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RADIATION DAMAGE IN MOS INTEGRATED CIRCUITS PART I

VITALY DANCHENKO

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GSFC

GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

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ABSTRACT

Complementary and p-channel MOS integrated circuits made by four commercial manufacturers were investigated for sensitivity to radiation environment. The circuits were irradiated with 1.5 MeV electrons. The results are given for electrons and for the Co-60 gamma radiation equivalent. The data are presented in terms of shifts in the threshold potentials and changes in transconductances and leakages. Gate biases of -10V, +10V and zero volts were applied to individual MOS units during irradiation.

It was found that, in most of circuits of complementary MOS technologies, noticable changes due to radiation appear first as increased leakage in n-channel MOSFETs somewhat before a total integrated dose of 10^{12} electrons/cm^2 ($\sim 3 \times 10^4$ rads/cm^2, Co-60) is reached. The inability of p-channel MOSFETs to turn on sets in at about 10^{13} electrons/cm^2. Of the circuits tested, an RCA A-series circuit was the most radiation resistant sample.

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RADIATION DAMAGE IN MOS INTEGRATED CIRCUITS, Part I

I. INTRODUCTION

There are many advantages of Metal-Oxide-Semiconductor (MOS) integrated circuits (ICs) over bipolar ICs in the design of large-scale integrated logic and memory circuitry for spacecraft. Among these are extreme compactness and low power consumption. Such circuits are being orbited to an ever increasing extent. They have been flown or are planned to be flown on IMP-I, H and J, ATS, NIMBUS, Pioneer, Helios and many other missions.

MOS ICs are found to be more sensitive to space radiation than their bipolar counterparts. Consequently, we find ourselves under considerable demand from flight project people at Goddard and other NASA Centers, as well as from principal investigators for flight experiments outside NASA, who use or plan to use MOS type ICs, to investigate the instability of these circuits in the space radiation environment. Inquiries also come from foreign countries such as France, Germany and Denmark, to whom Goddard extends assistance in spacecraft electronics. In particular, many questions are being asked about complementary MOS integrated circuits. To meet these demands we have initiated an extensive program to systematically measure the sensitivity to radiation of MOS circuits. It is our intent that reports, similar to this, will be issued from time to time and made available to those who are involved in planning and design of space-circuitry.

Experience has shown that radiation effects in MOS ICs not only differ greatly from one manufacturer to another, but also change within a given company due to a continual effort in improving stability and production of MOS devices. These changes, directed primarily to facilitate production or lower threshold potential, may or may not improve radiation hardening. There is some direct effort on a laboratory scale to harden MOS ICs against radiation, but circuits available for space flight use at present have not been manufactured to be radiation resistant.

This report describes radiation effects in MOS integrated circuits most of which have been used by GSFC in space missions. Of the four MOS technologies investigated here three are of complementary and one is of strictly p-channel type. In the choice of ICs for the investigation and the presentation here, no preference whatsoever was given to any particular technology other than the requirement of GSFC for the data and availability of suitable samples for irradiation. The data are presented in terms of the shifts in the threshold potentials of individual MOS units, changes in the transconductances and leakages in n-channel units with various biases applied during irradiation. Other effects, such as breakdowns in the gate insulation and leakages in the drain-to-source junctions were also observed, but discounted here. Since some amount of handling of the samples was necessary, it was not directly evident that these effects were induced by radiation or caused by handling.

For those who are not familiar with a general aspect of radiation damage in individual MOS devices and its effect on the performance of an IC a short discussion of it is given in the Appendix.

II. EXPERIMENTAL APPROACH AND METHOD

A. Approach

In the investigation of the sensitivity of various MOS integrated circuits to radiation environment full current-voltage characteristics of individual MOS units in an IC were taken, rather than merely measure the degradation of the output of the circuit as a whole. In choosing this method we have the following advantages: 1) we are able to characterize individual MOS units in a circuit in a radiation environment separately, and thereby to determine whether the n-channel or the p-channel devices are responsible at the onset of the degradation of the circuit. 2) The degradation in the transconductances and the shifts in the threshold potentials may be measured separately in n- and p-channel devices. 3) It gives us some insight into the physical mechanism of radiation damage if the differences in the technologies of various MOS circuits are known. 4) Annealing of radiation damage, if any, can be observed at room temperature separately in n- and p-channel devices.

For practical purposes the degradation in the performance of an IC as a whole can be seen and predicted from the observation in the degradation of individual MOS units. The crucial points to observe in individual MOS units as a function of total accumulated radiation dose are when the V_{GT} of n-channel units approach zero gate bias, whereby the IC will become leaky, and when the V_{GT} of p-channel approach the total bias of V_{DD}, whereby the functionality of an IC will be impaired.

Since the sensitivity to radiation environment is dependent strictly on the processing technology of the gate oxide, the results of radiation damage in one MOS IC are valid and can be extended to any other IC having the same gate oxide technology.

B. Method

In selecting particular MOS ICs for the characterization of the radiation damage in a certain series of integrated circuits having the same gate oxide technology no preferences were exercised other than the simplicity of a circuit and the accessibility to the individual gates with direct voltage biases with respect to the substrates.

Since a shift in a threshold potential depends very strongly on the amount of gate bias applied with respect to the substrate during irradiation, several of the n- and p-channel gates on the same chip were biased with +10 and -10 volts continuously during irradiation, respectively. Others gates were shorted to the substrate and the rest were operated with a square wave of 10 volts (at 100 kHz) to simulate the actual operation of an IC. For example, if an IC contained four identical sections, then two of the sections were operated with a square wave, in the third section n-channels were biased and p-channels were shorted, and in the fourth section the biasing configuration was the reverse to that of the third. In this way, since it is done on the same chip of silicon, a very good comparison of the sensitivities to radiation under various biasing conditions are obtained. Experience has shown that if the two identical type devices are physically located next to each other on a chip of an IC, then they will have to be biased the same way. Otherwise, if one is biased with 10 volts and the other is shorted, during irradiation, then the shorted devices exhibits source to drain leakage, which usually disappears after a couple of days at room temperature. This is believed to be due to the adsorption of gas ions on the surface of the chip. Since some of the MOS units remain shorted or biased for relatively long periods of time in space environment this effect is important, and should be investigated further.

Integrated circuits were irradiated with 1.5 MeV electrons from Van de Graaff accelerator at Goddard and the electron fluxes were measured with calibrated Faraday cup. Irradiations were performed in steps until a final total accumulated dose of 10^{14} e/cm^2 was reached. At this total dose the performance of most of the MOS ICs was degraded beyond their usefulness. The radiation effects due to electrons may be converted to the effects with Co-60 gamma source by using the factor 2.8×10^{-8} rads/electron/cm^2. This factor was taken from the work by W. L. Brown, J. D. Gabbe and W. Rosenzweig[1] and checked out by an experiment to be within 10% correct. The conversion to Co-60 gamma ray sensitivity is indicated on all the data graphs at the upper horizontal axis.

After each radiation step a full I-V characteristic of each MOS device in an IC was taken in a semilog representation, where the logarithm was that of the drain current. From these curves the changes in the threshold potential, transconductance and leakage were measured. The leakage measured in most cases was that of the individual devices, but in some cases a total leakage of all the n-channels in parallel was measured. Since most of the MOS ICs investigated had diode protection, it was not possible to measure directly the shift of the threshold potentials in n-channel devices below about -0.7 V. In that case the shifts in V_{GT} were extrapolated by the use of the shapes of the curves of the devices which, for example, were shorted during irradiation and therefore were completely represented above the zero gate voltage line. These curves were matched to the high current portion of the curves of the measured device. These extrapolation are considered to be valid since it was observed that the production of the radiation-induced interface states is only a weak function of the applied bias during irradiation.

III. RESULTS

A. Solid State Scientific, Complementary, SCL-5102 Quad 2 Input NAND.

These integrated circuits were chosen for the tests because of their extensive use by various flight projects and because a ready access to the individual gates for biasing purpose and testing. The ICs were obtained from the company in early spring of 1971 and represented the latest MOS technology at that time. At the time of the preparation of this report the company was in the process of changing and cleaning up their oxide gate technology, so that the radiation effects in the new technology will most probably be reported in the next issue of this report.

A schematic and a photograph of the 5102 irradiated are shown in Fig. 1. Figures 2 and 3 show the shifts in the threshold potentials of n- and 1-channels respectively, irradiated with +10V, +10V square wave 50% duty cycle and zero volt, gate biases for n-channels, and -10V, -10V square wave of 50% duty cycle and zero volt, gate biases for p-channels. A considerable stability in radiation environment is exhibited by the MOS units irradiated with zero gate biases of both n- and p-channel type. A shift of n-channels irradiated with zero gate bias upward indicates that an electron trapping in the oxide predominates as compared to the hole trapping.[1,2] The degradation in the transconductances is shown in Figs. 4 and 5 for n- and p-channels, respectively. Although, the initial transconductance of n-channels is high for this technology as compared to other manufacturers, it's degradation is more severe as compared to others. It also indicates a slight bias dependence, particularly in p-channel units. The leakages begin already at about 5×10^{11} e/cm^2 for the devices irradiated with +10V fully on biases, as shown in Fig. 6, and increase quite rapidly with dose. As shown in Fig. 3, the threshold potentials of p-channels irradiated with -10V fully on gate bias approach the threshold potential of 10V at about 5×10^{12} e/cm^2. Thus, it would appear from these data that the ICs will become too leaky before the loss of functionality (due to the p-channels not being able to turn on) will set in. The data in Fig. 7, however, show that the n-channels of this technology exhibit a considerable recovery of the threshold potentials at room temperature as compared with the p-channels. In space environment, therefore, at a small enough dose rate the n-channels may not show any leakage at all before any loss of the functionality will be evident.

B. RCA COS/MOS (complementary symmetry MOS) Circuits

1. Low threshold integrated circuits, CD 4001 Quad 2 Input NOR

These ICs were obtained from RCA at the end of 1970 and represent the technology just before the switch over to the so-called "A-series" technology. The ICs were designed to operate also at 5 volts input levels and at higher speeds. Consequently, they were irradiated both with 10V and 5V gate biases for comparison purposes.

Figure 8 shows the photograph and a schematic of an irradiated IC and Figs. 9 and 10 show the shifts in the threshold potentials of n- and p-channel MOS units, respectively. The n-channel units, irradiated with +10V and zero gate biases, have developed leakages in the gates and their measurements had to be terminated soon after a few irradiation doses. Whether these gate-to-substrate as well as some of drain-to-source leakages were caused by radiation could not have been ascertained and, therefore, their analysis is not included in this report. The worst case for p-channels happens already at a dose of 10^{12} e/cm^2 when the threshold potential approaches the -10V value for the fully on during irradiation. This is a factor of 5 sooner than in Solid State Scientific technology. The leakages, as shown in Fig. 12, begin to show up at about the same level as in SSS technology. The initial transconductances of n-channels are much lower than in p-channel, but the overall degradation in the transconductances is much less than in SSS technology (Figs. 11, 4 and 5). Fig. 13 shows the total leakage of the n-channel part of the IC and is about the same dependence on the dose as the worst case in the individual leakages (Fig. 12).

The results for 5V irradiation biases are shown in Figs. 14 through 17. As expected the overall shifts in the threshold potentials (Fig. 14) are smaller than in the case of 10V bombardment biases (Figs. 9 and 10). The leakages in the n-channels also develop later in dose (Fig. 16) than in the case of 10V bombardment bias. The degradation in the transconductances is about the same in both cases since it is a weak function of the gate bias.

In the context of this comparison the important question, which is being asked by many circuit designers, is: From the radiation damage point of view which of the two gate biases is better to use, high or low? These data show clearly that although the shifts in the threshold potentials for the lower gate biases are smaller, the 5V value of the threshold potential is reached already at a dose of about 4×10^{11} e/cm^2 in the case of 5V operation mode (Fig. 14), whereas the 10V value of the threshold potential is reached at a dose of about 10^{12} for the case of 10V operation. So that the loss of functionality will happen sooner in the case of 5V operation as compared to 10V operation. The leakage, however, will happen later in the case of 5V operation.

2. COS/MOS Pair plus Inverter of the Earlier Vintage, CD 4007 Dual Complementary

The data on CD 4007 presented here were obtained on an IC made by RCA sometime in the middle of 1969. The integrated circuit is shown in Fig. 18 and the results in Figs. 19 through 22. The sensitivity to radiation of these ICs is not much different from the sensitivity of ICs made one and a half years later (CD 4001 irradiated at 10V bias). The peculiar feature of these devices is that even p-channel devices show some recovery in the threshold potentials when the irradiation is discontinued for two or three days. This is indicated by the breaks in the curves in Fig. 19. But as soon as the irradiation is resumed the shape of the curve is regained. This suggests that the processes responsible for the recovery are of low activation energy and, therefore, are easily counteracted by additional irradiation. The reason for the recovery of a p-channel with fully on gate bias during irradiation after about 6×10^{12} e/cm^2 is not known. The initial values of the transconductances were much lower in n-channels than in p-channels and the degradation was observed to be small, as shown in Fig. 20.

The recovery of the threshold potentials at room temperature is shown in Fig. 22. Here, as in the case of Solid State Scientific, the n-channels exhibit faster recovery than the p-channels.

3. RCA CD 4001, New "A Series"

In the beginning of 1971 RCA has introduced its new "A-series." The letter A appears after the number of an IC, for example, CD 4001A. The company claims that it has cleaned up its gate oxide technology, with the result that the ICs are more reliable and less radiation sensitive. The results of the tests of two such ICs are shown in Figs. 23, 24 and 25. As can be seen from these results a considerable improvement in radiation hardness has been achieved. A significant difference in radiation response is observed in the case of p-channel devices. Aside from increased radiation hardness, a reversal in the gate bias dependence is observed (Fig. 23). In the previous gate oxide technology a p-channel with gate bias applied during irradiation suffers a greater shift in the threshold potential. In this technology the shift is greater in the case of zero gate bias. In p-channels irradiated with the gate bias the response is about the same for gates with fully on bias or 50% duty cycle. This response of the new RCA devices is very similar to the responses of p-channels of Motorola and AMI to be discussed below.

Fig. 24 shows the degradation in the transconductances of n- and p-channels. The degradation is considerably greater in this technology than in the previous one (compare Fig. 11). Also, it exhibits a much greater gate bias dependence in p-channels. In fact, it is very similar to the gate bias dependence in the shifts of the threshold potentials, which indicates that the greater shift of the threshold potentials in zero gate bias devices is most probably due to the greater production of ionized interface states.

The leakages in n-channels of this IC appear only in devices with fully on 10V gate bias at about 2×10^{12} e/cm^2 (Fig. 25). The threshold potentials of the devices with 50% duty cycle and zero gate bias never reach the zero gate bias line of Fig. 23, as radiation dose increases. This is due to the balance between electron and hole trapping and, as radiation dose increases, the electron trapping predominates.

From these data it can be predicted that if the ICs from this new A-series is constantly operational in space environment, it will pass a radiation dose of 10^{14} e/cm^2 before a leakage or a loss of functionality will be observed. To substantiate these results, however, more tests of the A-series need to be performed.

C. Motorola Complementary Circuits, 2501 Quad 2 Input NOR

The Motorola Complementary 2501 – Quad 2 input NOR circuit that was irradiated is shown in Fig. 26. Fig. 27 shows the results of the shifts in the threshold potentials of n- and p-channels units with the various gate biases applied during irradiation. The response in p-channels is very similar to the response of RCA's new A-series. The radiation hardness of the n-channels, however, is very poor with the leakage starting already at 2×10^{11} e/cm^2 (Fig. 29). The degradation in the transconductance is shown in Fig. 28 and here again the degradation in n-channels is very rapid and dose dependent. The production of radiation-induced interface states in p-channels with zero gate bias during irradiation is most probably responsible for the larger shift in the threshold potentials in those devices (Fig. 27 and 28).

D. American-Microelectronics Inc., (AMI) p-Channel Integrated Circuit, MXO3C 10 Channel Switch

For comparison purposes one entirely p-channel IC made by AMI was irradiated. A schematic and photograph of AMI MXO3C – p-channel, 10 channel switch is shown in Fig. 30. The shifts in the threshold potentials bombarded with various gate biases are shown in Fig. 31. Here, as in Motorola and RCA's A-series, the reversal of bias dependence is observed: a device with zero gate bombardment bias exhibits a larger shift than the ones with applied gate bias. It is expected that for this type of a circuit in the worst case the loss of functionality will happen at about 5×10^{13} e/cm^2. The degradation in the transconductances is shown in Fig. 22 and is comparable to the degradations in RCA's A-series and Motorola p-channels.

IV. CONCLUSIONS

Selective biasing during irradiation of individual MOS units in an integrated circuit has proven to be a good method to characterize the radiation sensitivity of individual MOS devices as well as an IC as a whole. In general, the results have shown that in most of the complementary circuits tested, the radiation effects will appear first as a leakage in n-channel devices somewhat before the integrated dose of 10^{12} e/cm^2 is reached. The loss of functionality will appear soon after the total accumulated dose of 10^{12} e/cm^2, when the value of the threshold potential will reach the biasing voltage.

In the complementary type ICs the most radiation resistant integrated circuits were found to be those of RCA within the new A-series. However, to substantiate this more tests are necessary with other types and batches of these ICs. As compared to complementary, the p-channel IC made by AMI is the most radiation resistant from those tested simply because it does not contain the n-channels, which are prone to leakage first in most of the complementaries tested.

V. APPENDIX. Radiation Damage in MOS Devices

Radiation damage in the MOS devices is evidenced by two major effects: a shift in the threshold potential and degradation in the transconductance.

A. Shift in the Threshold Potential

As an energetic particle (or a shower of secondary electrons resulting from a primary energetic particle) passes through the gate insulator, it ionizes the insulator, producing an electron-hole pair in the oxide. Some of the electrons excited in this way migrate to the semiconductor and/or to the metal of the gate contact, leaving behind a net positive charge in the insulator. This process is schematically shown in Fig. 32. The accumulation of positive charges in the gate oxide results in a shift of the current-voltage, I-V, characteristic along the gate potential, which continues to increase as long as the positive charge in the gate oxide continues to build-up. Since the excess build-up of charges in the gate oxide is that of positive charge, the shift in I-V characteristic in both n- and p-channel devices is toward more negative values of the gate potential. Examples of the shifts in I-V characteristics are shown in Figs. 34 and 35 for n- and p-channel MOS devices (GME), respectively, having the usual thermally grown gate oxides. The numbers at each curve are the total accumulated dose of 1.5 MeV electrons per cm^2 at the MOS devices unshielded except for the covers of the flat packs. Strictly speaking, in this type of effect, the operation of the device has not been really damaged in the full meaning of the word; the operation of the device has been merely shifted to another region of the gate potential, if we neglect the accompanying changes in the transconductance. This shift, which usually can be reversed by thermal annealing[4,5], is the first effect that one observes during irradiation and is the most harmful effect in the operation of and MOS circuit as a whole.

Threshold potential of an MOS device, V_{GT}, is usually defined as the gate potential at which 10 μa of drain current flows and is the definition adhered to in this report. In Figs. 34 and 35 the values of the threshold potentials are the gate voltages at which I-V characteristics cross the 10 μa vertical line.

B. Degradation of the Transconductance

Transconductance, g_m, is usually given in the specifications for single MOS devices, and is defined as the change in the drain current per unit change in the gate potential. In the data of this report it is measured in the vicinity of the threshold potential. In general, transconductance characterizes the degree of "cleanliness" of the channel region from the interface states and other charge traps and gives a measure of "channel resistivity."

Irradiation causes a decrease in the transconductance in both n- and p-channel MOS devices. This degradation is due to the production of interface states by radiation. Interface states act as momentary charge traps, which in the course of channel current flow trap charge carriers momentarily and then reemit them again into the conduction band. This trapping and reemitting of the charge carriers decreases their mobility and causes the resistivity of the channel to increase. The decrease in the transconductance may be observed in Fig. 34, for example, as the slopes of the I-V characteristics increases with increasing accumulated radiation dose. In most of the MOS complementary integrated circuits measured in this report the increase in the slopes is greater in n-channels than in p-channels. This is probably due to the greater mobility of electrons and the smaller physical size of the n-channel units as compared to the p-channel units.

VI. EFFECTS OF THE SHIFT IN THE THRESHOLD POTENTIALS AND DEGRADATION IN THE TRANSCONDUCTANCE ON THE OPERATION OF MOS IC

In a complimentary IC the effects of the shifts in the threshold potentials of both n- and p-channel devices and their degradation of the transconductances have to be considered.

As the threshold potential of the n-channel device decreases due to radiation (Fig. 34), currents increase because the n-channel device tends to conduct and switch sooner. The voltage drop across the n-channel MOS device will cause the output not to have a full power supply swing. Also, noise immunity degrades rapidly as the threshold potential moves near the ground potential. Finally, as the radiation dose continues to increase, the dynamic power consumption becomes too excessive because the n-channels stay turned on even with zero gate bias.

In p-channel devices radiation causes an increase in the threshold potential (Fig. 35). When this occurs, switching slows down since it becomes harder to turn the device on. Delays in the output signals increase since the switching becomes more sluggish. This will occur until the device will no longer conduct. At this point no static current exists, the circuit is unable to switch from one state to another, and no logic function can be performed.

Whatever happens first, either the effects with n-channel or p-channel MOS units in an IC, depends both on the charge trapping capabilities of the respective gate oxides and the values of the gate voltages applied to the devices during irradiation. Both shifts, occuring at the same time, multiply the effects and the degradation becomes very complicated.

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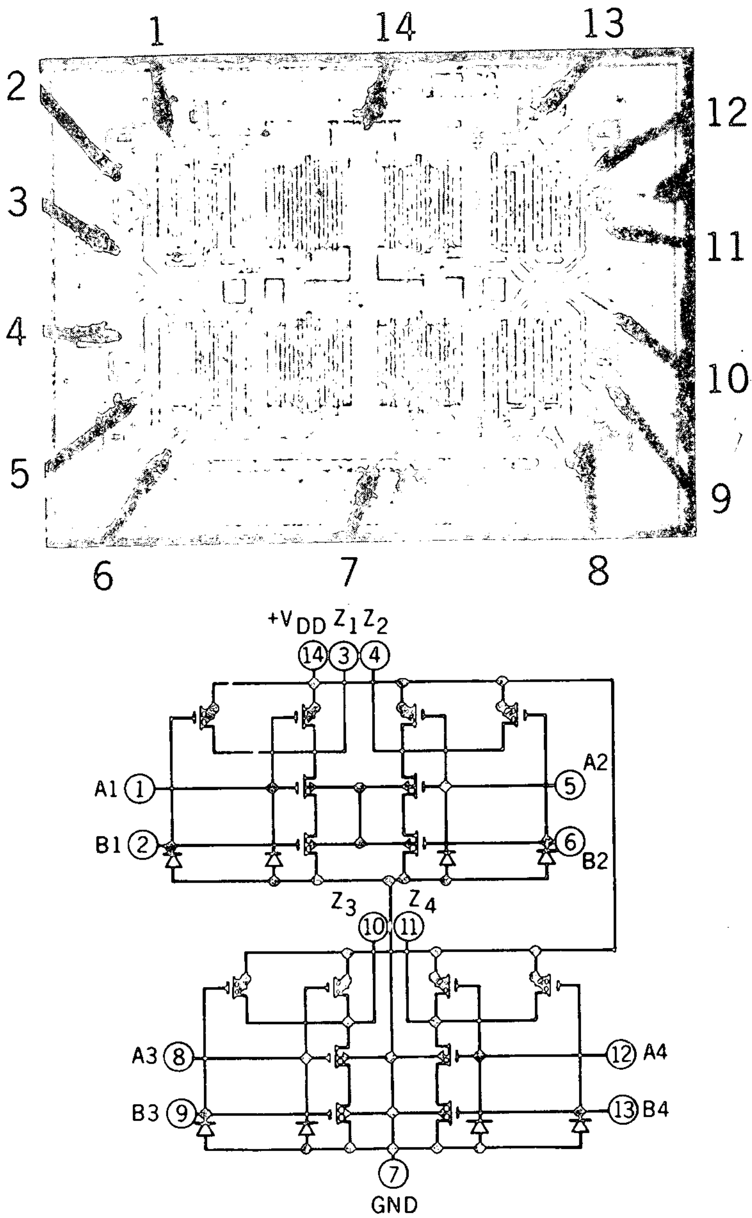


SOLID STATE SCIENTIFIC SCL – 5102 – COMPLEMENTARY
POSITIVE NAND

Figure 1. Schematic and photograph of an irradiated IC made by Solid State Scientific, Inc

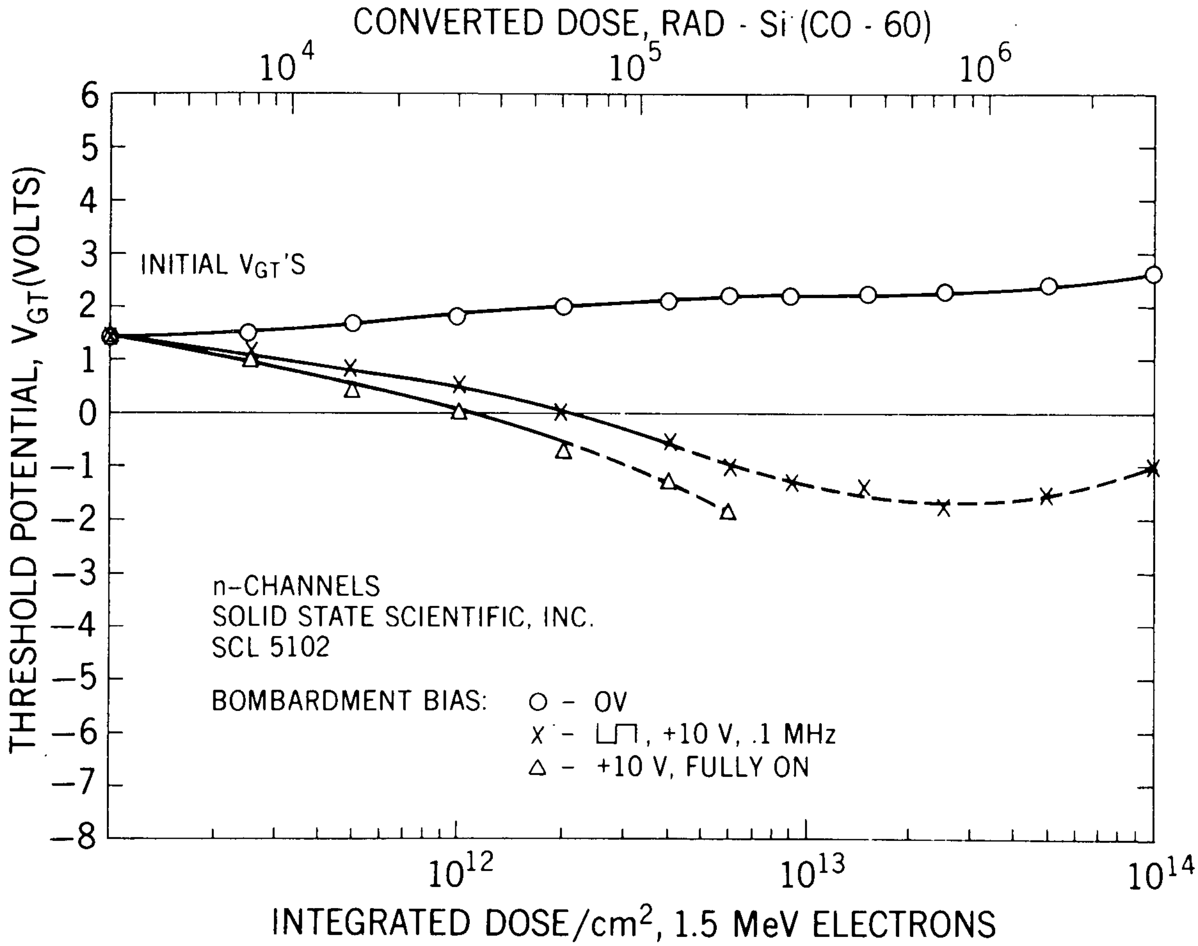


Figure 2. Shift in threshold potentials in n-channel MOS devices of Solid State Scientific IC irradiated with various gate biases

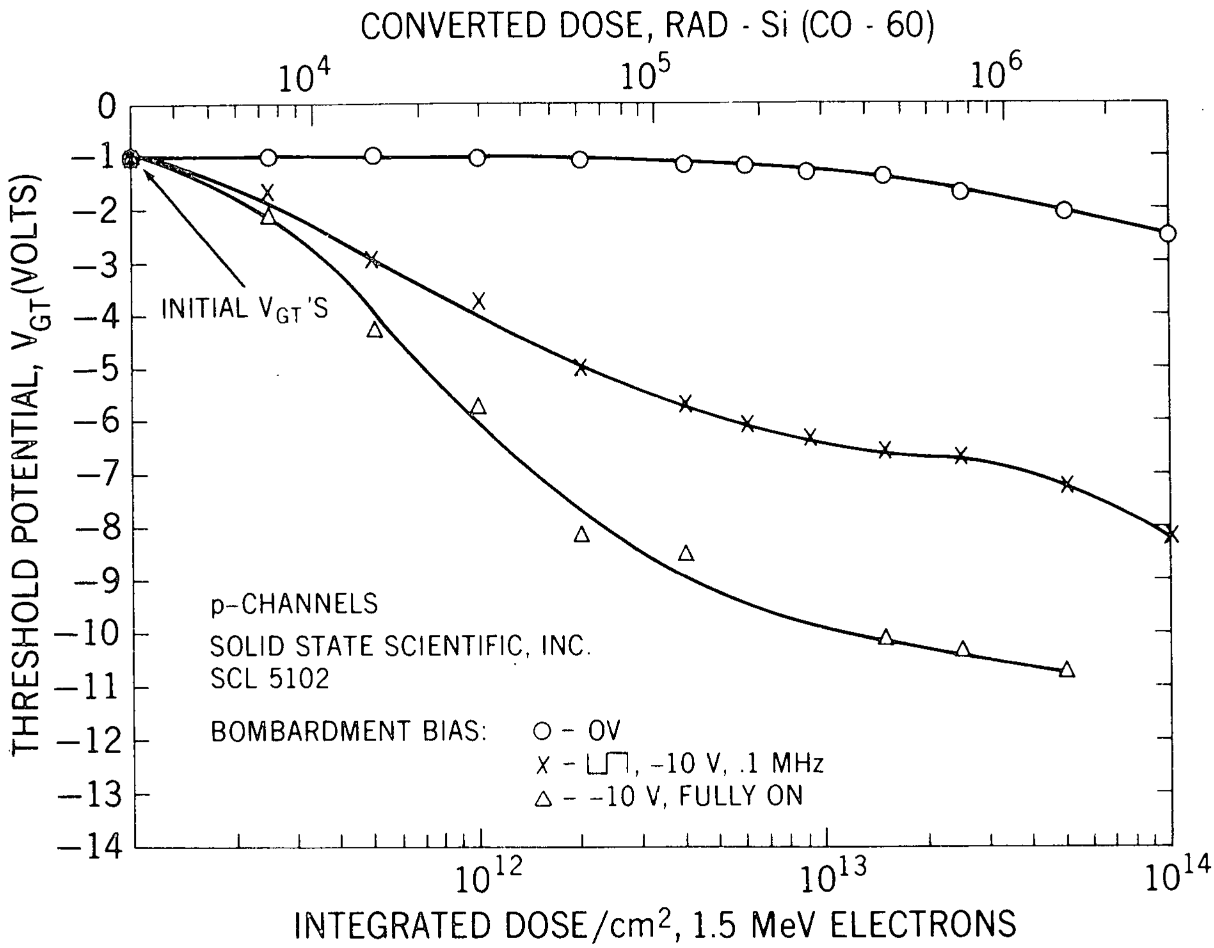


Figure 3. Same as Fig. 2, except p-channel devices

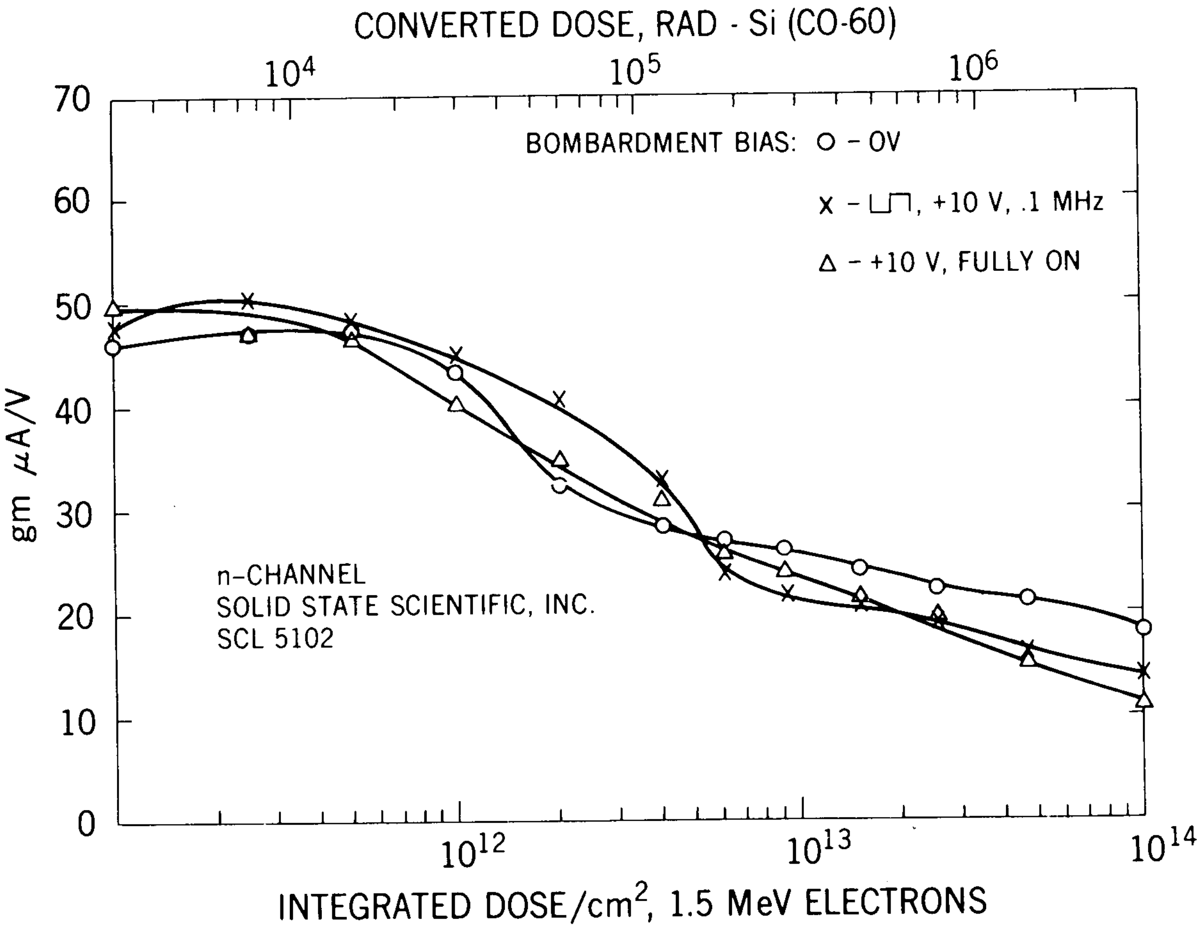


Figure 4. Degradation in transconductances, g_m's, in n-channels of Solid State Scientific, Inc., as a function of total accumulated radiation dose

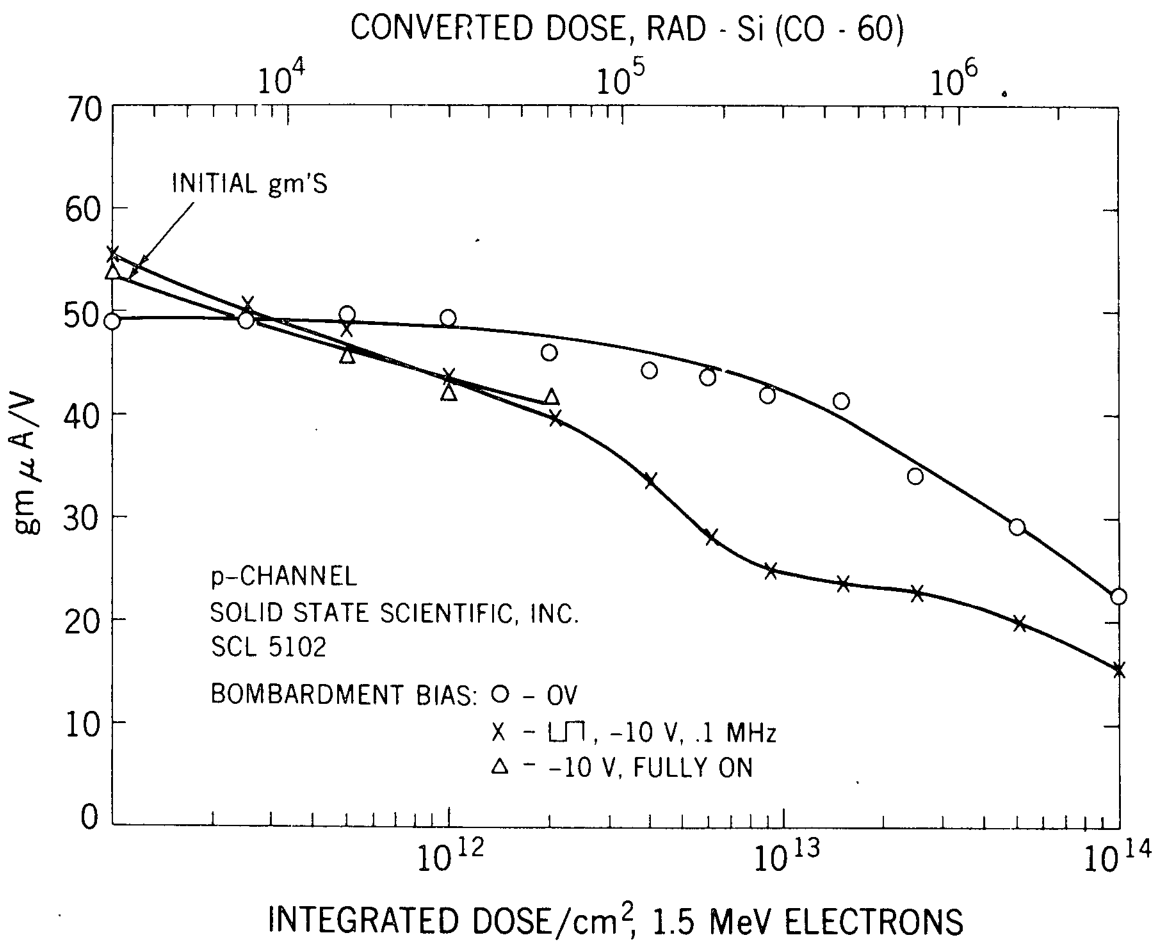


Figure 5. Same as Fig. 4, except p-channels

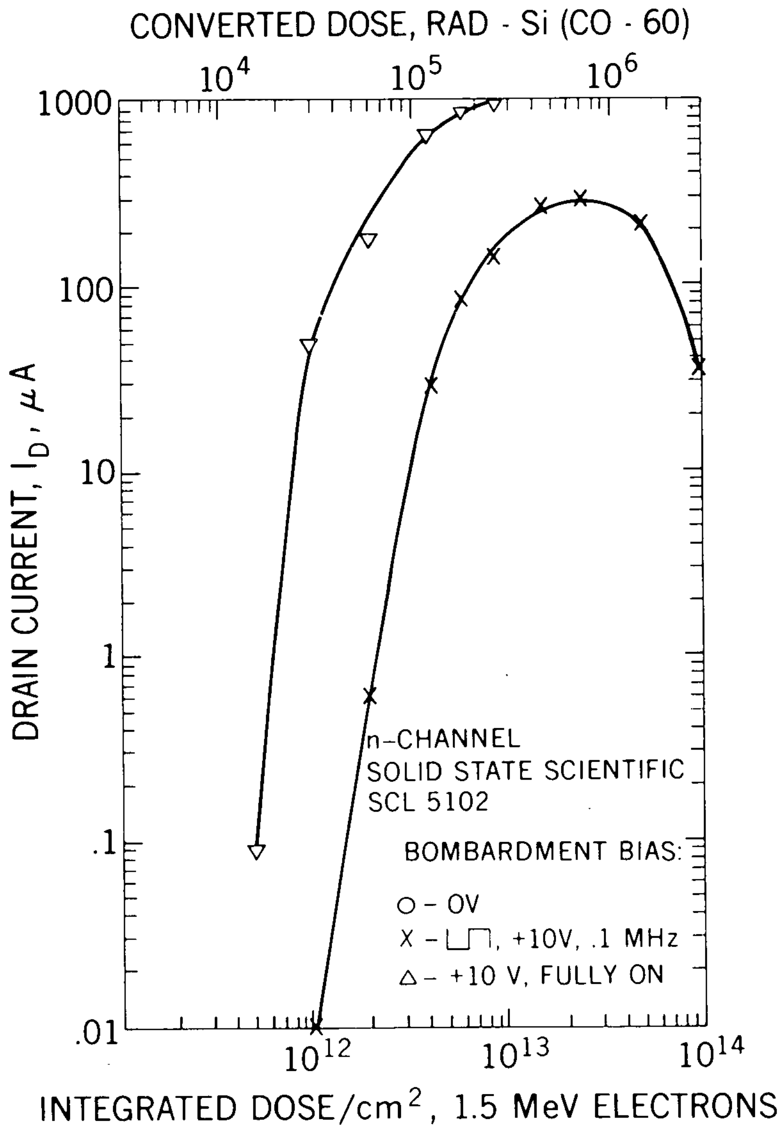


Figure 6. Leakage in n-channels of Solid State Scientific ICs as a function of total accumulated radiation dose

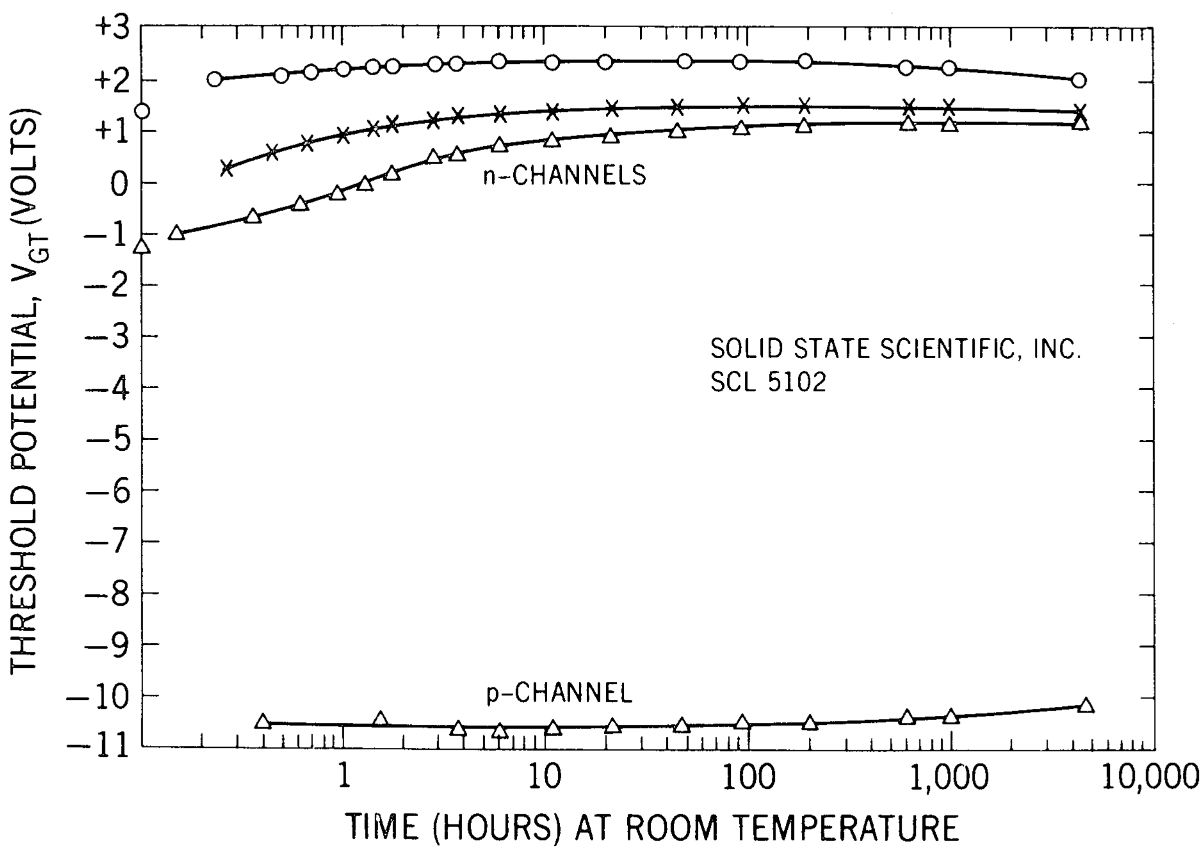
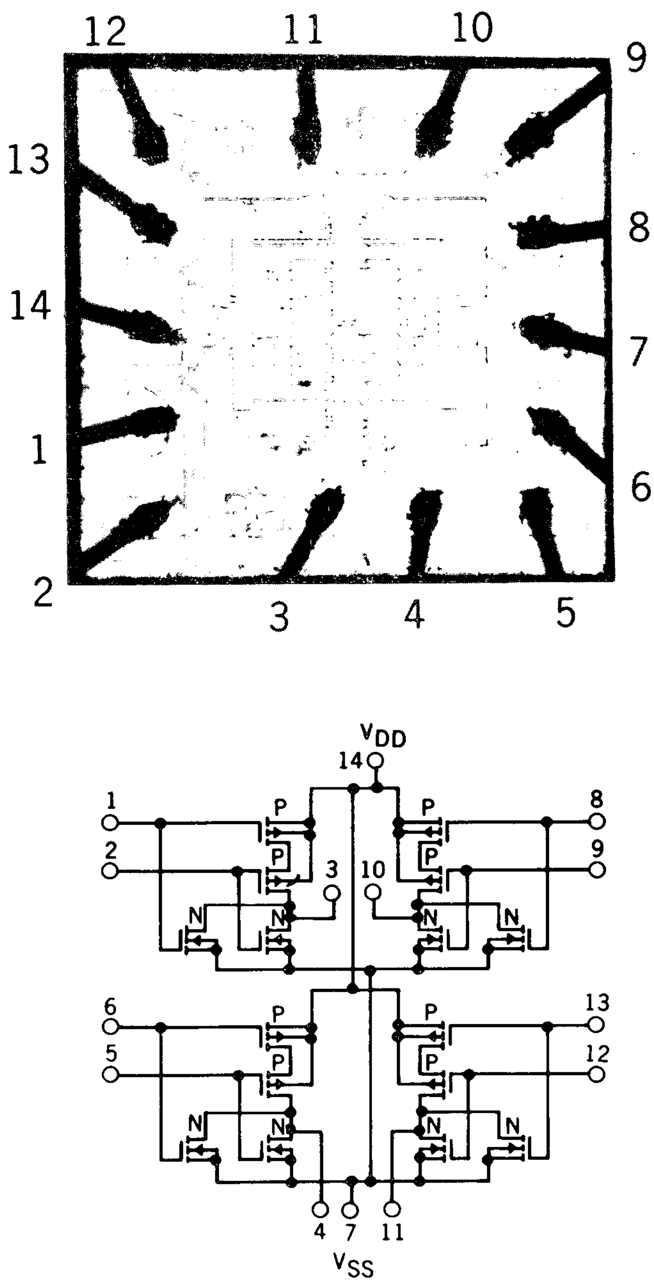


Figure 7. Recovery of threshold potentials in n-channel and p-channel MOS devices of Solid State Scientific ICs at room temperature



RCA CD 4007 – COMPLEMENTARY
DUAL COMPLEMENTARY PAIR PLUS INVERTER

Figure 8. Diagram and photograph of an irradiated RCA IC

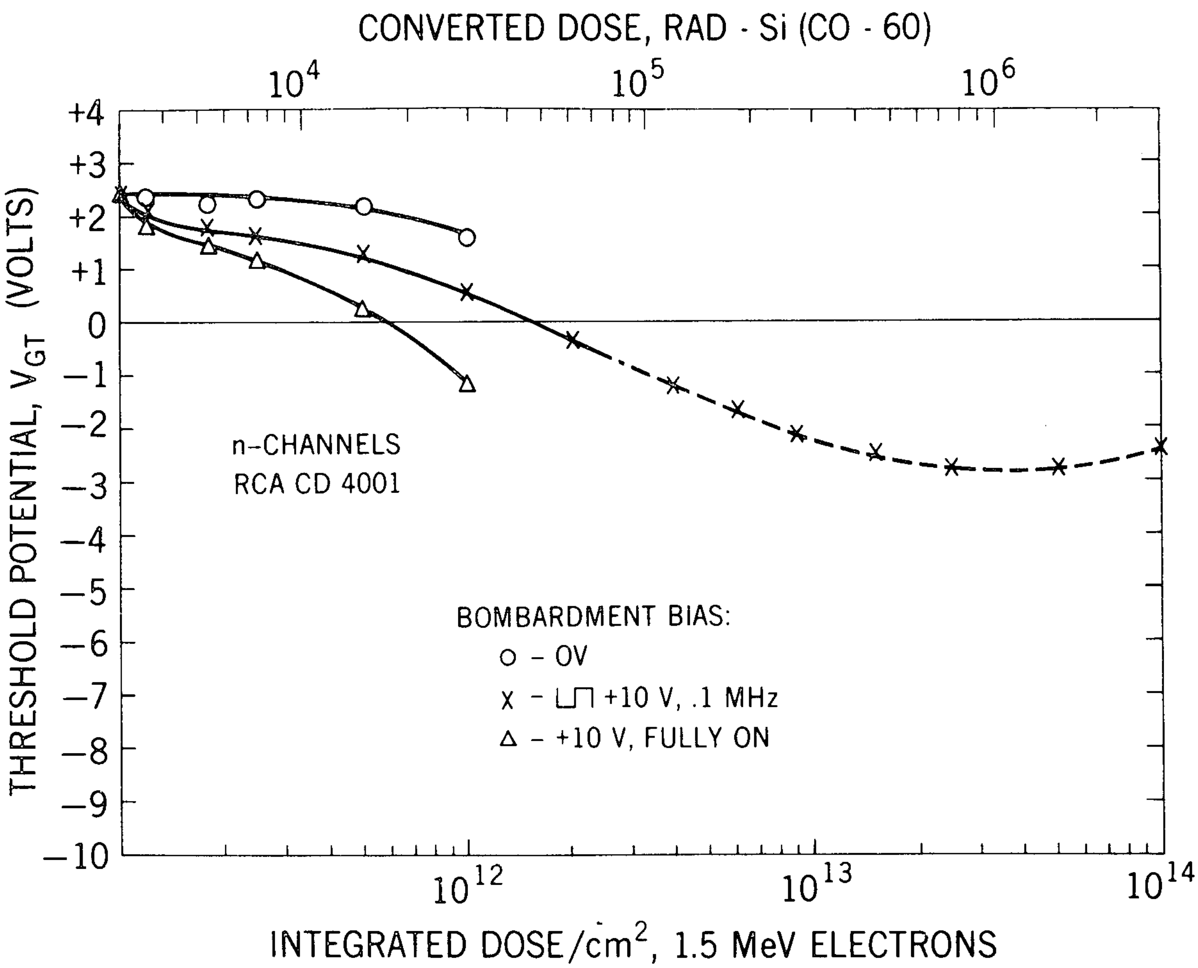


Figure 9. Shifts in the threshold potentials in n-channel MOS devices of RCA IC bombarded with various gate biases

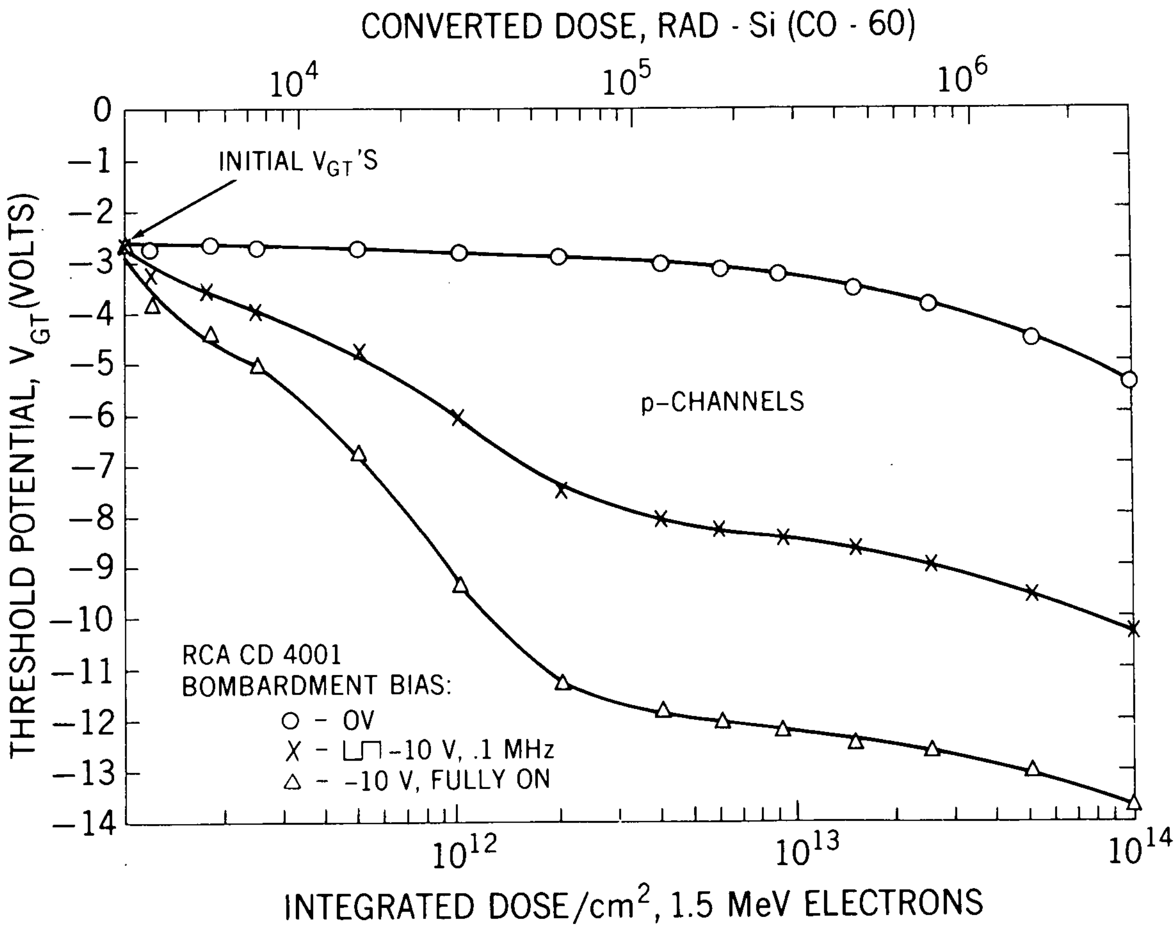


Figure 10. Same as Fig. 9, except p-channels

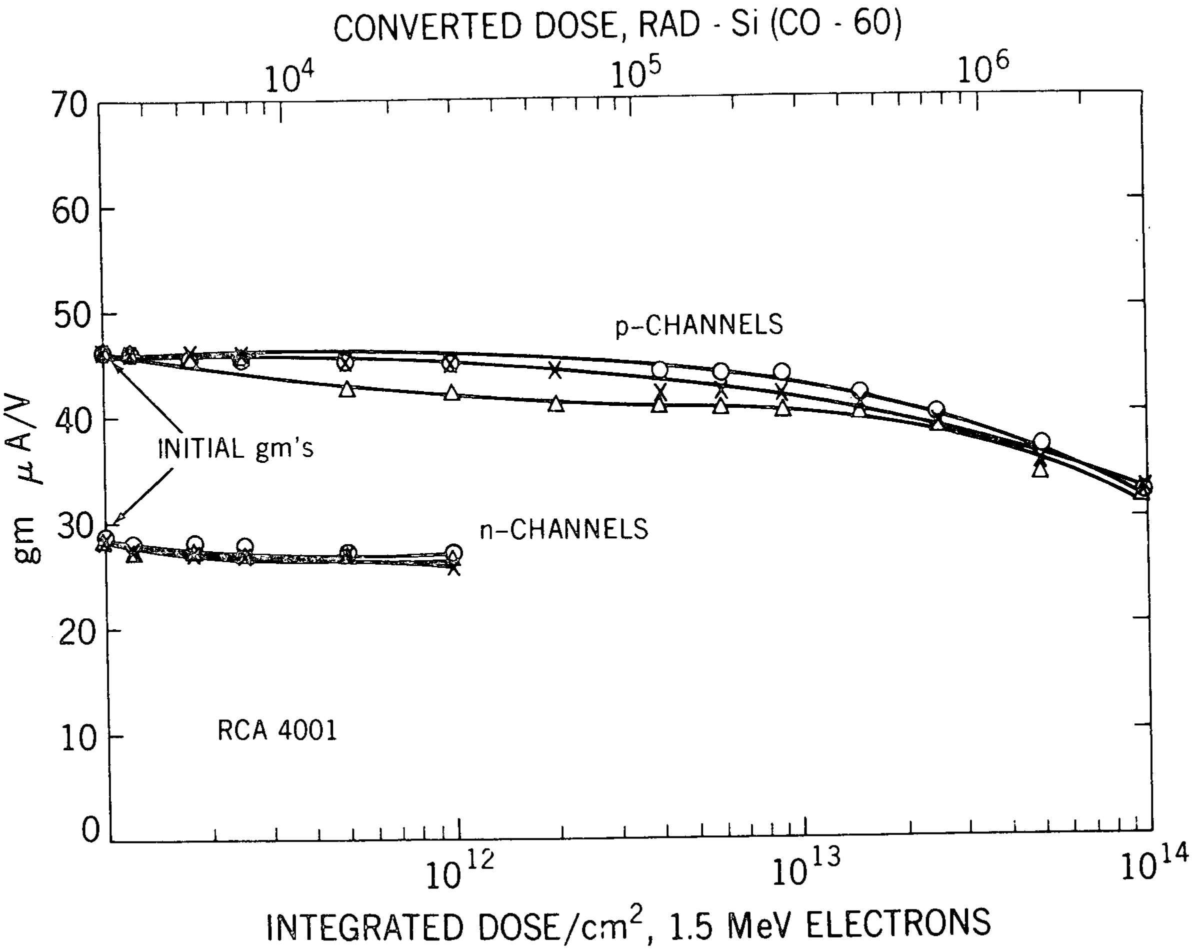


Figure 11. Degradation of the transconductances in n-channel and p-channel MOS devices of RCA

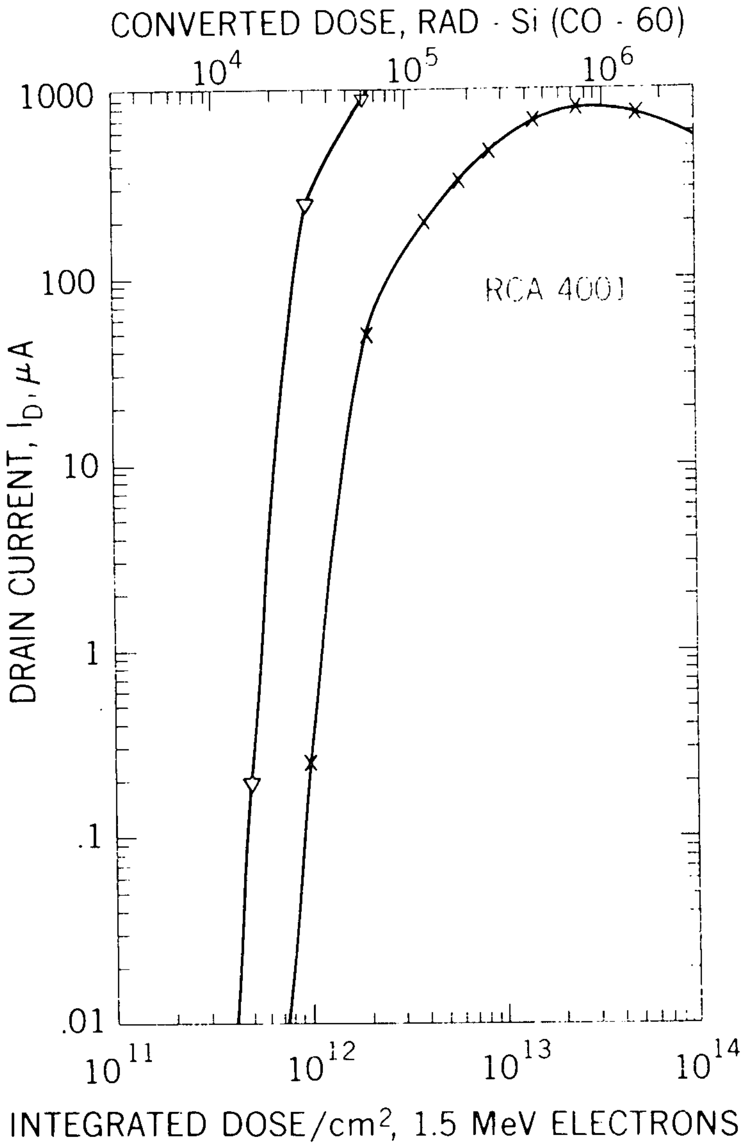


Figure 12. Leakage in n-channels of RCA IC as a function of total accumulated radiation dose

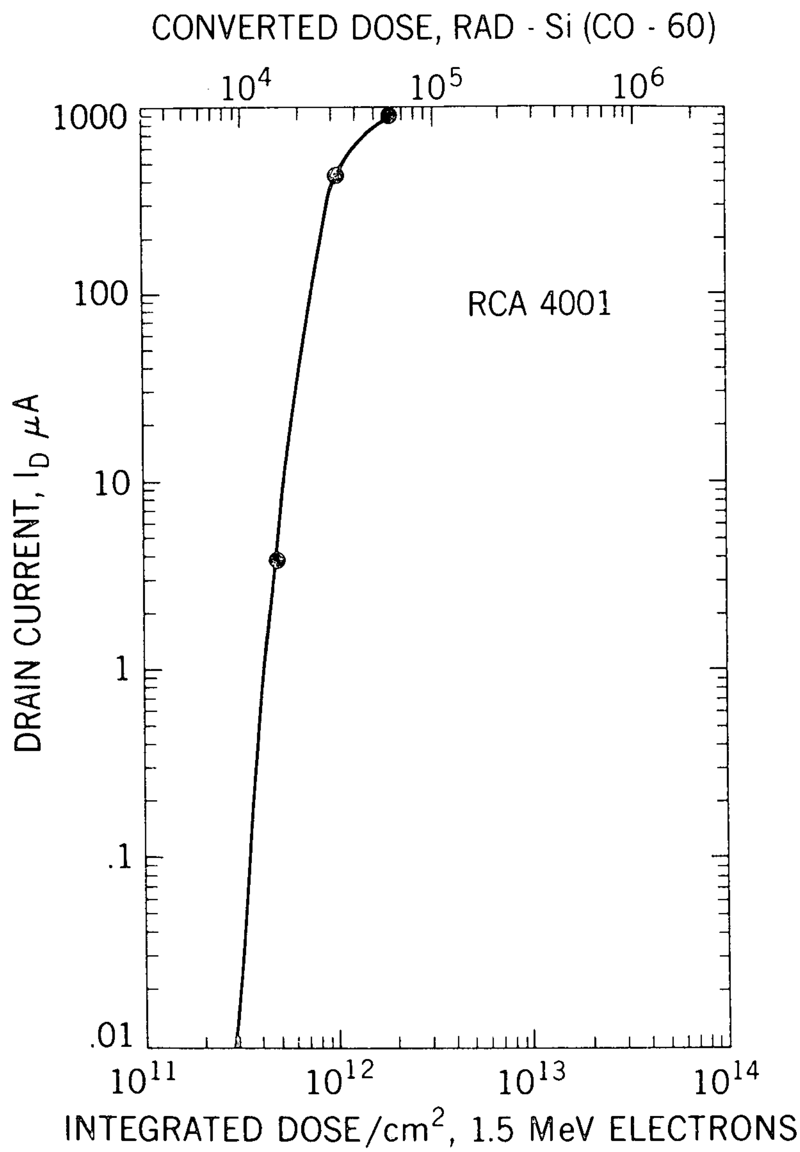


Figure 13. Same as Fig. 12, except total leakage in all 8 n-channels

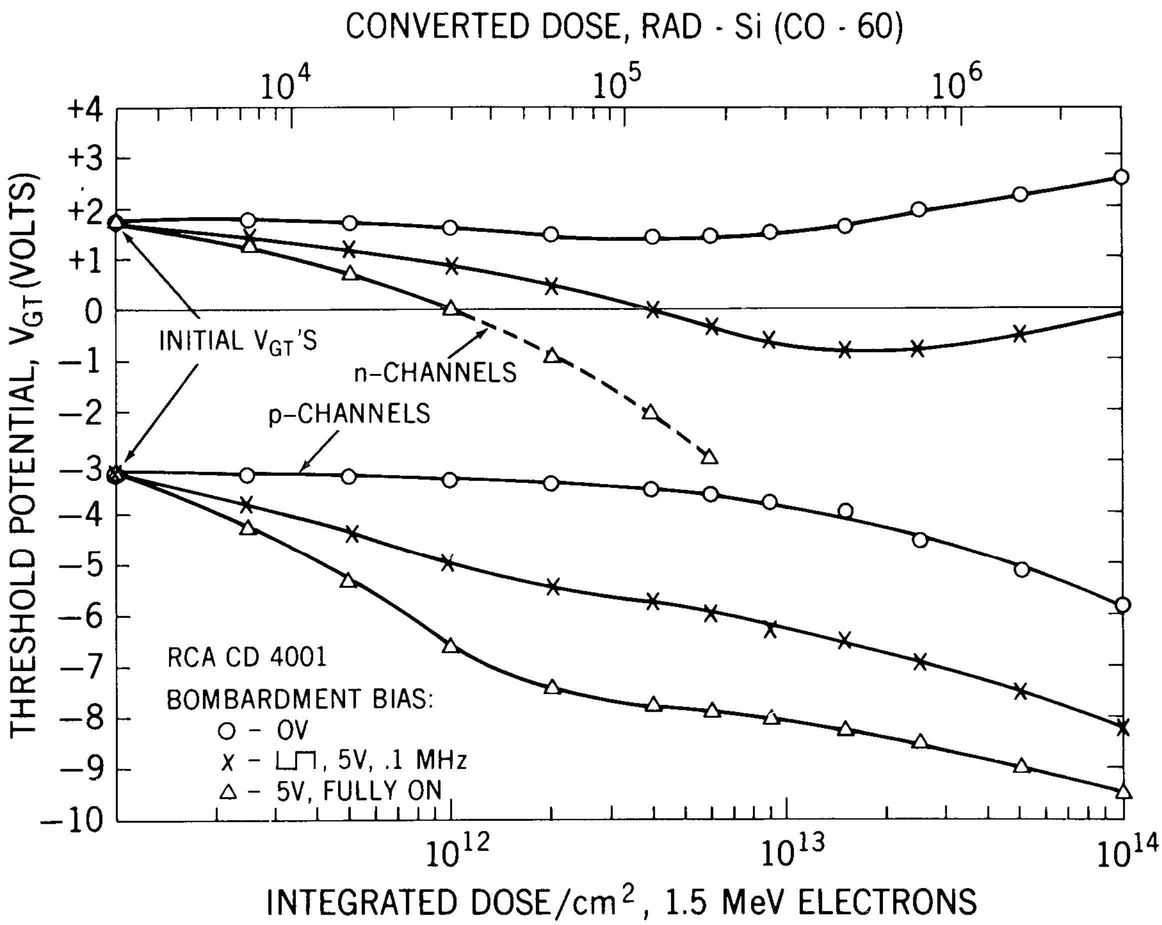


Figure 14. Same as Figs. 9 and 10, except irradiated with 5V gate biases

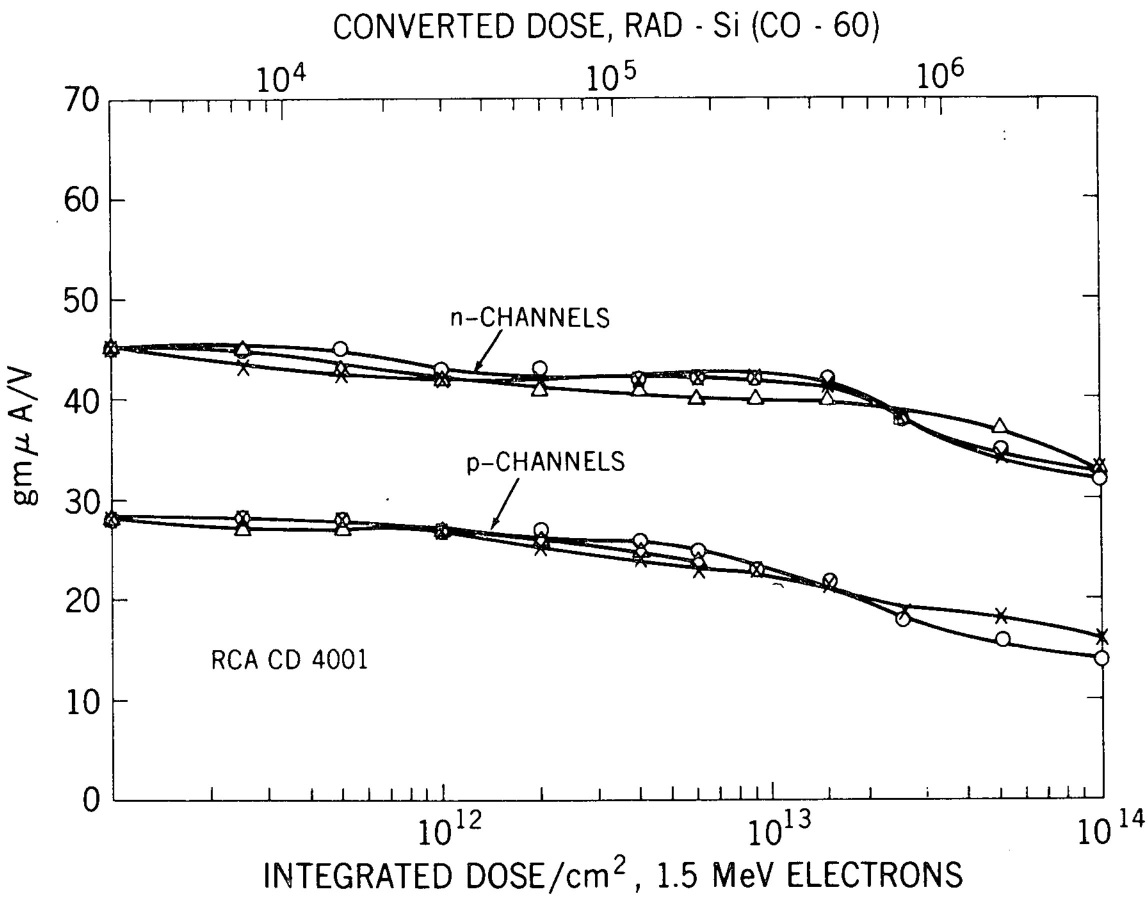


Figure 15. Same as Fig. 11, except irradiated with 5V gate biases

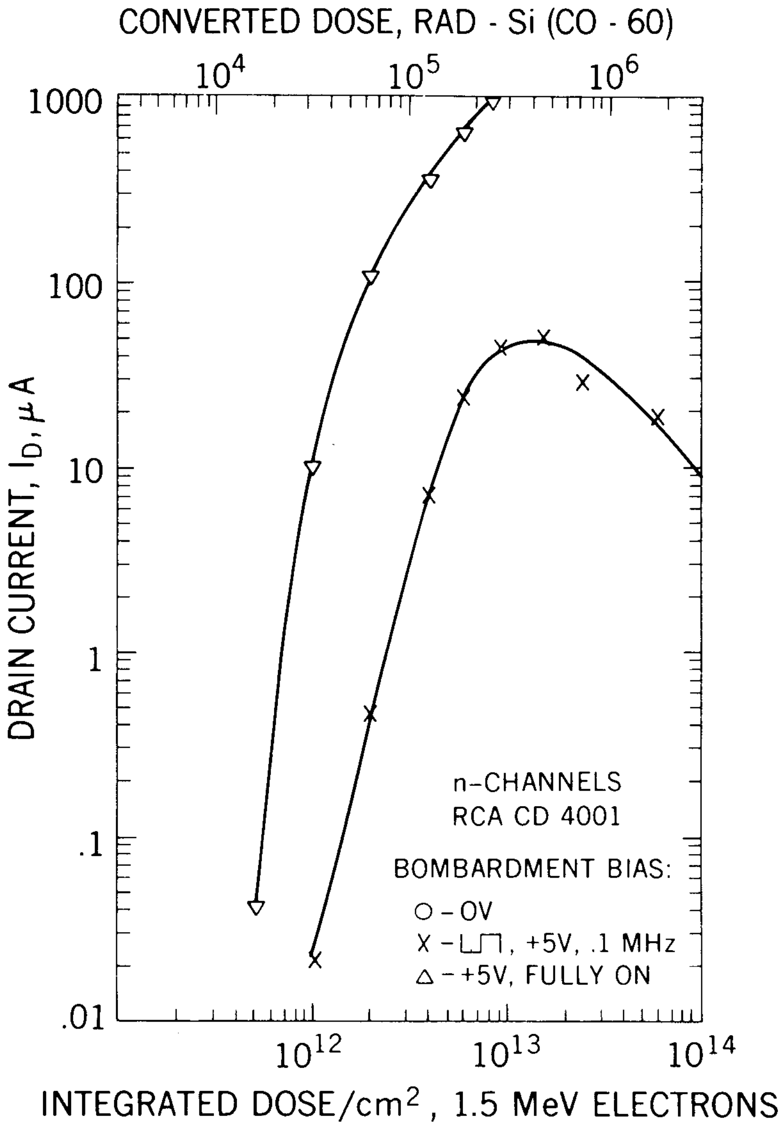


Figure 16. Same as Fig. 12, excepted irradiated with 5V gate biases

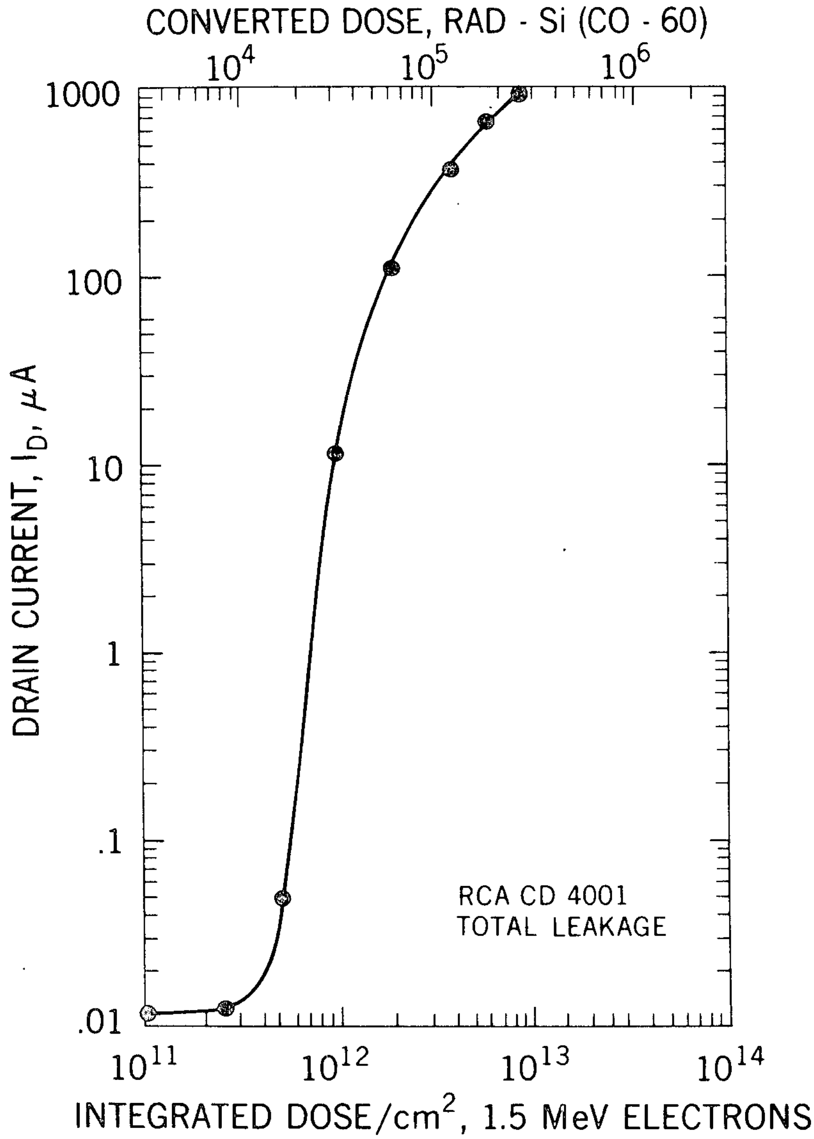
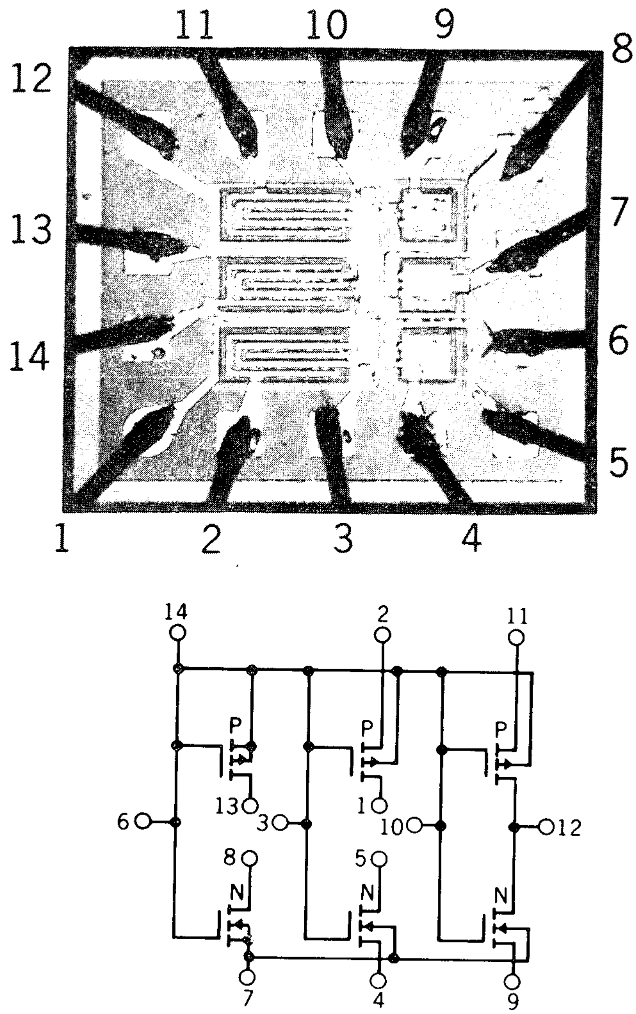


Figure 17. Same as Fig. 13, except irradiated with 5V gate biases



RCA CD 4007 – COMPLEMENTARY
DUAL COMPLEMENTARY PAIR PLUS INVERTER

Figure 18. Schematic and photograph of irradiated RCA CD 4007 IC

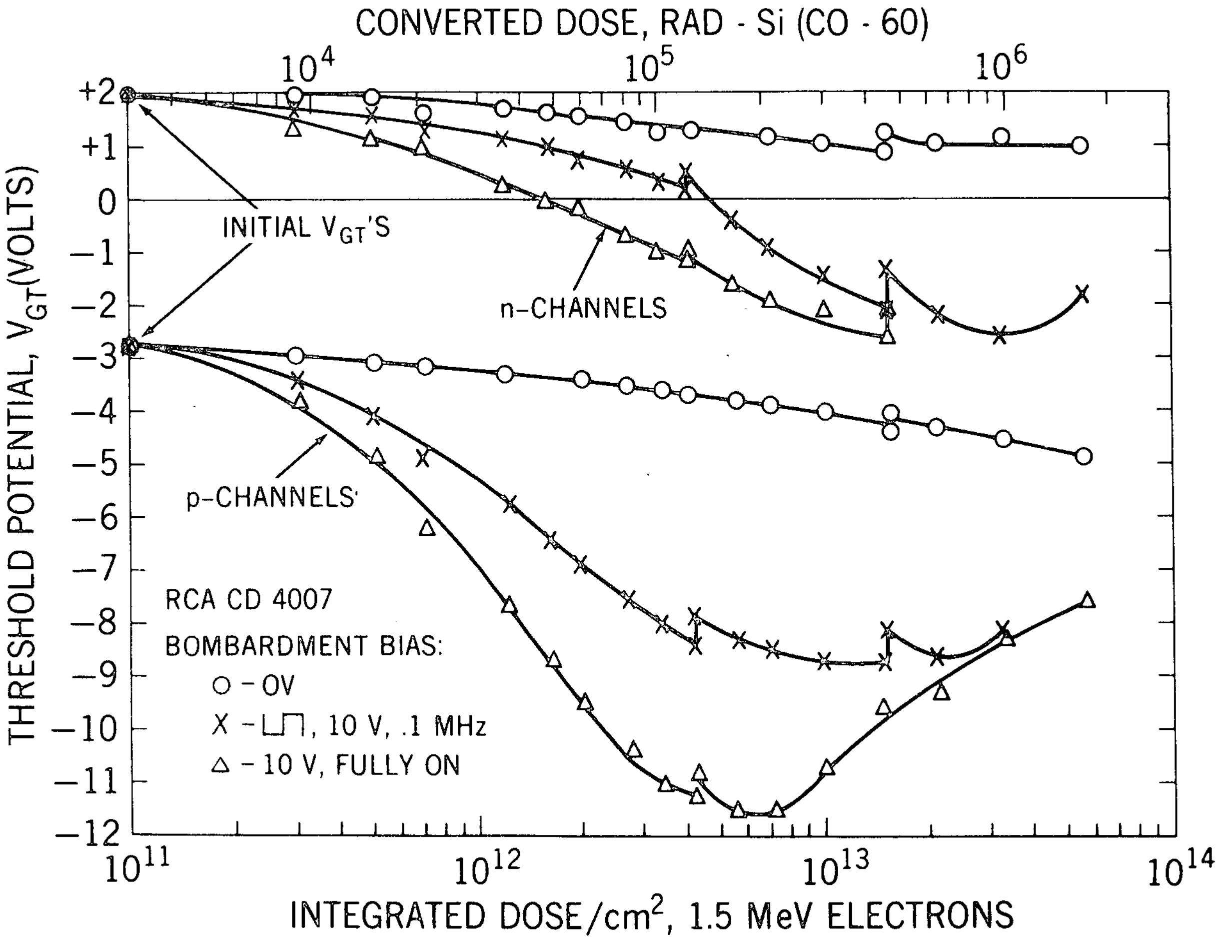


Figure 19. Shifts in threshold potentials of n- and p-channel MOD devices of RCA IC, irradiated with various gate biases

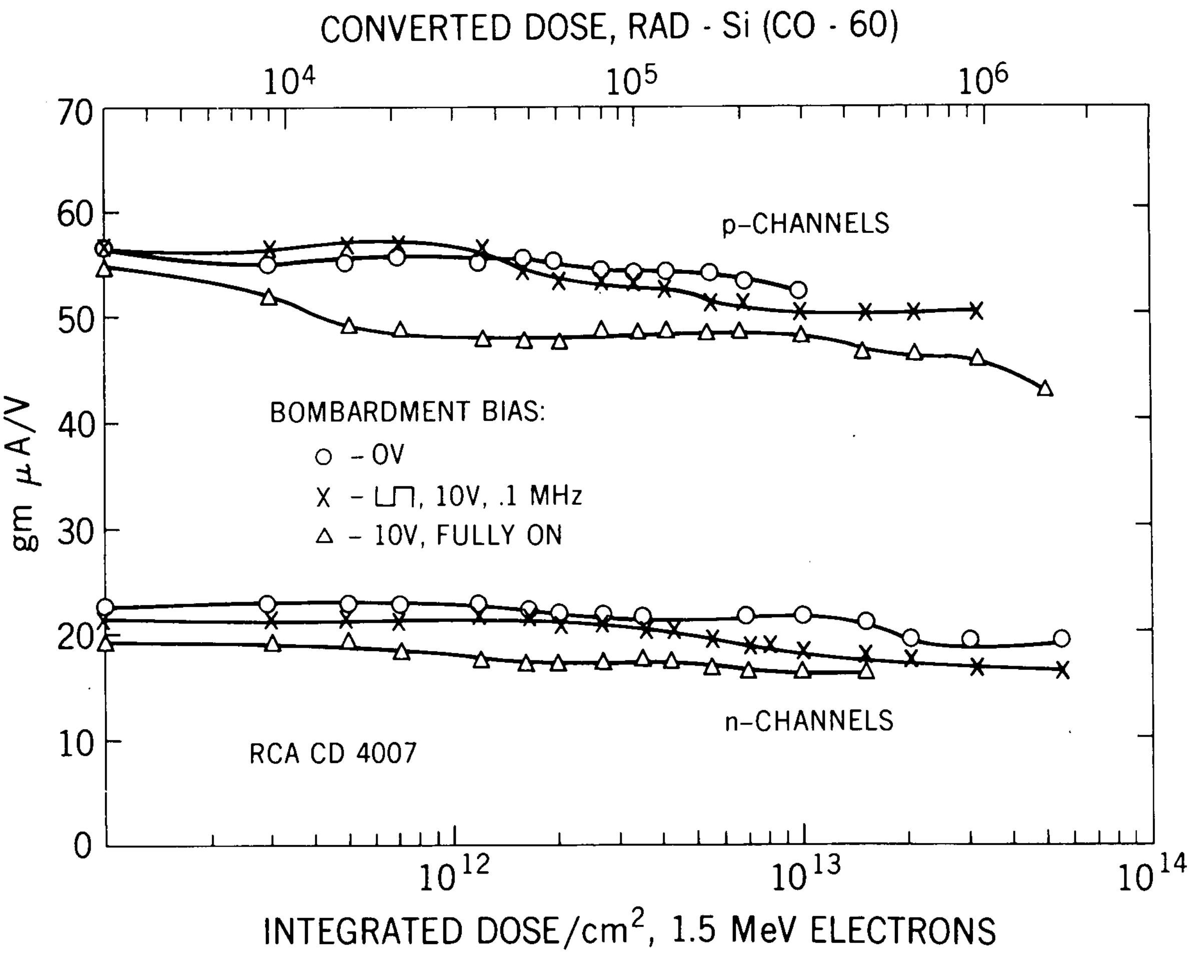


Figure 20. Degradation of the transconductances in n- and p-channels of RCA IC as a function of total accumulated radiation dose

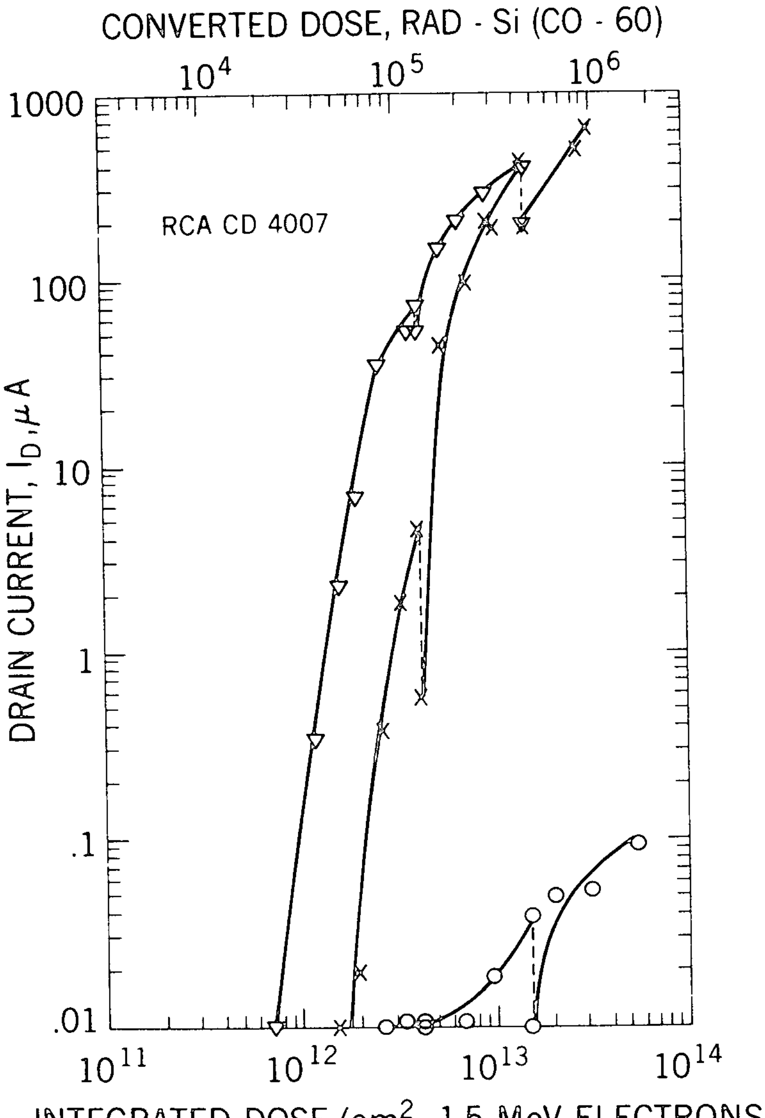


Figure 21. Leakage in n-channels of RCA IC, irradiated with various gate biases

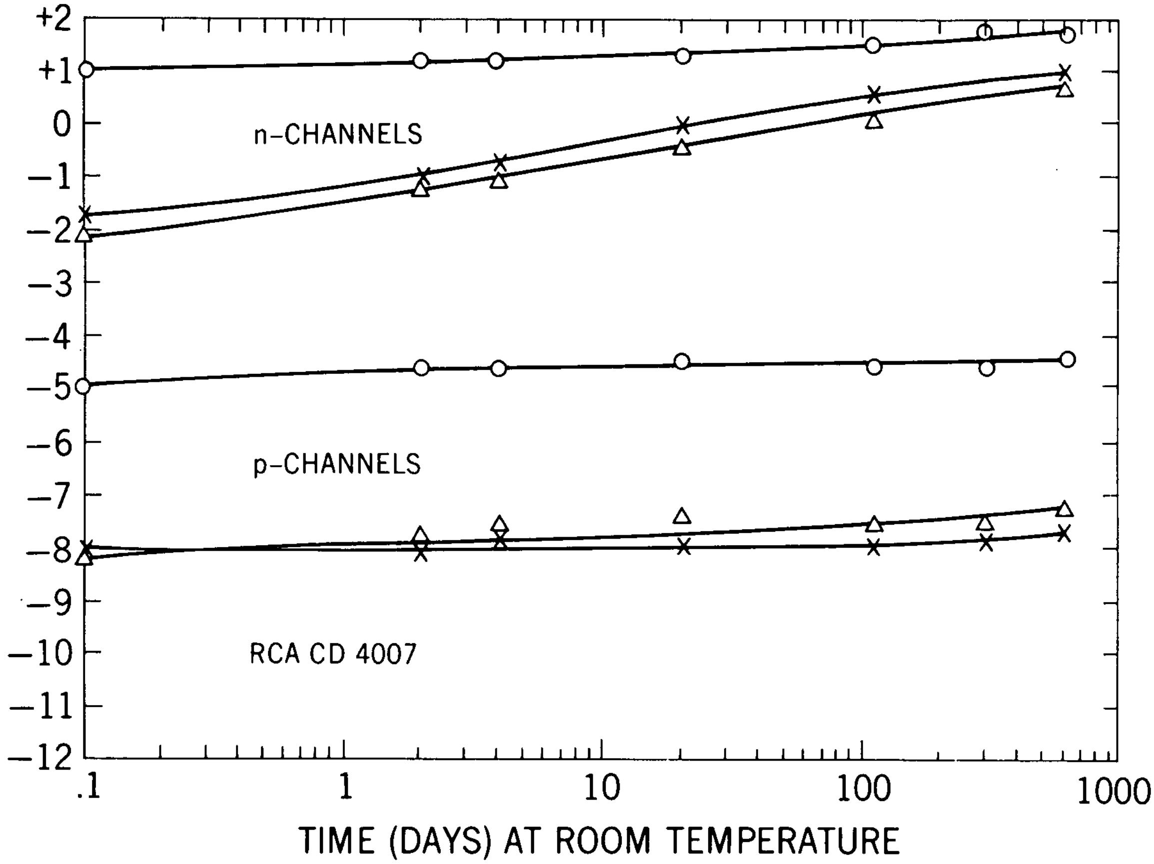


Figure 22. Recovery of threshold potentials in n- and p-channel MOS of RCA IC at room temperature

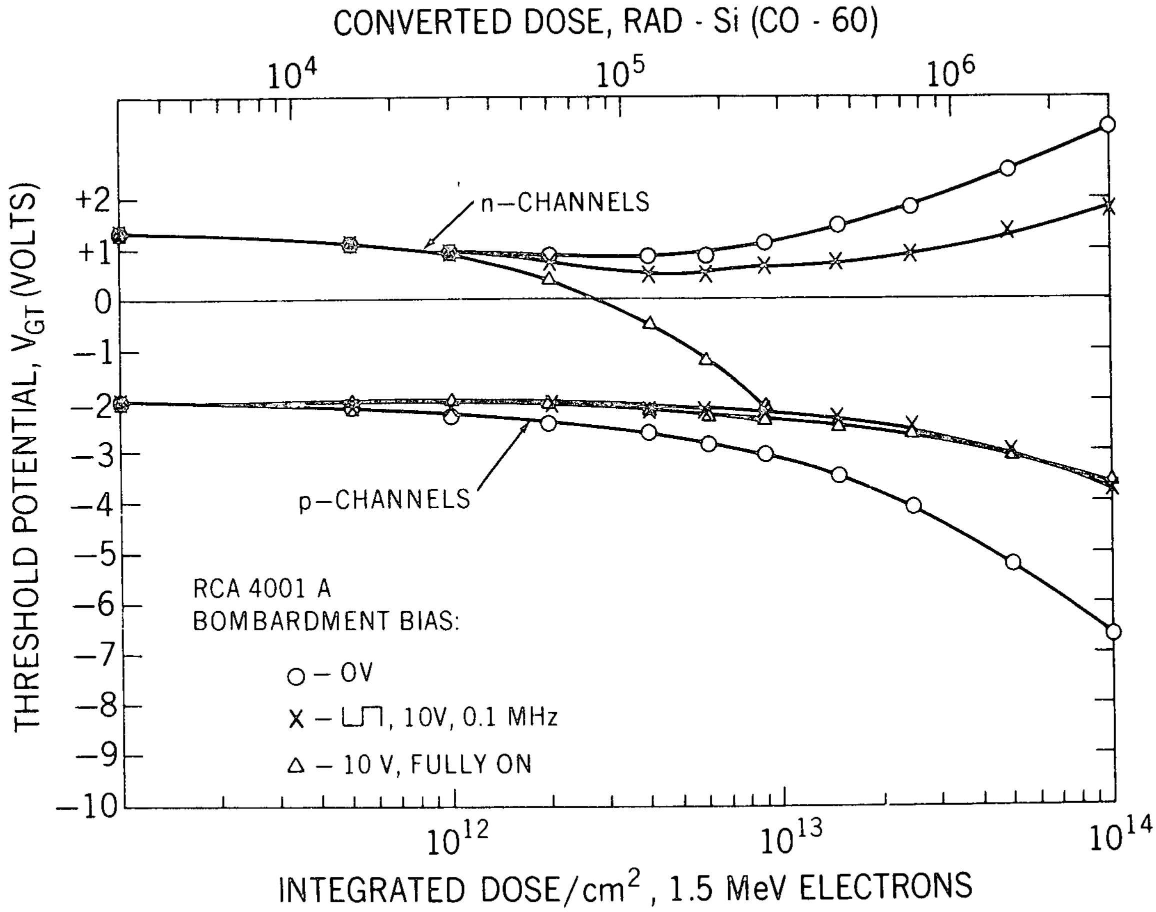


Figure 23. Shifts in the threshold potentials of n- and p-channel MOS devices of RCA new new A-series, irradiated with various gate biases

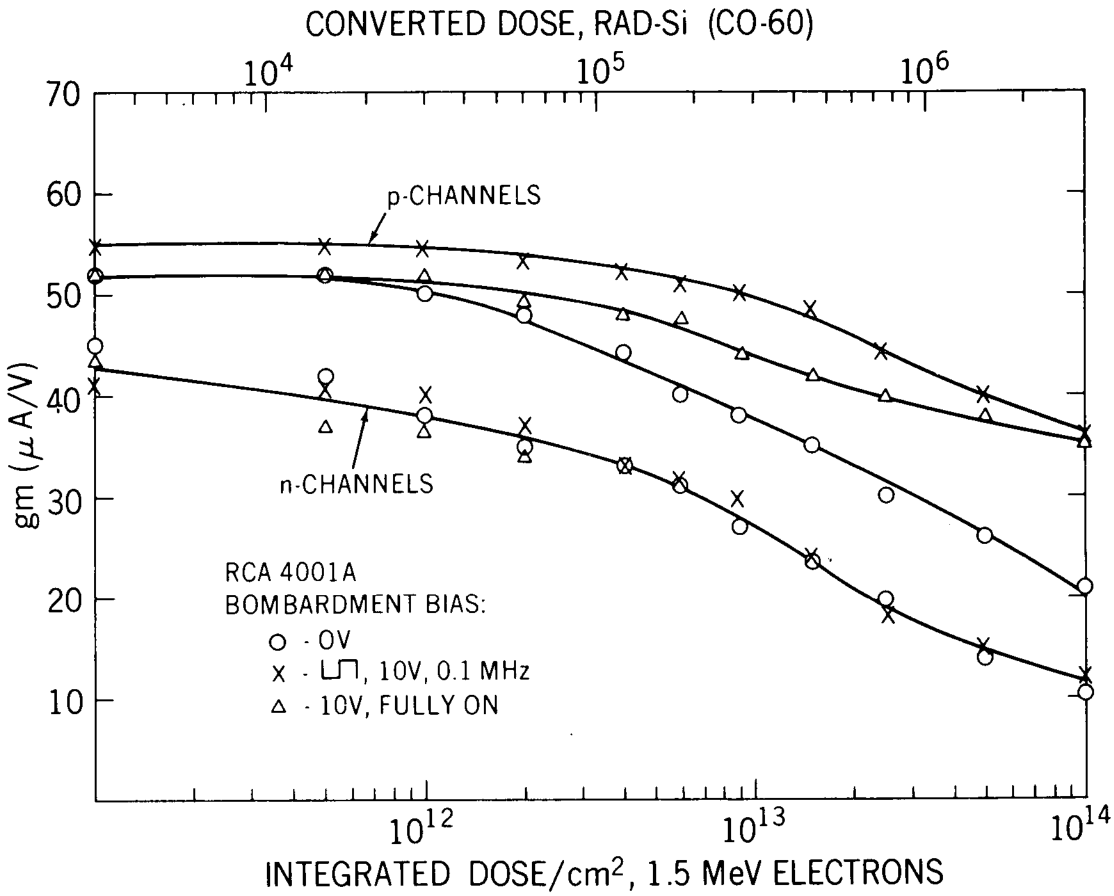


Figure 24: Degradation in transconductances in n- and p-channels of RCA new A-series, as a function of total accumulated radiation dose

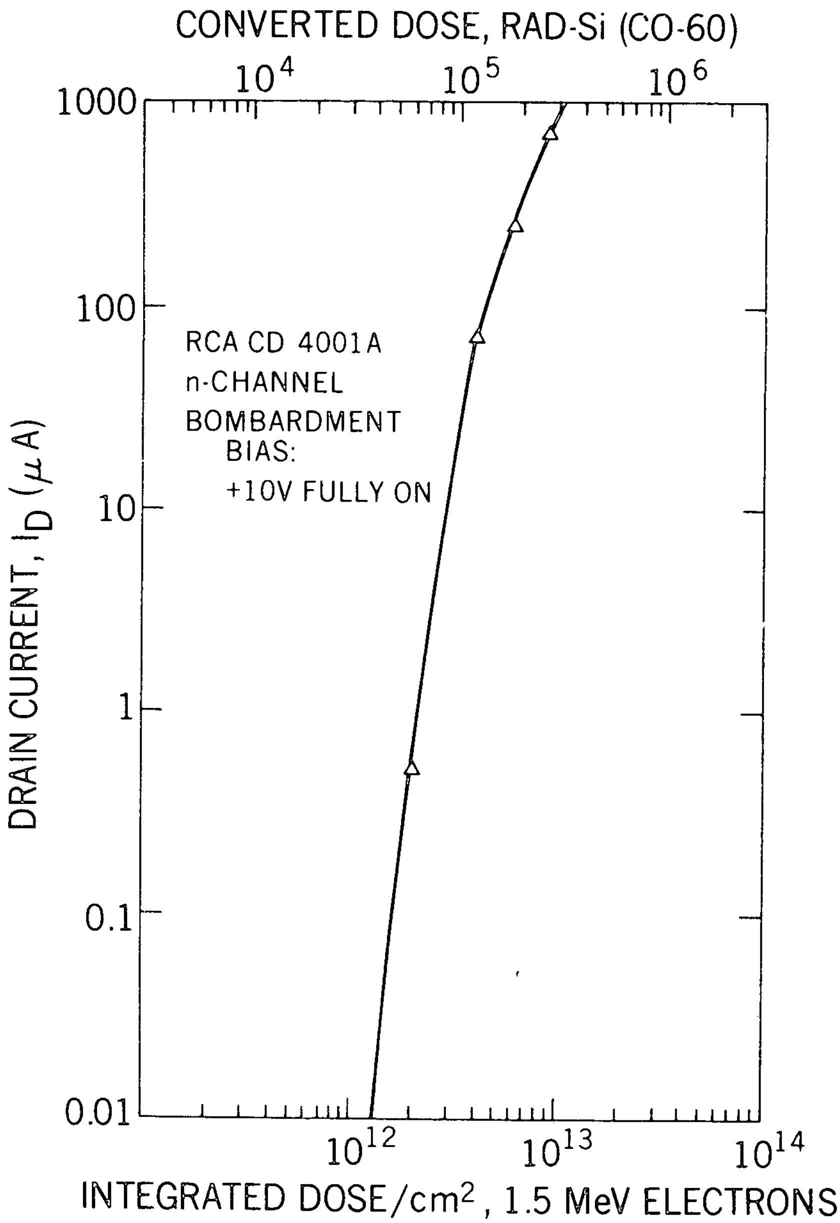
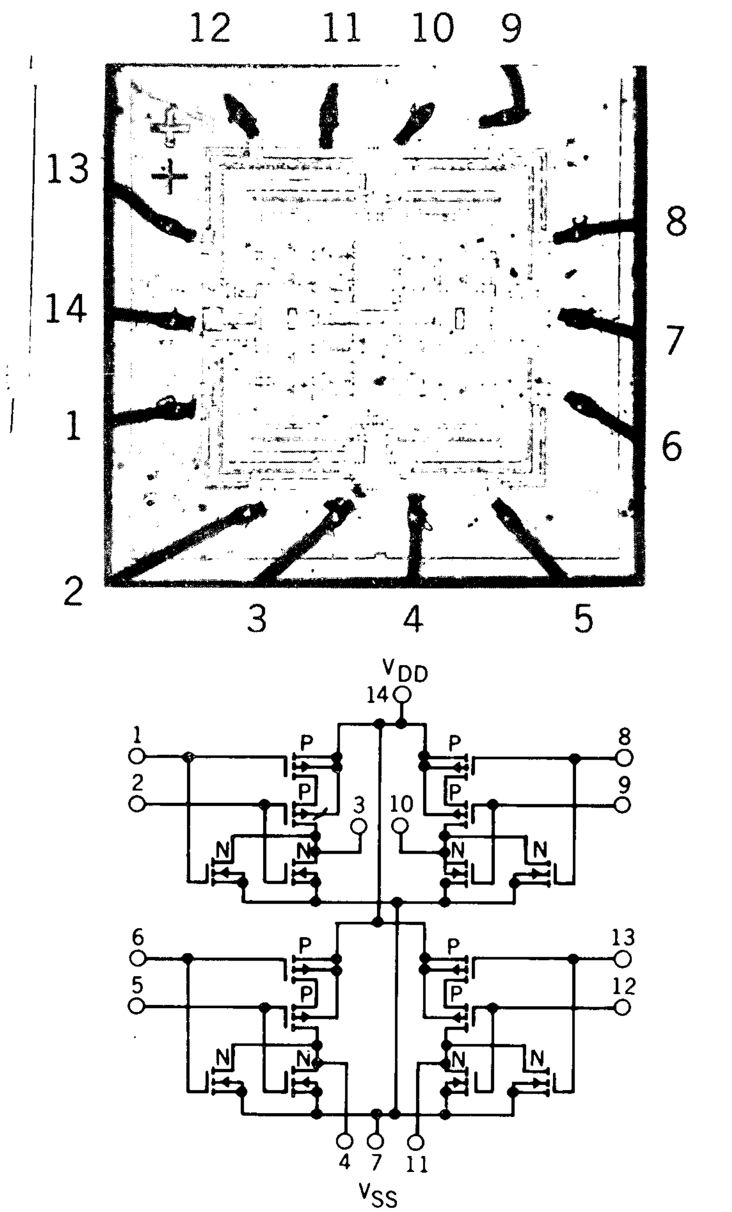


Figure 25. Leakage in n-channels of RCA new A-series



MOTOROLA 2501 – COMPLEMENTARY QUAD 2 INPUT NOR

Figure 26. Diagram and photograph of irradiated Motorola IC

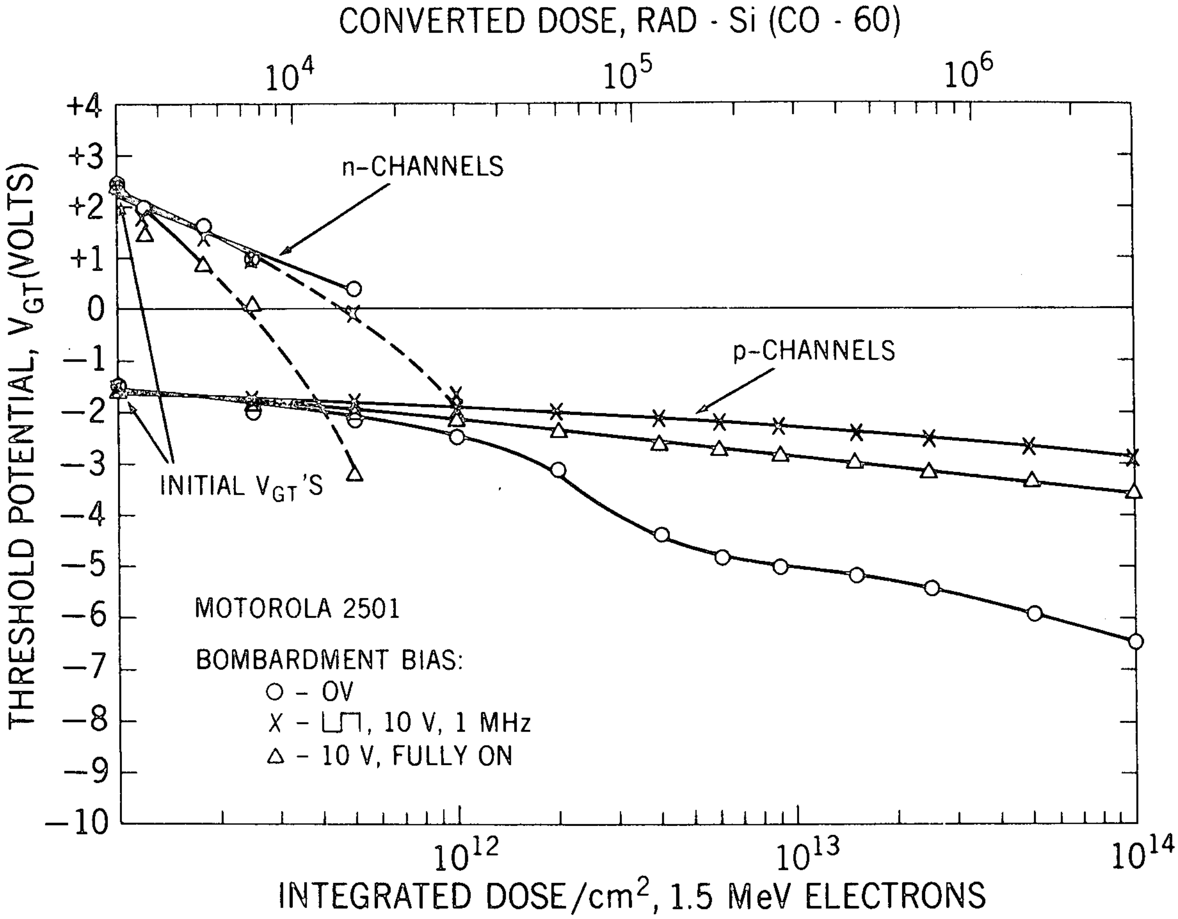


Figure 27. Shifts in the threshold potentials of n- and p-channel MOS devices of Motorola IC, irradiated with various gate biases

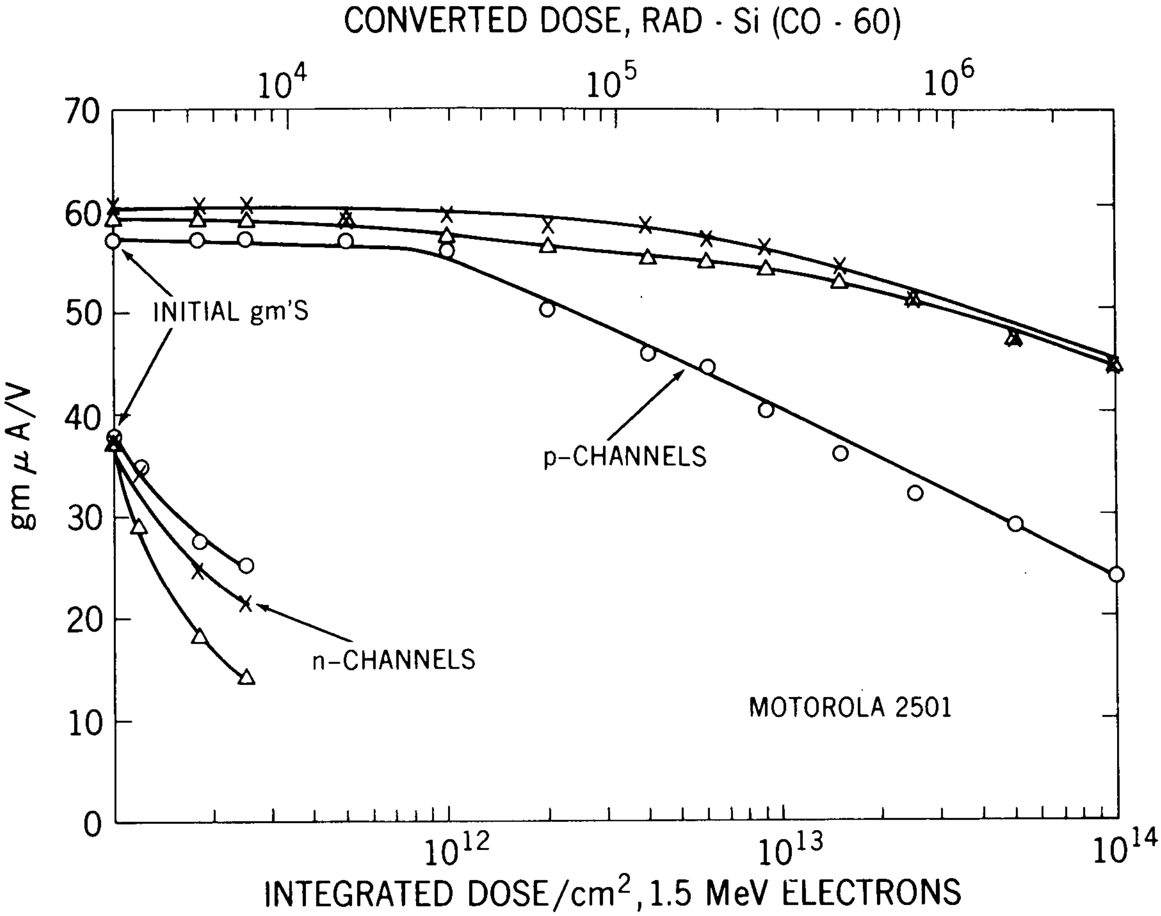


Figure 28. Degradation in tansconductances in n- and p-channels of Motorola IC

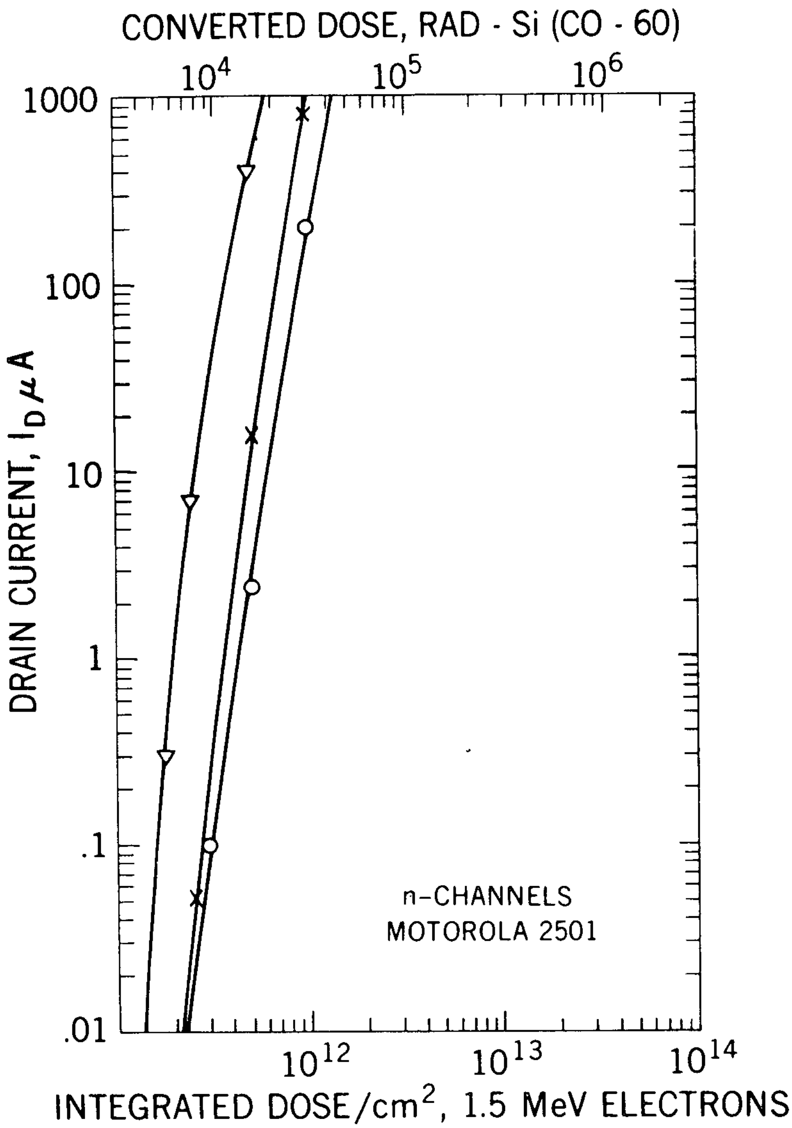
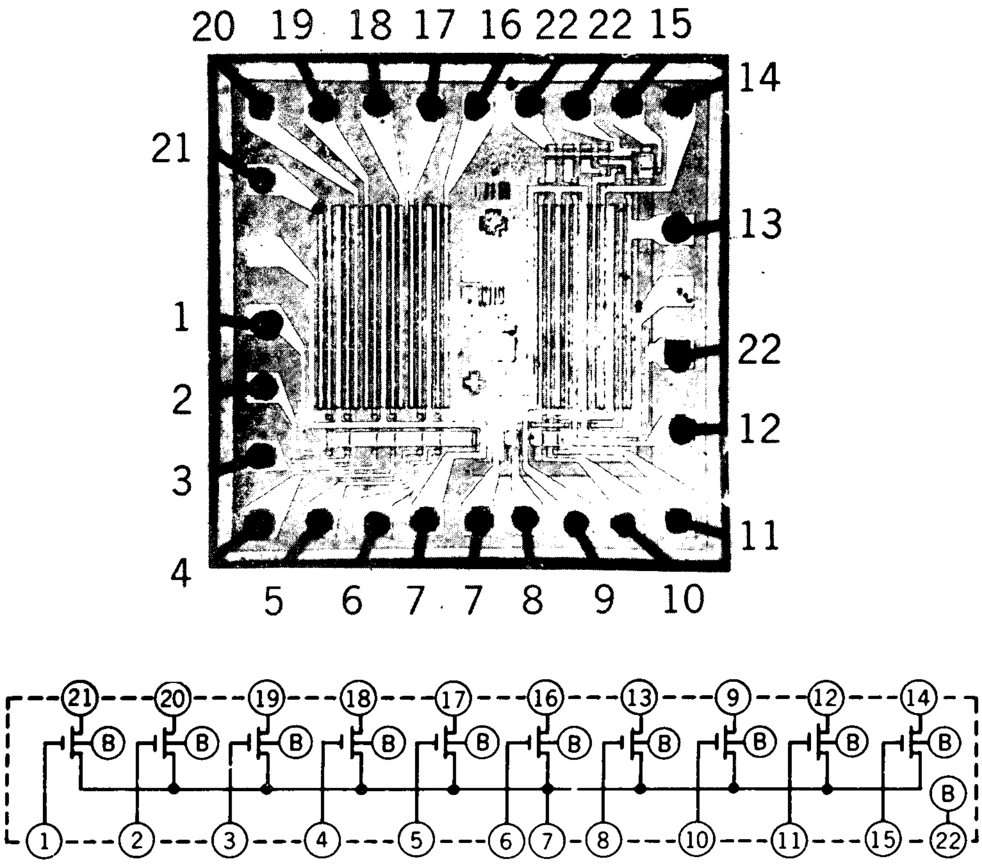


Figure 29. Leakages in n-channels of Motorola IC, irradiated with various gate biases



AMI S – 1304 OR MXO3C – p-CHANNEL, 10 CHANNEL SWITCH

Figure 30. Schematic and photograph of an irradiated AMI p-channel IC

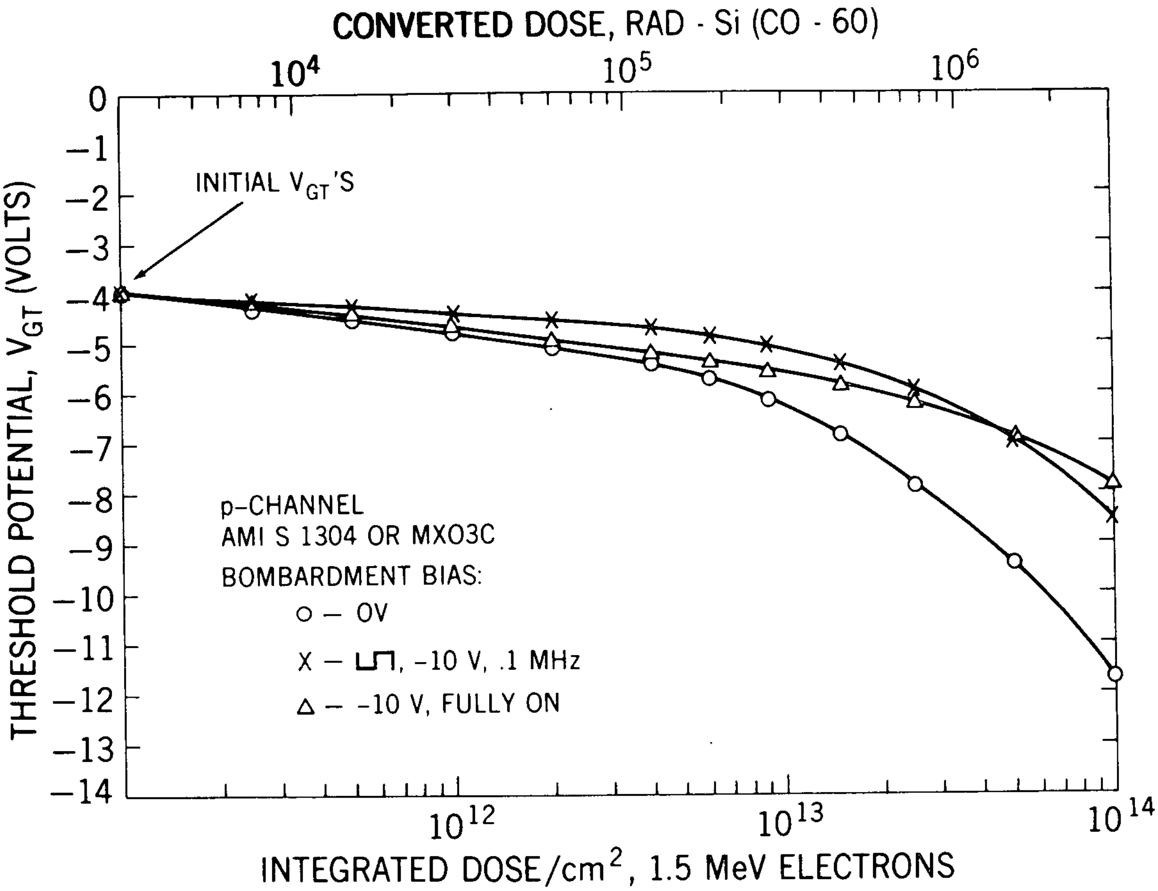


Figure 31. Shifts in the threshold potenials of p-channel MOS devices of AMI p-channel IC, irradiated with various gate biases

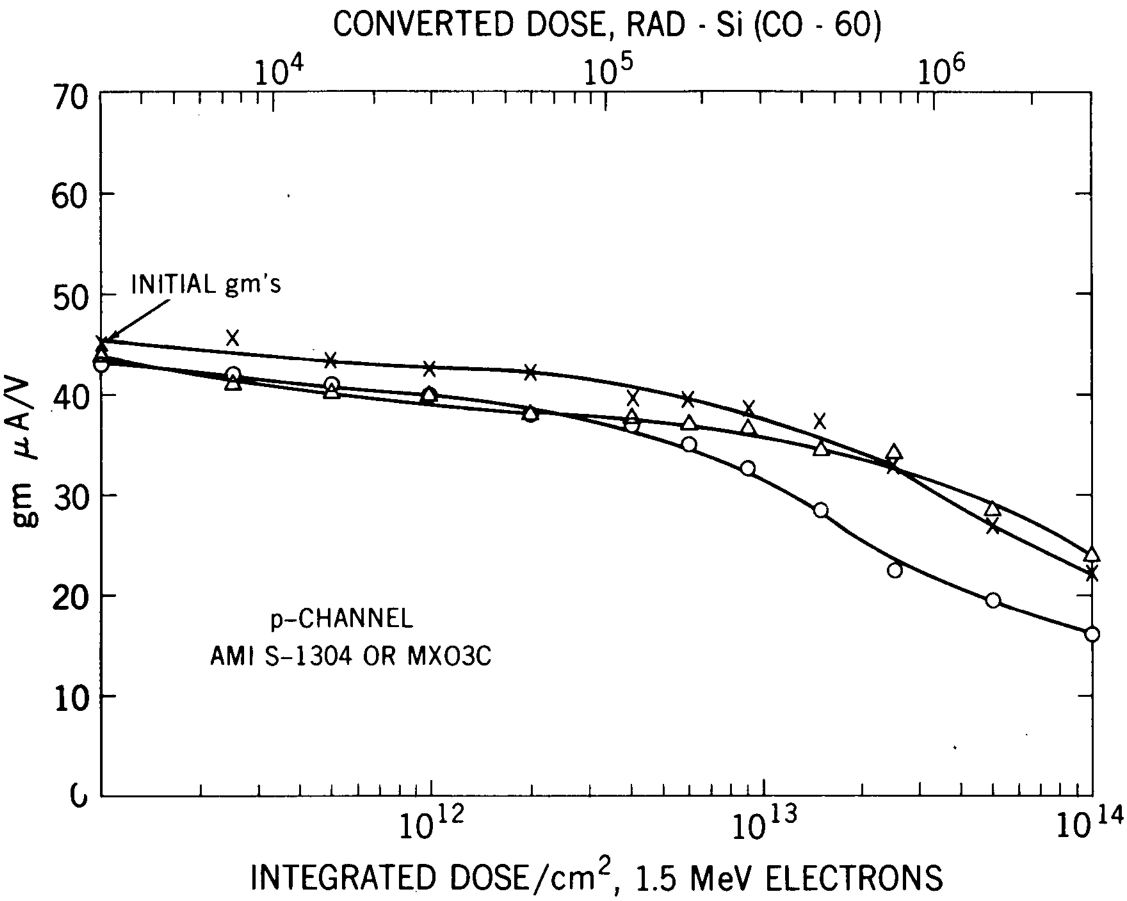


Figure 32. Degradation in transconductances in p-channels of AMI p-channel IC

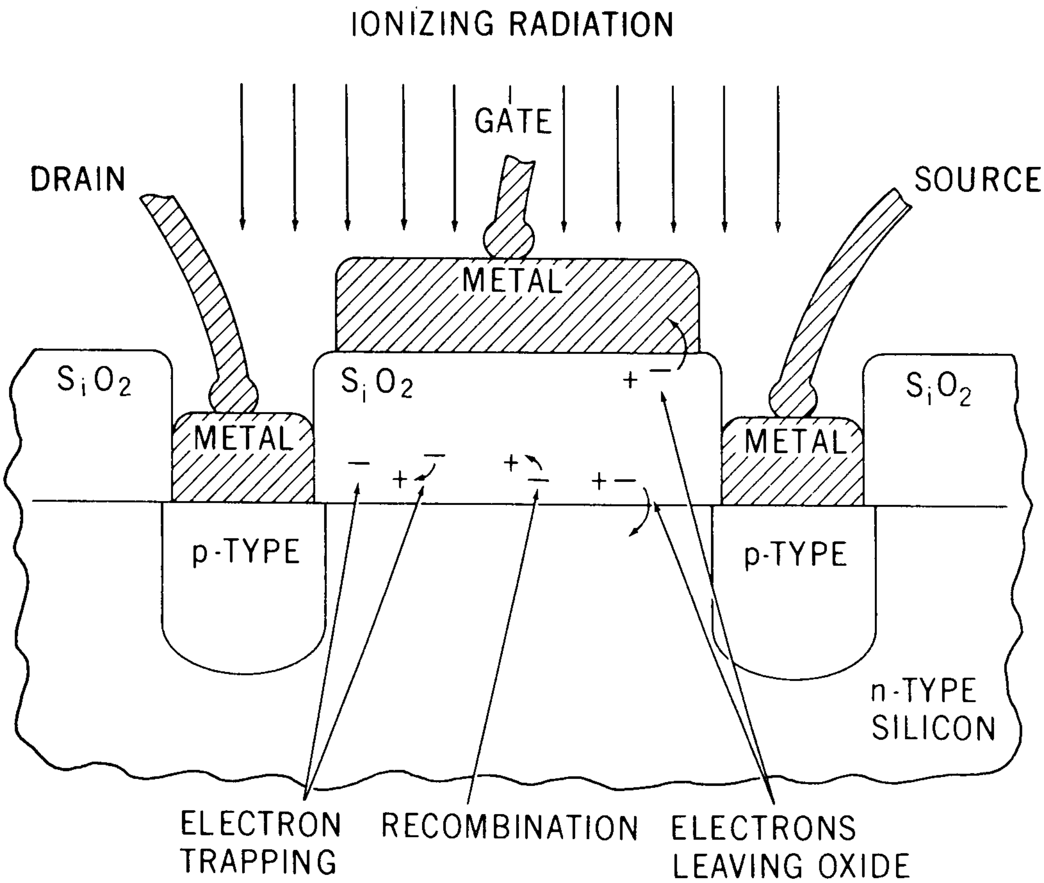


Figure 33. Radiation damage in a single MOS device unit

2

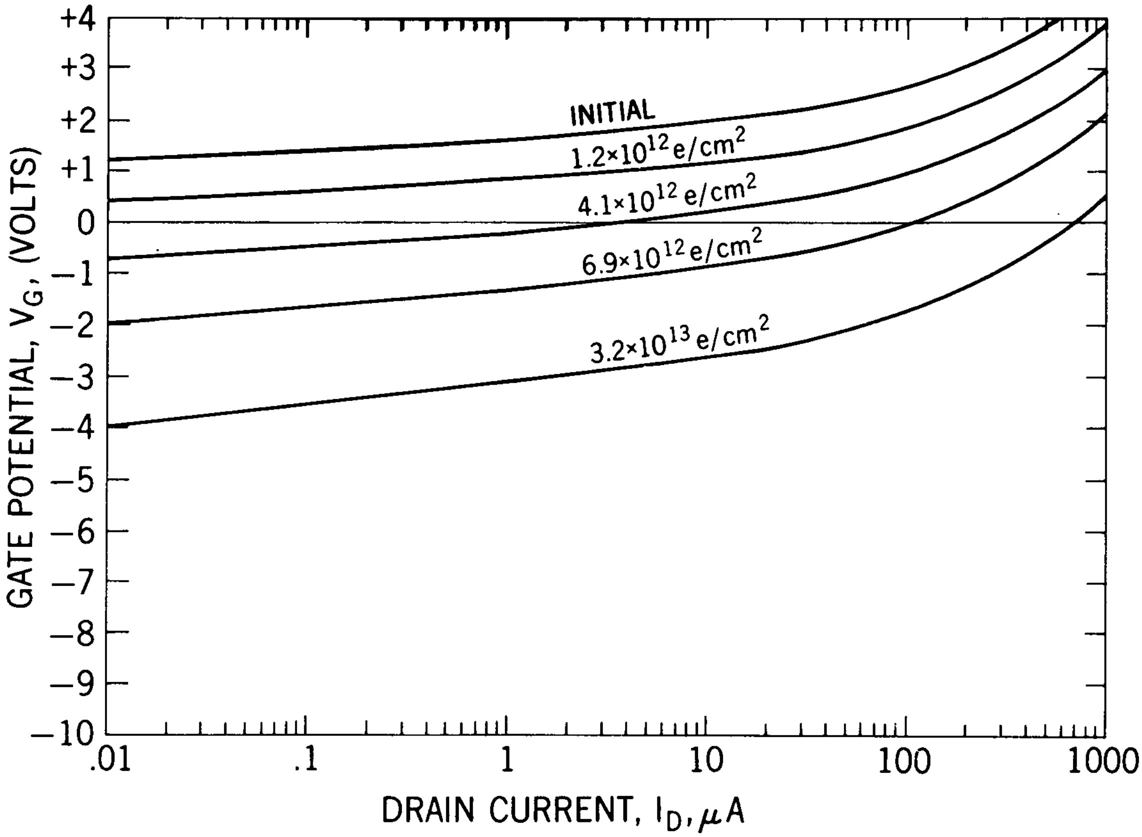


Figure 34. Shift of the I-V characteristic of n-channel MOS device (GME) with various radiation total accumulated doses

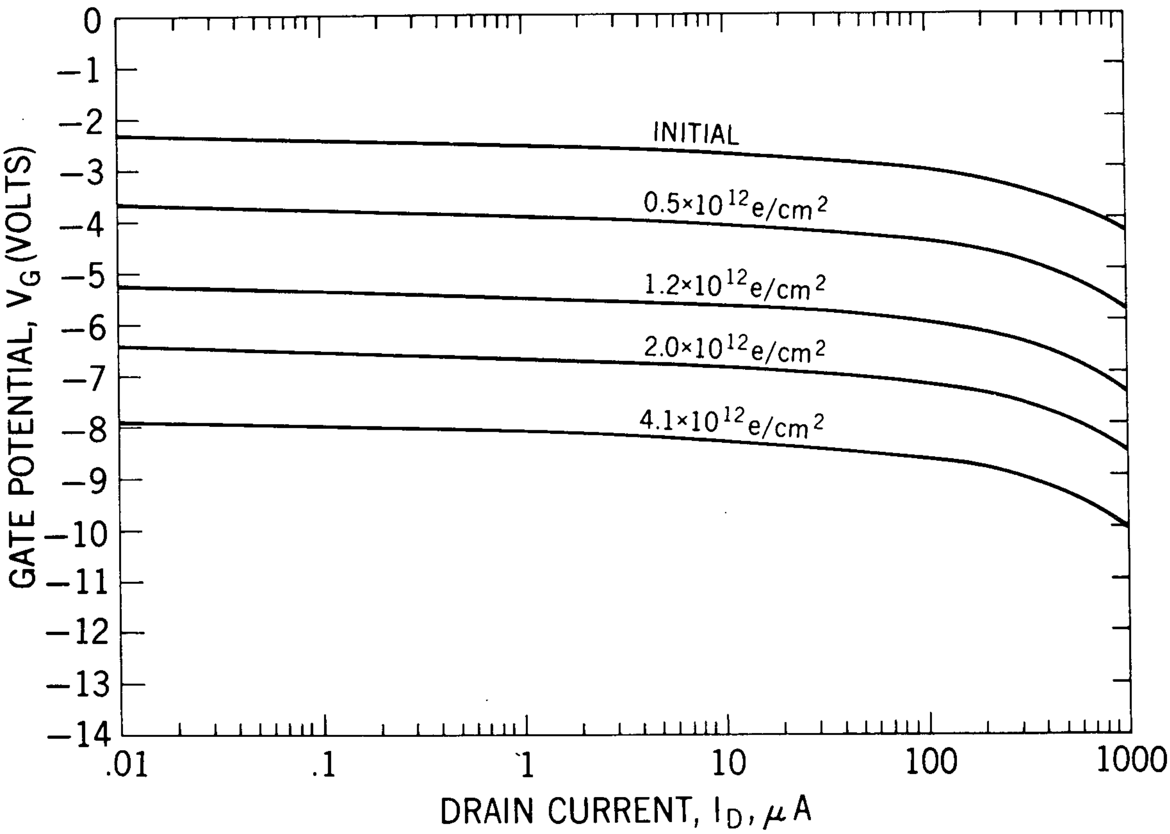


Figure 35. Same as Fig. 34, except p-channel MOS device

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Figure 33. Radiation damage in a single MOS device unit.

Figure 34. Shift of the I-V characteristic of n-channel MOS device (GME) with various radiation total accumulated doses.

Figure 35. Same as Figure 34, except p-channel MOS device.