01 Jan 1970

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ELECTRIC FIELD STRENGTH DEPENDENCE OF SURFACE DAMAGE IN OXIDE PASSIVATED SILICON PLANAR TRANSISTORS*

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ABSTRACT

A dependence of surface degradation induced by ionizing radiation in matched oxide-passivated silicon planar epitaxial transistors on junction fringing electric field strength present during exposure is reported. The electric field strength and gamma dose dependence are investigated of the decrease in the forward current gain, h_{FE} (as reflected by the increase in the surface recombination current component), the increase in the surface recombination velocity (as reflected by the increase in the reciprocal of the minority carrier lifetime), and the increase in junction capacitance. Empirical prediction equations have been derived, for matched devices, correlating the normalized base current increase and the normalized surface recombination velocity increase with the average junction electric field strength present during irradiation and the total gamma dose. The ionizing radiation induced surface recombination and surface channel components are analyzed from a study of the reciprocal slope term, "n", obtained from forward and inverse configuration current-voltage data.

INTRODUCTION

Experimental and theoretical investigations have established that the response of silicon planar transistors to ionizing radiation varies with the initial conditions[1-3] at the Si-SiO_2 interface and the junction bias[4-6] applied during irradiation. Several mechanisms for surface degradation at the Si-SiO_2 interface have been postulated.[5,7] The degradation in silicon surface properties is manifested by the enhancement, depletion, or inversion of silicon surfaces caused by the accumulation of space-charge in the SiO_2 layer above the Si surface resulting in changes in the surface potential of the semiconductor.[8-11] In addition, the accumulation of fast surface states alters the surface recombination velocity in the p-n junction region.[7,12,13]

The two base current components induced by ionizing radiation, which can dominate h_{FE} at low currents, are the surface space-charge region recombination current, I_{SRG}, and the surface channel current, I_{CH}.[5,14] I_{SRG} results from recombination in the emitter-base space-charge region of injected carriers from the base and emitter. This process takes place in the space-charge region at the Si-SiO_2 interface where a high concentration of recombination centers exists. The resultant current component varies with emitter-base forward bias voltage as $\exp(qV_{BE}/nkT)$ where $(1.5 < n < 2)$.[14] Surface channel formation takes place when the oxide space charge above the silicon is of sufficient magnitude to cause inversion of the silicon under the Si-SiO_2 interface. When the p-type base of an n-p-n transistor is inverted near the p-n junction, a channel is formed that appears as an extension of the n-side of the junction over the surface of the p-side. This increase in junction area results in the increase in junction capacitance. The surface channel component of current, I_{CH}, also varies with forward voltage as $\exp(qV_{BE}/nkT)$. For I_{CH}, however, the exponential slope constant, n, generally ranges from 2 to 4.

Although previous investigators[1-8] observed surface degradation to follow a general trend, they were unable to obtain definite relations for predicting the changes in the parameters affected by surface damage. In this work certain normalization procedures are developed for device parameters which are then used to obtain a prediction technique for surface damage. This paper examines in detail the effects of the fringing junction electric field strength (parallel to the surface) at the emitter-base and collector-base junction on surface degradation, and the feasibility of correlating the change in transistor parameters (surface base current component, minority carrier liftime, and junction capacitance) to the strength of the fringing electric field at the junction and to the total gamma dose for matched devices.

EXPERIMENTAL PROCEDURE

In this study, groups of matched devices with varying biases (both forward and reverse) applied to the emitter-base and collector-base junctions were exposed to ionizing radiation to examine the electric field strength dependence of surface damage. The devices were fabricated by Texas Instruments from the same wafer and in the same diffusion run. Devices from the same batch were screened in order to "match" them. These "matched" devices were selected such that the initial I-V, C-V, and lifetime characteristics were within $\pm 5\%$ of each other. The University of Missouri - Columbia Co-60 source (5000 Curie strength) was used to irradiate the devices, which were enclosed in an aluminum chamber. The devices were irradiated in seven steps up to a total dose of 3.70×10^6 rads (Si) with transistor parameter measurements made after each step.

Current-voltage characteristics for the test devices before and after irradiation were measured and recorded by an Automatic Data Acquisition System,[15] with an overall absolute accuracy of $\pm 1\%$ of reading and a precision of $\pm 0.3\%$ of reading in the range from 10^{-10} amperes to 2×10^{-1} amperes (over 9 decades). The junction capacitance measurements were made on a Micro-Instruments Digital Capacitance Tester[16] and were corrected for socket and header capacitances. The measurement frequency is 1 MHz. Minority carrier lifetime measurements were obtained using a Tektronix Type 555 oscilloscope with a Type S recovery time plug-in unit.[17] During all measurements, the devices were kept at room temperature (27°C ±0.1°C) in a Delta Design MK2310 Temperature Control Chamber.

*This work supported by the Atomic Energy Commission under contract AT(11-1)-1624.

[+]This paper represents work done in partial fulfillment of the requirements for an advanced degree at the University of Missouri - Rolla.

[x]Contribution number 100 of the Graduate Center for Materials Research.

FIELD STRENGTH DEPENDENCE OF SURFACE LEAKAGE CURRENTS

One group of matched devices had their emitter-base junctions biased differently during exposure to produced different average electric field strengths at the junction (parallel to the surface). The average electric field strength was calculated by dividing the total voltage at the junction (built-in potential, V_T, and applied voltage, V_a) by the width of the space-charge region during irradiation. An applied bias of 3.0 volts reverse corresponded to a field strength of 1.26×10^5 V/cm. With zero volts bias the field strength was calculated to be 4.61×10^4 V/cm, and a 0.5 volts forward bias corresponded to a field strength of 2.7×10^4 V/cm. It should be noted that in MOS devices the electric field is normal to the Si-SiO_2 interface and can be made zero or negative, but this is not possible in bipolar devices where the field is parallel to the interface (the electric field extends from the n-type to the p-type side of the junction).

For comparison of devices with different initial interface state densities, it was found necessary to normalize the observed increase in the surface current component by dividing by the pre-irradiation base current, I_{BO}. Table I and Table II list the normalized increases in base current (forward measurement configuration) for gamma dose levels from 1.12×10^5 to 1.85×10^6 rads (Si) for the various biases applied at the emitter-base (Table I) and collector-base junctions (Table II) during irradiation. Figure 1 is a plot of the normalized increase in base current, ΔI_B, as a function of total gamma dose, γ, with average junction electric field strength present during exposure as a parameter. The curves A, B, and C (data from Table I) for which only the emitter-base junction was biased during exposure can be described by an equation of the form,

$$\frac{\Delta I_B (V_{BE}, E_r, \gamma)}{I_{BO}(V_{BE})} = K_s (E_r) \cdot \{1 - \exp[-\alpha(E_r)\cdot\gamma]\}, \tag{1}$$

where the damage saturation parameter, K_s, and the surface damage introduction rate parameter, α, are explicitly functions of the average junction electric field strength during irradiation, E_r. The rate of surface damage introduction and the damage saturation parameter (saturation occurs at approximately 10^6 rads (Si)) are both observed to be increasing functions of the average junction electric field strength present during exposure. The dependence of α and K_s on the average electric field strength is given by the expressions,

$$K_s (E_r) = K_{so} \cdot E_r^n = 0.19 \cdot E_r^{0.42}, \tag{2}$$

and

$$\alpha (E_r) = [1+E_r/E_o]/\gamma_o = [1+E_r/9.0\text{x}10^4]/6.0\text{x}10^5. \tag{3}$$

The solid lines (A, B, C) in Figure 1 are plots of Equation (1), and good agreement with the experimental data is noted.

Curves D and E in Figure 1 (data from Table II) are typical plots of the normalized increase in the base current versus gamma dose for similar devices with only the collector-base junction biased during exposure to 3.0 volts reverse (Curve D) and 0.5 volts forward (Curve E). It is interesting to note that biasing the collector-base junction during exposure affects the emitter-base junction. The saturation value of the surface leakage current for the unbiased emitter-base junction is greater for a reverse bias on the collector-base junction (Curve D) than for both junctions unbiased (Curve B). It is important to note that a fringing electric field exists for the unbiased junction as a result of the built-in potential, V_T. The saturation value of the emitter-base surface leakage current for forward biased collector-base junction (Curve E) is less than for both junctions unbiased (Curve B). This can be explained on the basis that a bias on the collector-base junction has the effect of biasing the emitter-base junction to maintain zero current at the open emitter contact.

MINORITY CARRIER LIFETIME MEASUREMENTS

The gamma induced interface states at the intersection of the space-charge region with the SiO_2 passivating layer act as recombination centers for minority carriers thus increasing the surface recombination velocity.[7,12,13] The effect of the junction electric field strength on the degradation of the minority carrier lifetime was investigated by plotting $(1/\tau_B - 1/\tau_o)$ versus the total gamma dose in Figure 2 where τ_o and τ_B are the pre-irradiation and post-irradiation minority carrier lifetimes, respectively. The form of the curves can be written as:

$$(1/\tau_B - 1/\tau_o) = K_\tau(E_r) \cdot \{1-\exp[-\alpha_\tau(E_r)\cdot\gamma]\}. \tag{4}$$

The lifetime saturation parameter, K_τ, can be expressed as

$$K_\tau(E_r) = K_{\tau o} \cdot E_r^m = 95.5 \cdot E_r^{0.68}, \tag{5}$$

and the lifetime damage introduction rate is given by

$$\alpha_\tau(E_r) = [1+E_r/E_{\tau o}]/\gamma_{\tau o} = [1+E_r/9.5\text{x}10^5]/1.5\text{x}10^5. \tag{6}$$

The similarity of the forms of Equations (1) and (4) indicates that the degradation of the surface minority carrier lifetime follows a trend similar to the normalized base current increase. This is to be expected since the increase in surface leakage current is directly related to the increase in the reciprocal of the minority carrier lifetime.

It should be emphasized that E_r is the average fringing electric field strength at the junction during exposure and is parallel to the Si-SiO_2 interface. For the matched devices used in these investigations, the die is bonded to the header and hence the collector lead is in contact with the encapsulating metal can which is N_2 filled. An electric field exists between the can and the base and emitter regions of the device die in a direction normal to the Si-SiO_2 interface as a result of the potential difference between the can and the die and is in a direction to attract ions to the surface. Calculations indicate that this normal electric field is too weak to effect the buildup of surface states. In order to show experimentally that the effect of the potential between the metal can and die had a negligible effect on the transistor parameters studied, a set of experiments were conducted with devices whose leads were insulated from the encapsulating can. Biases ranging from 0 to 30 volts were applied between the metal can and Si die during exposure and devices were irradiated to a gamma dose of 1×10^6 rads (Si). The normalized base current increase $(\Delta I_B/I_{BO})$ was computed for the devices (measured for both the emitter-base and the collector-base junction) and the results showed negligible difference in the surface damage at the emitter-base junction (as indicated by the emitter-base junction current data) and collector-base junction (as indicated by the collector-base junction current data) for devices with various biases applied between can and die. No measureable difference in degradation was

observed between devices which had a can to die bias of zero volts and 30 volts. These results clearly indicate that the buildup of interface states in passivated bipolar transistors is strongly dependent on the electric field parallel to the Si-SiO_2 interface, while the effect of the electric field normal to the Si-SiO_2 interface (and the N_2 environment)[4] is negligible. This situation is opposite to that found for MOSFET's and can be explained on the basis that the magnitude of the perpendicular electric field strength is very much less for the case of the bipolar device than that for the case of the MOSFET.

Interestingly, the curves in Figures 1 and 2 for bipolar transistors are similar to the curves obtained by Mitchell[10] (his Figures 8 and 9) for MOSFET devices. Both the increase in the I_{SRG} current component (Figure 1) and surface recombination velocity (Figure 2) are caused by an increase in the density of electron states located within the silicon forbidden gap at the SiO_2 interface. The voltage shift, ΔV, observed by Mitchell[10] (his Figures 8 and 9) is caused by charge buildup in the SiO_2 and is an increasing function of both positive and negative gate biases applied during irradiation. It can be noted from the similarity of the two sets of curves that the buildup of interface states and fixed charge follow a similar trend with electric field/bias and dose, although no immediate correlation between the two can be obtained. This is expected because of the differences between interface states and fixed charge states. Moreover, a constant gate bias on an MOS device does not correspond to a constant electric field strength because of the densification[9] of the silicon-dioxide caused by the modification in structure of the SiO_2.

SURFACE CURRENT COMPONENTS

Degradation of transistor current gain caused by ionizing radiation is attributed to two base current components, the surface recombination base current component, I_{SRG}, and the surface channel base current component, I_{CH}, which can be identified by the reciprocal slope term, n, in the expression $I_B(\gamma)=C\cdot \exp(qV_{BE}/nkT)$, where $n \leq 2$ for I_{SRG} and $n > 2$ for I_{CH}.[5,12] This method, however, does not quantitatively identify the two components but instead determines which of the two currents is dominant. The dominance of I_{SRG} or I_{CH} causing h_{FE} degradation varies with the total accumulated dose, the magnitude and polarity of bias during irradiation and dopant concentrations at the Si-SiO_2 interface.

Figure 3 is a plot of the current-voltage characteristics of test device #21 (EB reverse biased to 3.0 volts during irradiation) with gamma dose as a parameter to saturation. The reciprocal slope term "n" is seen to increase from 1.4 before irradiation to 2.25 at a saturation dose level of 10^6 rads (Si). Interestingly, "n" is constant at low and moderate current levels. At higher current levels "n" is observed to decrease slightly as would be expected from the increased recombination in the bulk base region at higher current levels. To study the surface degradation at the collector-base junction, current-voltage characteristics were taken with the device operating in the inverse configuration. When operating a transistor in the inverse configuration (i.e., with the emitter functioning as a collector and the collector functioning as an emitter) it is possible to study the surface damage at the collector-base junction, as reflected by the increase in the surface channel base current component, I_{CH}. Figure 4 is a plot of the I-V characteristics of device #23 (CB reverse biased to 3.0 volts during irradiation) with gamma dose as a parameter. The "n" term increases very rapidly from 1.23 before irradiation to 7.4 at saturation doses. Note that "n" is observed to decrease at higher measurement currents although it still maintains a value greater than 2, indicating that although the I_{CH} current component is dominant, the contribution of the surface recombination current and the bulk base region recombination current cannot be neglected.

JUNCTION CAPACITANCE AND SURFACE CHANNEL FORMATION

Emitter-base and collector-base junction capacitance measurements were made on the same group of devices at various dose levels to study surface channel formation. The normalized junction capacitances at zero bias for the emitter-base and collector-base junctions for various junction biases applied during irradiation are tabulated in Tables III(a) and III(b). Data from Table III(a) indicate that the variation in junction capacitance at the emitter-base junction is negligible (smaller than the experimental error of the measurement system) for all the devices with emitter-base and collector-base junctions biased during irradiation. This is to be expected since the surface of the p-type base at the emitter-base junction is more heavily doped than the surface of the p-type base at the collector-base junction (because of diffusion under the oxide during fabrication). Hence inversion and channel formation on the p-type base surface are restricted at the emitter-base junction. This is an important criterion in the fabrication of ionizing radiation tolerant devices.[18] A very limited extent of channel formation at the base side of the emitter-base junction at higher doses was observed as reflected by an n value of 2.2 at saturation doses discussed earlier.

Table III(b) lists the normalized collector-base capacitance data, $C(\gamma)/C(0)$, for different bias conditions. The extent of channel formation is most marked for the reverse biased collector-base junction (#23, maximum electric field strength). The reverse biased emitter-base junction causes a channel to form on the surface of the p-type base at the collector-base junction indicating that a reverse bias applied to the emitter-base junction has the effect of reverse biasing the collector-base junction. The channel is observed to recede at higher doses.

Figure 5 shows the structure of the test devices used in this work. The maximum distance the junction can extend into the p-type base by channeling (at the collector-base junction) is 20 μm since it cannot extend across the metal contact. Thus the maximum increment of junction area caused by extension of the junction into the p-type base region would be

$$\Delta A_{max} = \pi\left[[115]^2 - [95]^2\right] \times 10^{-8}\ cm^2.$$

The total maximum junction capacitance after the extension of the junction into the base side would be[19]

$$C + \Delta C_{max} = \frac{\epsilon A}{x_m} + \frac{\epsilon \Delta A_{max}}{x_c} \quad (7)$$

where,

- ΔC_{max} = maximum increment in junction capacitance caused by channel formation,
- x_m = width of the collector-base space-charge region in the bulk material,
- x_c = width of the space-charge region below the channel,
- A = initial area of collector-base junction,
- ΔA_{max} = maximum increase in area caused by channel formation.

If we assume $x_m = x_c$ (which is not correct, as will be

discussed below in conjunction with the calculation of numerical values for x_c and x_m) then the total observed junction capacitance could be expressed as

$$C + \Delta C_{max} = \frac{\epsilon(A+\Delta A_{max})}{x_m} , \quad (8)$$

from which,

$$\frac{A + \Delta A_{max}}{A} = \frac{C + \Delta C_{max}}{C} , \quad (9)$$

where,

$$\frac{A + \Delta A_{max}}{A} = 1 + .32 = 1.32 \text{ (for the device in Figure 5).}$$

For a typical device (collector-base junction reverse biased to 3.0 volts during irradiation), the observed maximum increment in capacitance was given by a $\Delta C_{max} = 7.74$ so that,

$$\frac{C + \Delta C_{max}}{C} = 1 + \frac{7.74}{6.32} = 1 + 1.22 = 2.22.$$

It can be seen that the increment in the junction capacitance (caused by channeling) would be much greater than that allowable by the area increase alone under the SiO_2 passivation on the p-type base. In the present situation, it was assumed that $x_m = x_c$; however, this assumption is not valid since experimental data would require channel lengths longer than the physical dimension of the device geometry. The depletion layer width at the surface, calculated from the expression $\Delta C_{max} = \epsilon \Delta A_{max} / x_c$, is found to be $x_c = 1.81 \times 10^{-5}$ cm. By comparison, the depletion layer width in the bulk is $x_m = 4.5 \times 10^{-5}$ cm. Note that x_c is only slightly more than one-third of x_m. The narrowing of the depletion layer width, parallel to the surface, as shown in Figure 6, could be explained if one visualizes that inversion of Si under the SiO_2 layer causes the concentration of the average negative charge to exceed the acceptor atom concentration, N_A ($N_A \geq N_D$), at the surface of the base at the collector-base junction. Assuming uniform concentration, the average negative charge concentration in the channel at saturation is calculated to be 3.7×10^{16} /cm^3. This is approximately 3 times the donor atom concentration in the collector substrate and hence accounts for the narrower depletion layer width below the channel, relative to the width in the bulk. Figure 6 gives the steps in formation of channel by ionizing radiation.

DISCUSSION

Although previous investigators[1-11] observed surface degradation to follow a general trend, they were unable to obtain definite relations for predicting the changes in the parameters affected by surface damage. In this work empirical prediction equations have been developed from correlations of the normalized increase in the surface base current and the increase in the reciprocal of the minority carrier lifetime with the total gamma dose and with the average junction electric field strength during irradiation. The similarity of the forms of Equations (1) and (2) indicates that the degradation of the surface minority carrier lifetime follows a trend similar to the normalized base current increase. This should be expected since interface states act as recombination centers for the minority carriers, thus increasing the surface recombination base current component, I_{SRG}, because of increased surface recombination velocity.

The effect of biasing the collector-base junction on the degradation at the emitter-base junction was investigated. The curves (D and E) in Figure 1 indicate that the saturation value of the normalized surface current at the emitter-base junction is the greatest for the reverse biased collector-base junction (Curve D) and least in the case of the forward biased collector-base junction (Curve E). Similar results have been reported by Nelson and Sweet,[5] although no explanation was given for the effect of collector-base biasing on the degradation of the emitter efficiency. These results are explained on the basis that a reverse biased collector-base junction has the effect of reverse biasing the emitter-base junction, and a forward biased collector-base junction has the effect of forward biasing the emitter-base junction to maintain zero current at the open contact. Similar results have been obtained from capacitance-voltage data in this investigation. A reverse bias on the emitter-base junction causes the collector-base junction to be reverse biased, enhancing channel formation at that junction.

The electric field strength dependence of the increase in surface recombination velocity at the emitter-base junction can be accounted for by either of two processes: (1) an introduction of new interface (fast) states (surface states which can exchange charge rapidly with the bulk silicon), or (2) a change in surface potential leading to an increased surface-recombination rate at the interface states already there. The latter effect can be achieved by a buildup of fixed charge in the oxide (slow states, which cannot exchange charge rapidly with the bulk silicon). Charge migration[7] in the SiO_2 layer under the influence of junction fringing fields parallel to the Si-SiO_2 interface explains the positive charge buildup in the SiO_2 above the p-type base, resulting in depletion and subsequent inversion of the Si (on the p-type base at the collector-base junction), the charge buildup rate being an increasing function of the fringing field strength. The surface damage introduction rate, α, and the damage saturation parameter, K_s, were observed to be increasing functions of the field strength and an empirical fit has been obtained correlating these parameters with the average field and the dose for matched devices. It should be emphasized that the fringing field, parallel to the surface, is the dominant cause of buildup of surface states and the electrode nature of the can has been found to be an insignificant cause of degradation in silicon passivated planar bipolar transistors. With the planar bipolar devices used in this study, it was not possible to calculate the initial surface state density directly and hence the method of normalizing the surface base current increase by the initial base current becomes essential to compare degradation in devices having varying initial interface state densities.

The surface recombination generation current, I_{SRG} (as indicated by $n \leq 2$), is the dominant gamma induced current component at the emitter-base junction and is observed to be an increasing function of the average field strength and total gamma dose. The surface channel current component, I_{CH} (as indicated by $n > 2$), is the dominant form of degradation at the collector-base junction. This is further indicated by the measureable increase in junction capacitance only at the collector-base junction. The preferential channel formation on the p-type base at the collector-base junction is attributed to a lower dopant concentration at the surface (caused by diffusion of impurity atoms under the oxide mask during fabrication) resulting in easier inversion.

ACKNOWLEDGEMENTS

The authors are indebted to J. Bereisa, Jr. for many valuable discussions and to W. C. Cannon and V. K. Dutta for their assistance in data reduction and analysis. A note of thanks is extended to Dr. Walter T. Matzen of Texas Instruments for providing test devices and to the United States Atomic Energy Commission for their support of this research effort under contract AT(11-1)-1624.

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TABLE I. Normalized base current increase at various gamma doses for devices with different biased applied at the emitter-base junction during exposure.

Total Gamma Dose Rads (Si)	Device #21 $E_r=1.26\times10^5$ V/cm $\Delta I_B(\gamma)/I(0)$ ($V_{BE}=-3.0V$)	Device #27 $E_r=4.61\times10^4$ V/cm $\Delta I_B(\gamma)/I_B(0)$ ($V_{BE}=0.0V$)	Device #08 $E_r=2.71\times10^4$ V/cm $\Delta I_B(\gamma)/I_B(0)$ ($V_{BE}=+0.5V$)
1.12×10^5	7.5	3.5	2.7
2.24×10^5	15.2	7.9	7.2
3.36×10^5	18.2	11.5	9.2
6.72×10^5	23.0	16.9	12.5
1.01×10^6	25.5	18.4	13.9
1.34×10^6	25.2	17.2	15.0
1.85×10^6	26.1	17.4	15.8

TABLE II. Normalized base current increase at various gamma doses for devices with different biases applied at the collector-base junction during exposure.*

Total Gamma	Device #23 E_r=4.9x10^{4}V/cm $\Delta I_B(\gamma)/I_B(0)$ (V_{BC}=-3.0V)	Device #19 E_r=1.2x10^{3}V/cm $\Delta I_B(\gamma)/I_B(0)$ (V_{BC}=+0.5V)
1.12×10^5	16.0	0.23
2.24×10^5	18.7	0.25
3.36×10^5	18.9	0.37
6.72×10^5	19.0	0.65
1.01×10^6	19.5	0.73
1.34×10^6	19.6	1.86
1.85×10^6	19.8	1.84

***Note:** V_{BE} and V_{BC} is the applied bias at the respective junctions during irradiation. E_r is the average electric field strength at the junction during irradiation.

TABLE III-a. Normalized emitter-base junction capacitance, C (γ)/C (0), for devices with various biases applied at the emitter-base junction during irradiation.

Total Gamma Dose rads (Si)	Device #21 E_r=1.26x10^{5}V/cm (V_{BE}=-3.0V)	Device #27 E_r=4.61x10^{4}V/cm (V_{BE}=0.0V)	Device #08 E_r=2.71x10^{4}V/cm (V_{BE}=+0.5V)
0	1.00	1.00	1.00
1.12×10^5	0.97	0.97	0.97
2.24×10^5	0.98	0.98	0.97
3.36×10^5	1.00	0.99	0.98
6.72×10^5	0.98	0.98	0.97
1.01×10^6	1.00	0.98	0.98
1.36×10^6	0.98	0.98	0.97
1.85×10^6	1.00	0.98	0.98
2.36×10^6	1.00	0.98	0.99
3.03×10^6	1.00	0.98	0.97
3.70×10^6	1.00	0.98	0.98

Note: Negligible change in the emitter-base junction capacitance was observed for devices with the collector-base junction biased during exposure.

TABLE III-b. Normalized collector-base junction capacitance, C (γ)/C (0), for devices with various biases applied at the junctions during irradiation.

Total Gamma Dose rads (Si)	Device #21 E_r=1.26x10^5 V/cm (V_{BE}=-3.0V)	Device #27 E_r=4.61x10^4V/cm (V_{BE}=0.0V)	Device #08 E_r=2.71x10^4V/cm (V_{BE}=+0.5V)	Device #23 E_r=4.9x10^4V/cm (V_{BC}=3.0V)	Device #19 E_r=1.2x10^3V/cm (V_{BC}=+0.5V)
0	1.00	1.00	1.00	1.00	1.00
1.12×10^5	1.07	0.99	0.98	1.09	0.98
2.24×10^5	1.07	1.00	1.00	1.08	0.99
3.36×10^5	1.20	1.02	1.04	1.75	1.00
6.72×10^5	1.27	1.03	1.04	2.22	1.01
1.01×10^6	1.25	1.04	1.04	2.22	1.01
1.34×10^6	1.22	1.04	1.04	2.21	1.01
1.85×10^6	1.18	1.04	1.06	2.20	1.01
2.36×10^6	1.17	1.04	1.06	2.16	1.01
3.03×10^6	1.13	1.04	1.07	2.14	1.02
3.70×10^6	1.12	1.04	1.07	2.11	1.02

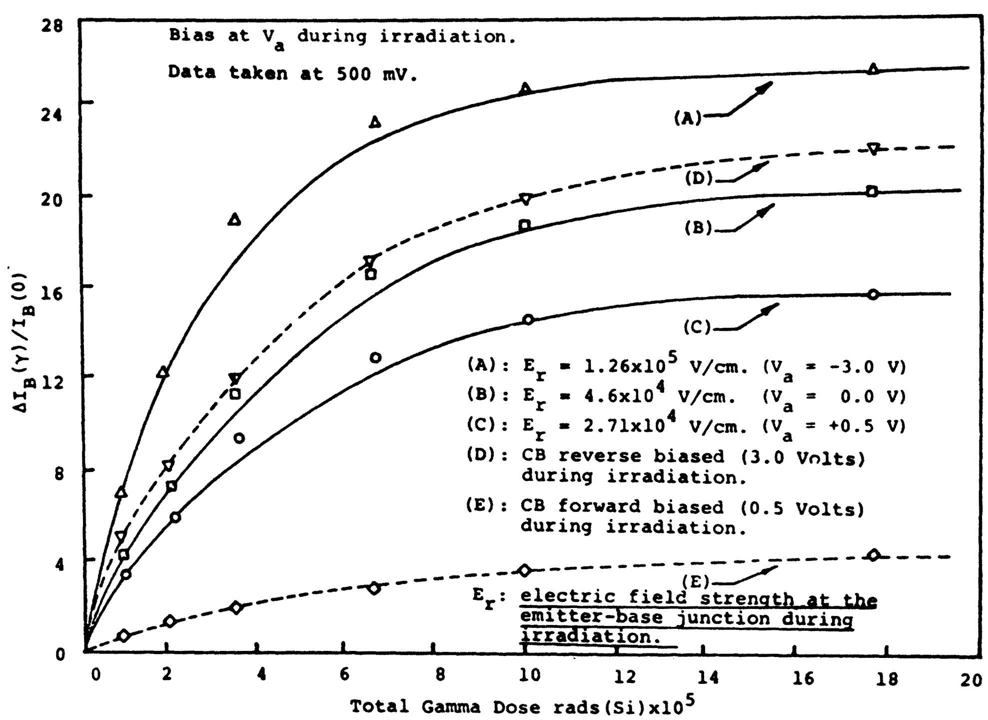

Fig. 1. Normalized base current increase versus total gamma dose for devices with varying junction electric field strengths during irradiation.

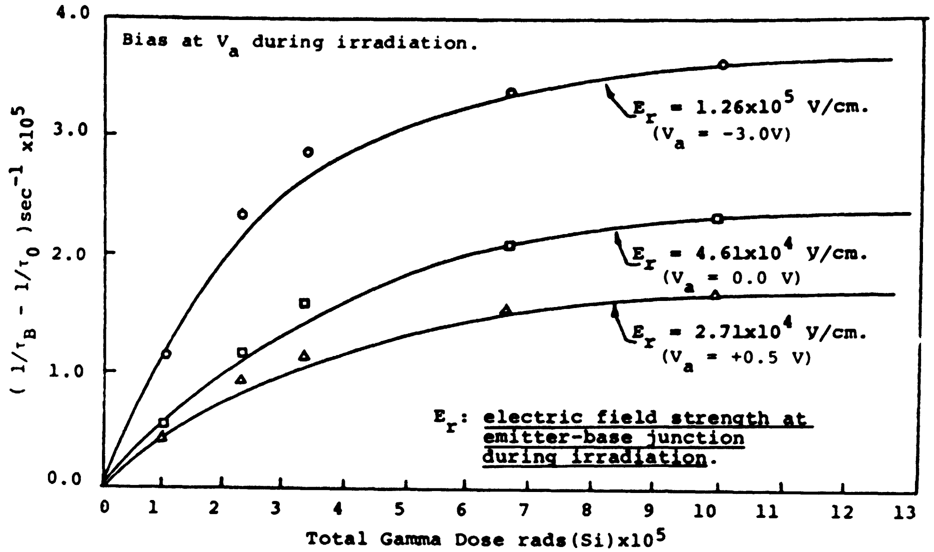

Fig. 2. Change in surface recombination velocity (reciprocal of minority carrier lifetime), versus total gamma dose for devices with varying junction electric field strengths at the emitter-base junction during irradiation.

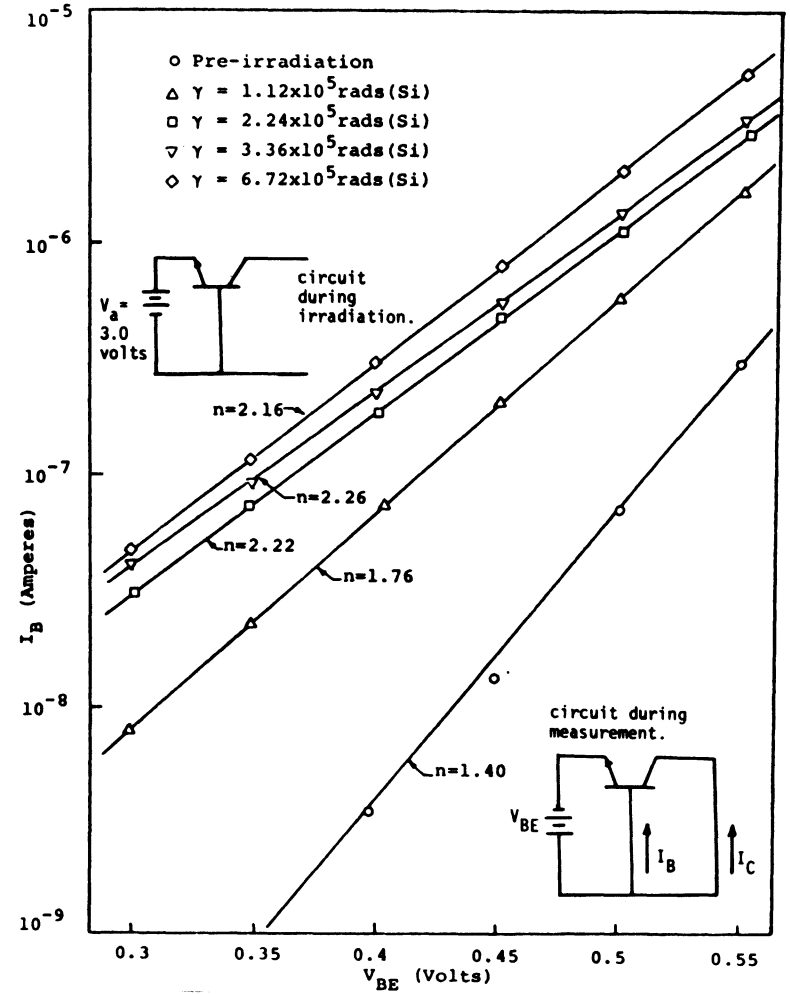

Fig. 3. Current versus voltage for device # 21 at different dose levels with the emitter-base junction reverse biased to 3.0 volts during irradiation.

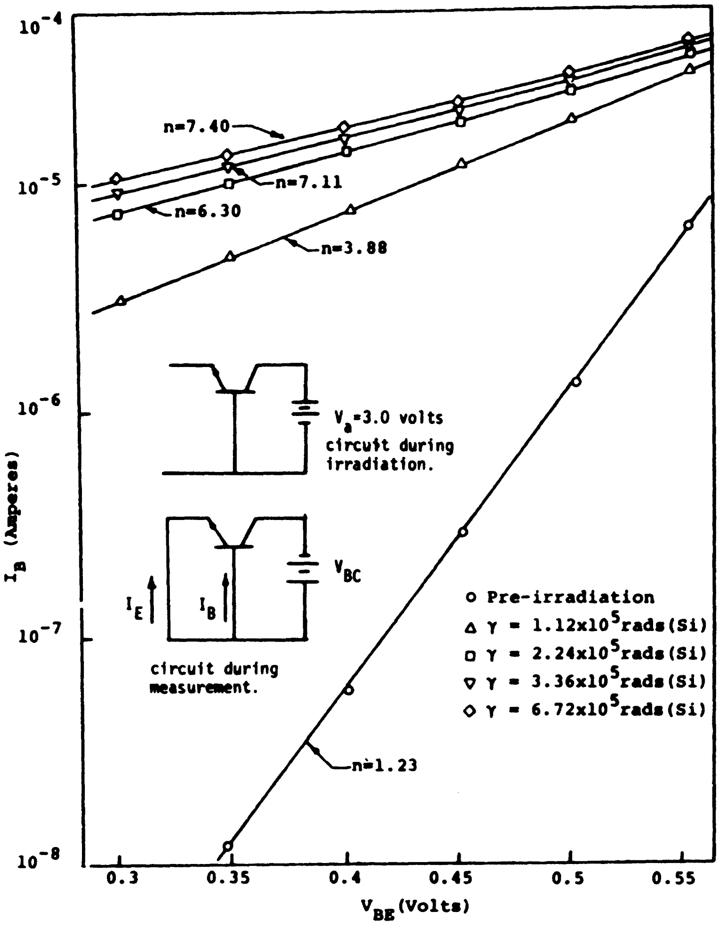

Fig. 4. Current versus voltage for device # 23 at different dose levels with the collector-base junction reverse biased to 3.0 volts during irradiation.

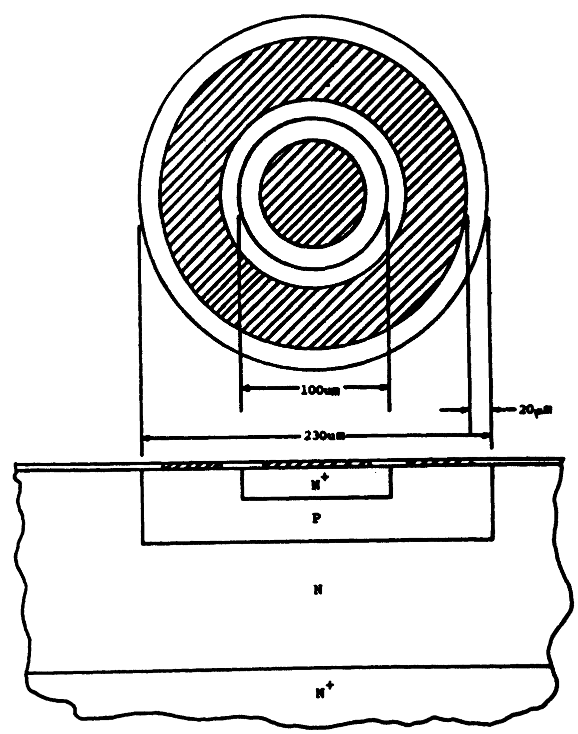

Fig. 5. The geometrical structure of planar epitaxial transistors used in this work.

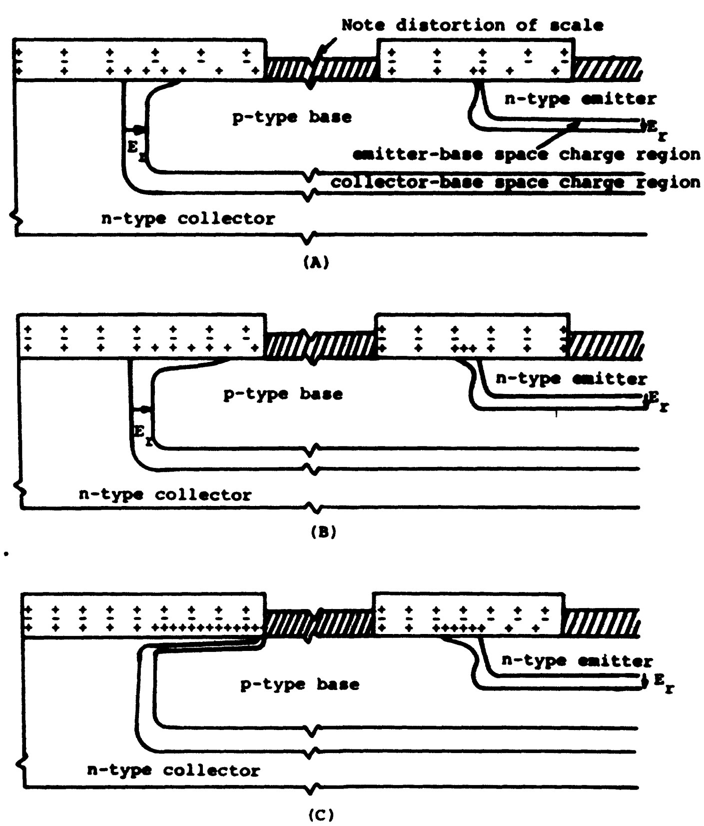

Fig. 6. Steps in formation of channel by ionizing radiation:

(A) Onset stage of channel formation.

(B) Intermediate stage of channel formation.

(C) Saturation stage of channel formation.