# RF Power Coupling And Plasma Transport Effects In Magnetized Capacitive Discharges

P. M. Ryan[a], M. D. Carter[a], and D. J. Hoffman[b]

[a]*Oak Ridge National Laboratory, Oak Ridge, TN*
[b]*Applied Materials, Santa Clara, CA*

**Abstract.** Static magnetic fields have been used to expand the operational envelope, increase power efficiency, and control processing parameters in capacitively-coupled radio frequency plasma discharges. A simple physical model has been developed to investigate the roles of the plasma dielectric tensor and plasma transport in determining the ion flux spatial profile along a wafer surface over a range of plasma density, neutral pressure and magnetic field strength and orientation. The model has been incorporated into the MORRFIC code[1] and calculations have been made for a capacitively-coupled 300-mm etch tool operating at frequencies greater than 100 MHz. A Lieberman sheath model[2] show effects that can occur when the sheath voltages are made to be consistent with the driven RF fields in the collisional unmagnetized limit; other sheath models will also be considered. A two-dimensional transport model accounts for magnetized cross-field diffusion. Results isolate magnetic field effects that are caused by modification of the plasma dielectric from transport effects that are caused by the reduced electron mobility perpendicular to the magnetic field.

**Keywords:** Capacitively-coupled plasma sources, plasma etch tools
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## INTRODUCTION

Control of the ion flux profile at the surface of the wafer is important in optimizing the etch rate uniformity of a capacitively-coupled plama processing tool. One such method of uniformity control uses solenoidal B-fields [3]. This paper introduces a computational model designed to evaluate the contributions from plasma transport and rf power deposition in the magnetized medium to the reactive ion flux distribution at the wafer surface.

## THE MODEL

### RF Power Deposition and Plasma Generation

The RF power deposition is calculated from Maxwell's equations in the frequency domain

$$\nabla \times \vec{E} = i\omega\vec{B} \tag{1}$$

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$$\nabla \times \vec{B} = \mu_0 \vec{J} - i\omega\mu_0\varepsilon_0 \overline{K} \bullet \vec{E} \tag{2}$$

where $\overline{K}$ is the magnetized cold plasma dielectric tensor. The energy available for ionization is proportional to the RF power deposited inside a volume comparable to a mean-free path for inelastic electron-neutral collisions.

$$S(\vec{x}) = \frac{n_n(\vec{x}) \int_{Vi} P_{rf} d^3x}{E_{ion}(\vec{x}) \int_{Vi} n_n d^3x} \tag{3}$$

For a magnetized plasma where $\rho_e < \lambda_{inelastic}$, the electron motion is constrained perpendicular to B. The model averages the RF power over a flux tube having length $\pm \lambda_{inelastic}$ along the field line and a radius of $\rho_{eip}\sigma_{en}/\sigma_{inelastic}$. Here $\rho_{eip}$ is the electron gyroradius corresponding to the energy required for ionization of the gas and the cross section ratio is roughly the number of collisions before significant energy loss by the electrons. The average energy required for ionization, $E_{ion}$, can be represented in terms of $\sigma_j$, the inelastic collision cross section resulting in energy loss $E_j$, and $\sigma_i$, the ionization cross section, where <> represents an average over the electron distribution function.

$$E_{ion} \equiv \frac{n_e n_n \sum_j \langle \sigma_j v \rangle E_j}{n_e n_n \langle \sigma_i v \rangle} \tag{4}$$

## Plasma Transport

The model employs the 2D diffusion equation for plasma transport

$$S(\perp,\|) \approx -\frac{\partial}{\partial \|} D_{\|} \frac{\partial n(\perp,\|)}{\partial \|} - \frac{\partial}{\partial \perp} D_{\perp} \frac{\partial n(\perp,\|)}{\partial \perp} \tag{5}$$

where $S$ is the local source rate and $D_{\|}$, $D_{\perp}$ are the diffusion coefficients parallel and perpendicular to the magnetic field. We assume ambipolar diffusion along field lines,

$$D_{\|} \approx D_A \tag{6}$$

and classical cross-field diffusion in strongly magnetized regions

$$D_\rho \approx \frac{n_n \sigma_{en} v_{te}}{2} \rho_e^2 \tag{7}$$

where $v_{te}$ and $\rho_e$ are the electron thermal speed and gyroradius. Friction effects caused by ion thermal motion ($m_i >> m_e$) allow the ambipolar diffusion coefficient to be simplified to the product of the acoustic velocity and the electrostatic potential gradient scale length,

$$D_A \approx C_s L_i = \frac{C_s}{n_n \sigma_{in}} \sqrt{\frac{T_e}{\gamma T_i}} \tag{8}$$

Ambipolar diffusion at weak magnetic fields transitions to classical cross-field diffusion for strong magnetic fields according to

$$D_\perp \approx \frac{D_A D_\rho}{D_A + D_\rho} \tag{9}$$

The boundary conditions at either end of a field line are governed by diffusion into the sheaths at the ion acoustic speed, $C_s$. For the magnetized plasma case where variations in the perpendicular direction are small, the density variation along a field line is parabolic. For the special case where each sheath boundary has the same $D_A$ and $C_s$, the pre-sheath feeds plasma into the sheaths at the same rate. The sheath thicknesses must then be adjusted to make the plasma flow consistent with the applied voltages at each end of the field line.

A sheath model based on Lieberman's work was iterated in MORRFIC[4]. For low plasma densities or high powers, the iteration process converged but, for some parameters of experimental interest, the electric field in the sheath collapsed locally. The sheath thickness was fixed for the calculations presented here.

## THE GEOMETRY

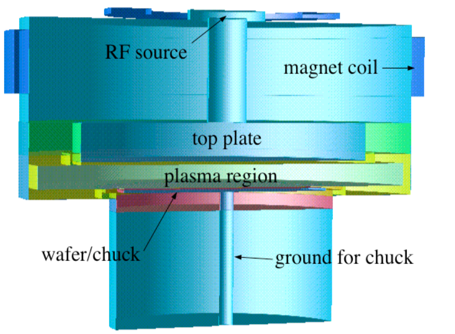


**FIGURE 1.** Geometry of capactive discharge chamber showing the plasma region between the powered top plate and the chuck (grounded) and the dc solenoidal coil.

**FIGURE 2.** Example of the plasma density distribution in a magnetized discharge. The spatial uniformity of the ion flux to the wafer can be controlled with the applied magnetic field.

The geometry of the capacitive discharge chamber used in this study is shown in Figure 1. It is a simplified version of a commercial dielectric etch tool, with the aspect ratio altered sufficiently to avoid disclosing any proprietary information while revealing the fundamental properties of the discharge. High frequency source power (>150 MHz) is applied to the upper electrode to initiate and sustain the discharge. The lower electrode, or chuck, on which the wafer sits, is normally rf-biased with the application of one or more lower frequencies (2-12 MHz); for simplicity, the lower electrode remains grounded in these studies. One magnetic field coil is shown in Figure 1 and is used to produce a diverging B-field at the wafer surface; more such coils can easily be added to tailor the field shape. In these studies, an identical image coil (not shown) could also be positioned below the plane of the wafer to generate either pure mirror fields (B-radial = 0) or cusp fields (B-axial = 0) at the wafer surface.

## INITIAL RESULTS

The effect of the radial component of the magnetic field on the plasma density profile at the wafer can be understood in terms of an enhanced confinement of ions at the edge. On axis the magnetic connection length $L_c$ is equal to the gap spacing, $L_G$, while off-axis $L_c \approx L_G(1 + B_r^2/B_z^2)^{½}$. This contributes to an increased confinement time, as shown in Figure 3, that scales as

$$\bar{\tau} \approx \left[\left(1+\frac{B_r^2}{B_z^2}\right)^{1/2} + \frac{L_G}{6L_i}\left(1+\frac{B_r^2}{B_z^2}\right)\right]\left(1+\frac{L_G}{6L_i}\right)^{-1} \qquad (10)$$

where $L_i$ is an electrostatic potential gradient scale length. Figure 4 is a MORRFIC calculation showing the depletion of central density and increase in edge density as the magnetic coil current is increased.

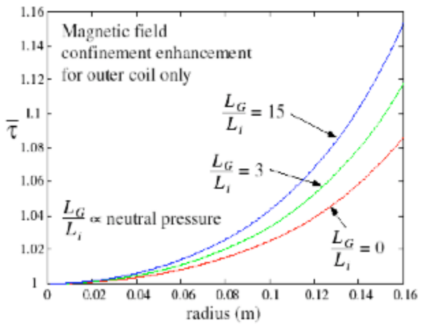


**FIGURE 3.** For magnetic field strengths and neutral collision parameters such that the electron transport is dominated by the magnetic field, the radial component of the static magnetic field can enhance the plasma confinement at the wafer edge.

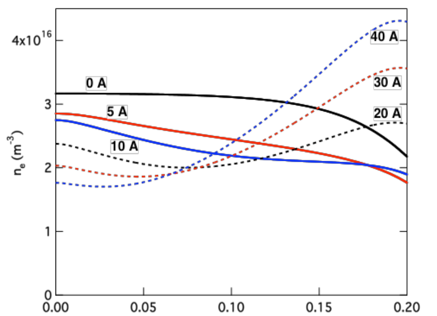


**FIGURE 4.** MORRIC calculations of plasma density at wafer surface as a function of solenoid coil currents for a magnetic cusp geometry. The source power is 400 W, $n_0 \sim 10^{20}$ m$^{-3}$, and the sheath thickness is fixed at 1.5 mm.


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