Synchrotron radiation-induced surface-conductivity of SiO_2 for modification of plasma charging

C. Cismaru[a] and J. L. Shohet
Center for Plasma-Aided Manufacturing and Department of Electrical & Computer Engineering, University of Wisconsin-Madison, Madison, Wisconsin 53706

J. P. McVittie
Center for Integrated Systems, Stanford University, Stanford, California 94305

(Received 20 December 1999; accepted for publication 21 February 2000)

In this work, we investigate the electrical surface conductivity that is temporarily induced in SiO_2 by exposure to monochromatic vacuum-ultraviolet synchrotron radiation for modification of plasma charging. Special preprocessed test structures were exposed to controlled fluxes of monochromatic synchrotron radiation in the range of 500–3000 Å (approx. 4–25 eV), the energy band of most plasma vacuum-ultraviolet radiation. The highest oxide surface conductivity is achieved during irradiation by photons with energies between 15 and 18 eV. This enhanced oxide surface conductivity holds the potential to discharge high-aspect ratio structures that charge up during plasma processing due to electron shading, and thus minimize plasma-processing-induced damage to semiconductor devices. © *2000 American Institute of Physics.* [S0003-6951(00)00316-8]

During plasma processing, charging of dielectrics plays a leading role within the damage mechanisms of semiconductor devices. However, device damage is also influenced by plasma-emitted x-ray, vacuum ultraviolet (VUV), and ultraviolet radiation.[1–3] It was determined that most processing plasmas emit radiation in the VUV energy band of 4–30 eV, with most of the radiation above 9 eV, the latter of which is approximately the energy band gap of SiO_2.[4] The radiation is absorbed in the exposed oxide layers and it results in the generation of electron-hole pairs. Although it has been established that electron-hole-pair generation in the oxide increases the SiO_2 bulk and interface trapped-charge density, which may affect device reliability,[5,6] we believe plasma VUV irradiation of silicon oxide can have a beneficial effect by inducing a temporarily enhanced oxide conductivity. This can reduce dielectric charging, especially that induced by electron-shading effects[7] during plasma etching of high aspect-ratio devices, by providing a safe way to discharge these structures and, thus, minimize charging damage. The enhanced conductivity can also have beneficial effects on the etching properties of SiO_2 such as reduction of notching, sidewall bowing, and trenching.

The goal of this work is to establish the effect of VUV radiation on the surface conductivity of SiO_2. The use of special semiconductor test structures, upon exposure to VUV radiation, enabled us to monitor the induced currents along the surface of SiO_2 layers as a function of the applied electric field.

It is desired that the investigation of the VUV-induced surface currents in SiO_2, as a function of oxide electric field, takes place under exposure of the test structures to processing plasmas, while the VUV-emission intensity and wavelength is measured. However, these measurements are not possible during plasma exposure because the plasma provides an additional current path to interfere with our measurements. To eliminate this, we used monochromatic synchrotron radiation in the same photon energy range to expose the test structures under vacuum. An additional advantage of using monochromatic synchrotron radiation is the ability to determine the dependence of measured quantities on the wavelength of the incoming radiation.

The exposure of the test structures was performed at the Synchrotron Radiation Center at the University of Wisconsin-Madison. The monochromatic light was supplied by the Aladdin synchrotron storage ring, passing through a VUV monochromator. The electron beam used to generate the synchrotron radiation had a current of up to 250 mA, at an energy of 800 MeV. The VUV monochromator that was connected to the beamline is a normal-incidence monochromator, in a Seya-Namioka mount, with an output energy range of 4–30 eV, and a bandpass of 3 Å.

Measurements of the VUV-induced currents along the surface of the oxide layers were made by using interdigitated, comb-like aluminum structures deposited on top of 1-μm thick thermally grown SiO_2 layers (Fig. 1) on Si substrates. The thickness of the oxide layer ensures that no current passes through the oxide between the aluminum ''fingers'' and the silicon substrate. Each structure has 2×25 aluminum fingers and an active area of exposed oxide of 6 mm$\times$6 mm. Several variations of this structure were built so as to have three different separation distances between the aluminum fingers of 5, 7, and 25 μm. The actual distances between the fingers as measured after fabrication were 5.6, 7.4, and 25 μm.

The test structures were mounted in a special vacuum chamber coupled to the beamline monochromator. The mounting unit was set so as to have normal incidence of the VUV beam on the surface of the structure. The monochromatic synchrotron light was focused on the test structure (the position of the light spot is shown in Fig. 1), with a spot dimension of 1 mm$\times$6 mm. During the measurements, the

[a]Present address: Conexant Systems, Inc., Newport Beach, CA 92660.

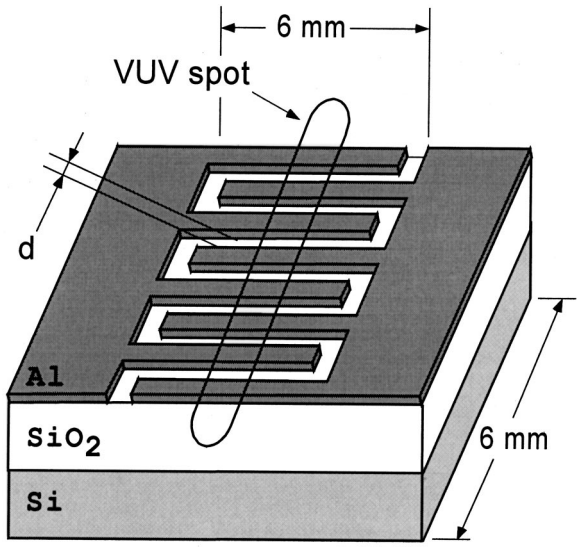

FIG. 1. Schematic of the test structure used for surface conductivity measurements of SiO_2 (not to scale).

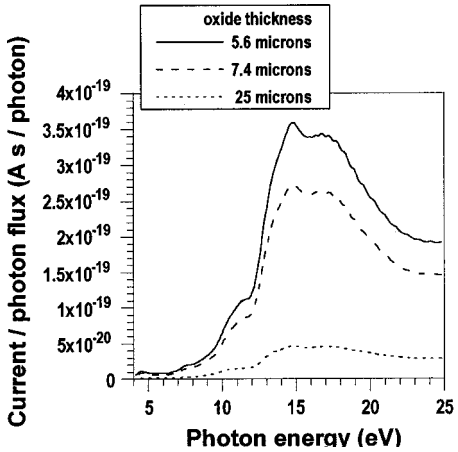

FIG. 2. VUV-induced electric current per unit photon flux as a function of photon energy, measured between electrodes positioned apart at various distances (5.6, 7.4, and 25 μm), for an applied voltage of 3.2 V.

chamber was evacuated to pressures in the 10^{-8} Torr range. For the measurements of the VUV-induced currents along the surface of the SiO_2 layer in between the aluminum fingers, electrical connections were made from the test structures to outside circuitry through vacuum feedthroughs. The test structures were connected in series with a Keithley 486 Picoammeter with a resolution of 10 fA and a variable-voltage battery pack with a maximum voltage of 100 V. A possible contribution to the measured current, in addition to the radiation-enhanced conductivity, is that due to secondary electron emission from the aluminum. The estimated emission current is too small to account for the measured values and, in addition, should scale with voltage and not electric field as seen in Fig. 3, for different electrode spacing.

Due to the fact that the monochromatic VUV photon flux incident on the test structures was not constant with respect to the photon wavelength, measurement of the absolute flux as a function of photon wavelength was needed prior to VUV exposure. The vacuum chamber has provisions for the measurement of the incident VUV flux without breaking the vacuum by using a calibrated photodiode of the type AXUV-100, manufactured by International Radiation Detectors, Inc. The maximum photon flux was 2×10^{12} photons/s at a photon energy of 11 eV, for an electron beam circulating in the synchrotron ring of 800 MeV energy and 200 mA intensity. This level of radiation is similar to that emitted by most high-density processing plasmas.[4]

To make sure that the exposure of the oxide layer to VUV radiation does not change the electrical properties of the oxide irreversibly, measurements of the surface currents were made as a function of the photon energy (wavelength) (Fig. 2) on pairs of identical test structures, by sweeping the photon wavelength upward from 4 to 25 eV for one structure, and then downward for the other structure. We also replicated the measurements several times by using the same structures. Because differences in these measurements were not higher than 5%, we concluded that the radiation of this intensity did not inflict permanent changes in the electrical properties of the oxide layer that can be traced through these measurements. Measurements of the VUV-induced currents were also made as a function of the voltage between fingers and the distance between them.

Due to the fact that the synchrotron photon flux reaching the sample is nonuniform with respect to wavelength, the measured electric current had to be referenced to the corresponding photon flux as a function of photon energy (wavelength), as measured by the calibrated photodiode. The data in Fig. 2 is represented in units of ampere-seconds/photon (current/photon flux) as a function of photon energy and voltage applied to the structures, for the three different test structures (5.6, 7.4, and 25 μm distance between finger electrodes).

An important feature in these measurements is that, for a constant electric field, the maximum current is obtained for irradiation with photons with energy between 15 and 18 eV. We believe this is due to several factors. First, at low photon energies (below the SiO_2 band gap), very few electron-hole pairs are generated upon absorption of incident radiation. Therefore, the measured current is very low. Second, at photon energies between 9 and 15 eV, less of the generated electron-hole pairs reach the structure's electrodes at lower energy, and the electrons and holes undergo recombination. Thus, the current will increase with increasing photon energy. Third, at high photon energies (above 18 eV), photon penetration in the oxide is lower (less than 200 Å).[8] In this case, two situations may exist: (1) the shallower conductivity layer and the higher photon energy may determine a higher density of generated electron-hole pairs close to the oxide surface, which may induce a velocity-saturation condition for these charge carriers as they travel across the oxide, and therefore a lower current; and (2) a higher photon energy increases the probability that photogenerated electrons are lost to the vacuum, by transferring sufficient energy to the electrons to cause them to leave the surface of the test structure. This, in turn, will also decrease the measured current.

To understand the dependence of the VUV-induced oxide surface currents on the electric field, similar measurements were made by changing the dc bias applied between the finger electrodes in the range of 0–100 V, while irradiating the test structures with monochromatic synchrotron light of 15 eV photon energy and constant photon flux. The

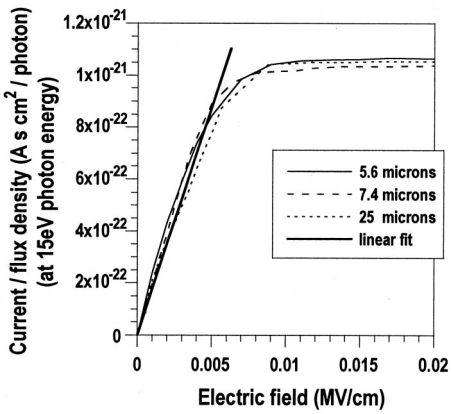

FIG. 3. Electric current across the SiO_2 surface measured between electrodes positioned apart at various distances (5.6, 7.4, and 25 μm), per unit photon flux density and photon energy of 15 eV, and a fit over the linear dependence of the measured current on the applied electric field.

results are displayed in Fig. 3. The measured current per unit photon-flux density is linear with the applied electric field up to a saturation value of about 7 kV/cm. Considering a measurement error of $\pm 5\%$ of the measured value, the currents follow the same curve, irrespective of the distance between the measuring electrodes.

This dependence of the measured current on the applied electric field under irradiation with photons of energy higher than the SiO_2 band gap energy pointed us toward a simple model based on a photoconductor.[9] Due to the fact that electrons are much more mobile than holes, they are swept out of the oxide in the presence of an electric field much faster than the holes. Therefore, in steady state, the number of electrons in the oxide is much smaller than the number of holes, and thus, the VUV-induced electric current is governed by hole transport. The current (in amperes) is then

$$I = eY\tau\mu\Phi\frac{V}{d^2}, \tag{1}$$

where e is the electronic charge, Y is the absolute yield of SiO_2 (generated e-h pairs/absorbed photon), τ and μ are the hole lifetime and mobility, respectively, Φ is the incident photon flux in number of photons per second, V is the applied voltage, and d is the distance between the measuring electrodes.

In Eq. (1), variables I, Φ, V, and d are known quantities. Thus, it is possible to use Eq. (1) with a parameter $C = eY\tau\mu$ to fit the data. In the case presented in Fig. 3, the fitting parameter has a value of $3.5\times10^{-26}\,\mathrm{cm^2\,s\,\Omega^{-1}}$ for exposure to 15 eV radiation. In Eq. (1), the fitting parameter C is the only variable to depend on the radiation wavelength. Therefore, it will have the same dependence on the photon energy as the measured current per unit photon flux, which is shown in Fig. 2. Thus, based on the value of C found for radiation of 15 eV energy, similar values of C can be determined for other photon energies, and, by integration over plasma emission spectra,[4] values of C for various high-density plasmas can be obtained, such as $1.2\times10^{-26}\,\mathrm{cm^2\,s\,\Omega^{-1}}$ for argon, and a value of $0.9\times10^{-26}\,\mathrm{cm^2\,s\,\Omega^{-1}}$ for oxygen. In these cases, the oxide surface conductivity can be calculated as $4.4\times10^{-12}\,\Omega^{-1}$ for argon and $4.5\times10^{-13}\,\Omega^{-1}$ for oxygen. The implications of these levels of the VUV-induced surface conductivity of SiO_2 in minimizing the charging damage can be analyzed for a particular plasma processing step, such as high-aspect-ratio metal etch with a SiO_2 hard mask. We believe that, in such a case, the oxide VUV-induced surface conductivity is very efficient in reducing the amount of differential charging induced by electron shading.

In summary, we measured electrical surface conductivity of SiO_2 exposed to monochromatic VUV synchrotron radiation by use of special test structures, exposed to controlled fluxes of VUV light in the range of 500–3000 Å (approx. 4–25 eV), the energy band of most high-density plasma VUV radiation. For irradiation with photons of energy higher than SiO_2 band gap energy, the results show a similar dependence of the VUV-induced current on the applied electric field to a simple photoconductor. Depending on the intensity of the irradiating VUV light, the induced oxide conductivity can hold the potential to reduce differential charging induced by the electron-shading effect during etching of high-aspect-ratio features.

The authors wish to thank R. Hansen at the Synchrotron Radiation Center for technical assistance during the experiments. SRC is a national facility, funded by the National Science Foundation under Award No. DMR-9531009. This work was also supported in part by the National Science Foundation under Grant No. EEC-8721545 and the Semiconductor Research Corporation under Contract No. 98-1J-106.

[1] R. A. Gdula, IEEE Trans. Electron Devices **26**, 644 (1979).
[2] T. Yunogami, T. Mizutani, K. Suzuki, and S. Nishimatsu, Jpn. J. Appl. Phys., Part 1 **28**, 2172 (1989).
[3] T. Mizutani, in *International Symposium on Plasma Process-Induced Damage*, edited by K. P. Cheung, M. Nakamura, and C. T. Gabriel (NCCAVS, Sunnyvale, CA, 1996), p. 157.
[4] C. Cismaru and J. L. Shohet, Appl. Phys. Lett. **74**, 2599 (1999).
[5] S. A. Bell and D. W. Hess, J. Electrochem. Soc. **139**, 2904 (1992).
[6] A. W. Flounders, S. A. Bell, and D. W. Hess, J. Electrochem. Soc. **140**, 1414 (1993).
[7] K. Hashimoto, Jpn. J. Appl. Phys., Part 1 **32**, 6109 (1993).
[8] T. Tatsumi, S. Fukuda, and S. Kadomura, Jpn. J. Appl. Phys., Part 1 **33**, 2175 (1994).
[9] R. H. Bube, *Photoconductivity of Solids* (Wiley, New York, 1960).