APPLIED PHYSICS LETTERS VOLUME 85, NUMBER 5 2 AUGUST 2004

Pulsed inductively coupled plasmas as a method to recoup uniformity: Three-dimensional modeling study

Pramod Subramonium[a]
Department of Chemical and Biomolecular Engineering, University of Illinois, 1406 W. Green Street, Urbana, Illinois 61801

Mark J. Kushner[b]
Department of Electrical and Computer Engineering, University of Illinois, 1406 W. Green Street, Urbana, Illinois 61801

(Received 26 November 2003; accepted 2 June 2004)

High plasma density sources such as inductively plasmas (ICPs) are commonly used for microelectronics fabrication. Design constraints often result in systems which have asymmetric gas pumping which can in turn produce azimuthal nonuniformities in plasma properties. These asymmetries are reinforced by a positive feedback between nonuniformities in conductivity and power deposition. In this letter, we discuss computational results from a three-dimensional model for pulsed operation of ICPs sustained in argon as a means to recoup azimuthal symmetry of plasma properties which may result from asymmetric pumping. We found that azimuthally asymmetric plasma properties produced by continuous operation gradually become more uniform during pulsed operation due to the interruption of the positive feedback and allowing interpulse diffusion to smooth asymmetries. © *2004 American Institute of Physics*. [DOI: 10.1063/1.1776617]

High plasma density sources, such as inductively coupled plasmas (ICPs) are commonly used for microelectronics fabrication.[1–5] Due to design constraints, ICP systems often have discrete nozzles or single-sided pumping.[6,7] Previous experimental[7,8] and computational investigations[9,10] of ICP reactors showed that asymmetric pumping may result in azimuthally asymmetric species densities and fluxes which ultimately translate to, for example, nonuniform etch or deposition yields. These geometric and flow asymmetries become more critical as wafer sizes increase.[11]

Flow-induced nonuniformities in densities can feedback and intensify through the plasma conductivity. Feedback through the nonuniform conductivity makes the power deposition nonuniform, which in turn results in nonuniform electron impact ionization sources and plasma conductivity. Thus, the nonuniform power deposition reinforces the flow-induced asymmetries. Pulsed operation of ICPs may be a means to recoup azimuthal uniformity by breaking this positive feedback and mediating asymmetries by diffusion during the afterglow following power pulses. These processes provide a more azimuthally uniform set of initial conditions for the subsequent power pulses. In this letter, we discuss results from a three-dimensional (3D) computational investigation of pulsed ICPs.

The model employed in this investigation is a moderately parallel implementation of the 3D Hybrid Plasma Equipment Model (HPEM3D).[10] The plasma transport and numerical algorithms used in HPEM3D are extensively discussed in Ref. 12. The parallel hybrid model employs "task parallelism" to simultaneously execute different modules of the HPEM3D on three processors of a symmetric multiprocessor computer having shared memory. As such, the model is the 3D analogue of the two-dimensional parallel model described in Ref. 13. The modules executed in parallel are the electromagnetics module, the electron energy transport module and the fluid kinetics module. Plasma properties from these modules are frequently exchanged in shared memory without interrupting the time evolving calculation being performed in other modules.

Pulsed operation of ICPs was recently reviewed in Ref. 13. In these devices, the radio-frequency power deposition is typically square-wave modulated with pulse repetition frequencies (number of on–off cycles per second) of kHz to 10 kHz, and duty cycles (fraction of an on–off period with power on) of 10%–50%. During the power-off portion of the cycle, the electron temperature rapidly falls to thermal values, thereby shutting off high threshold processes, such as ionization and excitation. In electronegative gas mixtures, such as those containing Cl_2, the decrease in electron temperature during the afterglow may increase rates of dissociative attachment, thereby increasing negative ion densities.

The model was employed to investigate pulsed Ar ICPs with asymmetric pumping. The reactor, schematically shown in Fig. 1(a), has azimuthally symmetric coils and gas injection, but an asymmetric pump port occupying the quadrant on the right-hand side of the (r,θ) plane. The antenna has uniformly azimuthal conduction currents to eliminate asymmetries that may result from either transmission line effects or the shape of the antenna. The gas injection is through a showerhead placed below the coils. The base case conditions for pulsed operation are argon, 5 mTorr, 160 sccm, a peak power of 600 W (average power of 300 W, carrier frequency of 10 MHz) modulated at a pulse repetition frequency of 10 kHz and a duty cycle of 50% (50 μs power on followed by 50 μs power off). There is no bias on the substrate.

The consequences of pulsed operation relative to continuous-wave (cw) operation on the azimuthal uniformity of a given plasma parameter $\phi(r,\theta)$ are quantified by an asymmetry factor β. β is a measure of the relative root-

---

[a] Present address: Novellus Systems, Inc., 11155 SW Leveton Dr., Tualatin, OR 97062; electronic mail: pramod.subramonium@novellus.com

[b] Author to whom correspondence should be addressed; electronic mail: mjk@uiuc.edu

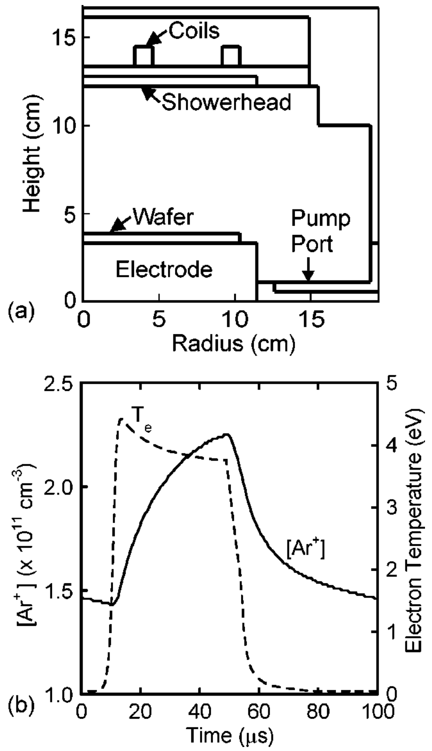

FIG. 1. Reactor and plasma properties. (a) Reactor schematic in the (r,z) plane showing showerhead and pump port locations. The pump port occupies only the quadrant on the right-hand side of the (r,θ) plane. (b) Ion density and electron temperature during pulsed operation (Ar 5 m Torr, 10 kHz, 50%, duty cycle, average power 300 W).

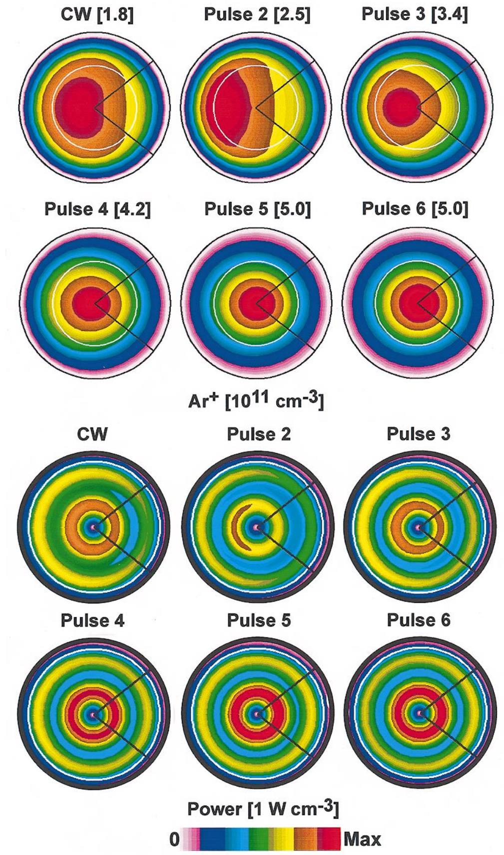

FIG. 2. (Color) Plasma properties during cw operation and averaged over a pulse period for pulses 2,3,4, 5, and 6 following cw operation. (Average power 300 W, 5 m Torr, 160 sccm, 10 kHz, duty cycle 50%). (Top) Ar^+ density above the wafer. The maximum ion density (10^{11} cm^{-3}) is noted in each figure. (Bottom) Power deposition below the dielectric window. The white circle is the outline of the electrode. The black wedge in the right quadrant denotes the pump port. The plasma properties gradually become more uniform during pulsed operation.

mean-square deviation of $\phi(r,\theta)$ from its azimuthal average, $\phi(r)$, which is then averaged over all radii. $\beta > 1$ implies $\phi(r,\theta)$ is less uniform during pulsed operation compared to cw operation. $\beta < 1$ implies $\phi(r,\theta)$ is more uniform. $\beta = 0$ is absolutely azimuthally uniform.

Reactor averaged electron temperature T_e and ion density are shown in Fig. 1(b) in the pulse-periodic steady state during pulsed operation for the base case. T_e peaks at the leading edge of the power-on pulse due to finite power being deposited into a smaller inventory of electrons which survive the previous afterglow. The electron and ion densities increase during the power-on pulse, not quite reaching a steady state at the end of the active glow.[14] In the early afterglow, T_e thermalizes within 10–20 μs. This decrease in T_e shuts off ionization, as well as reduces the rate of ambipolar diffusion, resulting in a slow decrease in ion density in the remainder of the afterglow.

cw operation of ICPs with asymmetric pumping can result in a nonuniform Ar^+ density and power deposition as shown in Fig. 2 for 300 W average power. The Ar^+ density is shown ≈1 cm above the wafer. Power deposition is shown ≈1 cm below the showerhead. Species injected through the showerhead or produced by reactions near the pump port have a shorter residence time compared to those opposite the pump port. This results in a larger energy deposition per atom in the remote volumes of the reactor, thereby producing larger rates of excitation and ionization. The small density variations (higher further from the pump port) also results in a gradient in excitation and ionization, larger in the higher-density regions. The resulting nonuniform electron impact sources produce larger electron densities at these remote sites. As the electron and ion densities are azimuthally asymmetric, the plasma conductivity is also nonuniform, resulting in asymmetric power deposition which further increases the asymmetries in electron impact sources. This positive feedback reinforces the asymmetries in densities produced by asymmetric pumping.

Improved azimuthal uniformity can be achieved by reducing this positive feedback between nonuniform electron density and power deposition by using pulsed operation. To demonstrate this concept, the ICP reactor was first operated in a cw mode to attain a quasi-steady azimuthally asymmetric state. The cw operation was followed by a series of pulses at the same average power until a pulse-periodic steady state was achieved. Pulse averaged $[Ar^+]$ and power deposition for pulses 2 through 6 following cw operation are also shown in Fig. 2. The pulse periodic steady state that is obtained after 6 pulses is an accurate representation of a quasi-steady state, as confirmed by computing additional pulses. During the afterglow following pulses, rapid thermalization of electrons through inelastic collisions significantly reduces the asymmetric electron impact sources. The thermal diffusion which then occurs during the afterglow mitigates the nonuniformities in species densities. At the end of the afterglow, species densities are more uniform providing a more uniform set of initial conditions for the subsequent pulse. The power deposition during the next pulse is therefore more symmetric, which in turn improves the azimuthal uniformity of electron

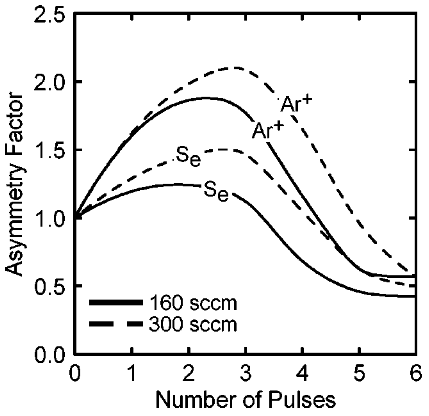

FIG. 3. Asymmetry factor for Ar$^+$ density above the wafer and electron impact ionization sources below the dielectric for several pulses following cw operation. (Average power 300 W, 5 m Torr, 10 kHz, duty cycle 50%). Asymmetry factors show nonmonotonic behavior during pulsed operation.

impact sources. These effects play out over several pulses to make plasma properties more azimuthally uniform.

During cw operation, $[\mathrm{Ar}^+]$ peaks off center $(1.7 \times 10^{11}\ \mathrm{cm}^{-3})$ at ≈ 4 cm on the stagnant side of the reactor due to the nonuniform distribution of residence times and gas density. The radial peaks in power are dominated by the location of the coils. Azimuthally, however, there are minima in power in the quadrant of the pump port and maxima opposite. The peak in $[\mathrm{Ar}^+]$ shifts to the center of the reactor after several pulses accompanied by improved azimuthal symmetry in power deposition.

The improvement in azimuthal uniformity is not necessarily monotonic. To maintain a constant average power for a 50% duty cycle, the peak power during the activeglow (600 W) is larger than cw operation (300 W). The larger power during the activeglow momentarily increases the azimuthal asymmetries in species densities by increasing the positive feedback. In the initial stages of pulsed operation, this increased positive feedback offsets the mitigating effects of diffusion during the afterglow. For example, at the end of the second pulse, the Ar$^+$ density is offset by ≈ 9 cm from the center towards stagnant zone. However, during the subsequent pulses as diffusion begins to dominate over the positive feedback, the peak shifts to the center, eventually making the Ar$^+$ density azimuthally symmetric. The trends for power deposition are similar to those for the ion density.

The plasma density is higher with pulsing than during cw operation having the same average power. This trend results from the more efficient ionization at the leading edge of the power-on pulse which is coincident with the peaking of T_e.[13] This improvement in ionization efficiency is likely detrimental to recouping uniformity with pulsing since it perpetuates the positive feedback.

Asymmetry factors for $[\mathrm{Ar}^+]$ and electron impact ionization sources during pulsed operation for flow rates of 160 and 300 sccm are shown in Fig. 3 for six pulses following the cw operation. The initial increase in β (less uniform) is attributed to an increase in positive feedback due to the larger peak power deposition during the activeglow. With additional pulses, diffusion during the afterglow begins to dominate over the increased positive feedback ultimately producing a pulse-periodic steady state which has improved azimuthal uniformity. On increasing flow rates to 300 sccm, the recovery time with pulsing is longer as the initial flow-induced asymmetries are larger.

Argon was chosen for this study since the positive feedback is particularly strong for the pressure and power regimes of interest and so pulsing is most beneficial. In these regimes, $[\mathrm{Ar}^+]$ generally increases with increasing pressure at constant power, and the increase in metastable states with increasing power generally increases the efficiency of ionization. As such, most of the processes which lead to azimuthal nonuniformities are power driven. Operating at lower powers where, for example, multistep ionization is not as important or where skin depths are longer would likely reduce the positive feedback. Pulsing with lower peak power would also recoup uniformity more rapidly.

Feedback is not always positive. There are gases for which the efficiency of net electron production decreases with increasing power or pressure, and so pulsing might not be as beneficial. For example, the rate of dissociative attachment to H_2 increases with vibrational exctation.[15] Local increases in power deposition which increase $[H_2(v)]$ decrease net electron production efficiency by increasing attachment, which produces negative feedback. Gases in which products of dissociation are more attaching than the parent gas might also display negative feedback.[16]

In conclusion, cw operation of ICP reactors with asymmetric pumping can result in asymmetric plasma properties which are reinforced by a positive feedback loop between conductivity and power deposition. Pulsed operation of ICPs can reduce this feedback and aid in mitigating azimuthal asymmetries. Employing a 3D model, we found that diffusion during the afterglow smoothens species densities, which then results in a more azimuthally uniform power deposition during subsequent pulses. In Ar ICPs, azimuthal symmetry of plasma properties was improved by $\approx 50\%$ during pulsed operation compared to cw operation. Many different power formats may be employed to optimize uniformity, from purely pulsed operation to longer periods of cw operation followed by a series of pulses.

This work was supported by the Semiconductor Research Corp., the National Science Foundation (Grant No. CTS03-l5353), and the Computational Science and Engineering program at the University of Illinois.

[1] J. Hopwood, Plasma Sources Sci. Technol. **1**, 109 (1992).
[2] J. H. Keller, Plasma Sources Sci. Technol. **5**, 166 (1996).
[3] U. Kortshagen, A. Maresca, K. Orlov, and B. Heil, Appl. Surf. Sci. **192**, 244 (2002).
[4] T. Makabe and Z. L. Petrovic, Appl. Surf. Sci. **192**, 88 (2002).
[5] Z. L. Petrovic and T. Makabe, Mater. Sci. Forum **282**, 47 (1998).
[6] M. H. Khater, L. J. Overzet, and B. E. Cherrington, J. Vac. Sci. Technol. B **16**, 490 (1998).
[7] T. A. Kim and E. S. Aydil, J. Appl. Phys. **92**, 6444 (2002).
[8] T. A. Kim, S. J. Ullal, V. Vahedi, and E. S. Aydil, Rev. Sci. Instrum. **73**, 3494 (2002).
[9] T. Panagopoulos, D. Kim, V. Midha, and D. Economou, J. Appl. Phys. **91**, 2687 (2002).
[10] M. J. Kushner, J. Appl. Phys. **82**, 5312 (1997).
[11] D. J. Economou, T. L. Panagopoulos, and M. Meyyappan, Micro **16**, 108 (1998).
[12] R. L. Kinder, A. R. Ellingboe, and M. J. Kushner, Plasma Sources Sci. Technol. **12**, 561 (2003).
[13] P Subramonium and M. J. Kushner, J. Vac. Sci. Technol. B **20**, 313 (2002).
[14] H Hebner and C. B. Fledderman, J. Appl. Phys. **82**, 2814 (1997).
[15] J. N. Bardsley and J. M. Wadehra, Phys. Rev. A **20**, 1398 (1979).
[16] P. Subramonium and M. J. Kushner, J. Appl. Phys. (to be published).