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Coupling of a vacuum-ultraviolet-radiation source to a processing system

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A hollow capillary array is examined as a coupling window between an electron cyclotron resonance plasma vacuum ultraviolet (vuv) source and a separate processing chamber. The transmission of vuv through the capillary array as a function of wavelength is measured and shown to agree with theoretical calculations. A silicon wafer with a dielectric surface is then placed in the processing chamber and exposed to vuv, both with and without the capillary array. A Kelvin probe is used to measure the surface charge induced on the wafer by photoemission in both cases, which confirms the previously measured transmission values. The results show that a capillary array can efficiently couple vuv radiation from a source to a processing chamber without significant modification in the spectrum and its resulting effects on a material. © *2006 American Institute of Physics*.
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I. INTRODUCTION

Plasma processing is a staple in the semiconductor industry, used in fine-line pattern definition, selective processing over topography, planarization, and resist stripping.[1] During such processing, materials are often exposed to plasma-generated vacuum ultraviolet (vuv) radiation, which, depending on its energy, may have several effects on dielectric surfaces exposed to the radiation. The chief effects are (1) photoconductivity produced by electron-hole pair production, (2) photoinjection from the underlying substrate, and (3) photoemission.

The goal of this work is to examine the effectiveness of coupling a supplemental vuv source into a plasma-processing reactor. Previous work has shown that vuv radiation may have a synergistic effect on plasma damage and has the potential to reduce charge buildup on dielectric surfaces.[2] We use, as a model system, an electron cyclotron resonance (ECR) plasma source which is one of many plasma sources that can produce vuv radiation. In order to expose dielectric surfaces to supplemental vuv radiation, yet keep the ECR vuv source separate from a processing system, a coupling window must be used between two different chambers. Capillary-array windows with broad spectral transmission bandpass and proven durability have been successfully used in the past to satisfy such requirements.[3] A capillary-array window has a number of distinct advantages, especially if the vuv source operates at a different pressure from the processing system. The capillary array allows differential pumping[4] while still permitting a vacuum connection between the two systems without significant vuv absorption which is a characteristic of solid windows such as LiF or MgF in this portion of the spectrum.

This work focuses on measuring and comparing the effects of vuv radiation passing through a port joining the vuv source and the processing system incident on a dielectric surface with and without the presence of a capillary-array window. The calculated and measured values of vuv transmission as a function of photon energy will be compared as the operating parameters of the ECR vuv source are changed.

II. CAPILLARY ARRAY

To determine if the capillary array is suitable for vuv coupling, two parameters are needed. They are (1) the pressure differential that can be supported on each side of the array and (2) the vuv transmission through the array as a function of photon energy. The glass-capillary array used in this experiment was donated by Lucatorto of NIST. Figure 1 shows a microscope photograph of the capillary array. The thickness of the array was measured using an infrared micrometer and found to be 1 mm. The hole diameters are approximately 20 μm. The hole density, which is the number of holes per unit area, is approximately 1300 holes/mm^2. The open area, defined as the ratio of the hole area to total array area, was estimated from the photograph to be 53%.

To calculate the pressure drop through the capillary-array window, it is necessary to calculate the conductance of the window.[5] The total conductance of the capillary-array window is given by[3]

$$C = \varepsilon A\left(\frac{D}{L}\right)\left[\frac{P_{\mathrm{av}}D}{32\eta} + 4\frac{K}{\pi}\left(\frac{1+K_1P_{\mathrm{av}}D}{1+K_2P_{av}D}\right)\right] \quad \mathrm{cm}^3\ \mathrm{s}^{-1}, \quad (1)$$

where $K=\pi^{1/2}/6(2kT/m)^{1/2}$ cm/s, $K_1=1/\eta(m/kT)^{1/2}$ (μbar $\times$cm)$^{-1}$, and $K_2=1.24K_1$. m is the molecular mass of the feed gas, D is the diameter of the holes in the array, L is the length of the holes in the array, η is the viscosity of the feed gas, P_{av} is the average pressure of the gas on both sides of the capillary array, and kT is the thermal energy of the gas. We assume that the gas on either side of the capillary array has the same thermal energy. ε is defined as the ratio of open area to the total area of the array.[3] For the capillary array

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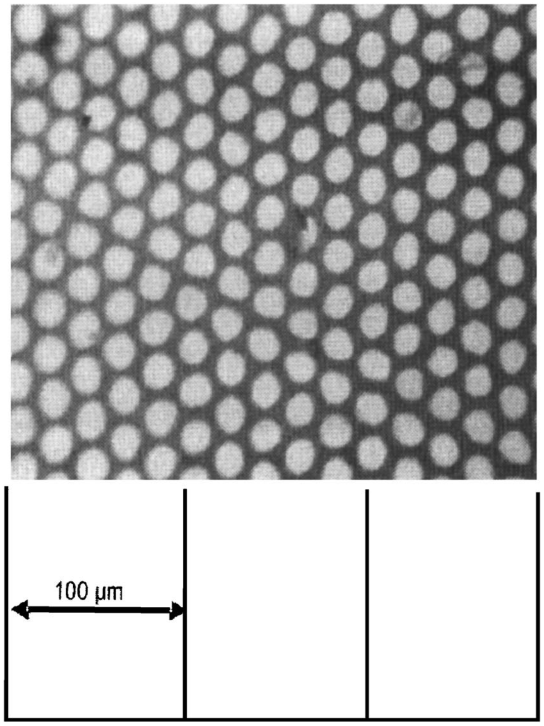

FIG. 1. Microscopic photograph of capillary array.

used here and its expected operating conditions, the conductance was computed to be 0.21 l/s which remained roughly constant over the normal range of operation of the system.

III. MEASURED PROPERTIES OF THE CAPILLARY-ARRAY WINDOW PLACED BETWEEN A vuv SOURCE AND A PROCESSING CHAMBER

Figure 2 shows the experimental setup in which we use the capillary array. The vuv is generated from an ECR plasma source which then passes through a coupling orifice into a separate processing chamber. In the ECR source, a 2.45 GHz, 2 kW microwave generator was coupled along the axis of the vacuum chamber through a quartz window. A turbomolecular pump was connected at the opposite end of the vacuum chamber. A mass-flow controller provided argon gas feed. The capillary-array window was mounted in a port that connects the ECR vuv source chamber with a small processing chamber. The opposite side of the small processing chamber was connected to a vacuum monochromator, which can measure spectra for wavelengths between 500 and 3000 Å.

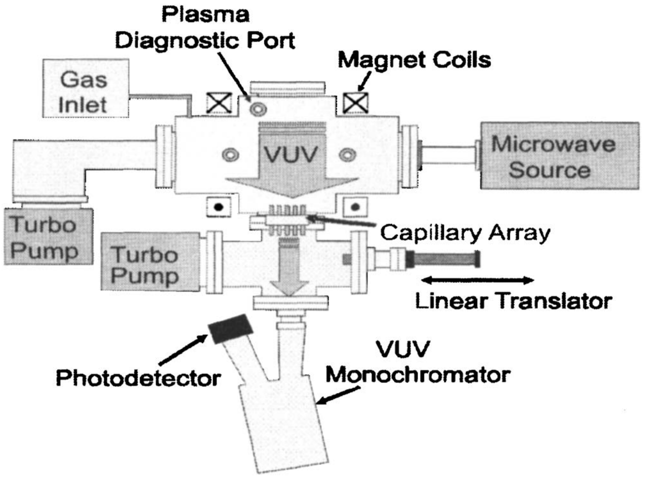

FIG. 2. Electron Cyclotron vuv source.

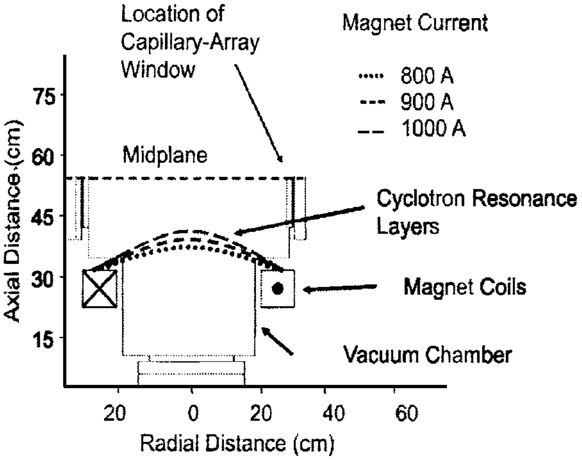

FIG. 3. Resonance locations in the ECR chamber.

To examine the variation in the vuv spectra as well as vuv transmission through the capillary array as a function of ECR source parameters, the following quantities were varied: (1) cyclotron resonance location (which is a function of the magnet current) within the ECR vacuum chamber, (2) ECR system gas fill pressure, and (3) incident microwave power.

First, the change in the vuv spectrum as the location of the resonant layer varied was measured. This was accomplished by varying the dc magnet current. The resonance occurs where the dc magnetic field is 875 G. Figure 3 shows how the 875 G magnetic surface moves with varying magnet current. As the magnet current increases, the resonance location moves closer to the midplane of the chamber.

The resonant layer was fixed at three locations corresponding to magnet currents of 800, 900, and 1000 A. Figure 3 shows that the resonant layers are curved and therefore their location was specified by indicating the point of closest approach of the layer to the midplane of the vacuum chamber. Thus, using this convention, the layers were located 20, 17, and 15 cm from the midplane when the magnet currents were set to the values specified above.

Figure 4 shows the measured vacuum ultraviolet spectra for the above conditions. Two argon peaks at 1066 and 1048 Å are shown. The maximum intensity of these peaks occurs at a magnet current of 1000 A, which is expected because the resonant layer is closest to the midplane where the capillary-array window is located. It should be noted that it was not possible to increase the magnet current beyond 1000 A due to power-supply limitations.

To determine the effect of pressure variation on the vuv spectrum, the incident microwave power was set to 500 W while the pressure inside the chamber was varied from 11 to 23 mTorr with the location of the cyclotron resonant layer set at 15 cm from the midplane. It was found that the maximum intensity of the 1066 Å line occurred at a pressure

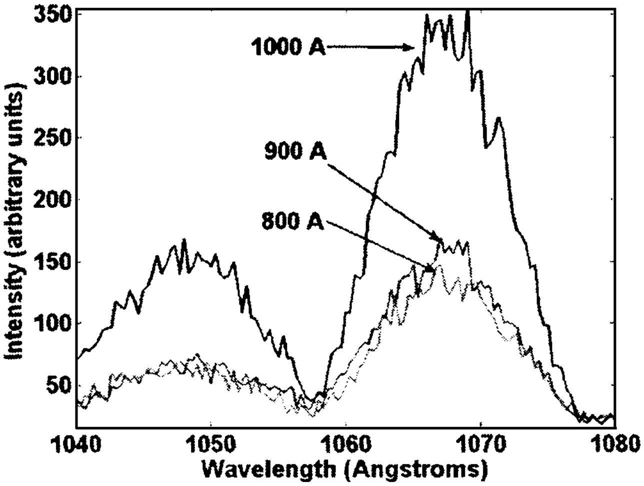

FIG. 4. Argon spectra as the resonance location was moved.

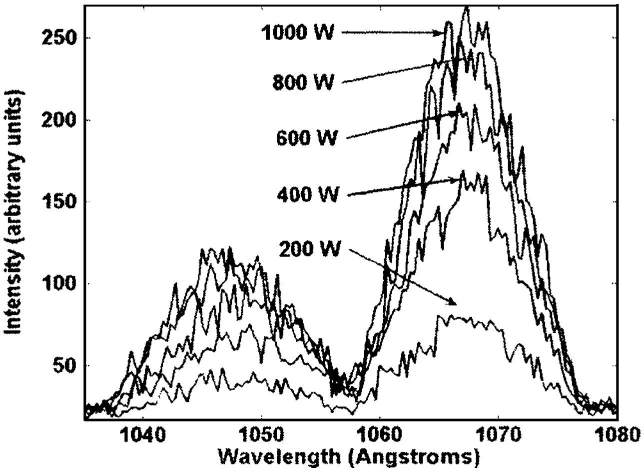

FIG. 6. Argon spectra for varying microwave power.

of 19 mTorr, as seen in Fig. 5. The peak-height ratio of the 1066 to the 1048 line is also a function of pressure, and, as to be expected, increases at the higher pressures since the plasma temperature decreases at higher pressures.

The operating pressure and location of the resonant layer were then fixed at 17 mTorr and 15 cm from the midplane, respectively, while microwave power was varied. As seen in Fig. 6, the intensity of the spectrum at all wavelengths increases with microwave power. However, it can be seen that the spectral heights do not increase linearly with respect to microwave power. This is likely since as the plasma parameters change, the plasma load on the microwave source also changes and the plasma density and temperature are not linear functions of microwave power.

Since the goal of this work is to use the ECR plasma as a supplemental source of vuv radiation fed into the processing chamber, the transmission characteristics of the capillary array must be determined when it is used as a coupling device between the ECR system and the processing chamber and compared with the transmission through the port in the absence of the capillary array. To measure the vuv transmission, the capillary array was mounted on a small aluminum plate attached to a linear translator that was placed in the small processing chamber, as shown in Fig. 7. For comparison, the aluminum plate also contained an identical opening without the capillary array. Thus, by moving the linear translator, the array or the opening without the array could be placed in front of the port joining the ECR-vuv source and the small processing chamber. This arrangement is shown in Fig. 8. For these measurements, argon plasma was produced at a pressure of 22 mTorr and 400 W microwave power with the resonant layer located at a distance of 15 cm from the midplane. When either the array or the empty opening was placed in front of the orifice, the monochromator was scanned from 1000 to 1300 Å.

Figure 9 shows the transmission comparison for vuv radiation through the orifice with and without the capillary array. As can be seen in the figure, the peak-height ratio with and without the array present remained relatively constant over all wavelengths and was found to be approximately 47%. The theoretical transmission value for the capillary array was calculated using ray optics to be 40%[6] which is in good agreement with the experimental results.

By tailoring the vuv spectrum so that photon energies are greater than the sum of the band gap and electron affinity energies of a dielectric layer, it is possible to generate photoemitted electrons which produce a positive surface charge on the dielectric. To measure this, a 3000 Å thick oxide-

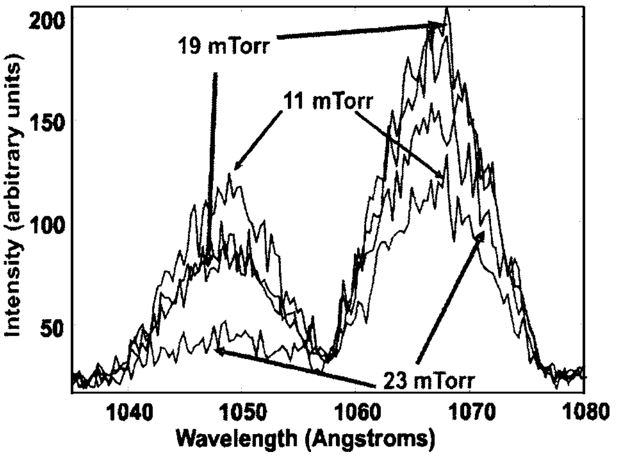

FIG. 5. Argon spectra for varying pressure. The curves are labeled with the operating pressure, except for that at 16 mTorr which is unlabeled to minimize clutter. It is readily observed that as the pressure increases, the ratio of the peak heights increases which indicates, as expected, that the plasma temperature decreases.

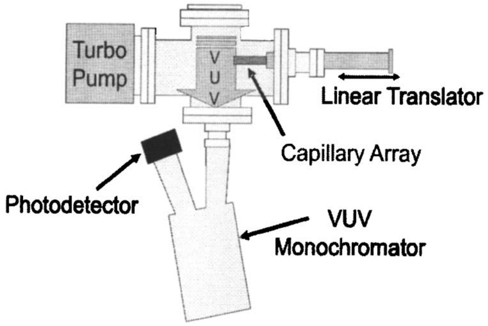

FIG. 7. Aluminum plate mounted to linear translator inside electron cyclotron vuv source.

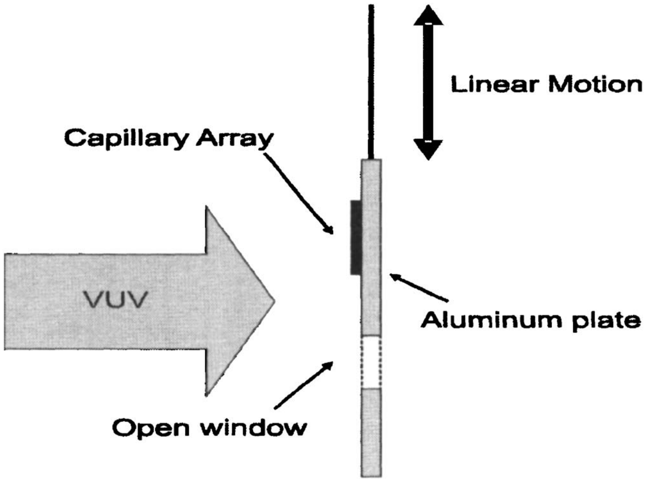

FIG. 8. Capillary mounted on movable plate for testing transmission.

coated silicon wafer was placed on a second aluminum plate which was also attached to the linear translator so that the capillary would lie between the wafer and the incident vuv, as shown in Fig. 10. Argon plasma was created at a pressure of 22 mTorr and 400 W and the location of the resonant layer was set at 15 cm from the midplane.

Two exposures were made. First, the oxide-coated wafer was exposed to vuv for 10 min in two places, one of which was in front of the capillary array and the other in front of the opening without the array. Two-dimensional surface potential maps that are generated from the residual photoemitted surface-charge regions on the wafer were measured with a Kelvin probe.[7,8] The regions of high surface potential were rectangular, corresponding to the shape of both the capillary array and the opening. From the surface potential map shown in Fig. 11, it can be seen that a higher peak surface potential was induced on the dielectric surface through the opening without the array than through the capillary array. This is likely because the capillary-array image can be considered to be a superposition of individual pinhole views, which tends to smooth out the variations seen in the open window case.

Based on these results, the vuv exposure was repeated but in this case the capillary-array region was exposed for 20 min, while the opening without the array was exposed for 10 min. From the Kelvin probe surface potential maps for this second exposure, it was seen that the charge induced in both regions was approximately equal, indicating that the transmission is roughly 50% which agrees quite well with the calculated values.

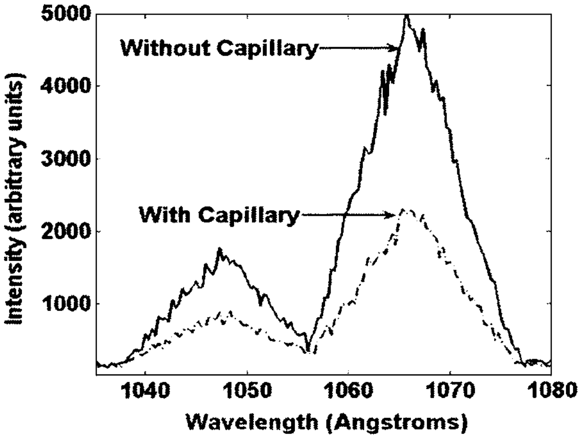

FIG. 9. Argon spectra with and without capillary array.

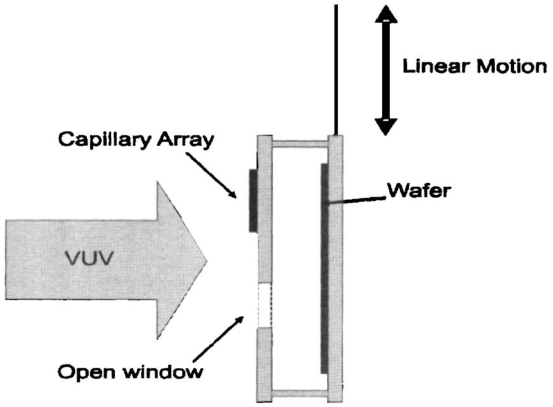

FIG. 10. Capillary and wafer mounted on movable plate for testing vuv-induced charge.

IV. CONCLUSIONS

We have shown that we can efficiently couple supplemental vuv into a separate processing chamber using a capillary array. With a vuv transmission of the order of 50%, we have shown that the vuv produces identical effects on a dielectric, e.g., photoemission and a resulting positive charge, with and without the presence of the capillary array.

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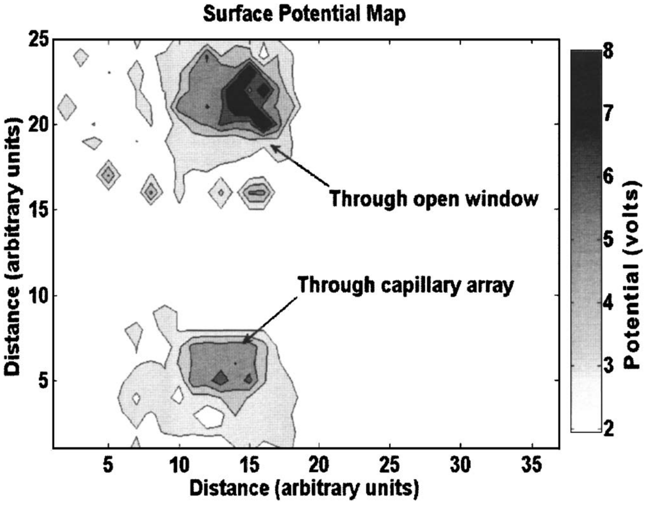

FIG. 11. Surface-potential map as measured with Kelvin probe. Both maps were obtained for the same exposure time. Note that the maximum surface potential without the capillary array is 50% larger than that obtained with the capillary array present.

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