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A RADIATION HARDENED FIELD OXIDE†

by

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ABSTRACT

This paper describes the development of a radiation-tolerant field oxide compatible with both MOS and bipolar technologies. Data is presented which illustrates that nonguardbanded devices utilizing conventional field oxide structures cannot be expected to survive an ionizing radiation dose above approximately 5 x 10^4 rads (Si) due to inversion of p-type silicon surfaces under metallized areas. The radiation hardened oxide was evaluated with both aluminum and polycrystalline silicon gate MOS structures and they conclusively demonstrate that this oxide eliminates the field inversion problem for radiation levels in excess of 10^6 rads (Si).

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INTRODUCTION

A major limitation of CMOS, N-channel MOS and bipolar integrated circuits in an ionizing radiation environment is the build-up of fixed charge in the oxide under metallized areas which results in inversion of the surface over p-type regions. In the MOS technologies, this inversion layer degrades the isolation between N-channel transistors, thus increasing the circuit leakage current and ultimately preventing functional operation. Hardened MOS circuits typically employ heavily diffused guardbands around the N-channel devices to prevent surface inversion, which concommitantly decreases the circuit packing densities and, for a silicon gate technology, can add several process steps to the circuit fabrication. For bipolar technologies, the radiation induced inversion layer typically increases the base leakage current. This can dramatically reduce the device gain for both high gain and low current transistors which are typically used in linear integrated circuits.

The purpose of this work was to investigate the radiation-induced threshold shifts in conventional field oxides with both aluminum and polycrystalline silicon gate electrodes, and to develop a radiation hardened field oxide which was compatible with both MOS and bipolar technologies.

EXPERIMENTAL PROCEDURE

MOS capacitors were used for characterization of the field oxides in an ionizing radiation environment. The capacitors were fabricated on both .8-1.3 ohm-cm phosphorous doped and 3-5 ohm-cm boron doped silicon wafers, with dry, steam, deposited, and radiation hardened oxide dielectrics whose thicknesses ranged from .1 to 1 micron. Both aluminum and polycrystalline silicon gate electrodes were used in these experiments.

The metal gate capacitor electrodes were formed by shadow masking a high purity aluminum deposition from an induction source evaporation. Polycrystalline silicon electrodes were deposited undoped by chemical vapor deposition, and then doped by a phosphorous diffusion to a sheet resistivity of approximately 50 ohms per square. Contact to the polycrystalline silicon was made with induction source evaporated aluminum. Back contacts to all of the wafers were fabricated by evaporating chromium/gold onto the backs of the wafers.

The flat-band and threshold voltages for the MOS capacitor structures were determined from the high frequency capacitance-voltage characteristics taken on at least four representative capacitors from each process variation. The same capacitors were then irradiated in Sandia's Co^{60} gamma irradiation facility (GIF). During the irradiation, one capacitor was biased at +10 volts, while a second, adjacent capacitor was biased at -10 volts. The radiation induced flatband and threshold voltage shifts were then determined from the post-irradiation high-frequency capacitance-voltage characteristics of the capacitors.

In order to more thoroughly characterize the radiation hardened field oxide, CMOS inverters were fabricated using the hardened field oxide for the gate dielectric. The inverters had no gate protection diodes so that sufficient gate voltage (positive and negative) could be applied to turn both the N-channel and the P-channel devices on. The threshold voltages for these devices were determined from $\sqrt{I_{DD}}$ versus V_G plots by measuring the drain current (I_{DD}) at V_{DD} = 10V while the gate was ramped positive and negative to turn the N-channel and the P-channel devices on respectively. During irradiation, the gate and V_{DD} were biased at +10V with respect to V_{SS} (ground).

EXPERIMENTAL RESULTS

The radiation induced N-channel and P-channel threshold shifts measured on metal gate capacitor structures with conventional field oxides are shown in Fig. 1. The dry oxides shown in Fig. 1a offer approximately a factor of two improved hardness over the steam (Fig. 1b) and deposited (Fig. 1c) field oxides. However, it is impractical to consider growing dry oxides greater than 5000 Å to 6000 Å thick due to the excessively long oxidation time required. All of the conventional field oxides exhibited a linear dependence of threshold shift on the oxide thickness for oxide thicknesses greater than approximately 2000 Å. Also, both the N-channel and P-channel threshold shifts were large and negative resulting in inversion of the surface over the p-type substrates, and accumulation of the surface over the n-type substrates. The pre-irradiation threshold voltage for the N-channel capacitors were all less than +25 volts for the oxide thicknesses investigated in this work. Therefore, without the use of heavily doped guardbands, circuits fabricated using these field oxides would have excessive leakage, and probably would not function for ionizing radiation doses in excess of approximately 5×10^4 rads (Si) Co^{60}.

The threshold shifts of polycrystalline silicon gate capacitors were similar to those of the metal gate capacitors for the conventional field oxides. Figure 2 shows the radiation induced threshold shift as a function of total dose for a 6000 Å steam field oxide with a polycrystalline silicon gate. These data agree well with the metal gate/steam field oxide data (Fig. 1b).

The radiation induced threshold shifts for aluminum gate and polycrystalline silicon gate capacitors with the radiation hardened field oxide were investigated as a function of oxide thickness and radiation dose. For the aluminum gate capacitors, the N-channel threshold shift was positive, while the P-channel threshold shift was negative. This results in accumulation of the surface over both the n-type and p-type substrates. At 10^5 rads (Si), the radiation induced threshold voltage shift was almost independent of oxide thickness from .6 to 1.2 microns, unlike conventional oxides.

The polycrystalline silicon gate, with an 8.6 KÅ hardened field oxide dielectric, capacitor data is presented as a function of total dose in Fig. 3. For these silicon gate structures, the N-channel threshold shift is small and negative for doses $<10^6$

rads (Si) Co^{60}. The maximum N-channel threshold shift of -3.5 volts occurs at a total dose of approximately 5 x 10^4 rads (Si). The threshold shift then turns around, becoming positive at a dose slightly greater than 1 x 10^6 rads (Si).

Although the N-channel shift is negative for the silicon gate structures, the magnitude of the shift is sufficiently small that the p-type surfaces will not invert. Also, the P-channel (n-type substrate) threshold shifts for these silicon gate structures are negative, but significantly smaller than was observed for corresponding metal gate structures. There is an indication of saturation effects beginning to occur in the P-channel structures above 1 x 10^5 rads (Si).

Figure 4 shows the radiation induced N and P channel threshold shifts as a function of dose for CMOS inverter circuits with a 10 KÅ radiation hardened oxide gate dielectric, and an aluminum gate electrode. Again, we observed a positive N-channel threshold shift, and a negative P-channel threshold shift, consistent with the measurements on capacitors. The positive N-channel threshold shift and the negative P-channel threshold shift are both in the proper direction to prevent inversion of the surfaces. However, the heavy accumulation of the surfaces for large radiation doses may affect the surface breakdown characteristics of some device structures.

Inverter circuits using an 800 Å thick radiation hardened gate oxide have also been fabricated. Preliminary radiation results on these devices display the same general behavior observed in the field oxides, with a +1.6 volt (+10 volt bias) N-channel shift, and -0.9 volt (0 volt bias) P-channel shift for a 10^6 rads (Si) exposure.

The radiation hardened oxide is fabricated with conventional silicon integrated circuit process techniques and does not degrade under subsequent thermal (up to 1100°C) stresses. The process is also compatible with general bipolar and MOS technologies in use today.

CONCLUSIONS

We have demonstrated that it is possible to fabricate a radiation hardened field oxide for integrated circuits and it eliminates the radiation induced field inversion observed with conventional field oxides. It can therefore eliminate guardbands in MOS circuits so that significant improvements in speed and circuit density may be realized. Also, it will be possible to harden existing nonguardbanded circuits in both metal and silicon gate technologies. In the bipolar area, it will prevent the gain degradation due to an ionizing radiation environment in many bipolar integrated circuits, especially in linear circuits.

More work is being done to characterize the hardened field oxides' transient annealing behavior, and the effects of process variations on the radiation characteristics of the oxide. Work is also in progress to determine the applicability of the hardened field oxide to various integrated circuit technologies.

FIGURE CAPTIONS

Figure 1

Radiation induced N-channel and P-channel threshold shift as a function of oxide thickness for dry, steam, and deposited oxides dielectric MOS capacitors with aluminum metal gates.

Figure 2

N-channel threshold shift as a function of ionizing radiation dose for 6000 Å steam oxide dielectric MOS capacitors with n-type polycrystalline silicon gates.

Figure 3

N-channel and P-channel threshold shift as a function of ionizing radiation dose for silicon gate capacitors with an 8600 Å radiation hardened field oxide dielectric.

Figure 4

N-channel and P-channel threshold shift as a function of ionizing radiation dose for aluminum metal gate CMOS inverters with a 10,000 Å radiation hardened oxide used as a gate dielectric.

Fig 1a

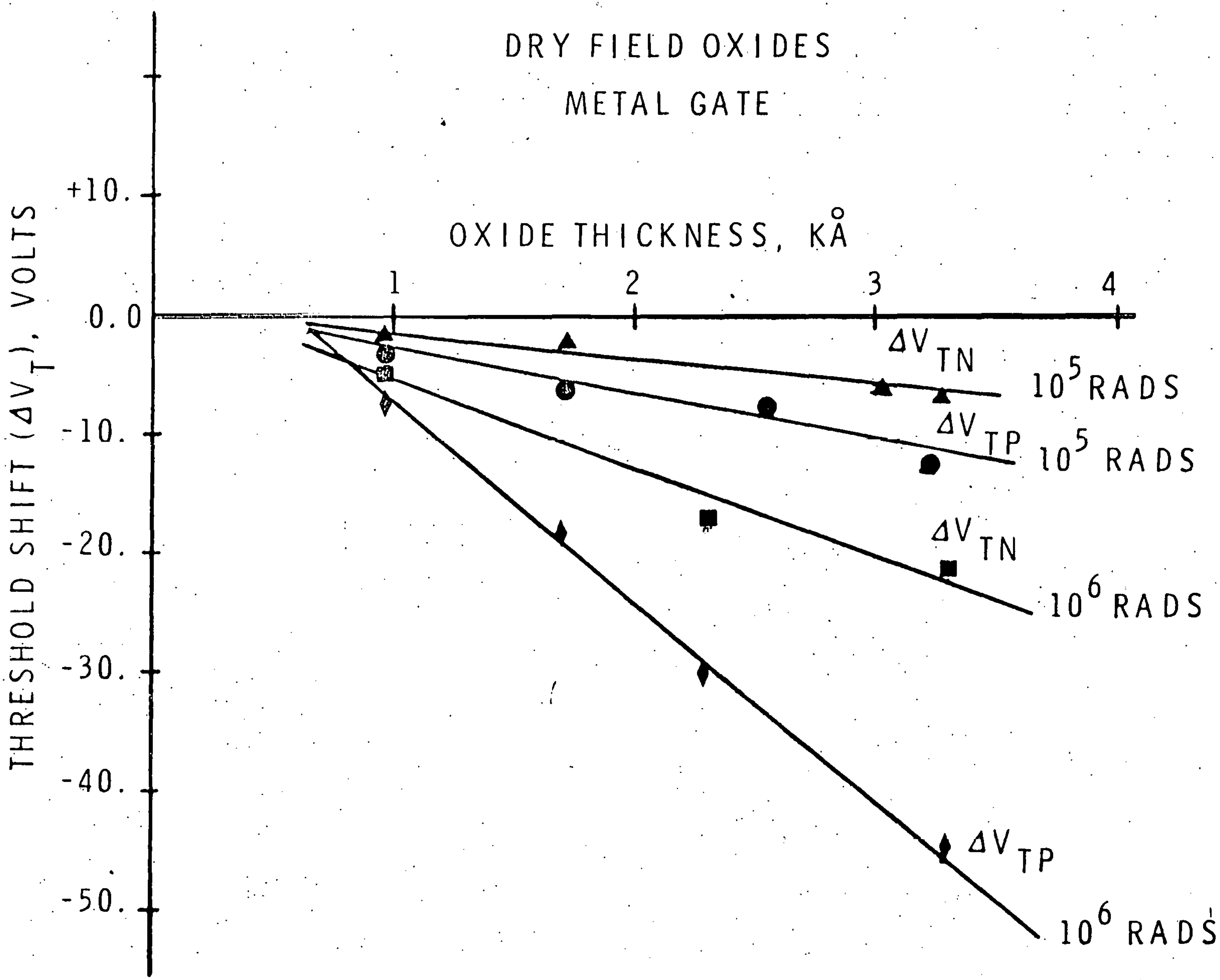

DRY FIELD OXIDES
METAL GATE
OXIDE THICKNESS, KÅ
1
2
3
4
+10.
0.0
-10.
-20.
-30.
-40.
-50.
THRESHOLD SHIFT (ΔV_T), VOLTS
ΔV_{TN} 10^5 RADS
ΔV_{TP} 10^5 RADS
ΔV_{TN} 10^6 RADS
ΔV_{TP} 10^6 RADS

Fig 1b

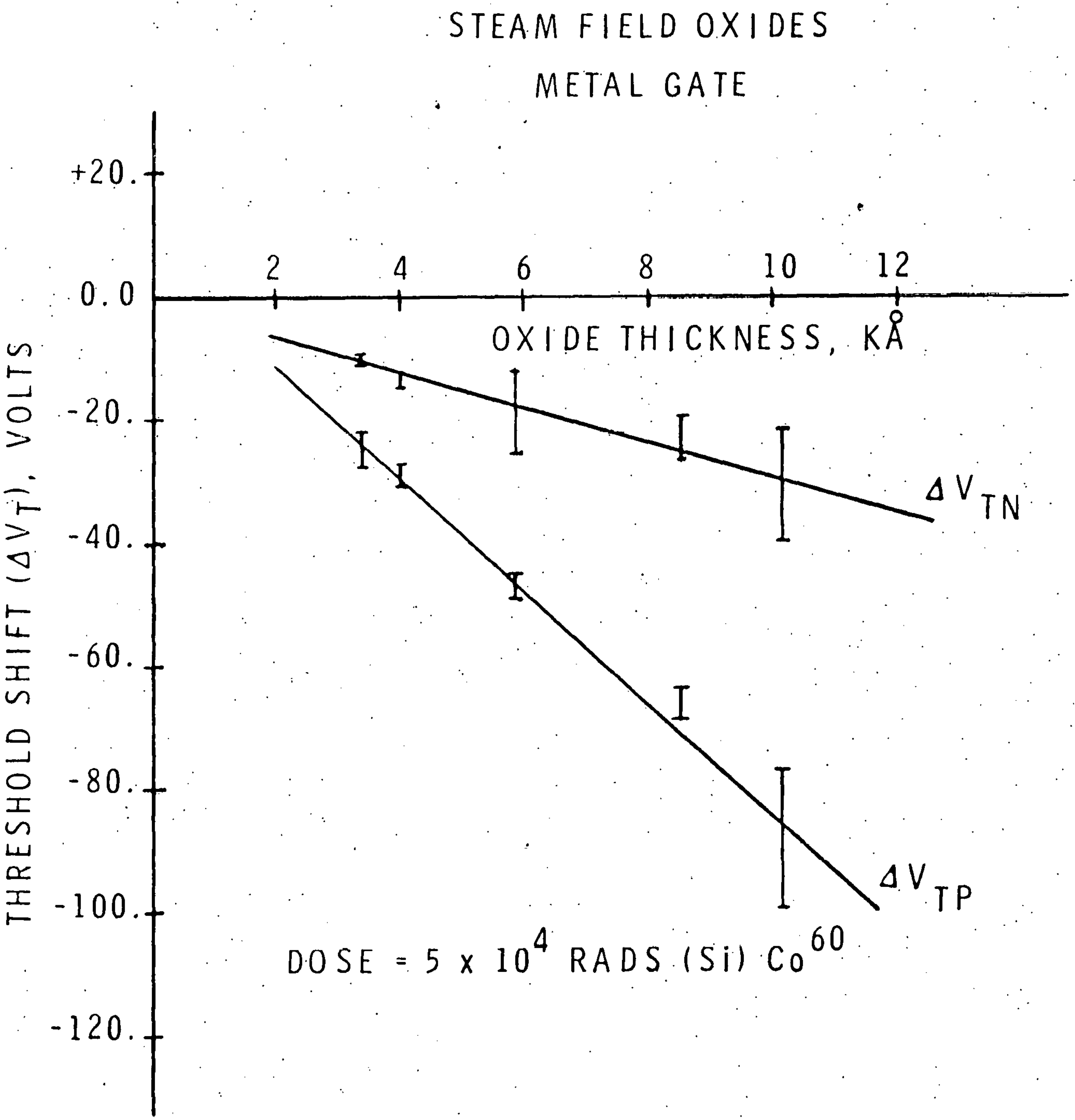
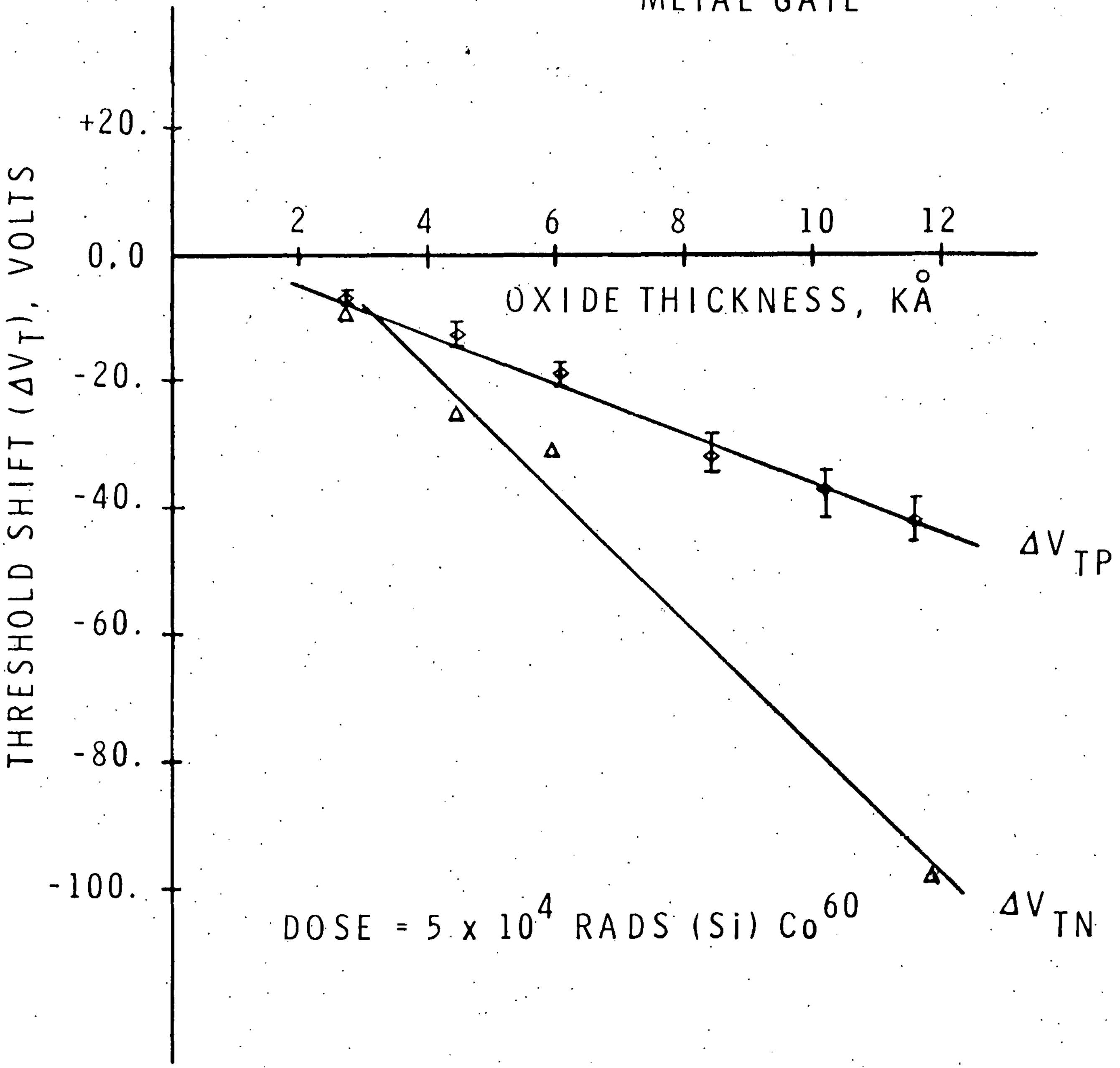

STEAM FIELD OXIDES
METAL GATE
+20.
0.0
-20.
-40.
-60.
-80.
-100.
-120.
2
4
6
8
10
12
OXIDE THICKNESS, KÅ
THRESHOLD SHIFT (ΔV_T), VOLTS
ΔV_{TN}
ΔV_{TP}
DOSE = 5×10^4 RADS (Si) Co^{60}

Fig. 1c

DEPOSITED FIELD OXIDES
METAL GATE



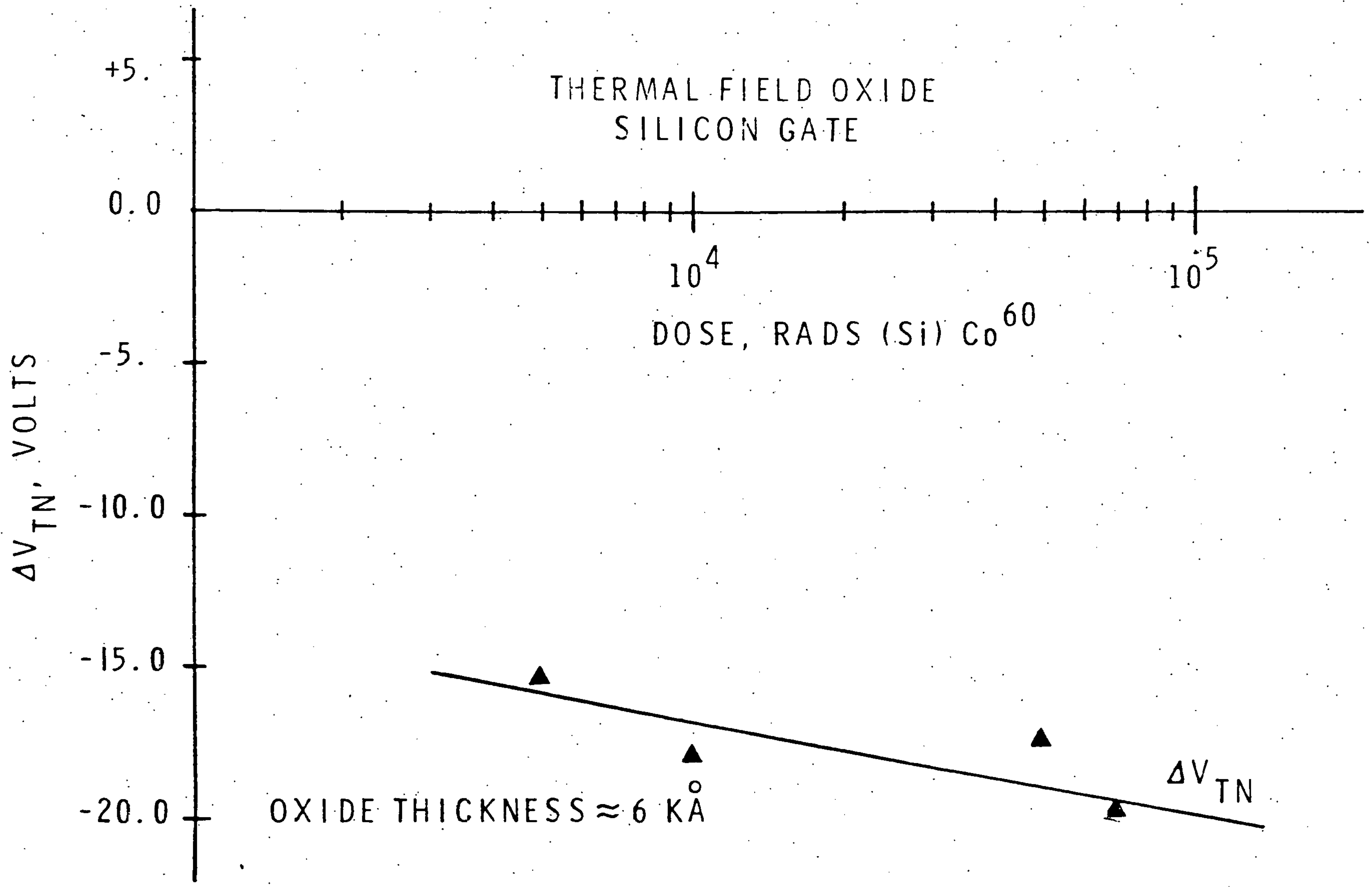

THERMAL FIELD OXIDE
SILICON GATE
+5.
0.0
-5.
-10.0
-15.0
-20.0
ΔV_{TN}, VOLTS
10^4
10^5
DOSE, RADS (Si) Co^{60}
OXIDE THICKNESS ≈ 6 KÅ
ΔV_{TN}

Fig. 2

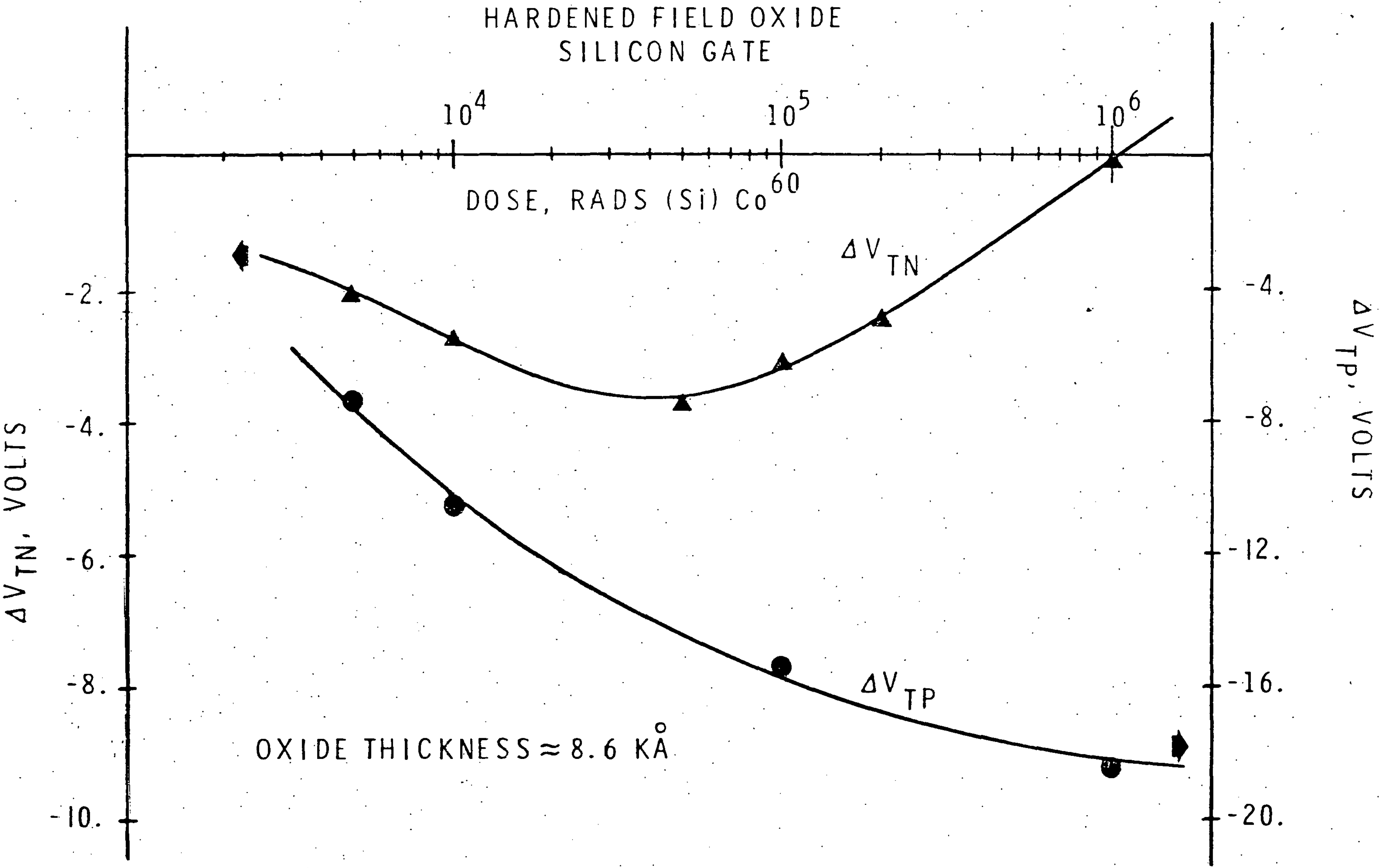
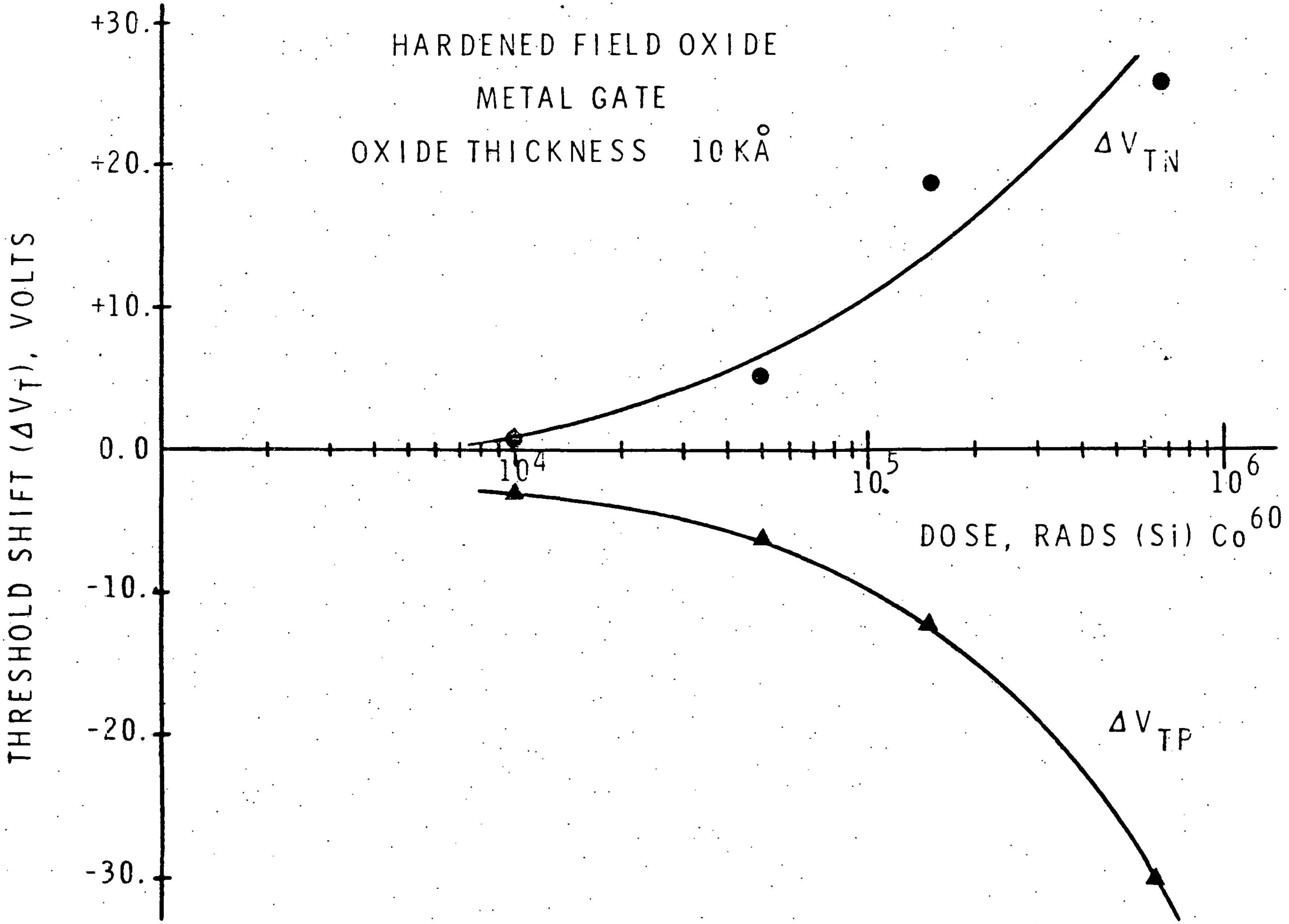

HARDENED FIELD OXIDE
SILICON GATE
10^4
10^5
10^6
DOSE, RADS (Si) Co^{60}
ΔV_{TN}
ΔV_{TP}
OXIDE THICKNESS ≈ 8.6 KÅ
-2.
-4.
-6.
-8.
-10.
ΔV_{TN}, VOLTS
-4.
-8.
-12.
-16.
-20.
ΔV_{TP}, VOLTS

Fig-3


HARDENED FIELD OXIDE
METAL GATE
OXIDE THICKNESS 10 KÅ
THRESHOLD SHIFT (ΔV_T), VOLTS
+30.
+20.
+10.
0.0
-10.
-20.
-30.
10^4
10^5
10^6
DOSE, RADS (Si) Co^{60}
ΔV_{TN}
ΔV_{TP}