Surface potential due to charge accumulation during vacuum ultraviolet exposure for high-*k* and low-*k* dielectrics

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The surface potential due to charge accumulation during vacuum ultraviolet irradiation of high-*k* and low-*k* thin dielectric films is measured. Measurement of the substrate current, which is the sum of the charge-accumulation and photoinjection currents, allows an *in situ* monitoring of the charge accumulation during irradiation. The relationship between the substrate current and the calculated *in situ* surface potential is also found, eliminating the need for a separate surface-potential measurement. With a high photon dose, the surface potential and substrate current reach a steady-state value with no further net charge accumulation. [doi:10.1063/1.3481079]

Vacuum ultraviolet (VUV) irradiation has significant effects on both high-*k* and low-*k* dielectric materials during plasma processing.[1–3] Multiple processes including photoemission, photoinjection, photoabsorption, and photoconduction take place[4,5] and modify the defect-state concentrations[6–8] and total accumulated charge[9,10] within the dielectric layer. During VUV irradiation, the charge accumulation in the dielectric provides significant information about the properties of the dielectric material.

Using synchrotron radiation, it is possible to carry out VUV irradiation over a wide range of photon energies on different dielectric materials.[11,12] In this letter, both high-*k* and low-*k* dielectric materials were exposed to VUV exposure. The high-*k* dielectric material is 250 nm SiN ($k \sim 7.6$) plasma-enhanced-chemical-vapor deposited on silicon substrate. SiN has a band gap of 5.8 eV.[13] As a result, 5.5 eV VUV photons were irradiated on the high-*k* sample. The low-*k* dielectric is 266 nm porous SiCOH ($k \sim 2.65$) that is deposited on silicon. It has a band gap of around 9 eV.[14] In this case, it was irradiated with 8 eV VUV photons. In both cases, the photon energies were chosen to be below the band gap of the dielectric materials. This was set in this way because the defect state energies are usually expected to be located within the band gap.[14,15] We hypothesize that if the VUV photon energy is less than the band gap of the dielectric material, charge accumulation during irradiation is produced by charges trapped in the defect states within the dielectric layer.

During exposure, the substrate currents shown in Fig. 1 were measured as a function of VUV photon dose. The substrate current has two components—photoinjection and charge accumulation. It must be pointed out that the substrate current is equivalent to the photoemission current. Figure 1 shows that the substrate current decays with increasing photon dose and reaches a steady state for both high-*k* and low-*k* dielectrics. For the high-*k* sample, the substrate current starts at a high value and decays faster compared to the low-*k* sample. This is mainly due to the difference of the number of trapped charges in defects in each dielectric. The steady-state substrate current is equal to the photoinjection current, since no further charge accumulation occurs at this point.[12] During the charge accumulation phase, we assume that the photoinjection current is this steady-state value. Based on this assumption, any current larger than the photoinjection current, contributes to charge accumulation. Thus, the charge accumulation as a function of exposure time can be calculated using

$$Q(t) = \int_0^t [I_{\mathrm{emi}}(\varphi) - I_{\mathrm{inj}}(\varphi)]d\tau, \quad (1)$$

where I_{emi} and I_{inj} are the photoemission and photoinjection

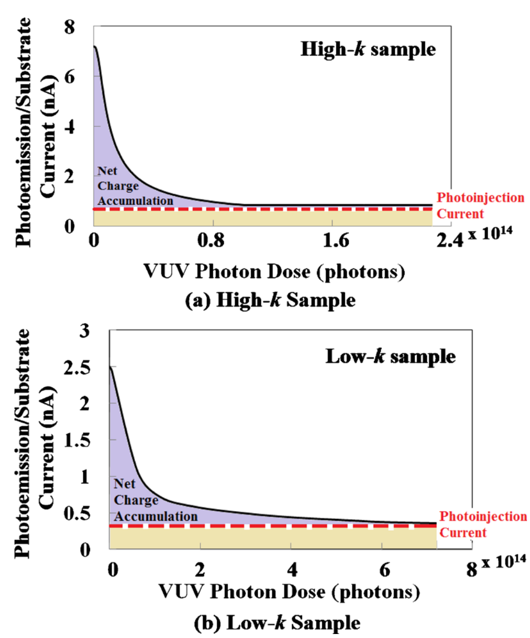

FIG. 1. (Color online) Photoemission/substrate current during VUV irradiation: (a) high-*k* dielectric; (b) low-*k* dielectric. The dashed line shows the photoinjection current which is assumed to be constant during the exposure.

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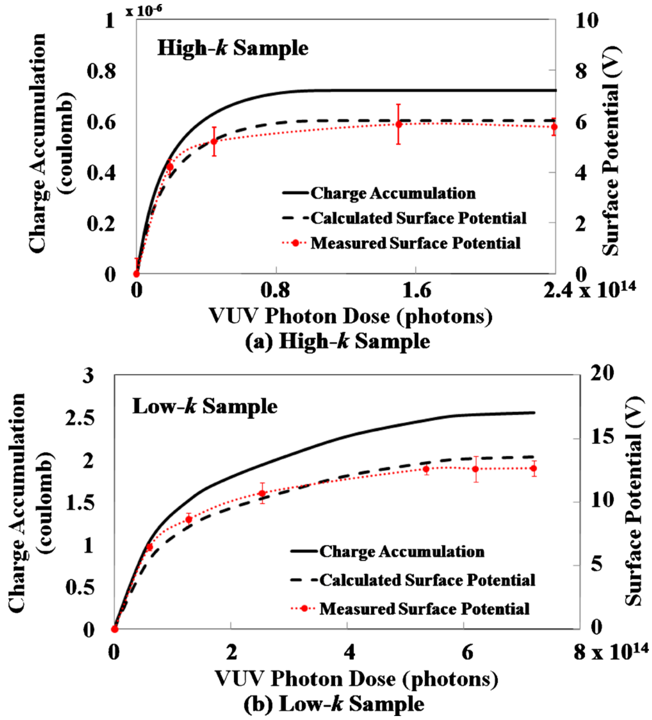

FIG. 2. (Color online) Charge accumulation (solid lines), calculated (dashed lines without markers), and measured surface potential (dashed lines with markers) as a function of VUV photon dose for (a) high-*k* dielectric and (b) low-*k* dielectric.

currents as functions of photon dose φ. Also, the photon dose φ, as a function of exposure time t, is written as

$$\varphi = f(t) \quad \text{or} \quad t = f^{-1}(\varphi), \tag{2}$$

$f(t)$ is the functional relation between time and photon dose. If the dose rate is independent of time, then $f(t)$ is linearly proportional to time. As time increases, the synchrotron flux normally decreases, which makes $f(t)$ a second-order polynomial. As a result, $f(t)$ can be obtained by measurement so that it is always a known function. Hence, the net charge accumulation as a function of photon dose can be obtained using

$$Q(\varphi) = \int_0^{\varphi} [I_{\mathrm{emi}}(\phi) - I_{\mathrm{inj}}(\phi)] f^{-1'}(\phi) d\phi, \tag{3}$$

where $f^{-1'}(t)$ is the derivative of the inverse function of f.

The charge accumulation and surface potential for both samples are shown in Fig. 2 as a function of photon dose. The photon dose is obtained by integrating the measured photon flux [in photons/$(\mathrm{cm}^2\ \mathrm{s})$] over the beam area and the exposure time. The solid lines represent the charge accumulation in the dielectric during exposure. It can be seen that as the photon dose increases, the dielectric layer continues to accumulate positive charge until a steady-state value is reached. Since the applied VUV photon energy is below the band gap of the dielectric, the total amount of the charge accumulation corresponds primarily to the number of trapped charges in the defect states in the dielectric. For the high-*k* (SiN) sample, the total trapped charge was estimated to be 0.7×10^{-6} C. For the low-*k* (SiCOH) sample, the trapped charge amount was 2.5×10^{-6} C.

Furthermore, the charge accumulation is related to the surface potentials of the dielectric samples. This was measured using a Kelvin probe system[10] shown in Fig. 3. The equivalent circuit for the Kelvin probe with the sample is two capacitors in series. The effective capacitance has a similar form as in Ref. 16

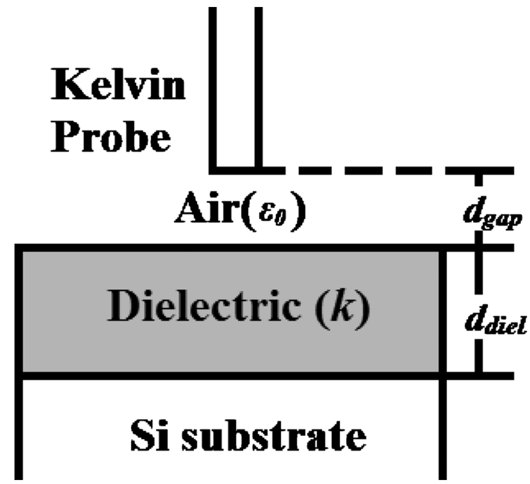

FIG. 3. The structure of the Kelvin probe with a dielectric sample to be measured.

$$C_{\mathrm{eff}} \approx \frac{N C_{\mathrm{diel}}}{1 + \dfrac{k d_{\mathrm{gap}}}{d_{\mathrm{diel}}}}, \tag{4}$$

where C_{eff} is the effective capacitance of the Kelvin probe system, N is the number of readings for surface potential within the VUV beam profile, k is the relative dielectric constant of the dielectric, d_{gap} and d_{diel} are the thickness of the air gap and the dielectric layer, respectively. C_{diel} is the capacitance of the dielectric layer which is as follows:

$$C_{\mathrm{diel}} = \frac{k \cdot A}{d_{\mathrm{diel}}}, \tag{5}$$

where $A = 10\ \mathrm{mm}^2$ is the area of the Kelvin-probe tip.

According to Eqs. (4) and (5), the effective capacitances for high-*k* and low-*k* samples are 118 nF and 189 nF, respectively. We assume the effective capacitances are constant during VUV exposure. Then, the surface potential as a function of VUV photon dose can be related to the charge accumulation during exposure as

$$V_{\mathrm{surf}}(\varphi) = \frac{Q(\varphi)}{C_{\mathrm{eff}}}, \tag{6}$$

where V_{surf} is the surface potential as a function of photon dose φ, $Q(\varphi)$ is the charge accumulation, and C_{eff} is the effective capacitance from Eq. (4).

Using Eq. (6) and the Kelvin probe, the surface potential as a function of photon dose was calculated and measured. The results are shown in Fig. 2. From Fig. 2, it is seen that the measured surface potential matches well with the calculation. With a relatively high photon dose, all the electrons in the defect states have been depopulated and the charge in the dielectric reaches its steady-state limit. Steady state is also seen in the surface potentials at high photon doses for both high-*k* and low-*k* dielectrics. Hence, by measuring the substrate current alone, *in situ* charge accumulation and surface potential can be obtained.

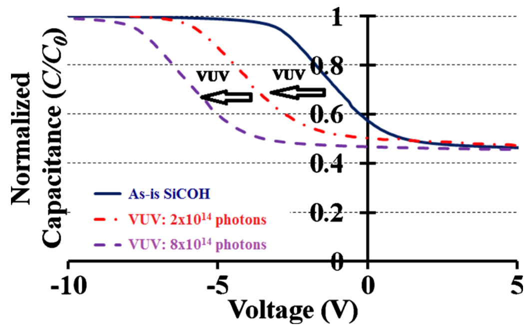

FIG. 4. (Color online) Capacitance-voltage characteristics of SiCOH sample before and after VUV exposures with different photon doses (C_0=55.45 pF).

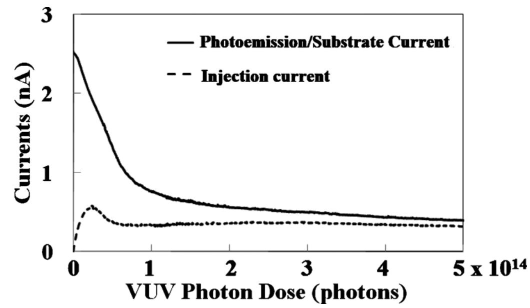

FIG. 5. Photoemission and injection currents during 8 eV VUV exposure for SiCOH.

In addition, flat band voltage shifts in the capacitance-voltage (C-V) characteristics were observed after VUV exposure. These flat band voltage shifts indicate trapped charge accumulation within the dielectric layer. For example, Fig. 4 shows the flat band voltage shifts for SiCOH after VUV exposure. The shift increases with higher photon doses until it saturates. This result is consistent with the charge accumulation measured with surface potential after VUV exposure.

On the other hand, however, there is some deviation of the measured surface potential from the calculation. At the beginning of the exposure, the charge actually accumulates faster than the calculation and accumulates more slowly at higher photon doses. The deviation comes from the fact that the photoinjection current was assumed constant during VUV exposure.

To correct this, using the measured surface potential, it is possible to use an inverse calculation to obtain the photoinjection current during VUV exposure. First, the charge accumulation as a function of photon dose can be calculated using the measured surface potential and effective capacitance. Then, using the expression for charge accumulation in Eq. (3), it is found that

$$Q(\varphi) = C_{\text{eff}} V_{\text{surf-measured}}(\varphi) = \int_0^{\varphi} [I_{\text{emi}}(\phi) - I_{\text{inj}}(\phi)] f^{-1'}(\phi) d\phi, \quad (7)$$

where $V_{\text{surf-measured}}$ is the average surface potential obtained from the Kevin probe. Taking the derivative of both sides of Eq. (7) and rearranging, we get

$$I_{\text{inj}}(\varphi) = I_{\text{emi}}(\varphi) - \frac{C_{\text{eff}} V'_{\text{surf}}(\varphi)}{f^{-1'}(\varphi)}. \quad (8)$$

The first term on the right hand side of Eq. (7) is the photoemission current which is equal to the substrate current. The second term is the difference between the photoemission and photoinjection currents due to charge accumulation during exposure. The calculated photoinjection current using Eq. (8) for the low-k dielectric sample is shown in Fig. 5.

This indicates that if substrate current and surface potential as a function of photon dose are known, then the *in situ* injection current can be derived from these measurements. From Fig. 5, it is seen that it is valid to assume the photoinjection current to be approximately constant and equal to its steady-state value during exposure.

In conclusion, positive net charge accumulations were calculated for both high-k and low-k dielectric materials during VUV exposure. The amounts of the trapped charges are 0.7×10^{-6} C and 2.5×10^{-6} C, respectively, for high-k and low-k samples. The charge accumulation is related to the surface potential which matches well with the experimental measurement. It is shown that *in situ* measurement of the substrate current will yield the charge accumulation and surface potential during exposure. Furthermore, *in situ* injection currents can be found by measuring both substrate current and surface potential as functions of photon dose.

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