An Electrodeless High Density Plasma Source for Large Area Thin Film Processing

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ABSTRACT

High density plasma sources, such as inductively coupled plasma (ICP), helicon, electron cyclotron resonance (ECR), and microwave, have been successfully used to increase etch and deposition rates for a variety of processes in the semiconductor manufacturing market. However, scaling these high density sources to large areas has proven difficult—particularly where there is a need for very uniform processing. Plasma sources in use for large-area coating, cleaning or etching continue to be the same DC or low-frequency magnetron or capacitively-coupled systems which have been used for the past two decades. In this work, we present an electrodeless high density plasma source which is suitable for large area processing. The source uses an induction-coupled power delivery method to generate plasma within a long rectangular cavity. It is theoretically scalable to nearly any industrially relevant size. Results on a 13.56 MHz, 1.2 Meter long prototype are presented for Argon and Oxygen chemistries. 950 mm long processing regions with less than 4% non-uniformity were obtained for both gases. In 1 mTorr of pure Argon, the average charge density in the uniform region was 5 x 10^{11} cm^{-3}; for pure Oxygen at 1 mTorr, an average charge density of 1.5 x 10^{10} cm^{-3} was obtained while maintaining the same uniform region. This source will increase the processing rate for a variety of industrial applications, including LCD manufacturing, architectural glass cleaning and coating, cleaning and deposition on large-area polymer films and large-scale solar cell production.

INTRODUCTION

The use of high density plasma sources for IC manufacturing is widespread, with products available from multiple vendors (such as Lam Research Corporation, Applied Materials, Novellus, MKS Instruments, Advanced Energy Industries, etc.). These sources are used for etch and PECVD of thin films, as well as surface modification. Although they add some complexity to a process system, the use of an additional high density plasma source decouples ion and radical production (or flux) from ion energy. Hence, higher process rates are achievable without increasing energy deposition (or damage) to the substrate.

Use of high density plasma sources for large area processing has not become prevalent. In part, typical device geometry sizes made on a large scale are less demanding, but also because these plasma sources are difficult to scale while maintaining plasma and process uniformity.

This paper addresses scaling of previously demonstrated ICP, helicon, and ECWR sources to process large substrates. Of particular interest is the use of a source to perform PECVD on plastic (at low temperature). The new source has applications on present generation tools, and on future roll-to-roll processing systems.

HIGH DENSITY PLASMA SOURCE CANDIDATES

Volume-coupled sources

Several source technologies were considered at the outset of this project, including Inductively Coupled Plasma (ICP), microwave Electron Cyclotron Resonance (ECR), helicon, and low frequency Electron Cyclotron Wave Resonance (ECWR). All of these discharges decrease the required power to sustain a given plasma condition by reducing the energy lost by the plasma volume across one or more of the plasma container boundaries. Power (P) carried to the walls can be approximated in most cases by the following relation [1]:

$$P = en_s u_B A\left(E_c + E_i + 2T_e\right) \tag{1}$$

Where e is the electron charge, n_s is the plasma density at the edge of the sheath, u_B is the Bohm velocity, A is the loss area, E_c is the energy lost in collisions in the plasma, $2T_e$ is the average energy carried by electrons, and E_i is the energy carried by ions across the sheath. RF parallel plate and DC discharges transport the majority of their energy across the sheath, resulting in a large E_i term. For the same plasma conditions (density, electron temperature and chamber loss area), a system that can couple energy into the bulk of the plasma with a lower sheath term will require lower power to sustain the same plasma than a parallel plate or DC system. All high density plasmas improve the achieved density per applied power in this way.

ICP sources are the most prevalent of the source candidates for this project. They are also simpler to construct, with no required external magnetic field. Addition of magnetic field with specific geometry can result in helicon [2] or ECWR [3] modes. Much larger applied magnetic field enables the use of inexpensive magnetrons for microwave ECR.

Low temperature PECVD on plastic substrates of gate SiO_2 has been demonstrated using both ECR and helicon sources [4]. In this comparison of ECR- and helicon-deposited gate oxides, however, the transistors fabricated using the helicon sources exhibit larger drive currents than devices made using ECR. ECR also requires a large magnetic field, which must be uniform over a large region to ensure uniform processing. Therefore, ECR sources were removed from the source candidate list.

Helicon and ECWR excitation mechanisms are very similar, arising from a similar treatment of a magnetized plasma driven by induction field from an external antenna. The appropriate linearized form of Maxwell's equations for homogeneous plasma with an applied static magnetic field in the z direction is:

$$\left(\frac{\omega\mu_0 e n_0}{kB_0}\right)\mathbf{B} = \alpha\mathbf{B} = \nabla\times\mathbf{B} \tag{2}$$

$$\nabla^2\mathbf{B} + \alpha^2\mathbf{B} = 0 \tag{3}$$

A detailed treatment of equations (2) and (3) in cylindrical coordinates can be found in Chen [5], which gives the usual cylindrical solution of

$$\begin{aligned} B_z &= -2\left(\alpha^2-k^2\right)^{-\frac{1}{2}} CJ_m\left(\left(\alpha^2-k^2\right)^{\frac{1}{2}} r\right)\sin\left(m\theta+kz-\omega t\right) \\ B_\theta &= -0.5C\left(\alpha^2-k^2\right)^{-\frac{1}{2}}\left(\left(\alpha+k\right)J_{m-1}+\left(\alpha-k\right)J_{m+1}\right)\sin\left(m\theta+kz-\omega t\right) \\ B_r &= 0.5C\left(\alpha^2-k^2\right)^{-\frac{1}{2}}\left(\left(\alpha+k\right)J_{m-1}+\left(\alpha-k\right)J_{m+1}\right)\cos\left(m\theta+kz-\omega t\right) \end{aligned} \tag{4}$$

These equations describe circularly polarized waves traveling along the applied magnetic field; via superposition, solutions for a variety of cylindrical boundary conditions can be obtained. For non-cylindrical geometries, it is also possible to obtain a general solution for (2) and (3). Starting with a different general expression (5) for B, and using (2) followed by (3), the general dispersion relation (6) is obtained [6].

$$\mathbf{B} = \hat{\mathbf{x}}A_x e^{\left(i\left(kz+mx+ny-\omega t+\varphi_x\right)\right)} + \hat{\mathbf{y}}A_y e^{\left(i\left(kz+mx+ny-\omega t+\varphi_y\right)\right)} + \hat{\mathbf{z}}A_z e^{\left(i\left(kz+mx+ny-\omega t\right)\right)} \tag{5}$$

$$\alpha^2 = k^2 + m^2 + n^2 \tag{6}$$

Requiring further that the divergence of B is 0 (7), defines the phase lags in the x and y components to equation 8, and the amplitudes Ax and Ay to equation 9:

$$\nabla\cdot\mathbf{B} = 0 \tag{7}$$

$$\begin{aligned} \varphi_x &= Tan^{-1}\left(\frac{-n\alpha}{mk}\right) \\ \varphi_y &= Tan^{-1}\left(\frac{m\alpha}{nk}\right) \end{aligned} \tag{8}$$

$$\begin{aligned} A_x &= \left(\left(\frac{km}{k^2-\alpha^2}\right)^2 + \left(\frac{n\alpha}{k^2-\alpha^2}\right)^2\right)^{\frac{1}{2}} A_z \\ A_y &= \left(\left(\frac{kn}{k^2-\alpha^2}\right)^2 + \left(\frac{m\alpha}{k^2-\alpha^2}\right)^2\right)^{\frac{1}{2}} A_z \end{aligned} \tag{9}$$

This solution in Cartesian coordinates describes elliptically polarized waves. Because of the phase difference requirement imposed by (8), the magnetic field vector for the wave rotates in space (see Figure 1), and has a phase velocity similar to the cylindrical solution. A phase velocity comparison of the cylindrical, Cartesian and ECWR [3] treatments is contained in Figure 2.

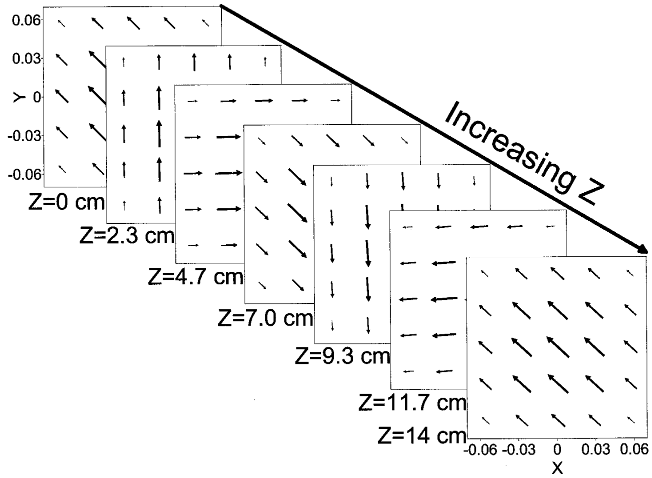

Figure 1. B in the x-y plane with increasing z. m=n=1, Note rotation of the vector field as a function of increasing z.

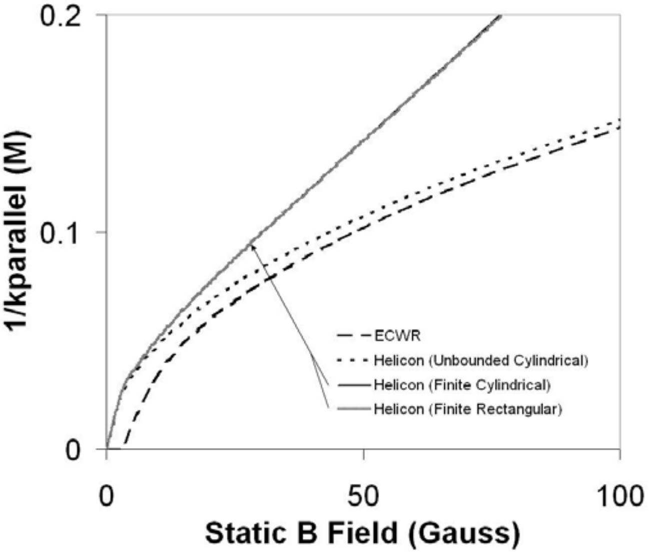

Figure 2. $^{1}/k_z$ vs. static B field for bounded cylindrical, free cylindrical, ECWR and rectangular solutions. For the rectangular case a 7cm x 7cm box is used; for the bounded helicon case, the chamber radius is 6 cm.

SOURCE CONSTRUCTION AND TESTING

Test System

A rectangular source designed to produce a 1 meter long uniform region for plasma processing was constructed. The source was designed to operate as an ICP, or with the application of a static field, as a rectangular helicon source. The source was mounted on an Applied Films ATX process chamber with approximately 5 m^3 chamber volume. An array of 16 Langmuir probes were installed onto a robot arm capable of sampling the interior region surrounding the outlet of the source. The probes were held in saturation at -25 V DC with respect to the chamber walls. Each probe area was 29.6 mm^2. Density was inferred using the Bohm current approximation, assuming a 5 eV electron temperature. Power was provided by an Advanced Energy 10 kW 13.56 MHz Apex RF Power Unit and corresponding automatic matching system. The chamber was pumped via a combination Edwards QDP80 dry pump and two CTI Cryogenics CryoTorr 10 systems. Chamber pressure was controlled manually via total gas feed. Figure 3 is a photograph of the source mounted on the test system. Density scans were obtained for a variety of conditions. A sample argon scan is shown in Figure 4.

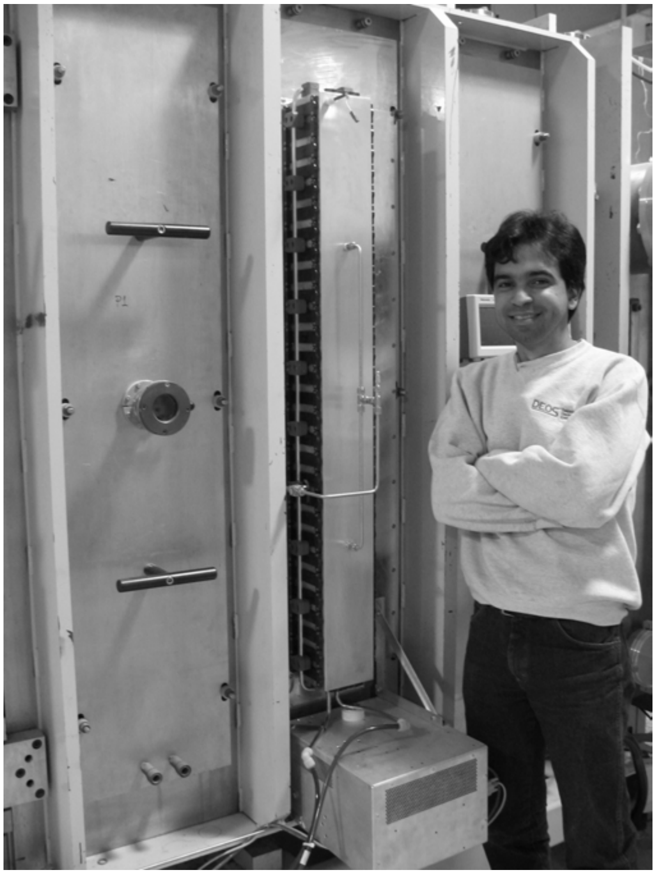

Figure 3. Rectangular source mounted on the test station. Source length is 1.3 meters, with an interior cross-section of 10 cm x 10 cm.

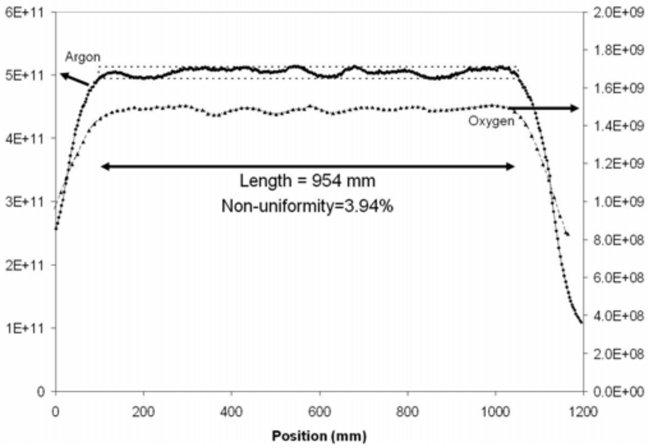

Figure 4. Density (cm^{-3}) versus position (mm) along the Source. The argon plasma is using 8200 Watts at a pressure of 0.90 mTorr. The oxygen plasma case is using 4800 Watts, at a pressure of 1.0 mTorr.

Table 1. Operational Summary.

Characteristic	Target	Measured
Plasma Density linear non-uniformity (Argon) [(max-min)/mean]	< 4% < 2 mTorr	3.9% 0.9 mTorr
Uniform Region	>750 mm	954 mm
Average Argon Density	>5 x 10^{11} cm^{-3}	5 x 10^{11} cm^{-3}
Oxygen non-uniformity	<4%	3.6%
Stable Operating Pressure	< 1 mTorr	0.5 to >100 mTorr

CONCLUSION

A rectangular source was designed and constructed for PECVD applications over large area. Both the initial theoretical treatment of the problem and the initial test source met original performance expectations. The source created uniform, dense plasmas similar to those found in high density 300 mm wafer processing systems, but over a much larger region. Even larger sizes may also be feasible, but additional engineering will be warranted.

Continuing work with this source will shift focus from physical plasma measurements to the characteristics of films deposited using this source. A suitable linear substrate handling system (again based on the modified Applied Films ATX R&D system) is being prepared. The first CVD processes slated for investigation will be SiO_2 for thin-film transistors on plastic. In the future, the source should also be useful for amorphous and poly-crystalline silicon deposition.

ACKNOWLEDGMENTS

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