Commun. Fac. Sci. Univ. Ank. Series A_2 A_3
V. 43. pp. 9-23 (1994)

OPERATION OF BIPOLAR AND FIELD EFFECT TRANSISTORS IN RADIATION ENVIRONMENTS

FOUAD A.S. SOLIMAN

Nuclear Materials Authority, Maadi P.O. Box 530, Cairo, Egypt.

(Received Nov. 12, 1992; Revised May 5, 1994; Accepted June 6, 1994)

ABSTRACT

An investigation of radiation damage in bipolar and field effect transistors is presented. For low frequency transistors, 90 % of the damage in forward current gain occurs at low γ doses around 100 K. rads. On the other hand, the effects on microwave transistors occur at higher-dose levels up to 100 x 10^6 rads. The damage effect has minimum that usually corresponds to the low (0.10 mA) and higher (300 mA) ends of the operating collector current range of a device. Also, the collector-base junction capacitance was shown to decrease with irradiation. Field effect traasistors exhibited high resistance against radiation exposure, and their electrical output characteristics were un sensitive to gamma doses up to 500 x 10^6 rads. Finally, annealing of radiation-damaged transistors were determined where shelf annealing, at room temperature, for a period of 90 days exhibits gaain recovery less than 20 %. Oven annealing at 200 °C was compared to annealing by power dissipation within the silicon waters.

INTRODUCTION

It has been found that the degradation of transistor parameters during irradiation is due to both the structural damage in the crystal latttice and to changes in the surface properties of the crystals (George, 1971). The main parameters of transistors are the gain and, in particular, the reverse collector current, are very sensitive to the surface state. A change in the recombination properties of the surface layer, particularly in the immediate vicinity of the emitter p-n junction, affects first the base current transport coefficient. The production of inversion layers and of surface channels in the vicinity of p-n junction leads to a considerable increases current accross the junction. Surface processes excited by ionizing radiation occur even at small radiation doses which, usually, are insufficient to produce appreciable bulk damage. The changes in the base current transport coefficient, associated with surface proceses, approach saturation but this does not apply to changes in the reverse collector current. It has been found that the surface effects are caused primarily by ionization phenomena in the oxide layers of crystals and in their immediate vicinity. This explains why such effects are so easily induced by high energy radiation as well as by low–energy radiation which cannot cause bulk damage.

Degradation Mechanism Analysis

The expression for reciprocal gain was (Soliman, 1990):

$$\frac{1}{h_{FEO}} = \frac{I_B}{I_c} = \frac{I_D + I_{RG} + I_S + I_{RB} - I_{CBO}}{I_c} \tag{1}$$

where :

I_C : collector current

h_{FEO} : forward current gain before irradiation

I_{RG} : recombination–generation current

I_{CBO} : junction leakgage current

I : surface leakage current

I_{RB} : recombination current in the junction

I_D : diffusion current

The effect of radiation can be written as:

$$\frac{1}{h_{FE}} = \frac{I_B}{I_C} = \frac{I_B(O)}{I_C} + \frac{\triangle I_B}{I_C} = \frac{1}{h_{FEO}} + \frac{\triangle I_B}{I_C}, \tag{2}$$

$$\frac{\triangle I_B}{I_C} = \frac{\triangle I_B}{I_C} + \frac{\triangle I_{BB}}{I_C} + \frac{\triangle I_B}{I_C} + \frac{\triangle I_{BB}}{I_C} - \frac{\triangle I_{CBB}}{I_C} \tag{3}$$

The effect of radiation on the emitter efficiency term (I_B / I_c) is given by the expression derived as:

$$I_D / I_C = D_p.W_b.n_p / 2.D_n.\ L_p.\ N_D \tag{4}$$

where :

D_p, D_n : diffusion constants for holes and electrons respectively

W_p : base width

n_p : density of electrons in p–side

L_p : hole diffusion length

N_D : donor impurity density

This term is small compared to other components contributing to the reciprocal gain for two reasons. First, it increases due to the decrease of the minority carrier lifetime in the emitter which causes a reduction in the diffusion length in the emitter. Second, since reduction in the lifetime is proportional to $\varnothing^{-1}$, the reduction in the diffusion length is proportional to $\varnothing^{-1/2}$ since $L^2 = D.\tau$ (τ is the lifetime of minority carriers).

The surface term I_S / I_C which is caused by radiation dominate the damage effect at small total exposure but is overcome by the displacement terms usually before $(1 / h_{FE})$ becomes greater than 0.005 at normal operating current ranges.

Although the percentage increase in the junction leakage can be large, due to displacement radiation, the leakage current components that I_{CBO} / I_C can be safely ignored. The elimination of three of the base current components reduces Equ. (3) to:

$$\frac{1}{h_{FE}} = \frac{1}{h_{FEO}} + \frac{\Delta I_{RG}}{I_c} + \frac{\Delta I_{RB}}{I_c} \tag{5}$$

The recombination–generation component dominates the base current after radiation exposure at low values of collector current. For a transistor in which the carriers are transported across the base region primarily by drift, the base transit time is proportional to the base width. In that case I_{RG} / I_c and I_{RB} / I_c are both proportional to the base transit time. The dependence of both reciombination terms on the base transit time explains in part why consistent results are obtained even at low current when the gain degradation is put in the form:

$$\Delta \frac{}{h_{FE}} = \frac{\Delta I_B}{I_C} \,.\, t_b .\, (\Delta K') = t_b .\, K'.\varnothing \tag{6}$$

where; K', composite damage constant that includes the effect of recombinations in the emitter–base junction as well as in the base region. Typical values for K' for various radiation types are shown (Soliman, 1990). The value of the raciprocal gain after irradiation is given by:

$$\frac{1}{h_{FE}} = \frac{1}{h_{FEO}} + t_b .\, K'.\varnothing \tag{7}$$

where; $\varnothing$ is the radiation fluence.

Junction Leakage

Junction leakage is assumed to result from the carriers generation rate in the depletion layer. This rate is increased by defects in the depletion region created by nuclear radiation displacement damage. The collector–base junction leakage is:

$$I_{CBO} = q\ [A_c \cdot X_c] \cdot [n_i \cdot R_i] \tag{8}$$

where :

A_c : collector area,

n_i : intrinsic carrier concentration,

X_c : width of deflection layer,

R_i : intrinsic recombination rate.

The effect of nuclear radiation will appear in the form of increase in the recombination rate, thus;

$$\begin{aligned} I_{CBO} &= q\ [A_c \cdot X_c] \cdot [n_i (R_i + \triangle R_i)] \\ &= q\ [A_c \cdot X_c] \cdot n_i R_i + K' \cdot \varnothing] \end{aligned} \tag{9}$$

Breakdown Voltage

The collector–base breakdown voltage (BV_{CBB}) is determined by the radius of curvature of the junction and the doping on the more lightly doped side of the junction. We should expect radiation displacement effects to increase the breakdown voltage since it reduces the effective impurity concentration. One can calculate V_{CEO} for a transistor from the following equation:

$$BV_{CEO} = BV_{CBO} / (h_{FE})^{1/m} \tag{10}$$

where a value of m = 5 was assumed, which gave a BV_{CEO} of 55 volts for a 10 mA gain of "50".

Experimental Procedures

Nine different types of bipolar silicon transistors namely: 2N4124 (npn), 2N4401 (npn), 2N5190 (npn), BF178 (npn), 2N4403 (pnp), 2N4126 (pnp), 2N3906 (pnp), 2N5193 (pnp), and 2N5194 (pnp), and two Field Effect Transistors of the type 2N4861 and 2N5115 were chosen for studyung the radiation effects on their characteristics.

During the course of the study the characteristics of each transistor were examined using a universal test fixture which is a plug–in device for use with "577–177–D1" storage Tektronix curve tracer systems.

The "577–177" combination, with the D1 display unit module, is a dynamic component tester which used in plotting the electrical (I–V) curves from which input–or output–characteristics and forward current gain factor can be calculated.

RESULTS AND DISCUSSION

Detailed study was performed on the various type transistors and their forward current gain factors (h_{FE}) were calculated before and after γ–exposure. Fig. 1 shows typical relationships between the h_{FE}, for the transistor types: 2N4403, 2N3 906, 2N4126, 2N4124 and 2N4401, and the absorbed γ–dose, where h_{FE} is shown to be seriously affected by γ–exposure. For all the transistor types, h_{FE} was decreased rapidly to a certain value, depending on the traasistor type, at absorbed dose around 150–200 krads. Longer γ–exposre periods, up to a total absorbed dose of 200.0 Mrads, illustrate almost no further decrease in h_{FE} values.

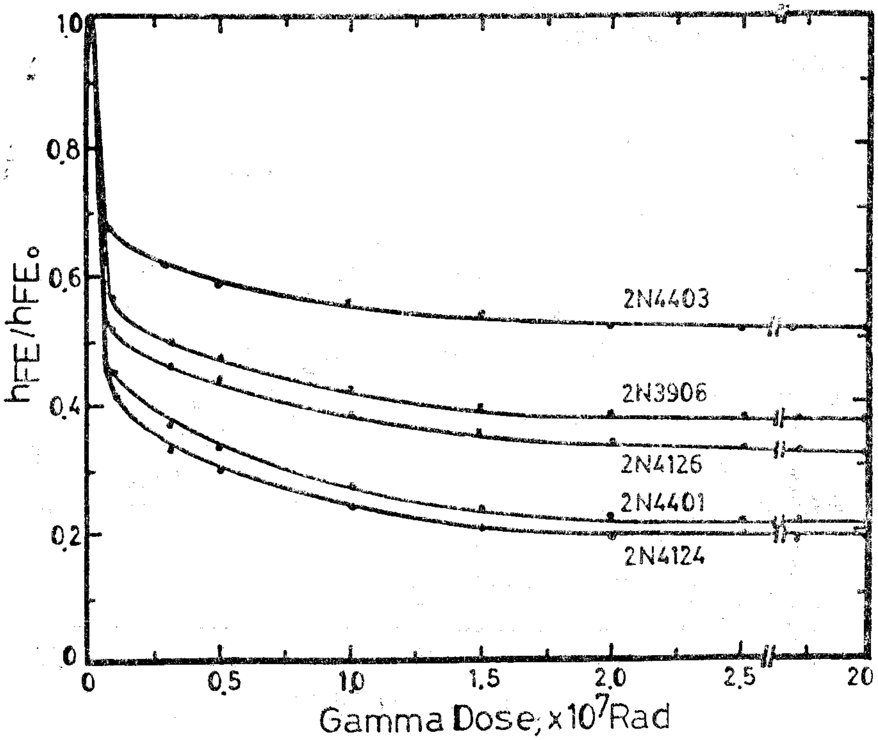

Fig. 1. Typical Relationship Between Forward Current Gain Factors and Gamma Dose for Different Transistors Type.

The radiation damage effects as a function of the operating current during measurements of the forward current gain changes is shown in Fig. 2 for three typical transistors irradiated together. It is clear that at operating collector current value less than 0.30 mA and values higher than 300 mA, the damage effect is low that usually corresponds to the low and high ends of the operating range of a device. Maximum damage effects appear to be at collector current value around 10.0 mA where the devices forward current gain factors were shown to be with values of 120, 95 and 20 although their initial values are 240, 124 and 35 respecitvely.

(C–V) *Characteristics*

Figure 3 shows that the (C–V) curves of the collector–base junction changes with irradiation fluence. At zero bias, 71 % drop in capacitance

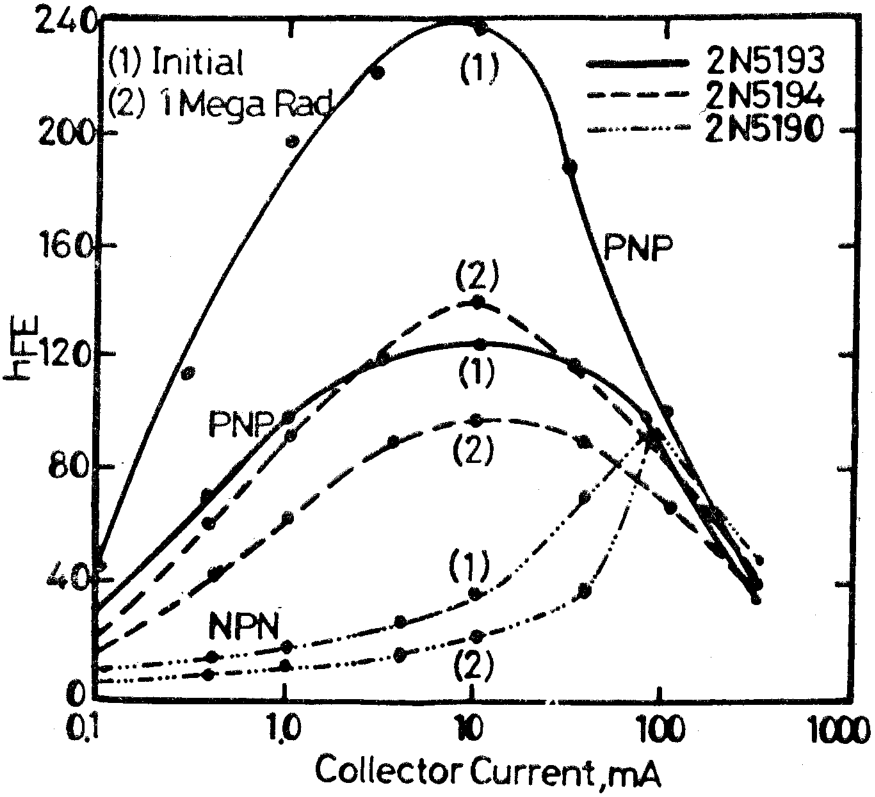

Fig. 2. Forward Current Gain Factor, for Different Transistors Type, as a Function of Collector Current and γ–Dose.

after 8.0 x 10^{15} n / cm^2 occurs. This drop in capacitance is attributed to a widening of the zero–bias depletion width due to carrier removal effects (Rageh, 1988). At large values of reverse bias, capacitance decreases only slightly with irradiation (6–8 %). This is due to the fact that the collector depletion region has "punched–through" to the n–substrate at this bias, and much larger radiation fluence are required to produce significant carrier removal effects in $n^{\pm}$–layer. (C–V) capacitance measurements provided an excellent means of monitoring the formation of channels on transistors. The magnitude of the capacitance measurements, however, was not indicative of the magnitude of I_{CEO} increases or gain damage.

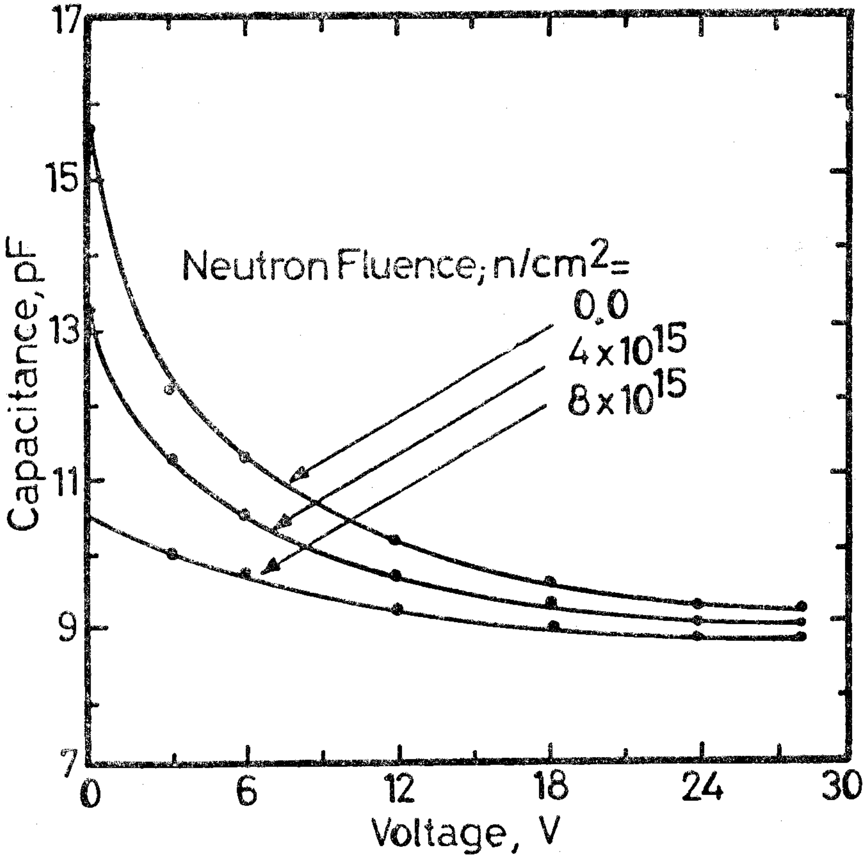

Fig. 3. Capacitance–Voltage Characteristics of the Collector Base Junction of Irradiated Silicon Transistors.

Microwave Transistors

Microwave transistors are essentially scaled-down (size-wise) version of low-frequency transistor. Radiation damage to low-frequency bipolar transistors has been shown to be as a decrease in current gain factor due to radiation induced recombination in the base region (Rageh, 1988). For microwave transistors, the base width is sufficiently narrow so that this effect can be neglected at low irradiation dose (Graham, 1971). Changes in the low frequency parameters, current gain of microwave transistors (White, 1970) occurs at higher γ doses (Fif. 4) due to excessive recombination in emitter-base space region and emitter bulk region.

Reverse Diode Characteristics

I_{CO} and I_{EO} are the leakage currents within the safe operating region of reverse voltage and are intended to yield comparative, evaluate information as to permissible operation, surface condition and tempera-

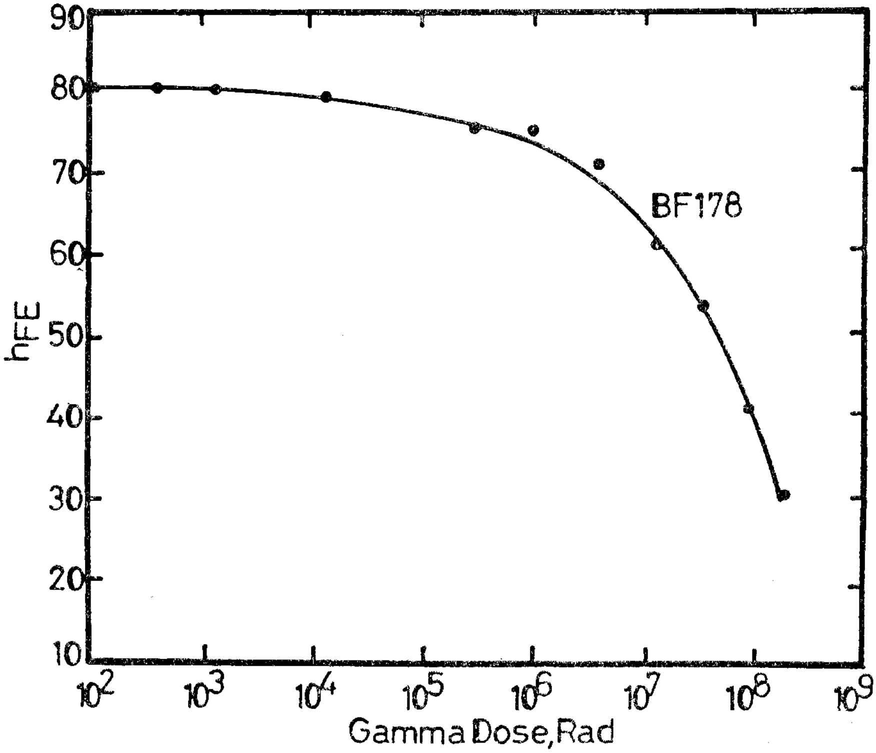

Fig. 4. Low-Frequency Current Gain Versus Gamma Dose for Microwave Transistors.

ture effects on operation. The breakdown voltage tests are indicative of the maximum voltage that can be applied to the device and serve to indicate the voltage at which "avalanche–breakdown" and "thermal–runaway" take place (Soliman, 1989).

Investigation of gamma radiation effects on the different leakage currents are shown in Fig's. 5 and 6. The collector-emitter leakage current. for two different transistor types, with base terminal left either open (I_{CEO}) or shorted to the emitter (I_{CEO}) were plotted under the influence of two different γ–doses of 1.0 and 5.50 M. rads, as a function of V_{CE}. On the other hand, the collector–emitter leakage current and collector–emitter breakdown voltage are measured under the influence of γ–dose of values 1.0 M. Rads and 5.0 M. Rads.

Field Effect Transistos

A Filed Effect Transistor (FET) consists, basically, of a semi–conducting current channel, the resistance of which is controlled by an electric field applied perpendicular to the direction of current flow. It is basically a voltage–controlled resistor which its value can be varied by changing the width of the depletion layer extending into the channel (Janousek, 1988). The FET is unipolar and the current flow depends only on the majority carriers. There is no significant role for the minority carriers, this is why the FET is less affected by temperature and radiation than the bipolar transistors.

In FET's the dominant effect of trapped oxide charges is to produce semi–permanent shifts in the V_{GS}–I_{DS} characteristics for the device, by altering the device threshold voltage. Past studies in the "Si–SiO_2" system have shown that the polarity of the trapped–oxide charge is positive (trapped holes) and that its location in the "SiO_2" varies with the applied gate bias during irradiation. Several models have been proposed to explain the charge build–up observed in the oxide after exposure to ionizing radiation. Basically, the models fall into two categories (Janousek, 1988); intrinsic models based on bonding defects in pure SiO_2 and extrinsic models based on motion and trapping by impurities. As a result, three damage mechanisms have been identified; (1) an increase in the net surface state density, (2) a decrease in substrate resisitivity, and (3) a decrease in carrier mobility in the channel. The surface effect is usually dominant, although the bulk resistivity effect becomes increasingly important as the resistivity of the substrate is decreased.

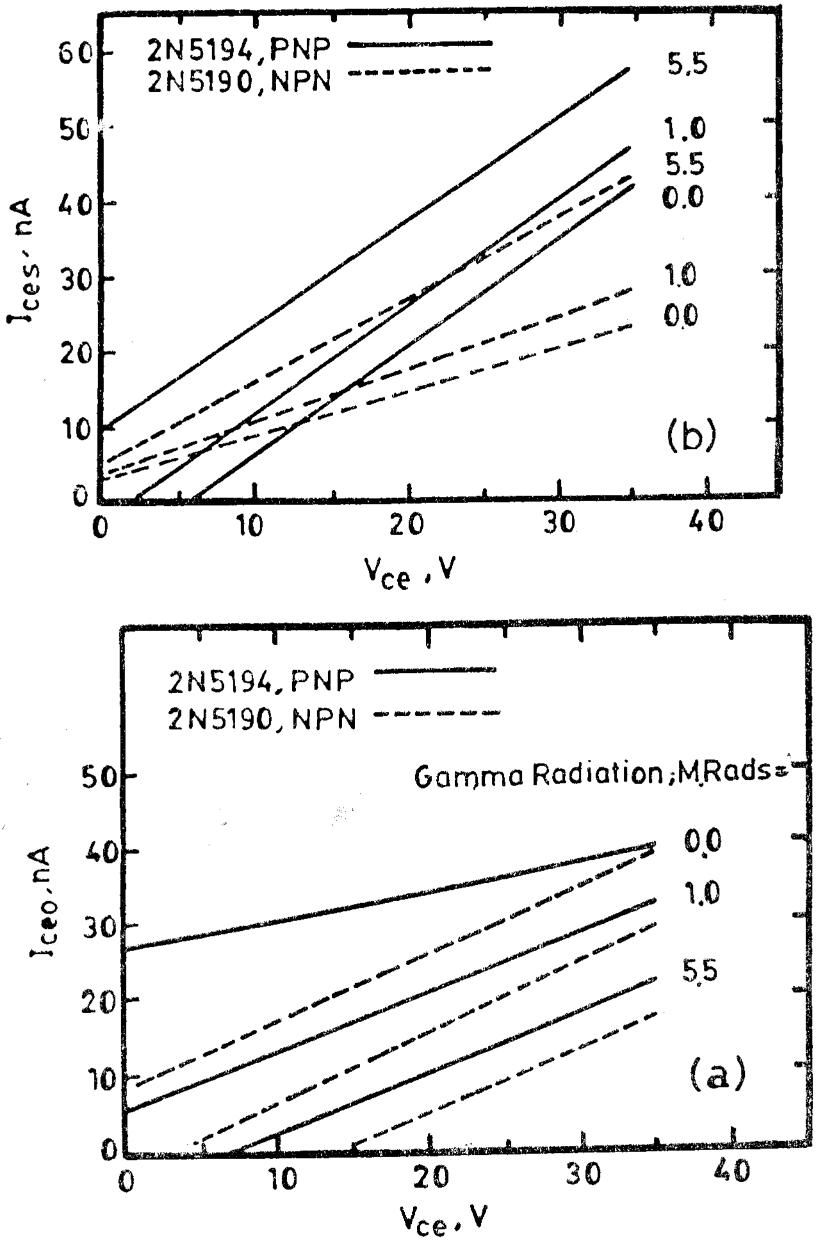

Fig. 5. Gamma Radiation Effects on Collector Emitter Leakage Current with (a) Base Open and (b) Base Shorted to Emitter.

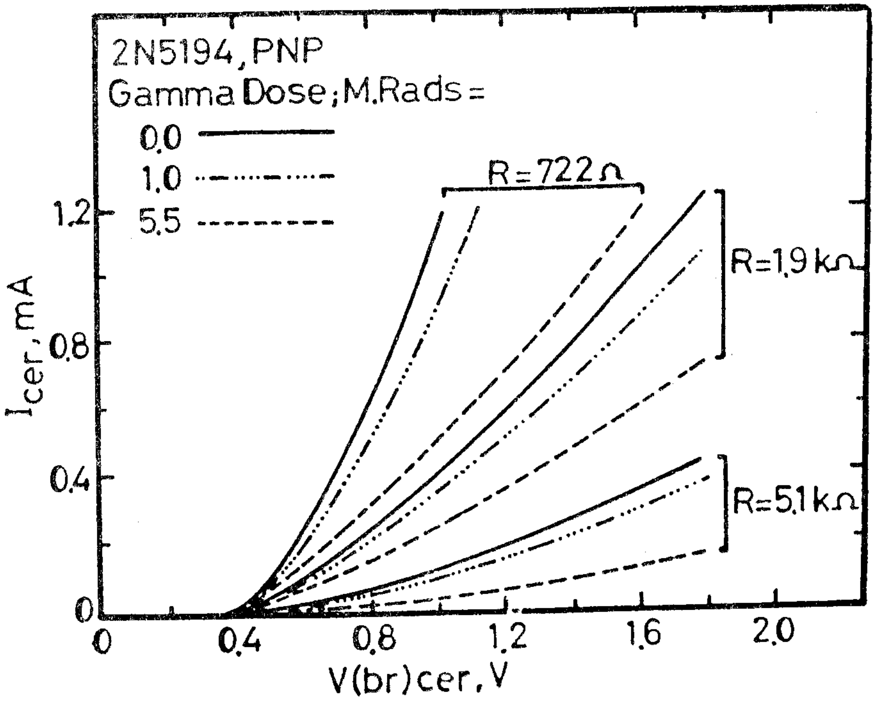

Fig. 6. Gamma Radiation Effects on Collector–Emitter Leakage Current and Collector–Emitter Break-down Voltage. (R: Rbe).

The effect of γ–rays on Si FET has been investigated. The device (I_B–V_{DS}) curves, transconductance and punch–through voltage were measured before and following γ exposure with doses up to 450 x 10^6. The variations in static transconductance, punch–through voltage and I_{DSS} of the proposed samples were plotted, (Fig. 7–Fig. 10) as a function of γ–dose. For the two transistor types, transconductance was decreased from 65.0 $(\Omega\text{–cm})^{-1}$ down to 55.0 $(\Omega.\text{cm})^{-1}$ for transistor type 2N4861 and from 56.0 $(\Omega\text{–cm})^{-1}$ down to 46.0 $(\Omega\text{–cm})^{-1}$ for transistor type 2N5115, at absorbed dose value about 450 x 10^6 rads. The punchthrough voltage is found to be almost unsensitive to γ–exposure for the transistor type 2N4861. In the case of the transistor type 2N5115, the punch through voltage decays slightly with gamma–dose. The change in the voltage is found to be less than 10 %.

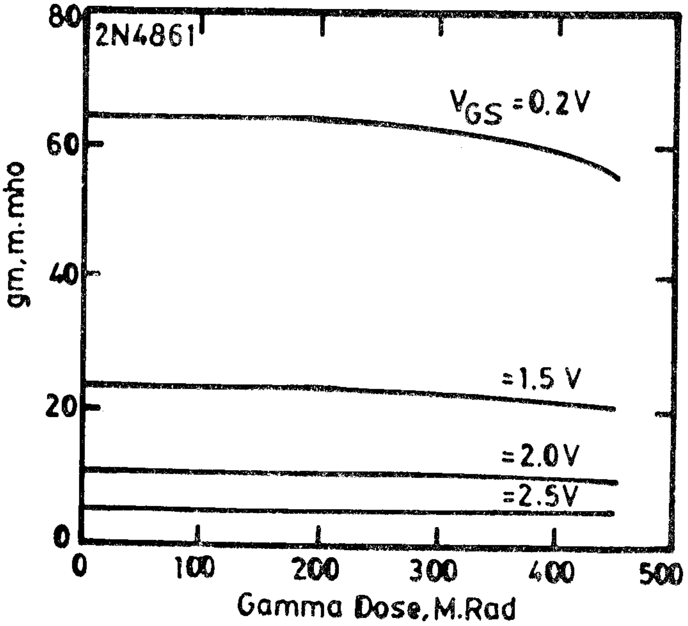

Fig. 7. Gamma Radiation Effects on the Static Transconductance of Silicon F E T's.

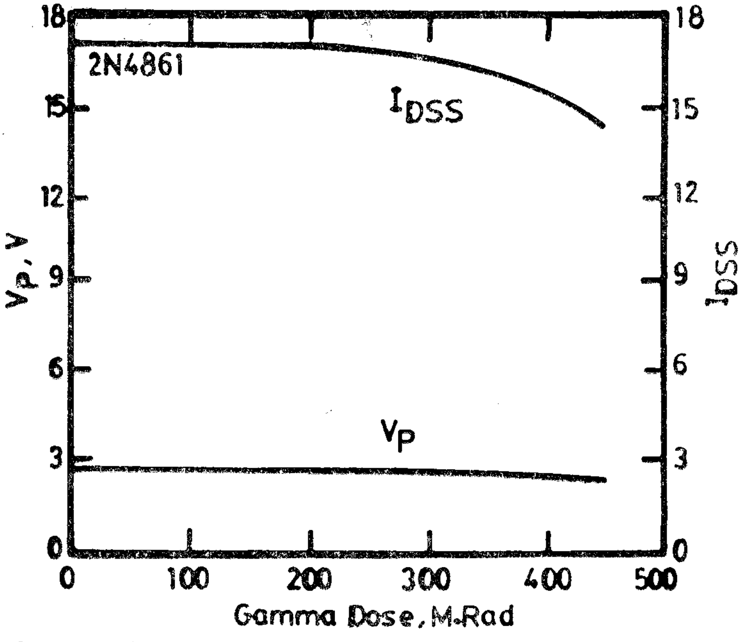

Fig. 8. Gamma Radiation Effects on the Punch–Through Voltage and Drain–Source Current of silicon FET's.

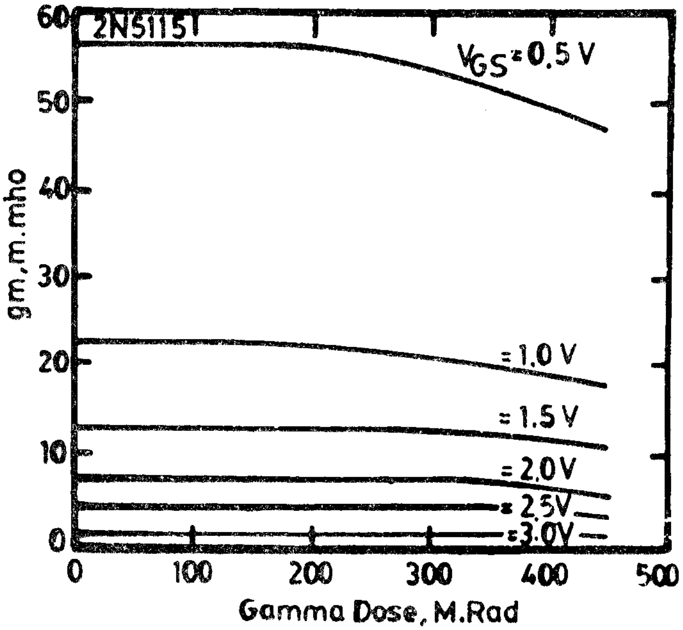

Fig. 9. Gamma Radiation Effects on the Static Transconductance of Silicon FET's.

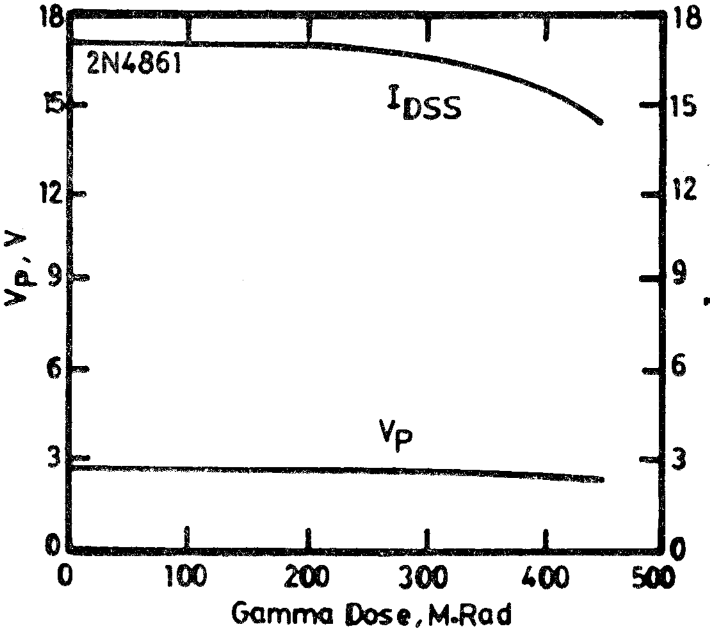

Fig. 10. Gamma Radiation Effects an the Punch–Through and Drain Source current.

Annealing of Radiation Damage

Effect of annealing on the h_{FE} of the γ–irradiated transistors are studied. Recovery in the value of h_{FE} at room temperature was small. After 90 days, less than 20 % of the original loss in gain was recovered for Co–60 damaged devices.

Oven annealing at 250 °C was compared to annealing by power dissipation within the silicon wafers. Transistors were placed in a circuit which maintained constant emitter current for fixed periods of time. The results are shown in Fig. 11. which shows the plot of recovery in h_{FE} versus constant emitter current flowing for 36–hour period. The steady–state temperature, in °C, of the outside of the can at a given emitter current is indicated at the top of the figure. The recovery in h_{FE} for oven temperature of 200 °C for 6 hours is shown. The recovery is defined as (Soliman, 1990):

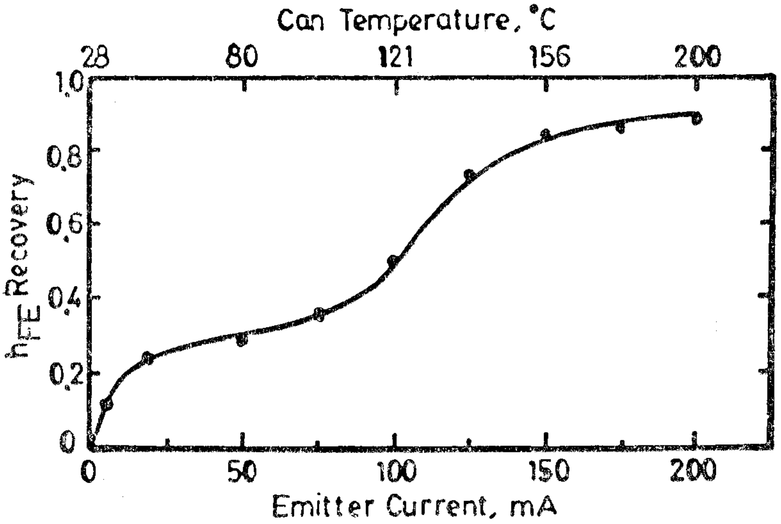

Fig. 11. Recovery in h_{FE} Versus Constant Emitter Current for a 36–Hour Period.

$$R = \frac{h_{FE2} - h_{FE1}}{h_{FE0} - h_{FE1}} \tag{11}$$

where :

h_{FE0} : the gain before irradiation

h_{FE1} : the gain after irradiation

h_{FE2} : the gain after annealing

Thermocouples were used to monitor the can temperature.

CONCLUSIONS

The effects of γ and neutron–radiation on the characteristics of different bipolar and Field Effect Transistors are investigated. From experimental results it is determined that the major radiation effects on bipolar transistors are the pronounced decrease in the forward current gain factor. The damage effect, as a function of the operating current, is low that usually corresponds to the low and high ends of the operating range of a device. Collector–base junction capacitance of the device is found to decrease slightly with irradiation. For microwave transistors, the base width is sufficiently narrow, so that less radiation effects in the low frequency parametrs occurs.

REFERENCES

GEORGE, W.L. and CLARK, L.E., "Experimental Determination of Gain Degradation Mechanisms", IEEE Trans. Nuc. Sci., NS-18, No. 6, Dec. 1971, pp. 387–395.

GRAHAM, E.D., CHAFFIN, R.J. and GWY, C.W., "Radiation Effects on Microwawe Bipolor Transistors", IEEE Trans. Nuc. Sci., NS-19, No. 8, Dec. 1972, pp. 335–342.

JANOUSEK, B.K., YAMADA, M.E., and BLOSS, W.L., "Neutron Radiation Effects in GaAs Junction Field Effect Transistors", IEEE Trans. Nuc. Sci., NS-35, No. 6, Dec. 1988, 0pp. 1480–1486.

JANOUSEK, B.K., YAMADA, M.E. and BLOSS, W.L., "Neutron Radiation Effects in GaAs Ion-Implanted Field Effect Transistors", Jour. Appl. Phys., Vol. 63, 1988, pp. 1668–1685.

RAGEH, M.S.I., ASHRY, H.A., EL-BEHAY, A.Z. and SOLIMAN, F.A.S., "Neutron Irradiation Effects on Some Semiconductor Devices Performance"; Isotopenpraxis, 24 (1988) g, pp. 345–348.

SOLIMAN, F.A.S., "Theoretical Analysis of Radiation Effects on Silicon Power Diode Characteristics"; Isotopenpraxis, 24 (1989) g, pp. 349–355.

SOLIMAN, F.A.S., "Some Analyses of Radiation Effects on PNP Silicon Devices", Isopotopenpraxis 26 (1990) 5, pp. 225–229.

WHITE, M.H., and THURSTON, M.O., "Characterization of Microwave Transistors", Solid State Electronics, Vol. 13, No. 2, 1970, pp. 523–529.