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Modeling of Profile Effects for the LLNL Large Area Inductively Coupled Plasma Source

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Abstract

Inductively coupled plasma (ICP) sources are one of the most important high density plasma configurations developed in recent years. Next generation technology requires plasma processing systems with high uniformity over very large areas. We present here a comparison betewen computer modeling and experimental results from the LLNL Large Area ICP Source. The LLNL experiment has a 30" diameter and is designed to study 400mm processing. Computer simulations using the fluid code, INDUCT94, are used to explain variations in the plasma density profile measurements as a function of inductive power and gas pressure. Trends in density profile versus pressure and power found in the simulation match those found in the experiment. Uniformity of the order of several percent was found to be possible over a 400mm diameter area.

The trend toward processing of 400mm diameter wafers is driving the development of high density sources with good plasma uniformity over a large area. One of the most promising new sources is the inductively coupled plasma (ICP) source. One attractive feature of this source is its relative simplicity, e.g., no DC magnetic fields are required for their operation. Recent studies have reported experimental characterizations [1, 2] and computer modeling [3, 4] of these devices. Most of the studies have concentrated on smaller area ICPs. Here we present modeling of the LLNL 30" diameter ICP and compare our results with measurements on this reported by Richardson, Egan, and Benjamin [5]. A brief description of the reactor can be found in that paper.

We used the INDUCT94 code to model the ICP [4]. The transport portion of the code consists of the electron continuity equation, the inertialess electron momentum equation (drift-diffusion approximation), the electron energy equation, Poisson's equation, and the ion continuity and momentum equations. The equations are solved with finite differencing in space. As time is advanced, the equations are solved sequentially and the code continues until a steady state is reached. Sheaths are resolved to the extent that the spatial grid resolution permits. The electron energy equation is solved implicitly while keeping all other variables fixed to avoid the conductivety numerical time constraint. The electron continuity and Poisson's equation are solved implicitly while keeping all other variables fixed to avoid the dielectric relaxation numerical time constraint.

The EM portion of the code is the ORMAX EM solver [6]. ORMAX is a time harmonic code that solves a reduced set of Maxwell's equations in the ICP chamber and then calculates the power deposition in the plasma. The power deposition is then used in the transport portion of the code as a source term in the electron energy equation. ORMAX requires plasma conductivity which can be easily found from the plasma temperature and density calculated in the plasma portion of the code. ORMAX also calculates the inductive voltage drop and capacitive current drop for each ICP coil turn. These quantities are used to advance a circuit model that couples the ICP coils to a current source. The current source can be scaled to acheive a fixed total power deposition in the plasma. The average voltage on the coils can also be coupled into Poisson's equation solved in the transport portion of the code.

We completed simulations in Ar at various pressures and powers and plotted the radial density and E_θ profiles, unnormalized and normalized to the peak value, at the height in the chamber at which the Langmuir and Bdot probe measurements were taken. Figure 1 shows results for 10 W, 100 W, 600 W, and 1200 W of inductive power at a fixed pressure of 10 mTorr. The 10 W case cannot be acheived experimentally in Ar but was done to demonstrate profile effects for very low densities that occur in N_2. Figure 2 shows results for 5 mTorr, 10 mTorr, 20 mTorr, and 50 mTorr at a fixed power of 1200 W. The 20 mTorr case was repeated with the coil voltages included in the solution of Poisson's equation (CC case).

Comparing the density plots of Fig. 1 to power variation plots of Fig. 2 in Richardson, Egan, and Benjamin, we observe the same general trends in profile variation with power. For higher power at fixed pressure, the average density increases, but the density profiles are not strongly effected. Note that the normalized 600 W and 1200 W profiles are nearly identical. As the power is dropped, however, the profiles begin to flatten. The 10 W case shows the same kind of flattening observed in N_2 as shown by the power variation plots of Fig. 3 in Richardson, Egan, and Benjamin.

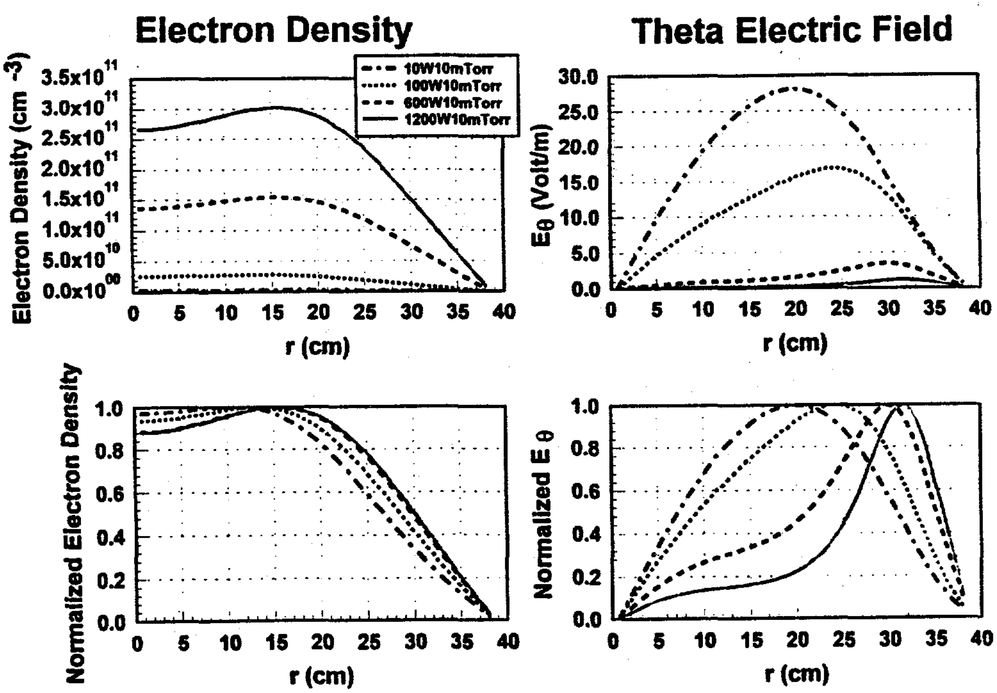

Figure 1: Model radial profiles in Ar as a function of rf power, 10 mTorr, z ~ 2.125".

This profile effect may be explained qualitatively in terms of the skin depth, the scale length over which electromagnetic energy is deposited. The skin depth is essentially a function of density: $\delta \propto n^{-1/2}$. From a power balance, density increases with power for a fixed pressure [7]. Thus for increasing power, the skin depth *decreases* leading to more localized heating. If the heating is more localized, it may be expected that the density profiles may be more peaked. For factor of two changes in power, the change in skin depth is small and thus the Ar profiles do not change much. When power is dropped to 10 W, however, the skin depth increases an order of magnitude over the 1200 W case. The fields penetrate farther into the plasma, hence the increasing E_θ magnitudes with decreasing power. With the heating less localized, the density profile flattens. The effect appears more pronounced in N_2.

Comparing the density plots of Fig. 2 to the pressure variation plots of Fig. 2 in Richardson, Egan, and Benjamin, we observe the same general trends in profile variation with pressure. For higher pressure at fixed power, the density increases and the density profiles become more peaked.

The density effect can be explained qualitatively in terms of particle and power balances and the profile effect can explained in terms of thermal conductivity. For a fixed power, a particle balance predicts decreasing electron temperature for in-

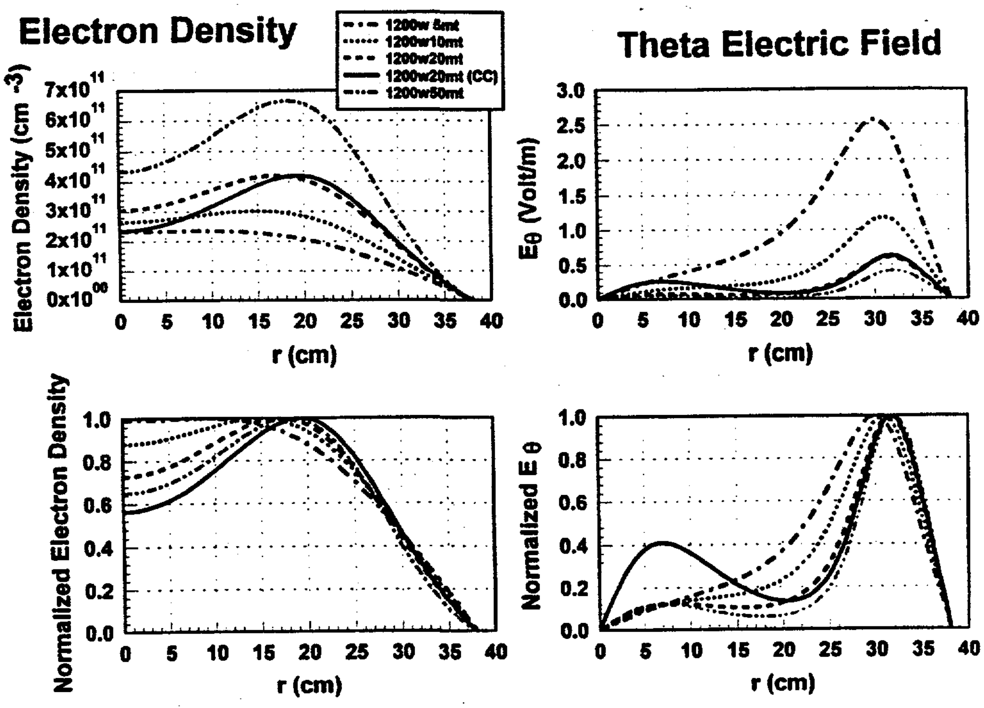

Figure 2: Model radial profiles in Ar as a function of pressure, 1200 W rf power, z ~ 2.125".

creasing pressure in a simple gas such as Ar [7]. Furthermore, for a fixed power, the power balance equation can be solved for density to give $n \propto (u_B \epsilon_L)^{-1}$, where u_B is the Bohm velocity and ϵ_L is the energy loss per ionization. As pressure increases, temperature decreases which leads to a larger ϵ_L but a smaller u_B. For $T_e > 1eV$ in Ar, the product $u_B \epsilon_L$ goes down with decreasing temperature thus leading to an *increasing* density. Furthermore, for small skin depths, increasing pressure reduces the electron mean-free-path, derceasing the ability of thermal conductivity to spread the rf power throughout the plasma. This results in enhanced off axis peaking in the ionization rate and the density.

When the transport solution of Poisson's equation includes the coil voltage, the average density remains the same, but the profile becomes more hollow and the density peak is pushed farther out from the center. This capacitive coupling (CC) case produces a profile for 1200 W, 20 mTorr that is in better agreement with the observed profile. The dielectric window causes a large voltage drop from the coil to the plasma so that heating due to capacitive fields is not a valid explanation for the effect. The dielectric window does not smooth out the coil-to-coil voltage variation and so this variation may be changing the density profile. We are repeating the simulation with finer resolution to determine if the effect is real or a by product of course sheath resolution.

Our initial modeling of the LLNL Large Area ICP shows good agreement with the experiment in observed trends in density magnitude and profile over a large range of pressures and powers and has increased our general understanding of the source. Future works in modeling include adding more chemistry data to model electronegative gases and gas mixtures and extending the coil and circuit model to include the matching network. With these additions, we will gain an ability to more closely model practicle devices and determine prescriptions for enhancing uniformity.

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References

[1] A. E. Wendt, L. J. Mahoney, and J. L. Shohet, 45th Gaseous Electronics Conference, paper LB-5, Boston, MA, 1992 (unpublished).

[2] J. Hopwood, C. R. Guarnieri, S. J. Whitehair, and J. J. Cuomo, *J. Vac. Sci. Technol.* **A 11**, 147,152 (1993).

[3] G. DiPeso, V. Vahedi. D. W. Hewett, and T.D. Rognlien, *J. Vac. Sci. Technol. A* **A 12**, 1387 (1994).

[4] R. A. Stewart, P. Vitello, D.B. Graves, E.F. Jaeger, and L. A. Berry, *Plasma Sources Science and Technology* **4**, 36 (1995).

[5] "LLNL Large-Area Inductively Coupled Plasma (ICP) Source Experiments", R. A. Richardson, P. O. Egan, and R. D. Benjamin, 12th Intl. Symposium on Plasma Chemistry, Minneapolis, MN, 1995.

[6] L. A. Berry, E. F. Jaegar, and J. S. Tolliver unpublished.

[7] M. A. Lieberman and A. J. Lichtenberg, *Principals of Plasma Discharges and Material Proceseeing*, John Wiley and Sons, New York, 1994, Chapter 10.