Radiation And Annealing Characteristics Of Neutron Bombarded Silicon Transistors

L. S. Su

G. E. Gassner

C. A. Goben
Missouri University of Science and Technology

RADIATION AND ANNEALING CHARACTERISTICS OF NEUTRON BOMBARDED SILICON TRANSISTORS*

L. S. Su[†α], G. E. Gassner[†β] and C. A. Goben

Space Sciences Research Center

University of Missouri-Rolla

Summary

Operating a silicon planar epitaxial transistor in the inverse configuration allows one to demonstrate clearly the importance of the neutron-induced base current component and its degradation of the emitter efficiency, and, because of the much larger depletion layer, to compute a volume dependent damage constant applicable to all silicon p-n junctions. The importance of minimizing the absolute change versus relative change in radiation hardening studies is clearly illustrated. Surface effects were found to be significant for transistors mounted in gas-filled cans. The diffusion potential was predicted, on theoretical grounds, to vary with neutron fluence, and the theory was experimentally confirmed. Isochronal and isothermal annealing data were obtained for the inverse configuration and from these data, it is concluded that the neutron-induced defect centers are field dependent.

Introduction

A neutron-induced base current component which increases in proportion to neutron fluence has been previously reported[1-3] which dominates the transistor current gain over a wide range of current levels and is primarily responsible for the degradation of current gain at low and intermediate current levels through degradation of the emitter efficiency. This base current component was expressed as

$$I_{B_{INC}} = K_1 \cdot A_E \cdot \phi \cdot \exp\left(\frac{qV_{BE}}{nkT}\right), \qquad (1)$$

where A_E is the effective emitter area (cm^2), K_1 is the area damage constant (amperes/cm^2/nvt), ϕ is the neutron fluence (neutrons/cm^2), and $n \simeq 1.5$. This expression is area dependent and not volume dependent as would be expected. Although recombination is known to be a volume process, it was not previously possible to determine the volume dependence in the emitter-base space-charge region.[1-3] The more detailed study necessary to determine this volume dependence can be done by reversing the role of the emitter and collector so that one can study the effects of neutron radiation in the much larger space-charge volume of the wider collector-base junction.

Impurity profiles[4] of 2N914 transistor structures indicate that the depletion layer width of the collector-base junction is about 5 times wider than that of the emitter-base junction. Since the effective area of the collector-base junction is 5.39 times that of the emitter-base junction, interchanging the roles of the collector and emitter yields an effective volume of the inverse "emitter-base" junction about 27 times that of the normal emitter-base junction. From equation (1), I_{BINC} should increase by a factor of about 27 if the device is operated under the same conditions as in the normal configuration. Therefore, the behavior of the neutron-induced base current which originates in the bulk space-charge region can be determined more accurately in the low current region below the onset of voltage deviation (emission crowding). Quotation marks will be used to distinguish the inverse case.

Since the carrier concentration in the emitter of a 2N914 transistor is about 10^5 times that of the collector, the Fermi level in the emitter region lies closer to the conduction band than does the Fermi level in the collector region. Thus, inversion layers are more easily formed in the "emitter-base" junction region. This allows the study of radiation-induced surface effects by using devices having identical characteristics but biased at different junction voltages.

Anomalous annealing phenomena, which have also been studied previously,[1-3] indicate that neutron-induced defects in the emitter-base space-charge region of a transistor anneal differently from defects in the neutral base region. A slight field dependence of the annealing of these neutron-induced defects was observed recently but appeared to be quite complex.[5] Additional information can be gained by performing annealing studies on transistors operated in the inverse configuration.

The irradiations of the devices were performed in the Research Reactor at the University of Missouri-Rolla. This reactor is a "swimming pool" type and has a maximum power level of 200 kW, corresponding to a neutron flux of 1.8×10^{11} n/cm^2/sec and a gamma dose rate of 1.3×10^3 rad (H_2O)/sec at the test location. Since there is disagreement as to the process and amount of annealing of radiation damage in silicon at

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α Present affiliation: IBM, Fishkill, N. Y.

β Present affiliation: U. S. Army.

δ Special Devices used in this study were obtained from Texas Instruments, Inc., Dallas, Texas, and Motorola, Inc., Phoenix, Arizona.

room temperature (T = 27°C), a room temperature annealing check of the devices used in this study was performed. The check showed less than one-half of one per cent change over a 24 hour period when stored at room temperature. Since this amount of annealing was considered to be negligible, the electrical testing,[6] irradiation, and storage were done at room temperature.

Investigation of Inverse Gain Parameters

Inverse Base and Collector Currents

The type of transistors chosen for study of the inverse characteristics were p-n silicon planar-epitaxial transistors with a ring-dot structure both with and without gold doping, fabricated by Texas Instruments with impurity profiles, junction depths and geometry identical to that of the 2N914. Figure 1 shows the "base" and "collector" current versus "emitter-to-base" voltage for one of the 2N914 transistors and was selected as being typical of the devices measured. For this device the "base" current is larger than the "collector" current. This is to be expected since: (1) the area of the "collector" is much less than the area of the "emitter"; (2) the device being studied has a graded base, and when operated in the inverse manner the electrons injected into the base region will experience a net retarding field acting on them giving them more time in which to recombine; and (3) since the "base" is doped more heavily than the "emitter", the back injection of holes into the "emitter" becomes significant.

Figure 2 shows the "base" and "collector" currents versus "emitter-to-base" voltage for one of the special devices before and after exposure to a neutron fluence of 6.0×10^{13} nvt. The "collector" current is seen to decrease slightly with neutron fluence, and the voltage bendaway due to emission crowding begins at lower voltages. The neutron-induced component of base current for the inverse case is similar to that found previously[1-3] for the forward case.

Examination of Figures 1 and 2 shows that the "base" current of the gold-doped 2N914 is larger than the post-irradiation "base" current of the non-gold doped special device yielding a much smaller initial current gain for the gold-doped device. At an "emitter-to-base" voltage of 0.5V, the "base" current of the special device is 4.6×10^{-6} ampere while the "base" current of the 2N914 transistor is 8.3×10^{-5} ampere (18 times larger). Since the neutron-induced component of base current is equal in both the 2N914 and the special device (they have equivalent geometry, profile and junction depth), it is readily seen that the relative increase in "base" current will be smaller for the 2N914 than for the special device; hence, yielding smaller relative degradation of the transistor current gain for the 2N914. Therefore, on a relative basis, the 2N914 would appear to be more radiation tolerant than the special device because of its much larger pre-irradiation "base" current. It should be apparent that absolute change in base current with neutron fluence is much more significant than relative change for radiation hardening studies.

The Components of Inverse Common-Base Current Gain

Since the "collector" is very heavily doped and operated at low bias, the inverse current gain, α_R, can be expressed as the product of two terms, $\alpha_R = \gamma_R \beta^*_R$, where γ_R is the inverse emitter efficiency, β^*_R is the inverse base recombination term, and the subscript, R, denotes inverse, or reverse, operation.

When a transistor is operated in the inverse configuration, it can be shown that the "collector" current can be expressed as

$$I_{CR} = \frac{\beta^*_R \cdot A_{ER} \cdot k \cdot T \cdot \mu_n \cdot n_i^2}{\tilde{N}_A} \exp(qV/kT), \quad (2)$$

where n_i is the intrinsic carrier density, A_{ER} is the "emitter" area, μ_n is the average electron mobility in the base, $\tilde{N}_A$ is the number of majority carriers per unit area of the base region, β^*_R is the inverse base recombination term, and I_{CR} is the current collected by the "collector" of the transistor. It has been found that of these variables, μ_n, $\tilde{N}_A$,[1-3,7] and β^*_R will change with neutron radiation. The factors n_i^2, $\tilde{N}_A$, k, T, and exp(qV/kT) will be equal for either the forward or inverse case.

The changes in the inverse base recombination term, β^*_R, with irradiation can be found if the changes in I_{CR}, μ_n, and $\tilde{N}_A$ with neutron fluence are known. Since the devices under study have graded bases, the variation of mobility across the base region will be different for the forward and inverse cases; however, one usually considers the average mobility across a graded base which is the same in either direction.

Solving equation (2) for the normalized inverse base recombination term yields

$$\frac{\beta^*_R(\phi)}{\beta^*_R(\phi = o)} = \frac{I_{CR}(\phi)}{I_{CR}(\phi = o)} \cdot f(\phi) \quad (3)$$

where $f(\phi)$ is the normalized ratio of mobility to sheet resistivity as determined in previous work.[7]

Since the variations of $\tilde{N}_A$ and μ_n with neutron fluence are known,[7] the variation of the inverse base recombination term with neutron fluence can be determined from equation (3) by measuring the changes in "collector" current.

The inverse common base current gain, α_R, is easily found by taking the ratio of measured "collector" current to "emitter" current. It is possible to solve for the normalized inverse emitter efficiency, γ_R, by normalization of the inverse common base current gain and division by the normalized inverse base transport factor, hence:

$$\frac{\gamma_R(\phi)}{\gamma_R(\phi = o)} = \frac{\alpha_R(\phi)/\alpha_R(\phi = o)}{\beta^*_R(\phi)/\beta^*_R(\phi = o)}. \quad (4)$$

Figures 3 and 4 show the variation of inverse common base current gain and its components versus neutron fluence, ϕ, for the 2N914 transistor and for one of the special devices, respectively.

The inverse emitter efficiency is seen to decrease faster than the inverse base recombination term with neutron radiation for either gold-doped or non-gold doped devices. This illustrates clearly the importance of the emitter efficiency, since in modern high-frequency, high-gain devices, the neutron-induced current component will dominate the changes in current gain. The relative change in the emitter efficiency of the gold-doped device is less than that in the non-gold doped device (since the base current in the gold-doped device was so large before irradiation).

Comparison of Figures 1 and 3 with Figures 2 and 4, respectively, shows that the gold-doped devices, with their initially large base current and low gain, are more radiation tolerant on a relative basis, while the non-gold-doped devices show less absolute degradation. Therefore one could improve the radiation tolerance of devices by either fabricating initially poor devices, or preferably, by minimizing the depletion layer volume. Notice that the latter case also improves the frequency response and the initial gain.

Volume Damage Constant

Recombination is a volume process and even the process of surface recombination requires a finite volume. Previous work[1-3] has shown that the neutron-induced base current component of base current originates in the bulk space-charge region of the emitter-base junction and should, therefore, be dependent on the volume of that region. Examination of equation (1) reveals that a volume dependence would result by proper interpretation of the constant, K_1. If the constant, K_1, is expressed in terms of a volume damage constant, K_v, times the emitter-base depletion layer width, $X_m(V)$, then equation (1) will be volume dependent as would be expected on theoretical grounds. The increase in "base" current was found for several different types of transistors (including the special devices and 2N914's) to a fluence level of 7.5×10^{14} n/cm^2. Knowing the increase in "base" current over the voltage range of interest (0.0V-1.0V), the constant K_1 was found for each of the devices by using equation (1). The values obtained for K_1 are shown for some of the different devices in Table 1. The table shows that K_1 generally decreases with increasing voltage.

Once the values of K_1 for the different devices are known, it is possible to solve for the volume damage constant, $K_v = K_1/X_m(V)$, provided the depletion layer width, $X_m(V)$, is known. By measuring the junction capacitance of the depletion region at different voltages, it is possible to determine the depletion layer width using the relation;

$$X_m(V) = \frac{\varepsilon A}{C(V)},$$

where ε is the permittivity of the material, A is the area of the junction, and C is the junction capacitance.

The values of the volume damage constant, K_v, as a function of "emitter-base" voltage are summarized in Table 1 for a few voltages. The average values of K_v are then determined. These results are shown in Table 2 for the various types of transistors. Examination of Table 2 reveals that the damage constant, K_v, increases slightly with increasing voltage. This increase is attributed to measurement error due to diffusion capacitance and a possible dependence of the permittivity on neutron fluence.

Since K_v is a damage constant, dependent upon the damage done by fast neutrons to silicon devices, it should be possible to determine a value of K_v for the emitter-base junction when the device is operated in the normal fashion. A direct calculation of K_v for previous work[1-3] could not be carried out, since the emitter-base depletion widths for the devices tested were not measured. However, a comparison can be made between the ratios of emitter capacitance to collector capacitance and the ratios of area damage constants for the two junctions. From this comparison it was determined that K_v for emitter junctions agreed to within 20% of the value of K_v for the collector junction. Thus, K_v is a volume damage constant that is representative of fast neutron damage to silicon p-n junctions.

Inverse Emitter Junction Characteristics

Neutron-Induced Surface Effects

The special devices used in this surface radiation effects study were obtained from Texas Instruments and Motorola and had impurity profiles and junction depths identical to those of the 2N914 transistor. However, these devices differed from the 2N914 in that they were not gold doped.

Four devices, plus one set of three devices with identical characteristics, were irradiated in nine steps to a neutron fluence of 2×10^{14} nvt. In the set of three devices, one was reverse biased at 3.0V, the second was forward biased at 0.5V, while the third device was unbiased during irradiation. The remaining four devices were unbiased during irradiation. All the bias voltages were applied to the "emitter-base" junction.

The "emitter-base" junction capacitance (C_{BER}) of devices biased at different voltages during irradiation (measured at an externally applied junction voltage of V_{BER} equal 0.0V) versus neutron fluence is shown in Figure 5. For the devices unbiased or forward biased at 0.5V, C_{BER} has only a slight increase in capacitance (less than 5%) with fluence to a level of 2×10^{14} nvt. The capacitance of the device reverse biased at 3 V during irradiation increased very rapidly with fluence to a level of 6×10^{13} nvt and then remained relatively constant at about two times the pre-irradiation capacitance.

The environment within the transistor cans for 2N914's and the special devices used in this work is nitrogen gas, which can be ionized by nuclear radiation. A reverse biased junction induces a strong field across the junction which either attracts negatively charged ions to the n-side or attracts positively charged ions to the p-side. Charge neutrality is then achieved by the attraction of oppositely charged carriers from the semiconductor bulk. If the doping concentration of either region is sufficiently low, an inversion layer is formed in spite of the oxide passivation. The radiation-induced inversion layer increases the junction area and causes an increase in junction capacitance.

The inverse base current-voltage characteristics with neutron fluence as a parameter for the device reverse biased at 3.0V during irradiation are shown in Figure 6. At the fourth ($\phi_4 = 2 \times 10^{13}$nvt) and the fifth ($\phi_5 = 4 \times 10^{13}$nvt) irradiations, a base current component with reciprocal slope terms of $n \simeq 2$ and 2.8, respectively, has appeared in the low-voltage region. This additional surface recombination current component produced by a radiation induced inversion layer is small and causes an effective increase in base current only for low forward "base-emitter" voltages. At higher forward "base-emitter" voltages, the bulk recombination current is larger than the surface recombination current, and the former dominates in this range. Figure 6 shows that a larger fraction of this inversion layer, which causes this additional current component increase, anneals at room temperature in approximately four weeks. No large increase of I_{BB} in the low voltage range appeared in any other device.

Table 3 summarizes values of τ_{BE} as a function of neutron fluence for seven devices. It should be noted that while τ_{BE} decreases with radiation, it is not a function of junction voltage applied during irradiation. The inversion layer is formed only on the device reverse biased at 3.0V during irradiation. It should be noted from these data that the radiation induced inversion layer does not appreciably affect the minority carrier lifetime in the base region. The reverse bias on the "emitter-base" junction of 3.0V during irradiation was used on other devices, and the same phenomena were found

Radiation and Annealing Characteristics of the Diffusion Potential (V_T)

The diffusion potential, V_T, for a p-n junction in nondegenerate material at thermal equilibrium is given by

$$V_T = \frac{kT}{q} \cdot \ln \frac{N_D \cdot N_A}{n_i^2} , \tag{5}$$

where the parameters have the usual definitions. The following empirical expressions are used for the dependence of hole and electron concentrations on neutron fluence: $N_D = N_{Do} \cdot \exp(-\phi/k_n)$, $N_A = N_{Ao} \cdot \exp(-\phi/k_p)$, where N_{Do} and N_{Ao} are the initial carrier concentrations and k_p and k_n are the concentration damage constants for holes and electrons, respectively. After substitution, one obtains for V_T:

$$V_T = \frac{kT}{q}\ln\frac{N_{Do} \cdot N_{Ao}}{n_i^2} - \frac{kT}{q}\left(\frac{1}{k_n} + \frac{1}{k_p}\right)\phi = V_{To} - \frac{kT}{q}\frac{\phi}{k_T} \tag{6}$$

Equation (6) predicts that V_T should decrease linearly with neutron fluence for a step p-n junction.

The diffusion potential may be calculated from capacitance-voltage data. For nondegenerate material at thermal equilibrium, the junction capacitance is generally expressed:[8] $C=K(V_T-V_{BER})^{-m}$, where V_T is the diffusion potential, V_{BER} is the externally applied junction voltage, K is a constant, and m is a constant which is between $\frac{1}{2}$ and $\frac{1}{3}$. A computer program, using a least-squares fitting of the capacitance equation to the measured data of the junction capacitance versus the externally applied voltage, can be used to estimate the value of V_T. Since the diffusion capacitance increases with externally applied forward bias (thus increasing the capacitance reading and yielding erroneously smaller values for V_T) the capacitance values were measured at small forward and reverse biases near zero (-60mV to + 60mV). The diffusion potential, V_T, of the devices was estimated at every fluence level using the least-squares fitting technique and found to decrease linearly after neutron radiation as predicted theoretically with a slope of $(1/k_T) = 1.27 \times 10^{-16}$ cm^2.

The diffusion potential was also estimated using the same least-squares fitting technique after certain isochronal annealing runs. Values of the diffusion potential (normalized to its pre-irradiatiation value) as a function of isochronal annealing temperature are presented in Table 4. It is observed that V_T increased after isochronal annealing but that it did not return to its pre-irradiation value.

Dependence of Annealing Rate on Voltages Applied Externally to the "Emitter-Base" Junction During Annealing

The activation energy[9] can be calculated by combining the data from both isothermal and isochronal annealing of two identical devices. It is thought that neutron radiation introduces many defect levels[10] which are distributed throughout the forbidden energy band with some dominating the characteristics. In order to determine the effect of different biasing voltages on the annealing rates in a certain temperature range, three sets of paired devices were annealed, with each pair being annealed at a different junction bias voltage. One device of each pair was used for isothermal annealing and the other device of each pair was used for isochronal annealing. This also allows one to study the field dependence of the annealing rate of neutron-induced defects in both the bulk space-charge region and the neutral base region.

Three pairs of devices with nearly identical characteristics (matched to within 10 per cent) were irradiated to a fluence of 5×10^{14} nvt. The changes in the characteristics of each pair of devices were nearly identical after neutron radiation. During the annealing, the "emitter-base" junction of one pair of devices was forward biased at 0.5V, that of the second pair of devices was reverse biased at 3.0V, while that of the third pair of devices was unbiased. The "collector-base" junction was open circuited during the annealing. After each annealing run, current-voltage characteristics of each device were measured in the inverse operating configuration.

Inspection of the annealing curves in Figures 7, 8, 9 and 10 reveals that there is no sudden change in the concentration of the defect states with respect to temperature or time. These results agree with previous work on both bulk material[11] and silicon transistors.[5]

Activation energies of 0.19 ± 0.04eV and 0.86 ± 0.15eV in the bulk space-charge region, and 0.34 ± 0.06eV and 0.98 ± 0.18eV in the neutral base region were calculated by combining data from both isothermal and isochronal annealing of two identical devices.[9] These activation energies agree well with the values found by previous investigators.[12-15]

Previous analyses have shown that negatively charged centers, which are related to defects thermally annealed in the vicinity of 200°C in n-type germanium, are annealed at a lower temperature when an electric field is impressed at the junction[12,13]. Therefore, the annealing rate of defects in the bulk space-charge region for a reverse biased and an unbiased device should be larger than that for a forward biased device in the termperature range where negatively charged centers are annealed. In the temperature range from 150°C to 180°C the annealing rate of defects in the bulk space-charge region for the device reverse biased at 3.0V and the unbiased device is larger than that for the device forward biased at 0.5V as shown in Figures 7 and 8. Thus this annealing is thought to represent the annealing of negatively charged centers.

The unannealed fraction of defects in the bulk space-charge region increases for some of the isothermal annealing runs in the temperature range from 50°C to 100°C, as shown in Figure 8. Reverse annealing of defects with an activation energy equal to (E_C - 0.17eV) in n-type silicon has been observed previously by Inuishi and his associates[14,15] and was attributed to an increase in the number of A-centers (oxygen-complexes).

The defects in the neutral base region, as represented by the changes in collector current, anneal more than 100% as shown in Figures 9 and 10. This result has been observed in other annealing experiments[5] and implies that not only annealing of neutron-induced defects took place but also annealing of other defects (e.g., oxygen vacancy complexes, interstitials etc.)[5] occurred. The improvement in the post-annealing collector characteristics (less than 20%) due to this annealing is very slight compared to the total annealing of the collector characteristics. The devices were pre-annealed at 250°C for 12 hours in this work. These data suggest that a longer pre-irradiation baking at perhaps higher temperature would be helpful.

When the device is reversed biased at 3.0V during annealing, part of the defects originating in the neutral base region are affected by the electric field due to the extension of the junction, thus enhancing the annealing rate of defects in the neutral base region. The annealing rate of defects in the neutral base region for the device reverse biased at 3.0V should therefore be larger than that for the unbiased device and the device forward biased at 0.5V, and such is the case as may be seen from Figures 9 and 10.

DISCUSSION

It was shown that analysis using inverse parameters can be very useful, particularly in demonstrating the importance and significance of the neutron-induced base current and for determining the volume damage constant, K_V. From comparison with the previously reported emitter-base area damage constant, it was inferred that this damage constant is a measure of damage to the lattice and is applicable to all silicon junctions. The components of inverse current gain behaved similarly to the forward components. The inverse emitter efficiency was shown to be a sharply decreasing function of neutron fluence and accounted for the largest degradation of inverse current gain. The importance of minimizing absolute changes versus relative changes in radiation hardening studies has been clearly illustrated. Since the carrier concentration in the emitter of such devices is about 10^5 times that of the collector, the Fermi level in the emitter region lies closer to the conduction band than does the Fermi level in the collector region. Thus, inversion layers are more easily formed in the "emitter-base" junction region when the device is operated in the inverse configuration, allowing the study of surface effects.

Experiments have been performed with a bias applied to the new "emitter-base" junction to change the depletion layer volume during neutron radiation with a 3.0 Volt reverse bias. Surface effects in the form of an inversion layer adjacent to the "emitter-base" junction have been observed to cause the base current to increase by a factor of 5 to 10 in the low "emitter-base" voltage region (Figure 6), and the "emitter-base" junction capacitance to increase by a factor of approximately 2 at a fluence of 2×10^{14} nvt and a gamma dose of 1.44×10^{6} rad(H_2O) (Figure 5). There were no measurable changes in minority carrier lifetime in the base region due to the inversion layer. The reverse biased "emitter-base" junction voltage induces a strong field across the junction which either attracts negatively charged ions to the "emitter" or positively charged ions to the base. If positively charged ions are attached to the base surface, the inversion layer will form on the base side of the "emitter-base" junction. Such an inversion layer would account for no more than a 31% increase in capacitance. Since the increase in capacitance was more than 31%, and since the radiation induced inversion layer did not appreciably affect the minority carrier lifetime in the base region, one may conclude that this inversion layer is caused by the entrapment of negatively charged nitrogen ions in the "emitter" region.[17] Formation of negatively charged nitrogen ions by ionizing radiation has not been reported in the literature. It is quite possible (due to the strong electronegativity of nitrogen) that electrons dislodged from the metal cannister by the neutron bombardment[18] could ionize the nitrogen gas. These negative ions would then be adsorbed by the oxide surface over the "emitter" region thus causing the formation of the inversion layer on this n-type region.

Surface effects due to neutron radiation have been previously thought to be negligible.[19] This experiment shows that an inversion layer is formed at the transistor surface near a junction if the doping concentration is low and if the junction is reverse biased during irradiation for devices mounted in gas-filled cans. This inversion layer was found to be significantly annealed at room temperature in approximately 4 weeks (Figure 6).

A computer program using a least-squares fitting technique was used to estimate the value of the diffusion potential, V_T, by using the measured data of junction capacitance versus externally applied voltage. A decrease in the diffusion potential, V_T, was predicted on theoretical grounds and was observed experimentally following neutron radiation. The experimental results show that the diffusion potential of the "emitter-base" junction decreased to approximately 90% of its pre-irradiation value at a neutron fluence of 5×10^{14}nvt. The diffusion potential increased after the isochronal annealing but did not anneal completely to its pre-irradiation value. Both the diffusion potential (V_T) and the anomalous neutron-induced base current (I_{BINC}) are related to the bulk space-charge region. Since both V_T and I_{BINC} do not anneal completely to their pre-irradiation value, one may infer that the defect centers in the bulk space-charge region are strongly affected by the junction field.

For the annealing studies, pairs of devices with nearly identical characteristics (matched to within 10 per cent) were irradiated to a fluence of 5×10^{14}nvt, then annealed. Dominant activation energies of 0.19 ± 0.04eV and 0.86 ± 15eV in the bulk space-charge region, and 0.34 ± 0.06eV and 0.98 ± 0.18eV in the neutral base region were calculated[10] from the isochronal and isothermal annealing data. The experimental activation energies agree well with previously calculated values.[12-15]

The unannealed fraction of defects in the bulk space-charge region increases for some of the isothermal annealing runs in the temperature range from 50°C to 100°C. This was attributed to an increase of A-centers (oxygen-complexes).[14,15]

The annealing process of neutron-induced defects is a function of many parameters[5,11-15] (i.e., type of defect, type of complex, electric field, injection level, temperature etc.), but certain parameters will dominate in a small temperature range, making it easier to study the annealing phenomenon. The data indicate that the annealing rate of defects in the neutral base region is enhanced by the field, and furthermore, that the annealing rate in the p-type neutral base region is decreased by the minority carrier injection which agrees with previous work by Sander and Gregory.[13]

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References

1. Goben, C. A., "Neutron Bombardment Reduction of Transistor Current Gain," Sandia Laboratory, Albuquerque, New Mexico, (Publication), SCR-64-1373, 1964.
2. Goben, C. A. and Smits, F. M., "Anomalous Base Current Component in Neutron Irradiated Transistors," Sandia Laboratory, Albuquerque, New Mexico, (Publication), SCR-64-195, 1964. Presented at 1964 IEEE Nuclear and Space Radiation Effects Conference, 1964.
3. Goben, C. A., "A Study of the Neutron-Induced Base Current Component in Silicon Transistors," IEEE Radiation Effects Conference, Ann Arbor, Michigan, 1965. <u>IEEE Trans. on Nuclear Science</u>, <u>NS-12</u>: 5, 134-146, 1965.
4. Chow, M. C., "Recombination Statistics for the Neutron-Induced Base Current Component," Ph.D. Dissertation, Library, University of Missouri-Rolla, 1968.
5. Chott, J. R. and Goben, C. A., "Annealing Characteristics of Neutron Irradiated Silicon Transistors," <u>IEEE Trans. on Nuclear Science</u>, <u>NS-14</u>: 6, 134-146, 1967.
6. Bartling, D. L., Jenkins, C. R. and Goben, C. A., "An Automatic Data Acquisition System for Semiconductor Device Testing," <u>IEEE Trans. on Instrumentation and Measurement</u>, <u>IM-17</u>: 1, 19-28, 1968.

7. Goben, C. A., Smits, F. M. and Wirth, J. L., "Neutron Radiation Damage in Silicon Transistors," IEEE Trans. on Nuclear Science, NS-15: 2, 14-29, 1968.
8. Phillips, A. B., Transistor Engineering, McGraw-Hill, New York. pp. 64; 86-91; 108-115; 270-295, 1962.
9. Meechan, C. J. and Brinkman, J. A., "Electrical Resistivity Study of Lattice Defects Introduced in Copper by 1.25-MeV Electron Irradiation at 80°K," Phys. Rev., 103: 1193-1202, 1956.
10. Easley, J. W., "The Semiconductor Device in Radiation Damage Research," 7th International Conference on the Physics of Semiconductors, Radiation Damage in Semiconductors, Academic Press, New York and London, pp. 241-363, 1964.
11. Stein, H. J., "Introduction Rates of Electrically Active Defects in n- and p-Type Silicon by Electron and Neutron Irradiation," J. Appl. Phys., to be published, 1968.
12. Baruch, P., "Mobility of Radiation-Induced Defects in Germanium," J. Appl. Phys., 32: 4, 653-659, 1961.
13. Sander, H. H. and Gregory, G. L., "Transient Annealing in Semiconductor Devices Following Pulsed Neutron Irradiation," IEEE Trans. on Nuclear Science, NS-13: 6, 53-62, 1966.
14. Tanaka, T. and Inuishi, Y., J. Phys. Soc. Japan, 19, p. 167, 1964; Y. Inuishi and K. Matsuura, J. Phys. Soc. Japan, 18: Suppl. III, 240, 1963; as cited in reference 15.
15. Hasiggati, R. R. and Ishino, S., "Defect Mobility and Annealing in Irradiated Germanium and Silicon," 7th International Conference on the Physics of Semiconductors, Radiation Damage in Semiconductors, Academic Press, New York and London, pp. 259-273, 1964.
16. Waite, T. R., "Diffusion-Limited Annealing of Radiation Damage in Germanium," Phys. Rev., 107: 2, 471-478, 1957.
17. Su, L. S., "Radiation and Annealing Characteristics in Neutron Bombarded Transistors Operated in the Inverse Configuration." M.S. Thesis, Library, University of Missouri-Rolla, 1968.
18. Coppage, F. N., Sandia Corporation, Personal Communique.
19. Messenger, G. A. and Spratt, J. P., "The Effect of Neutron Irradiation on Germanium and Silicon," Proc. IRE, 46: 1038-1044, 1958.

Table 1
Summary of information from irradiation of various transistor structures.

		$K_1(V)10^{-21}$ (amperes/cm^2/(nvt)			$K_v(V)10^{-17}$ (amperes/cm^3)/(nvt)		
CODE		0.30V	0.35V	0.45V	0.30V	0.35V	0.40V
2N914	#41	5.0	3.4	2.0	7.1	7.2	7.4
Spl Dev	#42	2.5	2.1	1.7	6.2	5.9	6.0
2N18A	#01	2.9	3.1	3.0	4.2	5.3	5.6
2N760	#01	2.9	2.7	2.7	3.1	4.0	6.2
40360	#01	4.7	4.7	*	4.9	6.1	*

*Destroyed

Table 2
Summary of volume damage constants of various npn transistor structures.

Code	Structure	n	$K_v 10^{-17}$
2N914	Planar-Expitaxial	1.56	7.2
Spl Dev	Planar-Expitaxial	1.55	6.0
2N718A	Planar	1.50	5.0
2N760	Mesa	1.42	5.5
40360	Diffused Junction	1.50	5.6

$$\Delta I_{BR} = K_v \cdot X_m(V) \cdot A_{ER} \cdot \phi \cdot \exp(qV/nkT)$$

$$\langle n \rangle = 1.51$$

$$\langle K_v \rangle = 5.6X10^{-17} \text{ (amperes/cm}^3\text{)/(nvt)}$$

Table 3
Base-emitter lifetime (ns) versus neutron fluence.

	bias voltage during irradiation						
	+0.5	-3.0	0.0	0.0	0.0	0.0	0.0
Dev. No.	#13	#65	#96	#59	#63	#28	#62
10^{13}nvt	values of τ_{BE} in nanoseconds						
0.0	130	130	130	208	208	208	208
1.0	104	83	87	104	104	104	104
2.0	59	69	70	78	78	78	78
4.0	39	35	35	42	42	42	43
6.0	26	26	26	26	26	26	26
8.0	26	21	20	21	21	21	21
10.0	*	*	*	*	*	*	*

#13, #65 and #96 are triplicate devices
#59, #63 and #28, #62 are pairs of devices
*beyond the limit of measurement

Table 4
Diffusion potential after isochronal annealing, normalized to its pre-irradiation value versus annealing temperature.

Temperature (°C) of annealing	27	75	95	155	255
Normalized V_T (%)	89.2	89.4	90.0	90.8	91.6

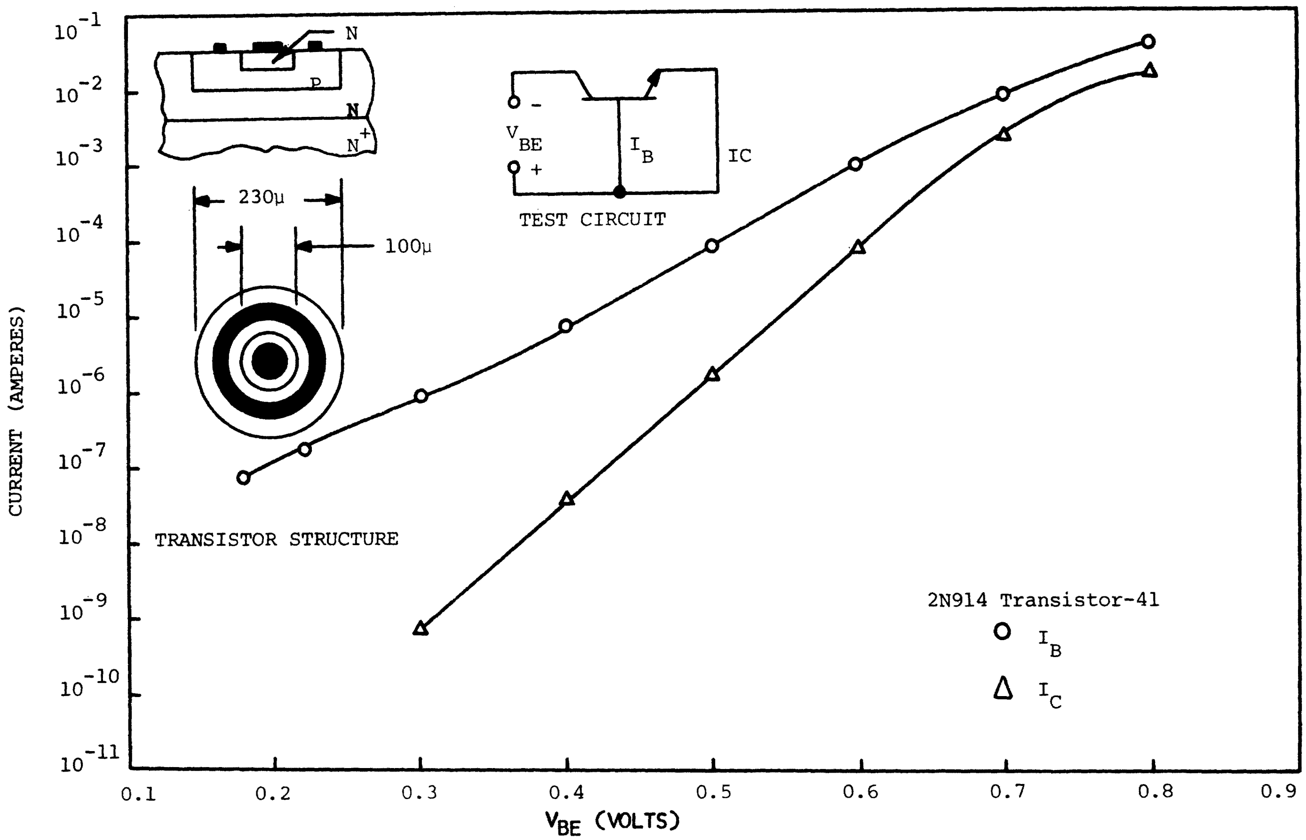

Fig. 1. Pre-Irradiation Inverse I-V Characteristics (Gold-Doped Device).

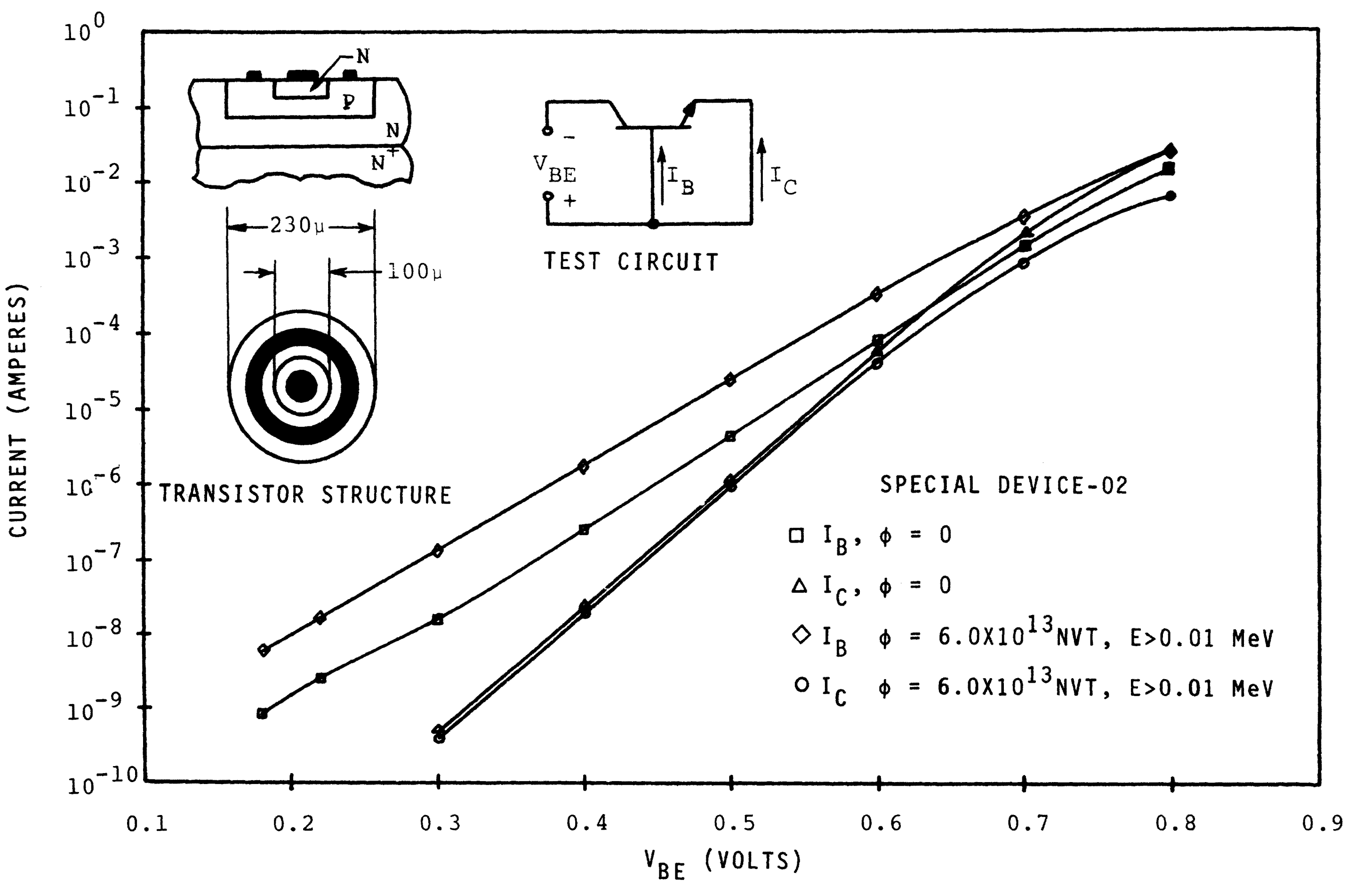

Fig. 2. Pre- and Post-Irradiation Inverse I-V Characteristics (Non-Gold-Doped Device).

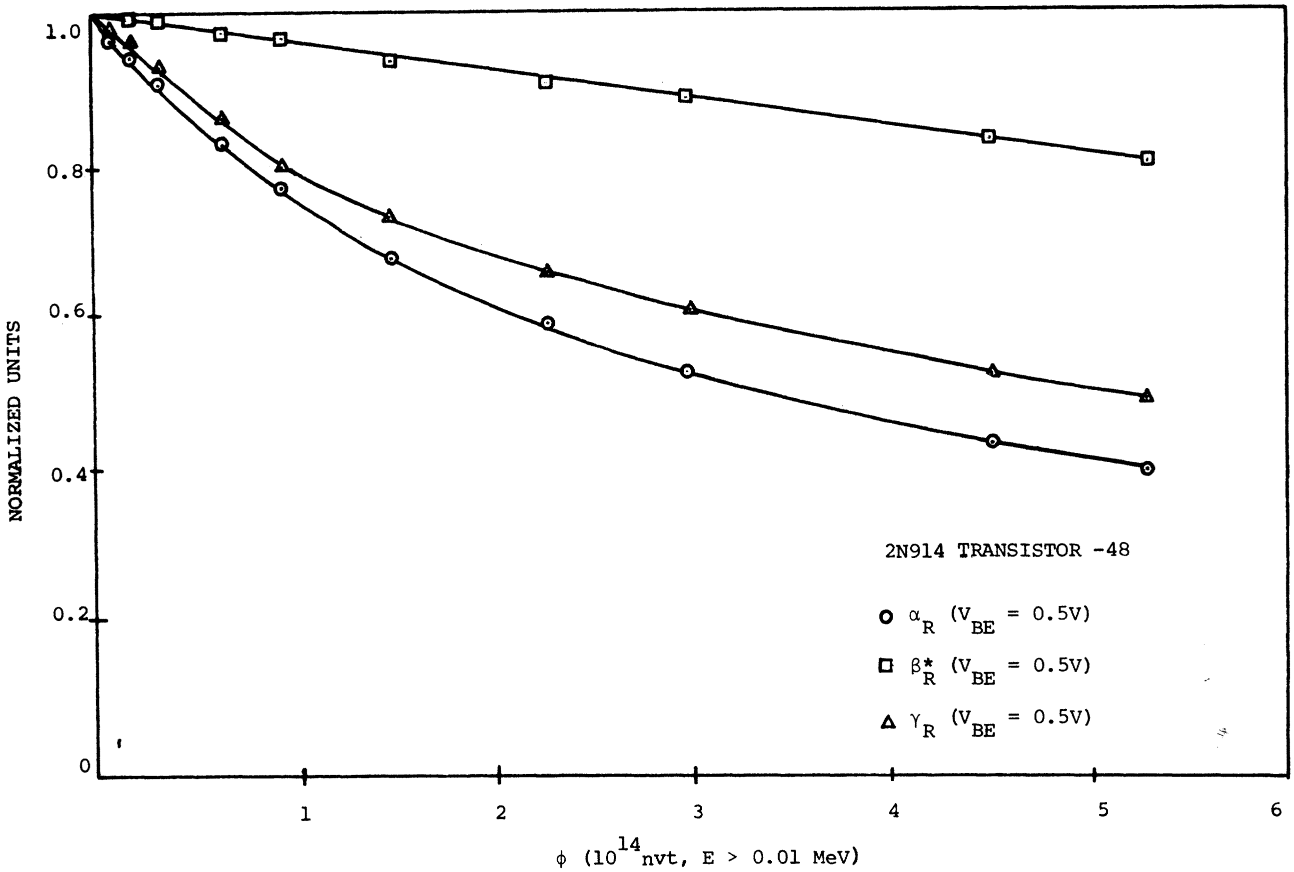

Fig. 3. Inverse Common Base Current Gain Versus Neutron Fluence (Gold-Doped Device).

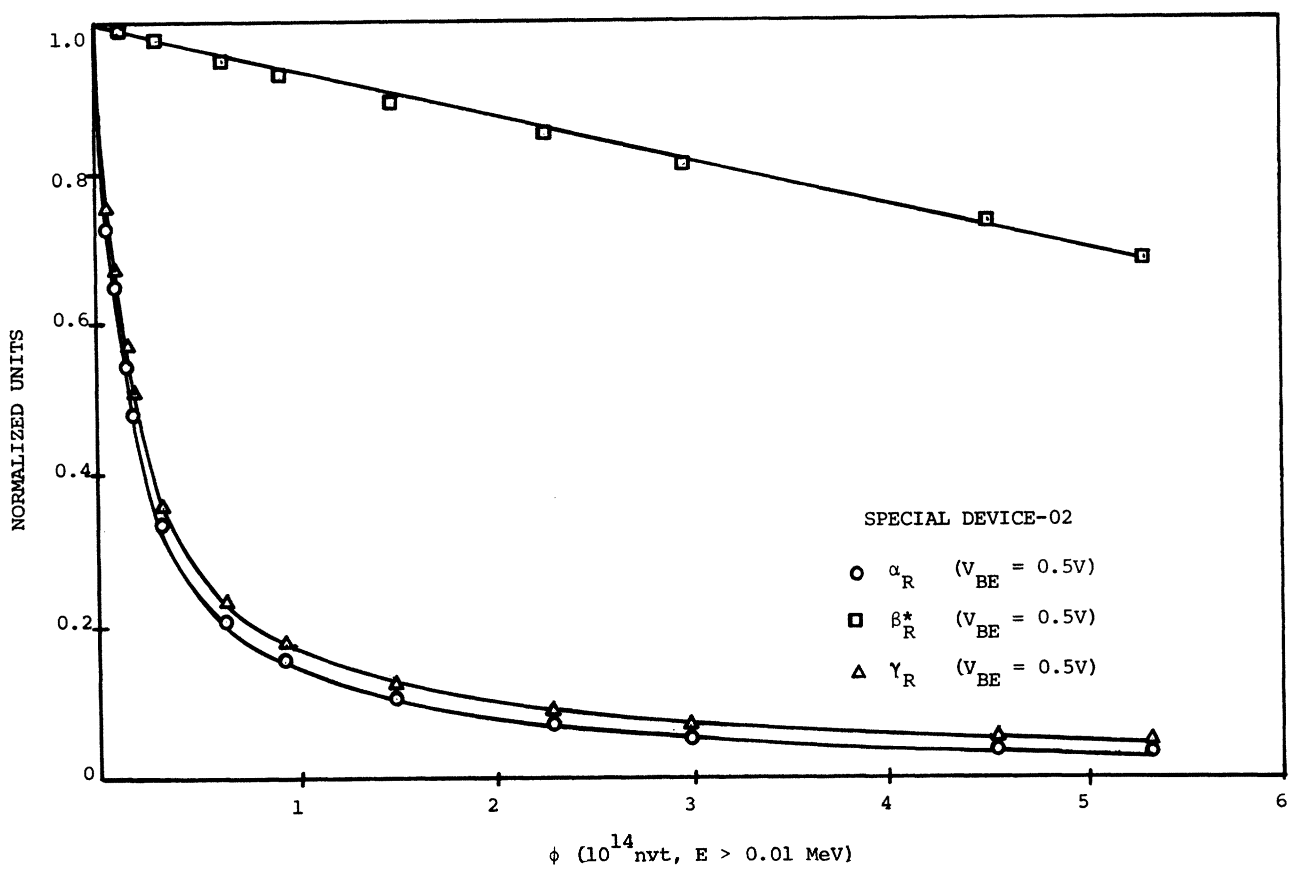

Fig. 4. Inverse Common Base Current Gain Versus Neutron Fluence (Non-Gold-Doped Device).

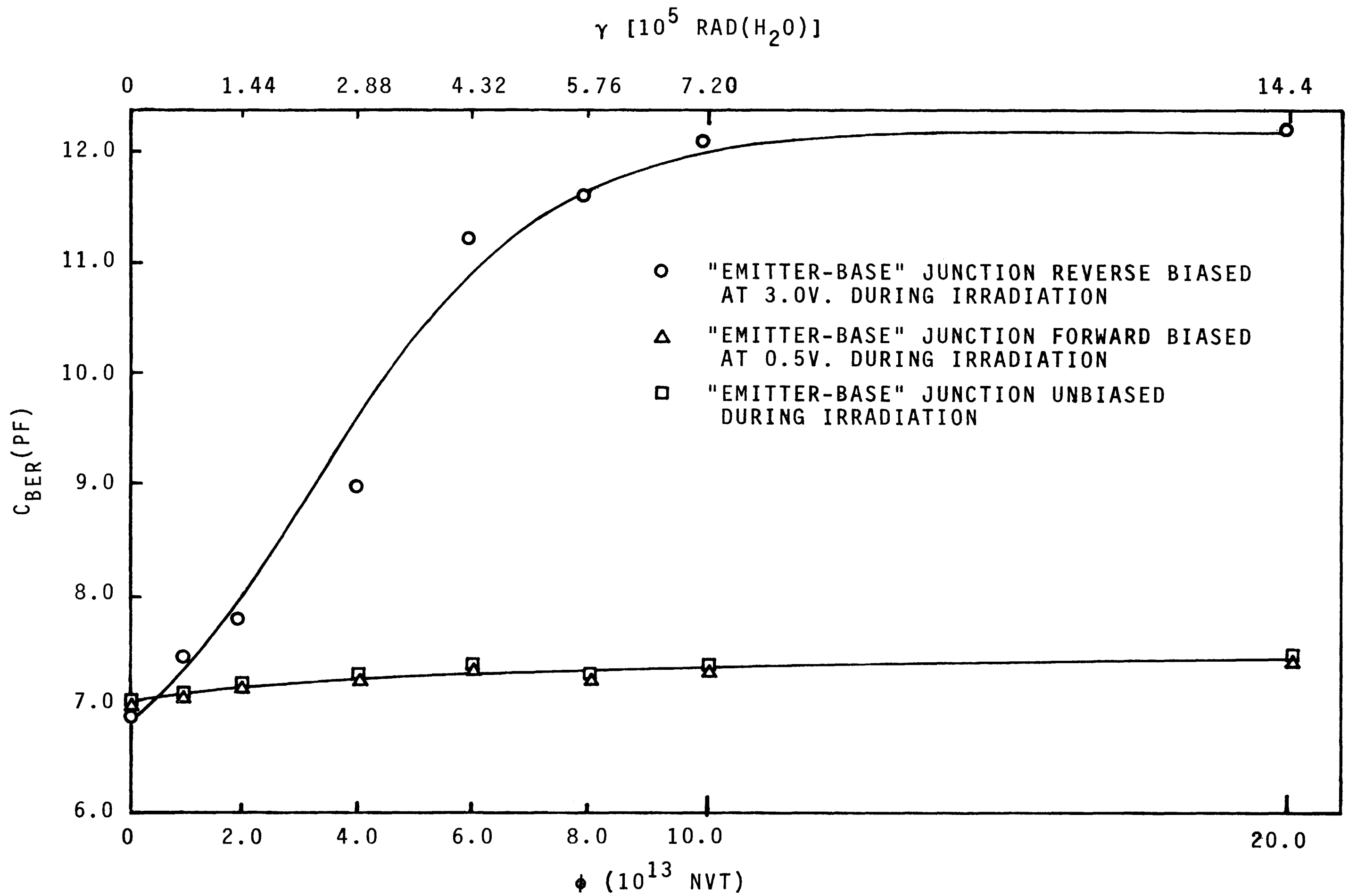

Fig. 5. "Emitter-Base" Junction Capacitance Versus Neutron Fluence (Measured at 0.0V DC).

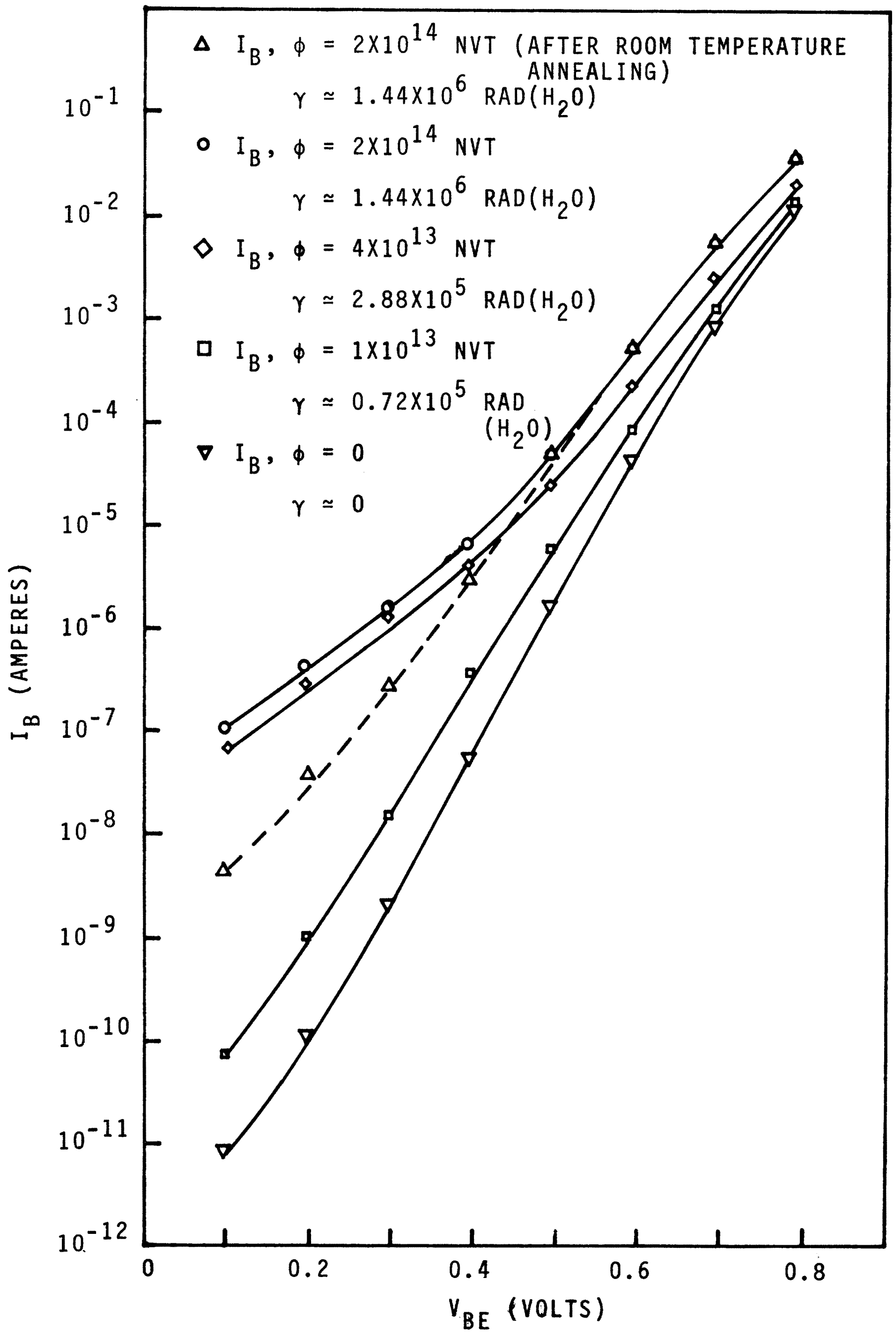

Fig. 6. Inverse Base Current-Voltage Characteristics for the Device Reverse Biased at 3.0V During Irradiation.

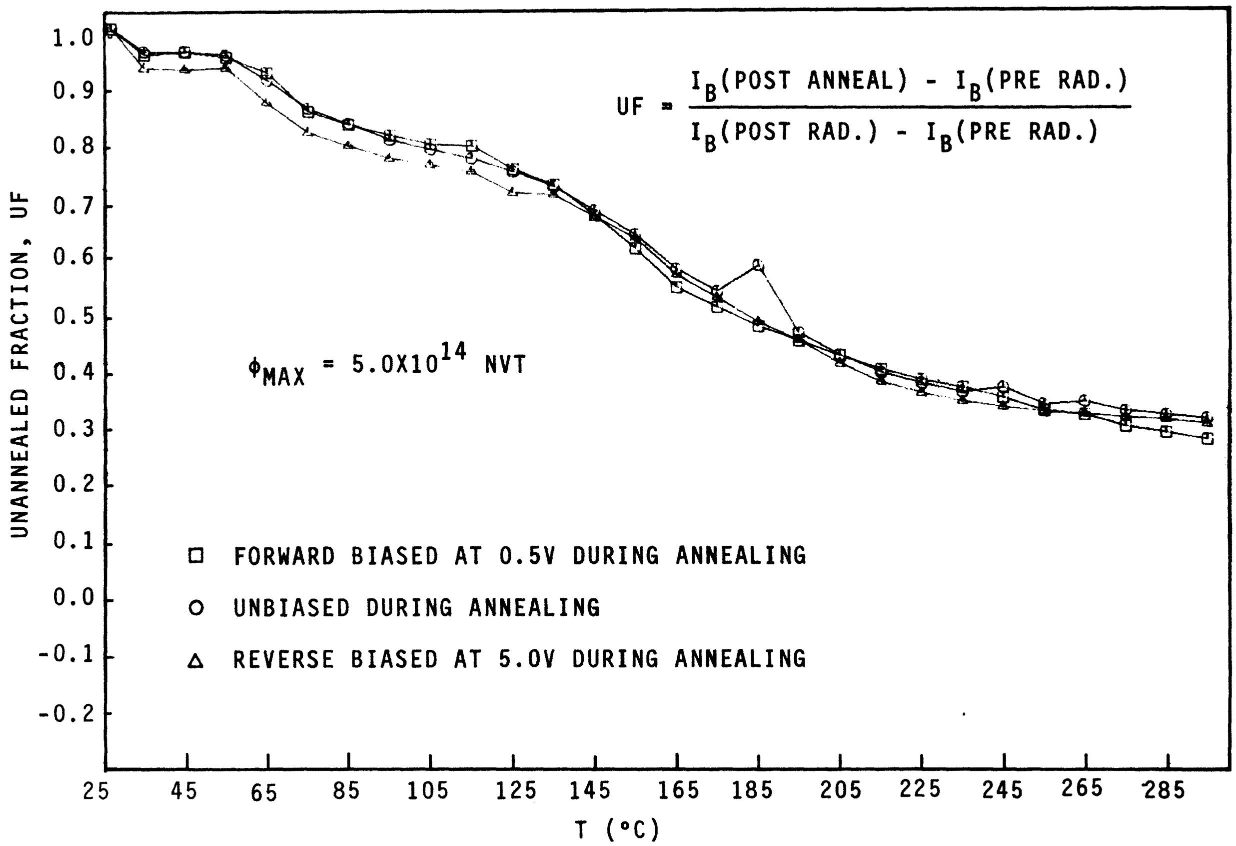

Fig. 7. Isochronal Annealing Curves for Defects in the Bulk Space-Charge Region Versus Temperature for Devices Biased at Three Different Voltages During Annealing.

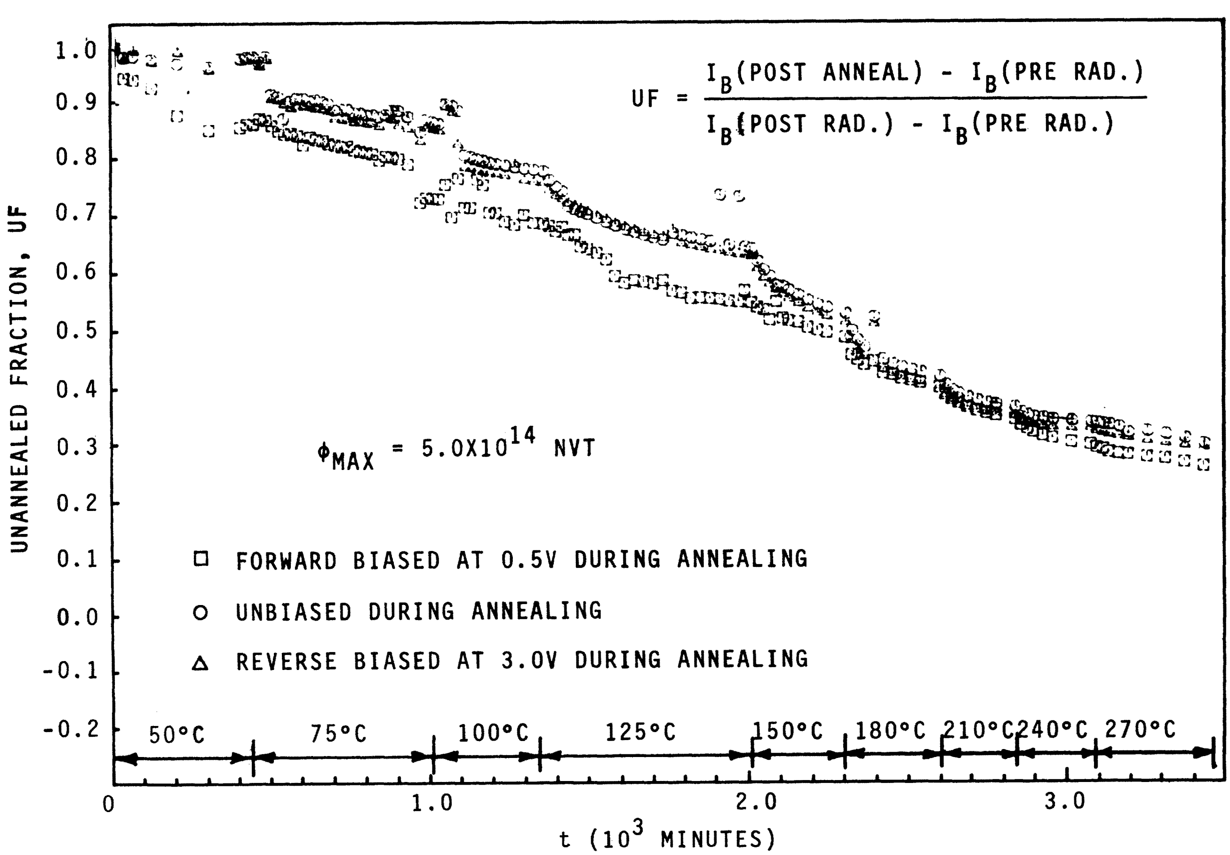

Fig. 8. Isothermal Annealing curves for Defects in the Bulk Space-Charge Region Versus Time for Devices Biased at Three Different Voltages During Annealing.

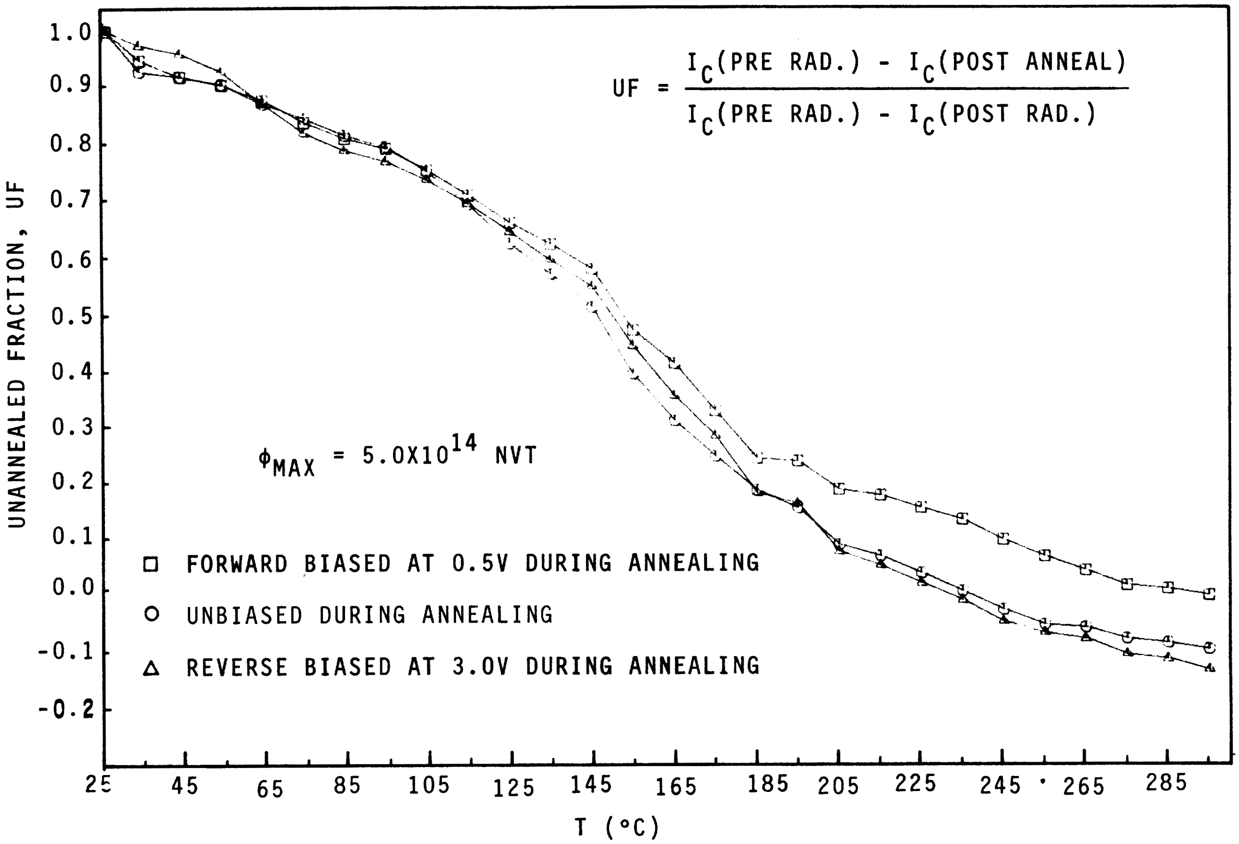

Fig. 9. Isochronal Annealing Curves for Defects in the Neutral Base Region Versus Temperature for Devices Biased at Three Different Voltages During Annealing.

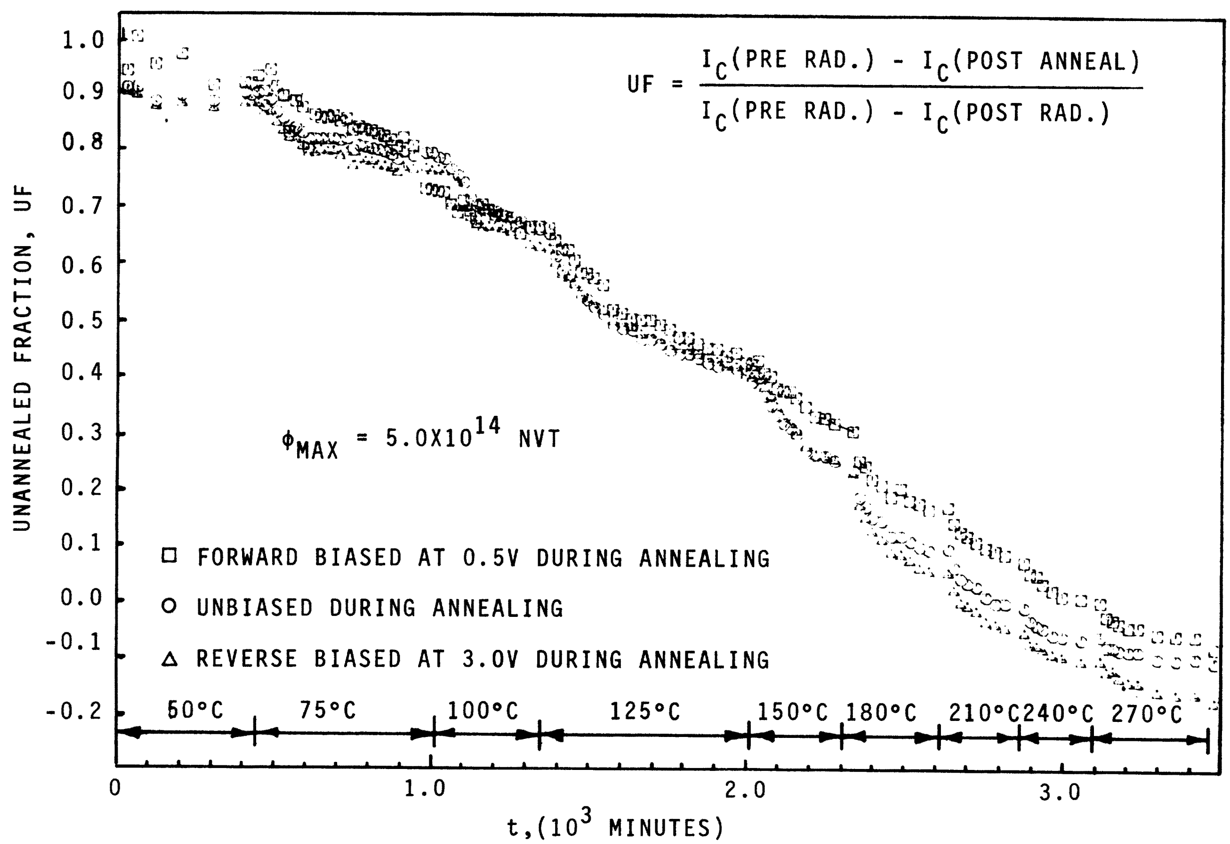

Fig. 10. Isothermal Annealing Curves for Defects in the Neutral Base Region Versus Time for Devices Biased at Three Different Voltages During Annealing.