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RECOMBINATION STATISTICS FOR NEUTRON BOMBARDED SILICON TRANSISTORS**

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Summary

This paper presents a recombination statistical model for the neutron-induced base current component reported previously. The derivation was based on the following: 1) the current equation for the induced current component developed previously; 2) the Shockley-Read-Hall statistics for holes and electrons; and 3) the recombination statistics derived by Sah, Noyce and Shockley for sites in the bulk space-charge region. The recombination statistics model depends on the diffusion potential, the junction voltage, the activation energy, temperature, and the ratio of capture cross-sections for holes and electrons. The utility of such a recombination statistical model is illustrated by using measured parameters to predict the neutron-induced base current for p-n junction transistors and by comparing the results with measured base currents. Further, the temperature variation of the reciprocal slope term is calculated from the model and found to agree well with experiment.

Introduction

Most electrical effects of radiation damage in semiconductors arise from the introduction of defect states into the forbidden band. From the recombination statistics developed by Shockley, Read and Hall[1-4] (SRH), the electrical properties of a defect state may be described by four parameters: the defect concentration (N_R, cm^{-3}); the defect energy (E_R, eV); and two cross sections, the hole capture cross section (σ_p, cm^{-2}) and the electron capture cross section (σ_n, cm^{-2}). The recombination process may be described by a mathematical model (i.e., recombination statistics), and these recombination statistics, which depend on the above mentioned parameters, will predict the neutron-induced current variations when the model is accurately fitted to the physical process. This paper presents a study of the recombination statistics for neutron bombarded silicon transistors.

In order to study the recombination statistics for the neutron-induced space-charge region base current component, several parameters were investigated. Capacitance-voltage measurements led to the determination of the device impurity distribution[5,6] which was then employed to calculate the concentration of neutron-induced defect levels (N_R) and the dependence of the diffusion potential (V_T) on neutron fluence.[7] The current-temperature characteristics yielded an activation energy, 0.23 eV, close to values given by other investigators[8-10].

The formulae for obtaining the limiting lifetimes, τ_{pr} and τ_{nr}, from transistor lifetimes in various regions were derived in this work. The capture cross-sections for holes and electrons were then calculated from N_R, τ_{pr} and τ_{nr}. All these parameters were used in the construction of a statistical model for the reciprocal slope term (n) in the expression $\exp(qV_{BE}/nkT)$.

Based on the model for the neutron-induced base current component previously[11-15] developed and the recombination statistics in the space-charge region given by Sah et al.[16,17], this paper develops a recombination statistical model for the neutron-induced space-charge region base current component. Subject to certain constraints, this model can be used for predicting the base currents of any diffused junction transistor operated in a neutron environment and may be extended to a more general model for other types of transistors. The dependence of the reciprocal slope term (n) on temperature is implicitly included in the developed recombination statistical model. The exponential fall-off rate for the density of states is also studied in this paper.

The two constraints governing the application of this model for the prediction of the base current are the fluence level to which the device has been subjected and the operating injection level of the device. This model is not accurate in predicting the total base current at low injection levels nor at high injection levels, since it is only concerned with the neutron-induced space-charge region base current component. This particular current component dominates the base current primarily at intermediate injection levels, and the extent of its influence increases with increasing fluence.

Minority Carrier Lifetimes, Capture Cross-Sections for Holes and Electrons

Minority Carrier Lifetimes

The expression for minority carrier lifetime, the relationships of limiting lifetimes (τ_{nr} and τ_{pr}) with base region and collector region minority carrier lifetimes and other parameters have been derived in detail[18]. These expressions are summarized below for convenience. The lifetime expression is

$$\tau = \frac{\tau_{pr}(n + n_r) + \tau_{nr}(p + p_r)}{n + p} \quad . \qquad (1)$$

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The relationships for the limiting lifetimes and collector lifetimes are:

$$\tau_{pr} = 1/N_R C_p; \qquad \tau_{nr} = 1/N_R C_n; \tag{2}$$

and in the n-type collector, where n>>p,

$$\tau_C \simeq \tau_{pr}[1 + \exp(\frac{E_R - E_F}{kT})]; \tag{3}$$

and in the p-type base, where p>>n,

$$\tau_B \simeq \tau_{nr} + \tau_{pr} \cdot \exp(\frac{E_R + E_F - 2E_i}{kT}); \tag{4}$$

where p_r, n_r = the hole and electron concentrations that would exist if the Fermi level coincided with the energy level E_R of the centers,

τ_{pr}, τ_{nr} = lifetimes of holes and electrons in highly n-type and p-type materials, respectively,

τ_B = base region minority carrier lifetime,

τ_C = collector region minority carrier lifetime,

N_R = concentration of defect centers,

E_i = intrinsic Fermi energy,

C_p,C_n = capture probabilities for holes and electrons.

From measured time constants associated with the p-n junction devices, the minority carrier lifetimes in the various regions of the device were calculated. That is, the values of τ_{EB} and τ_{BC} were calculated using data from risetime and storage time measurements, and from these the base and collector region lifetimes were calculated.[19] They are given by

$$\tau_B \simeq \tau_{EB}, \tag{5}$$

$$\tau_C \simeq \frac{\tau_{EB} - \tau_{BC}}{\tau_{EB} \cdot \tau_{BC}}, \tag{6}$$

from which the minority carrier lifetimes in both base and collector regions are obtainable.

The empirical expression[20,21] for the relationship of minority carrier lifetime with neutron fluence can be written, for low to moderate fluences, as:

$$\frac{1}{\tau} = \frac{1}{\tau_o} + K \cdot \phi, \tag{7}$$

where τ_o = pre-irradiation minority carrier lifetime,

τ = post-irradiation minority carrier lifetime,

K_τ = minority carrier lifetime radiation damage factor,

ϕ = neutron fluence.

The pre-irradiation values of τ_{EB}, τ_{BC}, τ_B, τ_C, and the lifetime damage constants for τ_B and τ_C for the devices used in this work are listed in Table 1. These values were obtained from curve fitting the observed data by a least-squares fitting technique.

Determination of Defect Activation Energy

The Automatic Data Acquisition System[22,23] was used to measure the base and the collector currents at constant emitter-to-base bias at a specific temperature. The temperatures used in this work were -60°C, -50°C, -40°C, -30°C, -20°C, -10°C, 0°C, 10°C, 20°C and 27°C. From the I-V data for different temperatures, log(I) (at constant bias) versus 1/T was plotted by machine (Calcomp Model 556 Plotter). A computer program using a least-squares fitting technique was employed to find the best-fit of log(I_B) vs 10^3/T. The value of the dominant activation energy (E_c - 0.23eV) obtained by this process from a study of nine devices was found to be independent of both bias and neutron fluence for all fluences of interest in this work.

Concentration of Neutron-Induced Defect Centers

The concentration of the neutron-induced defect centers, N_R, can be determined from knowledge of the impurity distribution at various neutron fluences. The technique[24] used for the determination of the impurity concentration of a p-n junction followed the method of Hilibrand and Gold[5], using the Lawrence and Warner[6,18] curves and correction factors[5]. The technique was used for both the emitter-base and base-collector junctions. The impurity profile in the vicinity of the metallurgical junctions was determined by forward biased capacitance measurements, and that in the normally "neutral regions" adjacent to the junction depletion layers was determined by reverse biased capacitance measurements.

In this work, it was assumed that the impurity distribution of double-diffused 2N914 planar-epitaxial transistors and the other special devices fabricated for this work (which were identical except they were not gold doped) would have a depth dependence of[25]

$$N(x) = N_{OE}\mathrm{erfc}(L_E x) - N_{OB}\exp(-L_B^2 x^2) + N_{BC}, \tag{8}$$

where N_{BC} = the background concentration,

N_{OE} = the surface concentration for the emitter diffusion,

N_{OB} = the surface concentration for the base diffusion,

x = the depth (distance from the surface).

The impurity concentration data obtained for regions adjacent to the junctions were then used in the fitting of N(x) given by equation (8). Typical values of N_{OE} = 2.5 X 10^{20} cm^{-3}, N_{OB} = 6.0 X 10^{18} cm^{-3}, N_{BC} = 1.1 X 10^{16} cm^{-3}, L_E = 1.15 X 10^6 cm^{-1} and L_B^2 = 0.69 X 10^{12} cm^{-2} were obtained. The impurity profiles at various neutron fluences for a particular device (Special Device #40) are illustrated in Figure 1. It should be emphasized that the curves in Figure 1 are computer output plots of equation (8). The impurity distribution has been determined by measurement of the profile in the vicinity of the junction and extrapolated by computer-fitting equation (8) to the measured data points in the vicinity of the junctions.

The effective concentration of the neutron-induced defect centers, N_R, has the approximate empirical expression, $N_R = \Delta N/2$, where ΔN is the change in concentration (cm^{-3}). Other investigators have reported carrier removal rates of 1.5 to 1.7 for n-type silicon and 2.9 to 3.0 for p-type silicon[26,27]. A value of 2 was used as an approximation in this work.

The frequency dependence of the capacitance of junctions with deep traps is described in the literature[28-30]. This dependence must be considered when determining the impurity profile. A paper describing the technique for determining the impurity distribution after neutron radiation is presently being prepared by the authors. Nevertheless, any other technique for determining the post-irradiation defect concentration, such as assuming a constant carrier removal rate, could be used[26,27].

Determination of the Diffusion Potential (V_T)

A series of clusters (8 in this work) of six voltage-capacitance points, at one or two per cent intervals in capacitance was taken. It was assumed that the capacitance as a function of voltage (V_{BE}) could be given by $C = K/(V_T - V_{BE})^m$ for the range covered by each cluster, where K, V_T, and m are constants within each cluster. The depletion layer width, x_m, is given by $x_m = A\varepsilon/C_a$, where C_a is the capacitance corresponding to the average voltage of a cluster.

The capacitance-voltage data were used as the input of a computer program; a non-linear least-squares fit was used to obtain a best fit to the capacitance data. The output of the computer program yielded K, V_T and m.

Limiting Lifetimes and Capture Cross-Sections

Knowing the activation energy (E_R)[24], the minority carrier lifetimes, and determining the Fermi energy (E_F) from relationships given by Lindmayer and Wrigley[31], one can determine the limiting lifetimes by using equations (3) and (4). Table 2 shows the calculated τ_{pr} and τ_{nr} at various neutron fluences at 300°K for two devices.

The capture cross-sections for holes and electrons are $\sigma_p = C_p/v_p$ and $\sigma_n = C_n/v_n$ where v_p, v_n are the thermal velocities for holes and electrons[9,32].

The capture probabilities of the sites for holes and electrons were calculated by using equation (2) and the calculated defect concentration (N_R) and the values for τ_{pr} and τ_{nr}. The capture-cross-sections for holes and electrons were then obtained by using the above equations. The thermal velocities for holes and electrons used in this work are $v_p = 1.5 \times 10^7$ (cm-sec^{-1}) and $v_n = 2.0 \times 10^7$ (cm-sec^{-1}) as given by Messenger[9]. Table 3 lists some typical values for σ_p and σ_n.

Due to the accuracy of the lifetime measurements, only the first two digits of the data for the capture cross-sections are significant and the data are approximately constant.

Recombination Statistics - Model Fitting

Sah-Noyce-Shockley Theory of Junction Space-Charge Recombination-Generation Current

The theoretical expression for I_{BN} is given in the Sah-Noyce-Shockley theory[16] as

$$I_{BN} = \frac{2qn_i A x_m}{(\tau_{pr}\tau_{nr})^{1/2}} \cdot \frac{f(b) \cdot \sinh(qV_{BE}/2KT)}{q(V_T - V_{BE})/kT}, \qquad (9)$$

where

$$f(b) = \int_{z_1}^{z_2} \frac{dz}{(z^2 + 2bz + 1)}, \qquad (10)$$

$$b = \exp\left(\frac{qV_{BE}}{2kT}\right) \cdot \cosh\left[\frac{E_R - E_i}{kT} + \frac{1}{2} \cdot \log_e\left(\frac{\tau_{pr}}{\tau_{nr}}\right)\right] \qquad (11)$$

$$z_{1,2} = \left(\frac{\tau_{pr}}{\tau_{nr}}\right)^{1/2} \cdot \exp\left[\pm \frac{q(V_T - V_{BE})}{2kT}\right]. \qquad (12)$$

The Expression for the Reciprocal Slope Term for the Neutron-Induced Base Current Component

The neutron-induced base current is given[11-15,33] by the following equation,

$$I_{BN} = K_v \cdot A_E \cdot x_m(V_{BE}) \cdot \phi \cdot \exp(qV_{BE}/nkT) \qquad (13)$$

where K_v is a volume damage constant with units of (amp/cm^3) / (neutron/cm2), and $x_m(V_{BE})$ is the depletion layer width of the emitter-base junction. A value of K_v was calculated as 5.6×10^{-17} for n-p-n silicon junction transistors used in this investigation[33]. Taking the derivatives of the logarithm of I_{BN} from equation (9), one obtains[34]

$$\frac{d}{dV_{BE}}(\log_e I_{BN}) = \frac{1}{x_m} \cdot \frac{dx_m}{dV_{BE}} + \frac{q}{kT} \cdot \frac{1}{2} \cdot \coth\frac{qV_{BE}}{2kT} + \frac{d}{dV_{BE}}[\log_e f(b)] + \frac{1}{V_T - V_{BE}}, \qquad (14)$$

and from equation (13), one can show that the reciprocal slope term is

$$\frac{1}{n} = \frac{kT}{q}\left[\frac{d}{dV_{BE}}(\log_e I_{BN}) - \frac{1}{x_m} \cdot \frac{dx_m}{dV_{BE}}\right]. \qquad (15)$$

Combining equations (14) and (15) one obtains

$$\frac{1}{n} = \frac{1}{2}\coth\frac{qV_{BE}}{2kT} + \frac{kT}{q}\frac{1}{V_T - V_{BE}} + \frac{kT}{q}\frac{d}{dV_{BE}}[\log_e f(b)]. \qquad (16)$$

If the emitter-base bias (V_{BE}) is larger than 0.15V at room temperature, then $qV_{BE}/2kT > 4$ and coth $(qV/2kT) \simeq 1$, and equation (16) becomes

$$\frac{1}{n} = \frac{1}{2} + \frac{kT}{q}\frac{1}{V_T - V_{BE}} + \frac{kT}{q}\frac{d}{dV_{BE}}[\log_e f(b)]. \qquad (17)$$

The integral given by f(b) in equation (10) may be evaluated under three cases:

1. when $b < 1$, it yields

$$f(b) = \frac{1}{\sqrt{1 - b^2}} \arctan \left[\frac{2\sqrt{1 - b^2} \cdot \sinh\frac{q(V_T - V_{BE})}{2kT}}{(\frac{\tau_{nr}}{\tau_{pr}})^{1/2} + (\frac{\tau_{pr}}{\tau_{nr}})^{1/2} + 2b \cdot \cosh\frac{q(V_T - V_{BE})}{2kT}} \right]. \quad (18)$$

2. when $b = 1$, it yields

$$f(b) = \frac{2 \cdot \sinh \frac{q(V_T - V_{BE})}{2kT}}{(\frac{\tau_{pr}}{\tau_{nr}})^{1/2} + (\frac{\tau_{nr}}{\tau_{pr}})^{1/2} + 2 \cdot \cosh \frac{q(V_T - V_{BE})}{2kT}} \quad (19)$$

3. when $b > 1$, it yields

$$f(b) = \frac{1}{2\sqrt{b^2 - 1}} \cdot \log_e \left[\frac{(\frac{\tau_{nr}}{\tau_{pr}})^{1/2} + (\frac{\tau_{pr}}{\tau_{nr}})^{1/2} + 2b \cdot \cosh\frac{q(V_T - V_{BE})}{2kT} + 2\sqrt{b^2 - 1} \cdot \sinh\frac{q(V_T - V_{BE})}{2kT}}{(\frac{\tau_{nr}}{\tau_{pr}})^{1/2} + (\frac{\tau_{pr}}{\tau_{nr}})^{1/2} + 2b \cdot \cosh\frac{q(V_T - V_{BE})}{2kT} - 2\sqrt{b^2 - 1} \cdot \sinh\frac{q(V_T - V_{BE})}{2kT}} \right] . \quad (20)$$

A multivariate least squares fitting technique[35] was used to construct a statistical model for the reciprocal slope term from equation (17) with equations (18), (19), and (20). The resulting statistical model is:

$$\frac{1}{n} = 0.4107 + \frac{kT}{q} \cdot \frac{6.55 \times 10^{-2}}{V_T - V_{BE}} + \frac{kT}{q} \cdot \frac{2.948}{E_R - E_i} + 6.34 \times 10^{-3} \cdot \log_e [(\frac{\sigma_p}{\sigma_n})^{1/2} - (\frac{\sigma_n}{\sigma_p})^{1/2}]. \quad (21)$$

Equation (21) is the recombination statistical model for the reciprocal slope term (n) which predicts the neutron-induced base current component for n-p-n silicon transistors with considerable accuracy when used in equation (13).

Note that since E_R is not a function of neutron fluence and, as seen from Table 3, σ_n/σ_p is very nearly constant with fluence, the only neutron fluence dependence of 1/n arises from V_T. This dependence is discussed in reference 32.

Three examples are presented (Figures 2, 3, and 4) which illustrate the utility of the recombination statistical model in prediction of the neutron-induced base current component for n-p-n silicon transistors.

Temperature Dependence of the Reciprocal Slope Term (n)

In the derived recombination statistical model for n, temperature (T) is explicitly included; thus, the dependence of n on temperature is explicitly studied. Figure 5 shows the predicted and observed temperature dependence of 1/n, in which $E_R - E_i = 0.32$eV, $V_T - V_{BE} = 0.48$V and σ_n/σ_p is a parameter. The experimental value of σ_n/σ_p from Table 3 lies in the range of 40 to 50. Examination of the curves of Figure 5 shows that the value of σ_n/σ_p needed to obtain a theoretical 1/n-curve which would pass through the experimental data points lies in approximately the same range. Thus, one can conclude that the derived model for the neutron-induced base current accurately predicts the effects of neutron radiation in a silicon p-n junction.

Discussion

The neutron-induced base current component was first identified in 1964 and found to be of bulk and not of surface origin and, hence, was attributed to recombination-generation in the bulk space-charge region. The exact nature of the recombination statistics of this neutron-induced base current component depends mostly on four parameters (N_R, E_R, σ_p and σ_n) which largely describe the electrical properties of a defect state. That is, the recombination process may be described by a mathematical model if the model is accurately fitted to the physical process.

In this work, the impurity profile in the vicinity of metallurgical junctions was determined by forward biased capacitance measurements, and that in the normally "neutral regions" adjacent to junction depletion layers was determined by reverse biased capacitance measurements. The dependence of the diffusion potential (V_T) on neutron fluence was derived from capacitance-voltage measurements as a function of neutron fluence.

The dominant activation energy (E_R) determined from current-temperature measurements has the value of 0.23eV. This activation energy was found to be independent of neutron fluence at low to moderate fluences.

The minority carrier lifetimes in base and collector regions were calculated from the measured transistor risetime and diode storage time. The lifetime damage constants $K_\tau = 2.3 \times 10^{-7}$ (cm^2/n-sec) in the p-type base region and $K_\tau = 8.5 \times 10^{-9}$ (cm^2/n-sec) in the n-type collector region were obtained. From the values of N_R, τ_B, τ_C, E_R, and E_F, the ratios of electron to hole capture cross-sections have been found to be in the range of 40 to 50.

A statistical model of n was developed, and the dependence of n on temperature is correctly given by the model. From the given example, it can be seen that this statistical model of n gives a good fit to those current levels for which $V_{BE} < 0.75$ volts. Discrepancy between the predicted and observed values in the higher current levels suggests there may be another neutron-induced base current component which dominates the base current in the higher current level range. In addition, emission crowding complicates the study for values above 0.75V.

The model developed in this investigation was derived for n-p-n silicon junction transistors and may be extended to a more general model for other types of transistors.

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Table 2
Limiting lifetimes at 300°K

	Spec. Device #40 (ring-dot)		Spec. device #68 (Tetrode)	
ϕ 10^{13} nvt	τ_{nr} 10^{-7} sec	τ_{pr} 10^{-7} sec	τ_{nr} 10^{-7} sec	τ_{pr} 10^{-7} sec
0.1	1.21	19.06	1.39	10.51
0.9	1.07	16.90	1.18	8.90
1.2	0.94	14.79	1.00	7.56
2.1	0.78	12.34	0.81	6.11
3.9	0.59	9.32	0.59	4.45
6.2	0.45	7.03	0.43	3.24
8.3	0.37	5.80	0.35	2.63
10	0.31	4.93	0.29	2.22
18	0.20	3.18	0.19	1.40
23	0.16	2.55	0.15	1.11
29	0.13	2.08	0.12	0.90
31	0.12	1.86	0.11	0.81
41	0.097	1.53	0.087	0.66
53	0.077	1.21	0.069	0.52

Table 3
Capture cross-sections for holes and electrons

	Spec. Device #40		Spec. Device #68	
ϕ 10^{13} nvt	σ_n 10^{-15} cm^{-2}	σ_p 10^{-16} cm^{-2}	σ_n 10^{-15} cm^{-2}	σ_n 10^{-16} cm^{-2}
0.1	9.21	1.93	5.24	1.03
3.9	9.41	1.93	5.25	1.03
10.	9.22	1.93	5.24	1.03
53.	9.22	1.93	5.24	1.03

Table 1

Lifetimes and damage constants

Unit	τ_{EB} ns	τ_{BC} ns	τ_B ns	K_{τ_B} X10^{-7}	τ_C ns	K_{τ_C} X10^{-9}
40	122	115	122	2.31	1.93	4.52
46	123	117	123	2.29	2.28	5.37
47	123	119	123	2.29	3.56	4.66
48	130	123	130	2.23	2.24	2.72
62	137	121	137	2.71	1.03	8.59
68	144	125	144	2.62	0.98	8.02

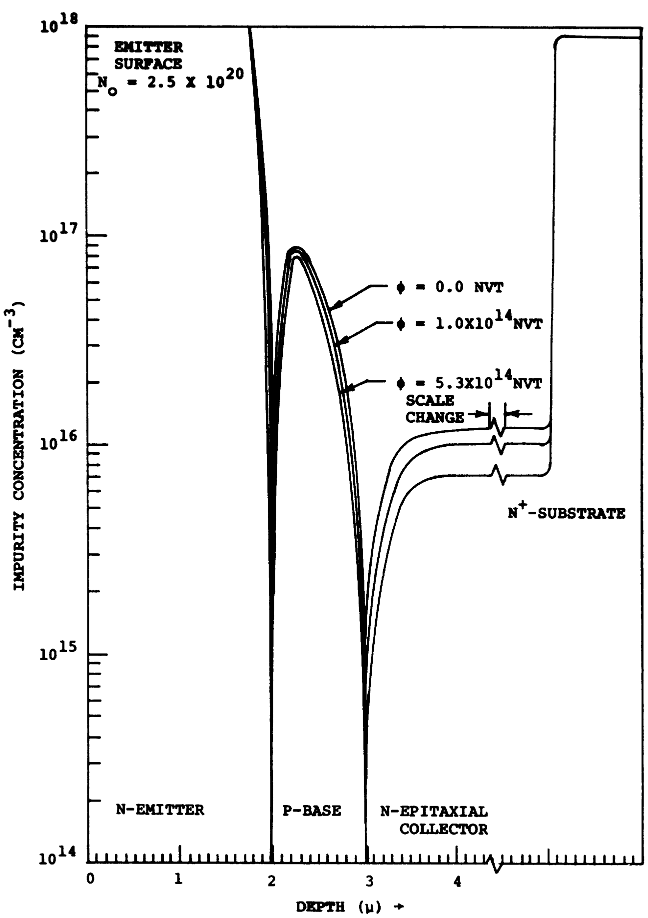

FIG. 1. PLANAR-EXPITAXIAL TRANSISTOR IMPURITY PROFILE AT VARIOUS NEUTRON FLUENCES (SPECIAL DEVICE #40).

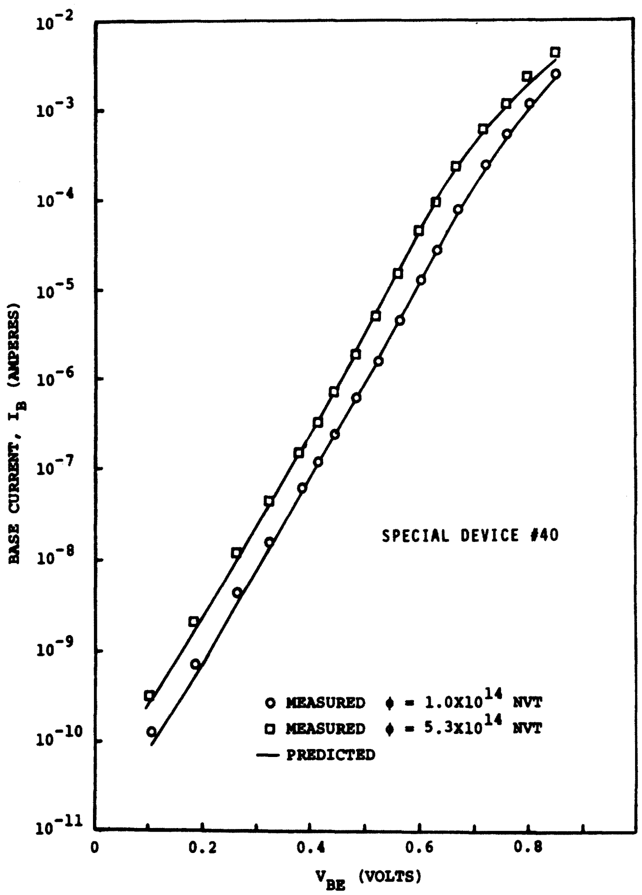

FIG. 2. PREDICTED AND OBSERVED BASE CURRENT VERSUS EMITTER-BASE BIAS (SPECIAL DEVICE #40).

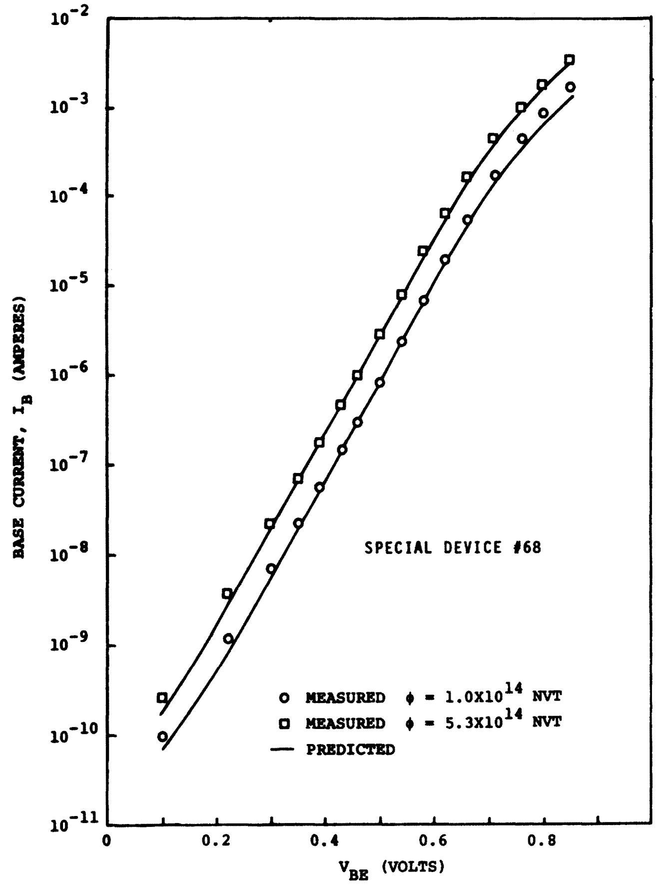

FIG. 3. PREDICTED AND OBSERVED BASE CURRENT VERSUS EMITTER-BASE BIAS (SPECIAL TETRODE DEVICE #68).

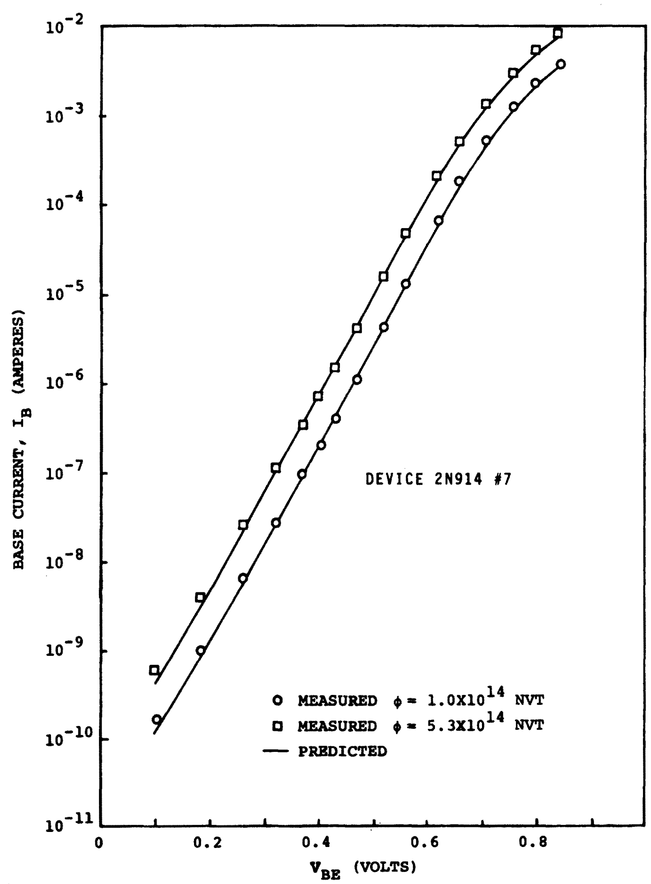

FIG. 4. PREDICTED AND OBSERVED BASE CURRENT VERSUS EMITTER-BASE BIAS (DEVICE 2N914 #7).

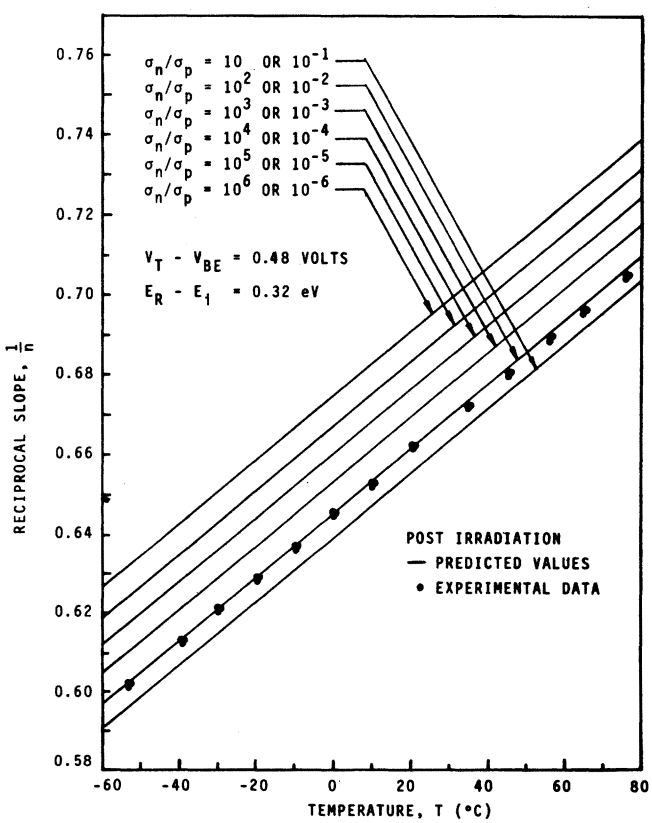

FIG. 5. PREDICTED AND OBSERVED TEMPERATURE DEPENDENCE OF THE RECIPROCAL SLOPE, 1/n, FOR n-p-n SILICON TRANSISTORS.