TECHNICAL PROGRESS REPORT

MASTER

NUCLEAR RADIATION EFFECTS ON SILICON P-N JUNCTIONS

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ON
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ABSTRACT

A set of recombination statistics for the neutron-induced base current component in p-n junction semiconductor devices has been created from a theoretical basis and has been checked against experimental data and found to predict the change in the base current quite well over the range where the neutron-induced current component dominates p-n junction device behavior. Work has begun on developing a model for analyzing and predicting the behavior of p-n junction semiconductor transistors with knowledge only of the basic device parameters, the applied voltages or currents at the metallic contacts, and the neutron fluence. This model does not depend on the arbitrary definition of "neutral" and "space-charge" regions used in previous attempts at constructing such analytical and/or predictive models. A large increase in bulk recombination at moderate to high injection levels has been theoretically predicted and experimentally confirmed. Models for the base recombination change (base transport factor change) have been constructed and checked against experimental evidence. Further work is in progress in this area. Studies of p-n junction devices operated in the inverse configuration have been made and have contributed to the understanding of the introduction rate of the neutron-induced current component — volumetric introduction rate was found to be 5.6×10^{-17} amperes/cm³ nvt. Additionally, an interesting surface effect was found. Studies of the neutron-induced changes of the collector junction parameters are under way, and an anomalous effect indicating recombination (rather than generation, which would be expected) in the collector junction has been observed. The field dependences of the neutron-induced defects and their effect on the damage introduction rate is under investigation. The size, shape, and orientation of defect clusters in a p-n junction depletion layer is being investigated with the aid of a Scanning Electron Microscope. The mobility of radiation-induced defects under the influence of an electric field is being investigated via especially constructed p-n junction devices. The effects of neutron radiation on the high-frequency parameters of p-n junction semiconductor devices (a heretofore neglected area of research) is being studied via scattering parameter measurements. A quasi-tunneling model is under consideration to determine if this model will correctly predict the observed changes induced by neutron bombardment at low and intermediate current levels.

TECHNICAL PROGRESS STATUS OF EXPERIMENTS

Recombination Statistics for the Neutron-Induced Current Component

The neutron-induced base current component was first identified¹ in 1964 and found to be of bulk and not of perimeter origin and, hence, must be 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 the 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, recombination statistics, and these recombination statistics, which depend on the above mentioned parameters, will predict the correct value for n in $\exp(qV_{BE}/nkT)$ when 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 calculated impurity concentration data adjacent to the junctions were then employed in the fitting of $N(x) = N_{OE} \operatorname{erfc}(L_E x) - N_{OB} \exp(-L_B^2 x^2) + N_{BC}$, so that the impurity distribution of the transistor could be determined. From the determined impurity profile at various neutron fluences, the defect concentration N_R was calculated and the carrier removal coefficients for holes and electrons, $K_p = 2.6 \times 10^{-3} \times N_o^{0.23}$ and $K_n = 2.2 \times 10^{-3} \times N_o^{0.23}$, respectively, were obtained. The dependence of the 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 by using a Tektronix 555 Oscilloscope with a Tektronix Type R risetime and a Type S recovery time plug-in units. The lifetime damage constants of $K_T = 2.3 \times 10^{-7} \text{ (cm}^2/\text{n-sec)}$ in the p-type base region and $K_T = 8.5 \times 10^{-9} \text{ (cm}^2/\text{n-sec)}$ in the n-type collector region were obtained. From the values of N_R , τ_B , τ_C , E_R , and E_F , the capture cross section for holes has been calculated as $\sigma_p = 1.8 \times 10^{-15} \text{ cm}^2$ for electrons.

The reciprocal slope term, n , in $\exp(qV_{BE}/nkT)$ of the neutron-induced base current component studied in this work, is based on the model given for the neutron-induced base component by Goben,^{2,3} on Shockley-Read-Hall^{4,5} statistics and on Sah-Noyce-Shockley⁶ statistics. A statistical model for 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 densities for $V_{BE} < 0.75$ volts. Discrepancy between the predicted and observed values in the higher injection level suggests there may be another neutron-induced base current component which dominates the base current in the higher current density range. Additionally, emission crowding complicates the study 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. These results were published in more detail in a paper by Chow, Azarewicz and Goben⁷ (COO-1624-12) and Chow's doctoral dissertation⁸ (COO-1624-14) both of which are included with this report as reprints.

An Iterative Scheme for the Determination of Transistor Characteristics After Neutron Radiation

The feasibility of making steady state transistor calculations by applying boundary conditions only at the transistor metallic contacts and ignoring the arbitrary definitions of "neutral" and "space charge" regions has been shown by Gummel⁹. The data needed for those calculations were:

- 1) the impurity doping profile for the transistor;
- 2) the mobility as a function of impurity doping and electric field;
- 3) excess carrier generation-recombination statistics;
- 4) the applied emitter and collector voltages.

The approach used by Gummel⁹ was to assume that for narrow-base transistors, the electrostatic potential and hole-quasi-fermi levels are relatively unchanged by recombination until recombination becomes large. Therefore, the hole-quasi-fermi level could be expressed in terms of the electrostatic potential. Hence, an iterative scheme could be used to determine the transistor characteristics. This technique is being extended to the case of neutron irradiated transistors.

The iterative procedure is briefly outlined as follows;

- 1) obtain a starting value for the electrostatic potential;

- 2) using the electrostatic potential, calculate the quasi-fermi-potentials and obtain the hole and electron concentrations and recombination rate;
- 3) knowing the hole and electron concentrations, a correction on the electrostatic potential can be made using Poisson's equation;
- 4) repeat this process until the boundary conditions are satisfied.

The technique used for the determination of the impurity concentration of a p-n junction follows the method of Hilibrand and Gold¹⁰ using the Lawrence and Warner¹¹ curves and correction factors — a more extensive table of correction factors was prepared in this laboratory. This technique was used for both the emitter-base and collector-base junctions. 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 the junction depletion layers was determined by reverse-biased capacitance measurements.

The depth dependence of the impurity concentration for the double diffused devices used in this work follows the equation

$$N(x) = N_{OE} \operatorname{erfc}(L_E x) - N_{OB} \exp(-L_B^2 x^2) + N_{BC}, \quad (1)$$

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 Eq. (1).

It is well known that in any diffusion process the diffusivity is a function of concentration and field. The impurity profile has been calculated in recent work¹² incorporating the effects of doping and field interaction. But for the present work, where the impurity concentrations are small in the regions of interest (N less than $10^{19}/\text{cm}^3$), Eq. (1) gives a good fit to the actual profile. Hence, the impurity profile is determined from fitting Eq. (1) to the impurity concentration data obtained from the regions adjacent to the junctions.

For the determination of the impurity distribution in junction diodes from capacitance-voltage data, differentiation of the capacitance-voltage data is necessary. The problem of the frequency dependence of the capacitance measurements was considered. A model for

the junction with deep traps was conceived, based on the work of Sah and Reddi¹³ and Kleinknecht and Seiler¹⁴. Figure 1 shows this model for the case of two dominant trapping levels. The level E_{t+} changes charge state at x_{a1} , thus, effectively decreasing the number of charges in the region between x_1 and x_{a1} . This effect appears as a "notch" in the charge distribution. A similar effect occurs in the region between x_{a2} and x_2 .

It was determined from this model that the contribution to the capacitance of the charge variation at x_{a1} and x_{a2} is insignificant for the neutron-induced defect centers at the measuring frequency of the capacitance data acquisition system used,^{15,16} therefore, the concentrations determined from the capacitance-voltage data are in fact the post-irradiation concentrations at x_1 and x_2 .

Figure 1. Model for diffused junction with deep traps.

The charge distribution that results from this model can be doubly integrated to obtain the junction potential for the double-diffused devices used in this work. The resulting equations for the electric field and the potential distribution across the junction for the impurity distribution given in Eq. (1) are:

$$\begin{aligned}
E(x) &= -\frac{q}{\epsilon} \int N(x) dx \\
&= -\frac{q}{\epsilon} \left\{ N_{OE} (\operatorname{erfc}(L_E x) + \frac{1 - \exp(-L_E^2 x^2)}{L_E \sqrt{\pi}}) \right. \\
&\quad \left. - N_{OB} \frac{\sqrt{\pi}}{2 L_B} \operatorname{erf}(L_B x) + N_{BC} \right\} + \text{const.}, \quad (2)
\end{aligned}$$

and

$$\begin{aligned}
\Phi(x) &= \int E(x) dx \\
&= -\frac{q}{\epsilon} \left\{ N_{OE} (\operatorname{erfc}(L_E x) + \frac{x}{L_E \sqrt{\pi}} (1 - \frac{\exp(-L_E^2 x^2)}{2})) \right. \\
&\quad - \frac{\operatorname{erf}(L_E x)}{4 L_E} - N_{OB} (\frac{\sqrt{\pi}}{2 L_B} x \operatorname{erf}(L_B x) + \\
&\quad \left. + \frac{\exp(-L_B^2 x^2) - 1}{2 L_B^2}) + \frac{N_{BC} x^2}{2} \right\} - E(x_1) x + \text{const.}, \quad (3)
\end{aligned}$$

and

$$\Phi_n = \frac{N_R}{2} (x_{a1} - x_1) \{ (x_2 - x_1) + (x_{a2} - x_{a1}) \} \quad (4)$$

and the junction potential is

$$V_T - V = \Phi(x_2) - \Phi(x_1) + \Phi_n, \quad (5)$$

where $E(x)$ = the electric field

$\Phi(x)$ = the potential

E_R = the defect concentration.

With knowledge of the impurity profile and activation energy, a set of recombination statistics has been generated by Chow⁸ at this laboratory. These statistics are being modified using the junction model of Figure 1 to calculate more exactly the value of V_T , the junction built-in voltage.

Additional information on the recombination statistics and the mobility as a function of doping and field is needed. Other investigators^{9,17} have developed empirical relations for mobility as a function of doping and field, and these are being used in this work.

Base Transport Factor Change at Moderate and High Current Levels

Previous work of the principal investigator¹⁸ had indicated that the neutron-induced change in the "ideal" base current component is not equal to the change in collector current, but, in general, the increase in base current will exceed the "fall-off" in collector current. The relation between increase in base current and "fall-off" in collector current can be derived by solving the steady state continuity equation¹⁸ for the following two cases: the uniformly doped base, corresponding to no field in the base region; and the graded impurity concentration in the base, corresponding to an electric field in the base. This equation for an n-p device is given by;

$$\frac{1}{q} \frac{dJ_n}{dx} - \frac{N-N_p}{\tau_n} = 0, \quad (6)$$

where

$$J_n = qD_n \frac{dN}{dx} + q\mu_n NE$$

$$N(0) = N_e \exp(qV_{BE}/kt)$$

$$N(d) = 0$$

$$E = \frac{kT}{qN_A(x)} \cdot \frac{dN_A(x)}{dx}$$

N_e = the electron concentration at the base side of the emitter base space-charge region

d = the active base width

x = a length coordinate

E = the electric field in the base

N = the excess minority carrier concentration in the base

$N_A(x)$ = the device doping profile

The doping profile for the double diffused devices studied in the present work is quite involved⁷ which complicates the expression for the electric field in the bulk base region. The electric field is a function of position in the device and is retarding over the portion of the base closest to the emitter (23%) and aiding over the remainder of the base.

Since the electric field, E , the device doping profile, $N_A(x)$, the minority carrier mobility, μ_n , and the minority carrier lifetime, τ_n , are all functions of position, x , in the device and of neutron fluence, a closed form solution for the above mentioned continuity equation could not be obtained. Therefore, a numerical solution has been obtained and compared with several closed form solutions that are based on certain simplifying assumptions in order to determine a reasonable model for a graded base region.

Two closed form mathematical base region models have been derived, one for an exponentially graded base region, the second for a gaussian grade in the base region. In both instances, the minority carrier mobility and lifetime were considered to be independent of position in the base region. Neither model yet takes into account the fact that modern double-diffused devices have a retarding electric field over a portion of the base region nearest the emitter. This will be added in the coming year.

The excess minority carrier distribution in the base region according to the exponential model for low to moderate injection levels is given by:

$$n(x) = N_e \exp(x/F) [\cosh(x/Z) - \sinh(x/Z) \coth(d/Z)] \exp(qV_{BE}/kT) \quad (7)$$

where,

$$L^2 = D_n \tau_n$$

$$F = \frac{2kT}{qE}$$

$$\frac{1}{Z^2} = \frac{1}{F^2} + \frac{1}{L^2}$$

Normalizing the excess minority carrier concentration, $N(x)$, to the concentration, N_{CO} , which would have to exist in a homogeneous base to insure a constant collector current yields the following relation for the exponential model:

$$\frac{N(x)}{N_{CO}} = \frac{\exp(x/F) [\cosh(x/Z) - \sinh(x/Z) \coth(d/Z)]}{(d/Z) \exp(d/F) \operatorname{csch}(d/Z)} \quad (8)$$

where,

$$N_{CO} = \frac{J_C d}{qD_n}$$

$$J_C = qD_n \left(\frac{2N}{F} + \frac{dN}{dx} \right) @ x = d$$

Figure 2 shows the excess minority carrier concentration variation across the active base width normalized to a constant collector current with electric field strength as a parameter under low to moderate injection levels and with negligible recombination. The electric field strength for the exponential model is given by

$$\eta = \frac{qEd}{kT} = \ln \frac{N_A \text{ @ emitter}}{N_A \text{ @ collector}} \quad (9)$$

Figure 2 agrees well with previous work utilizing different methods.^{20,22}

Since the devices studied in this work have an effective η of approximately three, Figure 3 shows the excess minority carrier concentration across the base width for an η of three normalized to constant collector current with fluence as a parameter. As neutron fluence increases, recombination is enhanced, and a greater number of carriers must be injected into the base in order to maintain a given collector current.

The relationship between neutron radiation induced base current increase and collector current decrease can be obtained from the expression:

$$\begin{aligned} \frac{\Delta I_B}{\Delta I_C} &= \frac{J_E - J_C}{J_{CO} - J_C} \\ &= \frac{(1+(F/Z) (\coth (d/Z)) - (F/Z) \exp (d/F) \operatorname{csch} (d/Z))}{(1+\coth (d/F)) - (F/Z) \exp (d/F) \operatorname{csch} (d/Z)} \end{aligned} \quad (10)$$

where,

J_{CO} is the collector current density in the absence of recombination

$$J_{CO} = qD_n N_e (1/F) [1 + \coth(d/F)] \exp(qV_{BE}/kT)$$

Figure 4 is a plot of the ratio of base current increase to collector current decrease versus the reciprocal square of the minority carrier diffusion length for an active base width of 0.74 microns (2N914) with electric field strength as a parameter as predicted by the exponential model. For a homogeneous base the above ratio has a lower limit of 3 and for a steeply graded base the lower limit is unity¹⁸. In both cases the ratio increases with increasing recombination. Typical values for the test devices (2N914) for a series of several fluence levels are noted. The presence of an electric field not only reduces the ratio of base current increase to collector current decrease, but also makes it less sensitive to variations in recombination and hence neutron fluence.

Figure 2. Excess Charge Density Distribution In The Base Region Under Low-Level Injection Conditions

Figure 3. Excess Charge Density Distribution In The Base Region Under Low-Level Injection Conditions

The base transport factor, β^* , for the exponential model is of the following form:

$$\beta^* = J_C / J_E$$

$$= \frac{F \exp(d/F)}{Z \sinh(d/Z) + F \cosh(d/Z)} \quad (11)$$

where

$$J_E = q D_n N_e \left(\frac{1}{F} + \frac{\coth(d/Z)}{Z} \right) \exp(qV_{BE}/kT)$$

$$J_C = q D_n N_e \left[\frac{1}{Z} \exp(d/F) \operatorname{csch}(d/Z) \right] \exp(qV_{BE}/kT)$$

The base transport factor versus the reciprocal square of the minority carrier diffusion length with electric field strength as a parameter is shown in Figure 5. Typical points for the test devices are indicated. The base transport factor improves considerably in the presence of an electric field and also becomes less susceptible to increases in recombination with neutron fluence as the electric field in the base region is increased.

The results obtained from the exponential model are valid only for low to moderate injection levels and are in reasonable agreement with experimental data for double diffused devices. The gaussian model is being completed to obtain more accurate predictions since it is a more precise method of describing the actual device impurity profile and, hence, the electric field in the base region. Both models are being extended so as to include high injection levels and are being corrected for emission crowding effects due to transverse voltage drops which occur at higher injection levels.

The significant results obtained thus far are as follows: 1) A theoretical basis has been established to explain the experimentally observed increase in device radiation tolerance as a result of the presence of an electric field in the base; 2) The effective electric field strength in the base has been found to increase with neutron fluence; 3) The effect of an increase in electric field strength with neutron fluence tends to offset the effect of the corresponding decrease in the minority carrier lifetime. Therefore, the radiation-induced increase in the "ideal component" of base current essentially remains a constant multiple of the radiation-induced decrease in collector current for neutron fluence levels where double-diffused devices still retain their identity.

Figure 4. Ratio Of Base Current Increase To Collector Current Decrease

Figure 5. Base Transport Factor

Parameters of the Collector-Base Junction

Collector Multiplication Factor - M

Most of the previous work on collector multiplication, which has been on non-irradiated devices, has ignored the collector efficiency and has been primarily concerned with the collector multiplication factor²³⁻²⁶. This was possible because the devices chosen for those studies were alloy devices in which the collector efficiency is unity rather than single ended impurity process devices which are now in common use. The collector efficiency was also assumed to be unity in this study, which uses modern devices, since the injection levels were kept below that which would cause any significant enhancement of the collected current due to fields in the collector region.

A method similar to the one proposed by Miller²¹ is used to determine M, which has been found to follow the empirical relationship,

$$M = \frac{1}{1 - \left(\frac{V_{CB}}{BV_{CBO}} \right)^m}, \quad (12)$$

both before and after irradiation. The parameters BV_{CBO} and m change after neutron radiation. The breakdown voltage, BV_{CBO} , increases slightly with neutron fluence, and the exponent, m , decreases with neutron fluence. The collector base breakdown voltage, BV_{CBO} , of the devices used is related primarily to the impurity concentration in the epitaxial layer²⁷. The carrier removal rate²⁸ for electrons in n-type silicon is approximately $2 \text{ neutron}^{-1} \text{ cm}^{-1}$. The initial impurity concentration for the devices used is approximately $5 \times 10^{15} / \text{cm}^3$ so that the impurity concentration and breakdown voltage should not change appreciably for neutron fluences below $2.5 \times 10^{14} \text{ nvt}$. The devices under study have been irradiated to a fluence of approximately $1 \times 10^{14} \text{ nvt}$, and no appreciable change in the breakdown voltage has yet been observed.

Collector-Emitter Breakdown Voltage - BV_{CEO}

The collector-emitter breakdown voltage, BV_{CEO} , is given by the expression

$$BV_{CEO} = \frac{BV_{CBO}}{(h_{FE} + 1)^{1/m}}, \quad (13)$$

where m depends on the resistivity and conductivity type of the collector region, and for n-type silicon, $m \approx 4$. Since the common emitter current gain, h_{FE} , is a decreasing function

of neutron fluence², BV_{CEO} should increase with neutron fluence. This result has been observed in the experiments performed up to a fluence level of 1×10^{14} nvt.

Collector Output Conductance - g_c

The common base characteristics of each experimental device were photographed after each irradiation using a Tektronix Type C-12 camera and a Tektronix Type 575 curve tracer. The output conductance, g_c , is the slope of any member of this family of curves. Comparison of the common base characteristics of a typical device before irradiation to the characteristics of the same device after irradiation up to a maximum fluence level of approximately 1×10^{14} nvt has shown that the output conductance had increased after irradiation. This may be explained by considering the effect of the larger multiplication factor after irradiation. The collector-base voltage-dependent current component due to multiplication has become a significant fraction of the total collector current. Therefore, since the collector current increases significantly with increasing collector-base voltage, the output conductance has increased.

Collector-Base Leakage Current - I_{CBx}

The collector-base leakage current, I_{CBx} , can be obtained by extrapolating the linear portion of the $\log(I_C)$ vs. V_{BE} curve and taking the difference between the measured value of I_C and the extrapolated value of I_C . A close examination of this method has revealed that I_{CBx} decreased as V_{BE} is increased and V_{CB} is held constant. The exact mechanism of this anomalous phenomenon is not well understood at this time. However, if one were to postulate the recombination occurs in the collector depletion region, it could be explained. It should be noted that this recombination phenomenon appears to exist whether or not the p-n junction is subject to neutron bombardment.

Effect of the Collector Junction on the Emitter Efficiency - γ

When a reverse bias is applied to the collector-base junction, the collector-base depletion region widens. As a result, the base width narrows (Early effect)²⁹, and the concentration gradient of minority carriers in the base increases (for a fixed base-emitter applied bias). The minority carrier current injected into the base will therefore increase and, consequently, the emitter efficiency will increase. It should be noted that the emitter efficiency has been found to be an increasing function of V_{CB} whether or not the device had been subjected to neutron radiation.

Effect of the Collector Junction on the Base Transport Factor

(Base Recombination Term) - β^*

The Early²⁹ effect should cause β^* to slightly increase with V_{CB} whether or not the device is subjected to neutron radiation since recombination is a volume process and as such would decrease with a decrease in base width.

Anomalous Variation of Common Base Current Gain, α , with V_{CB} .

The collector multiplication factor is defined²³ as the ratio of the number of minority carriers leaving the collector junction to the number of minority carriers entering the collector junction. It should be noted that in this definition it is specifically assumed that there is no recombination (and only generation) within the collector-base junction. Therefore, M should be an increasing function of V_{CB} . The existing theory then leads to the conclusion that α is an increasing function of V_{CB} . Plots of α versus V_{CB} with V_{EB} as a parameter indicate that for the low V_{EB} 's, α decreases with V_{CB} initially and then increases. It is difficult to explain the anomaly in terms of existing theory. However, if one were to postulate that recombination occurred in the collector-base depletion region, then another term would have to be added to the definition of α so that $\alpha = \gamma \beta^* (\alpha^* M) \delta$, where δ is the collector recombination term. If δ were a decreasing function of V_{CB} , which had a slope that increased with V_{EB} , then this could afford a possible explanation. Further work will be done to determine or preclude the existence of recombination in the collector-base junction. Note that this recombination phenomenon exists even in the absence of neutron radiation and would be expected to be enhanced by neutron radiation. A second possible explanation for the anomalous behavior of α is that as V_{CB} is increased, the base width narrows and consequently the average value of the aiding electric field in the base decreases. This would be reflected by a smaller base transport factor, i.e., a decrease in β^* . Further efforts are being made to determine which explanation is correct or if there is yet another explanation.

Radiation and Annealing Characteristics in Neutron Bombarded Transistors Operated in the Inverse Configuration

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 ($K_v = 5.6 \times 10^{-17}$ amperes/cm³ · nvt). From comparison with the previously reported¹⁻³ 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 and the "emitter-base" junction capacitance to increase by a factor of approximately 2 at a fluence of 2×10^{14} nvt and gamma dose of 3.2×10^6 rad (H₂O). 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 percent increase in capacitance. Since the increase in capacitance was more than 31 percent, 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.³⁰ 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 canister by the neutron bombardment³¹ 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.

Surface effects due to neutron radiation have been previously thought to be negligible.³² 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 four weeks.

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 percent 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 preirradiation 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 percent) were irradiated to a fluence of 5×10^{14} nvt, then annealed. Dominant activation energies of 0.19 ± 0.04 eV and 0.86 ± 0.15 eV in the bulk space-charge region, and 0.34 ± 0.06 eV and 0.98 ± 0.18 eV in the neutral base region were calculated³³ from the isochronal and isothermal annealing data. The experimental activation energies agree well with previously calculated values.³⁴⁻³⁷

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° to 100° C. This was attributed to an increase of A-centers (oxygen-complexes).^{36, 37}

The annealing process of neutron-induced defects is a function of many parameters³⁴⁻³⁹ (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.³⁵ These results were published in more detail in a paper by Su,

Gassner, and Goben⁴⁰ (COO-1624-13) and additional information is available from Su's Master's thesis³⁰ (COO-1624-15) both of which are included as reprints with this report.

Field Dependence of Radiation Induced Defects

A study of the effect of bias during irradiation has been started and indicates that the damage constant $(K_V)^{40}$ is a function of bias applied to the junction during irradiation. A forward bias produces a smaller value of K_V than does zero bias, which in turn produces a smaller value of K_V than does a reverse bias.

The diffusion potential, V_T , was found to decrease with neutron fluence, and the junction capacitance was found to increase. This change can be related to physical changes in the junction depletion region through;

$$C = \frac{A \epsilon_r \epsilon_0}{x_m} \quad (13)$$

Equation (13) gives the junction capacitance, C , as a function of the junction area, A , the depletion layer width, x_m , and the permittivity.

The equation

$$C = \frac{K}{(-V + V_T)^{1/m}} \quad (14)$$

gives the junction capacitance, C , as a function of: K , which is a material constant; m , which is related to the type of junction and assumes the values of 2 for a step junction and 3 for a linearly graded junction; V_T , the diffusion potential; and V , the applied voltage during measurement.

Computer programs have been written using Eqs. (13) and (14) to calculate V_T , K , m and x_m as a function of neutron fluence and applied bias.

For the junction reverse biased during irradiation, an increasing dominance of a component of base current which has a reciprocal slope term of approximately 2 was observed. This may be due to a channel (measurements are being taken to determine the origin of this current component).

A more detailed study is being carried out to determine the damage constant, K_V , as a function of applied bias during neutron irradiation. The junction capacitance as a function of bias voltage is being measured to determine possible causes for the observed changes in V_T and K_V . From these measurements, it may be possible to gain some knowledge of the fundamental nature of the neutron-induced defects.

Investigation of Defect Clusters in the p-n Junction Depletion Region

Crystalline defects induced by fast neutrons were once thought to be composed of isolated point defects. More recent evidence⁴¹⁻⁴⁵ indicates that neutron-induced defects in semiconductors are primarily clusters of highly disturbed regions within the matrix. Gossick⁴⁶ and Cleland and Crawford⁴¹ have postulated a spherical region of high defect density surrounded by a space-charge region. Various attempts have been made to verify the validity of the Gossick model.

Investigations in the past, including those by Cleland and Crawford⁴¹, Whan⁴², and Stein⁴³, have concerned themselves primarily with bulk electrical effects. Parsons, Balluffi, and Koehler⁴⁴ did some work in an attempt to directly identify the structure and geometry of the cluster, although their work was only partially successful. More recently Bertolotti⁴⁵, at the University of Rome, has performed a series of experiments using various bulk semiconductors which he irradiated with high-energy neutrons. Using preferential etching and a replication technique in conjunction with an electron microscope, he was able to verify the existence of roughly spherical voids of a diameter which agreed quite well with theoretical values.

Goben² has indicated that recombination within the depletion region can contribute to adverse device operation after irradiation. For this reason, an attempt is being made to extend Bertolotti's work to an investigation of the existence of defect clusters and their geometry and structure within the depletion region of a p-n junction. It is hoped that by investigating the field dependence of the geometry of the structure more light will be shed upon the validity of the present model along with a better understanding of the cluster's production mechanism.

This investigation will be facilitated by using the new UMR Scanning Electron Microscope. As reported by Kimoto and Hashimoto⁴⁷, the technique of contrasts, which is a technique allowing the investigator to identify a region that has a potential gradient, acts as a tool in identifying the space-charge region surrounding the cluster. This technique, if adaptable to the magnitude of the cluster gradient, will enable an investigator to continuously monitor the cluster density, geometry, and size during an annealing run. The latter should establish the mechanism by which the defect clusters anneal and the dependence of these parameters as a function of time. When the existence and geometry of the cluster is established in the depletion region, an attempt to establish the effect of the cluster upon the energy band structure within the depletion region will be made. Treatment of the energy

band diagram outside the depletion region offers no problem, but the curvature of the band edges in the depletion region adds to the difficulty of solution.

A sample preparation technique is presently being perfected. This facet of the experiment is most critical and important. The method described by Gajda⁴⁸ is being used to allow high resolution microscopy work. It includes refined bevel cut, lapping, and polishing techniques to prevent destruction of the cluster structure and to allow resolution of its size and geometry. Samples have been prepared in a preliminary investigation of this technique.

Effect of Electric Field on the Mobility of Radiation Induced Defects in n-type Silicon

The electrical and optical properties of defects introduced by high energy irradiation of semiconductors, particularly in silicon and germanium, have been thoroughly studied.⁴⁹ Although the dominant energy levels of these defects are known⁴⁹, their identification in terms of structure is still under investigation. In silicon, greatly improved results have been obtained by using electron spin resonance and elasto-optical effects, which give a clear picture of the association of vacancies with chemical impurities. The Si-E center, which is a phosphorus-vacancy defect complex, is known to be the dominant defect in irradiated, oxygen free, phosphorus-doped silicon.⁵⁰ This defect is negatively charged and is associated with an energy level 0.43 eV below the conduction band. Annealing of the Si-E center has been found to take place in the range 100°-120°C.⁵¹

Recent studies by Baruch³⁴ have shown that the phosphorus vacancy defect complex produced in electron and gamma irradiated germanium were stable and immobile when thermally agitated in temperature ranges below which the defects are ordinarily known to anneal. However, an applied electric field across the junction was seen to cause the defects to drift with a calculable velocity. A p⁺n junction device was used to facilitate the study of defects in the n region (since, for this structure, the depletion layer spreads almost entirely into the n region when the device is reverse biased).

Capacitance-voltage measurements have been used to calculate the impurity profile in the p⁺n junction. Calculations from the changes in the impurity profile after each stage will yield the drift mobility of the defects at each stage of the electric field sweeping. The net impurity concentration at different points in the depletion layer can be calculated using Hilibrand and Gold's¹⁰ method for a one sided junction. Reverse biases from 10 to 70 volts establish the field across the junction of the device which has been isothermally annealed over a temperature range 40°-120°C with the annealing cycles ranging from 12

to 50 hours. Such studies characterize defect complexes in silicon in terms of their temperature dependent diffusion coefficient, drift mobility, and activation energy.

Nuclear Radiation Effects on High-Frequency Silicon p-n Junction Semiconductor Device

Parameters

Most of the research concerning radiation effects on semiconductor devices has been done with regard to d-c or low-frequency applications. As a result, the effects of radiation on the high-frequency characteristics of semiconductor devices are for the most part unknown. The changes in semiconductor high-frequency parameters due to neutron radiation are useful in determining the precise characterization of the degradation of semiconductor devices in a radiation environment. It has been demonstrated that the more commonly known device parameters (h -, y -) are not of practical use in high frequency considerations, but from both measurement and design points of view, the scattering parameters (or S-parameters) are of primary interest.⁵² Generalized scattering parameters have been defined by Kurokawa.⁵³ In defining "high" frequencies, ranges of interest must be specified; therefore, S-parameter data must necessarily be of swept-frequency origin, but a single-frequency S-parameter measuring system (0.1-2GHz) is sufficient for preliminary work. The single-frequency system is shown in Figure 9 in the equipment section.

The S-parameters describe the interrelationships of a unique set of variables (a_i , b_i), which are normalized complex voltage waves (or power waves) incident on and reflected from the i^{th} port of a two-port network. The linear equations that describe the network are

$$b_1 = S_{11}a_1 + S_{12}a_2,$$

$$b_2 = S_{21}a_1 + S_{22}a_2,$$

where the S_{ij} 's are the scattering parameters.

By definition,

$$a_i = \frac{V_i + Z_i I_i}{2\sqrt{\text{Re}(Z_i)}} \quad b_i = \frac{V_i - Z_i^* I_i}{2\sqrt{\text{Re}(Z_i)}}$$

where the asterisk denotes the complex conjugate, and

a_i = incident power wave at the i^{th} port (watts),^{1/2}

b_i = reflected power wave at the i^{th} port (watts),^{1/2}

V_i = voltage existing at the i^{th} port (volts),

Z_i = reference impedance of the i^{th} port (ohms),

I_i = current flow into the i^{th} port (ampere).

It is generally assumed that with a matched system, Z_i is positive real, and is therefore simply referred to as Z_0 .

Preliminary investigations have indicated that there is a marked alteration in the scattering parameters of transistors due to neutron radiation. The precise characterization of these changes is desired if information concerning the changes in bulk resistivity, base-region resistivity, and junction capacitances is to be better understood. Furthermore, a greater insight into the nature of defect centers and carrier recombination may be gained. Since a knowledge of the S-parameters of a transistor leads to a direct method of amplifier design⁵⁴, a prediction of the effects of neutron radiation on a transistor in an amplifier configuration can be derived.

Quasi-Tunneling Recombination Model

The reason for the large increase in recombination in the emitter-base space-charge region which dominates the transistor current gain at low and intermediate current levels¹ has previously been unexplained.

A model has been conceived in an attempt to explain this neutron-induced phenomenon. This model assumes that a quasi-tunneling recombination transition takes place in the emitter-base space-charge region. The model here presented assumes that an electron from the conduction band, when in the transition region, drops (energetically) to the neutron-induced recombination center in the band gap. Then, rather than dropping directly into the valence band (or equivalently a hole from the valence band moving directly up to the recombination center to recombine with the electron), the electron tunnels (with no change in energy) to the valence band (or equivalently, a hole tunnels, with no change in energy, to the recombination site and recombines with the electron), thus inducing the observed large (and previously inexplicable) neutron-induced component of base current.

Preliminary calculations have been made to show that this model is plausible and possible from the known warping or curvature of the conduction and valence band edges in the emitter-base transition region or a semiconductor p-n junction by using the Boltzmann tail of the probability distribution function and the energy level differences as activation energies. These calculations indicate that quasi-tunneling phenomenon of the type postulated in the emitter-base space-charge region is 3 to 4 orders of magnitude more likely to occur than a "normal" conduction band to valence band recombination transition via a recombination center. Calculations have been made using the device parameters of the 2N914

transistor to determine whether this tunneling can occur.³⁸ In an unbiased device, the distance that an electron would have to tunnel from the neutron-induced defect level to the valence band is some fraction of $200 \text{ \AA}$. These calculations imply that this tunneling distance would increase slightly under forward bias. Since it is well known that the tunneling distance in a tunnel diode is on the order of $100 \text{ \AA}$, it appears then, that it is possible for an electron to tunnel from the neutron-induced defect level to the valence band.

If the concentrations, capture cross sections, and energies of the neutron-induced defect centers are known, a device could be doped to simulate a device after neutron irradiation. Such a device could be used to substantiate the quasi-tunneling phenomenon. Detailed calculations will be made to replace the crude "order of magnitude" calculations, and more accurate measurements made to determine needed parameters. Special devices will have to be fabricated to experimentally substantiate this model. Semiconductor p-n junction devices will be fabricated by normal techniques on the single wafer of silicon which is doped on one half its area with impurities to approximate the concentrations, energies, and capture cross sections of defect centers induced by neutron bombardment and undoped on the other half of the wafer, and records kept on devices originating on the two halves of the wafer. Comparison of current-voltage characteristics measured on devices from the doped half of the wafer may be compared with measurements on semiconductor devices from the undoped half of the wafer before and after neutron bombardment of these undoped devices to substantiate the model presented.

EXPERIMENTAL MEASURING SYSTEMS AND CALIBRATION STANDARDS

Several experimental measuring systems are being used for data acquisition. These systems are for the measurement and recording of the voltage versus current characteristics, voltage versus capacitance characteristics, scattering parameters, minority carrier lifetimes and switching characteristics, small signal dynamic characteristics of the p-n junction devices and characteristics of integrated circuit devices under study. Calibration standards are maintained for the purpose of calibrating the experimental measuring systems.

Automatic Data Acquisition System

The Automatic Data Acquisition System which was designed and fabricated using both commercially available and especially fabricated special purpose equipment is used to obtain the large amount of current versus voltage data required to define the current-voltage characteristics of semiconductor p-n junction devices. This system is capable of making current and voltage measurements with an absolute accuracy of ± 1 percent of reading and a precision (repeatability) of ± 0.3 percent of reading in the range from 10^{-10} amperes to 2×10^{-1} amperes (over 9 decades). A block diagram of this system is shown in Figure 6.

The heart of this system is a Control Center^{15,16}, which controls the programming, measurement and recording sequence of the system. A signal is sent to the Programmer^{15,16} to program the John Fluke 383B Voltage/Current Calibrator which applies an emitter-base bias to the test device which is mounted in a sample holder contained within a Delta Design MK2310 Temperature Control Chamber. The collector-base bias is supplied by a manually controlled Harrison Laboratory 865C Power Supply or a digitally controlled John Fluke 383B Voltage/Current Calibrator. The currents are sampled by the Current Sampler^{15,16} whose output is amplified by low noise amplifiers and measured by a Dymec 2401C-M31 Digital Voltmeter. The emitter-base bias voltage is measured by a second Dymec 2401C-M31 Digital Voltmeter. The voltmeter readings are recorded along with resistor identification information (in digital form) supplied by the Autoranging Current Sampler. This information is serialized by a Dymec 2540B Coupler and recorded on a Friden Model SFD Flexowriter in both typewritten form and on punched paper tape. The punched paper tape is converted to IBM punched cards on an IBM 047 Tape-to-Card Converter, and the punched cards are processed by an IBM 360-50 Digital Computer. The computer output is the tabulated voltage versus current characteristics.

Figure 6. Block Diagram of the Automatic Data Acquisition System.

To increase the flexibility of the system and to shorten the time required to change programming, a paper tape-reader-programmer is being added. Since a paper tape reader-programmer capable of performing the desired functions was not available commercially, one has been designed and is being fabricated. The tape reader, a Friden Model STRA, was purchased commercially. The electronics necessary for programming information storage and interface are being fabricated by personnel of the Space Sciences Research Center. The addition of this paper tape reader-programmer will permit the programming of either or both John Fluke 383 Voltage/Current Calibrators while greatly reducing the time required to change from one set of preprogrammed values to another.

Capacitance-Voltage Measuring Systems

It was not possible to buy a commercial capacitance-voltage measurement system of the type desired. Consequently, a system was fabricated using a Micro Instruments 1201DS Capacitance Tester, Dymec 2901A and 2902A Master and Slave Scanner/Programmers, a Dymec 2401C-M31 Digital Voltmeter, and a John Fluke 383B Voltage/Current Calibrator for supplying the precise bias voltages needed for the determination of the change in junction capacitance with neutron fluence and bias voltage. The test devices in both systems are mounted in a sample holder which in turn is mounted in a Delta Design MK2310 Temperature Control Chamber. The output medium is a Hewlett-Packard R66-562AR Digital Recorder which records both the capacitance measured by the Micro Instruments 1201DS Capacitance Bridge and the applied voltage measured by the Dymec 2401C-M31 Digital Voltmeter (See Figure 7 for block diagram). A start command advances the Scanner/Programmers which digitally programs a voltage or current on a John Fluke 383B Voltage/Current Calibrator. This voltage or current is applied to the device under test. A capacitance reading and a voltage reading are taken and recorded on the Hewlett-Packard R66-562AR Digital Recorder. The system recycles automatically until all pre-programmed measurements have been made. The printed output record is punched on IBM cards and processed by the IBM 360-50 Digital Computer.

Alternately, when the Data Acquisition System described previously is not being used for voltage-current measurements, the Dymec 2401C-M31 Digital Voltmeters, Dymec 2540B Coupler and Friden SFD Flexowriter may be used as the output medium. For this mode of operation, the frequency output (proportional to capacitance) of the Micro Instruments 1201DS Capacitance Bridge is measured by one of the DVM'S in the Data Acquisition System while the other DVM measures the potential applied to the device under test. This information is then serialized by the Dymec 2540B Coupler and output by the Friden SFD

Flexowriter on both punched paper tape and typewriter copy. Data processing is accomplished in a similar manner to that described for the Automatic Data Acquisition System. The block diagram of the alternative system for the capacitance-voltage measurements is shown in Figure 8.

To facilitate the interconnection of the two systems for this alternative mode of operation, a single cable was constructed carrying all data, control, and signal lines. When the two systems are used separately, shorting plugs are placed over the chassis connectors on the two systems.

Scattering Parameter Measuring System

The S-parameter test system is designed to measure scattering parameters in the frequency range of 0.1 GHz to 2.0 GHz. Selection of the particular parameter (S_{11} , S_{12} , S_{21} , S_{22}) is accomplished by a front panel pushbutton on this Hewlett-Packard system.

The test head provides the reference plane for the device under test and provides a simple means of selecting the device configuration. Bias for the device under test is applied through the test set to the test head.

Before measurement, a calibration is performed by placing a standard short at the plane of the test device and adjusting the reference plane extension until the phase angle of S_{11} or S_{22} is 180° or by placing a 50-ohm through section at the plane of the test device and adjusting the reference plane extension until the phase angle of S_{21} or S_{12} is 0° . Either of these procedures calibrates the test set for all four "S" parameters.

To measure one of the parameters, the test signal is applied through a dual directional coupler to the appropriate test port. A part of the signal is fed from the coupler and is used as the reference channel signal. The reflected signal (S_{11} or S_{22}) or the transmitted signal (S_{12} or S_{21}) is then coupled out as the test channel signal. The reference channel signal and the test channel signal are taken from 50-ohm T-pads to a vector voltmeter where their amplitude and phase are measured. Figure 9 shows a block diagram of the S-parameter measuring system.

Due to delays in obtaining the specialized equipment needed for this system, it is not yet in operation.

Lifetime and Switching Characteristics Measuring System

The minority carrier lifetimes are obtained by using a Tektronix Type 555 Oscilloscope with a Tektronix Type S plug-in unit. With this plug-in unit, measurements of diode impedance, ohmic resistance, forward and reverse recovery time, junction capacitance, and minority carrier lifetimes can be made.

Figure 7. Block Diagram of the Capacitance-Voltage measuring System Using Digital Printer Output Medium.

Figure 8. Block Diagram of the Capacitance-Voltage Measuring System Using the Automatic Data Acquisition System Output Medium.

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A Type R plug-in unit is used to measure transistor rise, fall, delay and storage times. A Type 1S1 plug-in unit is used to extend the measurement capability of the oscilloscope to one gigahertz.

Permanent records of these measurements are made using a Tektronix Type C-12 Camera with Polaroid back mounted on the oscilloscope.

Small Signal Dynamic Characteristics Measuring System

A Tektronix Type 575 Oscilloscope with a Tektronix Type C-12 Camera is used to obtain and record the small signal dynamic characteristics of the devices under study. This unit provides a means of applying the bias voltages and drive voltages and currents to obtain families of curves which are recorded on photographic film for permanent record.

Integrated Circuits Testing System

An integrated circuits tester capable of making the precise measurements necessary to characterize the devices under study was not commercially available. A system is therefore being designed and will be constructed by personnel of the Space Sciences Research Center.

Figure 10 shows a block diagram of the Integrated Circuits Testing System. The device under study is mounted in the device holder which in turn is mounted in a temperature control chamber. Power to the device is supplied by the constant voltage supplies, the constant current supplies and the pulse generator. The switching matrix connects the input signal, d-c power, pulse generator and the measuring instruments to the proper device terminals.

Measurement of the d-c levels in the device are made on two digital voltmeters which are part of the Automatic Data Acquisition System described earlier. This data is recorded on the output unit of the Automatic Data Acquisition System. The oscilloscope with camera is used to display and record the waveforms of the switching characteristics of the device.

The purpose of the control unit is to control the operating sequence of the tester and to provide the digital programming for the constant voltage and constant current supplies. Input to this unit is in the form of punched paper tape or a typewriter keyboard.

When operating in the automatic mode, programming information for the d-c supplies and the device measurement configuration is read from the input tape. The control unit then programs the d-c supplies and switching matrix. After a delay to allow the device to stabilize, an encode command is sent to the digital voltmeters. Their readings are

Figure 9. Block Diagram of the Single Frequency S-Parameter Test System.

Figure 10. Block Diagram of the Integrated Circuits Test System.

recorded on the output unit of the Automatic Data Acquisition System. The tester then repeats this cycle until all programmed instructions have been completed.

When measuring the switching characteristics of a device, the tester is operated in the manual mode. The d-c supplies and the measurement configuration are programmed using the typewriter keyboard while the pulse generator is manually set to the proper amplitude and frequency. The output waveforms displayed on the oscilloscope screen can be recorded using the scope camera.

Scanning Electron Microscope

The Scanning Electron Microscope (SEM) recently acquired by the Space Sciences Research Center of the University of Missouri - Rolla is a model JSM microscope, manufactured by the Japan Electron Optics Laboratory Ltd. It has a magnification of approximately 70,000X in both the secondary and backscattered electron modes. Sample sizes can be on the order of 1.5 cm. in diameter. The sample chamber, which is evacuated to the order of 10^{-6} Torr, is fitted with vacuum electrical feedthroughs which enable the investigator to make electrical connections to both the sample and any peripheral electrical equipment which may be placed in the sample chamber. This machine requires less rigid sample preparation techniques than the conventional electron beam microscopes. Specifically, the elimination of the replication step allows the investigator to more easily conduct large involved investigations and to conduct real-time investigations where, for example, the voltages and currents of a semiconductor p-n junction may be varied concurrently with sampling.

Calibration Standards

Calibration standards are maintained for the purpose of calibrating the experimental measuring systems. These standards consist of four Eppley Standard Cells (Certified) mounted in a temperature control chamber, seven NBS type resistors (Certified) ranging in decade values from one ohm to one megohm, two standard capacitors (Certified) of 50 and 500pf., and a Leeds and Northrup type K5 precision potentiometer (Certified). A John Fluke Model 750 Reference Voltage Divider is used in the calibration of precision voltmeters and d-c calibrators. A John Fluke Model 720A Kelvin-Varley Divider is used in the calibration of bridge elements, voltage dividers, and precision potentiometers.

Software

A general data reduction program is used for the processing of the output data from the Automatic Data Acquisition System by the IBM 360-50 Computer. This program performs four major functions.

First, the device voltages and currents from the input voltage and resistance data are computed with corrections made for the voltage drop across the current sampling element.

Second, the values of emitter-base voltages, which are integral multiples of 10.0 millivolts, are interpolated. This interpolation provides a means of comparing currents and current gains at fixed values of base-emitter voltage.

Third, the applied base-emitter voltage versus base and collector currents and current gain is provided in tabular form together with heading information which includes device identification and measurement conditions.

Fourth, a machine plot (Calcomp Model 566) of input voltages versus the logarithm of base current and logarithm of collector current with printed device identification and fluence level is put out for use by the investigators in comparison studies. Each plotted page is a 14- x 10-inch graph of the form $\log(I)$ versus V_{BE} . This first program will return a plot of the logarithms of I_B and I_C versus V_{BE} for each device while a second plot program returns one plotted page depicting either $\log(I_C)$ or $\log(I_B)$ versus V_{BE} curves for as many devices as desired.

The running time for the first plot program is approximately two and a half minutes per device and the running time for the second plot program is approximately one minute per device.

In addition to the general data reduction program, special data reduction programs are used by each investigator to reduce data to the format needed in his research.

EXPERIMENTAL UNITS

In order to make all the necessary measurements to obtain the parameters needed to compute the quantities of basic interest, it was necessary to have special structures fabricated. Special structures of the type used in this research effort are described below.

Test structure 1 is simply a 2N914 silicon planar epitaxial transistor with ring-dot geometry used for measurement of current-voltage characteristics and junction capacitance.

Test structure 2 is a tetrode type planar epitaxial transistor with double ring-dot geometry which may be used for standard measurements of voltage-current characteristics and junction capacitance, and which, in addition, may be used for resistivity measurements. The transistor may be biased from one base contact to the other to change the potential distribution under the emitter ring, and consequently, to change the voltage-current characteristics.

Test structure 3 is essentially a van der Pauw sample in the base of a planar epitaxial transistor which may be used for determining resistivity, Hall effect constant, mobility, sheet carrier density, and junction capacitance.

Test structure 4 is an alloyed junction epitaxial device which is being fabricated for use in the study of mobility of radiation induced defects in phosphorous-doped silicon, is a p^+n junction device. A p^+n junction is used because the depletion layer penetrates almost entirely into the lightly doped n region when the device is reverse biased, thus facilitating the study of defects in the n region. The structure is a phosphorous-doped, 20 to 30 micron epitaxial layer with a minimum resistivity of 50 ohm-cm and is grown on an antimony-doped silicon substrate wafer. The substrate has a resistivity of 0.010 to 0.015 ohm-cm and a thickness of 11.0 to 11.7 mills. The junction is made by alloying an aluminum wire so that the junction area does not exceed 0.045 cm^2 .

All devices were fabricated in the same diffusion run, and the devices fabricated from a given slice of silicon were so identified. All have the same impurity profile and junction depths as the transistor code of interest.

The sheet carrier density, $\tilde{N}_A$, majority carrier mobility, μ_n , and base recombination term, β^* , are related to the collector current as indicated previously³⁻⁴. The sheet carrier density and the mobility may be obtained from Hall effect and sheet resistance by measurement on the special test structures. The behavior of the recombination

sites in the space-charge region is related to the non-ideal components of base current and, of course, to the variation of junction capacitance due to the charged recombination sites.

In the present project year, special devices were obtained for radiation effects studies. The devices obtained were fabricated from a single wafer (one wafer for each code group) with the impurity profiles and junction depths of the following transistor codes: 2N914, SA7473, SF2523 (ring-dot geometry); 2N918 (bar geometry); 2N2222 (star geometry); SA9900, SF2524 (double base geometry); SF2525 (Hall effect geometry); and UMC101 (alloyed junction epitaxial geometry).

The manufacturers were Texas Instruments (Dallas), Motorola (Phoenix), and University of Missouri (Columbia).

More of these special devices will be needed in the next project year; in addition, special devices will have to be fabricated experimentally to substantiate the quasi-tunneling model described above. Semiconductor p-n junction devices will be fabricated by normal techniques, on a single wafer of silicon, which will be doped on one half its area with impurities to approximate the concentration, energies, and capture cross sections of defect centers induced by neutron bombardment and undoped on the other half of its area. A record will be kept of the devices originating from the two halves of the wafer.

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DEVIATIONS

There were no significant deviations in the scope of the work agreed upon under the present contract.

The scattering parameter measuring equipment was more expensive than anticipated; however, because of the acquisition by the Space Sciences Research Center of a Scanning Electron Microscope the planned expenditure to modify the Electron Microprobe was not necessary, and these funds were sufficient to cover the added expense.

PUBLICATIONS

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- Irani, C.H., Johnson, P.E., Van Meter, J. L., and Goben, C.A., "Investigation of Defect Clusters in Silicon p-n Junctions," (COO-1624-17)

To Be Submitted for Publication in IEEE Transactions on Electron Devices

- Azarewicz, J. L. and Goben, C.A., "The Determination of the Doping Profile of Diffused p-n Junction Devices in the Presence of Deep Traps". (COO-1624-18)
- Bereisa, J., Jr. and Goben, C. A., "Determination of Graded Base Parameters in the Presence of Recombination at Low to Moderate Injection Levels". (COO-1624-19)

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Publications

Jenkins, C. R., "Passive Temperature Monitoring in a Radiation Environment", SC-TM-66-282, Sandia Laboratory (Albuquerque, New Mexico) 1966.

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