pressure of between $1.5.10^{-4}$ and $1.0.10^{-3}$ mbar as read on the Penning gauge. The pure nitrogen discharge was ignited at a constant current of 3 Amps. The main active species present in the plasma appear to be CN molecules and N_2^+ molecular ions as shown from the optical emission spectrograph of Figure 7.2. Growth duration was typically about half an hour to produce a coating of approximately 1um thickness. A point of interest is that it is considerably easier to sustain a high plasma current at low pressures when the discharge is Nitrogen as opposed to when it is Argon. Chen et al decided that this is due to the mass of Nitrogen being closer to that of carbon¹⁷.

Of the samples to be described later Sample 1 was grown in a nitrogen plasma at minus fifty volts substrate bias. The pressure in the vacuum chamber as read by the Penning gauge was $1.5.10^{-4}$ mbar. Sample 2 was grown in a nitrogen plasma with zero volts applied bias. The pressure in the vacuum chamber was $1.5.10^{-4}$ mbar. Sample 3 was grown at minus fifty volts bias. The pressure in the vacuum chamber was $1.5.10^{-4}$ mbar. Sample 3 was grown at minus fifty volts bias. The pressure in the vacuum chamber was $1.0.10^{-3}$ mbar. It is pictured in **Figure 7.3a**. No microstructure is visible under the SEM but


Figure 7.2: A typical optical emission spectrum for the Nitrogen plasma

7.4



Figure 7.3a: A 15x image of Sample No. 3 showing film breakup due to stress.



Figure 7.3b: A 600x image of Sample No. 3 showing blisters in the stressed area.

this particular sample exhibits a wrinkling effect which is characteristic of stressed films. It is possible that entrapped gas may somehow be contributing to this effect because the blisters visible in **Figure 7.3b** lie close to the stress pattern. It is noted that any attempt to produce coatings thicker than about 1.5um resulted in coating disadhesion from the substrate and that internal stresses are the likely cause.

IV Examination of the Carbon Nitride Coatings

a) <u>Infra-red spectroscopy</u> was used to analyse the coatings. The principle is that if electromagnetic radiation acts on a piece of matter and there is selective absorption the material will absorb different amounts of the components of the radiation of different wavelengths. The change in degree of absorption as a function of the wavelength is the absorption spectrum. This spectrum is a fingerprint for organic type bonds which have characteristic vibrational frequencies in the infra-red. The degree of absorption depends on the concentration of such bonding within the sample, the molecular absorption coefficient and the thickness of the sample according to the equation.

$$I = I_0 e^{-\alpha ct}$$

where I_0 is the light intensity without absorption, I is the intensity of light which has passed through the sample, t is the sample thickness, α is the molecular absorption coefficient and c is the concentration of the material under test.

Before examining the infra-red absorption curves obtained for the samples grown using the Dimag the results obtained by a group from Harvard, Zhang et al^{24} , for a deposition method which involves laser ablation of a graphite target together with intersection of the resulting carbon plume by a nitrogen atom source at the substrate surface are first described. See **Figure 7.4(a-d)**. These spectra show two overlapping bands at ~1500cm⁻¹ and ~1350cm⁻¹ and a third stretching mode at ~2200cm⁻¹. The overlapping bands at ~1500cm⁻¹ and ~1350cm⁻¹ are believed to correspond to C=N and C-N stretching modes and according to Zhang et al^{24} are consistent with an extended inorganic carbon nitride solid. The band at ~2200cm⁻¹ corresponds to a C=N



Figure 7.4(a-d): Infrared spectra of Carbon Nitride films produced by a deposition technique which uses laser ablation of a graphite target and the simultaneous intersection of the carbon ablation plume by an atomic nitrogen beam. The nitrogen composition values of the films in (a) - (d) were determined by RBS. The diagrams are due to Zhang et al²⁴.





Figure 7.5:Infrared spectrum for sample number 1 which contains 39at.%Nitrogen.Samples 2 and 3 give broadly similar spectra.

stretching mode. This represents a clear signature of the phase purity of the Carbon Nitride coatings. This can be seen in the Harvard results where infrared spectra for various Carbon Nitride coatings are shown together with results giving the percentage Nitrogen in the coating as determined by Rutherford Backscattering. See Figure 7.4(a-d). Figure 7.4a shows the infrared spectrum when the nitrogen incorporation is 30%. It can be seen that the ~2200cm⁻¹ C=N stretching mode is scarcely in evidence. Moving to Figure 7.4b and 35% Nitrogen incorporation this mode is still weak. This all changes at 41% to 47% Nitrogen incorporation when the C=N peak increases dramatically. See Figures 7.4c,d. These results suggest that increases in the Carbon Nitride composition above about 35% occur at the expense of forming a C=N impurity phase.

Figure 7.5 shows the infrared result obtained for Sample 1 which has the highest nitrogen incorporation of any coating obtained using the Dimag source. It can be seen by a visual comparison that the spectrum obtained is closest to Figure 7.4c obtained by Zhang et al. This generates the expectation that this sample should have about 41% incorporated Nitrogen. As we will see this forecast is broadly accurate.

b) <u>Rutherford Backscattering</u> was used to analyse the coatings to get a quantitative measure of the degree of Nitrogen incorporation. The principle of this technique is first outlined. Typically $2 \text{MeV}^4 \text{He}^+$ ions are obtained from a Van der Graaff accelerator and ions backscattered from the target are analysed for energy. In a head on collision with a target atom of mass M₂ the ion energy E is reduced to

$$\left\{\frac{M_2 - M_1}{M_2 + M_1}\right\}^2 E$$

after scattering. Thus target atoms can be identified___

The yield from a target is given by the differential cross-section which is proportional to

$$\left(\frac{Z_1Z_2}{E}\right)$$
Cosec⁴ $\left(\theta/2\right)$

where Z is the atomic number of the incident and target atoms, E is the beam energy and θ is the scattering angle. Thus target stoichiometry may be determined.

Sample	At. % Carbon	At. %	At. % Oxygen	At. % Iron
Number		Nitrogen		
1	57	39	0	0.037
2	68	26	0.04	0.017
3	58	38	0	0.039

For the Carbon Nitride coatings examined here the following results were obtained

Table 7.2: Elemental constituents for Samples 1,2 and 3 by RBS

The C/N results should be correct to better than $\pm 10\%$. Although these values are somewhat lower than the best results obtained by Zhang et al it is felt that there is still room to optimise the growth parameters and further improve nitrogen incorporation. Torng et al¹¹ reported up to 28.8 at.% Nitrogen incorporation using an r.f. diode sputtering technique. Sjöström et al¹⁸ reported up to 26 at.% Nitrogen incorporation using d.c. magnetron sputtering. Chen et al¹⁷ claimed 40 at.% incorporation using d.c. magnetron sputtering but if the infra red signature is indeed a good guide then the accuracy of this result must be called into question. Their C=N signature does not appear sufficiently strong to indicate a 40 at.% Nitrogen incorporation. That said the possibility that the material produced by Chen et al is different from that of Zhang et al cannot be ruled out. Recently, using r.f. sputtering, Axen et al⁴³ produced samples with up to 60at.% Nitrogen. The samples were obtained using a 100W bias over a temperature range from 100-500C. Axen et al also managed to obtain over 40at.% Nitrogen using d.c.

sputtering. It is not clear why some groups such as Sjöström et al¹⁸ obtain a relatively low 26at.% Nitrogen incorporation using essentially the same technique.

At any rate the high degree of Nitrogen incorporation only serves to highlight the Dimag as a potentially valuable research tool capable of yielding results which are difficult to obtain using conventional techniques. It is noted that the iron contamination comes from the target screws. The oxygen in sample 2 may be due to chamber contamination. Another result which can be obtained from the RBS analysis is the density of the coating. For Sample 1 this is 2.2 g/cm^3 , for sample 2 the density is 1.6 g/cm^3 and for sample 3 the density is 2.2 g/cm^3 . A value of 2.2 grms/cm^3 has also been reported by Chen et al¹⁷ as being characteristic of their Carbon Nitride coatings.

<u>Vickers Microhardness Testing</u> was performed on the coatings. This tests the hardness of a material by loading a diamond headed indenter and relating the dimensions of the indent to a hardness scale. The results are given in **Table 3**. These do not indicate any correlation between percentage nitrogen incorporation and coating hardness. Although not so hard as the archetypal TiN PVD coatings the hardness values given are as good as those of the Balzers WC/C coating of 1000HV. A caveat is that they are influenced by the underlying substrate. Furthermore, experimental error with this technique can be quite large and comparative testing would be best. At any rate the whole area of deposition of Carbon Nitride coatings with this apparatus has barely been touched upon. It is likely that the best coatings have yet to be produced.

Sample Number	Average Hardness (HV) at 25grm load	
1	1243	
2	1258	
3	1559	

Table 3: Vickers microhardness of Carbon Nitride coatings

V Conclusion

It has been confirmed using a combination of infrared spectroscopy and Rutherford Backscattering analyses that it is possible to obtain Nitrogen incorporation levels of **at least** 39% within a Carbon Nitride coating produced by the Dimag. This ranks with the best results obtained to date for standard d.c. sputtering techniques.

References

- 7.1) D. Marton, K.J. Boyd and J.W. Rabalais, J. Mod. Phys. B, 9, 3527 (1995).
- 7.2) A.Y. Liu and M.L. Cohen, Science 245,841 (1989).
- 7.3) A.Y. Liu and M.L. Cohen. Phys. Rev. B41, 10727 (1990).
- 7.4) A.Y. Liu and R.M. Wentzcovitch, Phys. Rev. B50, 10362, (1994).
- 7.5) M.R. Wixom, J. Am. Cer. Soc. 73, 1973 (1990).
- 7.6) T. Sekine, H. Kanda, Y. Bando, M. Yokoyama and K. Hojou, J. Mater. Sci. Lett. 9, 1376, (1990).
- 7.7) L. Maya, D.R. Cole, and E.W. Hagaman, J. Am. Cer. Soc. 74, 1686 (1991).
- 7.8) J. Kouvetakis, A. Bandari, M. Todd, B. Wilkins and N. Cave, *Chem. Mater.* 811, (1994).
- 7.9) K.M. Yu, M.L. Cohen, E.E. Haller, W.L. Hansen, A.Y. Liu and I.C. Wu, *Phys. Rev.* B49, 5034 (1994).
- 7.10) J.H. Kaufman, S. Metin, and D.D. Saperstein, Phys. Rev. B39, 13053 (1989).
- 7.11) C.J. Torng, J.M. Sivertsen, J.H. Judy and C. Chang, J. Mats. Res. 5, 2490 (1990).
- 7.12) T.A. Yeh, C.L. Lin, J.M. Sivertsen and J.H. Judy, *IEEE Trans. Magn.* 27, 5163 (1991).

- 7.13) D. Li, S. Lopez, Y.W. Chung, M.S. Wong and W.D. Sproul, J. Vac. Sci. & Tech A13, 1063 (1995).
- 7.14) S. Kumar and T.L. Tansley, Sol. State Comm. 88, 803 (1993).
- 7.15) D.R. Franceschini, C.A. Achete, and F.L. Freire, Jr., *Appl. Phys. Lett.* 60, 3229 (1992).
- 7.16) G. Mariotto, F.L. Freire, Jr., and C.A. Achete, *Thin Solid Films*, 241, 255 (1994).
- 7.17) M.Y. Chen, D. Li, X. Lin, V.P. Dravid, Y.W. Chung, M.S. Wong and W.D. Sproul, J. Vac. Sci. & Tech. A13, 1063 (1995).
- 7.18) H. Sjöström, L. Hultman, J.E. Sundgren, S.V. Hainsworth, T.F. Page,
 G.S.A.M Theunissen, J. Vac. Sci. & Tech. A14, 56 (1996).
- 7.19) O. Amir and R. Kalish, J. Appl. Phys. 70, 4958, (1991).
- 7.20) M.Y. Chen, X. Lin, V.P. Dravid, Y.W. Chung, M.S. Wong and W.D. Sproul, *Surf. Coatings Tech.* 54/55, 360 (1992).
- 7.21) S. Lopez, M.S. Wong and W.D. Sproul, J. Vac. Sci. & Tech A13, 1644 (1995).
- 7.22) M. Diani, A. Mansour, L. Kubler, J.L. Bischoff and W. Bolmont, *Diamond Rel. Mat.* 3, 264, (1994).
- 7.23) C. Niu, Y.Z. Liu, and C.M. Lieber, Science 261, 334 (1993).
- 7.24) Z. John Zhang, S. Fan and C.M. Lieber, Appl. Phys. Lett. 66, 3582 (1995).

- 7.25) Z. John Zhang, S. Fan, J, Huang and C.M. Lieber, *J. Electronic Mater.* 25, 57 (1996).
- 7.26) Z.M. Ren, Y.C. Du, Z.F. Ying, Y.X. Qiu, X.X. Xiong, J.D. Wu and F.M. Li, *Appl. Phys. Lett.* 65, 1361 (1994).
- 7.27) J. Seth, R. Padayath and S.V. Babu, Diamond Rel. Mater. 3, 210 (1994).
- 7.28) H.X. Han and B.J. Feldman, Sol. Stat. Comm. 65, 921 (1988).
- 7.29) J. Schwan, W. Dworschak, K. Jung and H. Erhardt, *Diamond Rel. Mater.* 3, 1034 (1994).
- 7.30) F. Fujimoto and K. Ogata, Jpn. J. Appl. Phys. 32, L420 (1993).
- 7.31) A. Bousetta, M. Lu, A. Bensaoula and A. Schultz, *Appl. Phys. Lett.* 65, 696 (1994).
- 7.32) A. Bousetta, M. Lu, A. Bensaoula and A. Schultz, J. Vac. Sci. & Tech A13, 1639 (1995).
- 7.33) F. Rossi, B. Andre, A. van Veen, P.E. Mijnarends, H. Schut, F. Labohm, M.P. Delplancke, H. Dunlop and E. Anger, *Thin Solid Films* 253, 85 (1994).
- 7.34) I. Gouzman, R. Brener, and A. Hoffman, Thin Solid Films 253, 90 (1994).
- 7.35) A. Hoffman, I. Gouzman and R. Brener, Appl. Phys. Lett. 64, 845 (1994).
- 7.36) A. Mansour and P. Oelhafen, Appl. Phys. A58, 437, (1994).
- 7.37) D.R. Franceschini, C.A. Achete, and F.L. Freire, Jr., W. Beyer and G. Mariotto, Diamond Rel. Mater. 3, 88 (1993).

- 7.38) S.S. Todorov, D. Marton, K.J. Boyd, A.H. Al-Bayati, and J.W. Rabelais, J. Vac. Sci. & Tech A12, 3192 (1994).
- 7.39) D. Marton, A.H. Al-Bayati, S.S. Todorov, K.J. Boyd, and J.W. Rabelais, Nucl. Instr. Meth. Phys. Res. B90, 277 (1994).
- 7.40) A.H. Al-Bayati, D. Marton, S.S. Todorov, K.J. Boyd, J.W. Rabelais, D.G. Armour, J.S. Gordon and G. Duller, *Rev. Sci. Instr.* 65, 2680 (1994).
- 7.41) D. Marton, K.J. Boyd, A.H. Al-Bayati, S.S. Todorov, and J.W. Rabelais, *Phys. Rev. Lett.* 73, 118 (1994).
- 7.42) K.J. Boyd, D. Marton, S.S. Todorov, A.H. Al-Bayati, and J.W. Rabelais, Diamond Rel. Mater. 3, 1277 (1994).
- 7.43) N. Axen, G.A. Botton, H.Q. Lou, R.E. Somekh and I.M. Hutchings, Surf. & Coat. Tech. 81, pg 262, (1996).

Chapter 8 - Conclusions and Recommendations

The main achievements of this work are:

CONFORMAL MAPPING

• What is believed to be an extension to standard technique in applying conformal mapping theory to magnets in the vicinity of a single ferromagnetic polygon. Note that the phrase 'single magnetic polygon' is used in the mathematical sense. That is to say that a corner of the polygon may be at infinity. This allows many more geometries to be treated than would otherwise be the case. For example refer back to Figure 4.4c and Figure 4.5 which indicate how to go about calculating the magnetic field for a closed field <u>dual</u> magnetron system. Note also that occasionally it may be possible to treat multiple ferromagnetic polygons of finite dimensions. For example it should be possible to find a solution to the problem of two line segments in opposition to one another. This may be an alternative route to finding a solution for the dual magnetron arrangement.

CONVENTIONAL SPUTTER MAGNETRON GEOMETRIES

- Development of an integral equation which completely describes the magnetic field for any 2-D magnetron subject to the following restrictions.
 - a) Magnets must effectively have locked-in magnetisation and permeability μ_0 .
 - b) The shape of any ferromagnetic(s) must be simplifiable to a standard geometry by using a Schwartz-Christoffel mapping.
 - c) Ferromagnetics are assumed to be infinitely permeable.

- Use of the above mentioned integral equation to find an analytic solution expressed in terms of elementary functions (Atn and Ln) for what may be referred to as the standard rectangular sputter magnetron geometry. Use of this solution to describe various related magnetron geometries and to discuss what is meant by the unbalance of a sputter magnetron.
- Application of the analytic solution above to a 'real world' magnetron geometry (Teer Coatings Services, Hartlebury, UK) and experimental support for the result. Description of the effective potential energy traps in front of these magnetrons.

THE DIMAG SPUTTER MAGNETRON GEOMETRY

- Recognition of the fact that equations given by Durand are readily adaptable to describing this Penning type device. Solutions in terms of known functions for the magnetic field within this geometry. Use of said solutions to calculate the effective potential well confining charged species within the device.
- Design and construction of a Penning type geometry named the Dimag for use as a general sputtering instrument. Achievement of low pressure discharge operation down to 3.10⁻⁵ mbar limited only by the available power supply. General characterisation of the device.
- Production of Carbon Nitride coatings with high 39% nitrogen incorporation as measured by Rutherford Backscattering Spectroscopy (RBS).

RECOMMENDATIONS FOR FUTURE WORK

- In Chapter 4 a method for obtaining a solution for the magnetic field due to two facing magnetrons is given. It needs to be worked out in detail.
- With regard to the Dimag this unconventional magnetron geometry is capable of throwing up surprises due to the completely different pressure and hence plasma intensity regime in which it operates by comparison with conventional magnetrons. The poisoning curves are an example of a puzzle requiring further investigation.
- Closed field magnetron sputtering should not be regarded as the last word in magnetron sputtering technology. Neither is the Dimag. Whereas the Dimag was developed according to the principle that a coating device capable of operating under unusual conditions should yield unusual coatings a better approach would be to have a difficult application to hand and then design a source to suit the application. This philosophy will guide any further equipment development. The difficulty with the former philosophy is that it is somewhat hit and miss.

List of Publications

Vapour deposited boron nitride thin films: a review. M.Z. Karim, D.C. Cameron, M.J. Murphy and M.S.J Hashmi Proc. Eurotech Direct '91, Birmingham, July 1991, pub. IMechE, p181-187 (C412/057)

Plasma deposition of cubic boron nitride films from non-toxic materials at low temperatures.M.Z. Karim, D.C. Cameron, M.J. Murphy and M.S.J HashmiSurface and Coatings Technology 49 (1991) p416-421

Magnetic fields in magnetron sputtering systems M.J. Murphy, M.Z. Karim, D.C. Cameron and M.S.J. Hashmi Surface and Coatings Technology 57 (1993) p1-5

Vapour deposited boron nitride thin films: a review. M.Z. Karim, D.C. Cameron, M.J. Murphy and M.S.J Hashmi Materials and Design, 13 (4) 1995 p207-214

Magnetic fields in 2-D magnetrons M.J. Murphy, D.C. Cameron and M.S.J. Hashmi J. Vac. Sci. & Tech. A, 13(4) 1995 p2151

Magnetic field in a commercial sputter magnetron M.J. Murphy, J. Monaghan, D.C. Cameron and M.S.J. Hashmi Proc. Irish Materials Forum Conference, Galway, 13th-15th Sept. 1995

A Penning type magnetron sputtering source and its use in the production of carbon nitride coatings.
M.J. Murphy, J. Monaghan, D.C. Cameron, A.K.M.S. Choudhury, M. Tyrrell, R. Walsh, M. Monclus and M.S.J. Hashmi
Int. Conf. On Thin Films and Metallurgical Coatings, San Diego, 22nd-26th April 1996 (This work is to be submitted to J. Vac. Sci. A)