

**Using capillary-array windows to minimize charged-particle bombardment effects
during plasma processing of thin films**

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ABSTRACT

The effectiveness of capillary-array windows to partially block charged particles in order to distinguish the effects of photon and charged-particle bombardment during plasma processing is investigated. The current drawn by a bare aluminum wafer chuck during plasma exposure for various biases is measured under three conditions: (1) bare chuck (2) chuck covered with a capillary-array window and (3) chuck covered with solid glass. From both simulation and experiment, a separation can be seen between electron current, ion current and photoemission. It is found that the capillary array blocks the majority of the charged particle flux during plasma exposure. When a negative substrate bias voltage is applied, electrons are repelled and the capillary-array window blocks a significant portion of the ion flux. Similarly, at positive biases, ions are repelled while the majority of electron flux is blocked by the capillary window. Photon transmission characteristics of the capillary-array window have been measured and the VUV transmittance is

approximately 50%. When the capillary array window is used during plasma exposure, dielectrics can be selectively exposed to VUV photons alone, or VUV photons combined with ions and/or electrons, by varying applied bias voltage. Hence, the damage mechanism on dielectrics during plasma processing can be evaluated.

I. INTRODUCTION

During plasma processing of microelectronic devices, charged-particle bombardment and photon irradiation take place.¹ These can cause damage to the dielectric material by changing the chemical structure and/or creating defects within the dielectric that can trap charge.^{2,3} In order to determine the damage levels, and the potential for curing the damage, it is essential to investigate and separate the influence of radiation and charged-particle bombardment during plasma exposure. Most of the work that has been done in this area deals with damage caused to the dielectric from the combined effects of charged-particle and photon bombardment or, by using synchrotron radiation, photons alone.⁴ It has been shown that charged-particle and photon bombardment each have distinct characteristic effects and cause different levels of damage to dielectric materials during plasma exposure.⁵ Ren and Nichols *et al.* used capillary-array windows to control the charged-particle bombardment on dielectric films during ECR plasma exposure. They reported significant reduction in surface charging and increased time-to-breakdown after plasma exposure using capillary-array windows.^{6,7}

The goal of this work is to quantify the actual effectiveness of capillary-array windows to block ion and electron fluxes during plasma exposure while letting a majority of the photon flux pass through.⁸ To investigate this, the current drawn by an aluminum wafer chuck during plasma exposure was measured. This current was then compared with that measured when the wafer chuck was covered with either a capillary-array window or solid glass.

II. EXPERIMENT

A. ECR plasma system

The plasma source used here is an electron-cyclotron resonance (ECR) system. The plasma conditions remained unchanged for each experiment: 400W of 2.45 GHz microwave power, 20 mTorr Argon neutral pressure, and 10 min of exposure time. Figure 1 shows the experimental setup. A picoammeter is used to measure the current drawn by the aluminum wafer chuck. A power supply connected to the wafer chuck inside the ECR chamber allowed for the use of a variable d.c.bias. The power supply was floated so that the picoammeter could be grounded. The setup is shown in Figure 2. The aluminum wafer chuck, 20 cm in diameter, was covered with Kapton tape for insulation except for a $1 \times 1 \text{ cm}^2$ open area that was exposed to the plasma.

B. Plasma Exposure

Three sets of exposures were made. They are: (1) the open area of the wafer chuck itself, (2) the open area covered with a 1-mm thick capillary-array window or (3) the open area covered with 2.5 mm thick Pyrex glass. The capillary-array window and glass were attached to the chuck with double-sided Kapton tape, which placed them one millimeter above the aluminum chuck as shown in Figure 2. The current drawn by the chuck as a function of the applied bias was measured for all three exposures described above. The bias voltage was varied between -40 and + 40V.

C. Capillary-Array Window and Solid glass

Capillary-array windows are commonly used in ion-energy analyzers to block stray ions.⁹ Figure 3 shows an SEM image of the borosilicate glass capillary-array window used here. The window is 2.5 cm in diameter and 1 mm thick. The holes are approximately 10 μm in diameter and the hole density is approximately 1300 holes/ mm^2 . The open area of the window is approximately 50%. Previous work has shown that the capillary-array window can pass synchrotron VUV radiation with a transmission efficiency of roughly 50%.⁸

In this ECR plasma system, both electrons and ions rotate around the magnetic field lines, which are roughly perpendicular to the capillary-array window. It must be noted that for the electron-cyclotron resonant magnetic field of 875 Gauss, (2.45 GHz) a typical argon ion orbit is about 1.8 mm in diameter. This is significantly larger than the hole diameters in the window. In addition, at the operating pressure of the ECR reactor, the mean-free path for ions is also much larger than the hole diameter. Thus, it can be inferred that nearly all of the ions that enter the capillary-array holes will collide with the walls of the

capillaries where they may be neutralized, adsorbed or reflected. If they are reflected, they will make more collisions with the walls of the capillary-array window and thus most ions are not likely to pass through the window. In addition, during plasma processing, more electrons will arrive at the walls of the capillary since electrons have higher mobility compared to ions, and build up a negative potential on the capillary surface until it reaches the floating potential.¹⁰ This negative potential on the surface of the capillary window will repel any more electrons arriving at the window. This is confirmed using a particle-in-cell simulation as will be shown in next section.

The solid glass used to cover the open area of the aluminum chuck is 2.5 mm thick borosilicate glass. This glass blocks all the electrons and ions from reaching the open area of the aluminum chuck during plasma exposure. Additionally, due to the transmission properties of Pyrex glass, UV and VUV photon flux from the plasma with energies high enough to cause photoemissive effects is blocked by the solid glass. This is discussed in detail in the following section.

III. RESULTS AND DISCUSSION

A. Photon Fluence

There are three major processes that can produce the net current drawn by the aluminum chuck. They are (1) charged-particle bombardment (2) photoemission of electrons from photons directly striking the bare aluminum surface and (3) return current from charged-particle bombardment and photoemitted electrons from the borosilicate glass in the capillary array or the solid glass cover collected by the vacuum chamber. This is shown

in Figure 4. Secondary electron emission effects can be neglected because the calculated secondary-electron emission currents from the aluminum wafer chuck¹¹ and borosilicate glass¹² are negligible compared with the measured substrate current. To separate the current that is generated by charged-particle flux from the current generated by photoemission, the bare aluminum chuck, capillary window and borosilicate glass were exposed to 12 eV synchrotron radiation. This energy was chosen to approximate that coming from the argon plasma. The photon flux from the plasma was estimated to be 3.64×10^{14} photons/cm² per sec.⁷ By comparing the synchrotron photoemission current with the measured current during plasma exposure and normalizing for the difference in photon fluxes, photoemission currents from the aluminum chuck, capillary-array window and solid glass in the presence of the plasma were found to be less than 1% of the entire substrate current. Thus, we conclude (1) that the current drawn by both the bare and the capillary array or glass-covered aluminum chuck is almost entirely from charged-particle-produced electron or ion currents from the plasma and photoemission effects are negligible.

In addition, when the solid borosilicate Pyrex glass cover is used, all UV and VUV photon flux from the plasma that can cause photoemission is completely blocked from reaching the open area of the aluminum chuck. The spectrum of the ECR argon plasma measured with a monochromator shows strong VUV argon lines at 104.8 and 106.6 nm.¹³ The transmission coefficient of borosilicate Pyrex glass for photons at these wavelengths is essentially zero.¹⁴ Thus we assume the glass blocks all UV and VUV photons that could cause photoemission during plasma exposure. The photons that do pass through the glass have relatively low energies (less than 4eV) and thus

photoemission effects due to these photons can be neglected. High-energy radiation such as EUV and X rays may pass through the glass cover, which can cause photoemission in the aluminum chuck and contribute to the measured substrate current. However, the current drawn by the wafer chuck when the solid glass cover is used is negligible compared to the current measured with the bare chuck or the capillary window. This is shown in Figure 5.

B. Current drawn by the aluminum wafer chuck

i. Bare wafer chuck

The current drawn by the chuck during Ar plasma exposure was measured while the bias on the chuck was varied from -40V to +40V as shown in Figure 2. Here, positive current refers to ion current, and negative current refers to electron current. When +40V bias voltage is applied, -80 μ A current is drawn by the bare wafer chuck as electrons are accelerated to the chuck while ions are repelled for this bias condition. As the applied bias is decreased, the current decreases but remains negative until the bias voltage is about -5V where the net current drops to zero. Thus, at this bias voltage the ion and electron fluxes become equal and cancel each other. As the applied bias becomes more negative, the net current drawn by the wafer chuck becomes more positive. At these bias conditions the electron current is suppressed and the ions are accelerated towards the bare wafer chuck resulting in a net positive current.

ii. Capillary-Array and Solid-Glass Window measurements

In order to investigate the effectiveness of the capillary-array window to minimize charged particle bombardment at various bias conditions, the open area of the wafer chuck was covered with a capillary window or solid glass and the current drawn by the metal chuck was recorded under the same plasma conditions and bias ranges as before. Figure 5 shows that the current drawn by the wafer chuck drops substantially when the capillary window was used to cover the open area of the chuck. It is also shown that the current drops to almost zero as expected, when a solid piece of glass is used to cover the chuck.

Figure 6 shows the current drawn by the chuck as a function of applied bias for the capillary-array window and solid glass. It is seen that when the applied bias is between 0V and +5V, there is no current drawn by the chuck for both the capillary-array window and solid glass. This shows that under these bias conditions, the capillary-array window blocks a majority of the charged particle flux and the remaining ion and electron currents cancel out. As will be shown, this is confirmed using an OOPIC numerical simulation¹⁵ as demonstrated in Figure 8(b). When 0V to +5V bias is applied, very few ions have velocities parallel to the walls of the capillary arrays and thus they do not reach the exposed area of the wafer chuck behind the capillary-array window. In a plasma environment, the capillary-array window develops a negative potential that repels electrons and enhances the negative bias on the wafer chuck. Small currents are recorded

at high bias voltages with the solid glass covering the chuck. These currents are attributed to a combination of currents produced by EUV and soft x-ray photons, conduction through the glass cover, and leakage currents, since the entire chuck is not perfectly insulated from the plasma. However, these currents are negligible compared with the currents recorded with the capillary-array window covering the chuck under the same plasma condition.

With the capillary-array window covering the wafer chuck, the current increases as the applied bias becomes more negative (-20V to -40V). This is because a larger number of ions have velocities nearly parallel with respect to the direction of the capillaries at high negative biases and the holes in the window can now allow more ions with higher velocities to pass through. However, the electrons are repelled by the capillary array because of the negative potential build up on the capillary-array surface as well as the negative bias on the wafer chuck.

When a higher positive bias is applied, the chuck draws more electron current. The magnitudes of the electron currents at positive biases are nearly the same as the magnitude of the ion currents drawn when negative bias voltages are applied to the wafer chuck. Electrons have higher mobility than ions so it is expected that the wafer chuck would draw more electron current at high positive biases. However, as stated above, the floating capillary window develops a negative surface potential that maintains a plasma

sheath at its surface. Thus electrons require energies high enough to overcome the negative surface potential of the window to reach the wafer chuck.

C. Simulation

The ion and electron flux during plasma exposure were simulated with an object-oriented particle-in-cell (OOPIC)¹⁵ code. The simulation also includes electron-neutral elastic, excitation, and ionization collisions, as well as ion-neutral charge-exchange collisions. The code was used to simulate the experiment and investigate the behavior of the charged particle fluxes for the three experimental conditions as follows: (1) bare chuck, (2) chuck covered with capillary window, and (3) chuck covered with solid glass. The simulation assumes that when the charged particles collide with the capillary walls, they are neutralized, reflected or refracted depending on their energy and angle of collision.

Figure 7 shows the simulated ion and electron fluxes for +20, zero and -20 V bias applied to the bare aluminum wafer chuck. As expected, the simulation shows that the electron flux increases as the bias becomes more positive, while the ion flux is reduced. Using the charged-particle fluxes from the simulation results, the currents under different bias conditions were calculated and it was found that the measured substrate currents match well with the simulation.

Figure 8 shows the simulation result for charged particles fluxes passing through the capillary-array window with the plasma condition as the experiments. In this Figure, it can be seen that at +20 V bias, almost all the ions are blocked while some electrons can still pass through the window. When the bias is 0V, there are a smaller number of

electrons passing through the capillary array. At -20 V bias, the ion flux increases substantially while almost all electrons are blocked from reaching the wafer chuck underneath the window. Thus, in this case, the substrate current is primarily due to ion bombardment. Using the charged-particle fluxes from the simulation, the currents under different bias conditions were calculated with the capillary window cover and it was found that the experimentally measured substrate currents match well with the simulation.

IV. Conclusions

This work has shown that capillary-array windows can block a significant portion of charged particles from passing through the window. A capillary-array window was placed on top of an aluminum wafer chuck and the current drawn by the chuck was measured under variable bias conditions. The results are compared with the current drawn by the bare wafer chuck under the same biases and plasma conditions. It shows that the current is reduced by over 90% when the capillary window is used to cover the aluminum chuck under all substrate biases. At negative biases, electrons are repelled and ions are blocked by the window, because only a small number of ions have velocities that are nearly perpendicular to the window in the presence of the ECR dc magnetic field. At positive biases, ions are repelled and the current drops by over 95% when the capillary-array window is used. In this case, almost all electrons are blocked due to geometric effects and negative potential buildup on the capillary-array surface. Under the plasma and bias conditions of this experiment, when the charged particle flux through the window is a minimum, essentially zero substrate current was measured with 0 to +5V

applied bias. The effectiveness of capillary-array windows to partially block charged particles in order to distinguish the effects of photon and charged-particle bombardment during plasma processing is thus demonstrated. As a result, the capillary array window can be used to identify the specific source of plasma damage to dielectric materials.

V. ACKNOWLEDGMENT

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References Cited

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- ¹ S. Uchida *et al.*, *J. Appl. Phys.* **103**, 073303 (2008).
- ² J. Bao *et al.*, *J. Vac. Sci. Technol. B* **26**, 219 (2008).
- ³ H. Ren *et al.*, *Appl. Phys. Lett.* **98**, 252902 (2011).
- ⁴ J. L. Lauer *et al.*, *J. Electrochem. Soc.* **157**, G177 (2010).
- ⁵ J. Lee and D.B. Graves, *J. Phys. D: Appl. Phys.* **43**, 425201 (2010).
- ⁶ M.T. Nichols *et al.*, *Appl. Phys. Lett.* **100** 112005 (2012)
- ⁷ H. Ren, Y. Nishi, and J. L. Shohet, *Electrochem. Solid-State Lett.* **14**, H107 (2011)
- ⁸ J.D. Chatterton *et al.*, *J. Appl. Phys.* **100**, 043306 (2006).
- ⁹ A. Dunaevsky, Y. Raitses, and N. J. Fisch, *Appl. Phys. Lett.* **88**, 251502 (2006).
- ¹⁰ B. Chapman, *Glow Discharge Processes*, (Wiley, New York, 1994), pp. 60-70.
- ¹¹ V. Baglin, *The Secondary Electron Yield of Technical Materials And Its Variation With Surface Treatment*, WWW Document, (<http://psec.uchicago.edu/Papers/>).
- ¹² K. Ooka, B. Dunn, J.D.Mackenzie, *Journal of Non-Crystalline Solids* **12**, 1 (1973)
- ¹³ H. Ren, G.A. Antonelli, Y. Nishi and J.L. Shohet, *Journal of Applied Physics*, **108**, 094110 (2010)
- ¹⁴ M. Halpern, H. Gush, E. Wishnow, and V. De Cosmo, *Appl. Opt.* **25**, 565 (1986)
- ¹⁵ Y. M. Sung *et al.*, *J. Appl. Phys.* **43**, 800 (2004).

Figure Captions

FIG.1 Schematic diagram of ECR plasma system

FIG.2 Experimental setup with circuit to measure current drawn by the substrate holder

FIG.3 SEM photograph of capillary array

FIG.4 Current drawn by the aluminum wafer chuck due to (a) charged particle bombardment and photoemission from the wafer chuck (b) photoemission from the capillary-array window or glass cover.

FIG.5 Current drawn by the aluminum chuck as a function of applied bias without capillary-array window or glass in front of the aluminum wafer chuck.

FIG.6 Current drawn by the aluminum chuck as a function of applied bias with the capillary-array window or solid glass covering the aluminum wafer chuck.

FIG.7 Ion and electron flux during exposure without window for (a) +20V bias (b) 0 V bias (c)-20V bias. The graph shows the 1cm exposed area of the wafer chuck

FIG.8 Ion and electron flux during exposure with window for (a) +20V bias (b) 0 V bias (c)-20V bias. The region from 3 to 7mm is the area of the wafer chuck covered by the window.

Figure 1

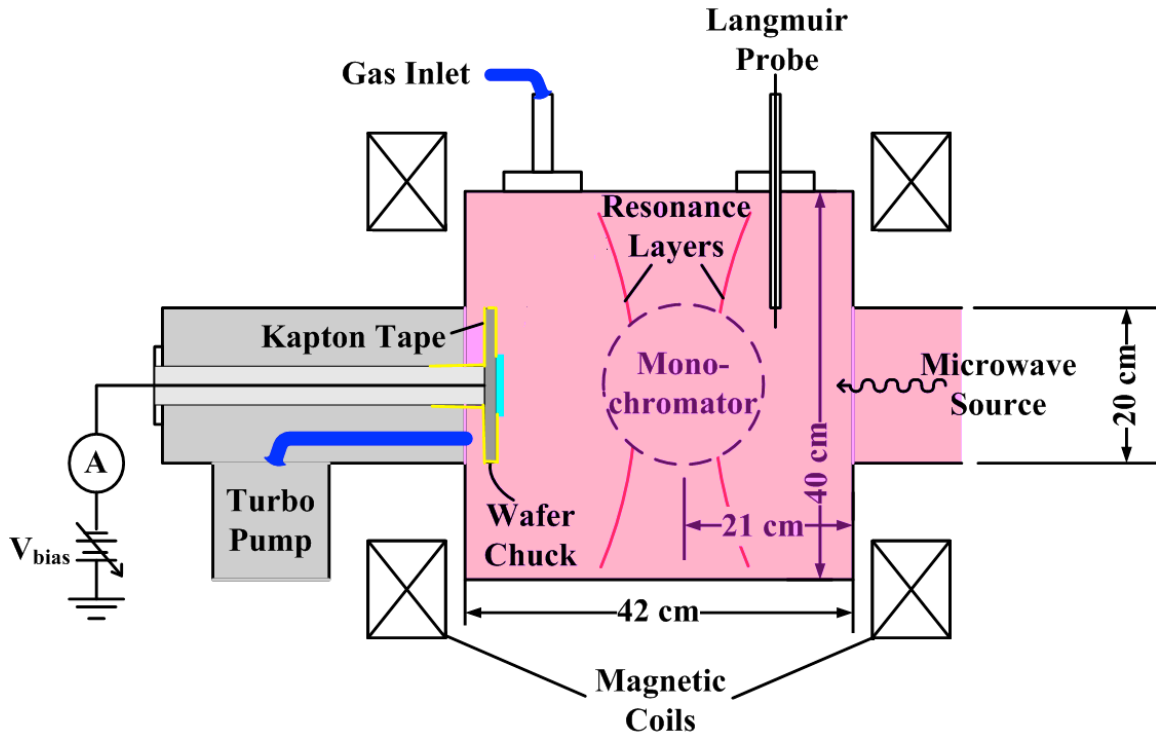


Figure 2

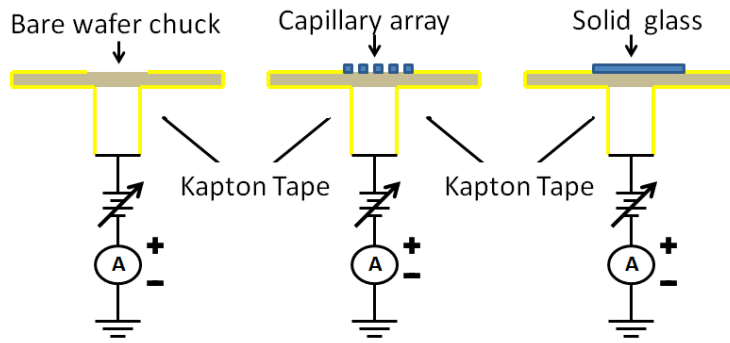


Figure 3

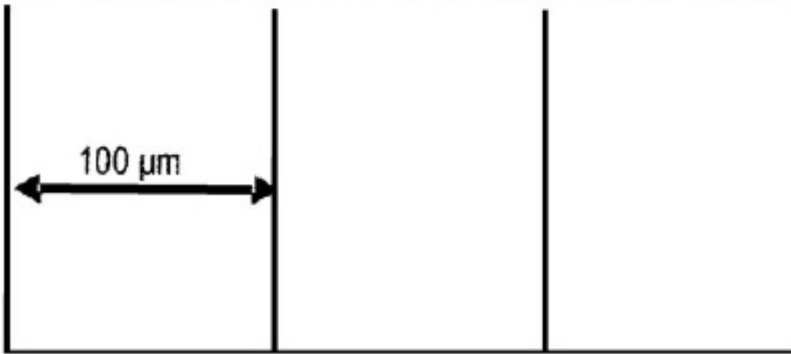
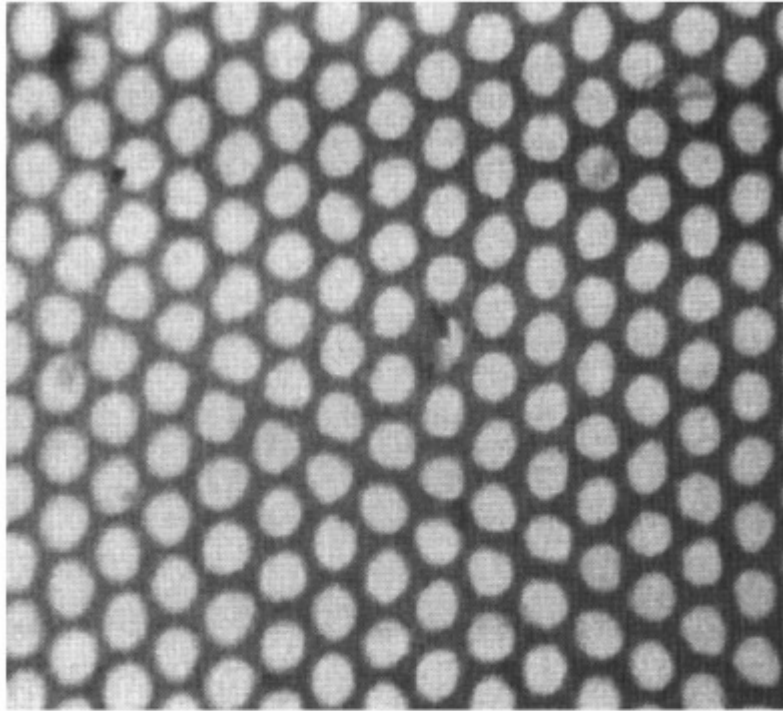
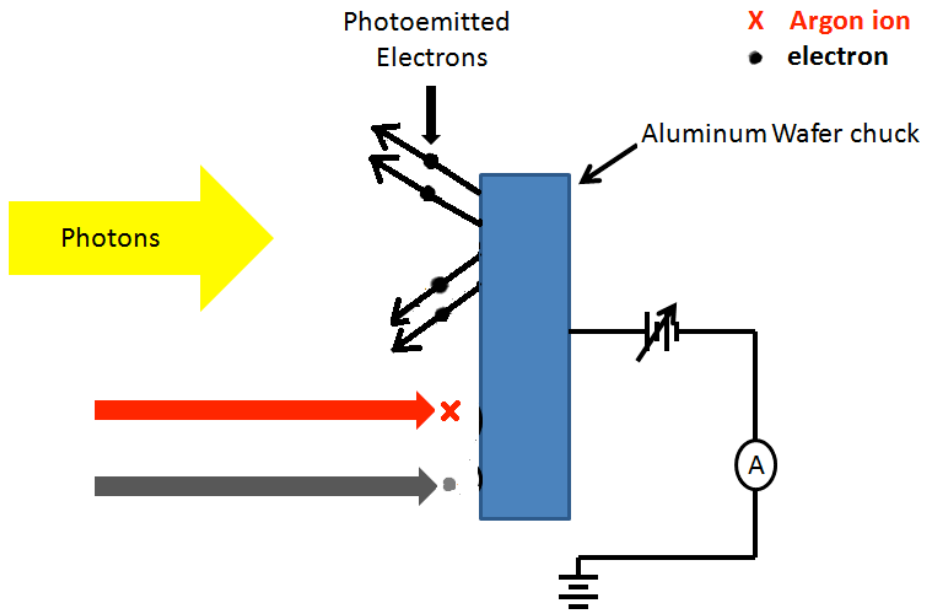


Figure 4 (a)



(b)

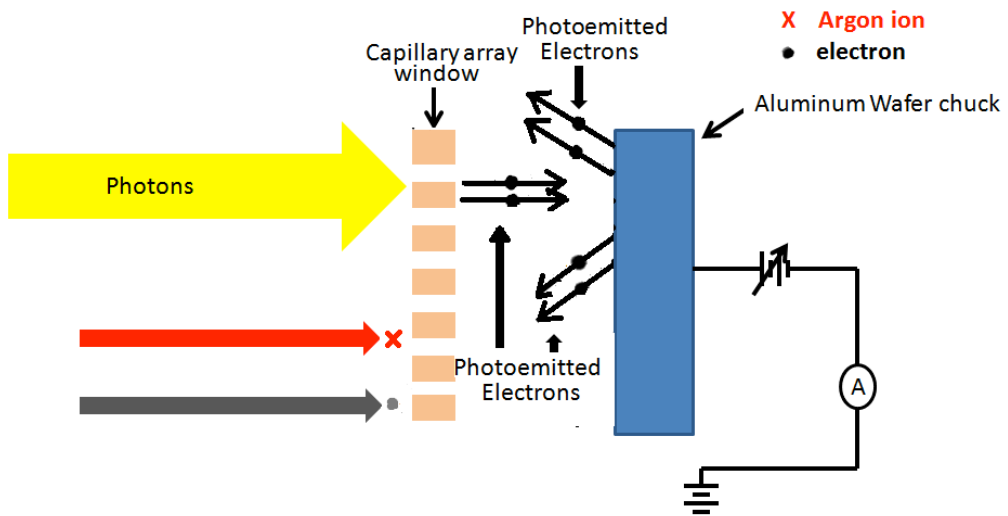


Figure 5

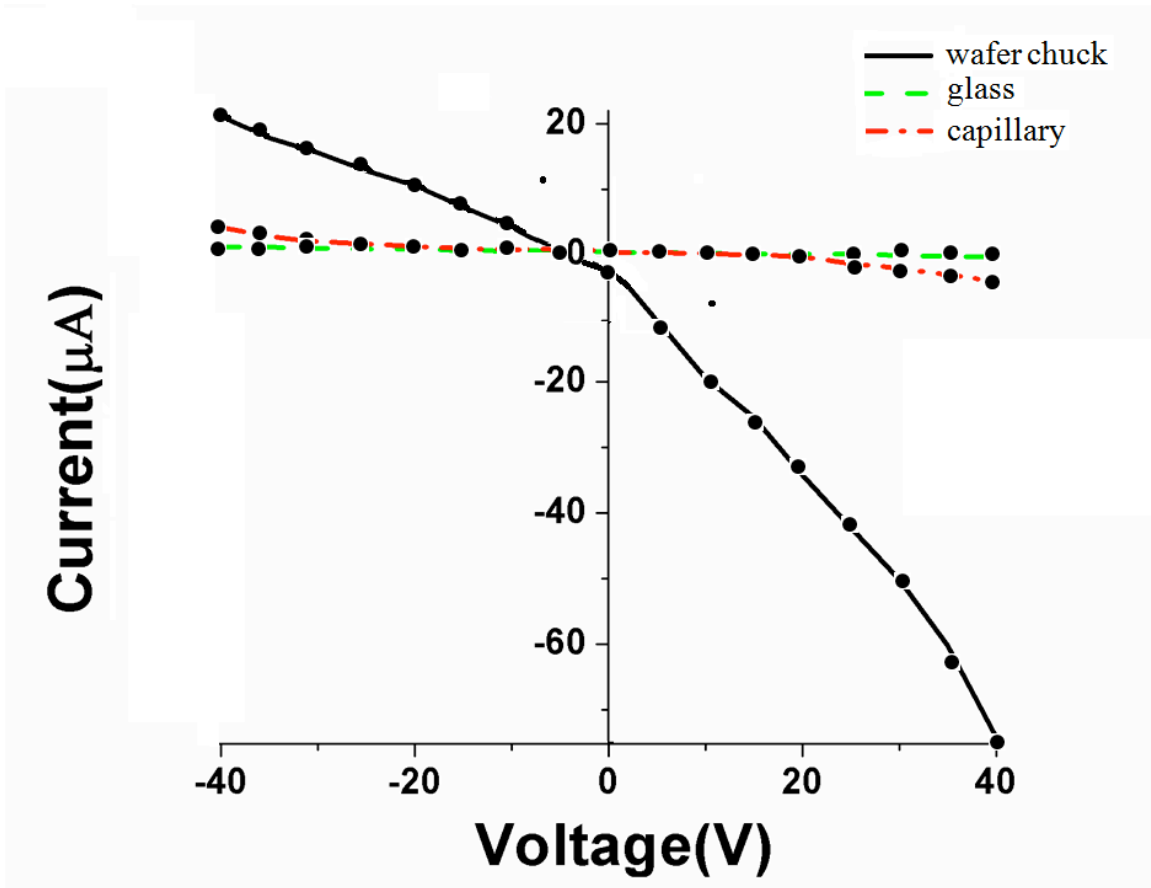


Figure 6

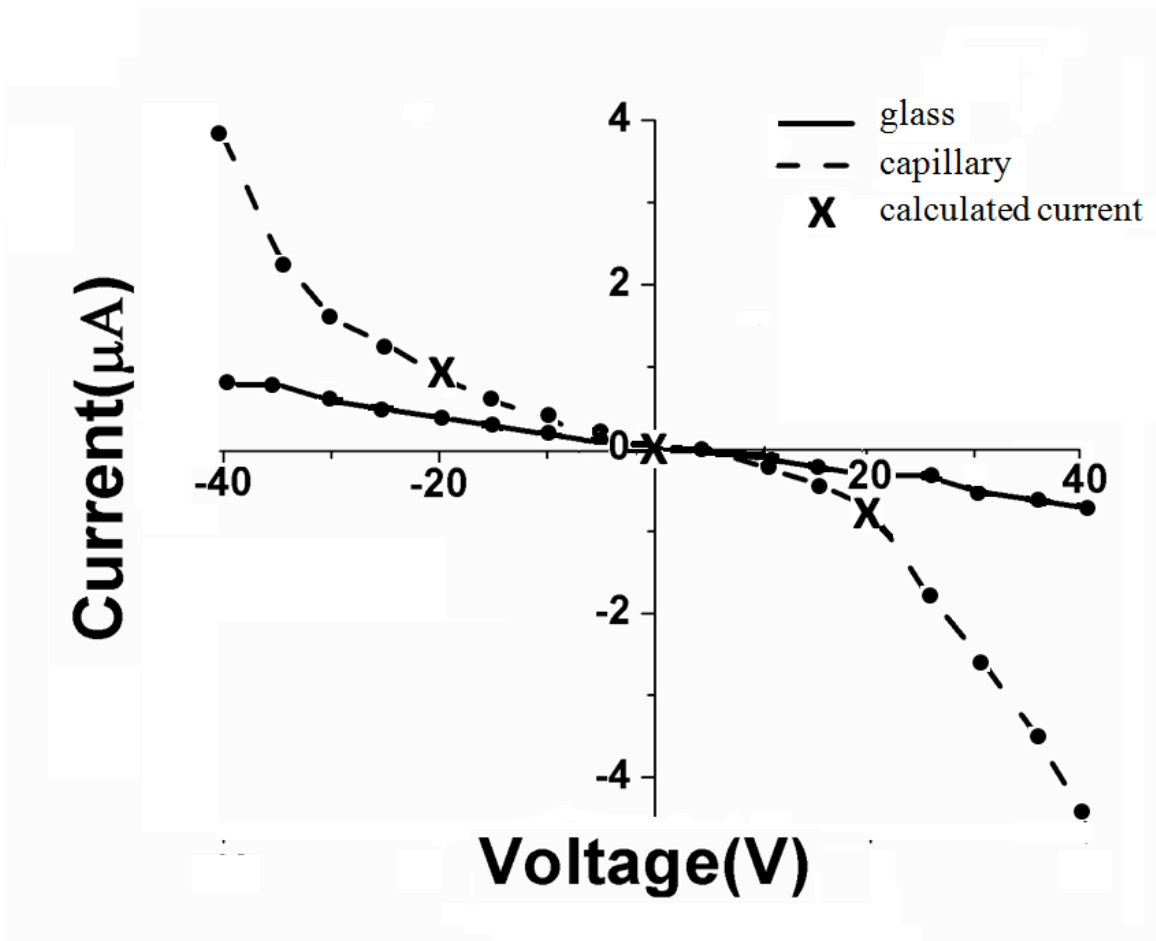
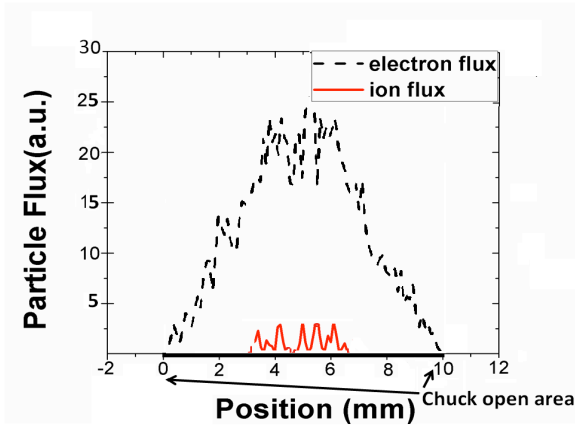
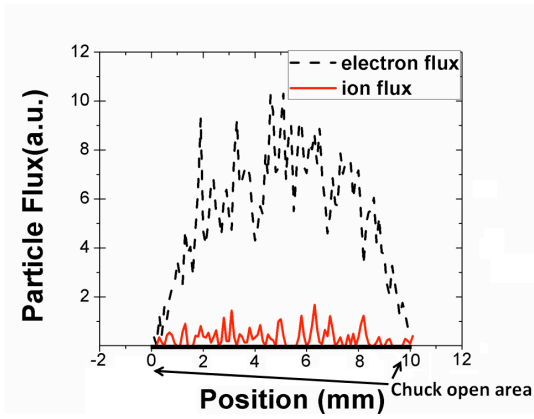


Figure 7

(a)



(b)



(c)

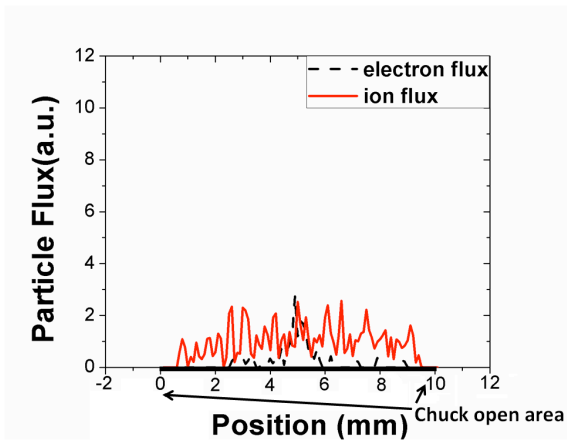
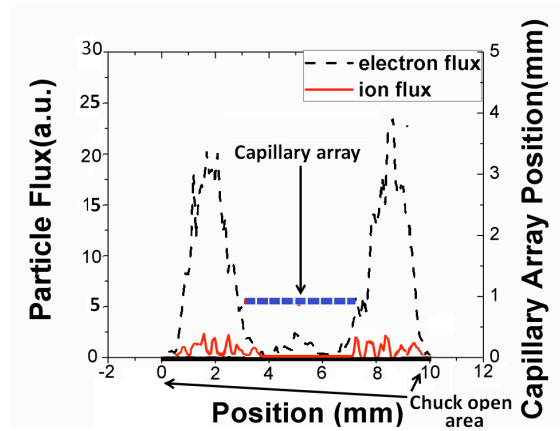
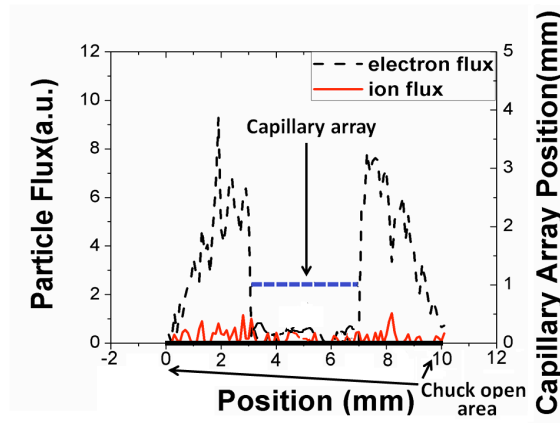


Figure 8

(a)



(b)



(c)

