Measuring vacuum ultraviolet radiation-induced damage

J. L. Lauer, J. L. Shohet,[a] and R. W. Hansen[b]
Center for Plasma-Aided Manufacturing and Department of Electrical and Computer Engineering, University of Wisconsin-Madison, Madison, Wisconsin 53706

(Received 7 October 2002; accepted 10 February 2003; published 1 July 2003)

During plasma processing of semiconductors, ultraviolet (UV) and vacuum ultraviolet (VUV) radiation are present, but their effects can be difficult to separate from those due to charged particles incident on the wafer. The contribution of VUV photon irradiation to gate-oxide damage, and damage to dielectric materials in general, was examined using two measurement techniques that can predict the possibility of damage. They are (1) surface potential measurements and (2) electrically erasable read-only memory transistors (CHARM-2 wafers). To isolate the radiation effects, unpatterned oxide-coated wafers and CHARM-2 wafers were exposed to VUV synchrotron radiation. VUV exposure of dielectrics and conductors results in an accumulation of positive charge due to photoemission. As a result, it can become difficult to distinguish the photoemitted from the plasma-deposited charge. In addition, it was determined that the UV monitors on CHARM-2 wafers did not respond to VUV radiation. © *2003 American Vacuum Society.* [DOI: 10.1116/1.1565152]

I. INTRODUCTION

In complementary metal–oxide–semiconductor (CMOS) device fabrication, plasma processing plays an important role since it has many advantages in terms of process convenience, directionality, and high resolution. However, conductors and dielectrics that are directly exposed to the plasma environment can charge up due to an imbalance of electron and ion flux to the conductor (e.g., electron shading[1,2] and nonuniform plasma[3] mechanisms). If a charged conductor is connected to the gate electrode of a CMOS device, this can lead to dielectric breakdown[4] of the gate dielectric through Fowler–Nordheim[5] tunneling. During the last decade, plasma-induced damage research has focused on the role of charged particles. Little or no consideration has been given to photon bombardment. To comply with the higher etch rates required for single wafer plasma processing, there is an increasing use and demand for high-density plasma tools.[6,7,27] The intensity of vacuum ultraviolet (VUV) radiation often becomes enhanced with high-density plasmas because the high-energy electron density is also increased, which often is responsible for producing VUV photons.

Two damage-measurement techniques for monitoring charged particle and photon irradiation damage in processing plasmas used today are (1) surface potential measurements[8] and (2) electrically erasable read-only memory transistors[9] (CHARM2 wafers). Surface potential measurements, obtained with the Kelvin method,[10,11] have been used to measure the net charge as a function of position that resides in an insulating film after it was exposed to a processing plasma. CHARM-2 wafers are EEPROM sensors that are specifically designed to record either the voltage, current flux, or ultraviolet (UV) dose during the plasma process. Many authors have examined and compared[4,12] both measurement techniques' abilities to monitor the plasma-processing environment and relate this information to the possibility of damage in real devices. Most authors conclude that, while each technique has its strengths, no single measurement can completely characterize all possible damage mechanisms. Instead, a combination of measurement approaches is needed,[4,12] with each measurement providing insight on which damage mechanism is the most dominant, and thus the most likely cause of plasma damage. Still, the frequent lack of correlation between damage monitors and product yields continues to nurture skepticism that perhaps not all mechanisms contributing to charging damage have been identified.[13] It is the purpose of this work to evaluate the ability of surface potential measurements and CHARM-2 wafers to respond to VUV irradiation and to determine whether VUV irradiation can produce or ameliorate plasma damage that has typically been interpreted as resulting from charged-particle bombardment.

II. BACKGROUND

In order to examine the effect of VUV irradiation to, and the potential degradation of, electronic materials it is necessary to discuss in some detail the basic mechanisms that result in charge being deposited or generated in both conductors and dielectrics from exposure to photon irradiation. It is also important to determine where within dielectric materials the charge accumulates.

During plasma processing, all surfaces within the vacuum chamber that are in the direct line of view of the plasma, including the wafer being processed, are bombarded with a flux of photons in addition to the fluxes of charges and neutral particles. The intensity and energy of the photon flux is dependent on the plasma processing conditions (i.e., pressure, rf power, feed gas, etc.). The plasma-emitted photons interact differently with the surfaces they irradiate depending on the energy of the photons and the electrical properties of the material they bombard. Four processes can occur: (1) photoemission from a conducting material, (2) photoemis-

---

[a] Electronic mail: shohet@engr.wisc.edu
[b] Present address: Synchrotron Radiation Center, University of Wisconsin-Madison, Madison, WI 53706.

sion from a dielectric material, (3) charge carrier generation in dielectric materials, and (4) photoinjection of charge carriers into a dielectric from an underlying conductor.

It is well known that photon bombardment of conductors can cause the ejection of electrons from a conducting surface (photoemission). For pure conductors, photoemission depends on the work function $e\Phi$ of the conductor, with a threshold for emission[14] of $hc/\lambda = e\Phi$, where h is Planck's constant, c is the speed of light, and λ is the wavelength of the photon. When a floating conductor is exposed to a flux of photons, with energies greater than the threshold for emission, it develops a net positive charge that continues to increase until the photoemitted electrons no longer have enough energy to overcome the resulting positive electrostatic potential on the conductor. In a processing plasma, positive charging of conductors exposed to the plasma has been typically interpreted as resulting from ion bombardment, but photoemission of electrons may also contribute to this potential.

Photoemission can also occur in dielectric materials.[15] In this case the photon energy threshold for photoemission depends on the energy band gap eV_{gap} and the electron affinity eV_{affinity} of the dielectric material. This is expressed as $hc/\lambda = eV_{\mathrm{gap}} + eV_{\mathrm{affinity}}$. When a dielectric is exposed to a flux of photons with the above energy, it will develop what is essentially a positive surface-charge layer, which continues to build up, just as the case of the conductor, until the photoemitted electrons no longer have enough energy to overcome the surface potential created by the surface charge layer.[15] The charge carriers (holes) that make up the surface-charge layer can redistribute within the dielectric, but their movement is limited by their mobility and the magnitude of the local electric field that may exist within the dielectric material. In general, charges produced on the surface will migrate into the bulk of the solid and form a volume space charge, unless caught in very deep surface traps.[16] As the dielectric surface is charging, so that fewer and fewer electrons are being photoemitted, the photon radiation will also generate electron–hole pairs that remain in the dielectric.

Dielectric materials bombarded with photons that have an energy larger than the band gap of the dielectric can also generate electron–hole pairs within the dielectric. The photons release their energy to electrons in the valence band and excite them into the conduction band, leaving a hole in the valence band. Irradiation of a dielectric with strongly absorbed radiation causes the generation of electron–hole pairs only in a very thin surface layer and produces what is effectively a surface charge. On the other hand, weakly absorbed radiation causes the generation of carriers throughout the bulk of the dielectric and thus creates a volume space charge.

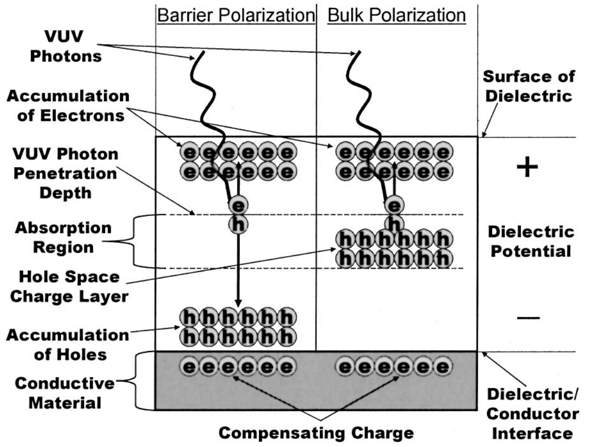

FIG. 1. Barrier ($\mu_h, \mu_e \gg 1$) or bulk ($\mu_h \ll 1, \mu_e \gg 1$) polarization that occurs when a dielectric is irradiated with ionizing radiation.

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 towards the boundaries of the dielectric, resulting in charge separation. The displacement of charge carriers and the resulting photocurrent drawn through the dielectric due to the electric field is dependent upon charge carrier mobility and recombination characteristics in the bulk of the dielectric.[17] If the dielectric is deposited on a conductor, the height of the dielectric–conductor barrier also plays an important role in this process. If the bulk mobilities of both carrier types are large and the dielectric–conductor barrier is high for the holes, then for a positive dielectric potential as is shown in Fig. 1, holes will accumulate at the dielectric–conductor interface and electrons will accumulate at the surface of the dielectric, producing what is called barrier polarization.[17] A compensating charge may be induced on the conductive material, unable to cross the energy barrier between the conductor and the dielectric, as shown in Fig. 1. When the height of the dielectric–conductor barrier is small enough so that the conductor will accept carriers from the dielectric, a floating conductor would then develop a net electrostatic charge, which can also contribute[18] to or reduce[19] gate dielectric damage.

If the bulk mobility of the electrons is significantly larger than that of the holes, then for a positive dielectric potential the electrons will accumulate at the surface of the dielectric and a space-charge layer of immobile holes will develop within the absorption region of the bombarding photons (Fig. 1), producing what is called bulk polarization.[17] In this case, the thickness and depth of the fixed space-charge layer will depend on the penetration depth of the incoming photons within the dielectric, since the holes are relatively immobile and remain near their point of generation. After irradiation, the charge distribution is greatly immobilized, but still subject to a dark current decay (typically over periods of the order of days).[17]

Irradiation by subband-gap photons is incapable of creating electron–hole pairs in the oxide, but is capable of exciting electrons from the silicon substrate into the oxide. While some studies show that the electron or hole injection from the silicon substrate into the oxide increases the interface trapped-charge density at the Si/SiO$_2$ interface,[20,21] others report that this photocarrier injection is beneficial, where it ''anneals'' the interface charge[22,23] through a recombination process.

In addition trapping, detrapping, and retrapping may occur when charge carriers are created or injected into the dielectric. These trap sites may be due to a wide range of crystal defects, such as impurities, stacking faults, dislocations, and other lattice defects, which give rise to additional but highly localized energy levels within the energy band gap. The traps may be deep or shallow in energy. If the difference in energy between the electron trapping level and the bottom of the conduction band is large compared to kT, where k is Boltzmann's constant and T is the temperature, the traps are considered deep, and vice versa. Shallow traps reduce the mobility of the carriers, since the induced thermal energy suffices to redissociate a carrier from such a trap. Note that in a processing plasma the value of kT at the surface of the wafer can be fairly large. However, the excitation of carriers from deep traps is a rare event that depends entirely on the value of kT and on the depth (in energy) of the trap.[16] The dominant type of SiO_2 defect (hole trap) responsible for radiation-induced trapped oxide charge has been identified by electron spin resonance techniques as the E' center, a trivalent silicon atom that has an unpaired electron in a dangling orbital and is back-bonded to three oxygen atoms.[23]

Since all of these photoinduced mechanisms are happening simultaneously in a plasma-processing environment, and many of them are confounded with plasma charging effects, it is difficult to pinpoint the role VUV irradiation plays in plasma damage to CMOS devices. Recent experimental work has shown that exposure to VUV as opposed to UV radiation has the possibility of producing either (1) further damage[18] or (2) a synergistic effect that decreases the damage produced by plasma-processing-induced charging.[19,24] In general, most plasma-processing systems generate significant amounts of VUV radiation concomitantly with UV and fluxes of charged particles. As a result, it is important to determine whether any plasma-damage monitors would be affected by the presence of VUV radiation.

III. EXPERIMENTAL CONFIGURATION

To separate the plasma induced damage effects of 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.[25–29] The synchrotron source at the University of Wisconsin, Madison was used as a source of VUV photons. Radiation from the synchrotron was passed through a normal-incidence Seya-Namioka monochromator with 400 μm slits that has an output energy in the range of 4–30 eV, and a bandpass of 3 Å. The beam was then passed directly into a vacuum chamber which was evacuated to 10^{-8} Torr.

The experimental system inserted in the vacuum chamber is shown in Fig. 2. It was used to measure how a floating oxide-coated semiconductor wafer charges up during VUV irradiation. The incident beam was oriented normally to the surface of the wafer. The photoemission current from the surface of the wafer, as well as the voltage on the silicon substrate, was monitored during VUV exposure. This was accomplished by placing an aluminum plate 3.5 cm in front of, but electrically insulated from, the wafer, as is shown in Fig. 2. The aluminum plate has a hole in it to allow the VUV photons to be normally incident upon the oxide-coated wafer. The photon beam was elliptical and measured to be about 25×10 mm^2 on the wafer surface. A dc bias voltage of 48 V was placed on the aluminum plate to insure that most of the photoemitted electrons would be collected. This also allows us to simulate a positive plasma potential above the wafer surface. The photoemission current was measured with a Keithley 486 picoammeter and the voltage on the substrate was measured with a Keithley 617 electrometer.

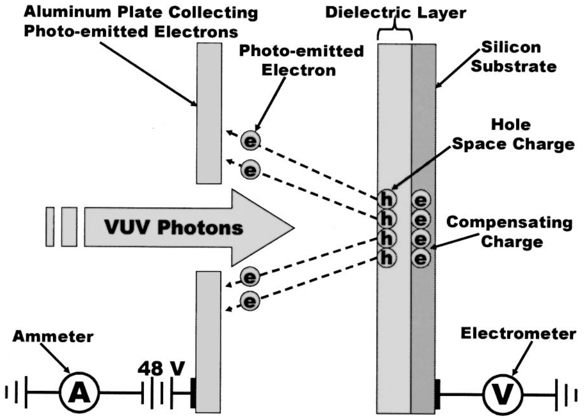

FIG. 2. Experimental system used to measure the photoemission current and substrate voltage during VUV irradiation.

A. Surface potential

Three hours after VUV exposure, the sample was taken out of the vacuum chamber and the surface potential was measured with a Kelvin probe.[8,30] When a vibrating electrode (Kelvin probe) is placed near the surface of a charged dielectric, the varying capacitance induces a time-varying voltage at the tip of the vibrating Kelvin probe. By compensating the field in the air gap between the charged dielectric and electrode with a dc voltage V_{SP} until the ac voltage (and thus the electric field above the dielectric) vanishes, 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, and d is the thickness of the dielectric. The Kelvin probe is a noncontacting device and has the additional advantage that a measurement of the air-gap thickness is not necessary to determine the effective surface-charge density.

A volume-charged dielectric behaves, as far as its external field is concerned, as if it had surface-charge densities on both its top and bottom surfaces. These quantities are therefore often referred to as ''projected'' or ''effective'' surface-charge densities,[17] and any volume-charge density can be expressed in terms of these effective surface-charge densities. The Kelvin probe can only measure the effective charge density; it cannot directly determine the charge distribution within the thickness of the dielectric.

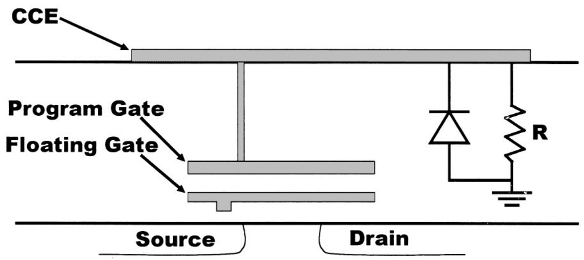

FIG. 3. Schematic of a CHARM2 device. These devices come in various forms and may include a diode and/or a resistor, as pictured.

B. CHARM2 wafers

CHARM2 wafers were also exposed to VUV radiation in the same experimental setup shown in Fig. 2 with the exception that, due to the size of the CHARM2 wafer (15 cm), the aluminum plate could not be placed in front of the wafer. Instead, the substrate of the CHARM2 wafer was biased with a dc voltage and the current to the substrate was measured.

Figure 3 shows the basic structure of the devices on a CHARM2 wafer.[12,31] The sensor is an EEPROM transistor that consists of a program gate, a floating gate, a source, and a drain. An antenna is connected to the program gate, and is often called the charge collection electrode (CCE).[32] The sensors on CHARM2 wafers come in various forms and may include a diode and/or a resistor, as shown in Fig. 3. Resistors are used to measure currents while diodes are used to choose the polarity of the charge to be measured. Electrostatic charge deposited on the CCE gives rise to a potential that is proportional to the amount of deposited charge and the capacitance between the CCE and the substrate. This potential programs the EEPROM memory transistors by altering their threshold voltages in proportion to the potential on the CCE. Thus the monitor is a polarity-sensitive peak voltage detector with memory.[33]

The addition of a diode connected between the CCE and the wafer substrate creates what is called a ‘‘unipolar’’ device, which provides for monitoring the peak negative or positive transient effects for the given polarity. Without the diodes, the EEPROM records only the peak value of the last transient, if sufficiently large, while erasing any record of a transient of the opposite polarity that may have occurred earlier.[33] This type of sensor is called a ‘‘simple’’ device. Design modifications to the EEPROM potential sensors can make them sensitive to UV radiation. A change in threshold voltage of a UV monitor is proportional to the integrated UV dose reaching the wafer during the course of the exposure. The three types of sensors are designed to record this information separately so that each of these effects can be measured without disturbing the other measurements.

IV. EXPERIMENTAL RESULTS

A. Surface potential measurements

The photoemission current measured during irradiation of a 3000 Å surface film of thermally grown SiO_2 on a silicon substrate by 12 eV photons at three different photon flux densities (10^{11}, 10^{10}, 10^9 photons/cm^2 s) is shown in Fig. 4(a) and the voltage of the silicon substrate during the same exposures is shown in Fig. 4(b). Note the exposure with the highest photon flux density has a very large transient photoemission current rising to its maximum within a few milliseconds and then dropping rapidly to zero. The voltage on the substrate also increases rapidly to nearly the bias voltage of the aluminum plate (48 V) in front of the irradiated dielectric.

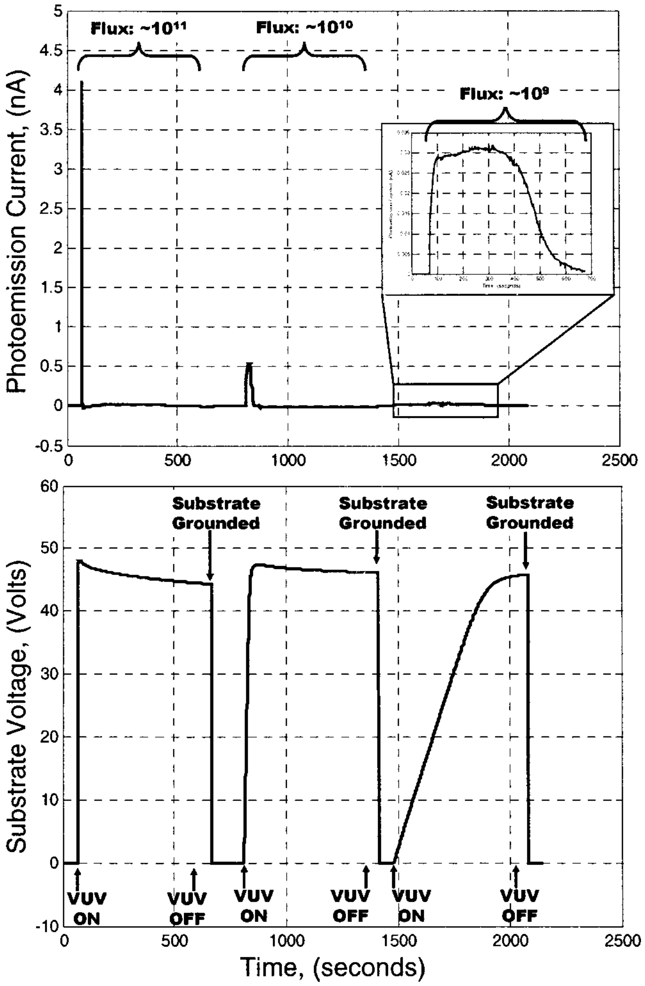

FIG. 4. (a) Photoemission current collected by the aluminum plate in front of the VUV irradiated SiO_2 coated silicon wafer as a function of time. (b) Voltage on the silicon substrate during the same exposure shown in (a). The photon fluxes as shown are 10^{11}, 10^{10}, and 10^9 photons/cm^2 s. The photon energy is 12 eV.

Very similar results are seen with the other exposures except that they do not charge up as quickly, as should be expected, since the photon flux density to the dielectric surface is much smaller. In all cases, the silicon substrate charged up to nearly the voltage that is on the aluminum plate, and remained at this potential until the silicon substrate was grounded. A positive charge was measured at the electrometer because of the compensation charge (see Fig. 2) that is attracted to the SiO_2/Si interface from the silicon substrate by the residual charge in the dielectric that was produced by photoemission.

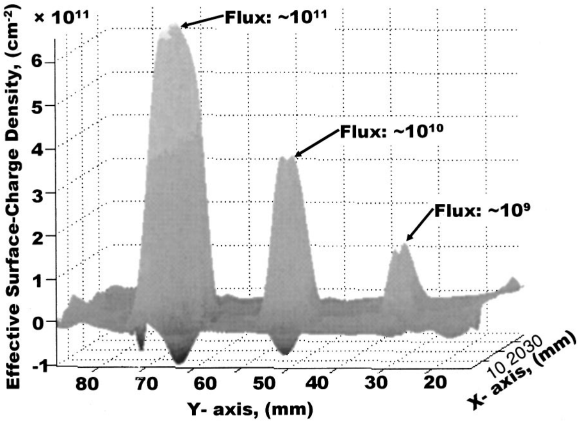

FIG. 5. Effective surface-charge density map measured after VUV exposure.

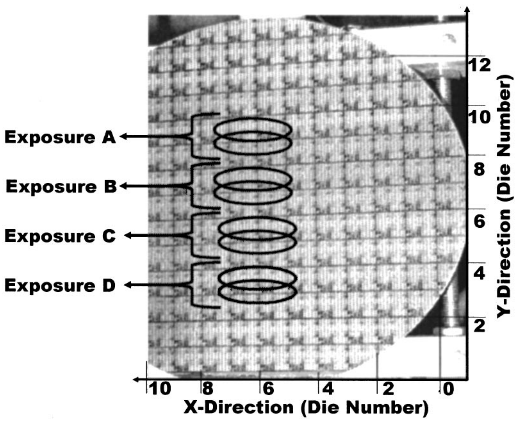

FIG. 6. Photograph of a CHARM2 wafer with the locations of multiple VUV beam exposures indicated by the elliptical circles.

If we consider that the aluminum collecting plate represents a positive plasma potential, a dielectric-coated conductor irradiated with ionizing photon radiation will attempt to charge up to the plasma potential, although the electrons in an actual plasma keep the surface of the dielectric at the plasma floating potential.[34]

By integrating the photoemission current in Fig. 4(a) over the time duration of each VUV exposure, we can find the total electron charge that was photoemitted and collected by the aluminum plate. In all three exposures for different photon-flux intensities, the total photoemitted charge was found to be about 1.6×10^{-8} C. Therefore, if photoemission were the only effect, we would expect the surface potential for all three cases shown in Fig. 4 to be the same. Figure 5 shows the effective surface-charge density measured after VUV exposure. It is clear that the surface potential is not the same in all three cases, and thus there must be some other effect taking place. We believe that the extra induced-charge density is due to charge carriers that are created in the oxide layer by the VUV photons. The charge carriers then drift in response to the electric field created by the photoemitted charge, causing charge separation. This produces a photo-emf that is set up in a direction perpendicular to the surface of the dielectric. This emf is called the Dember voltage.[16] However, the Dember voltage only develops if there is a difference in mobility of the carriers created. After irradiation, the charge distribution is greatly immobilized and is fixed. Thus the Dember voltage remains and can be measured with the Kelvin probe. However, depending upon the field direction, additional charge motion can take place.

The trapped-charge buildup in thick oxides deposited over a silicon substrate in areas between adjacent transistors can have detrimental effects on the performance of an integrated circuit. When enough positive charge builds up, the doped silicon substrate can invert and become conductive, thus resulting in "cross talk" between adjacent devices. Work by Sze[35] indicates that trapped oxide charge densities of 8.7×10^{10} /cm^2 and 3.2×10^{11}/cm^2 will invert *p*-type silicon substrates doped at 10^{15} /cm^3 and 10^{16} /cm^3, respectively.[28] Therefore, as seen in Fig. 5, this charge density has been achieved with a 600 s exposure to a 12 eV photon-flux density greater than 10^{10} photons/cm^2 s.

B. CHARM2 wafers

In order to determine the effects of VUV radiation on CHARM2 wafers, they were mounted in the vacuum chamber at the synchrotron using the same experimental system so that precise alignment of the VUV beam and the dies on the wafer surface could be obtained. This made it possible to quantify the charging effect of VUV irradiation. Figure 6 shows a photograph of a CHARM2 wafer with the locations of the VUV beam exposures indicated by the elliptical circles. Halfway through each exposure, the CHARM2 wafer was moved down 6 mm (as shown by the overlapping elliptical circles) while the VUV beam remained on to insure that at least one entire die would be exposed. It is important to note that because of the overlap, some dies would be exposed twice as long as the surrounding dies. The substrate of the CHARM2 wafer was biased at −48, +48, −48, and +48 V, for exposures A, B, C, and D respectively, while the current to the wafer substrate was measured. The photon flux density for all four exposures was 5×10^{10} photons/cm^2 s at an energy of 15 eV. The total exposure times were 600, 600, 300, and 300 s for exposures A, B, C, and D, respectively.

Before VUV exposure, the CHARM2 wafers were calibrated and programmed to a threshold voltage of approximately −5 V on a parametric tester. After VUV exposure, the wafers were returned to Wafer Charging Monitors for analysis. Figure 7 shows a wafer map of the maximum threshold voltage shift recorded on any positive "unipolar" device within each die. It can be seen that there is positive charge only under the locations of the VUV beam when the wafer substrate is biased with −48 V. Since no charge was deposited on the wafer from the synchrotron, the only possible source for charge must be photoemission of electrons. The unipolar devices exposed to VUV radiation when the wafer substrate was biased with +48 V showed no response to the VUV beam exposure. This is also consistent with photoemission, since the 15 eV photons are unable to create photoemitted electrons with energies greater than the bias voltage on

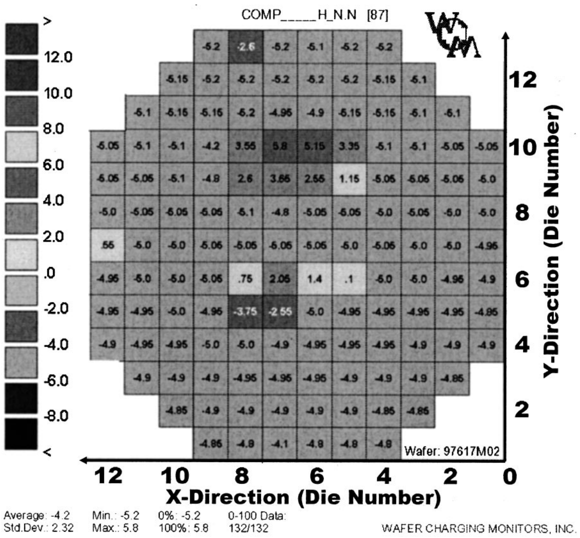

FIG. 7. Wafer map of positive "unipolar" devices: the maximum threshold voltage shift recorded on any positive unipolar device within their respective die.

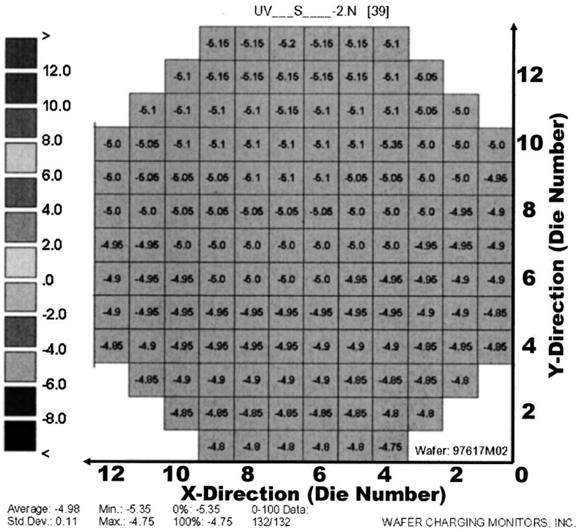

FIG. 9. Wafer map of UV sensors: the most sensitive UV sensor in each die.

the wafer substrate, and thus the electrons never leave the surface. Also note that the dies where the VUV exposures overlapped show a larger voltage shift than the surrounding dies.

Figure 8 shows a map of the maximum voltage shifts recorded on the "simple" devices (an EEPROM transistor attached between the CCE and substrate, no diode) within each die. Very similar results are seen to those in Fig. 7, although the voltage shifts are slightly larger than the unipolar devices (Fig. 6), since the diodes would be expected to leak a little bit.

Figure 9 shows a map of the threshold voltage of the most sensitive UV sensor[36] within each die on the CHARM2 wafer. It can be seen that there is no evidence of VUV under all conditions. This is consistent with the notion that 15 eV photons would be absorbed in the 1 μm oxide covering the UV detector, and therefore would not reach the EEPROM transistor.[36] During VUV irradiation of the CHARM2 wafer, the current flowing to the substrate for all four exposures was measured and is shown in Fig. 10. When the wafer was biased with −48 V (exposures A and C) there was a short pulse of current drawn when the VUV was turned on as well as when the wafer was moved half way through the exposure. The substrate current appears to be due to photoemission. When the CHARM2 wafer was biased with +48 V (exposures B and D) no current is drawn except for a small leakage current. The currents shown in Fig. 10 are consistent with results previously published[15] for VUV-irradiated aluminum oxide with similar bias conditions and experimental arrangements. Also, the negative "unipolar" devices on the VUV exposed CHARM2 wafer did not show any response to the VUV beam.

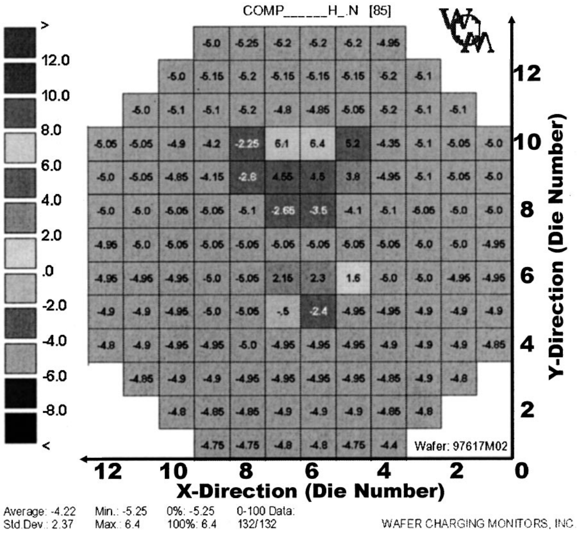

FIG. 8. Wafer map of a "simple" devices: the maximum threshold voltage shift recorded on "simple" device within their respective die.

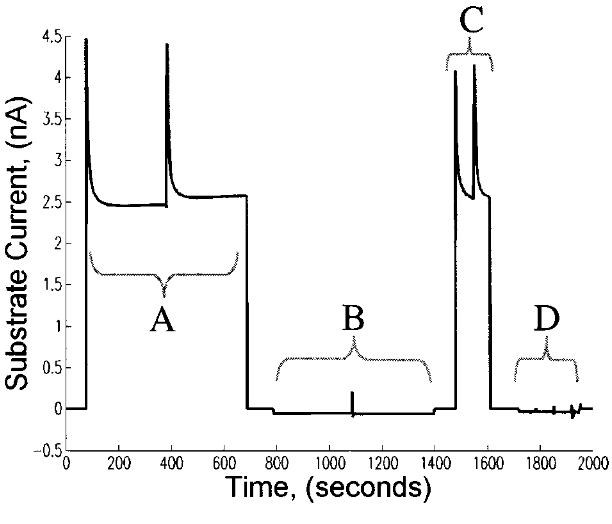

FIG. 10. Current to the substrate of the CHARM2 wafer during VUV irradiation as a function of time.

V. DISCUSSION AND CONCLUSION

This work has shown that when SiO_2 is exposed to a photon-flux density with an energy larger than its threshold for photoemission, it can induce a positive charge density on the dielectric. The amount of charge deposited by *photoemission*, for a fixed amount of time, depends on the photon flux intensity, the bias voltage, the thickness of the dielectric, and the photon energy and for long times, reaches a fixed value, as long as the photon energy is above the threshold for photoemission. However, the net charge in the dielectric results from both photoemission of electrons from the surface as well as from the charge carriers that are generated within the oxide. This type of charge accumulation in the oxide region between adjacent transistors may result in ''cross talk'' between devices.[35]

This work has also shown that the use of CHARM2 wafers must be made carefully, especially in those situations where VUV generation is significant, such as in processing plasmas. Positive-charge generation by VUV photoemission may result in CHARM2 wafers recording charge measurements that are higher than that produced by charged particle bombardment alone. In addition, the UV sensors on the CHARM2 wafers may not be able to detect that VUV radiation is present in the process chamber.

ACKNOWLEDGMENTS

The authors are grateful to W. A. Lukaszek of Wafer Charging Monitors and John Hu of LSI Logic for the loan of the CHARM-2 wafers and their analysis. This work was performed in part at the University of Wisconsin Synchrotron Radiation Center which is supported by the National Science Foundation under Grant No. DMR- 0084402.

[1] K. Hashimoto, Jpn. J. Appl. Phys., Part 1 **32**, 6109 (1993).
[2] K. Hashimoto, Jpn. J. Appl. Phys., Part 1 **33**, 6013 (1994).
[3] K. P. Cheung and C. P. Chang, J. Appl. Phys. **75**, 4415 (1994).
[4] C. T. Gabriel, J. Vac. Sci. Technol. A **17**, 1494 (1999).
[5] R. H. Fowler and L. Nordheim, Proc. R. Soc. London, Ser. A **119**, 173 (1928).
[6] S. Samukawa, Y. Ishikawa, S. Kumagai, and M. Okigawa, Jpn. J. Appl. Phys., Part 2 **40**, L1346 (2001).
[7] D. A. Buchanan and G. Fortuno-Wiltshire, J. Vac. Sci. Technol. A **9**, 804 (1991).
[8] A. Hoff, K. Nauka, T. Persoon, J. Lagowski, L. Jastrzebski, and P. Edelman, Proc. IEEE/SEMI Adv. Semi. Man. Conf. 185 (1997).
[9] A. M. McCarthy and W. Lukaszek, Proc. IEEE 1989 Int. Conf. Microelectronic Test Struct. **2**, 153 (1989).
[10] Lord Kelvin, Philos. Mag. **46**, 82 (1898).
[11] I. D. Baikie and P. J. Estrup, Rev. Sci. Instrum. **69**, 3902 (1998).
[12] M. Y. Lee, J. Hu, W. Catabay, P. Schoenborn, and A. Butkus, *Proceedings of the Fourth International Symposium on Process- and Plasma-Induced Damage* (1999), p. 104.
[13] W. Lukaszek, *Proceedings of the Fifth International Symposium on Plasma Process-Induced Damage* (2000), p. 26.
[14] B. Chapman, *Glow Discharge Processes: Sputtering and Plasma Etching* (Wiley, New York, 1980).
[15] J. L. Lauer, J. L. Shohet, C. Cismaru, R. W. Hansen, M. Y. Foo, and T. J. Henn, J. Appl. Phys. **91**, 1242 (2002).
[16] F. Gutmann and L. E. Lyons, *Organic Semiconductors* (Wiley, New York, 1967).
[17] *Topics in Applied Physics: Electrets*, edited by G. M. Sessler (Springer, Berlin, 1980).
[18] K. P. Cheung and C. S. Pai, IEEE Electron Device Lett. **16**, 220 (1995).
[19] C. Cismaru and J. L. Shohet, Appl. Phys. Lett. **76**, 2191 (2000).
[20] C. H. Ling, J. Appl. Phys. **76**, 581 (1994).
[21] L. Zhong and F. Shimura, J. Appl. Phys. **79**, 2509 (1996).
[22] R. J. Powell and G. F. Derbenwick, IEEE Trans. Nucl. Sci. **18**, 99 (1971).
[23] T. P. Ma and P. V. Dressendorfer, *Ionizing Radiation Effects in MOS Devices and Circuits* (Wiley, New York, 1989).
[24] C. Cismaru, J. L. Shohet, J. L. Lauer, R. W. Hansen, and S. Ostapenko, Appl. Phys. Lett. **77**, 3914 (2000).
[25] C. Cismaru and J. L. Shohet, Appl. Phys. Lett. **74**, 2599 (1999).
[26] T. Yunogami, T. Mizutani, K. Suzuki, and S. Nishimatsu, Jpn. J. Appl. Phys., Part 1 **28**, 2172 (1989).
[27] T. Tatsumi, S. Fukuda, and S. Kadomura, Jpn. J. Appl. Phys., Part 1 **33**, 2175 (1994).
[28] J. R. Woodworth, M. G. Blain, R. L. Jarecki, T. W. Hamilton, and B. P. Aragon, J. Vac. Sci. Technol. A **17**, 3208 (1999).
[29] J. R. Woodworth, M. E. Riley, V. A. Amatucci, T. W. Hamilton, and B. P. Aragon, J. Vac. Sci. Technol. A **19**, 45 (2001).
[30] W. A. Zisman, Rev. Sci. Instrum. **3**, 367 (1932).
[31] W. Lukaszek, *The Fundamentals of CHARM2*, Technical Note 1, Wafer Charging Monitors, Inc., Woodside, CA.
[32] M. J. Goeckner, S. B. Feich, J. Weeman, S. Mehta, and J. S. Reedholm, J. Vac. Sci. Technol. A **17**, 1501 (1999).
[33] W. Lukaszek, U.S. Patent No. 5,315,145 (24 May 1994).
[34] K. P. Cheung and C. P. Chang, J. Appl. Phys. **75**, 4415 (1994).
[35] S. M. Sze, *Physics of Semiconductor Devices* (Wiley, New York, 1995).
[36] W. Lukaszek (private communication).