RADIATION HARDNESS OF ALUMINIUM GATE CCD'S

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ABSTRACT

The effects of gamma radiation on p-channel three phase aluminium gate CCD's were studied. The transfer efficiency was measured by both optical and electrcial methods. In both cases for a majority of the devices the transfer efficiency increased with low dose in the 10 to 20 k rads range and then fell off rapidly. Above 60 k rads all the devices failed except for one. C-V measurements as a function of dose show typical large negative shifts in flat band voltages for 'soft' oxides for both positive and negative electrode bias. These C-V results are compared to the earlier American data on buried channel and two phase stepped-oxide surface-channel CCD's (ref 1,2). The RRE C-V curves after irradiation showed structure indicating that a change in carrier population over a narrow energy band in the silicon had been caused by the radiation.

INTRODUCTION

The effects of gamma and other ionizing radiations on MOS transistors has been well documented (ref 3). Many models have been proposed for the radiation interaction in terms of an increase in the charge density and modification of charge state of traps in the oxide and surface states at the silicon-silicon dioxide interface. It has also been shown that this interaction is critically dependent on the oxide processing and purity (ref 4,5).

In this paper preliminary results of the effects of gamma radiation on aluminium gate three-phase CCD's are given. C-V measurements were made and the flat-band shift was compared to previous results on two-phase stepped oxide surface channel (ref 1) and three-phase buried channel (ref 2) CCD's. Transfer efficiency of the irradiated devices was measured in two ways:

(1) using the scanning light spot technique (ref 6,7),

(2) using the electrical trailing pulse technique.

Finally, the change in full well current as a function of dose over the range 0 to 60 K rads was determined.

EXPERIMENTAL TECHNIQUE

8 bit serial CCD shift registers (ref 7) were used for all the measurements. There were made with standard p-channel MOS technology. The n type silicon substrate had a resistivity of 5 ohm cm and a (100) orientation. Boron diffusions were used for the source and the drain. 1500 Å of dry oxide was used for the gate oxide and no attempt was made to harden this oxide to radiation. 2000 Å thickness of

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aluminium was used for all the electrodes and the contact pads. The aluminium transfer electrodes were 12 microns long and 300 microns wide with a gap between the electrodes of 2.5 ± 0.3 microns.

The samples were irradiated with a cobalt 60 source which provided 105 k rads per hour. During irradiation the transfer electrodes for the majority of the devices were biased with -30 volts and the input and output gate and the output diode were biased with -10 volts. These biasing conditions were used because they corresponded to the normal operating voltages for the devices. For three of the devices a positive bias of +10 volts was applied to the transfer electrodes and the input and output gates for comparison with the negative bias results.

After irradiation C-V measurements were carried out. A standard type of high frequency (1MHz) capacitance measurement technique was used with a phase sensitive detector and a capacitance bridge system. The devices were measured in the absence of light in enclosed TO5 cans. The flat-band voltage was estimated from the C-V curves in the normal manner. A control CCD device which was unirradiated was used to check out the C-V equipment each time a new batch of irradiated samples was studied. The flat-band voltage from this control device varied by only 1%.

After the C-V curves had been obtained the transfer efficiency was measured. Two batches of six devices were studied at RRE using the scanning light spot technique (ref 6,7) and one batch of four devices was measured at AWRE using the electrical trailing pulse technique. In this way both the charge transfer loss between the electrodes and the loss due to charge residual after transfer were measured.

The optical transfer efficiency measurement technique which measures the charge loss between the transfer electrodes has been fully described elsewhere (ref 6,7). A light spot of the same length as the transfer electrode was scanned slowly over the CCD at a rate of 30 microns/minute. The light was modulated at 220 Hz. During the scan the device was operated at a clock frequency of 833 KHz. The clock voltage was -30 volts and the overlap was set to give maximum output. Two transfer efficiency measurements were made with two values of clock offset: (a) zero offset (b) with a negative voltage offset equal to the change in flat-band voltage caused by the gamma radiation. The input gate pulse was set with the same frequency and phase as the first clock voltage. The amplitude of the input gate pulse was set to give a half well (half the saturation output). Hence the devices were always measured with a 'fat zero' applied. The output was set to give maximum output without clock breakthrough. The source diffusion and the channel stop diffusion were earthed and the drain diffusion was biased with -10 volts through a 1.2 k ohm resistor.

The optical output from the device produced by the scanning light spot was detected by a lock-in amplifier. 25 peaks were observed on the X-Y recorder trace of the output from the lock-in amplifier. Each of these peaks corresponds to light falling on the gap between the transfer electrodes. The ratio of the amplitude of two consecutive peaks gives a measure of the inter-electrode transfer efficiency.

Since the amplitudes were also affected by device geometry and quality, a more accurate figure for the transfer efficiency was obtained by plotting the amplitude as a function of gap number. The 'optical' transfer efficiency was then calculated from the slope of the best fit line using the equation:

$$(n - 1)\eta_O = \ln(S_n/S_1)$$

where n is the number, η_O is the 'optical' transfer efficiency and S_n is the amplitude of the nth peak in the amplifier output signal, in arbitrary units, calculated from the best-fit straight line.

The residual charge loss was estimated from the ratio, R, of the output pulse to the next trailing pulse. Then the electrical transfer inefficiency ε_E was established by using the equation (ref 8): $\varepsilon_E = \frac{1}{NR}$ where N is the number of transfers.

The input gate threshold voltage determined from the transfer characteristic plot of the input gate voltage against the drain output. The full well current was calculated by operating the input gate at saturation voltage to give maximum drain output and measuring the voltage drop across a standard resistor in series with the drain.

C-V MEASUREMENTS

A <u>negative</u> shift in flat-band voltage was produced by gamma irradtation of the CCD regardless of whether it was under negative or positive bias. Figure 1 shows the shift plotted as a function of the dose in rads.

The negative bias curve is an average of six of the devices and is typical of all those obtained for the RRE devices which all showed changes of flat-band voltage of about -20 volts for doses of 200 k rads and all began to saturate in this region.

For the positive bias devices no saturation was observed and the curve shown in Figre 1 is the average for the three devices measured. The slower rate of saturation and the larger shift in flat-band voltage with positive bias is typical of the MOS devices (ref 9). These differences can be explained in terms of what happens under positive bias during electron-hole pair creation in the oxide by the gamma radiation. The electrons are more mobile than the holes and move towards the positively biased electrode; the holes, on the other hand, are not very mobile and are trapped or recombine before they can leave the oxide.

Also shown in Figure 1 are the results on Fairchild (ref 2) and RCA (ref 1) CCD's. In the case of the 60 bit Fairchild buried channel devices a 5 volts positive bias was applied to the transfer electrodes. The Fairchild curve is seen to be very similar to the RRE positive bias (+10 volts) curve. Neither the RRE nor the Fairchild oxides were prepared in any special way to make them 'hard' to radiation.

In the case of the RCA 64 bit two phase stepped-oxide surface-channel CCD's the oxide growth process was chosen to give a low interface-state density but no attempt was made to optimize the radiation hardness. Figure 1 shows that in the case of the aluminium gate device which was biased with -10 volts the oxide was 'hard' when compared to the RRE oxides with their -30 volts bias. The RCA polysilicon gate devices on the other hand were similar to the RRE devices when the difference in bias is taken into account.

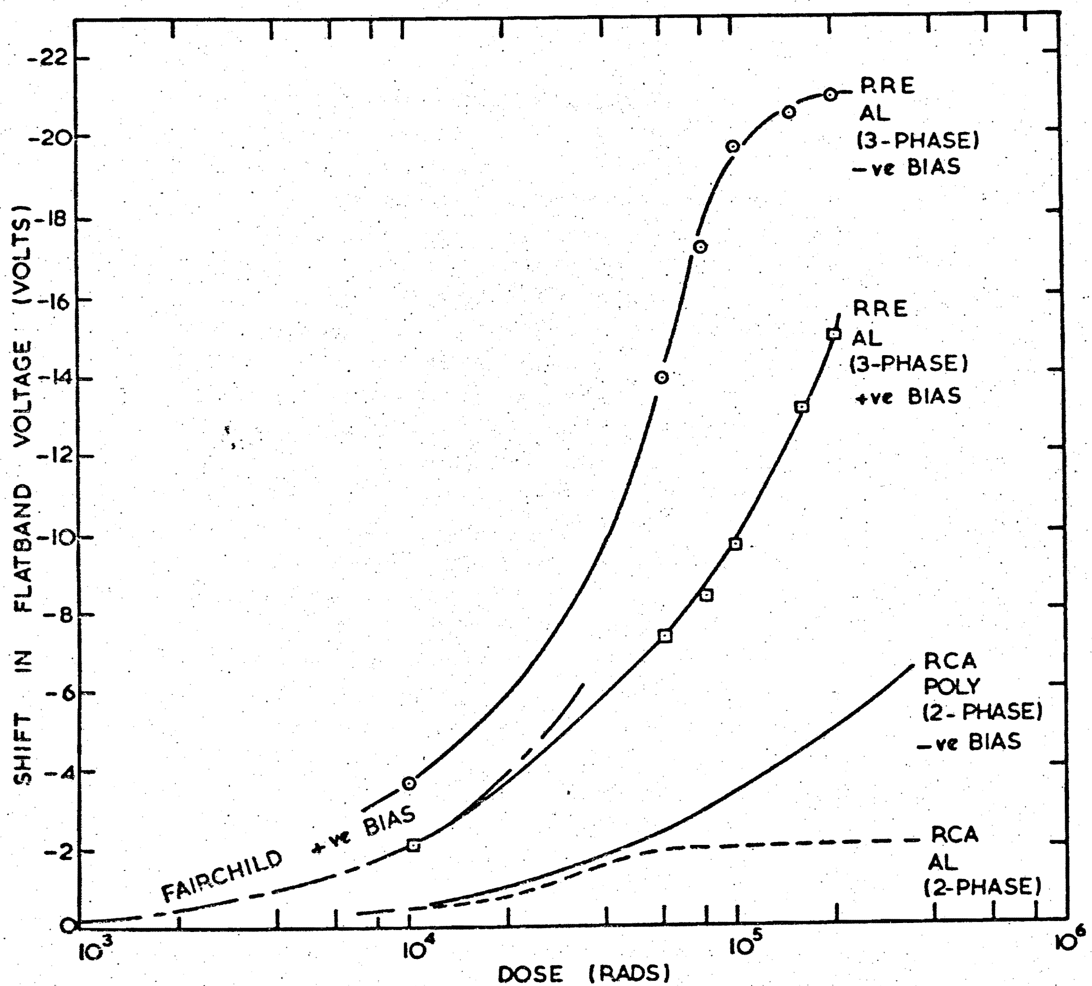

Figure 1. Average flat-band shift against total dose for RRE aluminium gate p-channel CCD's with positive and negative bias. For comparison results on Fairchild and RCA devices are also shown.

The RRE C-V curves are shown in Figure 2.

Before irradiation no structure was observed in the C-V curves but after 10 k rads dose structure is observed and this structure grows to a distinct bump at 40 k rads. The 40 k rad curve is shown in Figure 2. This structure was also observed in a quasi-static measurement on the 40 k rad irradiated device at about the same gate voltage. It is well known that this structure arises in C-V curves when a large concentration of a particular surface state is present having a single energy level associated with it (ref 10). This peak was observed for every device except one which had been positively biased and which showed a total shift in flat-band voltage of only -7 volts at 200 k rads (less than half the shift observed for the rest.)

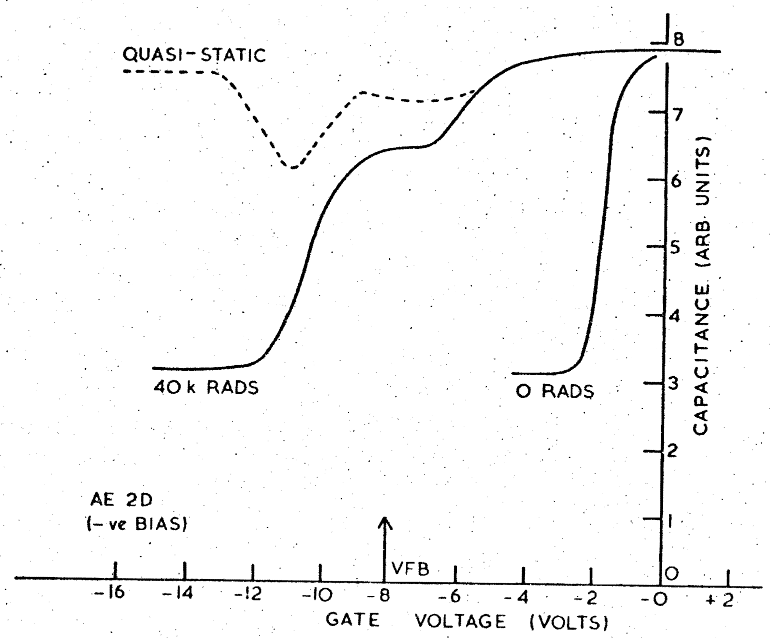

Figure 2. C-V curves comparing high frequency and quasi-static measurements.

INPUT GATE THRESHOLD VOLTAGE

Before the optical measurements were made the transfer characteristic of the devices were studied by plotting the output voltage from the drain against the input gate voltage. Figure 3 shows the threshold voltage change with dose determined from these curves.

As expected from the smooth change in flat-band voltage dose seen in Figure 1 no discontinuities were observed in the threshold voltage curves.

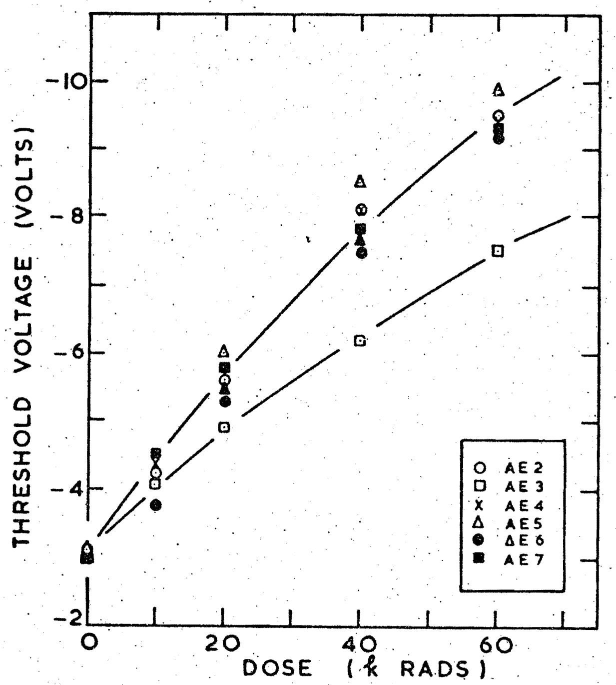

Figure 3. Change in input gate threshold voltage with dose.

OPTICAL TRANSFER EFFICIENCY

Figure 4 shows the optical transfer efficiency against dose for six devices. Zero clock offset was used for all the curves.

In five out of six of the curves the transfer efficiency reached a maximum for doses in the range 10 to 20 k rads. For the sixth in Batch A the transfer efficiency decreased continuously with dose. Interestingly enough this was the device with the 'harder' oxide mentioned above which showed no extra structure in the C-V curve even after 200 k rads of radiation. This was also the only device which operated after 80 k rads dose. The accuracy of the optical measurements was determined from a control device to be in the range $\pm 0.1\%$ to $\pm 0.3\%$.

Six other devices were studied as well as those shown in Figure 3. One of these showed identical behaviour to those of batch B, two other devices failed to work after the second irradiation and for three the error in measurement was too large.

Offsetting the clock voltages by the change in flat-band voltage produced no change in the maximum but made charge transfer possible for some of the devices which had failed when given 60 k rads.

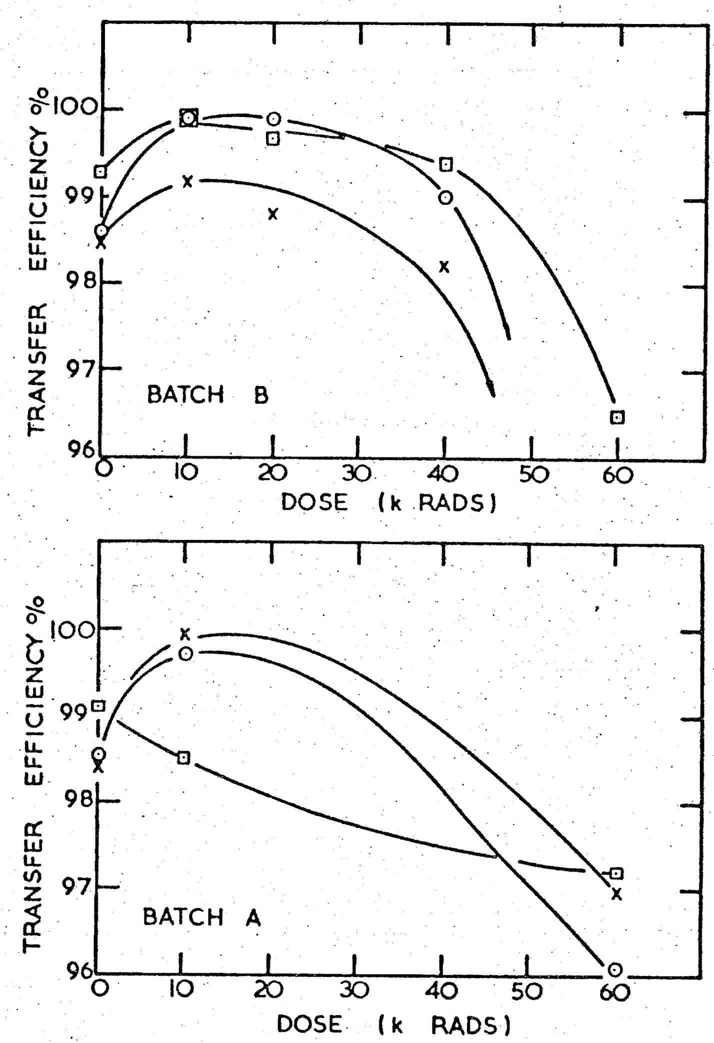

Figure 4. Optical transfer efficiency against dose.

ELECTRICAL TRANSFER INEFFICIENCY

Preliminary electrical results on four devices are shown in Figure 5(b) where the electrical transfer inefficiency is plotted against dose. The clock offset was readjusted for each measurement to compensate for the change in threshold of the devices. Two of the devices clearly show a minimum in transfer inefficiency which corresponds to the maximum observed in the optical transfer efficiency measurements. Just how closely they correspond has been shown in Figre 5(a) where they are compared with a typical curve taken from Figure 4 (Batch B). Both the zero offset and the compensated clock curves are shown for the optical measurement.

The other two curves shown in Figure 5(b) have no minima but they show little change in transfer inefficiency in the range 0 to 20 k rads.

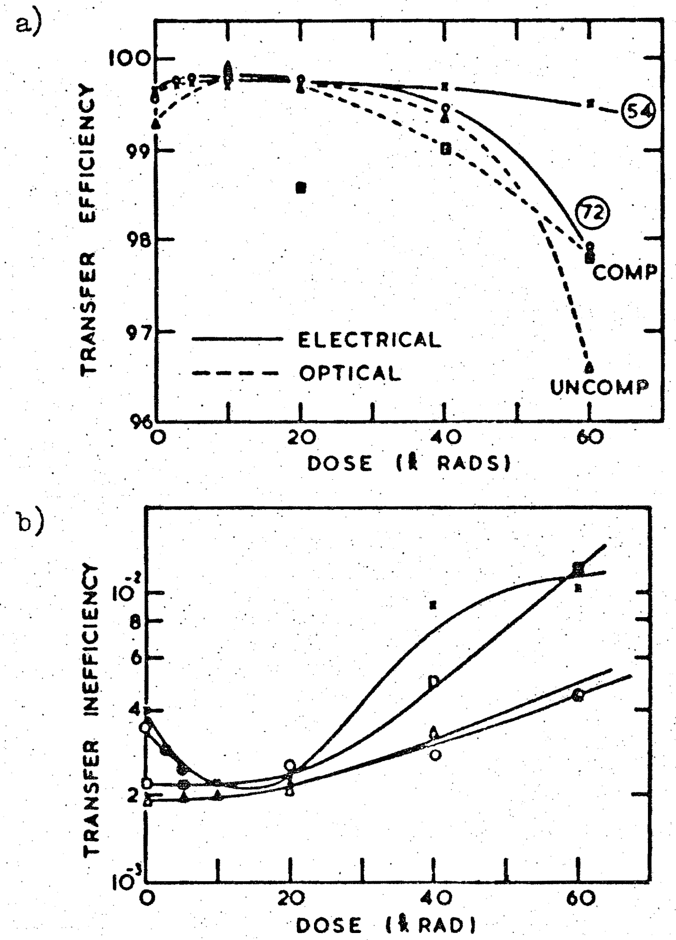

Figure 5. Electrical transfer inefficiency against dose in the lower set of curves. Electrical compared with optical transfer efficiency against dose in the upper set of curves.

FULL WELL CURRENT

As expected the full well current shown in Figure 6 decreased with dose with the clock voltage offset by the change in flat-band voltage.

The results for only two devices are shown but they are typical of all of the other seven that were measured. After 60 k rads the full well current had fallen to only half of the original unirradiated value.

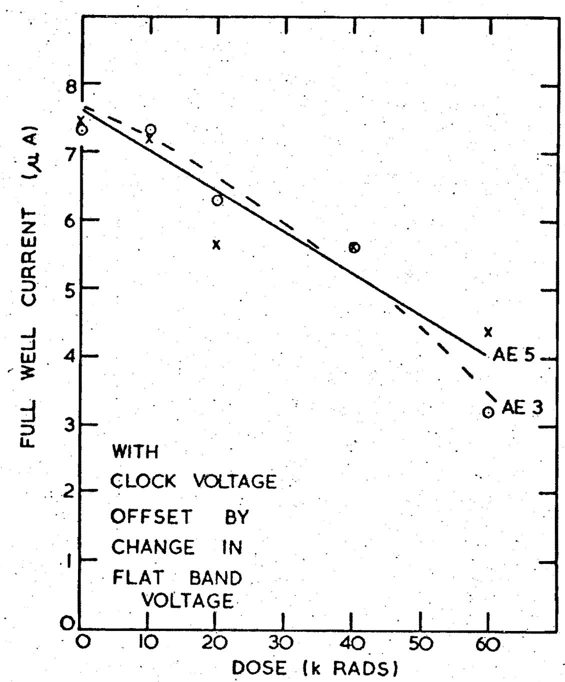

Figure 6. Decrease in full well current as a function of increasing total dose.

CONCLUSIONS

The dry oxides used in the p-channel CCD's that were studied were not 'hardened' to radiation so they showed a large negative shift in flat-band voltage with gamma irradiation for both positive and negative bias on the transfer electrodes. C-V curves after irradiation showed structure indicating that a change in population of the interface states around the single energy level had been induced by the radiation.

Optical and electrical transfer efficiency measurements showed that a small dose of up to 20 k rads increased the transfer efficiency for a majority of the devices. In one case the efficiency increased from 98.5 to 99.9%. For one device which was positively biased a decrease in efficiency was observed and for this same device the C-V curve showed no structure and the shift in flat-band voltage was less than half that observed for all the other devices. This implies that the structure or the energy level observed in the C-V curves may be associated with the improvement in performance of the CCD for low dose level. Further work will have to be carried out to confirm this implication. Other workers have observed similar peaks in the C-V plots (ref 11). Identification of the origin of these peaks is still an open question.

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