High-VHF Capacitive-Coupled-Plasma Technology, with Scaling to 450mm

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Abstract

Process demands on plasma etch have forced the development and introduction into manufacturing of new plasma technology. These process demands have, historically, been driven by device-scale shrinkage, and over the last decade the introduction of new material into the device stack and changes in photo-resist materials. The future devices will require tighter process control, adaptability to radical changes in materials, structures, and accommodating needs for process integration. In addition, factory economics is bringing in 450mm wafer size. One of the notable developments over the last 10 years has been the increased frequency of capacitively coupled plasma systems to include 100MHz and 162MHz. However, while further increases in frequency have been shown to provide improved process performance, they suffer from process non-uniformity due to wavelength effects. This has severe implications for 450mm tool development as frequencies will have to be reduced with resultant drop in performance and/or process window. Multi-tile plasma sources provide a solution, enabling substantially higher frequencies and enable scaling to large areas including 450mm wafers. The implications on the rf subsystem and the technical advantages of a novel class of divide-by-arbitrary-N power splitter is presented.

Introduction

Plasma etching remains one of the most challenging manufacturing steps in terms of continual process development due to the chip-design miniaturization, changes in device design such as fin-FET and MRAM; materials development such as low-k dielectrics, high-k gates, advances in barrier films, and requirements (refractory metals, non-volatile metals) for MRAM.

The equipment supplier needs to meet the technical demands while maintaining serviceability, system stability, and meeting customer cost expectations.

For more than the last decade the dominant technology for for dielectric etch has been the capacitively coupled plasma, and in particular operation with multiple frequencies. Operation at dual frequencies had enables some level of independent control between ion flux and ion energy [1]. Increasing the frequency of the high frequency element reduces the cross-coupling of the two frequencies. Increasing the rf frequency in a capacitively coupled plasma source has also resulted in improved process results. The process improvements can be in terms of selectivity, photo-resist damage, CD-bias, and driven by process-integration issues.[2,3] Why higher frequencies are better is not always clear, and contradictory evidence can be found. However uncertain the cause, the processing value cannot be denied as all major equipment suppliers have all developed systems with increased frequencies over the last 10 years.

But higher frequency is not the panacea for all problems, and voltage non-uniformities cause by ‘wavelength-effects’, stability of chamber return currents, and stability of the rf sub-system can be severe challenges.

Figure 1(a) shows cross-section schematics of a ‘traditional’ CCP system. The current path (shown for a fixed rf-phase with arrows) flows through the match-box, to the powered electrode, plasma, ground electrode and returns to the load-capacitor in the match-box flowing along the inside of the chamber. This current path crosses the vacuum seal between the bottom and top halves of the vacuum system – required to access the chamber for service and replacement of process-it hardware such as edge-rings – and the rf contact across this boundary must be stable to achieve tool performance and toll-to-tool matching. In some systems, such as the AMAT Enabler and TEL SCCM, a substantial amount of the current coupled into the plasma from the powered electrode flows radially through the plasma directly to the chamber wall including the upper-half of the chamber. This reduces the stress on the connection in terms of current density. However, now the impedance depends on the plasma between the active region and the walls which is typically process dependent – both gas mixtures and rf power. In addition, the radial current density in the active region of the plasma increases linearly with radius and this can cause radial variation in power coupling and plasma density.

Probably the biggest problem with high frequency is radial voltage non-uniformity. Consider the rf current flowing radially inward on the bottom face of the top electrode in Figure 1(a). For a uniform change in voltage, the radial current density drops linearly going to zero at the center. This is like a transmission line terminating with an ‘open’. The electromagnetic solution is a standing wave pattern, with a peak in voltage at the same location as the zero in current, and a characteristic length of ¼-wavelength of the rf signal. Here, the ¼-wavelength is in terms of electrical-length, so the physical length is $l=c/(4f*\sqrt{\varepsilon})$, where c is the speed of light, f is the frequency, and $\sqrt{\varepsilon}$ is the index of refraction of the plasma. The value for $\sqrt{\varepsilon}$ in these thin, bounded, partly resistive conditions is somewhat complicated, but 2-10 covers much of typical plasma processing conditions. Operating at 162 MHz could have wavelength-induced voltage non-uniformities with a characteristic physical length of 130 mm,

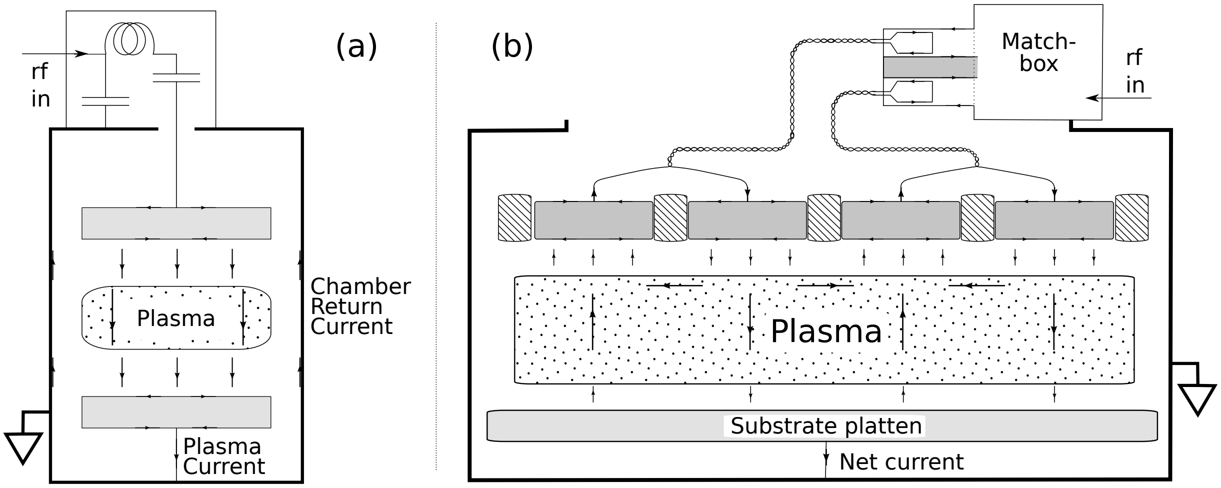

Figure 1: Traditional CCP plasma system (a) and multi-tile plamsa (b). Also shown are the currents at a fixed rf phase.

which is on the order of existing wafers, and certainly problematic for 450 mm wafer systems.

One solution to the wavelength problem is the use of Multi-Tile-Electrode configuration (see Figure 1(b)). For individual tile less that ¼-wavelength the voltage is uniform. TEL worked on a 7-tile system using 'phase-scrambled' rf phasing between the tiles to give a time-averaged uniform voltage. The control/feedback system for the necessary power and matching hardware appears to have prevented TEL from bringing the product into high-volume-manufacturing.

I propose a different rf power deliver operational mode in which neighboring tiles are powered out of phase in a push-pull configuration such that the total high-frequency current into the plasma is zero. In this paper I will explain advantages in terms of system stability, controlled current paths, wavelength-effects, and plasma-source pre-qualification can be achieved with this design.

Technical Needs/Challenges for Multi-Tile-Electrode

For application to oxide etching for semiconductor manufacturing the multi-tile plasma source has several practical constraints. To achieve the gas-flow, gas-residence-time, gas-pressure specifications of existing tools, it is likely that plasma height – the gap between the multi-tile-electrode and the wafer – will be 30-60 mm. Tile size will be close to the gap and the electrode area needs to be the wafer area plus the gap to prevent strong edge effects. The number of tiles is $N = (\pi\, 200^2 / \pi\, 25^2) \sim 64$ tiles for a 300 mm system, and close to 100 for a 450 mm system; That's a lot of tiles.

This, in turn puts restrictions on the rf power splitter used to excite the electrode. In particular, extendable to larger numbers of tiles would be desirable such that system confidence and can be carried forward from 300 to 450 mm systems, zero net current, high isolation between output ports, and low part-count both for system stability and maintenance.

Existing rf-Power Splitter Technology

rf Power splitters have been used for many years and many different topologies have been devised based on the needs of the application. Considering the 300 mm system proposed above with 64 tiles, 32 tiles at one rf phase and the other 32 at 180º phase difference, there are well established solutions. The most basic solution is based on ÷2 power splitters, either with outputs in-phase or 180º phase difference. Such a solution would consist of a single rf-power feed into a ÷2@180º splitter feeding two ÷2@0º splitters, feeding four ÷2@0º power splitters … until with 63 splitters the job is done. Phase errors are typically 3º and power splitting is accurate to 3%, resulting in 15% power variation and 16º of rf current phase error. In addition, the power splitters are 50 Ohm input, 50 Ohm output, so there is need for 64 matchboxes. Miss-match at one of these matchboxes would cause imbalance back up through the power splitter chain. As the single matchbox of traditional CCP systems often leads the Pareto chart for tool failures this does not seem appropriate for high-volume-manufacturing. I suspect this sort of challenge contributed to TEL's decisions to stop the phase-scrambled plasma source.

The PSTLD, a Suitable Power Splitter

To address the needs of the multi-tile-electrode system a new class of power splitter was developed[4,5] which we call a Power Splitter and Transmission Line Driver (PSTLD).

Consider the transmission line shown in Figure 2(a); when Z_l is close to zero (an electrical short) then the current and voltage standing wave pattern develops, as shown in Figure 2(b). Within each lobe of the standing wave the component is at constant phase. Thus, the current and the B_t (the azimuthal current in the coaxial transmission line) is at constant phase for the first ¼-wavelength from the short. The PSTLD is shown in Figure 3. It is comprised of a rigid coaxial line shorted at one end (front-left in Fig 3). The other end (back-right) is connected to the power source, typically through a matchbox. The cut-away gives view to the coupling loops, which are located azimuthally in the active region of the co-ax. The coupling loops are oriented such as to couple to the B_t field, with axial length typically under 1/8-wavelength.

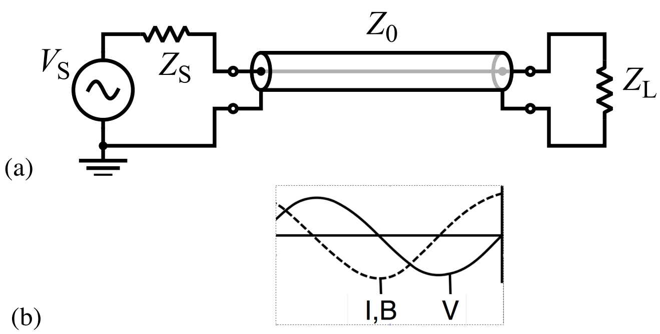

Figure 2: Transmission line (a) and current and voltage patterns along the length when Z_l is a short (b).

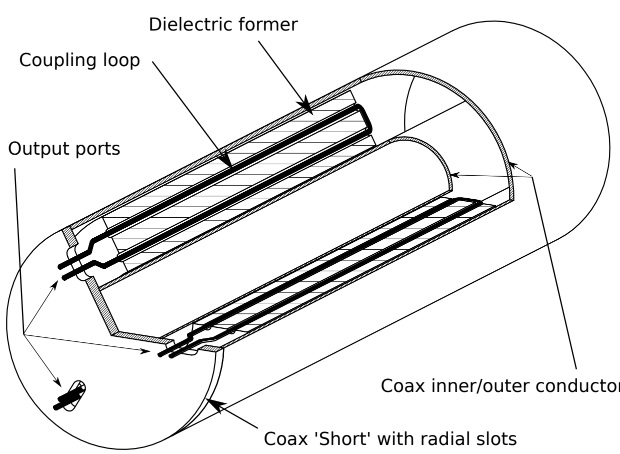

Figure 3: Schematic of The PSTLD configured to drive 6-tiles. Cut-away showing the coupling loops.

In this way the B_t field is constant phase along the length of the coupling loop, and induces current (and voltage) in the coupling loops. The loops exit the PSTLD through slots in the short whereupon they are connected to transmission lines leading to the tiles.

Configuring The PSTLD in this way provides many advantages for the multi-tile electrode plasma source. One principle advantage is that the equivalent technological approach can be used for and arbitrary number of output ports. Figure 3 shows a design with 3 output ports at 120º intervals, which would be used for a 6-tile electrode. By extension an arbitrary-N design would have coupling loops with azimuthal spacing of 360º/N.

The second principle advantage is due to the symmetry of the coupling loop, the induced current (voltage) is fully differential for all phases of the rf cycle. Thus, when coupled to a plasma there is zero net rf current. This, furthermore, reduces the sensitivity of changes in the rf paths within the chamber, as there is no net return-current flowing in the chamber.

An additional feature is that The PSTLD is very broad-band. The output loops are balanced-output auto-transformers, such that they will drive current into a short across the output port, or voltage across an open. Thus they are well suited for coupling to plasma which often exhibits negative differential impedance.

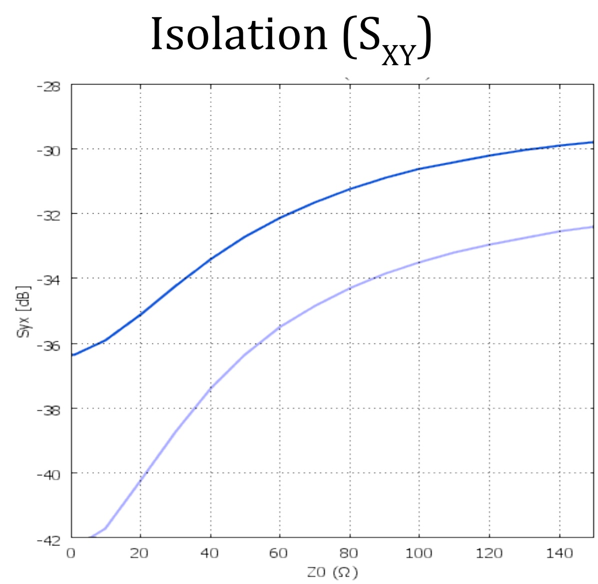

Figure 4: Cross-coupling between output ports vs port impedance in ÷15 power splitter configuration (30-tiles). Top curve is adjacent coupling loops, bottom curve is coupling loops diametrically opposed in the coaxial line.

Yet another advantage is that The PSTLD has high isolation between the separate output ports. To investigate the isolation between the output ports finite element modeling was done using Comsol MultiPhysics®. The PSTLD is an 'N+1 port' device with 1 input port, and arbitrary N output ports. Figure 4 shows drawings of the dielectric former used in the model for both a 15-output port and 45-output port splitter. Figure 5 plots the S_{xy} coupling coefficient; the cross-coupling between two output ports. The coaxial cylinders are sized for 4-1/8" rigid co-axial line, and the coupling loops are 230 mm in axial extent, the dielectric is PTFE, excitation frequency is 150 MHz. The cross-coupling is found to be -30 dB, which is quite high isolation. The high isolation prevents a fluctuation in plasma loading at one tile-boundary from affecting the rf power to the other tiles. This is particularly important for high pressures, electronegative gasses, and small plasma gaps, which all provide positive feedback to plasma density fluctuations and contribute to the formation of localized plasmas.

The PSTLD has been employed to excite multi-tile electrode plasma sources from 60 MHz to 400 MHz. Figure 5 plots the ion saturation current versus position across the 'Pastis' chamber which is a 3x4 array of tiles, each 100 mm by 100 mm, a 10 mm dielectric spacing between tiles, and a 55 mm plasma height. 'Pastis' is shown in cross-section in Figure 1(b). Operating conditions are 1.2 mBar nitrogen, with rf power of 1.6 kW at 60 MHz in a 'checkerboard' configuration as shown in Figure 1(b).

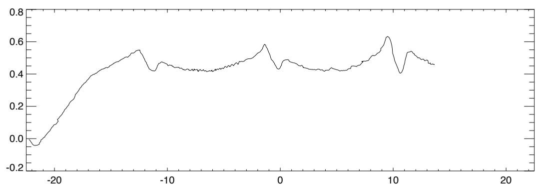

Figure 5: Ion saturation current versus position across the 'Pastis' system. Conditions of 1.6kW of 60 MHz at 1.2 mBar.

The ion-saturation current shows very good uniformity across the 4 tiles, and in particular is extremely symmetric. The profile shows a strong gradient approaching the plasma edge at -22 cm.

Figure 6 plots ion saturation current versus diameter in the 'Hawaii' plasma source has 4-tiles across the diameter of width 55 mm with a 16 mm gap between tiles and a very large plasma height of 220 mm. Operational conditions are 100 mTorr Argon, with rf power of 150 Watts at 400 MHz.

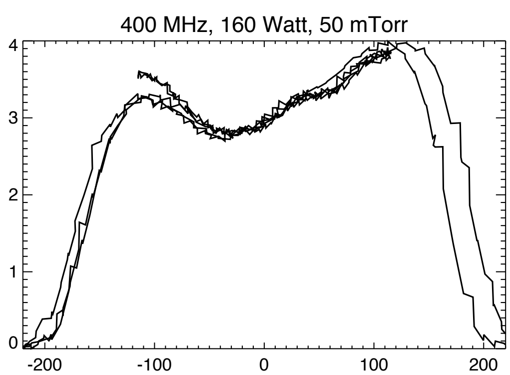

Figure 6: Ion saturation current across the diameter of the 'Hawaii' plasma source.

Again, the symmetry of the ion-saturation current is good. Plasma density extends fully to the edge of the plasma source width (280 mm) and drops rapidly outside the source region and approaching the walls.

The multi-tile approach has been tested on large-area applications at the size of 600 mm by 720 mm at 162 MHz with a plasma gap of just 8 mm with excellent results. Film thickness is uniform to 10% in the 600 mm direction and 30% in the 720 mm direction.[6]

Conclusions

The novel rf power splitter described seems a likely candidate for exciting multi-tile electrode capacitively coupled plasma sources. The unique combination of high isolation, scalability, and broadband performance from the high-VHF into the UHF are well matched to the challenges of multi-tile approach. The ability to scale the plasma source to large area operation at the high frequencies could be enabling for select semiconductor manufacturing processes both at 300 mm and forward scalable to 450 mm.

Acknowledgments

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