PHOTON ENERGY DEPENDENCE OF RADIATION EFFECTS IN MOS STRUCTURES

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ABSTRACT
MOS capacitors with oxide thicknesses of 750Å, 3500Å and 6000Å were irradiated using a Co60 source and a Cu target x-ray tube. At low fields across the oxides (<2MV/cm), shifts in the flatband voltages observed with Co60 were twice those measured with the Cu tube at the same oxide dose. At higher fields (>1MV/cm) the differences disappear. The observations are interpreted to be due to differences in the electron-hole recombination dynamics for the two radiation energies. Additionally, it was observed that the Si-SiO2 interface states trap holes with an efficiency that decreases as the square root of the electric field across the oxide.

I. INTRODUCTION

In recently completed measurements of dose and dose rate dependence of failures produced by ionizing radiation in 8080 microprocessors, we observed that the minimum dose at which failure occurred depended on the energy of the incident radiation. (1) If the failures were caused by radiation effects in the field oxides of the 8080's the failure doses observed for low energy (keV) sources were two times those measured for high energy (MeV) sources. On the other hand, if the failures were from radiation deposition in the gate oxides, a factor of about four between the low and high energy results was obtained. The difference was due to interface enhancement effects. After carefully checking the results we found no sources of error which could account for differences of this magnitude.

If such an energy effect is real, the complexity of the 8080 makes it difficult if not impossible to determine the precise mode of failure and the reason for the energy dependence. However, since 8080's are NMOS devices the failures most likely result from the deposition of ionizing radiation in the gate or field oxides and the subsequent trapping of some of the holes at or near the Si-SiO2 interfaces. Therefore, it seemed reasonable that a similar energy effect should be observable in simpler MOS structures such as MOS capacitors.

In this experiment we examine the effects produced by low and high energy sources using MOS capacitors. In Sections II and III we present an experiment and results which demonstrate that an energy effect also occurs in MOS capacitors. The physical mechanisms which result in the energy-dependent effects appear to be related to the recombination of the electrons and holes produced by the ionizing radiation. In Section IV, we review work in the literature which bears on recombination behavior in MOS structures. Finally in Section V, we complete the analysis of our data to obtain recombination results and compare them with the data discussed in Section IV.

II. THE EXPERIMENTAL PROCEDURES

In the present work we address the question of whether or not an energy dependence can be observed in radiation produced flatband voltage shifts of MOS capacitors. To answer this question, capacitors with oxide thicknesses of 750Å, 3500Å and 6000Å were irradiated at room temperature, both with and without biases, by low and high energy photon sources.

Each sample consisted of four 75x10^-3 cm diameter Al gate MOS capacitors mounted on TO-5 headers. The oxides were thermally grown in dry O2 on 3 to 5 Ω-cm n-type silicon substrates with (100) orientations. Four thousand Angstrom Al gates deposited with an r-f evaporator source completed the MOS structures. The Si substrate for the 750Å capacitors was grown by a float-zone technique; the substrates for the thicker samples were both Czochralski-grown Si.

High energy irradiations were performed on NRL's dry well Co60 (1.25 MeV) source at a dose rate of approximately 7x10^-2 rad(SiO2)/sec. The low energy irradiations were performed with a Machlett x-ray tube operated at 45 kV. With a 2.5x10^-2 g/cm² Ni Kβ filter, about 80 percent of the dose is from the Cu Kα line at 8 keV. The dose rate for these low energy exposures was approximately 3x10^-1 rad(SiO2)/sec. Positive biases between zero and 5 MV/cm were applied to the Al gates during irradiations.

C-V measurements were taken periodically during the irradiations with a Boonton 72AD capacitance meter and a voltage ramp. Since the capacitors were removed from the devices on the 30 to 60 sec after removal from the sources to provide additional time for hole transport to the Si-SiO2 interfaces.

Dosimetry for the experiment was carried out with CaF2 thermoluminescent dosimeter chips (TLD-200). During irradiations both samples and dosimeters were maintained in essentially "equilibrium" conditions; that is, the photoelectrons escaping the sample or dosimeter were replaced by a similar distribution of photoelectrons from surrounding materials. In the case of high energy radiations the ratio of the dose in CaF2 to that in SiO2 is equal to the ratio of the absorption in a CaF2 to that in SiO2. In the case of low energy radiations the conversion from dose in CaF2 to dose in SiO2 is somewhat more complicated. Here the spectral distribution of the source must be known in order to calculate the dose in the samples and dosimeters. Using measured and calculated spectral distributions for the x-ray tube, dose-depth distributions and integrated doses in both the dosimeters and samples were calculated. The integrated doses (ergs/chip) calculated for the dosimeters were found to agree within 10-15% with the measured values. These comparisons gave us confidence that the doses calculated for the MOS capacitors were also correct. A more detailed description of the procedures is in the Appendix.

Dose enhancement near the metal-oxide and oxide-silicon interfaces must also be considered. Little dose enhancement is expected in the MOS capacitors for the Co60 irradiations because the absorption is relatively uniform. However, the enhancement for the Cu radiation can be significant. The corrections applied for dose enhancement were derived from the calculations of Brown.(2) Figure 1 shows the average increase in the oxide dose as a function of oxide thickness for our Al gate structures and Cu spectrum. Dose-depth profiles for Al gate capacitors are shown in Brown's paper.
Finally, several tests were made during the course of the measurements to insure that dose rate or annealing effects were not complicating factors. A few samples were irradiated at dose rates approximately a factor of 10 greater than those used for the rest of the irradiations. The observed flatband voltage shifts were essentially identical to the shifts observed at lower dose rates. Additionally, biases were applied to the samples for 30 to 60 min prior to irradiation, and on some samples, for a similar period following the irradiations. No changes indicating charge injection or tunnelling (3,4) which would alter the results were observed. From these tests and from the general behavior of the results, we conclude that neither the dose rate of the tests nor annealing effects introduce any significant change to the results presented in the next section.

III. EXPERIMENTAL RESULTS

Typical C-V traces are shown in Fig. 2. Flat-band-voltage shifts as a function of oxide dose are shown in Fig. 3. The points in Fig. 3 are averages of shifts observed for two to four capacitors. The samples in these tests were biased at 6.25V. For this bias and for the dose range shown, the flatband-voltage shifts were found to be essentially linear. It should be noted that at any given dose level the change observed for capacitors irradiated by the Co60 source is approximately twice the change in the flatband voltage for capacitors irradiated by the Cu tube. In addition, the factor of two observed between the samples irradiated by high and low energy sources appears to be independent of sample thickness.

We irradiated other samples at several biases and measured the flatband voltage shifts as a function of dose. Figure 4 shows normalized flatband voltage shifts as a function of the electric field strength, E, in the oxide. The experimentally determined voltage shifts were normalized by dividing the measured voltage shift by the dose required to produce that shift and the square of the oxide thickness. For each oxide thickness, in Fig. 4, the normalized flatband voltage shift increases with increasing field to a peak at approximately 0.3 MV/cm. At higher fields the flatband voltage shift decreases. Also, it can be seen that at low fields the Cu x-ray tube data remains essentially a factor of two below the Co60 data, but at higher fields the two curves merge.

The field plotted in Fig. 4 should be the field experienced by the charges. This field is the sum of the applied field, a field, \( E_{\text{applied}} \), produced by differences in the metal and semiconductor work functions and other localized fields such as those produced by trapped charges or impurities. However, localized fields are difficult to estimate. As an approximation we plotted in Fig. 4 the sum of the applied field and the field produced by the metal-semiconductor work functions. The sum of these two fields, as an approximation to the real field, is consistent with the data of Herembick and Gregory (6) who observed that a minimum flatband voltage shift occurs at an applied bias equal in magnitude and opposite in sign to \( E_{\text{applied}} \).

Additionally, it has been observed that flatband voltages saturate with increasing dose as the trapped charge at the Si-SiO2 interface oxide alters the field within the oxide layers. The data used in Fig. 4 were obtained at dose levels below the onset of saturation effects.

The general characteristics of the three curves suggest that the flatband voltage shifts are affected by recombination dynamics within the oxide. At high fields where the electron-hole pairs can be separated more effectively, the same shifts are observed for high and low energy radiations. On the other hand, at low fields where recombination becomes significant the curves are separate. We will relate the observed flatband voltage shifts to the fraction of electrons and holes which escape recombination in Section IV. However, prior to discussing the data in Fig. 4 further we will digress briefly to examine recombination data in the literature.

IV. RECOMBINATION MEASUREMENTS

Electron-hole recombination in SiO2 is closely tied to photoconductivity and the production and trapping of holes in electronic devices. As a result many experimenters have performed measurements which provide some information on recombination in SiO2. References 6 to 23 are applicable to this discussion.

We have selected, for illustrative purposes, four sets of data from the references listed. The reader will find that the results shown in the other papers are, for the most part, in agreement with the four examples we present here. Figure 5 shows the fraction of the electron-hole pairs which escape recombination as a function of field from the works of Boesch and McGarity (7) R.C. Hughes (9) Farmer and Lee (13) and Srour, Curtis and Chiu (19). We will now briefly the experiments from which the data were obtained and adjustments to the original data we have made to facilitate the intercomparisons.

One adjustment made to the data was to modify the results so that the same average energy for the electron-hole production was used. In some of the early work, the energy required to produce an electron-hole pair had yet to be determined, and a variety of energies were assumed. In this comparison we will adjust all the data to a value of 18 eV/electron-hole pair. This value comes originally from an analysis by Ausman and McLean (24) of the data of Curtis, Srour and Chiu, (10) and as far as we are aware it is the generally accepted value for the average energy required to produce an electron-hole pair in SiO2.

Curve A in Fig. 5 was obtained by Boesch and McGarity from fast C-V measurements of 725Å MOS capacitors cooled to 80K. Linac pulses of 13 MeV electrons were used to irradiate the samples. In these measurements electrons which escaped recombination were assumed to be swept out of the oxide and holes remained essentially immobile. The capacitance data was therefore a measure of the unrecombined holes. Boesch and McGarity report their data in terms of the applied field, and therefore we have added a small correction for \( \Phi_{\text{ms}} \) to their data for consistency. The capacitances measured were consistent with the 18 eV/pair energy, thus no further correction was required.

Curve B is from the photoconductivity measurements of R.C. Hughes on 200 µm thick Suprasil 2 fused quartz samples. The radiation source was a flash x-ray source with an effective energy of approximately 30 keV. Hughes reported only the photoconductivity from the electron component of the charge. Hole motion was not observed, and holes were assumed to be immobile. The electrical contacts on both surfaces were Al and, thus, no correction for work functions is required. The major adjustment to Hughes data was to correct for the electron-hole formation energy.

Curve C is the result of photoconductivity measurements of Farmer and Lee. In that measurement 1250Å and 5000Å MOS capacitors were irradiated on a copper target x-ray tube. Although limited information on the characteristics of the samples is provided in their paper, the authors did make a correction for the
metal-semiconductor work function and other localized fields. (25) Therefore, we present their data without adjustments other than to use 18 eV/pair to predict the maximum photoductive current and hence, the fraction of charge which escapes recombination.

Finally, the three curves marked D are from Srou, Curtis and Chi. Capacitors with 1350Å oxides from wafers processed three different ways were irradiated with 5 keV electrons in this experiment. Adjustments to the data were for the electron-hole formation energy and $\phi_h$.

As can be seen from the four examples shown, the fields at which the same fraction of charge escapes recombination vary by almost an order of magnitude. However, there are important similarities between the curves. All of the curves, for example, have essentially the same shape. At low fields the fraction of charge escaping recombination increases nearly linearly with field. And at higher fields the manner in which the data approach total charge separation (no recombination) also has generally the same characteristic. These similarities suggest that it is likely that a single physical model can fit all of the data.

Finally, we will comment briefly on the models that have been used to interpret recombination data. Experimenters have attempted to explain their observations using either "geminate" (9) or "genuine" (24) recombination models. "Geminate" recombination refers to recombination of an electron with its parent hole. "Columnar" recombination, on the other hand, postulates ionization along a track, and that an electron can recombine with other holes along the track in addition to its parent hole. Although the "geminate" model has been used to fit some data, it has a serious flaw. The model predicts a temperature dependence.

Recent data (22) show no temperature dependence down to 4K, which is inconsistent. On the other hand, Ausman and McLean (24) rather convincingly fit a columnar model to the data of Curtis et al. (11) To illustrate the agreement between the model and data, two parameters, the number of ionizations per unit ionization energy and the radius of the columnar recombination region, are obtained. The values they obtained to match the data of Curtis et al. appear reasonable. Additionally, the model does not have a temperature dependence and would be applicable at low temperature. However, it is difficult to see how the model of Ausman and McLean, in its present form, can be used to explain all of the data in Fig. 5. Further work on the modeling of depo-

v. ANALYSIS AND DISCUSSION

In examining the field dependent data in Fig. 4, we observed that the flatband voltage shift data appeared to approach a bound or asymptotic value and that the square root of the field. Figure 6 shows one of the pairs of curves from Fig. 4 along with this bound indicated by a dashed line. The data shown in the previous section indicate that at sufficiently high fields all of the holes produced by ionizing radiation can get to the Si-SiO$_2$ interface. Thus, the dashed line of Fig. 6 shows the field dependence of the "efficiency" of hole trapping at the interface. Such a field dependence is consistent with the observation of Srou et al. (11) that the charge trapped at the interface dropped by a factor of two when the applied field was increased by a factor of four.

Therefore, we have assumed that the dashed line when extrapolated to lower fields is the shift in the normalized flatband voltage which would occur in the absence of any recombination. Thus, the fractional yield of holes can be obtained from the ratio of the measured flatband voltage shift to the value which would be obtained from this dashed line. Further confirmation of the reasonableness of such an assumption can be found using the data of Powell. (16) He reported both photocurrents and flatband voltage shifts as a function of field. Using the technique described, we were able to derive a curve for the fraction of charge escaping recombination which is consistent with the fraction obtained from his photocurrent measurements.

Figure 7 shows the results of applying the above technique to the data of Fig. 4. For comparison, the data previously shown in Fig. 5 is indicated by the light lines. In Fig. 7 the shape and position of the 350Å, and 6000Å capacitors coincide, while the results from the 750Å capacitors appear to be shifted to higher fields. Whether or not the oxide thicknesses or the substrate materials are, in some way, related to the observed differences is unknown. These factors may be significant if charge diffusion (26) and/or intrinsic or extrinsic defects are important to the recombination process.

After examining the data in the literature and comparing them with our own, we find that many unknown factors remain. Only about a factor of two in the recombination which is due to the energy of the incident photons or electrons can be attributed to a single effect. Further work, with careful attention to material and technique, is needed to determine what other important parameters are involved in the electron-hole recombination in SiO$_2$. Such work may have important implications to the hardening of MOS devices to ionizing radiation.

VI. SUMMARY

In summary, the observations of this study are listed below.

1. The energy dependence in the radiation effects reported previously for 8080 devices has been verified with MOS capacitors. The effect is produced by either photons or electrons. We found a difference of a factor of two in the flatband voltage shifts when data from Co$^{60}$ (1.25 MeV) and Cu (8 keV) irradiations are compared. These results suggest that in the earlier 8080 experiment, it was the deposition in the field oxides, rather than in the gate oxides, which caused failures.

2. The energy dependence is related to the recombination of electrons and holes in the oxide. At high fields, where recombination is minimized, the energy dependence tends to disappear.

3. All data which show the fraction of electrons and holes escaping recombination exhibit the same general behavior. However, the models which have been used to explain the data in the literature fall short of providing a satisfactory fit to all the data. It is likely that a fuller treatment is required to model the recombination behavior.

4. It was observed that the trapping of holes at the Si-SiO$_2$ interface decreases with a square root dependence of the field across the oxide.

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Initially, CaF$_2$ TLD-200 chips (3x3x0.9 mm) were calibrated in equilibrium conditions with a Co$^{60}$ source. During tests, the TLD's were placed as close as possible to the samples without interfering with the incident beam. Thus, the dosimeters were essentially in the same radiation field as the device tested. Attenuation, scattering and fluorescence of nearby components were considered in the placement of the dosimeters and interpretation of results. After exposure the TLD's were read on a Harshaw 2000 TLD reader, in a N$_2$ atmosphere, with the irradiated surface toward the photomultiplier tube.

High energy radiation from Co$^{60}$ produces a relatively uniform deposition in both the TLD’s and the capacitors. Techniques for interpretation of dosimetry at these energies have been documented in the literature. (27,28) In the Co$^{60}$ case, both TLD’s and capacitors were irradiated in near equilibrium conditions, and the dose measured in the TLD’s is representative of the dose in Si or SiO$_2$ when corrections are made for the energy deposition coefficients as long as contributions from low energy photons can be neglected. Tests performed on the Co$^{60}$ source indicate that the low energy photon contributions are negligible for these tests. (29) In addition, interface effects, which are atomic number dependent, should be small in the MOS structures of the capacitors since the materials at these interfaces have similar atomic numbers. (30)

Dosimetry for low energy spectra represents a much different problem since deposition in materials generally is not uniform and can vary greatly from material to material. In particular, the dose from a low energy source, such as measured with CaF$_2$ TLD chips, cannot provide the dose in an MOS device structure unless the spectral distribution of the source is known. Here we show the steps taken to determine the dose in the layered Si structures based on CaF$_2$ results.

Prior to exposing TLD’s to Cu x-ray tubes the spectral distribution was measured by energy-dispersive techniques and compared to a calculated distribution for the tube. (31) The shapes of the measured and calculated spectra were within approximately 10 to 20 percent. Therefore for subsequent dose determinations the calculated spectrum, Fig. A-1, was used.

Given the special distribution, the tube current, and the exposure time, the total dose and the dose-depth distribution (Fig. A-2) were calculated for the TLD’s. The total dose calculations agreed well with measurements; for example, for two exposures we calculated doses of 317 and 290 rads(CaF$_2$)/chip and measured 317 and 325 rads(CaF$_2$)/chip respectively. The dose-depth distribution suggested that two error sources should be considered: (1) the reduction in the dose near the front TLD surface due to photoelectron losses to the 1.5x10^{-3} cm Al foil wrapped around the TLD, and (2) the high surface dose, which approached 6x10^4 rads(CaF$_2$), since CaF$_2$ TLD’s show a nonlinear increase in response at such doses. The two effects tend to be at least partially cancelling and probably are not of major importance in these measurements since they account for only a small fraction of the total dose in the dosimeter.

Once satisfied that the calculated and measured dose in CaF$_2$ TLD’s were in agreement, we then used the same spectral distribution to calculate the dose, dose-depth profiles, and interface dose-enhancement effects for the MOS capacitors. These calculations are the subject of another paper in this issue (2) and are not discussed here.

REFERENCES


Figure 4. Normalized flatband voltage shifts as a function of field for the three oxide thicknesses.

Figure 5. The fraction of electrons and holes that escape recombination as a function of field. The data obtained from (A) Boesch and McGarrity, (B) R.C. Hughes, (C) Farmer and Lee, and (D) Srour, Curtis, and Chiu.

Figure 6. Normalized flatband voltage shifts as a function of field. The dashed line represents the flatband voltage shift expected if no recombination occurs.

Figure 7. The fraction of charge escaping recombination as a function of field for the three oxide thicknesses. Dashed line drawn through data for 750Å capacitors. Solid lines drawn through data for 3500Å and 6000Å capacitors. Light lines are data previously shown in Figure 5.

Figure A1 - Calculated spectral distribution for a Cu OEG-50 X-ray tube. Lines plotted with 2 keV width.

Figure A2 - Calculated dose-depth distribution near the front surface of a CaF$_2$ TLD chip for a 45 kV Cu X-ray tube spectrum.