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Effect of the dielectric–substrate interface on charge accumulation from vacuum ultraviolet irradiation of low-*k* porous organosilicate dielectrics

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ABSTRACT

We compare the effect of various dielectric–substrate interfaces on charge accumulation during vacuum ultraviolet irradiation of capped low-*k* porous organosilicates to find that more charges are trapped in a dielectric stack deposited on silicon compared with the same stack deposited on copper. Insertion of a 5-nm interfacial thermal oxide layer further increases the amount of trapped charges in the dielectric. The difference between the photoemission and injection currents determines the number of charges trapped in the dielectric as a result of irradiation. Fewer charges are trapped when the injection current increases.

1. Introduction

Low-*k* porous organosilicate glass (SiCOH) is being used to replace silicon dioxide as an interconnect dielectric [1]. SiCOH is often exposed to plasma processing during fabrication, which results in exposure to both to charged-particle bombardment and vacuum ultraviolet (VUV) irradiation [2,3]. It is known that VUV irradiation can generate trapped positive charges in the dielectric [4–7]. The trapped charges can also be generated in pattern dielectrics depending on the energy of the VUV photons [8]. In this letter, we find that the number of trapped positive charges generated in the dielectric under VUV irradiation is related to the properties of the dielectric–substrate interface.

In back of the line processing, SiCOH/SiCN stacks are now deposited on Cu, whereas much previous work on characterizing this effect has been on Si [9,10]. Here we irradiate films deposited on Cu and, for comparison, model Si/SiO_2 films with VUV of energies and fluxes typically generated during plasma processing. We find that the nature of the dielectric–substrate interface changes the number of trapped charges in the dielectric.

2. Background

The trapped charge generated in a dielectric under VUV irradiation appears because of the processes of photoemission and injection [4–6]. Trapped positive charges are generated when electrons are photoemitted from defect states in the bandgap of the dielectric. Conversely, photoinjection of electrons from the substrate into the dielectric repopulates the defect states, hence reducing the amount of trapped positive charges.

A self-consistent electric field is induced by the trapped charges in the dielectric [6,11]. The self-consistent electric field increases with increasing VUV photon dose because the number of trapped charges increases. As the self-consistent electric field increases, photoemission is reduced [6]. On the other hand, photoinjection of electrons from the substrate into the dielectric can be approximated to be a constant during VUV irradiation since it depends primarily on the dielectric–substrate interface-barrier energy and the photon flux per unit time [4].

In addition to photoinjection, electrons can also be injected into the dielectric and/or undergo conduction through the dielectric by Fowler–Nordheim tunneling [12,13]. The tunneling current from the substrate is proportional to the number of interfacial defect states. The injection current during VUV irradiation is therefore the sum of the photoinjection and tunneling currents. However from our observations of photoemission current and leakage current we expect the tunneling currents will be small as compared to the photoinjection currents. To show this, we looked at the surface potential decay after irradiation. The leakage current, caused by Fowler–Nordheim tunneling, is much smaller than the photoinjection currents and therefore will be neglected.

It is plausible that photoinjected and/or tunneling electrons can be conducted from the substrate–dielectric interface to the dielectric–vacuum interface and are photoemitted [5,6,14]. Thus, at any given

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time during VUV irradiation, the photoemitted electron current will be proportional to 1) the number of depopulated electrons from the defect states and 2) the number of photoinjected electrons. The trapped charges due to the photon depopulation of defect states will continue to increase until a steady state is achieved. In steady state, no more trapped charges will be generated in the dielectric and the photoemitted electron flux will equal the flux of injected 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, the photoemission current is equal to the substrate current.

3. Experiment

A dielectric stack of 15 nm SiCN($k=5$)/175 nm SiCOH($k=2.4$)/15 nm SiCN($k=5$) is deposited with plasma-enhanced chemical vapor deposition on the following substrates. (1) Si, (2) Si with 5-nm of thermally grown oxide, and (3) Cu/Ta/NiSi deposited on Si. SiCN forms an interface with these three substrates. SiCN was used as a capping layer, as it is often used in device fabrication to improve mechanical strength of dielectric [15]. The increased mechanical strength helps withstand chemical mechanical polishing during fabrication process [16]. A description of the samples is shown in Fig. 1.

The samples under investigation have the same dielectric stack but different dielectric–substrate interfaces. It should be noted that trapped charge are generated in both SiCOH and SiCN [5]. The thicknesses of SiCOH and SICN are same in the three samples, hence the total number of defect states in the dielectric will be same for the three samples. The only difference will come from the dielectric–substrate interface. We use the dielectric stack deposited on silicon as a reference, and compare it with the other two. In comparison to the reference sample, the presence of a thin thermally grown oxide layer reduces the density of interface defect states [17]. This occurs because the dangling bonds from the silicon crystal termination are reduced [18]. The reduced interfacial states result in a smaller Fowler–Nordheim tunneling current. Hence the net injection current into the dielectric from the substrate will be smaller. Smaller injection current means less repopulation of the depopulated defect states since the steady-state condition is a balance between depopulation by photon excitation and repopulation by injection. Hence, we expect more trapped charges to be retained in the sample deposited on Si with the interfacial thermal oxide as compared to the reference sample.

For the dielectric stack deposited on Cu, we expect fewer trapped charges to be trapped in this sample as compared with the dielectric stack deposited on Si (reference sample). Ideally, the SiCN–Cu interface has a lower interface-barrier energy (0.9 eV) as compared to SiCN–Si (1.7 eV) [4,19–21]. As a result, the photoinjection current will be larger across the SiCN–Cu interface and less trapped charge

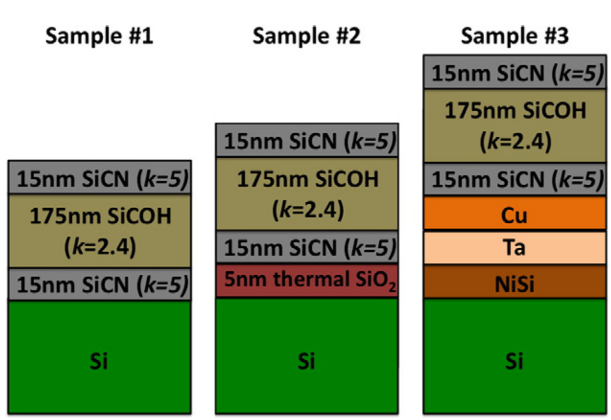

Fig. 1. The dielectric stack of SiCN/SiCOH/SiCN deposited on three different substrates.

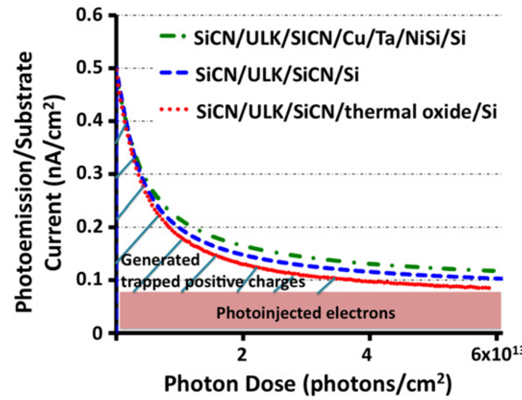

Fig. 2. Photoemission flux of SiCN/SiCOH/SiCN deposited on Cu, Si and Si with thermal oxide as a function of increasing dose of 8-eV VUV photons.

should be generated in this sample compared with the reference sample.

We have shown that VUV irradiation from plasma systems can be replicated by VUV irradiation at a synchrotron [22]. The UW-Madison synchrotron was used as a source of VUV photons. A picoammeter (Keithley-486) was used for photoemission/substrate-current measurements. The following measurements were made during irradiation: 1) VUV spectroscopy in which photoemission/substrate current is measured as a function of incident photon energy between 4.5 and 12 eV. A low photon flux was used in VUV spectroscopy to determine the spectrum in order to avoid generating appreciable trapped charges in the dielectric. 2) 8-eV VUV irradiation, which was chosen because it is less than the bandgap of SiCOH [4]. The photoemission/substrate current was measured as a function of time/dose during irradiation. The photon dose was determined as that necessary to achieve steady state. The VUV photon doses in this work (~10^{14}–10^{15} photons/cm^2) were comparable with photon doses received during typical plasma-processing steps. VUV spectroscopy was repeated after the 8-eV VUV irradiation.

Fig. 2 shows the photoemission/substrate current measured during 8-eV irradiation. As expected, the substrate current decreases with increasing photon dose for the three samples. The current is found to be same for the three samples at lower doses. This is because the samples have the same dielectric stack and hence, they are equally likely to generate the same number of photoemitted electrons. This will occur until the self-consistent electric field is created by trapped charges. However as the dose increases the self-consistent electric field builds up and hence we observe a difference in the photoemission/substrate currents.

In steady state, we see that the dielectric deposited on copper has the largest photoemission current, whereas dielectric deposited on Si with the interfacial thermal oxide has the lowest photoemission current at steady state. This occurs because the SiCN–Cu interface has a lower energy barrier in comparison to SiCN–Si. On the other hand, the interface energy barrier between SiCN and Si with thermally grown oxide is higher than SiCN–Si.

Table 1
Comparison of trapped charges generated by 8-eV VUV photons and photoinjection flux for SiCN/SiCOH/SiCN deposited on Cu, Si and Si with thermal oxide. The percentage increase or decrease in the trapped charge compared with the reference (top line) sample is indicated in the left-hand column.

	Trapped charges (#/cm^2)	Photoinjection current (pA/cm^2)
Stack/Si	2.25×10^{11}	103.4
Stack/oxide/Si	2.49×10^{11} (+10.7%)	84.6
Stack/Cu	2.00×10^{11} (−11.1%)	118.2

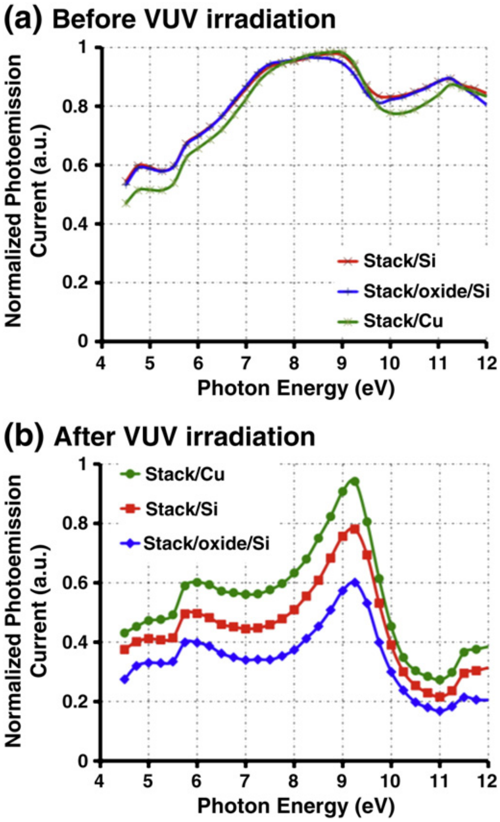

Fig. 3. VUV spectroscopy at 4.5–12 eV for SiCN/SiCOH/SiCN deposited on Cu, Si and Si with thermal oxide (a) before 8-eV VUV irradiation and (b) after 8-eV VUV irradiation.

To estimate the number of trapped charges generated per unit photon dose in the dielectric, we find the difference between the photoemission/substrate current and the injection current as a function of photon dose [23]. Then, we integrate the trapped charges generated per unit photon dose to obtain the total number of trapped charges. This can be expressed as

$$Q(t) = \int_0^t \left[I_{pe}(\varphi) - I_{pi}(\varphi)\right] d\tau$$

where I_{pe} and I_{pi} are the photoemission and photoinjection currents as functions of photon dose φ. Also, the photon dose φ, is a function of exposure time t. From the expression, it is expected that if photoinjection current is larger, the trapped charge accumulation will be lower.

Since we have assumed that the injection current is a constant, we can find the injection current from the steady-state photoemission/substrate current. The calculated value of trapped charges for the three samples after a VUV photon dose of 5.9×10^{13} photons/cm^2 is shown in Table 1. The injection current is also shown in the table. From the tabulated data, the inverse relation between trapped charges in the dielectric and injection current is verified. The dielectric deposited on Si with an interfacial thermal oxide had the most trapped charges, followed by the dielectric stack on Si. The dielectric stack on Cu had the smallest amount of trapped charges.

The results obtained from the substrate-current measurements were validated by VUV spectroscopy measurements at 4.5–12 eV. These are shown in Fig. 3. We observe that VUV spectroscopy curves for the three samples before irradiation overlap. Any small variations in the VUV spectroscopy curves are the result of irradiation during VUV spectroscopy. The spectrocospy flux was made as small as possible, but cannot be zero. However after 8-eV VUV irradiation, the dielectric stack on Cu had the largest photoemission/substrate current while the dielectric stack on Si with thermally grown interfacial oxide had the lowest photoemission/substrate current. This result is true for any photon energy between 4.5 and 12 eV.

4. Conclusion

Thus we find that the nature of the dielectric–substrate interface changes the number of trapped charges generated in the dielectric under VUV irradiation. This is because a lower dielectric–substrate interface energy barrier thereby increases the photoinjection current and therefore reduces the amount of trapped charges generated in the dielectric and *vice-versa*. Also the higher Fowler–Nordheim tunneling currents due to the increased interface defect states reduces the number of trapped charges generated in the dielectric during VUV irradiation. Consequently, modifications of the dielectric–substrate interface can be used as control knob to reduce positive charge accumulation during processing of low-*k* SiCOH.

Acknowledgements

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