ELECTRON BEAM IRRADIATION OF THINNED BACKSIDE ILLUMINATED CCDs

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ABSTRACT

The physical properties of backside illuminated 64 x 64 pixel surface channel CCD arrays and a 160 x 100 pixel buried channel CCD array when bombarded with electrons have been studied. The devices were mounted in a high vacuum system and irradiated with electrons generated by an electron gun. Basic measurements of EBS gain, dead voltage, transfer efficiency and dark current were performed to verify proper device operation. The surface channel devices were then irradiated with electrons of up to 8 keV energy for up to 98 hours while the buried channel device was irradiated with electrons of up to 20 keV energy for up to 134 hours. After localized prolonged irradiation at 8 keV, the surface channel devices exhibited a reversible (by temperature annealing) decay of responsivity to both electrons and photons and an increase in dark current. The buried channel device did not suffer a measurable loss of responsivity in irradiated areas after bombardment by 20 keV electrons for 134 hours. However, dark current did increase by a factor of approximately two in the irradiated region. If the dark current continued increasing at that rate, the wells would fill with dark current for an integration time of ~35 milliseconds after the device had been operating for ~3000 hours. These phenomena are attributed to soft X-rays generated by the impact of the electrons upon the silicon substrate which cause a change in the fixed charge in the oxide and an increase in the surface states at the silicon dioxide-silicon interface. Verification of an increase of interface states in the irradiated region of the 160 x 100 buried channel device was made by charge transfer efficiency measurements. The input threshold voltage of the lower serial register was measured before and after that area of the device was irradiated with 10 keV electrons. Threshold shifts were measured which were coincident with an increase in dark current in that region of the array. An estimate of the radiation dose deposited in the oxide was made using TLD detectors, yielding ~1600 rads (S_iO_2).

I. INTRODUCTION

The use of a thinned backside illuminated CCD as the electron sensor of an image intensifier has been demonstrated by several groups of researchers (Refs. 1, 2, 3, 4). The advantage of such an imaging CCD-tube combination is that photoelectric gain of the order of several thousand can be achieved because one electron-hole pair may be created in the silicon substrate for every 3.5 eV of energy of the incident electron. Consequently, the inherent noise of the CCD can be overcome by this gain mechanism, allowing photon shot noise limited performance at room temperature. Another aspect of this type of sensor is that the spectral response of the photocathode can be optimized for a given application.

This paper describes the results of measurements made to determine the physical properties of thinned backside illuminated CCDs when irradiated with electrons for prolonged periods of time (tens of hours). Both surface channel and buried channel devices were tested. The devices tested were not sealed in an image intensifier and did not undergo any stages of intensifier tube fabrication. Consequently, only physical effects generated by the electron beam itself were measured. Both kinds of devices were manufactured by Texas Instrument, Inc. The 160 x 100 buried channel device is of the same type which has been successfully operated in intensifier tubes Refs. 1, 2).

II. EXPERIMENTAL DESCRIPTION

The experimental arrangements used to make measurements were somewhat different for the two types of devices tested. The 64 x 64 surface channel device was completely mounted within the high vacuum system. Clock lines and other inputs and outputs were coupled into the system via a feed-through port. The 160 x 100 buried channel device had already been mounted to a vacuum header, which in turn was mounted to a vacuum system port using a mechanical o-ring pressure fitting. Several electron guns were used during these experiments. All guns were mounted on a port directly opposite the devices irradiated. A current monitoring Faraday bucket was mounted directly to the side of the CCDs. The electron beam could be steered into this pocket, permitting direct measurement of total beam current. An aluminum shield of 0.16 cm thickness with a pin hole was placed directly in front of all devices while in the system so that only a small area of the array was bombarded by the electron beam at any given time. This technique offered a high degree of control and safety from inflicting accidental damage to the arrays under test.

The 64 x 64 CCDs tested were three-phase n-channel devices capable of frame storage. The gate structure of these devices included single metalization non-overlapping electrodes. The electrode size was 0.3 x 1.2 mils with 0.1 mil gaps between transfer electrodes. The active area was 0.038 cm^2. A single diode-gate structure ran the entire length of the parallel registers across the top of the device and enabled the loading of fat zero into the parallel registers. A serial shift register at the bottom of the parallel array facilitated readout. A diode-gate input was provided on this register to allow fat zero and other electrical waveforms to be entered. A conventional two transistor pre-charge and float output circuit was employed for signal extraction. The thickness of the arrays was 11.4 microns ± 2.5 microns as measured by manufacturer. The thinned backsides were accumulated. Substrate doping was 1 to 2 x 10^{15} cm^{-3} while the surface orientation was <100>. The devices were operated in the frame storage mode during irradiation by an exerciser built specifically for the purpose.

The 160 x 100 buried n-channel array is identical to those used by Williams (Ref. 1) and Caldwell, et al. (Ref. 2) and described in detail elsewhere (Ref. 5). The device is a three-phase overlapping gate CCD without frame storage capability. Serial registers are provided on the top and bottom of the parallel registers allowing the parallel registers to be uniquely probed by inserting an electrical pulse in a serial register, transferring it through the parallel register under investigation and subsequent readout through the other serial register. The device is a nominal 10 μm thick and the backside is accumulated. The quantum efficiency of the device as measured by the manufacturer was 12% at 0.45 μm, 52% at 0.8 μm, and 2.5% at 1.1 μm. The device was operated in the full frame mode during irradiation by an exerciser built specifically for the purpose.

III. EXPERIMENTAL RESULTS

A. RESULTS WITH A SURFACE CHANNEL IMAGER

Experimental results obtained for four 64 x 64 surface channel devices are presented first. The devices were operated in the frame storage mode at a clock rate of 500 kHz corresponding to a frame integration period of 4 milliseconds. In this mode the integration area consisted of 64 x 32 pixels. The transfer efficiency of the serial register with 20% fat zero ranged between .9969 and .9973 for all devices tested. The dark current density of the devices was on the order of 12 nA/cm^2 measured at 26°C. All devices exhibited well defined dark current pattern noise. All signal measurements were made by the use of an oscilloscope. Care was taken to isolate the output signal cable from CCD clock lines to minimize clock pickup. The typical maximum full well signal amplitude from photo sites was 1.4 volts. Measurement of electron gain for one of the devices tested is plotted in Fig. 1. The plot indicates a dead voltage of 3.2 kV. Fig. 2 shows a plot of irradiation response versus time for 8 keV electrons. The electrons were illuminating a 7 x 7 matrix of elements for about 100 hours. An initial beam current per element of 16 picoamperes corresponded to a condition of 50% full well. No fat zero was used in the parallel register while 20% fat zero was injected in the serial register for all measurements. As the responsivity of the irradiated area decayed with time, it was noted that addition of parallel register fat zero immediately restored some response. However, after prolonged irradiation all response to electrons and photons was lost regardless of fat zero level. A curious phenomenon observed was a return of some responsivity to devices after they were left unclocked and not irradiated for some time ranging from 10 to 48 hours. However, when the electron bombardment was resumed, degradation proceeded at a much faster rate. A small increase in dark current was also observed in those areas irradiated by electrons.

The decay of responsivity to both electrons and photons occurred simultaneously with a similar inability to obtain charge transfer through regions which had been irradiated. This phenomenon was observed in the inability to transfer fat zero charge through parallel registers which had part of their structure illuminated. Fig. 3a shows one line output of a tested device before irradiation. The bottom output trace shows the signal level with 20% serial register fat zero. The upper trace shows the signal distribution when 00% parallel register signal is added. The location of the electron beam within this line when incident upon the device is shown in Fig. 3b. After all responsivity to the electron beam and the light was lost, an attempt was made to transfer full wells of charge through the affected area. This failed, resulting in a pronounced notch in the output as shown in Fig. 3c. The device was then removed from the vacuum system and heated in air to 85°C for three hours with all of its pins shorted together. It was then replaced in the vacuum system and found to be sensitive to both photons and electrons in the previously insensitive area. Attempts were again made to transfer full wells of charge through the affected area, and these were successful, as is shown in Fig. 3d.

B. RESULTS WITH A BURIED CHANNEL IMAGER

The 160 x 100 buried channel device was operated in the full frame mode at a clock rate of 500 kHz, an integration period of 108 milliseconds, and a read-out period of 36 milliseconds. The transfer efficiency of the lower and upper serial registers at 25% full well signals were 0.99906 and 0.9993, respectively. When signals that nearly filled wells were entered, efficiency decreased dramatically as expected because this increased the probability of transitions to interface states. The dark current density of the device was measured as 16 nA/cm^2 which was in good agreement with the manufacturer's data. The full well signal obtained from the parallel array was 0.375 volts. The energy efficiency, η, is plotted as a function of bombarding electron energy in Fig. 4. The plot shows a dead voltage at about 8 keV. Electron beam energies below this level caused a small response in the form of an increase in dark current apparently caused by local heating of the substrate which was coincident with the application of the electron beam. The energy efficiency of 0.5 at 20 keV corresponds to an EBS gain of ~2800.

The device was bombarded with 20 keV electrons for a prolonged period of time at one location of the array and with 10 keV electrons for a shorter period of time at another location. The irradiated region was uniformly bombarded through a circular aperture of 13.5 mils which corresponded to a diameter encompassing about 15 pixels. The electron beam current was set to achieve a signal 50% of a full well and corresponded to a beam current density of 0.075 nA/cm^2 at 20 keV. No dark current increase due to localized heating was noted at these current densities. Measurements were made by reading the wells out through the upper serial register. Fig. 5 shows the normalized increase in dark current signal for the irradiated region (20 keV electrons) as a function of irradiation time, which was accumulated intermittently over about three weeks. After 134 hours of bombardment, the increase in dark current in the region of irradiation could clearly be seen in the output of one line as shown in Fig. 6. This oscillograph shows a relative increase in dark current of about a factor of two over the pre-irradiation level. An increase in surface state density in the region of irradiation was observed by probing this area of the device with an electrically inputted pulse that filled one line of the raster. Fig. 7 shows the increased loss because of surface state trapping for a near full well signal and also shows the laggard charge in the following lines. As expected for operation in the buried channel mode (that is, no interface state trapping), this transfer inefficiency disappeared, as shown in Fig. 8. A second area of the array was subsequently illuminated with 10 keV electrons. At the end of an accumulated time of 25 hours, a very slight but perceptible increase in dark current was noted in this area as compared to pre-irradiated levels.

Another experiment was carried out to determine if a shift in the threshold voltage of one of the serial input gates could be observed. The aperture was placed over the input structure of the lower serial register. The electron beam also irradiated part of the parallel array. A series of pre-irradiation curves were made at different input diode voltages by plotting input gate voltage as a function of reset drain current on an x-y recorder. The region was then bombarded with 10 keV electrons until a noticeable increase in dark current was observed in the irradiated array region. At no time during irradiation was there noted an increase in dark current due to localized heating caused by the electron beam. An input gate voltage shift for constant input drain voltage was then observed as shown in Fig. 9. Continued irradiation of the area increased this shift toward lower gate voltages as shown in Fig. 9.

IV. ANALYSIS

Ionizing radiation causes a buildup of positive charge in the oxide of a MOS structure and an increase in the density of states at the oxide semiconductor interface. The trapped charge in the oxide produces a negative shift in the flat-band voltage of the device. However, a carefully designed and properly operated CCD can function satisfactorily after several volts of flat-band shift, since the charge transfer process in a CCD is fairly insensitive to flat-band voltage shift (Ref. 6). Of course, a potential-equilibration type input technique has to be employed to compensate for the input gate threshold voltage shift (Ref. 7). The buildup of interface states during ionizing irradiation causes an increase in transfer loss for surface channel devices and an increase in the dark current density for both surface and buried channel devices.

The changes in the dark current density and input gate threshold voltage observed after an electron beam irradiated CCD had been operated for over 100 hours can be attributed to the x-rays generated by the electrons incident on the silicon. Few bombarding electrons can reach the silicon-silicon dioxide interface because the range of 20 keV electrons in silicon is only 2.2×10^{-4} cm while the substrate is 10×10^{-4} cm thick (Ref. 8). However, x-rays are generated and a significant fraction of these penetrates to the oxide. Several experimentors have reported radiation damage in MOS devices which were exposed to the x-rays produced by electron beam bombardment of low Z materials (Refs. 9 and 10).

The x-radiation produced by electron bombardment of the silicon consists of two components, the continuous or bremsstrahlung radiation, distributed in energy from zero up to the electron beam energy, E_0, and the characteristic x-rays of the silicon which are sharply defined in energy. Because the absorption cross section of x-rays in a material is a function of the x-ray energy, a calculation of the fraction of the x-radiation which reaches the CCD oxide requires a knowledge of the entire spectrum. However, an estimate of this fraction can be made by considering the absorption of the characteristic x-ray. The intensity I of the K_α x-rays reaching the CCD oxide is related to the intensity I_O generated at the back of the CCD by

$$I = I_o e^{-\mu x} \quad (1)$$

where $\mu = 8.34 \times 10^2/\mathrm{cm}$ is silicon's absorption coefficient for its K_α x-rays and x is the thickness of the silicon substrate,(Ref. 11). I/I_O is equal to a .435 for x - 10 x 10^{-4}cm.

An estimate of the x-ray intensity at the silicon-silicon dioxide interface of the electron bombarded CCD was made by using square calcium fluoride ($Ca F_2$:Mn) thermoluminescent dosimeters (TLDs) .079 x 10^{-3} cm thick and .3175 x 10^{-3}cm on a side. The dosimeters were covered with 10 x 10^{-4} cm of aluminum foil and exposed to 10 keV electrons. The dose deposited in the detectors was used to determine the energy per unit area of the x-ray field at the detector's surface. The distribution of the absorbed energy in the TLD detector was considered in making the x-ray intensity calculation (i.e., most of the x-rays are absorbed within a few microns of the detector's surface).

The absorption coefficient for the silicon K_α x-ray in silicon dioxide was calculated from the tablulated values for silicon and oxygen using the expression (Ref. 9).

$$\mu_{SiO_2} = 0.47\mu_{Si} + 0.53\mu_{O_2} \quad (2)$$

Using this absorption coefficient in equation (1), one finds that the 1000 A^o thick film of silicon dioxide will absorb 1.7% of the incident energy from a beam of 1.738 keV electrons.

Finally, the dose deposited in the CCD oxide layer will be approximated by using the measured x-ray energy per unit area that penetrated the aluminum foil and the absorption coefficient for silicon K_α x-rays in silicon dioxide. The dose accumulated in the oxide of the thinned CCD which had been bombarded with 20 keV electrons for 134 hours is calculated to be 1,600 rads. The damage observed is what one would expect from a dose of 1,600 rads on the basis of previous experimental irradiation of similar devices that are reported in the literature (Ref. 7 and 12).

V. CONCLUSION

Surface channel and buried channel backside illuminated devices have been irradiated with controlled electron beams for prolonged periods of time (>100 hours). A small but consistent increase in dark current was observed in those areas irradiated. A measurement of charge transfer efficiency as a function of signal level was made with the buried channel device, which indicated an increase in the interface state density in the irradiated regions. The input of a serial register of the buried channel device was irradiated after which a negative shift in input gate threshold voltage was observed. These results are attributed to the generation of soft x-rays by the bombarding electron beam. A measurement of the dose was made by irradiation of TLD detectors. The effects noted above were consistent with those reported earlier (Refs. 7, 12) in which similar devices made by the same manufacturer were damaged by comparable doses of radiation.

VI ACKNOWLEDGEMENTS

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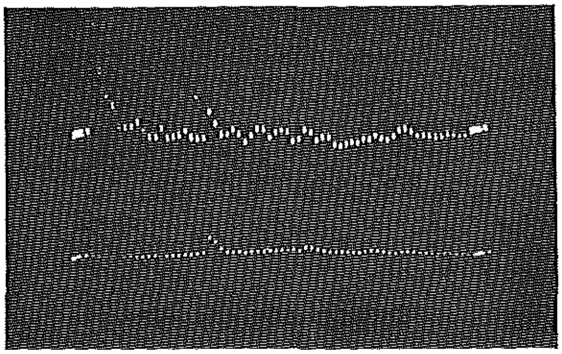

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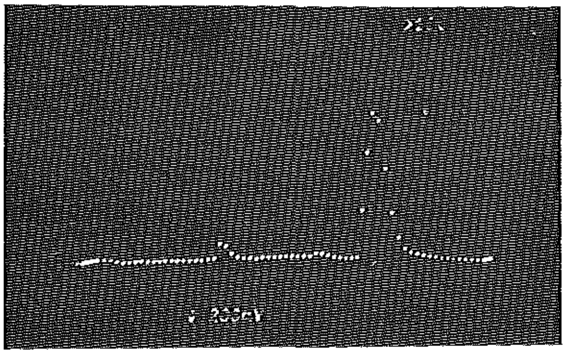

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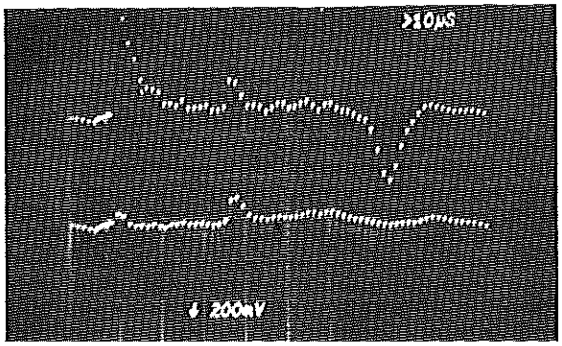

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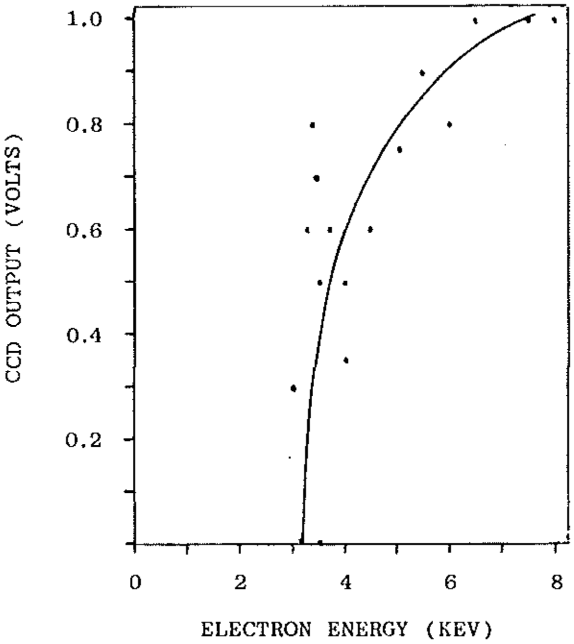

Fig. 1. EBS Gain versus electron energy for 64x64 Surface Channel CCD.

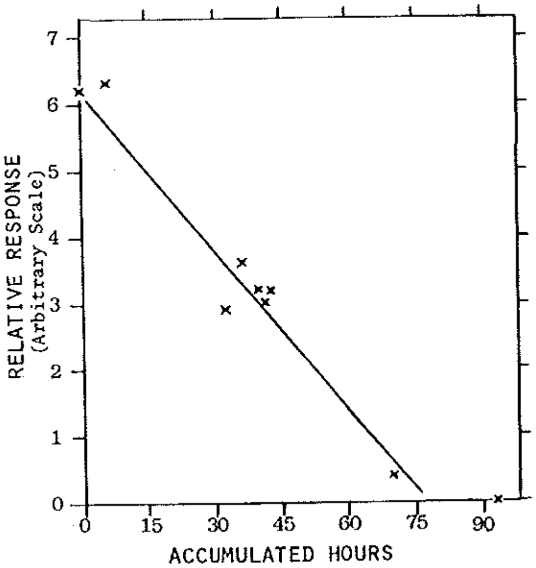

Fig. 2. EBS Response versus time for 8 keV electrons- Surface Channel CCD.

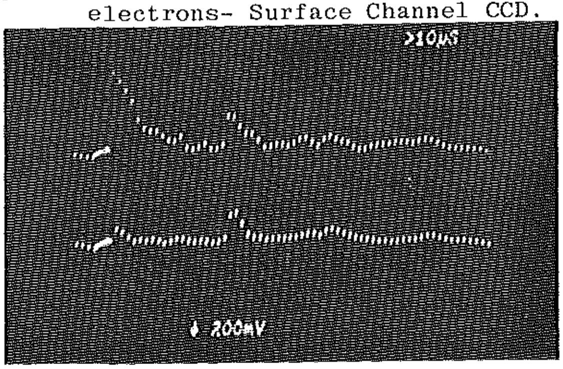

Fig. 3. Line output of Surface Channel CCD Before, During, and After Irradiation and After Temperature Anneal.

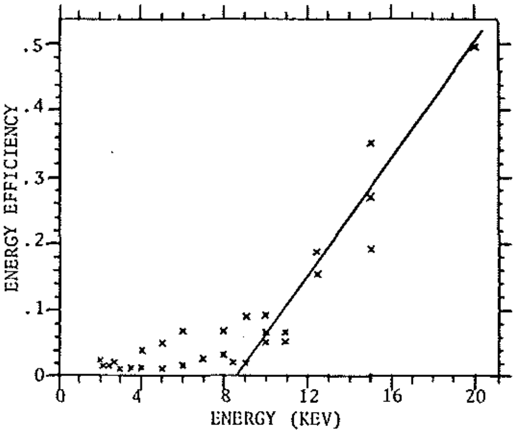

Fig. 4. Buried Channel CCD Energy Eff. versus electron beam energy.

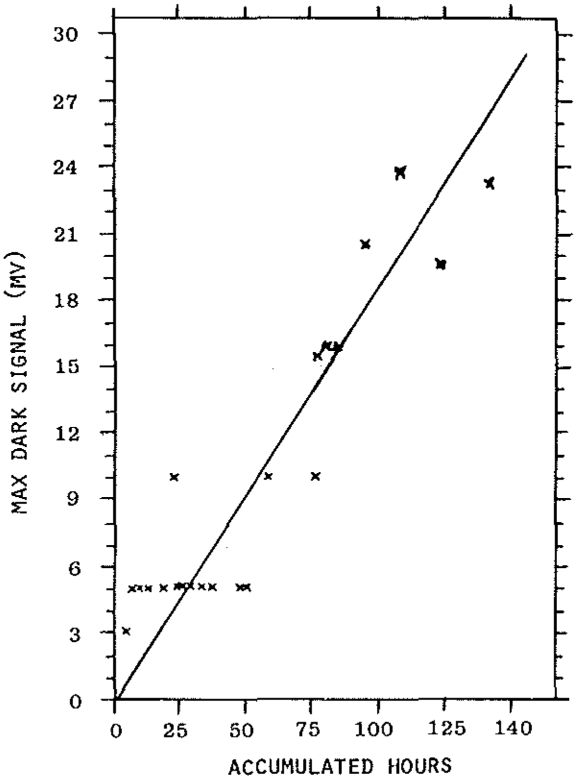

Fig. 5. Normalized increase in dark current versus time for 20 keV irradiation.

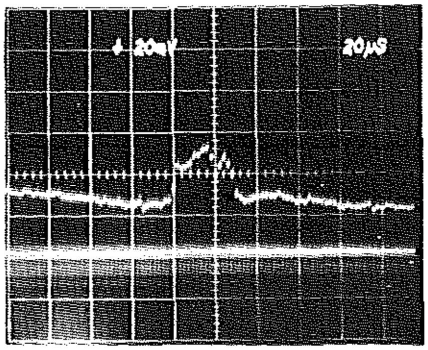

Fig. 6. Dark current irregularity due to prolonged electron beam irradiation.

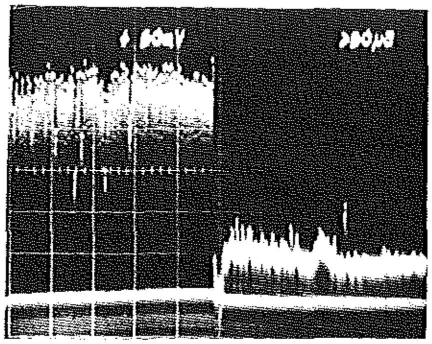

Fig. 7. Surface state trapping due to electron beam irradiation.

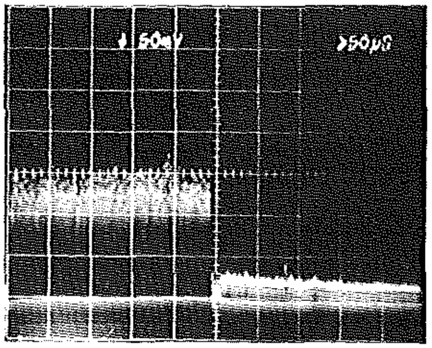

Fig. 8. Mitigation of trapping by buried channel operation.

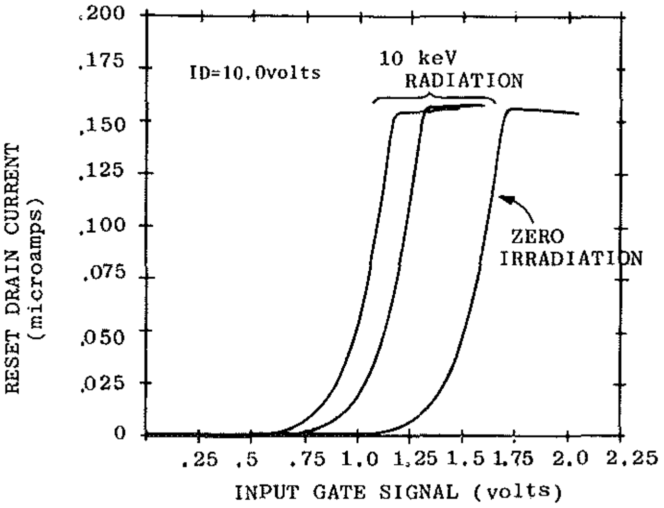

Fig. 9. Input Gate Threshold Voltage Shift as a Function of Irradiation.