Formation of Coulomb Crystals in a Capacitively Coupled Plasma

Vivek Vyas and Mark J. Kushner, *Fellow, IEEE*

***Abstract*—Dust particle transport in low-temperature plasmas has received considerable attention due to the desire to minimize contamination of wafers during plasma processing of microelectronic devices and as their use to study nonideal plasmas. Observations of dust particles in radio frequency discharges have shown that particles form Coulomb crystals and display collective behavior. Images are presented here of Coulomb crystals simulated in a capacitively coupled discharge. An abrupt splitting of a single hexagonal lattice into two lattices occurs with increasing substrate bias.**

***Index Terms*—Plasma applications, plasma properties, plasma sheaths.**

DUST PARTICLE transport in partially ionized plasmas has been the focus of many recent investigations as a consequence of concern over particle contamination of wafers during plasma processing of microelectronic devices and the use of particles to study nonideal plasmas. When particle densities are large, the particles may display collective behavior as the Coulomb interactions between the particles become dominant over thermal transport processes. Evidence of liquid and even solid-like behavior has been seen in a variety of discharges. For example, in a processing discharge, Boufendi *et al.* estimated the Coulomb coupling coefficient (potential energy/thermal energy) to be 10 for a parallel plate radio frequency (RF) discharge, $Ar/SiH_4 = 96/4$ at 120 mtorr, with a peak density of 10^8 cm^{-3} of 100 nm particles [1]. With high particle density and appropriate plasma conditions such as low power, low pressure, and moderate gas flow, the dust particles become more even ordered and form lattices with large coupling coefficients [2].

In this paper, computationally generated images are presented of plasma properties and dust particle lattices in a capacitively coupled RF discharge. The platform used in this study is a three-dimensional Monte-Carlo model, the Dust Transport Simulation (DTS) [3], in which particle trajectories are integrated under the influence of ion drag, fluid drag, electrostatic, thermophoretic, self-diffusive, gravitational, and Brownian forces. Coulomb forces are included between the particles using Debye–Huckle screening. The plasma properties used in the DTS (electron, ion, and neutral densities, fluxes and temperatures, and electrostatic potential, and fields) are obtained from the Hybrid Plasma Equipment Model (HPEM) [4]. The HPEM is a comprehensive simulator of low-pressure plasma reactors which has been described in detail in [4]. For the results discussed here, the following options in the HPEM were used. The electron transport coefficients were obtained using the electron energy equation. Continuity, momentum and energy equations were solved for ions and neutral particles. Electron transport was obtained using a drift-diffusion formulation coupled with a semi-implicit solution of Poisson's equation.

The model reactor is a modified Gaseous Electronics Conference reference cell. The lower electrode is powered at 10 MHz. The upper electrode was replaced by an annular plate so that, experimentally, particles could be observed from the top of the reactor [5]. A metal washer placed on the lower electrode acts as focus ring to warp the electric potential into a well to confine the dust particles. The plasma was sustained in argon at 95 mtorr with a flow rate of 300 sccm, which is exhausted through the pump port surrounding the lower electrode. The substrate bias was varied from 125 V to 250 V. Dust particles (radius 3.8 μm, mass density 2.33 g$\cdot$cm^{-3}, akin to that of amorphous silicon) were initially randomly distributed between the electrodes. Their trajectories were integrated for approximately 8 s until they settled into a quasi-stable geometric configuration. Raw images were generated using Tecplot (v 8.0) [6]. They were combined into the final image shown here using Adobe Photoshop (v 5.0) [7].

The image in Fig. 1 shows the ion density in the left panel and time averaged plasma potential in the right panel. Particle trapping locations are superimposed. The plasma properties are cylindrically symmetric while particle trajectories are followed in three dimensions. For a substrate bias of 250 V, a peak Ar^+ density of 1.5×10^{10} cm^{-3} and a peak plasma potential of 135 V are obtained, including -35 V dc bias on the substrate. The plasma penetrates through the annular grounded electrode into the upper chamber. The plasma potential is largely flat in the body of the plasma. Sheaths surround the annulus and there are large ambipolar electric fields in the periphery of the reactor. The ion density and plasma potential are conformal to the focus ring forming a potential well in which particles are trapped. The particles are well confined to this region. Particles not seeded in locations which can access the potential well formed by the focus ring are, for these conditions, eventually expelled from the bulk plasma. The particle density is sufficiently large, and their temperature sufficiently low, that a Coulomb crystal is formed having a coupling coefficient of $\approx$2000.

The morphologies of the Coulomb crystal lattices, as observed from the top of the reactor through the annular electrode,

Manuscript received July 12, 2001. This work was supported in part by Sandia National Laboratory, by the National Science Foundation, and by the Semiconductor Research Corporation.

V. Vyas is with the Department of Material Science and Engineering, University of Illinois, Urbana, IL 61801 USA (e-mail: vvyas@uiuc.edu).

M. J. Kushner is with the Department of Electrical and Computer Engineering, University of Illinois, Urbana, IL 61801 USA (e-mail: mjk@uiuc.edu).

Publisher Item Identifier S 0093-3813(02)03188-0.

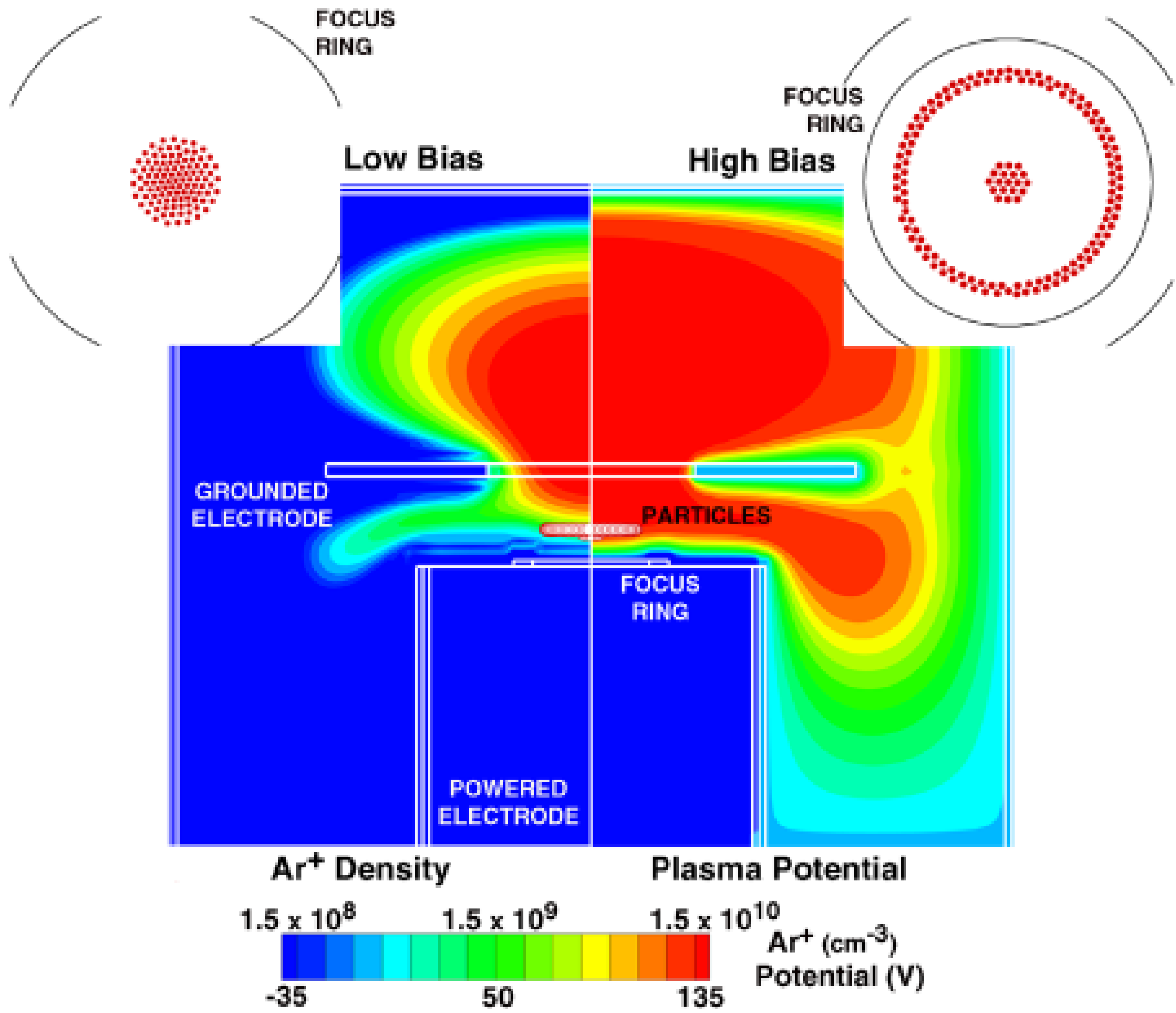

Fig. 1. Plasma properties and Coulomb crystals in a capacitively coupled discharge. Results are shown for an argon plasma, ion density on the left, and plasma potential on the right. The locations of trapped dust particles are shown above the focus ring. The insets show the top-down view of Coulomb crystals at low bias (left) and high bias (right). An abrupt splitting of the lattice from a single disk to a disk-and-ring arrangement occurs at approximately 200 V when increasing the bias.

are shown by the insets. Configurations are shown for low (150 V) and high (250 V) substrate biases. At the lower bias, a single disk-shaped lattice of dust particles is obtained which is confined to the center of the potential well. An abrupt splitting of the crystal into two lattices occurs at higher substrate biases (>200 V). The split lattices contain a central disk and an outer ring. The central disk is slightly lower in height (as discernable in the reactor image). The number of particles in the outer ring is insufficient to form a perfect two layer lattice and so dislocations occasionally occur. The splitting was observed irrespective of the number of initial particles seeded in the system. We speculate that a more narrowly defined central potential well and larger radial forces at higher biases are responsible for the splitting of the lattice. A larger fraction of initially seeded particles are expelled from the plasma at higher biases as well.

REFERENCES

[1] L. Boufendi, A. Bouchoule, R. K. Porteous, J. Ph. Blondeau, A. Plain, and C. Laure, “Particle–particle interactions in dusty plasmas,” *J. Appl. Phys.*, vol. 73, pp. 2160–2162, 1993.
[2] H. M. Thomas and G. E. Morfill, “Plasma crystal: Coulomb crystalization in a dusty plasma,” *Phys. Rev. Lett.*, vol. 73, pp. 652–655, 1994.
[3] H. H. Hwang and M. J. Kushner, “Simulation of the formation of Coulomb liquids and solids in dusty plasmas,” *J. Appl. Phys.*, vol. 82, pp. 2106–2114, 1997.
[4] R. Kinder and M. J. Kushner, “Wave propagation and power deposition in magnetically enhanced inductively coupled and helicon plasma sources,” *J. Vac. Sci. Technol. A*, vol. 19, pp. 76–86, 2001.
[5] G. Hebner, “Private communication,” Sandia National Laboratory, 2001.
[6] Amtec Engineering., Bellevue, WA. [Online]. Available: http://www.amtec.com.
[7] Adobe Corp., San Jose, CA. [Online]. Available: http://www.adobe.com.