Surface Potential Measurements of Vacuum Ultraviolet Irradiated Al_2O_3, Si_3N_4, and SiO_2

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***Abstract*—Vacuum ultraviolet radiation (VUV), generated during plasma processing of semiconductors devices can induce charge on dielectric materials. By exposing dielectric coated wafers to synchrotron radiation of varying energy, it is possible to separate the photoemission and photoconductive effects, both of which result in an increase in the surface potential of the dielectric. Maps of the surface potential induced on the dielectrics by VUV can be obtained by the use of a Kelvin probe.**

***Index Terms*—Plasma damage, plasma radiation, vacuum ultraviolet radiation (VUV).**

DURING plasma processing, charging of dielectrics plays a leading role within the damage mechanisms of semiconductor devices and plasma-processed materials in general. This damage mechanism is greatly influenced by the plasma-emitted vacuum ultraviolet (VUV) radiation. VUV radiation with energies in the range of 7–21 eV can induce charge on dielectric materials. The radiation is absorbed in the exposed dielectric and it results in the generation of electron-hole pairs. Electrons that have enough energy to escape the dielectric layer can then be photoemitted, leaving the positively charged holes in the dielectric. However, this can only occur when the dielectric is exposed to a flux of photons with an energy above its threshold for photoemission. When enough electrons are photoemitted, the dielectric will develop a positive surface-charge layer. As the dielectric surface charges so that fewer and fewer electrons are being photoemitted, the incident photons will generate electron-hole pairs that remain in the dielectric. This can only occur if these photons have an energy larger than the bandgap of the dielectric. Photons with wavelengths that are strongly absorbed by the dielectric cause the generation of electron-hole pairs only in a very thin surface layer and produces what is in effect a surface conductivity. On the other hand, radiation with wavelengths that are weakly absorbed by the dielectric causes the generation of carriers throughout the bulk of the dielectric and thus creates a volume conductivity. Under these conditions, free electrons in the conduction band and free holes in the valence band that escape initial recombination can travel under the action of an electric field toward the boundaries of the dielectric, resulting in charge separation. Charge separation causes the dielectric to become polarized, which also contributes to the surface potential of the dielectric.

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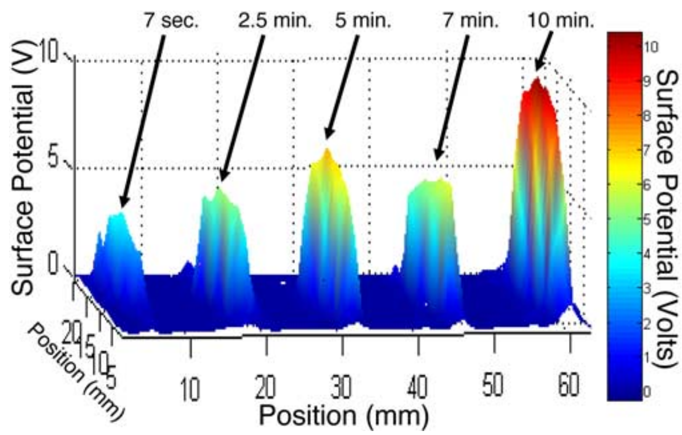

Fig. 1. Surface potentials measured with the Kelvin probe of 3000 Å of Si_3N_4 irradiated with 12-eV photons for various time durations.

To separate the damage effects, plasma-generated VUV radiation from charged-particle bombardment, we used monochromatic synchrotron radiation in the same photon energy range that is typically found in most processing plasmas [1]–[3]. The synchrotron source at the University of Wisconsin, Madison was used as a source of VUV photons to expose unpatterned dielectric-coated wafers. An elliptical photon beam with the dimensions of 25 mm $\times$ 10 mm was passed directly into a vacuum chamber connected to the synchrotron, which was evacuated to 10^{-8} torr. Dielectric-coated wafers were inserted into the vacuum chamber. The experimental arrangement has been previously described [4]. 3 h after VUV exposure, the samples were removed from the vacuum chamber and the surface potential was measured with a Kelvin probe.

Surface potential measurements, obtained using the Kelvin method [5], can determine the net charge as a function of position that resides in thin dielectric films after VUV irradiation. Once the surface potential is known, an estimate can be made for the VUV-induced charge density using the expression, $\sigma = -\varepsilon_0\varepsilon_r V_{SP}/d$. ε_0 is the permittivity of free space, ε_r is the relative permittivity of the dielectric, V_{SP} is the surface potential, and d is the thickness of the dielectric. The Kelvin probe measures both the charge due to photoemission (hole charge), as well the polarization charge due to a electron-hole pairs (an electric dipole after charge separation).

Surface potentials measurements on 3000 Å of Si_3N_4 irradiated with 12-eV photons and a photon flux of 6×10^{11} photons/(s cm^2) for time durations of 7 s, 2.5 min, 5 min, 7.5 min, and 10 min are shown in Fig. 1. It can be seen in Fig. 1 that the

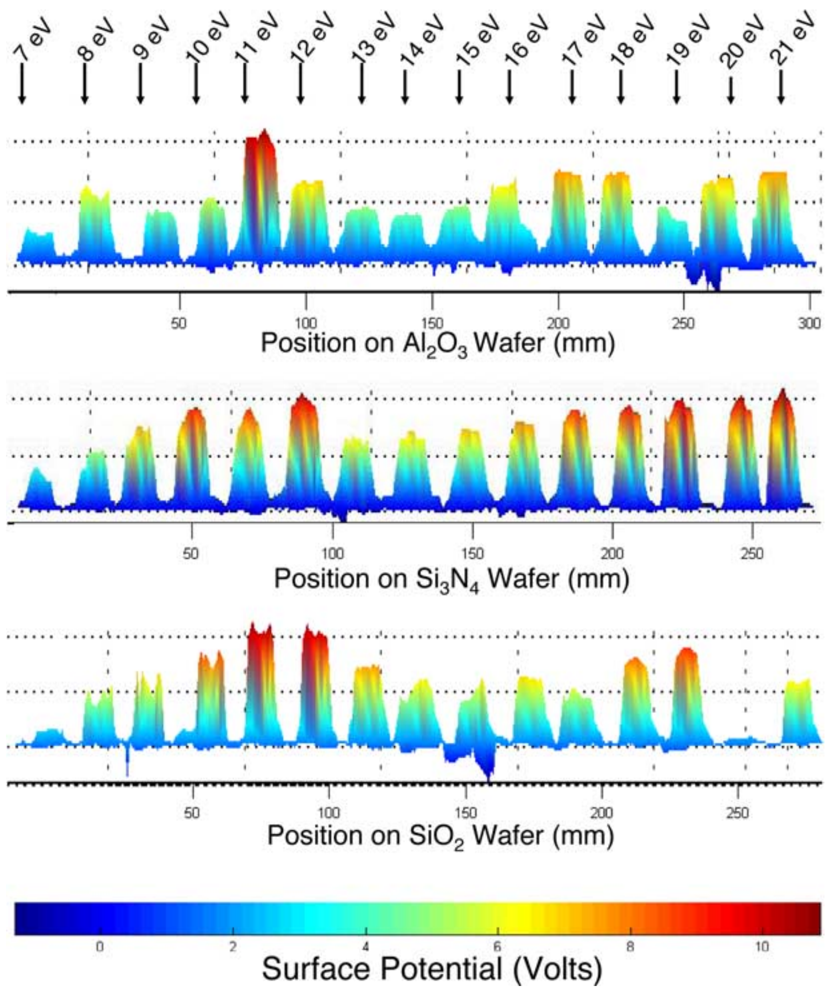

Fig. 2. Surface potentials (not normalized to photon flux) as a function of photon energy measured with the Kelvin probe on 3000 Å of Al_2O_3, SiO_2, and Si_3N_4 exposed to VUV for 10 min.

surface potential of Si_3N_4 increases to about 4 V and remains almost constant after 7.5 min of synchrotron radiation exposure. However, at some point in time between 7.5 and 10 min of irradiation, the surface potential increases to about 10 V. We believe that the initial charging of the dielectric to 4 V is caused by photoemission, which dominates at short exposure times and then saturates as the surface charge builds up. As more photons bombard the surface of the dielectric, more electron-hole pairs are being created. At longer exposure times, the electron-hole pair polarization charge begins to exceed the photoemission charge on the dielectric, thereby, resulting in the increase in the surface potential.

Fig. 2 shows the surface potential induced on 3000 Å of Al_2O_3, Si_3N_4, and SiO_2 after being irradiated for 10 min with VUV photons in the energy range of 7–21-eV. For both Al_2O_3 and SiO_2, it can be seen that 7 and 8 eV photons induce a minimal surface potential on the dielectrics. Since the energies of these photons are below the bandgap of both Al_2O_3 and SiO_2, we believe that this smaller surface potential is created by second-order photons from the monochromator. To verify this, a LiF window was placed between the monochromator and the wafer which absorbs all high-energy second-order photons. No photoemitted electrons were found under these conditions, and the surface potential did not increase. Also note that for 11- and 12-eV photons, the surface potential reaches its maximum and then drops for higher energy photons for all dielectrics. The threshold for photoemission for all of the dielectrics is believed to be around 11 or 12 eV. This is why the surface potential increases when the dielectrics are irradiated to photons in this range.

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