

## Plasma-assisted cleaning by metastable-atom neutralization

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# Plasma-assisted cleaning by metastable-atom neutralization

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Plasma-assisted cleaning by metastable atomic neutralization (PACMAN) is a process that can clean hydrocarbon from extreme ultraviolet photo masks and dissolve hydrocarbon particles. It was developed with semiconductor manufacturing and cleaning in mind. The PACMAN process works by utilizing helium metastable atoms to break apart the contamination to be cleaned. As helium metastables interact with the contaminant surface, bonding electrons from the surface are “stolen” by the metastable helium resulting in “holes” where a bonding electron used to be. In this way, the structure of the contamination is compromised and allows for the removal either through desorption of  $C_xH_y$  molecules or by chain scission of the hydrocarbon backbone. A model of the helium metastable density within the processing chamber has been developed in addition to experimental measurements of the metastable density at the sample surface. Cleaning efficiency has been linked to both helium metastable density as well as electric field in the plasma sheath. Electric field calculations in the plasma sheath reveal that an electric field pointing into the plasma is needed for achieving high cleaning rates of hydrocarbons since it pins the holes that are created to the surface and stops the hydrocarbon bonds from re-forming. Operating the PACMAN process in this fashion allows for cleaning rates of approximately  $1.2 \times 10^7 \pm 5.1 \times 10^5 \text{ nm}^3/\text{min}$  from a particle without causing damage to the surrounding structure of the sample being cleaned. Carbon contamination in the form of carbon films on lithographic material has been shown to clean at rates of approximately  $11.4 \pm 0.3 \text{ nm/min}$ . © 2013 American Vacuum Society. [<http://dx.doi.org/10.1116/1.4770500>]

## I. INTRODUCTION

One of the critical issues still facing the implementation of extreme ultraviolet lithography (EUVL) into mainstream manufacturing for integrated circuit production is cleanliness. The 13.5 nm photons are easily absorbed by many species; these include dust, thin film layers, and other debris present in the photons path. Carrying out EUVL inside a vacuum helps reduce the amount of photon loss; however, contamination is always unavoidable. Traditional cleaning methods employ the use of wet chemicals to etch contaminants off of a surface; however, this is limited in the sub-micron range of contaminant particles due to the lack of transport of sufficient liquid chemicals to the surface in order to achieve satisfactory particle removal.

According to the International Technology Road Map for Semiconductors (ITRS), the photomask must be particle free at inspection above 30 nm. When analyzing the ability of traditional methods to meet the cleaning needs set forth by the ITRS, these methods fall short and often add more contamination to the surface.

Metastable atoms and their interaction with surfaces have been studied for several different purposes: metastable probes, metastable beam lithography, and their role in desorbing gas species from surfaces.<sup>1–3</sup> There are two primary interactions that can occur when a metastable interacts with a surface: resonance ionization followed by Auger neutralization (AN) on a conductor or Penning ionization (PI) which is also known as Auger deexcitation (AD) on an insu-

lator. When a metastable atom collides with an ordinary metal, the 2S electron of the helium metastable tunnels into an empty level in the surface of the metal forming a helium ion. This process is called resonance ionization. This helium ion is then neutralized by an electron from the surface followed simultaneously by the emission of another surface electron. This process is called Auger neutralization.<sup>4</sup>

However, on an insulator, resonance ionization is suppressed because the 2S level of the helium metastable falls within the energy gap of the insulator. Thus, as the helium metastable interacts with the surface, an electron from an occupied orbital from the surface will transfer to the helium metastable with the subsequent ejection of the 2S electron.<sup>4</sup> The two interactions of the helium metastable with a surface can be seen in Fig. 1.

In a study by Kurahashi and Yamauchi<sup>5</sup> examining desorption of hydrogen from a surface, they conclude that if the helium metastable extracts a bonding electron from the hydrogen-surface bond, the bond becomes weaker. As the bond becomes weaker, the equilibrium bond distance lengthens. This weakening and lengthening of the bond changes the potential of the hydrogen-surface bond and the hydrogen can desorb from the surface.<sup>5</sup> A similar method is theorized to be the cause for the helium metastable cleaning of organic material.

With all this in mind, a new cleaning method has been developed to compliment these traditional methods such as using a low-energy hydrogen plasma. A plasma based method to clean organic contaminants from lithographic materials is presented in this paper and demonstrates the removal of hydrocarbon particles (polystyrene latex particles in this instance) in the range of 30–50 nm as well as the

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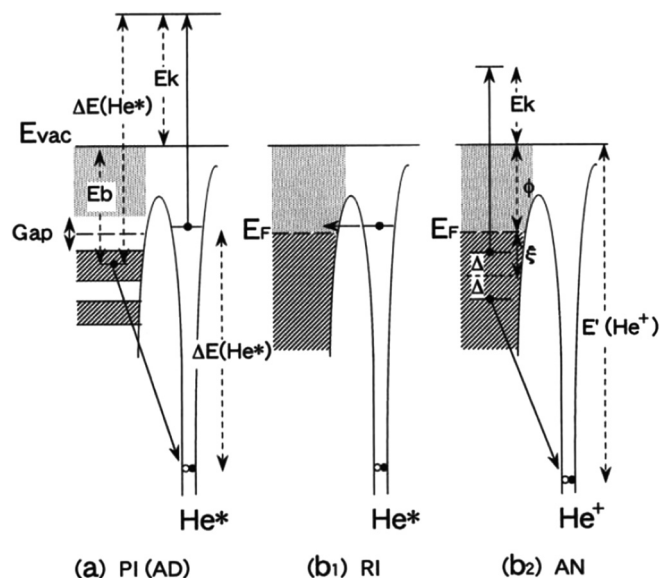


FIG. 1. Diagram for the energy transfer of metastable atoms to surfaces. (a) PI or AD on an insulator. (b) Resonance ionization on a metal. (c) Auger-neutralization on a metal (Ref. 4).

removal of 30 nm carbon film layers on silicon wafers. This method is called plasma-assisted cleaning by metastable atom neutralization (PACMAN).

## II. EXPERIMENT

The PACMAN experimental setup consists of a main chamber that houses the substrate. A  $m=0$  helicon source is used to produce the helium plasma. Helium is used due to

the fact that it has a low sputtering threshold on lithographic material due to its low mass and no chemical interactions. The substrate can be DC biased in either a steady state or a pulsed mode. The system is capable of processing a full 150 mm  $\times$  150 mm wafer. A load lock is used to load and remove the sample from the main chamber. This allows the integrity of the vacuum to be maintained and also for speed of processing the samples. A schematic of the PACMAN chamber is shown in Fig. 2.

Particle contamination is done by polystyrene latex particles obtained from Duke Scientific in aqueous solution, the chemical formula is  $C_8H_8$ . The test surface is made from N-type (phosphorus doped) silicon made by Addison Engineering. The wafers have a diameter of 25 mm and a resistivity from 1 to 10  $\Omega\text{cm}$ .

The removal rate is measured by taking an SEM of a region of interest on the wafer after the particles have been deposited. The diameter of particles is measured and a minimum of four particles are used. After the wafer has been processed through PACMAN, another SEM is taken postprocessing of the same region and the diameter of the particles measured. The difference between the particle diameters allows a removal rate to be determined.

## III. THEORY

Typically, when plasma is used in experiments, only the ions and electrons play an important role. However, energetic neutrals and metastables form a large component of any plasma. A metastable is an atom that is in an energy state that is quantum mechanically forbidden through

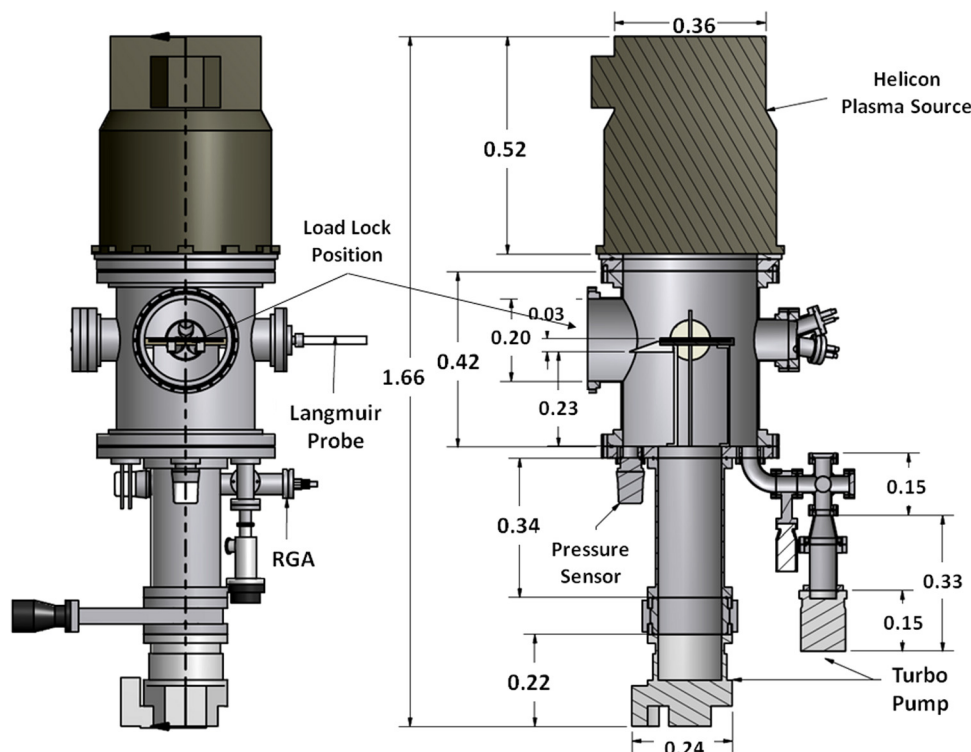


FIG. 2. (Color online) PACMAN chamber. The  $m=0$  helicon plasma source is in black on the right. Directly below it is the main chamber that holds the substrate. To the left is the load lock mechanism that allows the sample from being moved in and out without breaking vacuum. All dimensions shown are in meters.

conservation of momentum to decay into the ground state. Helium has two metastable states: a singlet,  $2^1S$ , and a triplet,  $2^3S$ . The energy level of the singlet is  $E_2I_S = 20.6$  eV and the triplet  $E_23_S = 19.8$  eV.<sup>6,7</sup>

The PACMAN process is based on three important mechanisms. One is the metastable density which plays the important role of introducing electronic holes in the surface by breaking bonds, second is the electric field, which maintains the broken bonds at the surface of the particle, and third the electron flux to the surface keeps broken bonds from reforming.

### A. Metastables

The density of helium metastable atoms in the plasma can be modeled through a collisional radiative model. In this type of model, it is possible to track the population and decay of higher energy levels of the helium atom that would result in a metastable atom in the  $2s$  singlet or triplet levels. The number of higher energy states to track depends on the complexity necessary to capture the major collisional and radiative processes. The extent to which the higher energy levels will be used to determine population states of the lower energy levels needs to be limited to some finite value based on the probability of the reactions. For this collisional radiative model, states up to and including the  $3s$  and  $3d$  state are used to calculate the population of the excited levels in the helium plasma.<sup>8</sup>

The resulting metastable densities in Figs. 3 and 4 show an increasing trend in density as electron temperature increases as well as operating pressure increases. At slightly greater than 100 mTorr, a decrease in the population of the metastable states is predicted indicating a transition between a plasma dominated by metastable loss to the wall to

destruction from neutral collisions as well as less metastable production due to increasing electron–neutral collisions. Measurements of singlet He metastable densities at high pressures in hollow cathode and Penning discharges have been done by Andruczyk *et al.*<sup>9</sup> Using an atomic absorption spectroscopy technique, those measurements showed that the metastable density increased with helium density up to a critical point, in this case around 800 mTorr, where collisional processes started to take over and the metastables lost energy through these collisions, thus seeing a dramatic reduction in the density of  $n_2I_S$  beyond that. The theoretical results rely heavily on assumptions made for electron density and temperatures as no Langmuir probe data were acquired in this pressure range. Thus, the graphs have been truncated at 100 mTorr as measured data and thus accuracy for the theoretical predictions in this pressure range are more reliable.

This model, while it calculates the singlet and triplet metastable densities, is only accurate for the specific input parameters, namely operating pressure, electron density, ion density, and electron temperature. Thus, reliable measurements of the input parameters are required to yield accurate results.

### B. Electric field

To calculate the electric field in the plasma sheath, Poisson's equation is used with three assumptions: the first is that electron density in the sheath is zero,  $n_e = 0$ . The second assumption is that the ion density,  $n_i$ , varies in the sheath from the potential variation, and that the energy of ions is zero at the plasma/sheath boundary,  $x = 0$  (Ref. 10)

$$\nabla^2 V = -\frac{en_i}{\epsilon_0}. \quad (1)$$

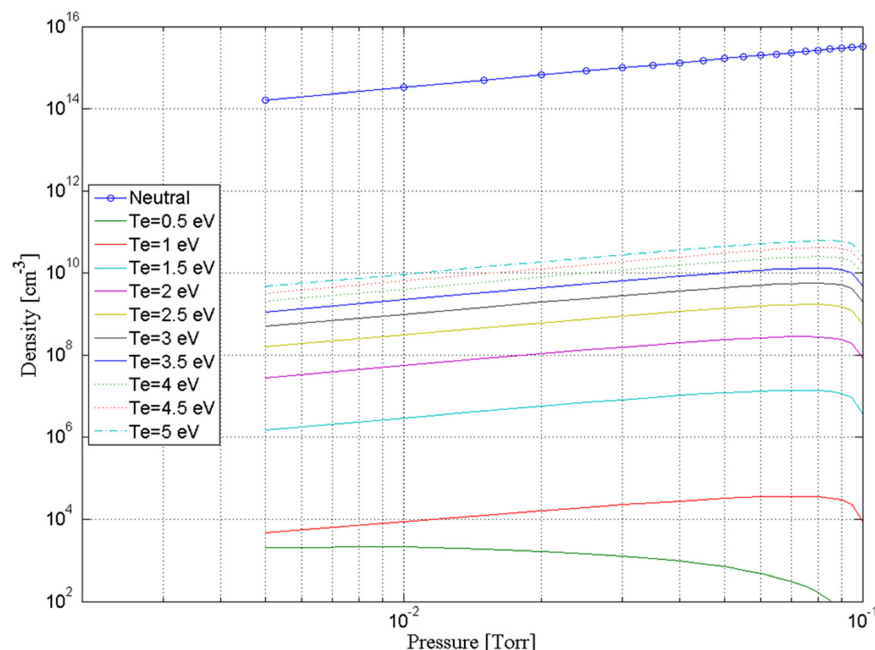


FIG. 3. (Color online) Singlet metastable density vs pressure accounting for transition into the metastable state from higher energy levels as well as allowing for ion, electron, and pressure variations.



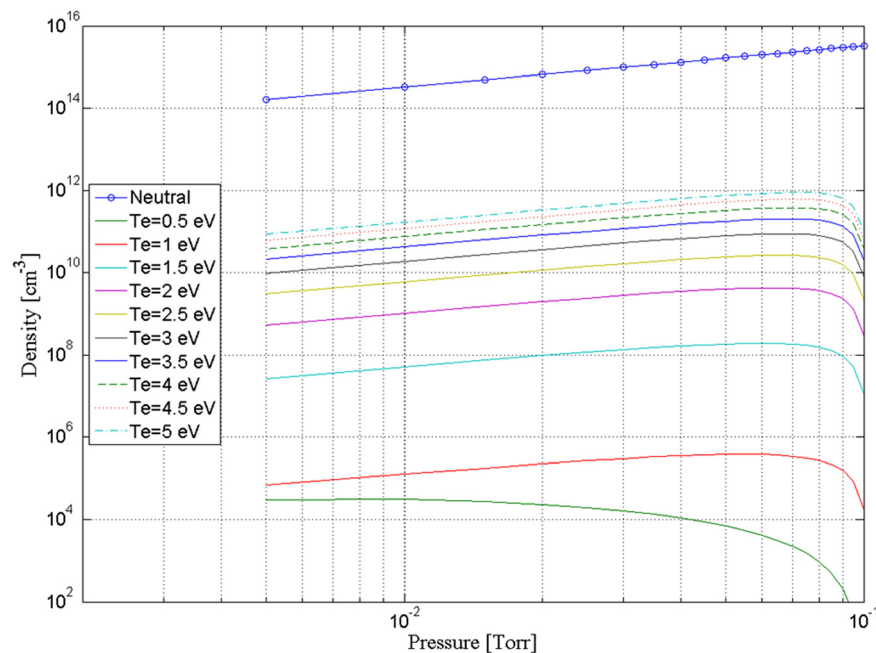


FIG. 4. (Color online) Triplet metastable density vs pressure accounting for transitions into the metastable state from higher energy levels as well as allowing for ion, electron, and pressure variations.

Applying the assumption that  $n_e = 0$  in the plasma sheath, where  $e$  is the elementary charge, ion density variation in the plasma sheath varies according to (Ref. 11)

$$n_i(x) = \frac{j_{i,0}}{e} \left( -\frac{2eV}{m_i} \right)^{-1/2}, \quad (2)$$

where  $J_{i,0}$  is the constant ion current and  $m_i$  is the ion mass.

One could continue on to calculate the potential versus location in the plasma sheath; however, knowing that  $E = -(dV/dx)$ , the electric field in the plasma sheath has been derived without making the assumption that  $V_{plasma} - V_{wall}$  is  $\ll T_e$ . The electric field in the plasma sheath region is thus

$$E = -2 \left( \frac{j_{i,0}}{e_0} \right)^{1/2} \left( \frac{2e}{m_i} \right)^{-1/4} (|V|)^{1/4} \pm (V). \quad (3)$$

The value of potential,  $V$ , used is the potential with respect to plasma potential, which is found by  $V_{wall,bias} - V_{plasma}$ . The term  $\pm(V)$  is used to denote the direction of the electric field. When the electric field points from the plasma into the surface [when  $V$  in Eq. (3) is negative], this is considered a positive electric field. When the electric field points from the surface into the plasma [when  $V$  in Eq. (3) is positive], this is considered a negative electric field. One conclusion apparent from the result derived in Eq. (3) is that the electric field does not depend on the location within the sheath. Thus, the electric field is considered constant throughout the plasma sheath.

The electric field directed into the surface encounters a perturbation when there is a particle in the way. If the particle was a conductor, it would set up an internal field to cancel the applied field from the plasma sheath due to the ability

of mobile charge carriers to adjust in the conductor.<sup>12,13</sup> However, a dielectric particle can only partially cancel the applied field. To model the electric field inside the dielectric particle, one can solve Laplace's equation for the potential inside and outside of the sphere as a boundary layer problem. The resulting equation is

$$\vec{E} = \frac{3}{\epsilon_r + 2} \vec{E}_0. \quad (4)$$

This result then shows that the electric field inside the particle is uniform and reduced in magnitude compared to the original electric field,  $\vec{E}_0$ .

### C. Electron flux

Electron flux to the surface is dependent on the densities of electrons in the plasma as well as the velocity of the electrons. Assuming a Maxwellian energy distribution for the electrons in the plasma assisted cleaning by electrostatics helicon plasma source, the flux of electrons to the surface is given as<sup>10</sup>

$$\Gamma_e = \frac{1}{4} n_e v_e, \quad (5)$$

where  $n_e$  and  $v_e$  are the electron density and velocity, respectively.

## IV. RESULTS

### A. Particle removal versus time

Figure 5 shows the time evolution of particle removal in a step wise fashion as well as the surface area of the particle. The points labeled "single tests" were run for 1 min increments with an air interval of at least 5 min between

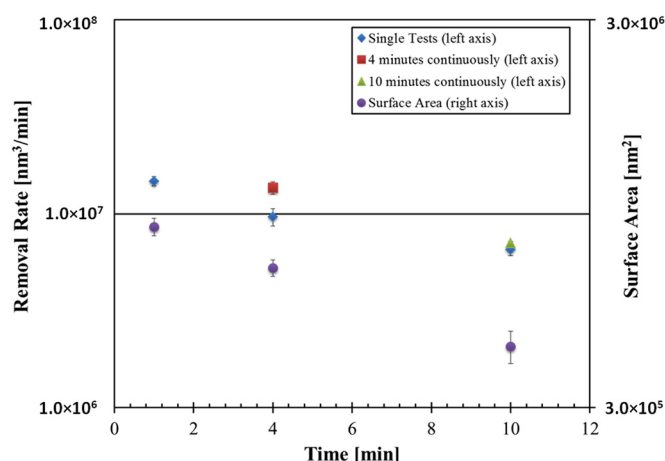


FIG. 5. (Color online) Graph of the removal rate measured vs processing time. As evident, the removal rate decreases with processing time. Plasma conditions: 2 kW plasma, 10 mTorr He, 100 SCCM.

subsequent experiments. After 1, 4, and 10 min of processing, images were taken of the sample of the same particles in order to determine removal rate via SEM. Then, two separate experiments were conducted in which samples were run for 4 min continuously and 10 min continuously. From Fig. 5, it can be seen that the removal rate remains relatively constant between the single tests and the tests run continuously, with the removal rate decreasing as total processing time increases. The decrease in the removal rate shown in Fig. 5 leads to the conclusion that some type of flux to the particle affects the removal rate. This is why removal rates are quoted in volumetric terms. As a particle shrinks, it has a variable surface area.

## B. Particle removal versus bias

As bias to the sample is increased positive with respect to ground (toward plasma potential), the electron flux to the surface as well as the electric field in the plasma sheath increase.

Figure 6 shows the results of increasing sample bias positively with respect to ground. An increase in the removal

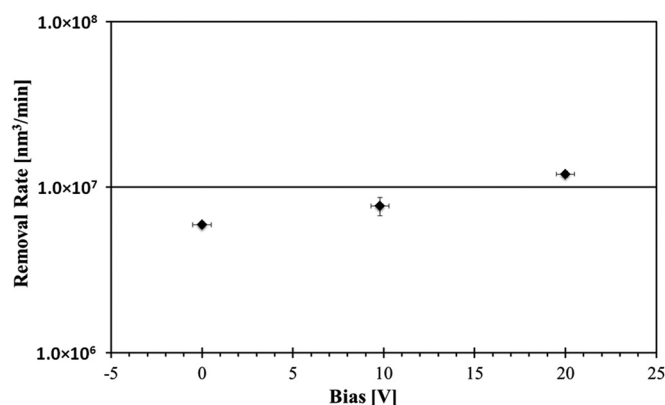


FIG. 6. Removal rate measured for three positive biases applied to the sample. The three biases are +20.1 V at 58.6 mA, 8.9 V at 14.26 mA, and 0 V at 0.54 mA. The removal rate is highest for the largest electron current drawn through the wafer and decrease with wafer bias. Plasma conditions: 2 kW plasma, 10 mTorr He, 100 SCCM.

rate is observed as positive bias is increased. This positive bias modifies two parameters relating to the plasma, the electric field in the plasma sheath as well as the electron flux to the surfaces being cleaned. It should be noted that the positive bias is done such that the plasma potential does not change. This is achieved by having a separate larger electrode that sets the plasma potential while allowing the sample to be biased.

Figure 7 shows the removal results of polystyrene latex (PSLs) from silicon wafers with the calculated electric field in the plasma sheath. As the electric field is changed to point less from the plasma into the surface (changing from positive to negative in the table), the removal rate increases.

## C. Effect of helium metastable density on removal

From experimental measurements and theoretical calculations, the metastable density at the sample level decreases with increasing operating pressure. The metastable density was measured using a metastable probe built in-house.<sup>8</sup> This is shown in Fig. 8. Measurements were done that show as pressure increases the metastable density decreases. With the mean free path becoming smaller at higher pressures, the increased probability of collisions with other elements in the plasma where a metastable will lose its energy increases. This in fact is something that has been observed by others in penning and hollow cathode discharges.<sup>9</sup> Having a population of helium metastable atoms is necessary but not sufficient for the removal of the hydrocarbons. A mesh was placed around the sample which shielded the plasma out; however, it still allowed metastable atoms to permeate through, since they are electrically neutral. UV photons from the boundary region of the plasma that exists around the mesh will also reach the samples. The set up is shown in Fig. 9. Removal rates were negligible with this, showing that aside from the metastables and UV that reaches the samples, the electric field and electrons were also needed.

Figure 10 shows the result of experiments run at varying operating pressures. Eight samples were tested in total, four with the sample and sample holder left floating and four

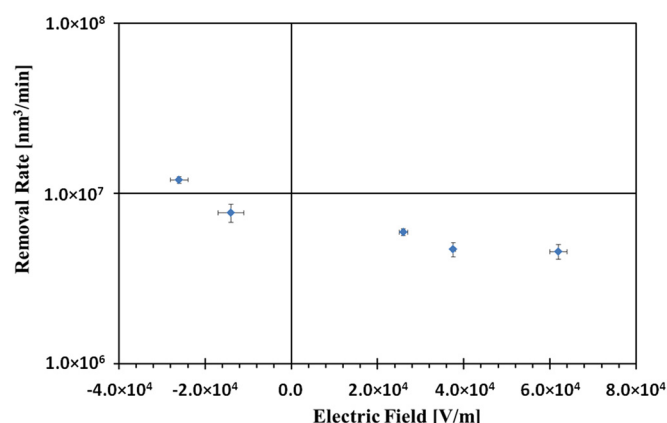


FIG. 7. (Color online) Removal rate vs the calculated electric field in the plasma sheath. As the electric field points less in the direction of the surface and more toward the direction of the plasma, the removal rate increases. Plasma conditions: 2 kW plasma, 10 mTorr He, 100 SCCM.

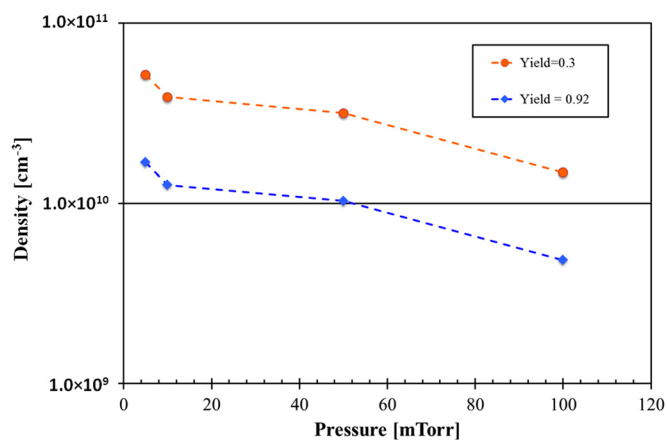


FIG. 8. (Color online) He metastable measurements with increasing pressure. The decrease in the metastable density is from energy loss through collisions with other species in the plasma and background gas. Plasma conditions: 2 kW plasma, 100 SCCM.

samples under a constant +9.8 V bias. The floating experiments show a general decrease in removal rate as the operating pressure is increased in the vacuum chamber. The experiments with a +9.8 V bias to the sample show a decrease in removal rate with increasing operating pressure. Note that the main chamber is remote from the plasma source, and its walls stay at room temperature, so we feel confident that the neutral gas density is proportional to the pressure.

To explain the behavior of the removal results in Fig. 10, several parameters between the plasma and sample interaction change. First, consider the floating sample data. The electric field of the plasma for the “floating” cases points from the plasma into the sample, with the electric field at 5 mTorr calculated as  $3.59 \times 10^4$  V/m, at 10 mTorr calculated as  $3.70 \times 10^4$  V/m, and at 50 mTorr calculated as  $2.63 \times 10^4$  V/m. As shown in the Sec. IV B, an electric field that points from the plasma into the sample and is increasing should decrease the removal rate. An increase of the electric field pointing from the plasma into the sample is what is calculated from the 5 to 10 mTorr case, and a reduction in the cleaning rate is also observed. However, at 50 mTorr, the

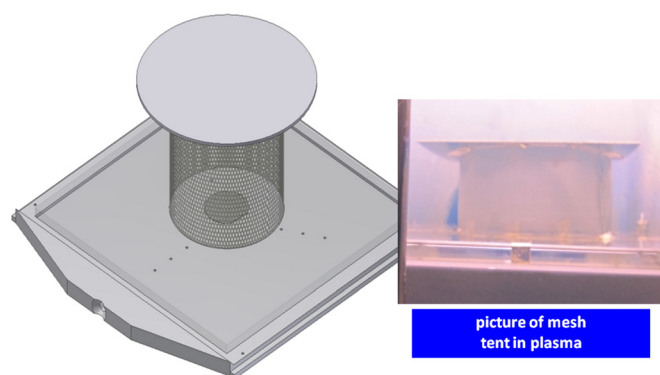


FIG. 9. (Color online) Mesh set up to screen out the ions and electron from the sample; it only allowed the metastable to penetrate into the mesh and onto the sample. With metastables only, a negligible removal rate was observed.

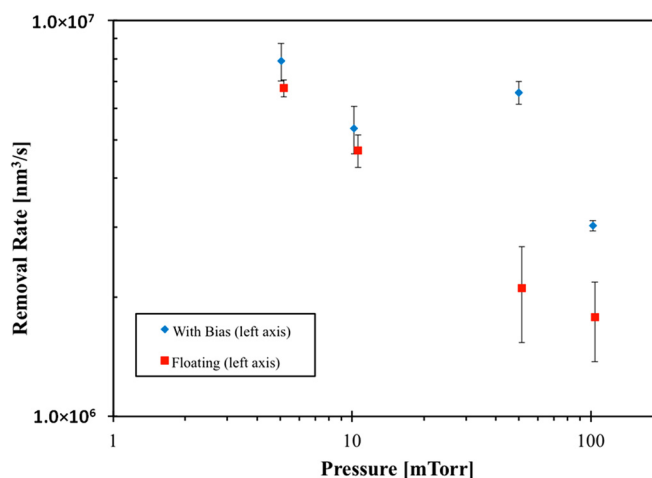


FIG. 10. (Color online) Removal rate vs operating pressure. A decrease in removal rate is observed with increasing pressure.

electric field pointing from the plasma into the sample decreases, but a decrease in the removal rate is still observed. One item to note is that plasma density measured with a Langmuir probe at the sample level does decrease from 10 to 50 mTorr. For increasing pressures up to 100 mTorr, plasma density does continue to decrease as well as metastable density. From the result of the analysis of the floating sample data in Fig. 10, the conclusion is drawn that the decrease in the removal rate seen is due to a decrease in the plasma density (electron flux) as well as metastable density versus increasing operating pressure.

Considering the “with bias” data in Fig. 6, a  $+9.8 \pm 0.5$  V bias is applied to the sample. From the trend observed in Fig. 6 for the data with bias, it is concluded that even though the helium metastable density decreases with increasing operating pressure, it is still of sufficient density that when a sample bias and thus increased electron current draw is used, removal rate does not decrease appreciably for increasing operating pressure up to 50 mTorr.

#### D. Effect of ion flux

Sputtering of a material is due to the incident ion flux being able to remove atoms from the top surface. An experiment involving an electromagnet, schematically shown in Fig. 11, was able to select ions to the sample while removing electrons, was used to study the effect the ions had on removal. With higher energy ions selected, a removal rate of  $4.6 \times 10^6 \pm 1.7 \times 10^5$  nm³/min is measured. As the energy decreases, the removal rate starts to increase. Eventually with no ions present on the sample, the removal rate was very high  $1.2 \times 10^7 \pm 1.1 \times 10^5$  nm³/min.

A couple mechanisms account for this trend that is seen. Metastable atoms were still present when the ions were incident on the sample. First is that the helium ions have a low sputtering rate and second they do liberate hydrogen out of the hydrocarbon lattice; thus a carbon layer is formed which does not allow the metastables to have as much of an impact since the energy required to break the bonds is higher. The removal slows down and the rate is reduced. With no ions



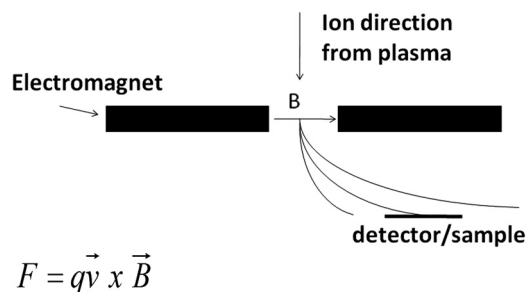


FIG. 11. Ion flux experiment; this showed that by removing ions from the sample, the removal rate was significantly increased.

there, the metastables are able to break the C–H bonds much more easily.

The reduced removal rate due to the carbon bonds has been seen in experiments involving a carbon film. At Illinois, a carbon film, approximately 22 nm in thickness, was grown on a silicon substrate. This was a carbon film with few hydrogen bonds, similar to what has been described above with the ions knocking out the hydrogen's and leaving a pure carbon surface. With the application of the PACMAN process (2 kW at 10 mTorr) for 1 min, a cleaning rate of the carbon film of 11.4 nm/min was achieved, shown in Fig. 12. Compare this to results if only PACMAN and sputtering yields calculated by stopping and range of ions in matter are used for 70 eV He on C at normal incidence, the removal

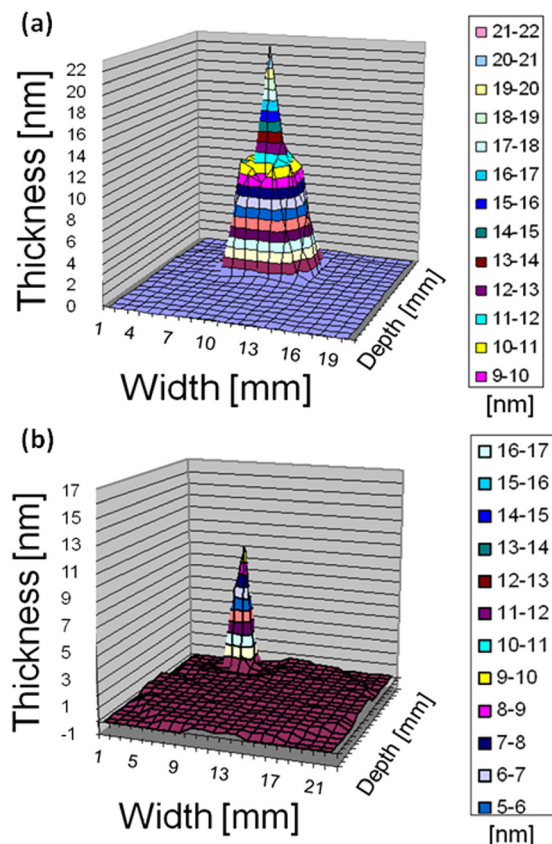


FIG. 12. (Color online) Images show the result of cleaning a carbon sample with the standard PACMAN cleaning technique. Carbon thickness was (a) 22 nm and was cleaned for 1 min. The resulting thickness was (b) 10.6 nm. A cleaning rate of  $-11.4 \pm 3$  nm/min was achieved.

rate from sputtering alone is at most 6 nm/min and likely much lower. A more sophisticated code, TriDyn,<sup>14</sup> gives an eight times smaller sputtering yield and thus a removal rate of  $\sim 0.75$  nm/min. Increasing negative bias, and thus increasing the sputtering only, increases removal yield slightly.<sup>8</sup> In addition, ion sputtering alone takes the spherical particles and flattens them as they shrink from the top down. In these experiments, particles were seen to retain their spherical shapes as their radii grow smaller and eventually disappear.

## V. DISCUSSION

There are two main ideas to take from the results presented in Sec. IV. The first is that the decrease in removal rate observed versus increasing operating pressure is a combination of metastable density change, plasma density (and thus electron flux) changing, as well as electric field changing. The second is that an applied bias to the sample will increase the removal rate seen with increasing operating pressure compared to the removal rate of a floating sample.

Two experiments were conducted to test for the removal of PSLs without plasma interacting with the sample but

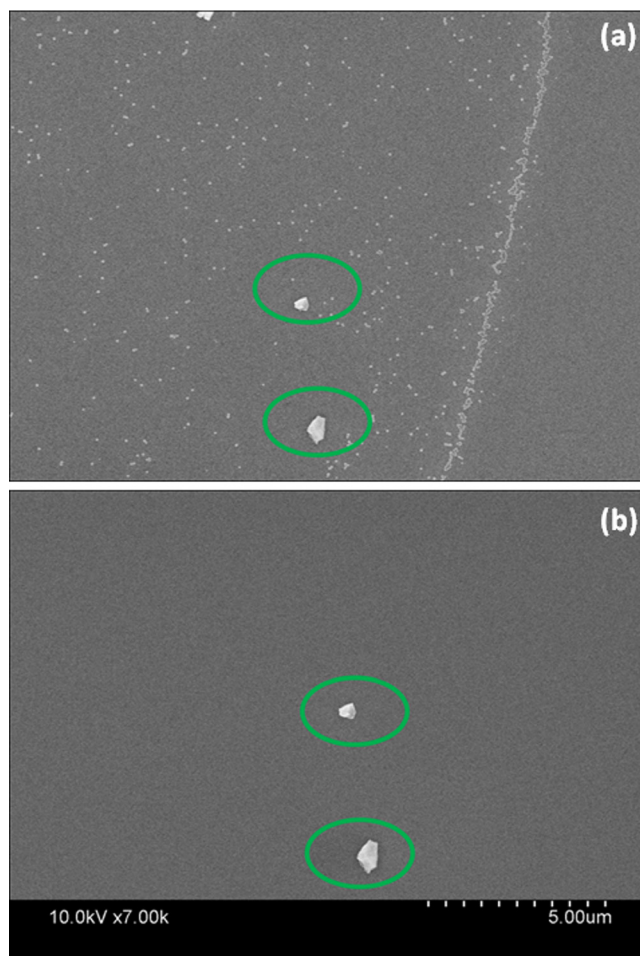


FIG. 13. (Color online) SEM images of the PACMAN process at work. Image (a) shows a surface with pellicles on the surface. Image (b) shows the same surface after 10 min of treatment. The large objects in the center are some other debris and used as a reference. Plasma conditions: 2 kW plasma, 10 mTorr He.



TABLE I. Overview of the components of the plasma and their respective effect on the removal mechanism.

Component	Comment
Processing time	Removal rate vs time decreases with time, since the surface area decreases
Electric field	Decreasing $E_{field}$ into surface raises removal rate; keeping holes at the surface increases removal
Electron flux	Electron flux alone does not provide removal
Ions	Elimination of ions altogether increases the removal of rate by not densifying the surface
Metastables and UV	Metastable and UV flux alone does not provide removal
Temperature	Temperature is a byproduct of plasma interaction, but temperature alone does not increase removal

while the sample was under a positive bias and drawing electron flux. A plasma-blocking mesh was used to block the plasma from reaching the lower half of the chamber while allowing for the helicon plasma source to operate normally. Tested were a  $+5.2 \pm 0.5$  V bias drawing  $0.4 \pm 0.1$  mA of current and a  $+9.8 \pm 0.5$  V bias drawing  $0.8 \pm 0.1$  mA of current. Both experiments showed a negligible removal rate. The combination of the mesh setup is 4.7% transparent, so a reduced cleaning rate, if any would be expected, since metastable production from the source region would also have to diffuse to the wafer. In order to achieve a higher removal rate to test whether or not particle removal occurs with helium metastables and a positive bias, an indirect plasma-based method of helium metastable production or other source would be needed that does not require for the plasma to be screened out, which ultimately limits the metastable throughput. Such a design could likely be accomplished with similar technology to an ion or electron gun.

In Fig. 6, the current drawn for the grounded sample (+0 V bias) and sample holder was 0.54 mA which is on the same order as the current drawn in the positive bias removal tests with the plasma-blocking mesh in place. This leads to the conclusion that electron flux alone in a 10 mTorr helium environment does not lead to particle removal and it is the electric field pointing toward the plasma that keeps holes at the surface and bonds broken. The right-most two points in Fig. 6 are at potentials above the plasma potential thus having an electric field which keeps holes at the surface. These are also the points of higher removal.

In Fig. 13, SEM images have been taken to show the actual removal of the pellicles from the surface. The top image shows the silicon surface with polystyrene on the surface. The large object on the left hand side is used as some silicon particle and is used as a reference. The bottom image shows the same surface after having been run through the PACMAN process for 10 min. It is clear to see that the particles have been removed from the surface.

Table I summarizes the separate components of the plasma and their effect on the removal of contaminants. Note that the plasma and gas is optically thick for UV photons so their effect is small.

## VI. SUMMARY AND CONCLUSIONS

The PACMAN cleaning technique removes contaminants from the surface through a combination of helium metastable impacts, electric field effects, and electron flux to the surface.

As helium metastables interact with the surface, they create electronic “holes” in the surface. To limit diffusion of these holes into the bulk of the contaminant, an electric field pointing from the surface of the contaminant into the plasma is necessary to maintain the holes near the surface of the contaminant so volatilization of the particle can be achieved. Electron flux to the surface helps maintain the broken bonds from reforming, allowing for the continued removal of the particle.

The removal results provide clear evidence that the variables of helium metastable density, electron flux, and electric field in the plasma sheath region are important parameters needed in order to achieve removal of the polystyrene latex nanoparticles. Through sample bias and plasma source power, the above parameters can be varied in order to change the rate of particulate removal seen in this investigation.

The removal rate of contaminants is observed to decrease with processing time. As the contaminant is being removed and becoming smaller, the surface area of the particle decreases. Without any modification to either the metastable helium flux or electron flux, the number of metastables and electrons interacting with the contaminant decreases thus leading to a theoretical decrease in the removal rate.

The conclusion that eliminating ions from the sample is beneficial for the PACMAN cleaning technique is derived from the experiments involving sample bias, as increasing the bias positively with respect to ground toward plasma potential yields a higher removal rate.

It was shown that modifying the electric field through the application of positive bias to the sample creating an electric field that points from the surface being cleaned into the plasma yields a higher removal rate.

From experiments that utilized electron flux only in a helium metastable environment, the conclusion is drawn that just electron bombardment of the sample is not responsible for the removal of contaminants. Also, the density of helium metastable atoms in the plasma was shown to affect the removal rate.

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