EFFECTS OF NEUTRON IRRADIATION ON THE CHARACTERISTICS OF A BURIED CHANNEL CCD AT 80°K AND 295°K

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ABSTRACT

Buried channel CCD shift registers have been irradiated with 15 MeV (average energy) neutrons in steps to $3x10^{13}$ n/cm^2. The irradiations were performed at 80°K and 295°K on operating devices with normal clocks and bias voltages applied. Dark current increased from the pre-irradiation value of 7 nA/cm^2 to 1600 nA/cm^2 at $1x10^{13}$ n/cm^2. The input gate threshold shift observed at 80°K was -0.9 volts per 10^{13} n/cm^2, a factor of 4 less than that predicted from a first-order calculation of the equivalent ionization dose of neutrons in the oxide. Transfer efficiency measurements yield a bulk electron trap creation rate for neutron irradiation ($\Delta N_t/\Delta\phi$) of 14.0 cm^{-1} at 295°K with a trap emission time constant of 25μs. At 80°K, the trap creation rate is 2.0 cm^{-1} with an emission time constant of 100 ms.

I. INTRODUCTION

Charge-coupled device (CCD) structures are attractive for application in space and strategic systems. Since these systems generally operate in a radiation environment, the behavior of CCDs is such environments must be characterized. The effects of both ionizing and displacement damage must be understood and controlled.

As in all MOS structures, ionizing radiation results in a build-up of positive charge in the oxide and an increase in the surface states of a CCD.[1] Since the charge transfer process in a CCD is relatively insensitive to flat-band voltage shifts, a carefully designed and properly operated CCD can function satisfactorily with as much as several volts of shift.[2] Some of the device properties which may be affected by ionizing radiation are (1) input threshold voltage, (2) dark current, (3) on-chip output amplifier gain, and (4) transfer loss to surface state trapping.

In addition to ionization effects, particle radiation can deposit energy in an MOS structure via displacement damage. In the silicon substrate this results in the creation of bulk traps which cause a reduction in the minority carrier lifetime and the removal of free carriers. The effects of bulk damage in CCDs tend to be obscured by ionization effects for charged-particle radiation. High energy neutrons, however, cause a large amount of displacement damage with relatively little ionization.[3]

In this work we report the effects of high energy neutrons on the properties of an unhardened CCD. The devices were irradiated while operating with all normal clocks and biases applied in order to simulate real conditions. Several devices were irradiated while operating at 80°K to reproduce conditions for proposed low temperature CCD applications. Buried channel CCDs with high preirradiation transfer efficiency were used to minimize the effects of surface state and preirradiation bulk defect trapping relative to neutron induced defect trapping.

II. EXPERIMENTAL CONDITIONS

The devices irradiated are 150-bit 4-phase buried n-channel CCD shift registers.[4] Pertinent structural parameters are: 0.3x5.0 mil phase gates, 1500 Å gate oxide, 6000 Å buried n-channel with implant dose $1.5x10^{12}$ phosphorus. The shift registers were operated at 500 KHz with 15 volt clock swing at a 60% duty cycle. When measuring transfer efficiency, the signal charge in each 'one' was kept at .375 or less of a full well to insure there was no trapping of signal charge by surface states. The fill-and-spill input technique was used to inject a burst of ones which are of equal magnitude to very high precision.[5]

The neutron irradiations were performed at the NRL cyclotron. The energy spectrum of the neutrons is a Gaussian distribution 0 to 35 MeV with a broad peak at 15 MeV. The maximum neutron flux employed was $5x10^9$ n/cm^2-sec. The amount of gamma radiation in the neutron beam was calculated to be 10^3 rad (Si) per 10^{13} n/cm^2.

The CCDs were operated with all normal biases and clocks applied during the irradiation. Device BC 57-7-7, which was irradiated at liquid nitrogen temperature, was maintained at 84°K throughout the entire sequence of alternating irradiations and measurements. Device BC 57-7-3 was irradiated at 84°K but room temperature measurements of device characteristics were made after each irradiation.

III. EXPERIMENTAL RESULTS

The CCD shift registers were irradiated through a sequence of doses to a maximum of 1 or $3x10^{13}$ n/cm^2. Device characteristics which were measured after each dose were (1) input gate threshold voltage, (2) full well capacity, (3) output voltage to output charge gain of the on-chip output amplifier, (4) CCD dark current, and (5) transfer efficiency. At $3x10^{13}$ n/cm^2, about a 7% decrease in the gain of the output amplifier was observed. There was no change in the full well capacity up to the maximum dose.

Measured values of the input gate threshold voltage shift for devices at 295°K and 84°K are shown in Figure 1. The magnitude of the threshold shift is larger at 84°K than at 295°K as expected from results on the effects of ionizing radiation in MOS structures at 77°K.[6] The observed threshold voltage shift is approximately -0.9 volt per 10^{13} neutrons/cm^2 at 84°K and is most likely due to the relatively small ionization effect of high energy neutrons in SiO_2. An approximate value for the effective rate of energy deposition by ionization for 15 MeV neutrons in silicon is 10^4 rad (Si) per 10^{13} n/cm^2.[3] Using this value for the neutron energy spectrum used in this work, and assuming the same ionization rate in SiO_2 as silicon, the maximum expected threshold voltage shift for 1500 Å oxide thickness is -4.0 volts per 10^{13} n/cm^2.[7] However, the average field in the oxide beneath the input gate is approximately 0.5×10^6 volt/cm which is considerably less than the field required to produce the calculated maximum threshold shift.[7] Also, the long elapsed time between irradiation and threshold measurement, up to 48 hrs at the largest dose, may have permitted some annealing of radiation-induced charge to take place.

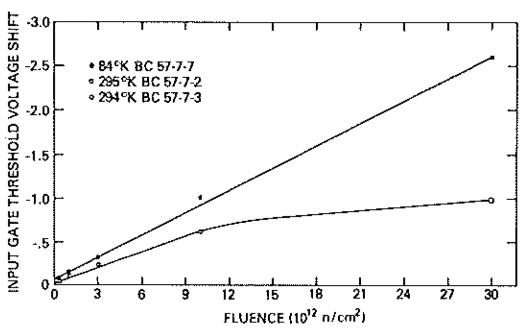

Fig. 1. Input gate threshold shift vs. neutron fluence, showing the expected greater shift at 84°K compared to the 295°K values

The effect of neutron irradiation on CCD dark current at 300°K is shown in Figure 2. The dark current for this CCD increased from the preirradiation value of 7 nA/cm^2 to 1600 nA/cm^2 at 10^{13} n/cm^2, in qualitative agreement with data published previously.[8,9] The surface generation component of the dark current was measured with an on-chip gated diode. During irradiation, the same biases applied to the CCD buried channel and one phase gate were applied to the gated diode implanted channel and gate, respectively. These results are also given in Figure 2 and show that the surface component of the dark current did not increase significantly with fluence. Therefore, the approximately linear increase in CCD dark current with neutron fluence is due to bulk generation within the CCD depletion region.

Measurements of the charge transfer inefficiency (CTI) for a CCD irradiated to 3×10^{13} n/cm^2 at 294°K are shown in Figure 3 for different amounts of signal charge. For this dose, the CTI is on the order of 1% which would make the device useless for most applications. As shown in Figure 3, the CTI is a function of the size of the signal packet. This effect can be attributed to non-uniform doping in the buried n-channel layer.[10]

The CTI is measured using the double pulse technique.[11] Briefly, a burst of 20 charge packets of equal magnitude (ones) is input to

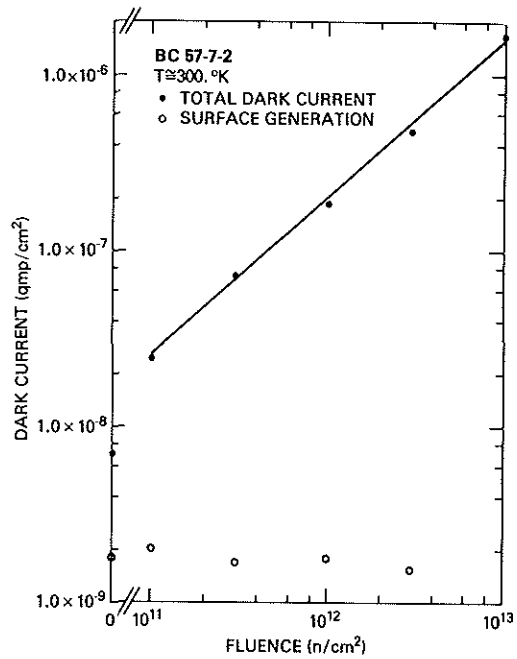

Fig. 2. Dark current density at 300°K as a function of neutron fluence, illustrating the linear relation between J_D and the neutron fluence.

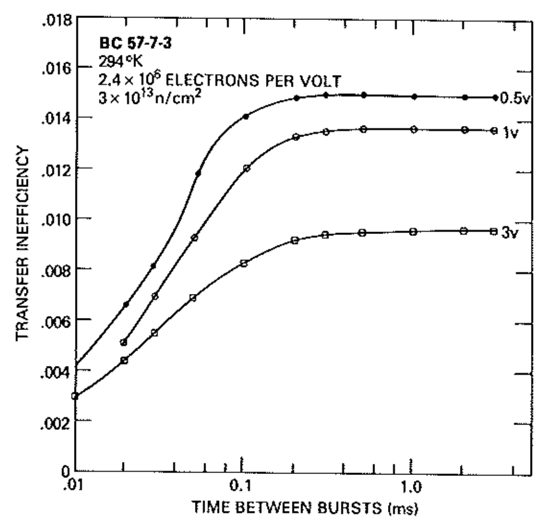

Fig. 3. Transfer inefficiency for a CCD at 294°K after 3×10^{13} n/cm^2 vs. time between bursts for three different signal levels. The dependence of inefficiency on signal level indicates non-uniform doping in the buried channel.

the CCD, followed by a number N_z of empty packets (zeros). Then a second burst of ones is input to the CCD and the loss in the leading ones is measured as a function of the time between bursts, $N_z T_c$, where T_c is one clock period (2μs). The effect of high energy neutron radiation is to create a number of bulk trapping levels in the buried channel layer. When a packet of signal charge electrons occupies the volume of semiconductor surrounding an empty trap, the trap captures an electron from the signal packet in a time which is usually short compared to a clock period. As the signal packet is transferred along the CCD to the next potential well, what happens to the trapped electron is a function of the electron emission time of the trap, τ_i: (1) If $\tau_i \ll T_c$ (the clock period), the trapped electrons will rejoin the signal packet and no effects of trapping will be observed. (2) If $\tau_i \gg N_z T_c$ then the traps remain filled; consequently, the traps will not remove charge from the signal packet and no effect on CTI will be observed. (3) If $T_c < \tau_i < N_z T_c$ then the traps will remove electrons from the signal packet and will re-emit them too late to rejoin the signal packet. This will be observed as loss in the signal packet at the output. For a single level of traps, the total loss in number of electrons is given by:[10,11]

$$N_{loss} = M\, V_{SIG}\, N_t\, e^{-T_t/\tau_i}\,(1-e^{-N_z T_c/\tau_i}) \qquad (1)$$

where M is the number of transfers, V_{SIG} is the volume occupied by the signal packet, N_t is the density of traps, and $T_t \simeq T_c/4$. If there is more than one level of traps, Equation (1) must be summed for all traps. Equation (1) shows that buried channel CCDs are relatively sensitive to bulk traps because every signal charge packet encounters traps under each phase gate. This increases the effective trap density by the number of transfers M, which for these devices is 600.

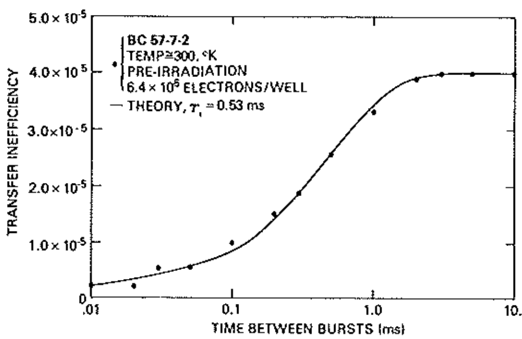

Fig. 4. Fit of the preirradiation transfer inefficiency data as a function of time between bursts to the theoretical loss curve for a single trap level (Eq. 1).

A curve of CTI vs. time between bursts for a typical sample at 300°K before irradiation is shown in Figure 4. The solid line is a best fit of Equation (1) to the data and shows a good fit between data and theory for a single level of electron traps with emission time 0.53 ms at 300°K. For long times between bursts, $N_z T_c \gg \tau_i$, and for $\tau_i \gg T_t$, Equation (1) reduces to

$$N_{loss} = M\, V_{SIG}\, N_t \qquad (2)$$

where N_{loss}/M is given by CTI multiplied by the number of electrons per well. Using Equation (2) with $M = 600$, $V_{SIG} = 2.25\times10^{-10}$ cm^3, and $N_{loss}/M = 262$ electrons, we obtain $N_t = 1.2\times10^{12}$ traps/cm^3 (preirradiation).

In this calculation we have assumed that the volume occupied by the signal charge is 3/8 of the thickness of the buried channel (a 3 volt signal divided by the 8 volt full well signal). This is equivalent to the assumption of uniform doping in the buried channel layer. As shown by the CTI measurements as a function of packet size in Figure 3, small packets occupy a larger volume than assumed in the linear approximation. This is a major source of error in this and the following trap density calculations.

Data showing N_{loss} as a function of time between bursts for a sample irradiated to 3×10^{12} n/cm^2 at 295°C is shown in Figure 5. The solid line shows the best fit of Equation (1) to the data. The data does not fit Equation (1) nearly as well as in the preirradiation case. A better fit would be obtained if a distribution in electron emission times of the traps is assumed. Similar effects have been observed with fast neutron induced bulk defects in JFETS by Gregory et.al.[12] They suggest that, because fast neutrons create defect cluster perhaps with many defects in each cluster, the properties of a individual defect may depend on its local environment within the cluster.

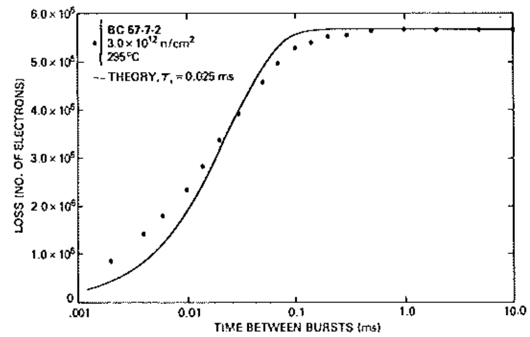

Fig. 5. Fit of the post-irradiation transfer inefficiency data as a function of the time between bursts to the theoretical loss curve indicating a broadening of the trap energy level.

The density of bulk electron traps created by high energy neutrons can be obtained from Equation (2) and the data in Figure 5 when $N_z T_c \gg \tau_i$. The calculated trap density is 4.2×10^{13} cm^{-3} at 3×10^{13} n/cm^2, or a bulk electron trap creation rate ($\Delta N_t/\Delta\phi$) of 14.0 cm^{-1} at 295°K. Data for the same sample at 10 ms between bursts is shown in Figure 6 plotted as Δ CTI (measured value of CTI minus the preirradiation value). vs. neutron fluence. Figure 6 shows an excellent linear relationship between Δ CTI, or number of bulk electron traps created, versus fluence. The data in Figure 6 shows a larger increase in CTI than was reported by Hartsell for similar devices using 1 MeV neutrons for the irradiation. Because the ratio of bulk displacement damage of 14 MeV neutrons to 1 MeV neutrons is 2.5, a larger increase in CTI is expected in this work.[3]

The CTI of a CCD at 84°K as a function of neutron fluence is shown in Figure 7. The data presented illustrate the fact that at fluences greater than 10^{12} n/cm^2, significant degradation

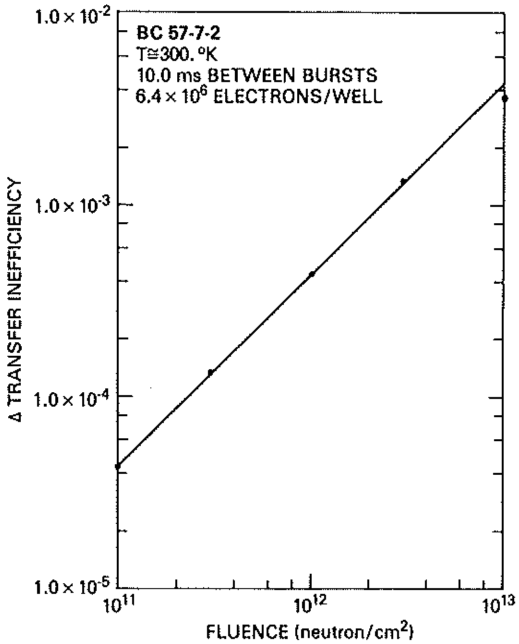

Fig. 6. Change in transfer inefficiency at 300°K as a function of neutron fluence, illustrating the linear relation between the increase in transfer inefficiency due to bulk trapping and the neutron fluence.

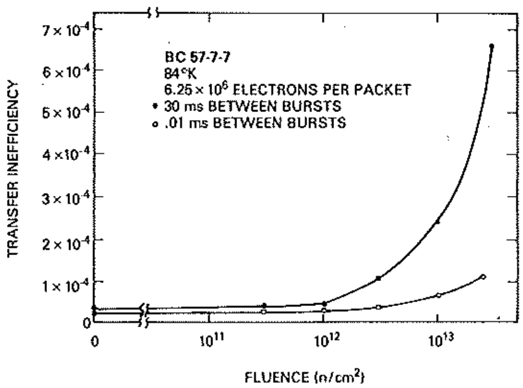

Fig. 7. Transfer inefficiency at 84°K as a function of neutron fluence for two times between bursts, demonstrating the importance of stipulating the time between bursts employed in transfer inefficiency measurements.

of the transfer efficiency occurs. The figure demonstrates the importance of exactly stipulating the conditions under which the CTI measurements are performed.

In Figure 8, the CTI of a CCD irradiated and measured at 80°K for a dose of 3×10^{13} n/cm^2 is shown vs. time between bursts (lower curve). The temperature of the device was then raised to 294°K and the data remeasured (upper curve). From Figure 8, the electron emission time at 294°K is approximately 25 μsec and the calculated trap creation rate $\Delta N_t/\Delta\phi$ is 10.4 cm^{-1}. Within experimental error, these values are the same as for the CCD irradiated at 294°K, and the conclusion is that lowering the temperature to 80°K

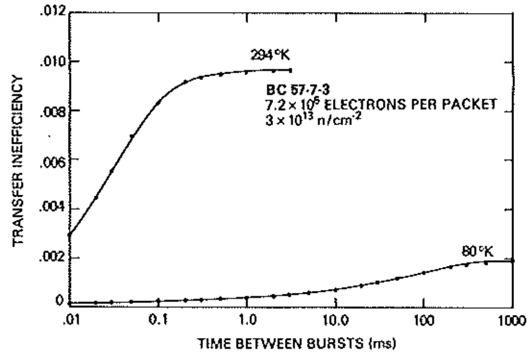

Fig. 8. Transfer inefficiency vs. time between bursts at 294°K and 80°K for a CCD irradiated to 3×10^{13} n/cm^2. At 80°K, the electron traps with emission times between 2μs and 1 sec have a smaller density than the traps effective at 294°K, which results in a smaller CTI at 80°K.

during the irradiation had no effect on the creation of these bulk traps.

The data in Figure 8 illustrates the temperature dependence of the electron emission time of bulk traps. At 80°K the emission time of the trap level which is seen at 295°K has increased to a time much longer than 1 second. Consequently, these traps are always filled during the double pulse measurements and do not affect the CTI. Instead, second level of electron traps appears at 80°K with a density of approximately a factor of 5 less than the 295°K traps ($\Delta N_t/\Delta\phi \approx 2.0$ cm^{-1}) and an electron emission time on the order of 100 ms.

Assuming that the two levels of electron traps observed at 295°K and 80°K are the major fast neutron electron traps in bulk n-type silicon, the sum of the trap creation rates for these levels would give the carrier removal rate for electrons, or $\Sigma\, \Delta N_t/\Delta\phi = 12.4$ cm^{-1} for BC 57-7-3. This value is larger than the values of carrier removal rate measured by Stein and Gereth which range from about 6 to 10 cm^{-1} for approximately 1 MeV (average energy) neutrons.[13] The value measured in this work is expected to be higher due to the larger damage constant of 15 MeV neutrons. In addition, the major source of error here is in the charge packet volume approximation discussed previously, which tends to overstate the actual trap density.

IV. SUMMARY

Buried channel CCD shift registers have been irradiated with high energy neutrons to a fluence of 3×10^{13} n/cm^2 at 80°K and 295°K with the devices operating. CCD characteristics measured were input gate threshold voltage, full well capacity, output voltage to output charge gain of the on-chip output amplifier, dark current, and transfer efficiency. There was no observable change in the full well capacity and only about 7% decrease in the output amplifier gain at 3×10^{13} n/cm^2. The dark current increased substantially to 1600nA/cm^2 at 300°K for 10^{13} n/cm^2 dose.

The input gate threshold shift was observed to depend on the temperature of the CCDs during irradiation and was larger at 80°K than 295°K, similar to the effects of ionizing radiation in MOS structures at liquid nitrogen temperatures. However, the observed threshold voltage shift was approximately a factor of 4 less than would have been predicted from a rough estimate of the ionization equivalent dose for high energy neutrons.

At 295°K, fast neutrons cause a substantial degradation in the charge transfer efficiency of the CCDs. At 3×10^{13} n/cm^2, the transfer inefficiency is about 1%, which would make the CCD unsuitable for most applications. At 295°K, the observed defect introduction rate for an average of 3 devices is 12.8 cm^{-1}, and the electron emission time of these bulk traps is about 25 μsec. At 84°K, the effect of neutron induced bulk defects on transfer efficiency is not nearly as severe due to the temperature dependence of the electron emission time constant.

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REFERENCES

1. Barbe, D. F., Killiany, J. M., and Hughes, H.L. "Effects of Gamma Radiation on Charge-Coupled Devices", Appl. Phys. Letts., 23, pp. 400-402, October 1973.

2. Killiany, J. M., Baker, W. D., Saks, N. S., and Barbe, D. F., "Effects of Ionizing Radiation on Charge-Coupled Device Structures", IEEE Trans. Nucl. Sci. NS-21, pp. 193-200,(1974)

3. Poll, R. A., "Electronic System Hardening Approaches", IEEE Trans. Nucl. Sci., NS-18, pp. 100-103, Dec. 1971.

4. Devices were fabricated by Texas Instruments, Inc., Central Research Laboratories, Dallas, Texas.

5. Killiany, J. M., and Baker, W. D., "Limitations of a Threshold-Insensitive CCD Input Technique in a Total Dose Radiation Environment", Proc. Int. Conf. Appl. CCDs (29-31 October 1975), pp. 369-374.

6. Harari, E., Wang, S., and Royce, B.S.H., "Low Temperature Irradiation Effects in SiO_2 Insulated MIS Devices", J. Appl. Phys. 46, pp. 1310-1317, March 1975.

7. Boesch, H. E., Jr., McGarrity, J. M., and McLean, F. B., "Charge Yield and Dose Effects in MOS Capacitors at 80°K", presented at 1976 IEEE Nuclear and Space Radiation Effects Conference, July 1976.

8. Hartsell, G., "Radiation Hardness of Surface and Buried Channel CCDs", Proc. Int. Conf. Appl., CCDs (29-31 Oct. 1975), pp. 375-382.

9. Williams, R. A., and Nelson, R. D., "Radiation Effects on Charge-Coupled Devices", IEEE Trans. Nuclear Science NS-22, pp. 2639-2644, (1975).

10. Mohsen, A. M., and Tompsett, M. F., "The Effects of Bulk Traps on the Performance of Bulk Channel CCDs", IEEE Trans. Elec. Dev. ED-21, pp. 701-712, November 1974.

11. Broderson, R. W., and Emmons, S. P., "The Measurement of Noise in Buried Channel CCDs", Proc. Int. Conf. Appl. CCDs (29-31 Oct. 1975), pp. 331-349.

12. Gregory, B. L., Naik, S. S., and Oldham, W. G., "Neutron Produced Trapping Centers in JFETS", IEEE Trans. Nucl. Sci. NS-18, pp. 51-59, December 1971.

13. Stein, H. J., and Gereth, R., "Introduction Rates of Electrically Active Defects in n- and p-Type Silicon by Electron and Neutron Irradiation", J. Appl. Phys. 39, pp. 2890-2904, May (1968).