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Publication Date
1965-03-16

UCRL-11936

University of California

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AEC Contract No. W-7405-eng-48

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ABSTRACT

P-channel enhancement mode field-effect transistors were irradiated with 7.5-MeV electrons in the range of absorbed dose from 10^4 through 10^8 rads. Another group of devices absorbed 10^6 rads of 7.5-MeV (peak) bremsstrahlung gammas, and a third group received an integrated thermal neutron exposure of 4×10^{14} n/cm^2. Data derived from static measurements are presented which shows postirradiation shifts in the gate threshold voltage V_{GST}, small signal transconductance g_m, drain-source leakage current I_{DSS}, and gate leakage current I_G. Preliminary data show the effects of postirradiation annealing at elevated temperatures.

INTRODUCTION

The Health Physics group at LRL is interested in the use of insulated-gate transistors for nuclear detection instrumentation. We are concerned with processing dc signals from ionization chambers ($I_S \geqslant 10^{-16}$A), and pulses from proportional counters such as the BF_3 (E_p = 0 to 100 mV, t_r = 50 to 200 nsec). Detectors such as these have very high internal impedances. Insulated-gate transistors can have very high input impedances (> 10^{15} ohms), transconductances of the order of 10^3 μmhos, and frequency response permitting use with pulses with rise times in the nanosecond range.

As an extension of previous work with insulated-gate electrometer ionization chambers,[1] we are concerned with the behavior of these transistors after they have received large doses of ionizing radiation. This is important if they are to be used near target areas of nuclear particle accelerators.

Irradiation Procedures

Five devices were used for each exposure and no device was used more than once. All devices studied were of the same type and origin.[2] They were not preselected, but they were required to exhibit normal characteristics. All but the thermal neutron exposures were made at the LRL Berkeley electron linear accelerator. LRL Livermore made their pool-type reactor available for the thermal neutron exposure.

Dosimetry

Cobalt glass dosimeters 1/16 in. thick were used for the electron and gamma exposures. The measurements of absorbed dose in the glass are accurate to ±5%. Because of the similarity between the glass dosimeters and the transistor material, and because the maximum range of 7.5-MeV electrons in glass is much longer than the transistor and dosimeter thickness, the measured dose in glass is assumed to be representative of the absorbed dose in the device under test. The beta-gamma component of the thermal neutron exposure was 7.4×10^4 rads (air) as measured with Li^7F, a thermoluminescent dosimeter. Gold foils were used to measure the thermal neutron flux density.

Device Measurements

Only static measurements of device characteristics were made; however, all devices were irradiated under simulated operating conditions. A drain supply voltage of 10.8 V was used with a common drain load resistance of 10^4 ohms. All gates were tied to their respective drains.

V_{GST}

The gate threshold or turn-on voltage, V_{GST}, was measured at $V_{DS} = V_{GS}$, $I_D = 10\,\mu A$.

g_m

Initial values of transconductance were measured at $V_{GS} = V_{DS}$ and $I_D \approx 1$ mA with a 10-mV dc signal applied to the gate. After irradiation, the transconductance was measured at the previous value of drain current by proper adjustment of gate bias.

I_G

Gate leakage current measurements were made by floating the gate and noting the rate of change of drain current. Starting conditions were $V_{GS} = V_{DS}$, $I_D \approx 1$ mA. Typically, prior to irradiation, and at 20 minutes after turn-on, 2/3 of the devices exhibit gate leakage currents of 1 to

2×10^{-15}A. This leakage, which is in a direction tending to make the gate more positive, diminishes as shown in Fig. 1, so that after about 5 hours the leakage rate is essentially constant. All measurements of I_G are started at precisely 20 minutes after turn-on. Devices exhibiting gate leakage currents $> \approx 10^{-13}$A shortly after turn-on do not improve significantly with "on" time.

I_{DSS}

Drain-source leakage current, I_{DSS}, was measured at $V_{GS} = 0$, $V_{DS} = -20$ V.

Body leads were connected to source leads during all exposures and measurements.

EXPOSURE RESULTS

Electron Exposures

Table I contains the data from which the graphs (Figs. 2 through 6) were derived. Except for Fig. 4, each data point is the average of five devices. I_{DSS} device #26 is an exception; it was rejected for graphical purposes as not being typical of the group. $I_{G's}$ (Fig. 4) were not averaged because of the wide variation of values, especially in the 10^8-rad group.

ΔV_{GST}

When a device is subjected to ionizing radiation the threshold voltage shifts upwards. The amount of this shift is shown in Fig. 2 to be 0.6 V for a 10^4-rad dose, bringing V_{GST} from a nominal -4.5 V to -5.1 V, as shown in Fig. 6.

g_m

The transconductance is unaffected at 10^4 rads, increases 10% at 10^5 rads, and declines to nearly 15% at 10^8 rads. See Fig. 3.

I_G

At 10^6 rads a change is apparent, and at 10^7 rads there are significant changes, but by less than a factor of 10 for four of the five devices; 10^8 rads produces changes ranging over six or more decades, as shown in Fig. 4.

I_{DSS}

No deterioration in drain-source leakage current is apparent at less than 10^6 rads, as shown in Fig. 5, while at 10^8 rads the leakage has increased tenfold.

BV_{DSS}

Drain-source breakdown voltages were not affected at 10^6, 10^7, and 10^8 rads, as shown in Table I.

BV_{GSS}

Gate-source breakdown voltages (compared with average figures because this is a destructive test) did not change at 10^7 rads and were not measured at 10^8 rads. See Table I.

10^6-Rad Gamma Exposure

From Table I:

V_{GST} increased 2.8 V,

g_m increased 12%,

I_G increased by a factor of about 2 (average).

I_{DSS} increased by a factor of about 3 (average), #40 omitted.

Some differences between the gamma and electron exposures might be due to the difference in specific ionization between the secondary electrons from the γ rays and those from the 7.5-MeV electrons.

4×10^{14} Thermal Neutrons/cm^2(Cd Ratio ≈ 500)

From Table I:

V_{GST} increased an average of 2.7 V on four devices and 7.3 V on #3,

g_m decreased an average on 5%,

I_G of the average increased nearly an order of magnitude,

I_{DSS} showed no significant change,

BV_{DSS} showed no significant change.

The large beta-gamma component (7.4×10^4 rads$_{air}$) accompanying this exposure makes the results difficult to interpret. V_{GST} changed by an amount which would suggest it was due to the beta-gamma component. I_G and g_m were degraded by an amount which, if due to the beta-gamma alone, would require the beta-gamma component to be an order of magnitude higher than was measured.

SOME EFFECTS OF ANNEALING

A number of irradiated devices were annealed at 200°C for 24 hours, and the following measurements were made:

V_{GST}

Figure 6 shows that the shift in turn-on voltage can be eliminated by annealing. In fact the 10^7- and 10^8-rad groups assumed postannealed values of V_{GST} lower than the preirradiated values. For the 10^8-rad group, the postannealed average turn-on voltage is -3.3 V.

g_m

On the average, g_m returned to within 3% of the preirradiated value.

I_G

Annealing improves the gate-leakage characteristics of some devices and leads to further deterioration of others.

I_{DSS}

The drain-source leakage characteristics of the 10^8-rad group were considerably improved. On the average I_{DSS} returned to its original value within a factor of about 3.

BV_{DSS}

Annealing had no deleterious affect on the 10^8-rad group.

BV_{GSS}

There is no significant difference in average values of BV_{GSS} between new devices and the annealed 10^8-rad group.

CONCLUSIONS

Shifting of the gate threshold voltage would appear to be the most significant radiation-induced change below 10^8 rads. If devices of this sort are to be used in high-level radiation areas where they might be expected to absorb continuously an average of about 10 rads/hour or more, some provision must be made for the shift in V_{GST}. Judicious use of lead shielding around the device could significantly reduce the absorbed dose. Use of differential circuitry, with the output signal taken between the drains of two equally irradiated devices, would be very helpful, especially if a large portion of the load were in the source. ΔV_{GST} may be more nearly the same for a differential pair on a single silicon chip.

ACKNOWLEDGMENTS

The authors wish to thank H. Wade Patterson for supporting and facilitating this investigation, and Douglas Pounds for operating the electron linear accelerator and making the cobalt glass dosimetry measurements. Also, we wish to thank the operators of the LPTR facility; Kenneth Case and Milan Knezevich for their work with the Li^7F dosimetry; and Willard Burns for the thermal neutron flux density measurements.

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

REFERENCES

*General Micro-Electronics Inc., Santa Clara, California.

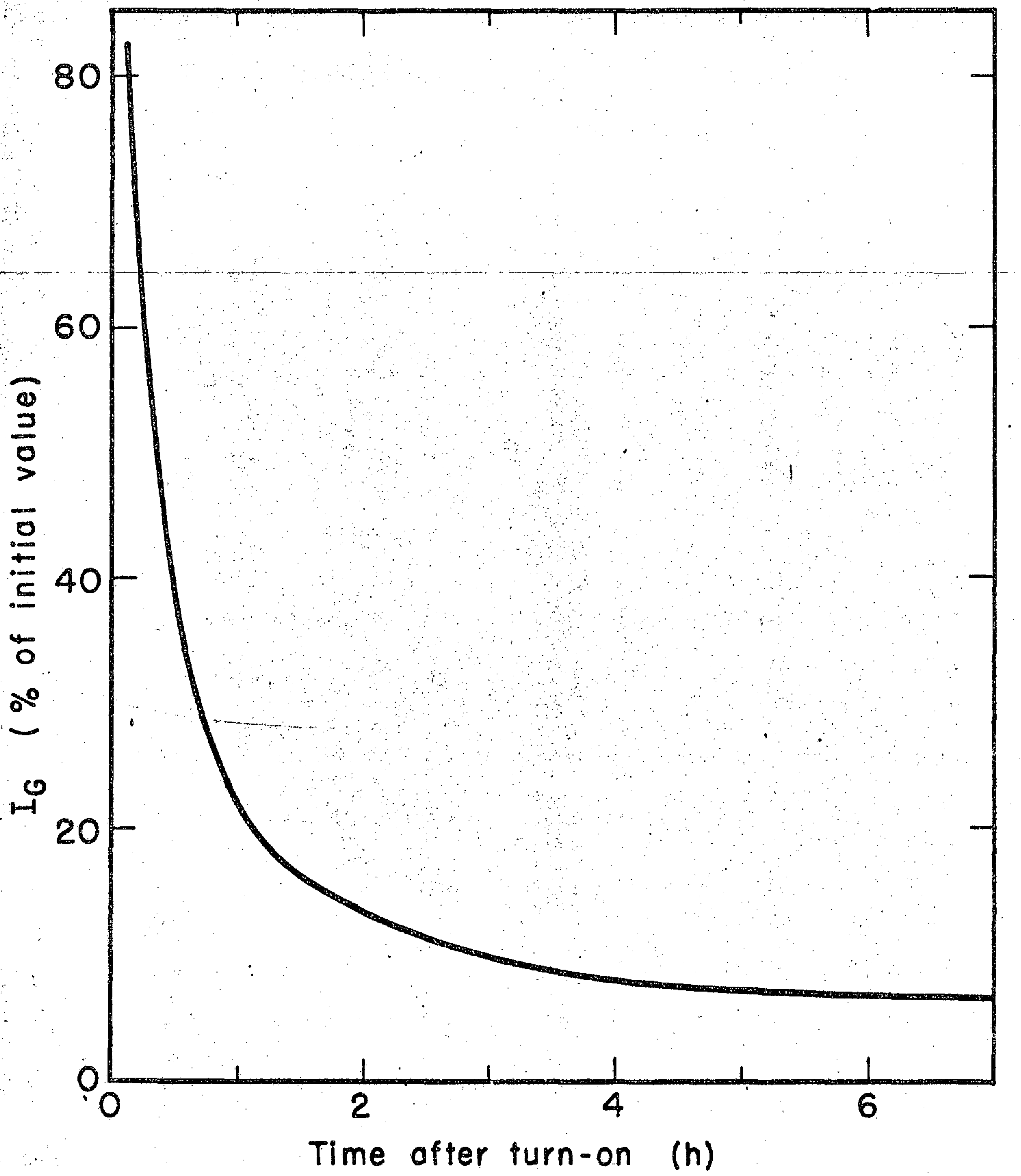
1. J. B. McCaslin, Electrometer for Ionization Chambers Using Metal-Oxide-Semiconductor Field-Effect Transistors, Rev. Sci. Instr. 35, [11], 1587-1591 (1964).

2. General Micro-Electronics Inc., Santa Clara, California, Type 2N3608.

Table I. Absorbed dose (rads).

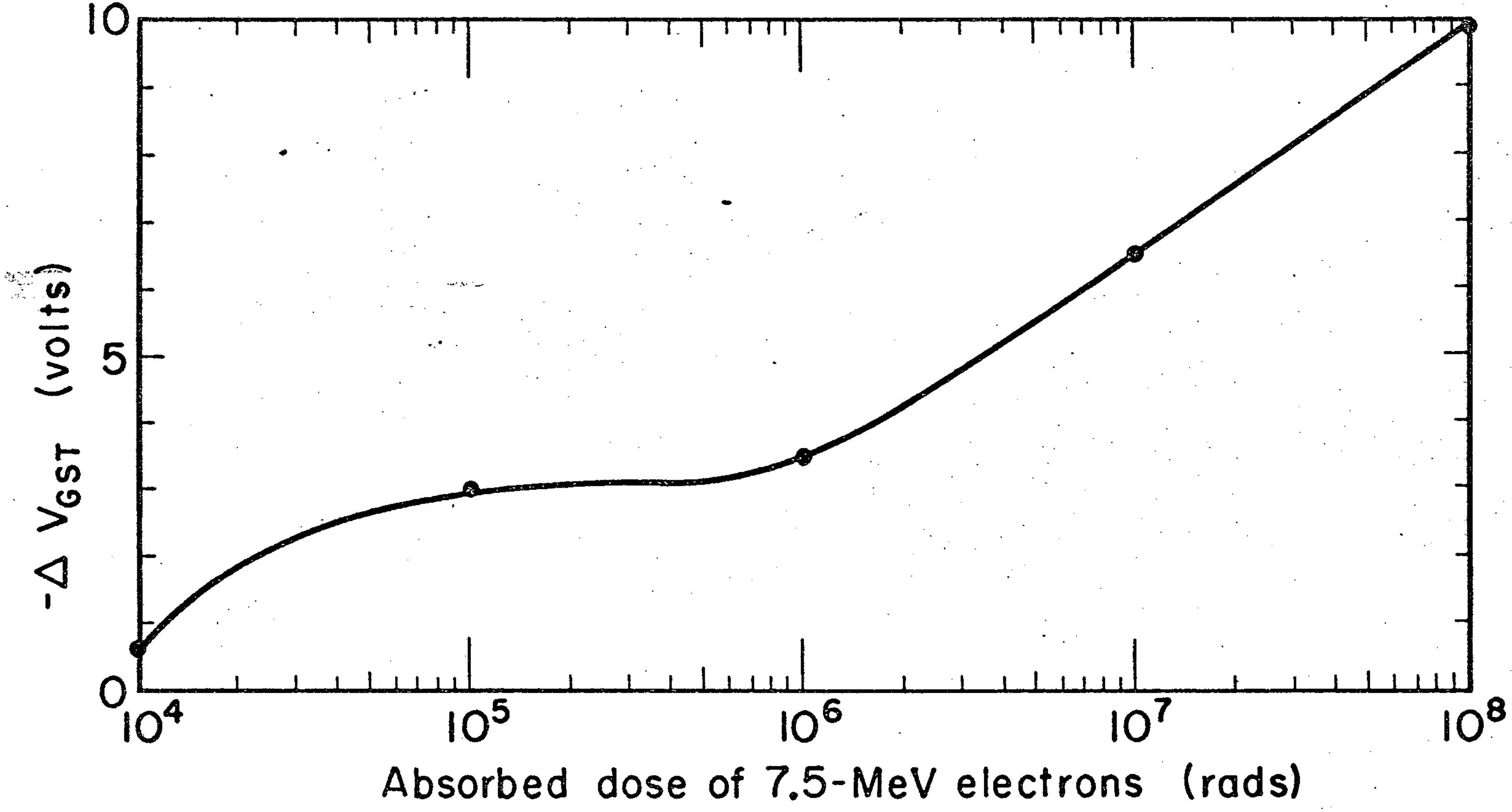
A, device number; B, preirradiation; C, postirradiation; D, postannealing; NC, no change; F, failure.

	7.5-MeV electrons																			$4\times10^{14} n_s/cm^2$			10^6 rads gammas			
	10^4			10^5				10^6				10^7				10^8				7.3×10^4 rads β^-, γ						
CHARACTERISTIC	A	B	C	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	A	B	C	D
V_{GST} (volts)	42	4.2	4.9	27	4.5	8.3	5.4	18	4.2	8.0	4.3	13	4.2	10.2	4.4	23	4.6	15.4	2.8	1	4.6	7.2	35	4.2	8.8	4.6
	43	4.6	5.1	29	4.4	6.9	4.7	19	4.3	8.0	4.2	14	4.6	11.1	4.2	24	4.5	16.0	3.0	2	4.9	7.6	37	5.0	8.8	4.4
	44	4.8	5.4	30	5.0	8.8	5.7	20	5.5	8.6	4.6	15	4.4	10.5	3.8	25	5.2	15.4	4.2	3	4.1	11.4	38	4.8	8.8	4.2
	45	4.5	5.0	32	4.4	6.8	4.7	21	5.0	8.5	4.8	16	4.4	11.0	4.2	26	4.2	10.8	3.8	4	4.1	6.8	40	3.8	11.6	5.8
	46	4.8	5.5	34	4.2	6.6	4.5	22	4.4	7.7	4.4	17	4.7	12.0	4.4	28	4.5	15.0	3.3	6	4.7	7.5	41	4.8	8.6	4.2
g_m (μmhos)	42	530	540	27	750	840		18	760	820	730	13	760	730	760	23	760	620	750	1	750	700	35	760	850	
	43	780	780	29	780	860		19	750	800	740	14	740	700	770	24	750	660	780	2	730	700	37	700	780	
	44	760	780	30	780	830		20	750	780	740	15	760	760	F	25	700	550	680	3	740	700	38	730	820	
	45	780	780	32	770	850		21	700	740	680	16	760	760	780	26	740	700	770	4	850	810	40	760	850	
	46	780	770	34	760	850		22	750	820	740	17	760	750	800	28	720	620	760	6	850	800	41	760	870	
I_G (A)·10^{-15}	42	1.1	1.7	27	2.7	2.8		18	2.1	3.1	9.4	13	2.0	9.0	$2.6^{.05}$	23	3.2	1.5×10^5	1300.	1	4.9	30.	35	1.5	1.6	
	43	1.2	1.2	29	3.1	1.2		19	1.3	1.9	1.2	14	4.4	16.	9.4	24	1.4	9.4	7.7	2	2.2	26.	37	1.3	2.2	
	44	1.2	0.6	30	1.4	1.8		20	1.4	4.3	2.9	15	1.2	5.0	F	25	50.	8.3	13.	3	3.8	28.	38	1.5	0.9	
	45	2.9	2.3	32	2.2	2.0		21	5.4	10.	3500.	16	2.2	39.	2100.	26	1.8	$>10^5$	520.	4	1.1	21.	40	0.8	4.2	
	46	1.0	1.2	34	5.0	5.2		22	1.1	2.3	2.2	17	1.6	14.	0.8	28	2.6	2400.	8.8×10^4	6	1.6	18.	41	1.2	2.1	
I_{DSS}(nA)	42	no change		27	3.0	3.0	11.7	18	no change			13	3.3	4.1		23	3.0	28.	4.2	1	2.0	2.4	35	1.9	4.7	5.0
	43	no change		29	1.1	1.0	2.9	19	no change			14	5.6	8.3		24	2.7	59.	6.1	2	4.5	4.7	37	1.1	8.1	4.0
	44	no change		30	4.1	4.0	5.0	20	no change			15	3.9	21.		25	4.3	21.	8.1	3	3.8	3.6	38	1.6	4.2	4.5
	45	no change		32	1.1	4.8	4.7	21	no change			16	2.3	8.3		26	2.7	520.	30.	4	2.8	2.4	40	3.3	220.	7.4
	46	no change		34	1.9	1.8	4.2	22	no change			17	2.1	13.		28	3.0	38.	4.7	6	2.7	2.1	41	1.3	3.2	3.5
BV_{DSS}										NC				NC				NC	NC			NC				
BV_{GSS}										NC (avg)				NC (avg)					NC (avg)							



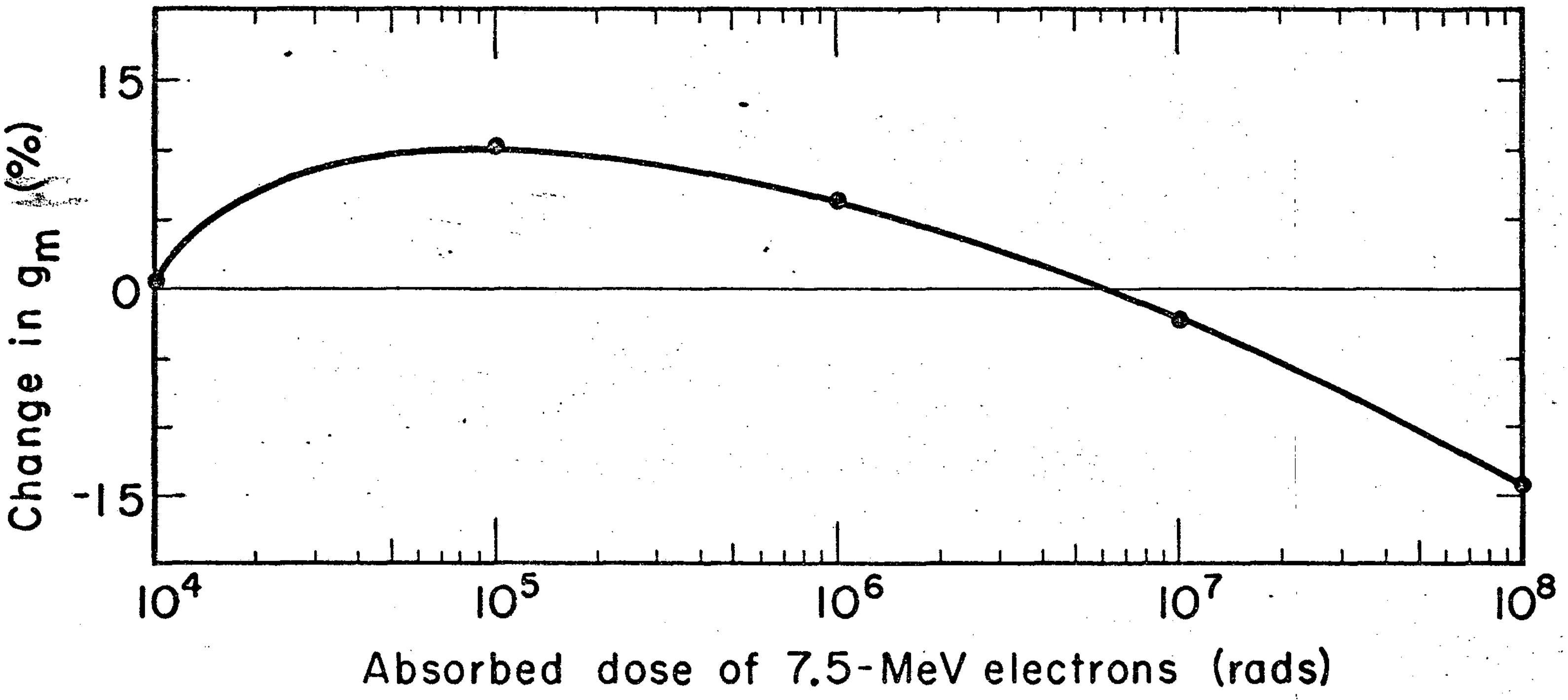
MUB-5650

Fig. 1. The lowest values of gate leakage current, I_G, are not realized until the device has been turned on for several hours.



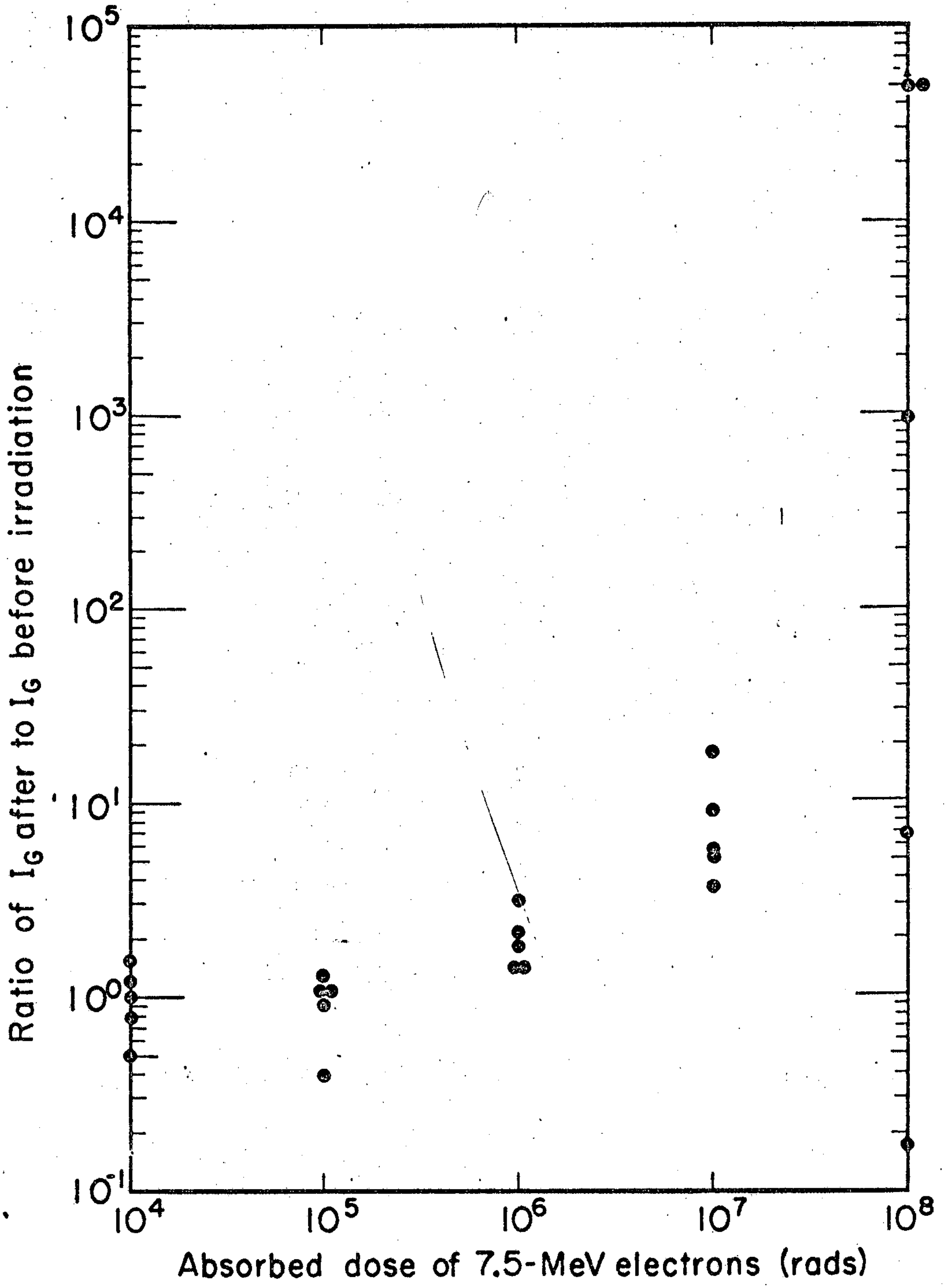
MUB-5651

Fig. 2. The gate to source voltage necessary to turn the device on (V_{GST}) increases with increasing dose. Figure 2 shows the amount of this change.



MUB-5652

Fig. 3. Small changes in transconductance occur for doses in the range of 10^4 to 10^8 rads.



MUB-5653

Fig. 4. The gate leakage current, I_G, shows little change for absorbed doses less than 10^6 rads. At 10^8 rads I_G becomes unpredictable.

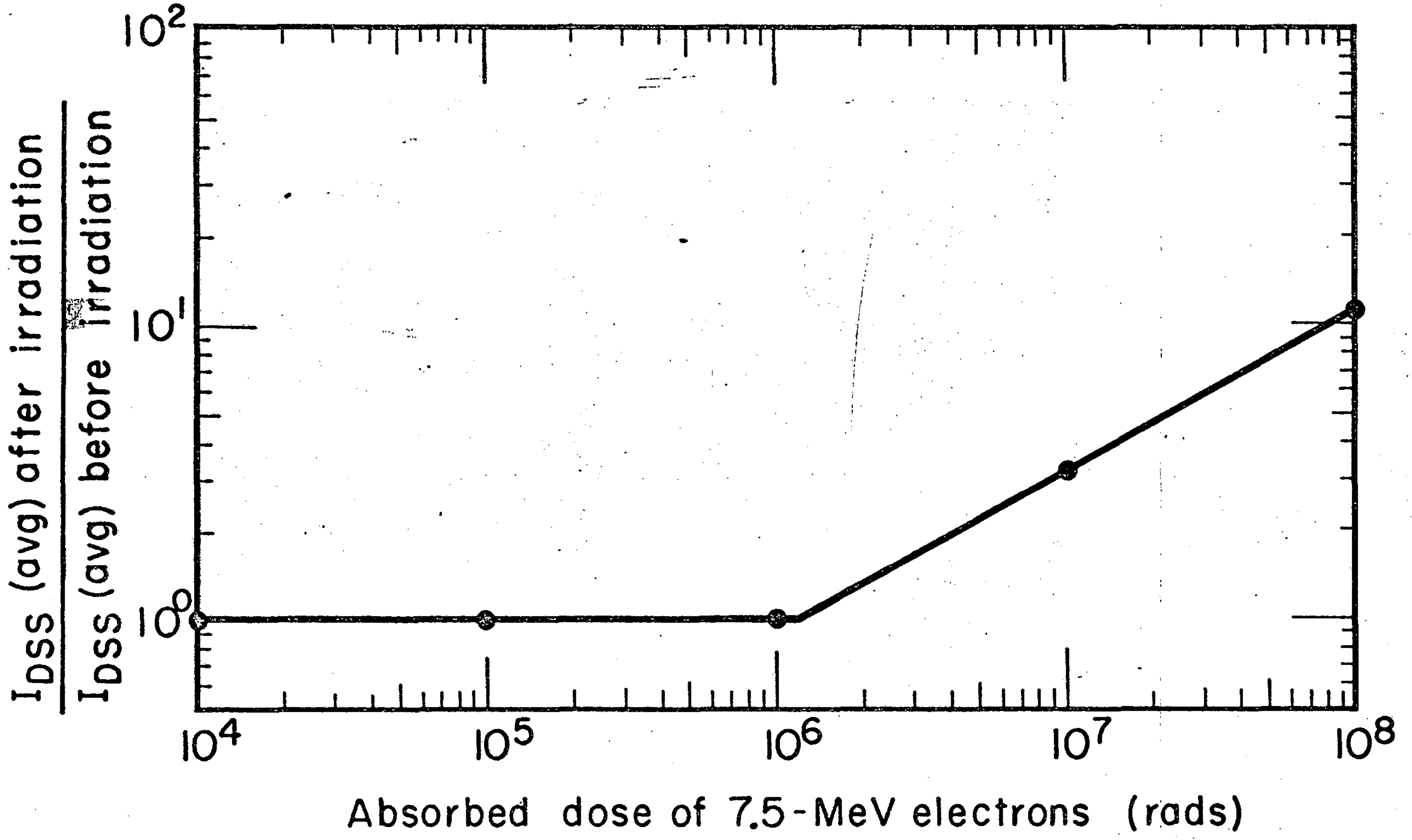


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Fig. 5. Drain to source leakage current with the gate biased off (I_{DSS}) is unaffected by radiation below 10^6 rads and is an order of magnitude higher at 10^8 rads.

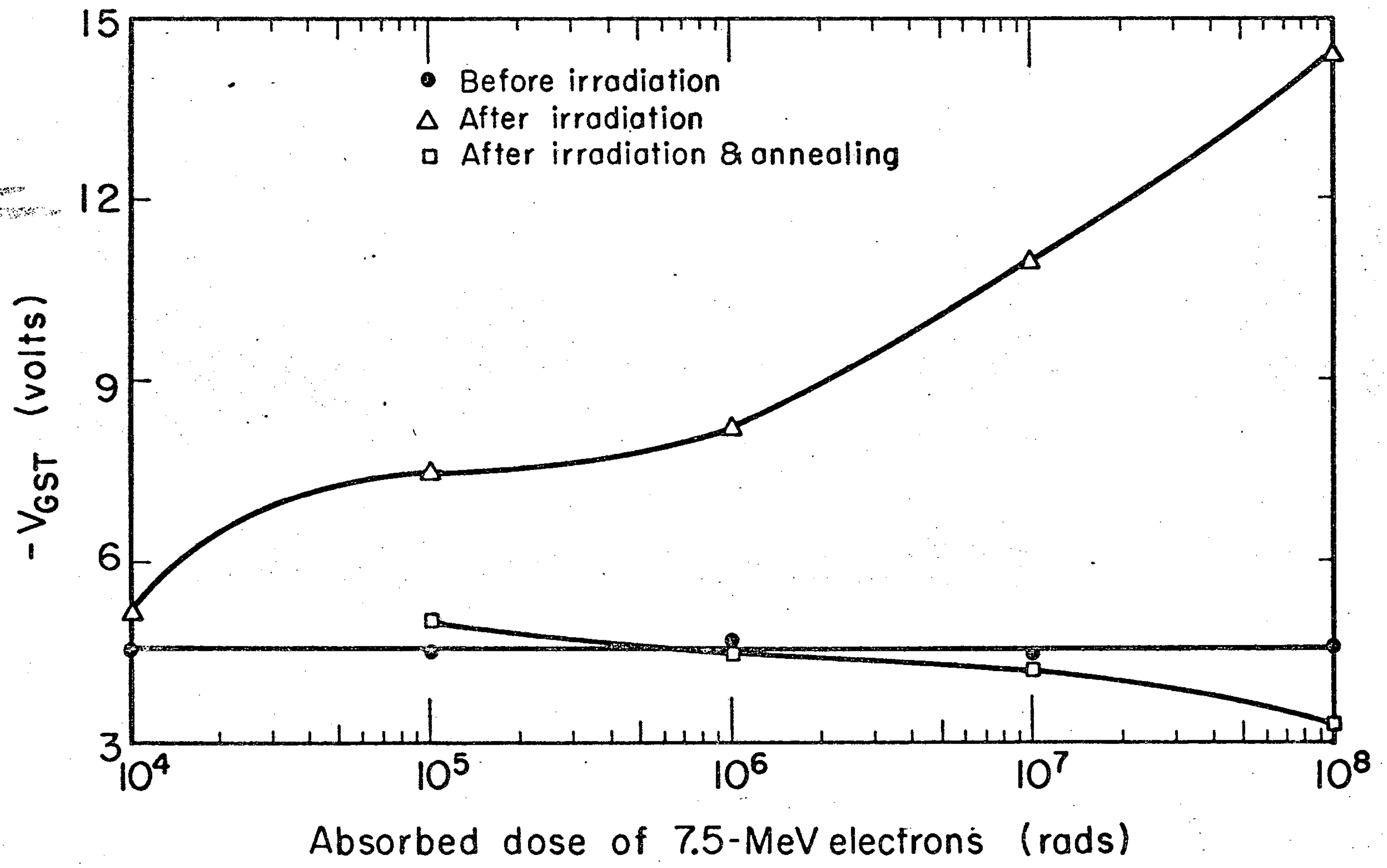

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Fig. 6. Annealing can remove the effects of radiation-induced increases in V_{GST}.