cf

UCRL -73872
PREPRINT
Conf-721008--2

LAWRENCE LIVERMORE LABORATORY
University of California/Livermore, California

X-RAY-INDUCED INTERFACE STATES IN SiO_2-Si AND CARRIER LIFETIME STUDIES IN ELECTRON-BEAM IRRADIATED SiO_2

R. Kalibjian
K. Mayeda
D. R. Ciarlo
T. A. Boster

September 8, 1972

This paper was prepared for presentation at the The Electrochemical Society, Inc. 142nd National Meeting, Miami Beach, Florida, October 8-13, 1972.

X-RAY-INDUCED INTERFACE STATES IN SiO_2-Si AND CARRIER LIFETIME STUDIES IN ELECTRON-BEAM IRRADIATED SiO_2*

R. Kalibjian, K. Mayeda, D. R. Ciarlo, and T. A. Boster

Lawrence Livermore Laboratory, University of California,
Livermore, California 94550

ABSTRACT

The interface state density in x-ray irradiated SiO_2-Si is determined. For 10^5 rads, the deep acceptor and donor states are 5 to 9×10^{12} states/eV-cm^2 (about one order of magnitude larger than that of the non-irradiated samples). Also, lifetime studies in SiO_2 are made in a time-of-flight type of experiment using an electron beam for the ionizing source. By direct experiment, the lifetime of electrons in SiO_2 is shown to be less than 7 nsec.

INTRODUCTION

Time-integral detection (TID) and time-resolved detection (TRD) of x-rays already have been reported[1,2] using a linear array of metal-oxide-semiconductor capacitor (MOS-C) devices. Readout of the stored charge for both TID and TRD is based upon the change in the flat-band voltage ΔV_{FB} (before and after x-ray irradiation). Since the surface states affect a shift in the flat-band voltage as shown in Fig. 1, it becomes desirable to investigate the x-ray-induced interface states in SiO_2-Si. For TRD the linear array of MOS-C devices is irradiated uniformly, while the elements are sequentially biased-on at Δt time intervals as shown in Fig. 2. The writing rate for TRD is dependent upon the lifetime of the carriers in the SiO_2; therefore, it becomes important to investigate carrier lifetime to determine a lower limit for Δt.

INTERFACE STATES IN SiO_2-Si

X-ray-induced interface states are measured using the temperature method,[3] which basically involves the maintenance of the flat-band condition when the temperature of the MOS-C is lowered. The MOS-C samples consist of 10 Ω-cm wafers with (111) surface orientation. Oxidation is performed at 1000°C for 70 min in a quartz tube system using a wet O_2 source from a quartz flask of boiled H_2O. Evaporated Al electrodes are used for the MOS-C field plates. A composite surface state density, i.e., at the conduction and valence band edges, is measured by using both n and p-type Si substrates.

With decreasing temperature, the flat-band condition is maintained by using a feedback circuit that allows the bias to the MOS-C to decrease (for p-type substrate) when the capacitance bridge tends to deviate from its null position. The compensating change in bias allows the flat-band capacitance, C_{FB}, to be locked-in. The basic system to lock-in C_{FB} is shown in Fig. 3. The system is tested for proper lock-in with the following method: 1) at some negative bias V_{BO} in the accumulation mode, the MOS-C is balanced on the bridge to the oxide capacitance C_{OX} in the open loop condition, 2) a small capacitance ΔC is placed in parallel to the MOS-C, and the system is locked-in (close loop) to the C_{OX} value, 3) under locked-in condition the bias value shifts to V'_{BO} as shown in Fig. 4, 4) the system is now operated under open loop condition with the bridge still set at C_{OX}, the bias at V_{BO}, and ΔC in parallel with the MOS-C, and 5) the bias is adjusted manually towards the V'_{BO} value until a null is registered at the bias value V''_{BO}. A plot of $(V'_{BO} - V''_{BO})$ vs $(V_{BO} - V'_{BO})$, shown in Fig. 5, indicates the error in ΔV_{FB} in the closed loop system to be about 10%. The feedback system does not automatically adjust the dissipation factor in the bridge in order to maintain an overall null. This error in some cases is insignificant; however, the null is observed by the operator. If excessive deviation occurs, manual correction of the dissipation control is exercised for overall null maintenance of the bridge.

A typical composite, interface state density plot is shown in Fig. 6 for a 0.5 μm thick oxide layer on Si. The non-irradiated MOS-C has deep acceptor states of 2.7×10^{12} states/eV-cm^2 peaked at 0.11 eV below the conduction band edge, whereas deep donor states increase slowly from 0.1×10^{12} to 0.6×10^{12} states/eV-cm^2 from 0.10 to 0.25 eV above the valence band edge. X-rays from a W target tube are used to irradiate the MOS-C sample. For 10^4 rads, the peak of the deep acceptor states shifts closer to the conduction band edge with a minimum of 0.6×10^{12} states/eV-cm^2 appearing at 0.19 eV below the conduction band edge; the deep donor states are approximately three times greater than the non-irradiated states. At 10^5 rads, the minimum of the deep acceptor states shifts to 0.15 eV below the conduction band edge with 0.8×10^{12} states/eV-cm^2; the density of states increases rapidly to 5×10^{12} states/eV-cm^2 at 0.25 eV below the conduction band edge. Also, the deep donor states are at 8.6×1[illegible] states/eV-cm^2 with a peak occurring at 0.23 eV above the valence band edge.

CARRIER LIFETIME STUDIES IN SiO_2

In an MOS-C detector, the hole lifetime τ_h in SiO_2 is assumed to be much less than the sweep-out time of the hole due to the applied electric field; otherwise, the charge-storage phenomena^4 would not occur. Additionally, the electron lifetime, τ_e, is assumed to be longer than the sweep-out time of the electron; otherwise, the sensitivity or ΔV_{FB} would not depend upon the bias level. Bias-enhanced sensitivity occurs because the electrons are swept out faster in time than the time taken for the electrons to be trapped. Sensitivity is proportional to the net positive charge of the trapped holes; therefore, the sensitivity will be greater for a higher electric field, since the electrons will have a larger drift velocity and thereby have a smaller probability to be trapped. Generally, the drift velocity of the carrier will saturate with increasing electric field, which means that the detector sensitivity ΔV_{FB} vs bias characteristics should also saturate. From published experimental data for the mobility-lifetime products and the theoretically estimated mobility, it appears the scattering-limited velocity for electrons in amorphous SiO_2 must be greater than 5×10^5 cm/sec. This conclusion is based upon the following consideration. For example, for holes[5] and electrons,[6] $\mu_h \tau_h \leq 10^{-10}$ cm^2/V and $\mu_e \tau_e = 10^{-9}$ cm^2/V, respectively, and[7] $\mu_e = 10$ cm^2/V-sec; therefore, the mean lifetime of the electrons before trapping is about $\tau_e = 10^{-10}$ sec and, for the holes, $\tau_h \leq 10^{-10}$ sec for an assumed hole mobility of $0.1\ \mu_e$. For bias-enhanced sensitivity to occur for a 0.5 μm thick SiO_2 layer, the electron velocity must be greater than 5×10^5 cm/sec in order that the transit time of the electron be less than the 10^{-10} sec electron lifetime.

X-ray detection has been performed[2] for $\Delta t = 5$ nsec with MOS-C detectors. The time resolution of the MOS-C detector should be equal to the electron lifetime that was estimated to be 0.1 nsec. It would be useful to confirm by direct experiment the electron lifetime in SiO_2. A laser strobing technique is presently under development that would allow the direct measurement in the subnanosecond range. Currently, a more conventional method, a time-of-flight experiment with a pulsed electron source, is used to investigate carrier lifetime in the 1 to 10 nsec range. The basic experiment consists of measuring the detector sensitivity ΔV_{FB} vs the time delay T of the bias field with respect to the ionization source as shown in the schematic of Fig. 7. A pulsed electron beam from a travelling-wave-deflector, electron gun is used as the ionizing source. The 0.75 μA beam is deflected across a 0.063 cm diam aperture in the collector system to generate the 2 nsec width pulses. Bias pulses of 1 nsec risetime are generated with an avalanche transistor that give 60 V amplitude and 200 nsec width pulses. As T is increased to approach τ_e, ΔV_{FB} should begin to decrease because the electrons will have a greater probability to be trapped and thereby reduce the net positive charge in the SiO_2. The ΔV_{FB} vs T experiment can be performed by varying T appropriately with delay cables.

A straight-through, all-metal valve separates the electron gun section from the collector end of the tube. The electron gun is continuously maintained in the pressure range of 10^{-9} Torr. With the installation of the MOS-C target, the demountable section is valved open to the high vacuum side only when the collector system is in the pressure range of 10^{-8} Torr after a 250°C bakeout. Coarse deflection position, focus, and astigmatism control of the electron beam is accomplished by observing the luminescence trace on the phosphor-dusted collector; fine adjustment control is made when the electron beam signal is observed on an auxiliary oscilloscope at a slow sweep speed of 50 μsec. The simplest method in which to position the electron beam in the middle of the linear sweep is to monitor the collector current signal as shown in Fig. 8. The current pip (due to the difference in secondary emission ratio of the collector electrode and the MOS-C field plate) permits easy identification of the collector aperture of the MOS-C. Because of the requirement of the post-deflection, accelerator voltage, a 0.01 μF coupling capacitor is used to probe for the beam current signal. For faster sweep speeds of 50 nsec, the narrow bandwidth of the coupling capacitor prevents the direct measurement of nanosecond width electron pulses. For this reason a geometric ratio method is used to ascertain the pulse width when the electron beam is swept at sub-microsecond rates. For example, in Fig. 8 the ratio of aperture time width to sweep time is $t_a/t_s = 0.035$ for $t_s = 50$ μsec; hence, for the 50 nsec sweep used in the time-of-flight experiment, $t_a = 1.75$ nsec. If desired, subnanosecond electron pulse widths can be generated with the traveling-wave deflector with a mercury relay pulser used as the sweep generator.

In order to observe a few volts shift in ΔV_{FB}, repetitive pulsing of the electron source is required. Figure 9 shows ΔV_{FB} vs the number of electron pulses with the 60 V bias pulse. Approximately 20,000 pulses are required to give a 2 V shift for a 4.9 keV electron beam that corresponds to a dosage of 0.035 rads per pulse in the 0.5 μm thick SiO_2. Each data point in the ΔV_{FB} vs T curve of Fig. 10 represents the integrated dosage for 20,000 pulses as monitored by the preset counter shown in Fig. 7. The fall-off time of the curve is 7 nsec and is equal to a factor of 2.5 times the RC time constant of the MOS-C collector section. This represents a measured capacitance of 55 pF of which 30 pF accounts for the MOS-C and the remaining 25 pF accounts for the stray capacitance in the 50 Ω transmission-line, collector system. Therefore, we conclude from Fig. 10 that the lifetime of electrons in SiO_2 must be less than 7 nsec.

CONCLUSION

The interface state density in SiO_2-Si increases by one order of magnitude when irradiated with x-rays for 10^5 rads. This effect perturbs the flat-band voltage shift. It is not serious in MOS-C x-ray detectors because the calibration of ΔV_{FB} vs dosage is performed with devices having similar interface state characteristics. For MOS-C detectors using TRD, the theoretical time resolution is about 0.1 nsec. TRD detection is performed in the nanosecond range and should be considered valid since, by direct experiment, we have shown that the electron lifetime in SiO_2 is less than 7 nsec.

ACKNOWLEDGMENTS

The authors wish to thank D. E. Campbell for assistance in circuit design, and J. P. Henz and J. E. Lynch for processing and fabrication of the MOS-C devices.

REFERENCES

* This work was performed under the auspices of the U.S. Atomic Energy Commission.

1. D. R. Ciarlo, R. Kalibjian, K. Mayeda, and T. A. Boster, IEEE Trans. Nucl. Sci., NS-19, No. 1, 350 (1972).
2. R. Kalibjian, D. R. Ciarlo, K. Mayeda, and T. A. Boster, IEEE Trans. Nucl. Sci., NS-19, No. 3, 339 (1972).
3. P. V. Gray and D. M. Brown, Appl. Phys. Lett., 8, 31 (1966).
4. K. H. Zaininger and A. G. Holmes-Siedle, RCA Review, 28, 208 (1967).
5. A. M. Goodman, Phys. Rev., 152, 780 (1966).
6. A. M. Goodman, Phys. Rev., 144, 588 (1966).
7. R. Williams, Phys. Rev., 140, A569 (1965).

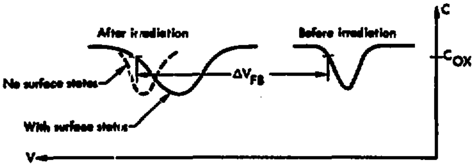

Fig. 1. Surface state effects upon the capacitance-voltage (C-V) curves.

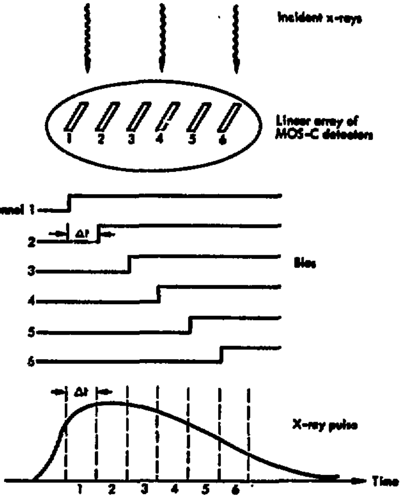

Fig. 2. Time-resolved detection using a linear array of MOS-C devices.

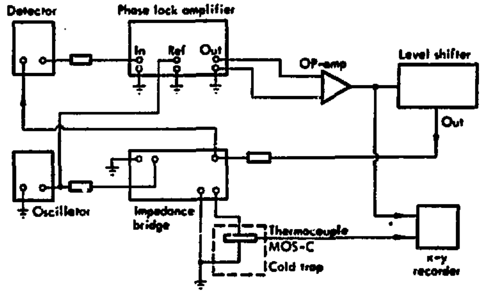

Fig. 3. Feed-back system to maintain flat-band condition.

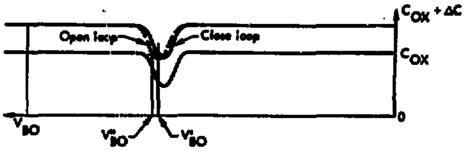

Fig. 4. Test scheme for proper lock-in.

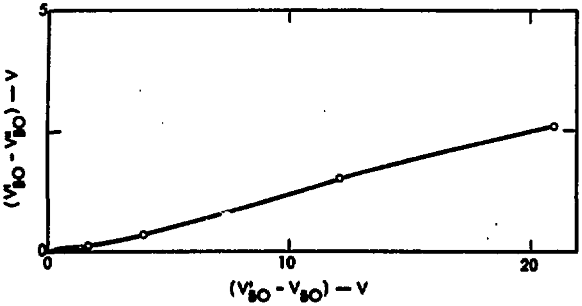

Fig. 5. Error curve for feedback circuit.

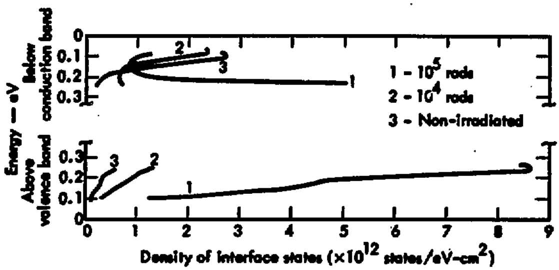

Fig. 6. Composite interface states vs. energy.

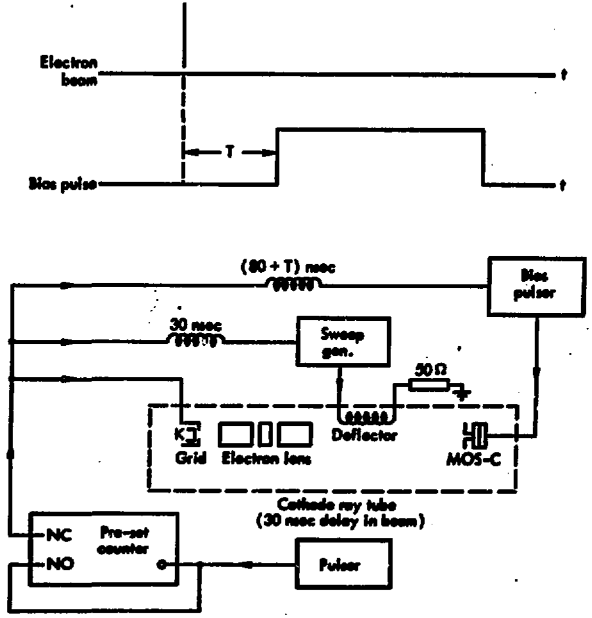

Fig. 7. Schematic of time-of-flight experiment.

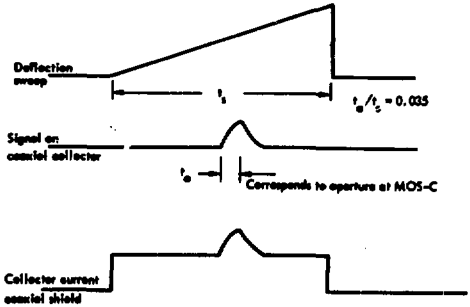

Fig. 8. Beam current signals.

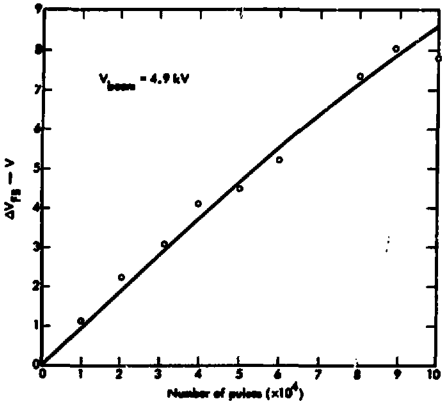

Fig. 9. ΔV_{FB} vs. number of pulses.

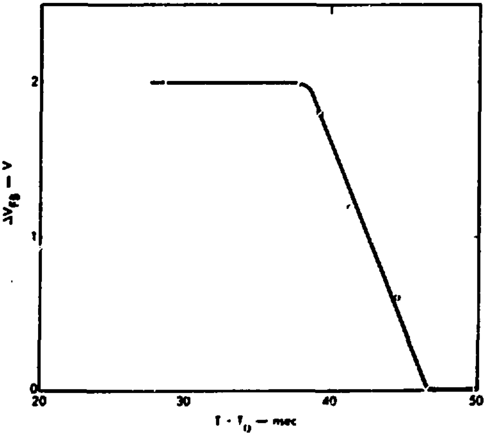

Fig. 10. ΔV_{FB} vs. T.