Radical and Electron Densities in a High Plasma Density-Chemical Vapor Deposition Reactor from a Three-Dimensional Simulation

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***Abstract*— High plasma density chemical vapor deposition (HPD-CVD) is being developed for producing interlevel dielectrics in microelectronics fabrication. We present images of radical and electron densities in an Ar/SiH_4 HPD-CVD inductively coupled reactor produced by a three-dimensional equipment model. The silane feedstock and silyl (SiH_3) radicals are rapidly dissociated, resulting is densities which are maximum near the nozzles. The silylene (SiH_2) radicals, the most fragmented species included in the simulation, are the most uniformly distributed.**

***Index Terms*—Gas discharges, plasma CVD, plasma materials-processing applications.**

HIGH plasma density chemical vapor deposition (HPD-CVD) is being developed for low temperature deposition of interlevel dielectrics [1]. HPD-CVD has the advantage of having high processing rates, however, due to the large degree of dissociation of the feedstock gases, one is less able to control the type, relative magnitudes, and spatial distribution of reactant fluxes to the substrate. This is particularly problematic when injection nozzles are used for the deposition gases. In this paper, images of a HPD-CVD inductively coupled plasma (ICP) reactor using an argon/silane (SiH_4) gas mixture are presented to illustrate the different spatial dependencies of radical and electron densities.

The simulation used in this study is the three-dimensional hybrid plasma equipment model (HPEM-3D) described in [2]. A new option to HPEM-3D, the ambipolar module (AM), was used for purposes of acceleration. The AM substitutes for the solution of Poisson's equation during specified iterations of HPEM-3D and provides an approximation for the electric fields for use in the transport equations. After densities and flowfields achieve a quasi-steady state using these approximate fields, Poisson's equation is then solved to refine the final results.

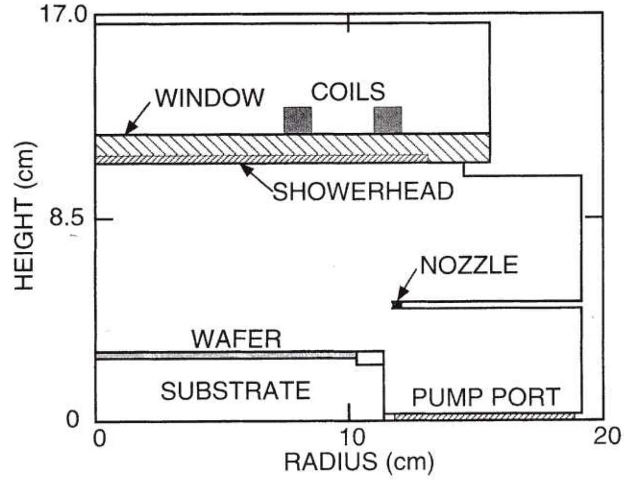

Fig. 1. Schematic of the reactor used in this study. Argon is injected through the shower head and silane is injected through the nozzles.

The reactor, schematically shown in Fig. 1, is an ICP powered by two azimuthally symmetric coils. Argon is injected through a shower head, while silane is injected through four symmetrically arrayed nozzles. Pumping is also symmetric, which results in the system being periodically symmetric in 90° quadrants. The gas mixture is Ar/SiH_4 $= 75/15$ at 15 mtorr with 600 W of power deposition. The species included in the model are Ar, Ar(4s), Ar^+, SiH_4, SiH_3, SiH_2, SiH_2^+, SiH_3^+, SiH_3^-, H_2, and H. The sticking coefficients for the silane radicals were 0.005 on all nonwafer surfaces and 0.15 and 0.25 on the wafer for SiH_3 and SiH_2, respectively.

The electron density and densities of SiH_4, silyl (SiH_3), and silylene (SiH_2) are shown in Fig. 2. The center image is a top view at the height of the nozzles. The outer images are volume plots, with cutouts at the azimuth of the nozzles and at the height of the substrate. The wireframe shows the approximate geometry of the reactor. The electron density has a maximum value of 3.6×10^{11} cm^{-3}, peaking in the center of the reactor. The nozzles, on whose surfaces the electrons recombine, produce a "scalloping" of the electron density which persists to the substrate. The silane density is largest at the outlet of the nozzle and disperses into the reactor. Although a portion of the decrease in silane density results from the dispersal, the silane is quickly, and nearly totally, dissociated by electron impact. SiH_3 is one of the dissociation products and has a large density only in the vicinity of the nozzle where the silane density is large. Its spatial distribution, though, is more uniform than that of the silane. SiH_2, a dissociation product of both silane and silyl radicals, has the most uniform spatial distribution, though it is consumed more rapidly on the wafer. The uniformity of fluxes of silane species to the wafer is poorest for the least fragmented species and best for the most fragmented species. Had more fragmented radicals been included in the simulation (e.g., SiH, Si), we anticipate the same trends would be observed.

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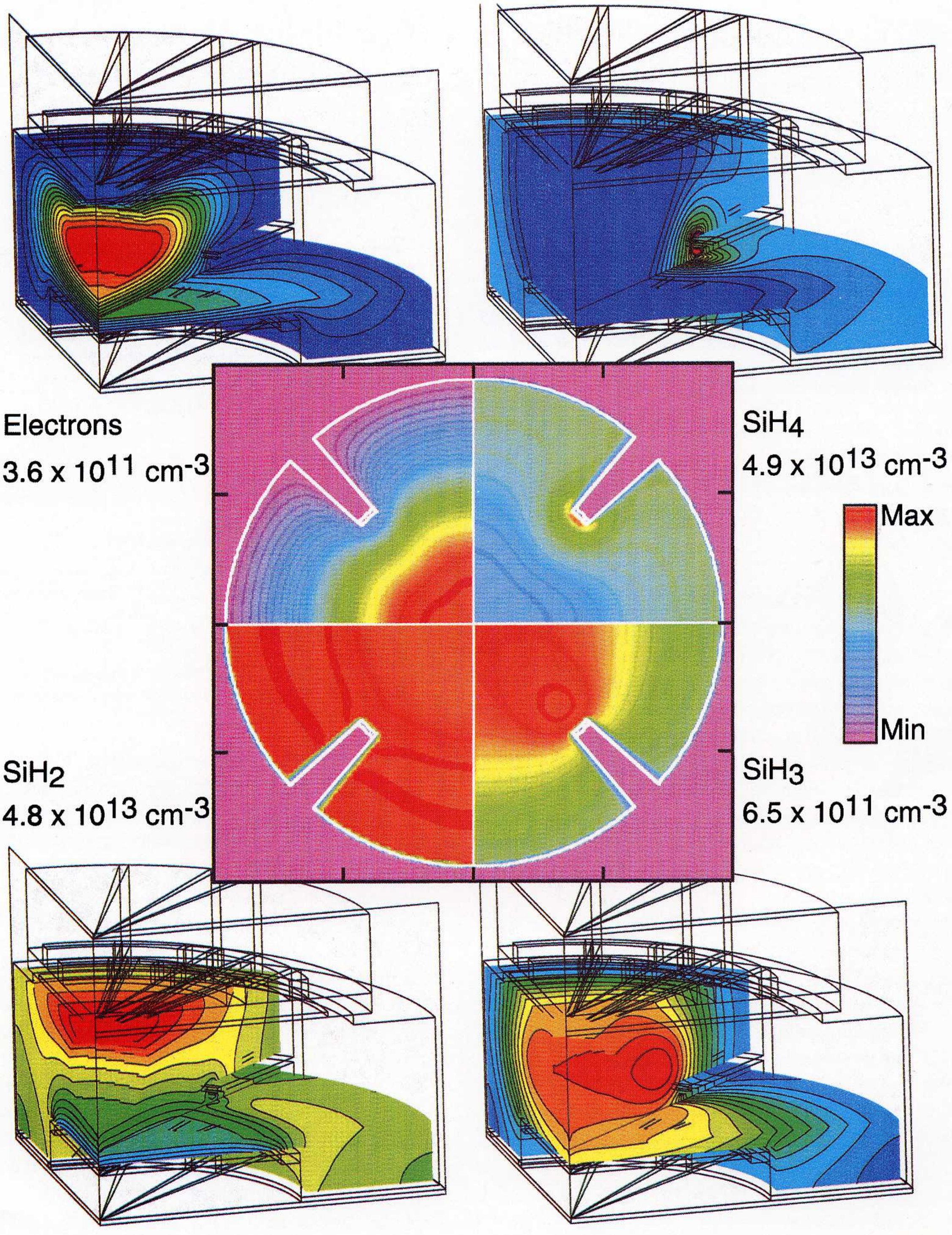

Fig. 2. Densities of electrons (top left), silane (top right), silyl (bottom right), and silylene (bottom left). The center image is a top view of the reactor at the height of the nozzles in which densities are shown as flood contours in a horizontal $[r, \theta]$ slice. The images in the adjacent corners are volume plots with cutouts at the azimuth of the nozzles and at the height of the wafer. Since densities are symmetric in 90° quadrants only a $\pi/2$ pie slices are shown. The maximum densities for each species are noted.

For the center images in Fig. 2, hierarchical data format (HDF) files were created using raw data from the HPEM-3D. The HDF files were then imaged into PICT files using Spyglass Transform on a Macintosh Power PC Model 8500. The outer four images were produced as separate EPS files using Tecplot®, a visualization package from Amtec Engineering, on a Sun Microsystems Enterprise 450. The PICT and EPS files were then combined using Claris Draw on the Macintosh.

REFERENCES

[1] P. Singer, "The future of dielectric CVD: High-density plasmas?," *Semicond. Int.*, vol. 20, pp. 126–134, July 1997.

[2] M. J. Kushner, "Consequences of asymmetric pumping in low pressure plasma processing reactors: A three-dimensional modeling study," *J. Appl. Phys.*, vol. 82, no. 11, pp. 5312–5320, 1997.