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Charging response of back-end-of-the-line barrier dielectrics to VUV radiation

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ABSTRACT

The response of SiN, N-SiC, O-SiC, and SiC dielectrics of varying thickness deposited on Si substrates to irradiation with vacuum ultraviolet (VUV) was compared. The resulting charge was evaluated by measuring the surface potential on the dielectrics after irradiation with 9.5 eV photons. The surface potential on all of the dielectrics was positive due to charge accumulation in traps located within the dielectrics. By comparing the surface potential on several thicknesses of dielectrics after VUV irradiation we can determine whether the trapped charges are in the bulk of the dielectric or at the dielectric–substrate interface.

1. Introduction

The minimum spacing between conductive lines in advanced integrated circuits (ICs) continues to decrease with each generation of technology [1]. As a result, the long-term reliability of ICs is becoming increasingly dependent on the reliability of the intermetal dielectrics [2] that often become damaged during back-end-of-the-line (BEOL) processing [3]. The local electric field, valence-band structure [4] and traps/defects within the intermetal dielectrics are very important parameters [5] that control the magnitude and path of the line-to-line leakage currents. In particular, traps located at or near the interface [6] between the low-k dielectric material and the dielectric diffusion-barrier/etch-stop layers act as a source of leakage current in Cu/low-k damascene structures [7]. Traps provide both a path for conduction [6] and enhancement of the local electric field [8] due to space-charge accumulation.

Dielectrics used in BEOL structures are often irradiated with photons of various energies during plasma processing [3,9], annealing [10], and curing [11,12] of porous materials. In particular, processing plasmas produce significant amounts of vacuum ultraviolet (VUV) radiation [13–15] which are capable of creating electron–hole pairs within dielectrics. As a result, VUV radiation has an impact on the electrical conductivity of dielectrics during plasma processing which can either contribute to [16–19] or mitigate [20–23] the trapped charge within dielectrics. It is very important to determine the trapping properties of BEOL-barrier dielectrics especially under irradiation with VUV photons because knowledge of the location and densities of the traps can be used to improve the fabrication process. For example, dielectrics are often directly exposed to the plasma-processing environment, and there is evidence that defects/traps generated during plasma processing [3,24] contribute to leakage currents [25]. The leakage current degrades both the performance and reliability of BEOL structures [5]. Hence an improved dielectric will have a better performance and reliability.

2. Background

VUV irradiation can cause electron–hole pair creation, photoconduction, photoemission and photoinjection of electrons from the substrate into the dielectric [26–28]. The level of these processes depends on the incident photon energy and the dielectric thickness. Electron–hole pairs will be formed if electrons are excited into the conduction band from the valence band or from defect states within the dielectric. Depending on their energy, the electrons and holes can travel in the dielectric with a number of them being photoemitted [29]. Electrons dominate the photoconduction process since the mobility of electrons is larger than the mobility of holes [30].

When the energy supplied by irradiation is greater than the sum of the bandgap energy and the electron affinity, photoemission can occur from the dielectric [29]. Photoemission can take place from electrons ejected from either the valence band or from the defect states present in the dielectric. Photoemission from the defect states

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leads to depopulation of electrons within the dielectric [26,27]. Thus, after photoemission, a dielectric develops a net positive charge.

Conversely, photoinjection reduces the number of trapped charges in the dielectric. The electrons injected from the substrate into the dielectric can repopulate the defect states [31]. It should be noted that photoinjection is a function of the thickness of the dielectric, since VUV photons must penetrate through the dielectric to generate electron–hole pairs in the substrate which are subsequently injected into the dielectric.

It is plausible that photoinjected electrons drift from the substrate–dielectric interface to the dielectric–vacuum interface, and are photoemitted [21,29]. The drift occurs through the dielectric conductivity, which is enhanced by photoconductive effects. Thus, at any given time during VUV irradiation, photoemitted electrons will consist of 1) depopulated electrons from the defect states and 2) photoinjected electrons. Trapped charges due to depopulation of defect states will continue to be created until a steady state is achieved. In steady state, no more net trapped charge will be generated in the dielectric, and the photoemitted electron flux will be equal to the flux of photoinjected electrons. In order to have a complete circuit, charge conservation dictates that when the substrate is connected to ground, the photoemitted electrons are returned to the substrate. Thus, in the steady state, the photoemission current is equal to the substrate current.

Trapped charges can be generated in the bulk of the dielectric or the dielectric–substrate interface depending on the location of defect states [32]. The location of trapped charges, whether in the bulk or at the dielectric–substrate interface, determines how the surface potential is affected by the dielectric thickness. If the defect states are located in the bulk of the dielectric, then the surface potential will be a function of dielectric thickness. This happens because, with increasing thickness, there will be more defect states in the bulk that can be depopulated. On the other hand, if the defect states are located at the dielectric–substrate interface, then the number of defect states will be independent of thickness. Hence, for interfacial defects, the surface potential should be independent of the dielectric thickness.

3. Experiment

In this work, we measure the surface potential [17,33] of SiN, N-SiC, O-SiC, and SiC dielectrics after VUV irradiation as a function of photon dose. Each dielectric was deposited using chemical vapor deposition on a Si substrate (<100>, 1–100 Ω/cm) with thicknesses of 50, 250, and 450 nm and was irradiated with 9.5 eV photons. Photons with this energy [13] are often emitted from processing plasmas that contain oxygen [15], i.e. ashing and etching plasmas. The dielectric constants and band gap energies of the dielectrics are listed in Table 1 [34–36].

The experimental arrangement used to irradiate the dielectric with synchrotron VUV radiation has been described in detail elsewhere [37]. Thus, we will only give a brief description of the arrangement here. The wafers were mounted in a vacuum chamber that was evacuated to a pressure of 1.3×10^{-6} Pa. At the location of the wafer, the VUV beam was elliptical and was approximately 25×10 mm in area. The total irradiation time was 10 min for all exposures, while the photon-flux density was changed for each exposure resulting in a different photon dose. After irradiation the surface potential was measured using a Kelvin probe [38,39].

Table 1
Dielectric constant and band-gap energy for SiN, N-SiC, O-SiC and SiC dielectrics.

Dielectric	Dielectric constant (k)	Band gap (eV) [approx.]
SiN	7	5.6
N-SiC	5	3.8
O-SiC	4.3	3.5
SiC	3.8	2.8

From the four samples of SiN, N-SiC, O-SiC, and SiC, we measure the surface potential as a function of photon dose for the thicknesses of 50, 250 and 450 nm. The measurements showed that the surface potential is always positive because electrons are depopulated from the defect states within the dielectric by the photons. In addition, the surface potential appears to saturate after a photon dose of 6×10^{13} photons m^{-2} for all thicknesses. This indicates that, for a dose of 6×10^{13} photons cm^{-2}, all of the trapped states have been depopulated, i.e., no more trapped charges are being generated, so the surface potential no longer increases.

To validate the presence of either interface trapped states or bulk trapped states in a dielectric, we compare the surface potential of 250 and 450 nm thickness. If the surface potential for the 450 nm thick dielectric is higher in comparison with the 250 nm thick dielectric for the same photon dose, we can conclude that the trapped charge is in the bulk of the dielectric. Conversely, if the two samples have the same surface potential, then we can conclude that the trap states were present at the interface. We should note that the penetration depth of the photons also defines the surface potential, as it will control the amount of photoinjection. We reiterate that the more photons that penetrate through the dielectric into the substrate, the higher will be the photoinjection current and hence the lower will be the surface potential. From the photoemission current curves shown in Fig. 1 for SiN and Fig. 2 for SiC, it can be seen that the photoemission current in steady state is much higher for the 50 nm thick dielectric than the 250 and 450 nm thick dielectrics suggesting higher photoinjection currents. Also, the photoemission current characteristics of the 50 nm think dielectrics were found to be similar to the photoemission current characteristics of an uncoated Si wafer (except for a 10 nm native oxide layer). The photoemission current from the silicon wafer is shown in Fig. 3. This explains the fact that there was a small reduction in photoemission current before steady state was achieved.

4. Results

Fig. 4 shows the average surface potential on 50, 250, and 450 nm thick SiN films after irradiation with various doses of 9.5 eV photons. The error bars shown in Fig. 4 represent one standard deviation of the average surface potential over the irradiated region on the dielectric surface. Note in Fig. 4 that there is no difference in the average surface potential measured on the 250 and 450 nm thick SiN for the same total photon doses even though the thickness of the dielectric is

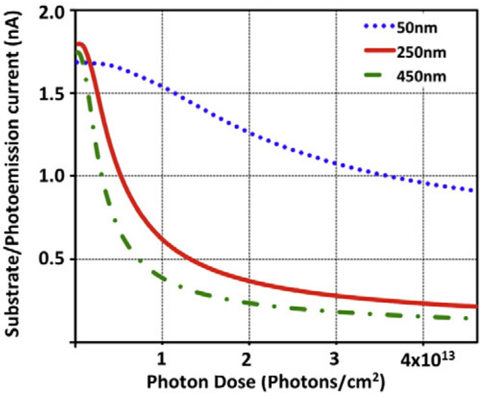

Fig. 1. Photoemission flux of 50 nm, 250 nm and 450 nm SiN film deposited on Si as a function of increasing dose of 9.5 eV VUV photons.

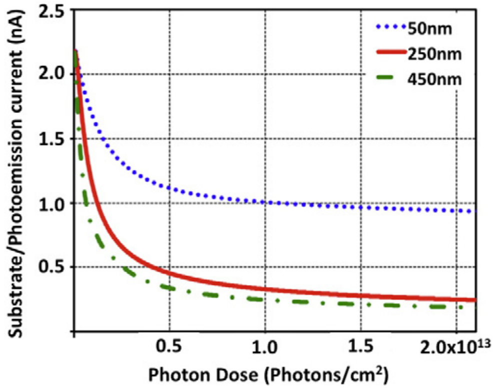

Fig. 2. Photoemission flux of 50 nm, 250 nm and 450 nm SiC film deposited on Si as a function of increasing dose of 9.5 eV VUV photons.

nearly doubled. Thus, based on the above argument, most of the trapped charge must be located at the interface. The 50 nm thick SiN had a much lower surface potential because of the higher photo-injection current, which has been shown in Fig. 1.

Fig. 5 shows the average surface potential on 50, 250, and 450 nm of N-SiC for several photon doses of 9.5 eV photons. The magnitude of the surface potential for all three thicknesses of N-SiC is nearly identical to the magnitude to the surface potential on the SiN dielectrics for the same total photon dose. For example, the surface potential of the 50 nm thick N-SiC saturates at around 3 V for photon doses larger than 6×10^{13} photons cm^{-2}, similar to the results for the 50 nm SiN shown in Fig. 4. In addition, there is only a very slight difference in the surface potential between the 250 nm and 450 nm thick N-SiC. This suggests that like SiN, positive charge is trapped near the N-SiC/Si interface rather than in the bulk of the dielectric.

Fig. 6 shows the average surface potential on 50, 250, and 450 nm of SiC for a range of 9.5 eV photon doses. We find that the surface potential is higher for the thicker films at a given photon dose. Hence, the defects have to be present in bulk rather than at the interface of SiC.

Fig. 7 shows the average surface potential measured on 50, 250, and 450 nm of O-SiC after VUV irradiation with 9.5 eV photons for a range of photon doses. Similar to SiC, there is a significant jump in the surface potential between the 250 nm and 450 nm thick O-SiC, which suggests that defect states are present in the bulk of the O-SiC.

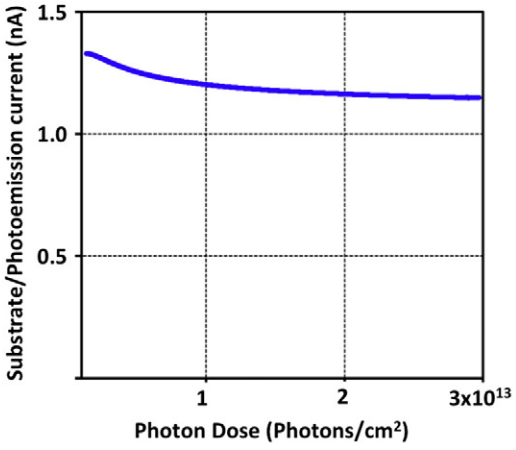

Fig. 3. Photoemission flux of Si as a function of increasing dose of 9.5 eV VUV photons.

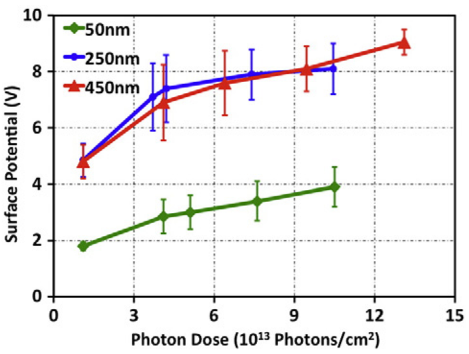

Fig. 4. Average surface potential as a function of total photon dose measured after irradiation of SiN films with thicknesses of 50, 250 and 450 nm to 9.5 eV photons.

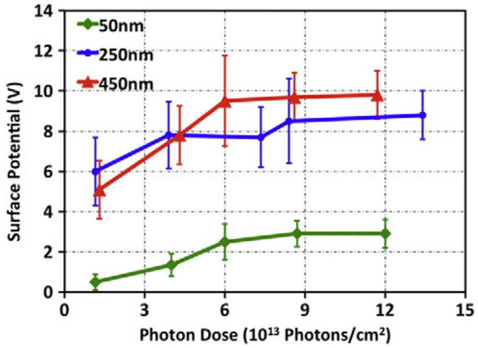

Fig. 5. Average surface potential as a function of total photon dose measured after irradiation of N-SiC films with thicknesses of 50, 250 and 450 nm to 9.5 eV photons.

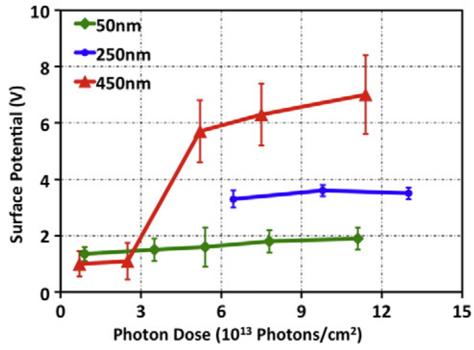

Fig. 6. Average surface potential as a function of total photon dose measured after irradiation of SiC films with thicknesses of 50, 250 and 450 nm to 9.5 eV photons.

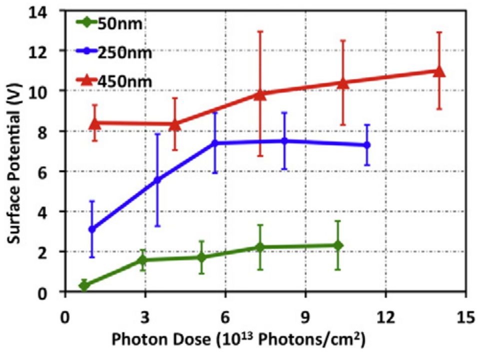

Fig. 7. Average surface potential as a function of total photon dose measured after irradiation of O-SiC films with thicknesses of 50, 250 and 450 nm to 9.5 eV photons.

5. Conclusion

In summary, the surface potentials on 50, 250, and 450 nm of SiN, N-SiC, O-SiC, and SiC after irradiation with 9.5 eV photons for several photon doses were measured and compared. From these measurements, it is possible to differentiate between bulk and interface trapped charge. Because the surface potentials on the SiN and N-SiC dielectrics are about the same for all thicknesses for a given photon dose, we can conclude that for these dielectrics, charges are trapped at the dielectric–substrate interface. Because the surface potentials for a given photon dose increase with increasing thickness for O-SiC and SiC, we can conclude that, for these dielectrics, charges are trapped in the bulk of the dielectric.

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