TE_{01} Excitation of an Electron Cyclotron Resonance Plasma Source

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***Abstract*— The uniformity of plasma generation in electron cyclotron resonance (ECR) reactors for materials processing, and the subsequent uniformity of fluxes to the substrate, are generally a function of the mode of the microwave radiation injected into the chamber. In this paper, a finite difference time domain (FDTD) simulation is used to demonstrate the consequences of exciting an ECR reactor using a TE_{01} mode. Due to the off axis peak in the electric field, power deposition and the plasma density peak off axis. Diffraction of the field around the resonance zone produces a secondary maximum in electron density downstream.**

***Index Terms*—Electromagnetic propagation in plasma media, plasma applications, plasma materials-processing applications.**

THE uniformity of reactant fluxes to the substrate in electron cyclotron resonance (ECR) reactors for materials processing is known to be a function of the uniformity of power deposition [1], [2]. Since the spatial distribution of power deposition is a function of the spatial distribution of the electric field in the resonance zone, the modal structure of the microwave field injected into the reactor is an important factor in determining plasma uniformity. To investigate these issues, a finite-difference time-domain (FDTD) simulation [3] for microwave injection and wave propagation was developed and was incorporated as a module into the two-dimensional (2-D) hybrid plasma equipment model (HPEM) [4]. The improved model was used to simulate the injection of TE_{01} mode microwave radiation and subsequent power deposition in an ECR reactor producing a plasma in nitrogen.

The 2-D, azimuthally symmmetric HPEM consists of an electromagnetics module (EMM), electron energy transport module (EETM), and a fluid kinetics simulation (FKS). Electromagnetic fields and power absorption are calculated in the EMM. Those fields are then used in the EETM to generate electron impact source functions and transport coefficients as a function of position. These parameters are then used in the FKS to integrate momentum and continuity equations for all heavy particles. A drift diffusion formulation is used for electrons to enable an implicit solution of Poisson's equation for the electric potential. The species densities and electrostatic fields produced in the FKS are transferred to the EMM and the EETM. This procedure is iterated until a converged solution is obtained. In prior works [4], the EMM employed an implicit frequency-domain solution for the electromagnetic field using the method of successive over relaxation (SOR). This method was found to be inadequate for resolving near field, short wavelength phenomena. The FDTD module was therefore developed to address ECR conditions. We typically used a mesh with 80 points per wavelength and took time steps of about 0.1 of the Courant limit, using an implicit, leap-frog integration technique.

The raw data for the images was generated by the HPEM on a Digital Equipment Corp. (DEC) Alphastation 600 5/500 workstation. The image of the reactor was generated on a Sun Microsystems Ultra 30 using graphical primitives based on the Solaris 1.2 Open GL Graphics Libraries. The image of plasma quantities were generated using Tecplot® (v7.0.1), a visualization package from Amtec Engineering, running on a Sun Microsystems Enterprise 450. The reactor and plasma images files were transferred to a Gateway 2000/4DX2-66, where Corel PhotoPaint/Draw (v.7) was used to construct the final image.

In the results shown here, we simulated the absorption of microwave radiation using a circular transverse TE_{01} mode electric field at 2.45 GHz delivering 750 W. The gas was nitrogen at 10 mtorr with a 10 sccm flowrate. The species included in the simulation are $N_2(X)$, N_2^+, $N_2(v)$, $N_2(A)$, $N(^2P)$, $N(^4P)$, and N^+. In the ECR reactor, shown in Fig. 1, N_2 is injected into the processing chamber through a gas ring located near the top of the reactor and pumped at the bottom of the reactor. The magnetic field is produced by two sets of coils. The top set determines the location of the resonance zone, which is approximately at the middle of the narrow portion of the reactor. The bottom coil is used to restrict flaring of the magnetic field in the lower portion of the chamber. A circular transverse electric TE_{01} wave is introduced at the top of the reactor through a waveguide antenna. The wave propagates through the dielectric window and into the processing chamber roughly parallel to the static magnetic field lines. Power deposition resulting from absorption of the electromagnetic wave energy occurs in vicinity the resonance zone (875 G), as shown in the left side of Fig. 1. The resulting electron density is shown in the right side of Fig. 1.

The TE_{01} mode has a maximum in amplitude at about half the radius of the injected wave. A small amount of power deposition occurs prior to the resonance in the vicinity of the peak in the electric field. The majority of the power deposition occurs in the resonance zone, which is a convex-down, dome shaped surface. Since power deposition scales with the square of the electric field amplitude, the deposition is strongly peaked at the radius of the maximum in the TE_{01} mode. A few percent (in amplitude) of the electric field leaks through (or diffracts around) the resonance layer, resulting in power deposition on the substrate side of the resonance zone. Since the cross-magnetic field mobility of the electrons is small, the off axis peak in power deposition results in the electron temperature

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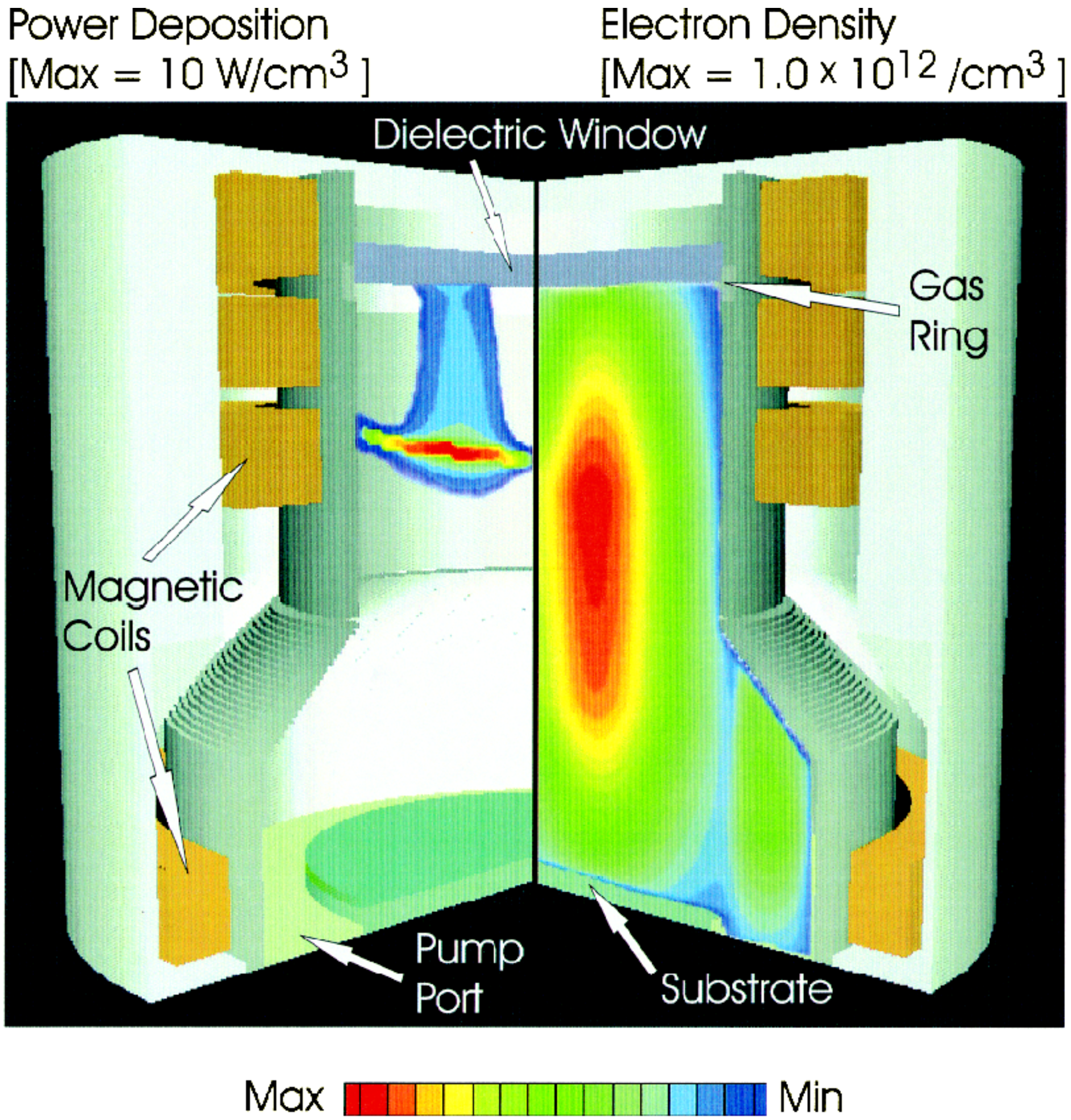

Fig. 1. Plasma characteristics for an ECR reactor operating in nitrogen at 10 mtorr and 750 W power deposition: (left) power deposition and (right) electron density. The plasma is generated using microwave radiation injected from the top of the reactor using a TE_{01} azimuthally symmetric mode.

and the electron impact ionization rates also having off axis peaks. The resulting electron density also has an off-axis peak, which extends downstream due to the large parallel mobility of the electrons. Some amount of cross field mobility and flaring of the magnetic field produces a more uniform density downstream.

Note that there is a weak local maximum in the electron density near the bottom magnetic field coil. This maximum results from there being a resonance near the coil. Electromagnetic radiation which survives its traversal through the upper resonance zone (or diffracts around it) produces a small amount of heating at the lower resonance, thereby producing a small local maximum in electron density.

In conclusion, an image of an ECR reactor sustained by an azimuthal microwave electric field in the TE_{01} mode has been presented. The off axis maximum in the electric field produces an off axis maximum in power deposition in the resonance zone. The small cross field mobility, and large parallel mobility, preserves the resulting off axis maximum in electron density downstream toward the substrate.

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