Regimes of particle trapping in inductively coupled plasma processing reactors

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Contamination of wafers by particles in plasma processing reactors is a continuing problem affecting yields of microelectronic devices. In this letter, we report on a computational study of particle contamination of wafers in a high plasma density inductively coupled plasma (ICP) reactor. When operating with an unbiased substrate, particles readily contaminate the wafer due to high ion fluxes which produce large ion-drag forces. Biasing the substrate with a radio frequency (rf) voltage counteracts the ion-drag forces by increasing the opposing electrostatic forces in the sheath, thereby shielding the wafer from incoming particles. We have found three regimes of particle contamination for different ICP powers and rf biases. At high rf biases and low ICP powers, particles trap at the edge of the sheath. At low rf bias and high ICP power, ion drag forces dominate, particles do not trap, and wafer contamination is problematic. At intermediate powers and biases, particles quasitrap, leading to moderate particle contamination. © *1996 American Institute of Physics.*
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Particle contamination of wafers in plasma processing reactors is a continuing problem in the semiconductor fabrication industry with respect to lowering yields of microelectronic devices.[1] Particles of 10 s nm to a few microns in size generally charge negatively to several hundreds to thousands of elementary charges, and as a result are subject to both ion drag and electrostatic forces.[2] Electrostatic forces generally accelerate particles away from surfaces and toward the maximum in the plasma potential. This force is strongest in and near the sheaths where electric fields are large (100–1000 s V/cm). Momentum transfer from ions, or viscous ion drag, accelerates particles in the direction of the net ion flux, usually toward the surfaces of the reactor. Particles often accumulate at sites where the net force on the particles is zero. In reactive ion etching (RIE) discharges, these dust trapping sites are typically at the boundary between the plasma and the sheath above or around the wafer, where the ion drag and electrostatic forces balance.[3,4] Other forces can also affect where particles trap, in particular fluid-drag forces and thermophoretic forces.[5]

High plasma density tools ($[e] \gtrsim 10^{11}-10^{12}$ cm^{-3}), such as inductively coupled plasma (ICP) reactors, are being developed for rapid etching of semiconductors. In ICP tools, ions are generated by electron impact ionization produced by electron heating from the inductive electric field. Ions are then accelerated into the wafer by a separate radio frequency (rf) bias applied to the substrate.[6–11] The ion flux, and hence ion drag forces, in high plasma density tools are sufficiently large that particles are typically not trapped at the sheath edge above the substrate if the substrate is unbiased, and so particles are driven to surfaces.[5] While electrostatic forces deep within the sheath may be large due to the increased electric field near the walls, ion-drag forces dominate over large distances within the bulk plasma. Particles generated in the central portion of the plasma have sufficient velocities due to ion drag to overcome the electrostatic forces near surfaces, resulting in deposition of particles onto the wafer. This situation has both benefits and detriments with regard to wafer contamination. An advantage is that small, yet growing particles, are driven out of the plasma prior to reaching a size which results in a killer defect of the device. The drawback is that particles which are large enough to be killer defects, as generated by heterogeneous processes, will also be driven to surfaces. In this letter, we discuss results from computer modeling study of ICP etching tools in which we investigate strategies for reducing the contamination of wafers by large particles. We find that there are regimes in the rf bias-ICP power parameter space in which the wafer can be shielded from particle contamination. This occurs at high rf biases and low ICP powers where the forces mimic those of RIE reactors.

The model we have used in this study consist of two modules: the hybrid plasma equipment model (HPEM),[12] and the dust transport simulation (DTS).[13] The HPEM generates charged particle densities, ion fluxes, and electric fields. A companion hydrodynamics simulation produces the velocity field of the feedstock gases and temperature gradients. These data are passed to the DTS in which the particle trajectories are computed. The HPEM used in this study is functionally the same as described in Ref. 12. The DTS is an extension of a previously described two-dimensional dust particle transport model.[13] The DTS tracks the trajectories of computational pseudoparticles, each representing a predefined number of actual dust particles. The forces included in the DTS are electrostatic, ion drag, thermophoretic, fluid drag by neutrals, and gravitational forces.[13,14] The gravitational force is usually several orders of magnitude smaller than the other forces and only becomes significant for particles larger than 10 s μm in radius. The ion-dust momentum transfer cross section required for computing ion drag forces was obtained from the semianalytic formula by Kilgore

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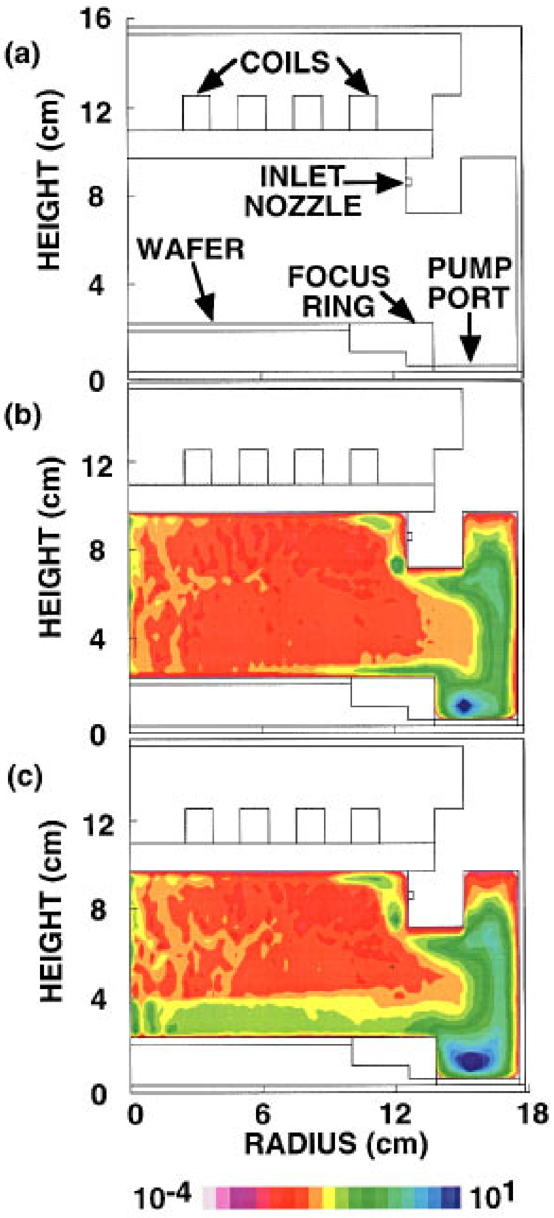

FIG. 1. (a) ICP configuration used in this study. A planar 4 turn coil generates the plasma. The wafer is surrounded by an alumina focus ring. The substrate is biased by a rf voltage. Time integrated fluences for 0.5 μm radius particles (b) without and (c) with a rf bias ($V_{\mathrm{rf}}=170$ V, $V_{\mathrm{dc}}=-32$ V). The conditions are 15 mTorr of Ar with a power deposition of 120 W and gas flow of 120 sccm.

et al.[15,16] Dust particles are initially randomly distributed in a predefined region of the reactor. Statistics are collected on the time particles spend in a particular numerical volumetric cell (r,z) and on the area density of particles collected on surfaces. The latter statistic is an area fluence while the former is a volume fluence. Particles spend longer periods of time traversing volumes near or at trapping sites, and hence the volume fluence has larger values in these regions. Sites through which particles slowly traverse but are not truly trapped are denoted *quasitraps*.

A schematic of a typical ICP reactor as used in this study is shown in Fig. 1(a). Plasma densities range from 10^{11} to 10^{12} cm^{-3}, for pressures of a few mTorr–10 s mTorr and power depositions of 100 s W–1 kW. The current densities to the substrate are higher than in conventional RIE discharges (10^{-4}–10^{-3} A/cm^2 for an ICP reactor compared to 10^{-5}–10^{-6} A/cm^2 for a RIE reactor). In this particular configuration the planar coils which generate the inductive azimuthal electric field are located above the quartz window. The gas input nozzles point inward. The pump port surrounds the lower electrode. This produces a gas flow which sweeps radially outward across the wafer. We used Ar gas for the cases discussed here. For typical operating conditions of Ar at 120 sccm, 15 mTorr, and 120 W of ICP power, the peak plasma density is 2×10^{11} cm^{-3}. For these conditions, most particles introduced into the plasma do not trap but are driven to the surfaces due to the dominating ion-drag forces. The dust particle's penetration of the sheath largely results from inertia gained from acceleration by ion drag forces in the bulk plasma. In the absence of rf biasing of the substrate, the electrostatic forces in the sheath are not sufficient to offset the particle's kinetic energy produced by ion drag forces. Therefore, particles are not trapped. These conditions suggest that by applying a sufficiently large rf bias to the lower electrode, one can decelerate the particles sufficiently to shield the wafer from the incoming dust particles.

The time-integrated volume fluence of trajectories for 0.5 μm particles, with and without an applied rf bias on the lower electrode ($V_{\mathrm{rf}}=170$ V amplitude, $V_{\mathrm{dc}}=-32$ V), are shown in Fig. 1 (120 sccm, 120 W, 15 mTorr). The maximum magnitudes for the electrostatic, ion drag, fluid drag, thermophoretic, and gravitational forces for 0.5 μm particles for the conditions in Fig. 1(b) are 1.0×10^{-7}, 3.3×10^{-7}, 3.1×10^{-8}, 1.0×10^{-9}, and 1.2×10^{-9} dynes, respectively, though these values occur at different locations in the reactor. Particles which start in the central portion of the reactor are accelerated toward the sheaths due to the large ion drag forces. In the case of an unbiased electrode [Fig. 1(b)], there is insufficient electrostatic shielding above the wafer for particles to become trapped near the plasma-sheath boundary. The particles penetrate the sheath and contaminate the wafer. Particles do, however, trap in the outer regions of the reactor where the ion flux is lower. In the case with a biased electrode [Fig. 1(c)], the larger electrostatic force above the wafer slows the particles which had been accelerated by ion drag thereby enabling the particles to become quasitrapped above the electrode. Particles reside in this trapping plane as they are radially accelerated out toward the pump port by the fluid drag force and some small component of the ion-drag force. The end result is significantly less particle contamination of the wafer.

These results suggest that different combinations of ICP power (which sets the ion drag force) and rf bias (which determines the electrostatic force) produce different regimes of tool operation with respect to particle contamination. These regimes are schematically shown in Fig. 2 where we have qualitatively assessed the propensity for particle contamination for different ICP powers and rf biases. The ''trapping'' regime is obtained with large rf biases and small ICP powers. These conditions mimic the forces normally associated with RIE configurations where the rf bias shields the wafer from negatively charged particles. The flux of particles to the wafer is therefore small. For moderate rf biases and ICP powers, or the ''quasitrapping'' regime, the particles

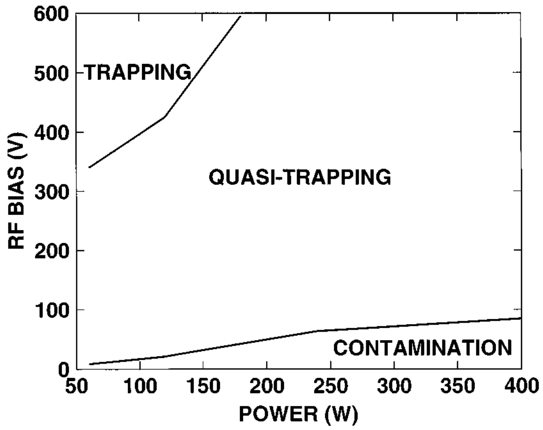

FIG. 2. Regimes for particle contamination based on ICP power and applied rf bias. All other conditions the same as in Fig. 1. In the ''trapping'' region, the wafer is electrostatically shielded from particles. In the ''quasitrapping'' region, where particles travel along the plasma-sheath boundary and eventually trap near the outer walls. In the contamination regime particles are driven to surfaces by ion drag forces.

reside for long periods of time above the electrode. Here, the axial components of ion drag and electrostatic forces nearly balance, with some radial acceleration due to the larger ion drag. A small amount of particle contamination will occur for particles which arrive at the sheath edge with large inertia. Finally, the ''contamination'' regime occurs at high ICP powers and small rf biases, conditions normally associated with high plasma density tools. The confining electrostatic forces are weak, and the axial electrostatic force is insufficient to balance the large inertial ion-drag component.

The relative particle fluence collected on the wafer as a function of radius is shown in Fig. 3 for an Ar plasma at 120 W for various applied rf biases. Increasing the rf bias from zero bias (contamination regime) to 170 V (quasitrapping regime) measurably reduces the particle fluence. When the bias is increased to 340 V, close to the trapping regime, the wafer is moderately shielded by the electrostatic forces, and the particle fluence is significantly reduced. The electrostatic force is essentially uniform across the wafer while the ion drag force peaks near the middle of the wafer due to the torroidal power deposition in ICP reactors. The particle collection is therefore greatest at central radii. For a bias of 425 V (trapping regime), the electrostatic forces balance or exceed the ion-drag forces and no particles are deposited on the wafer. Note that the fluence of particles deposited on the focus ring at radii larger than the wafer is nearly constant, regardless of biasing. The capacitance of the focus ring is small compared to the wafer which results in a large fraction of the bias voltage being dropped across the ring. This produces less electrostatic shielding of particles above the focus ring than above the wafer.

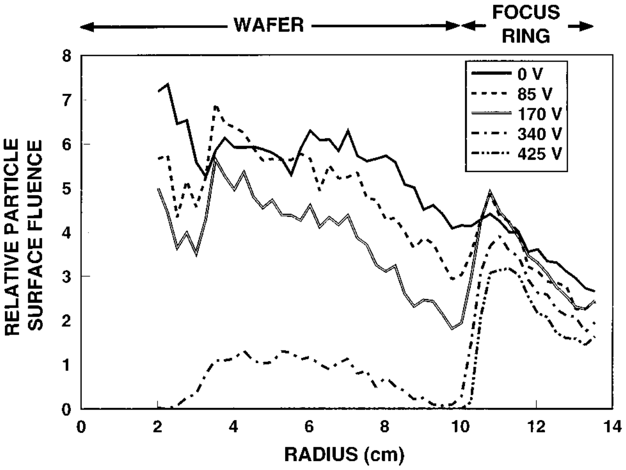

FIG. 3. Relative particle fluence for various applied rf biases for an ICP power of 120 W. For applied biases <400 V, the particles heavily deposit on the wafer. Wafer shielding becomes complete for biases ⩾425 V. Particle deposition on the alumina clamp ring is relatively unaffected by applied bias. Values are not shown for $r<2$ cm due to poor statistics.

In conclusion, three regimes for particle contamination of wafers have been described for an ICP plasma etching tool as a function of ICP power and rf bias. In the absence of an applied rf bias, ion-drag forces dominate and particles are accelerated to the wafer. For moderate rf bias voltages, the particles reside above the wafer for long periods of time (10–100 s of ms) in a quasitrapping mode, thereby reducing particle contamination. At high rf bias, the trapping is complete and the particle fluence to the wafer is low. For given ICP power, particles can be shielded from the wafer by applying a sufficient rf bias to counteract the ion-drag force.

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