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SEMICONDUCTOR JUNCTION DEVICES

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The Analysis of Radiation Effects in Semiconductor Junction Devices*

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Abstract

A computer program has been written for the prediction of transient and permanent radiation damage in junction devices. This program calculates the transient solutions of Poisson's Equation and the continuity equations throughout a one-dimensional structure. Mobility, lifetime and carrier generation are described by nonlinear functions of carrier density and current so that scatter limiting velocity, Shockley-Read-Hall recombination and avalanche ionization phenomena are described. Three examples are presented which illustrate the utility of such programs in predicting both ionization and displacement damage effects in a PIN diode and a bipolar transistors.

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I. Introduction

During the past decade, classical analysis techniques (1,2,3) have been used almost exclusively to predict the behavior of bipolar transistors, diodes and other junction devices in a radiation environment. In this approach, a large number of assumptions is made to reduce the complex partial differential equations describing carrier transport to a much simplified form which can be solved analytically. While this approach has produced many useful results and has been invaluable in developing an understanding of some radiation damage mechanisms, many of the classical assumptions are not valid for modern devices and, therefore, many phenomena observed in irradiated devices have not been predicted theoretically.

One method for eliminating most of the approximations required to solve the nonlinear partial differential equations describing device behavior is to use numerical solution methods and the digital computer. In this approach, the degree of approximation is determined only by the availability of material parameter information and by the capacity, speed and cost of the available computer. Except for these constraints, the device analyst is free to investigate theoretically the ramifications of any given approximation and develop a detailed understanding of any semiconductor device characteristic of interest. In a very real sense, the computer becomes a "laboratory tool" with which the analyst performs hypothetical experiments and evaluates the performance of a postulated device.

In this paper, a device analysis program is utilized to explore the basic mechanisms of transient and permanent damage in diodes and bipolar transistors. Since the only significant constraint imposed by the program is that the devices can be adequately described in terms of a single spatial variable, this program facilitates the prediction of most of the electrical and radiation characteristics of these structures. In addition, a procedure for utilizing a one-dimensional d. c. analysis to obtain an approximate solution for three-dimensional emission crowding effects in transistors is also presented.

The importance of this type of device analysis to the understanding of radiation damage is shown by considering three examples: (1) the prediction of transient photocurrents in PIN diodes with particular emphasis on saturation characteristics at high ionization levels, (2) the prediction of primary and secondary photocurrent generation in transistors, and (3) the prediction of the permanent changes in transistor characteristics which are caused by neutron irradiation. Although significant results are presented in each example, these analyses are not intended to be exhaustive studies of a particular structure. Rather, they demonstrate that detailed analysis by computer techniques provides a very effective means for developing greater insight into permanent and transient radiation damage in devices.

The remainder of the paper is organized in two independent sections. Section II considers the mathematical models used to describe carrier transport in devices and the numerical methods used to obtain the solutions. Section III discusses the predicted results of the transient and d. c. analyses of the PIN diode and the bipolar transistor. The latter section presents quantitative predictions of several radiation effects which have been mentioned in conjunction with experimental device studies.

II. Mathematical Representation and Solution Techniques

The electrical characteristics of a semiconductor device can be predicted theoretically by solving the equations describing the charge transport in the device subject to boundary conditions imposed by the device geometry at the electrical contacts. In general, the solution of the transport equations yields the hole and electron distributions as well as the electric field intensity throughout the device. These distributions are then used to calculate the terminal voltages and currents as a function of time.

Carrier Transport Equations

The distribution and motion of carriers within a one-dimensional semiconductor device structure can be obtained by solving three basic equations⁽⁴⁾: (1) the continuity equation for holes, (2) the continuity equation for electrons, and (3) Poisson's Equation:

$$\frac{\partial p}{\partial t} = g_p - \frac{1}{q} \frac{\partial J_p}{\partial x}, \quad (1)$$

$$\frac{\partial n}{\partial t} = g_n + \frac{1}{q} \frac{\partial J_n}{\partial x}, \quad (2)$$

$$\text{and } \frac{\partial E}{\partial x} = \frac{q}{K\epsilon_0} (p - n + N_D - N_A + \sum_i N_{Ti}^+) \quad (3)$$

$$\text{where } J_p = q \mu_p p E - kT \mu_p \frac{\partial p}{\partial x}, \quad (4)$$

$$J_n = q \mu_n n E + kT \mu_n \frac{\partial n}{\partial x}, \quad (5)$$

Boundary conditions are imposed at the device contacts by introducing the appropriate restrictions in Equations (3) through (5). For example, base and collector current boundary conditions for an NPN transistor are introduced by requiring that (5) is equal to the collector current density at the collector contact and (4) has a discontinuity equal to the base current density at a position corresponding to the base contact. Voltage boundary conditions are imposed by requiring that the integral of $E(x,t)$ over the interval between the two contacts equals the applied voltage. In addition, the electric field at the two end contacts is assumed to be zero. Initial values for the hole and electron densities are either furnished by the analyst or are given by the quiescent zero bias solution, i.e., the solution when $J_n + J_p = 0$ and $\frac{\partial p}{\partial t} = \frac{\partial n}{\partial t} = 0$.

* Note: The symbolic notation is described in the list of symbols contained in Appendix I.

In general, the functions g_p , g_n , μ_p and μ_n vary at each point in the device according to the value of n , p and E at that point. Although the specific functional relations discussed below are now used in the program, almost any type of point function could be used to approximate the mobility and recombination-generation properties of the material.

Carrier Generation-Recombination Expressions

The carrier generation terms g_n and g_p are each composed of three components: (1) carrier generation and recombination through defects, (2) impact or avalanche ionization, and (3) external generation such as that produced by ionizing radiation.

Hole and electron generation and recombination through defects are represented by two forms of Shockley-Read-Hall (SRH) models:⁽⁴⁾ single level models⁽⁵⁾ which characterize defects with neutral and single charge states, and (2) two-level models⁽⁶⁾ which permit donor, acceptor and neutral charge states. The generation-recombination rates through a single level center are given by two equations describing the rate of hole and electron capture from the valance and conduction bands,

$$g_{pdl} = v_{tp} \sigma_p (p N_T^- - p_1 N_T^0) \quad (6)$$

$$g_{ndl} = v_{tn} \sigma_n (n N_T^0 - n_1 N_T^-) \quad (7)$$

and a third equation describing the net rate at which electronic charge accumulates on the center

$$\frac{dN_t^-}{dt} = -g_{ndl} + g_{pdl} \quad (8)$$

If the center is an acceptor (i.e., it can capture an electron and become negatively charged), the charge density $-qN_t^-$ is entered in Poisson's Equation to account for the space charge of the trapped carriers. However, if the center is a donor, then the net positive charge $q(N_t - N_t^-)$ is entered in (3).

Similarly, the equations for the two-level model are

$$g_{pd2} = -v_{tp}p(\sigma_p^0 N_T^0 + \sigma_p^- N_T^-) + v_{tp}(\sigma_p^0 N_T^+ P_{LD} + \sigma_p^- N_T^0 P_{LA}), \quad (9)$$

$$g_{nd2} = -v_{tn}n(\sigma_n^+ N_T^+ + \sigma_n^0 N_T^0) + v_{tn}(\sigma_n^+ N_T^0 n_{LD} + \sigma_n^0 N_T^- n_{LA}), \quad (10)$$

$$\frac{dN_t^+}{dt} = -v_{tn}\sigma_n^+ (nN_T^+ - n_{LD}N_T^0) + v_{tp}\sigma_p^0 (pN_T^0 - N_T^+ P_{LD}), \quad (11)$$

$$\text{and } \frac{dN_t^-}{dt} = -v_{tp}\sigma_p^- (pN_T^- - P_{LA}N_T^0) + v_{tn}\sigma_n^0 (nN_T^0 - N_T^- n_{LA}), \quad (12)$$

and the net trapped charge $q(N_T^+ - N_T^-)$ is used in Poisson's Equation.

Unlike carrier generation through a defect level, generation by impaction ionization (g_{pI} and g_{nI}) or by ionizing radiation (g_{pR} and g_{nR}) produces holes and electrons at equal rates. In the latter case, the generation rates in silicon are related to the absorbed energy by the relation

$$g_{pR} = g_{nR} = 4.03 \times 10^{13} \gamma ((\text{rad Si}) - \text{cm}^3/\text{sec})^{-1}.$$

The impact ionization rates are strongly dependent upon the electric field intensity and the hole and electron current densities. These generation terms⁽⁴⁾ are given by

$$g_{pI} = g_{nI} = \frac{1}{q} (\alpha_n(E)J_n + \alpha_p(E)J_p) \quad (\text{cm}^{-3})$$

where $\alpha_n(E)$ and $\alpha_p(E)$ are given by the relations

$$\alpha_p(E) = 1.8 \times 10^7 \exp(-3.2 \times 10^6/E) \quad (13)$$

$$\alpha_n(E) = 2.4 \times 10^7 \exp(-1.6 \times 10^6/E) \quad (14)$$

These expressions were synthesized to fit the impact ionization data obtained by Lee,⁽⁷⁾ Chynoweth,⁽⁸⁾ and Moll and Van Overstraeten⁽⁹⁾ (see Fig. 1).

Mobility Expressions

In most analysis work, the mobility of holes and electrons is considered to be constant. However, in order to accurately predict carrier transport rates in devices where large electric fields or large doping variations exist, it is necessary to include in the analysis the variations of mobility with the electric field and the ionized impurities density.

For small electric fields and ionized impurity densities, lattice scattering is the dominant mobility limiting mechanism.⁽¹⁰⁾ However, if an appreciable density of ionized impurities exists, electrons and holes can be scattered by the Coulomb potential surrounding the impurities.⁽¹¹⁾ As shown in Fig. 2a, this additional scattering mechanism causes the effective mobility to decrease with increasing impurity density. Furthermore, the hole and electron mobilities are strongly dependent upon the electric field intensity.⁽¹²⁾ For high field intensities the carriers can gain sufficient energy between scattering events to appreciably increase their average energy or temperature. At this higher energy, interactions with the lattice become more probable and the mobility is reduced in such a way that the carrier drift velocity

approaches a limiting value as shown in Fig. 2b.

The experimental mobility data shown in Fig. 2 can be approximated by the following expressions:

$$\frac{1}{\mu_n} = \frac{1}{\mu_{no}} \left[1.0 + 81N_{Dt}/(N_{Dt} + 3.24 \times 10^{18}) + 3.0 \times 10^{-4} \frac{E^2(E + 1.3 \times 10^5)}{(E + 9.6 \times 10^4)} \right]^{\frac{1}{2}} \quad (15)$$

$$\frac{1}{\mu_p} = \frac{1}{\mu_{po}} \left[1.0 + 350 N_{Dt}/(N_{Dt} + 1.05 \times 10^{19}) + 3.3 \times 10^{-4} \frac{E^2(E + 1.35 \times 10^5)}{(E + 9.0 \times 10^4)} \right]^{\frac{1}{2}} \quad (16)$$

These expressions are plotted as solid curves in Fig. 2 and approximate the experimental data reasonably well. However, the continued use of this analysis program would warrant a more detailed investigation of the mobility function with special attention given to the manner in which the impurity and electric field dependent terms are combined.

Solution Procedures

Because of the nonlinearities in the equations describing the hole, electron and field distributions, obtaining a transient or even a steady state d.c. solution poses a very difficult numerical problem. The solution techniques used here were, for the most part, developed at Bell Telephone Laboratories for the analysis of the IMPATT diode^(13, 14) and subsequently modified to treat the three terminal device case.

The structure to be analyzed is first subdivided into a number of small increments. The equations are then normalized to reduce redundant coefficient calculations and standard difference approximations are used to approximate the spatial derivatives in Poisson's Equation and the continuity equations for each increment:

$$\frac{dp(N)}{dt} = \epsilon_p(N) - (J_p(M) - J_p(M-1))/\Delta x \quad (19)$$

$$\frac{dn(N)}{dt} = \epsilon_n(N) - (J_n(M) - J_n(M-1))/\Delta x \quad (20)$$

$$\frac{E(M) - E(M-1)}{\Delta x} = K(p(N) - n(N) + N_D(N) - N_A(N) + \sum_{i=1}^+ N_{Ti}(N)) \quad (21)$$

where the M^{th} mesh point is located midway between the major mesh points $N+1$ and N . It is customary to next employ the standard difference approximations in the current density expressions (4) and (5) and substitute these results in (19) and (20). However, it can be shown that this procedure leads to numerical instability whenever the voltage change between mesh points exceeds $2 kT/q$. Rather, (4) and (5) are treated as differential equation in p and n with J_n , J_p , μ_p , μ_n and E assumed constant between mesh points. The solution of these differential equations then relates J_n and J_p to the other variables:

$$J_p(M) = E(M) \left[\frac{p(N)\mu_p(N)}{(1.0 - \exp(-E(M)\Delta x))} + \frac{p(N+1)\mu_p(N+1)}{(1.0 - \exp(E(M)\Delta x))} \right] \quad (22)$$

$$J_n(M) = E(M) \left[\frac{n(N+1)\mu_n(N+1)}{(1.0 - \exp(-E(M)\Delta x))} + \frac{n(N)\mu_n(N)}{(1.0 - \exp(E(M)\Delta x))} \right] \quad (23)$$

These equations provide numerically stable estimates of the current density under all conditions; if the intermesh point voltage is small, these equations approach the standard difference relations, whereas when the voltage change is large, they approach the drift current density at either mesh point N or $N+1$.

Both steady state and transient solutions are obtained by employing a standard implicit integration method.⁽¹⁵⁾ By recursively substituting (21) into (22) and (23), and then substituting these expressions into (19) and (20), the field variable at each mesh point can be eliminated. The continuity equations for each mesh point can then be written symbolically in the matrix form

$$\frac{d}{dt} \begin{bmatrix} p^{(1)} \\ n^{(1)} \\ \vdots \\ p^{(L)} \\ n^{(L)} \end{bmatrix} = \begin{bmatrix} F_{p1} (p_1, n_1, p_2, n_2, t) \\ \vdots \\ F_{nL} (p_{L-1}, n_{L-1}, p_L, n_L, t) \end{bmatrix} \equiv F(Z, t) \quad (24)$$

The change in Z over a time interval Δt is then determined by using a first order difference expression for the derivative terms and evaluating F at some point between the initial value Z_0 and the value to be attained at $t + \Delta t$.

$$\begin{aligned} \frac{\Delta Z}{\Delta t} &= F(Z_0 + \alpha \Delta Z, t_0 + \alpha \Delta t) \\ &= F(Z_0, t_0) + \alpha \frac{\partial F}{\partial Z} \Delta Z + \alpha \frac{\partial F}{\partial t} \Delta t + \dots \end{aligned} \quad (25)$$

If the higher order terms in the Taylor series are negligible, (25) can be solved for ΔZ to obtain

$$\Delta Z = (U/\Delta t - \alpha \frac{\partial F}{\partial Z})^{-1} (F(Z_0, t_0) + \alpha \frac{\partial F}{\partial t} \Delta t) \quad (26)$$

For linear equations it can be shown that maximum accuracy is achieved when α is $\frac{1}{2}$. However, improved numerical stability generally results when α is in the range $\frac{1}{2} < \alpha \leq 1$. The transient analyses reported here use an α of $\frac{1}{2}$, while the improved stability afforded by an α of unity is used for d.c. solutions where large time steps and rapid convergence are required.

Emission Crowding Analysis

In a realistic transistor structure, the base current originating in the transition and bulk base regions flows laterally under the emitter and produces a gradient in the emitter junction voltage. At high bias levels, this voltage gradient is large and therefore the emitter current density at the emitter perimeter is much larger than the density at the center of the emitter. Thus, most of the emitter current flows through a small fraction of the total emitter area and high injection phenomena become important even though the average emitter current density is relatively low.

Although the analysis present here is generally restricted to the one-dimensional case, the effects of three dimensional emission crowding can be predicted from a one-dimensional analysis if the lateral voltage and carrier gradients are negligible compared to the gradients in the major dimension. Under this condition, the three-dimensional device can be viewed as a collection of one-dimensional structures with common emitter and collector contacts and with base contacts interconnected by a resistive network which simulates the base spreading resistance.

In the limiting case, the lumped parameter approach discussed above can be written in the form of a differential equation relating the lateral base voltage drop to the base current density versus base-emitter voltage characteristic of the one-dimensional structure. For the ring-dot structure, this equation has the form ⁽¹⁶⁾

$$\frac{\partial v_{be}(r)}{\partial r} = - \frac{1}{2\pi r} \int_0^r \rho(v_{be}(r)) I_b(v_{be}(r)) 2\pi r dr \quad (27)$$

where the base sheet resistivity is assumed to be dependent upon the injection level or $v_{be}(r)$.

After the emitter voltage distribution $v_{be}(r)$ has been calculated, the total base and collector current can be determined from the equations

$$I_b = \int_0^{R_c} I_b(v_{be}(r)) 2\pi r dr \quad (28)$$

and

$$I_c = \int_0^{R_c} I_c(v_{be}(r)) 2\pi r dr \quad (29)$$

Clearly, similar equations could be developed for almost any emitter shape.

III. Device Analysis

The mathematical models and numerical solution techniques discussed in the previous sections have been used to predict both ionization and displacement effects in semiconductor junction devices. These analyses all include the impurity and field dependent mobility expressions, as well as the impact ionization terms. The carrier generation, and recombination models used are specified for each case.

PIN Diode Analysis

The response of a reverse biased PIN diode to steady state and transient ionizing radiation has been analyzed by a number of investigators.^(17, 18) However, because of the assumptions required for closed form analytical solutions, these analyses have been restricted to low ionization levels

where the space charge produced by the radiation induced carriers does not significantly alter the electric field within the device. In the analysis presented in this section, this assumption is not imposed and steady state as well as transient solutions have been obtained for the general one-dimensional case.

The doping profile assumed for this analysis is shown in Fig. 3. The diode has heavily doped N^+ and P^+ regions diffused into the two faces of a 300 micron wafer of nearly intrinsic (6000 ohm-cm P-type or π -type) silicon. Since the transit time for these devices is relatively short compared to the carrier lifetimes normally found in noncompensated high resistivity materials, recombination does not play a major role in determining the radiation response and is frequently neglected. However, for completeness, a hole lifetime of about 100 μ s was introduced in the π region by including a density of $10^{13}/\text{cm}^3$ gold centers. Trapping was not considered.

When the PIN diode is reverse biased, a depletion region forms at the N^+/π junction and extends into the π region. By solving Poisson's equation and the continuity equations throughout this device, the variation of the electric field and hole density with position and applied bias voltage can be obtained. These solutions, which are shown in Fig. 4, indicate that the assumed structure fully depletes at a bias level of about 100 volts, i.e., the hole density is essentially zero over the entire π region, and that at the nominal operating voltage of 1000 volts, the electric field approaches a uniform value of 40,000 v/cm. It should be noted that with this large electric field, the carriers are approaching their scatter limiting velocities (See Fig. 2b) and the use of field dependent mobility terms is required for meaningful solutions.

Steady State Analysis: In a low level **steady** state ionization field, the holes and electrons produced by radiation are rapidly swept across the π region by the large electric field. Consequently, the density of free carriers is kept small and the net space charge produced by these carriers does not appreciably alter the field intensity. However, as the radiation intensity is increased, the space charge introduced by the separation of the hole-electron pairs significantly reduces the field in the interior of the π region. Figure 5, which shows the steady state electric field and hole distributions for energy deposition rates of 2.5×10^7 , 2.5×10^8 , 5.0×10^8 and 5.7×10^8 Rad(Si)/s indicates that a rate of only 2.5×10^8 Rad(Si)/s produces a measurable change in the electric field distribution while a rate of 5.7×10^8 Rad/s produces a factor of seven decrease in the central portion of the π region. Note also that as the field in the center decreases, there is a corresponding increase at both edges of the π region. As a result of this change in the electric field distribution, holes from the left side of the π region are quickly swept into the low field region where the drift velocity is much smaller. Consequently, the hole and, similarly, the electron densities in the central portion of the π region increase above the values obtained elsewhere in the π region. This crowding effect, which is clearly evidenced by the difference between the 5×10^8 and 5.7×10^8 Rad(Si)/s curves in Fig. 5b, increases rapidly with carrier generation until the carrier density in the center of the device is so large that recombination becomes significant and the collection efficiency of the diode is reduced.

At the time this analysis was performed, lifetime information for this device was not available. Therefore, a detailed investigation of the saturation characteristics was not warranted. However, based

upon the rapid growth of carrier density with dose rate, it is reasonably certain that energy deposition rates of the order of 10^9 Rad(Si)/s would produce a significant reduction in the collection efficiency of this diode.

Transient Analysis: When a fully depleted PIN diode is exposed to a short ($\sim 10^{-10}$ s) pulse of ionizing radiation, carriers generated in the π region drift at essentially scatter limited velocity to the N^+ and P^+ regions. Brown,⁽¹⁷⁾ has shown that for small doses the current waveform associated with each carrier current has a sawtooth shape which decays linearly from the peak emplitude achieved at the end of the ionization pulse to zero within the transit time for the carrier. The total photocurrent is the sum of the hole and electron current waveforms as shown in Fig. 6.

The transient analysis of the PIN structure under conditions of intense ionization is complicated by the buildup of a space charge inside the device. This charge buildup produces a very complex response and, therefore, it is instructive to examine this case and its implications in some detail.

When the assumed structure is exposed to a 0.5 ns, 6.25 Rad(Si) radiation pulse, the computed time evolution of the hole, electron and electric field distributions in the π region is as shown in Figs. 7a, 7b and 7c, respectively. Immediately after the pulse, the excess carrier

density and the electric field are essentially uniform throughout the π region. However, as time evolves, the holes drift to the right depleting the region near the N^+ contact of holes and producing the observed decrease in the hole density at the πN^+ junction. Similarly, the motion of electrons away from the P^+ region produces a corresponding decrease in the electron density at the πP^+ junction. As the carriers are swept out of the π region near the junctions, a space charge region forms and alters the electric field distribution as indicated in Fig. 7c, i.e., the field in the central portion of the π region decreases while the field at each junction increases in order to maintain a constant voltage across the device. As a result of the change in the field distribution, the drift velocity of carriers in the center of the π region is decreased markedly while the velocity of carriers near the junctions is increased. Thus, the carrier densities near the junctions decrease with time while the density near the center remains virtually unchanged. After 5.0 ns, a time which exceeds the normal carrier transit times, approximately one-quarter of the carriers produced by the radiation pulse has not been collected. Ultimately, recombination, diffusion and the small field still remaining in the central region erode the peak in the carrier distribution and the carrier densities return to their depleted values.

The effect of the transient electric field collapse on the photocurrent waveform can be inferred from the above discussion. In contrast to the low dose case, the hole and electron distributions indicate that a significant fraction of the radiation induced carriers remain at times longer than a normal transit time. It is clear therefore that the photocurrent during the first few nanoseconds after an intense radiation pulse must be proportionately less than in the

low dose case and a change in waveform must exist. This difference in photocurrent waveform is shown in Fig. 8 which is a plot of normalized photocurrent vs time for the ionization pulse shape shown in the insert and peak ionization rates of (a) 2.5×10^8 and (b) 2.5×10^{10} Rad(Si)/sec. Note that in case (a) the current waveform is essentially triangular, as predicted by Brown, and in addition, a small "tail" exists for at least 10 ns. This delayed current is caused by the collection of minority carriers from the N^+ and P^+ regions and can be minimized by reducing the depth of these regions. In contrast, however, the waveform for case (b) shows a more rapid decay in the 1 to 2 ns region because in this time domain the electric field in the center of the device is decreasing rapidly and, therefore, the rate at which free carriers are swept from the π region is becoming smaller. At about 5 ns, the carrier peaks shown in Figs. 7a and 7b are established and contain a stored charge which is proportional to the area between the two transient waveforms in Fig. 8. Note that the "tail" or delayed photocurrent resulting from the collection of the **carriers** which form these peaks, is now quite large and is decaying very slowly. For the case shown here, this delayed component contains approximately one-fourth of the total charge collected; however, both the relative magnitude and the collection time of this component increase with increasing dose or dose rate.

From the above analysis, it can be seen that the general characteristics of PIN diodes can be predicted readily with the analysis program. Although no experimental data are presented, experience with devices of the type analyzed confirms the depletion characteristics shown in Fig. 4 and the predicted collection efficiency. Furthermore, the transient waveform predicted for small doses agrees very well with the pulse shape expected from classical analysis.

The most significant result presented in this section is the prediction that significant field collapse occurs at steady state dose rates of 10^9 rad (Si)/sec (Fig. 5) and for prompt doses of only 6 Rad(Si) (see Figs. 7 and 8). Although this prediction has not been verified experimentally, it casts serious doubt on the utility of diodes of this thickness as high intensity, fast response radiation detectors. Certainly the presence of the long delayed photocurrent component shown in Fig. 8 and the fact that the relative amplitude of this component increases with increasing dose rate detracts significantly from the 4 ns time resolution expected on the basis of classical analysis.

Transistor Transient Response

The classical analysis of photocurrent production in transistors has been considered in several papers.^(1, 19) These analyses are basically restricted to low ionization levels where conductivity modulation, saturation and other high injection phenomena are unimportant. By removing these restrictions, however, considerable insight can be obtained concerning the mechanisms of photoresponse which are important in different modes of operation.

In order to demonstrate the various response mechanisms, a device having the doping profile shown in Fig. 9 was assumed. Since this device has a high resistivity ($\sim 10 \Omega\text{-cm}$) collector region and a reasonably narrow base, it is representative of the high voltage, medium frequency class of transistor. Although no particular effort was made to describe a commercial device, it would be roughly equivalent to the nonepitaxial 2N914 or the 2N1051. It was further assumed that carrier lifetimes were determined by a concentration of 5×10^{13} gold impurities per cm^3 . This concentration predicts a collector lifetime of approximately 0.1 μ sec and a base lifetime of 0.3 μ sec, values which are typical for high gain nonswitching transistors of the type shown.

Before calculating the transient photoresponse of the transistor, it is necessary to calculate the quiescent carrier and field distributions so that no portion of the predicted transient waveforms is caused by the application of the voltage and current bias. For this case, a collector-to-emitter voltage bias of 5.0 v and a base current density bias of $1.35 \times 10^{-2} \text{ a/cm}^2$ were chosen. These bias conditions predict a base-emitter voltage of 0.66 v and a collector current density of 6.4 a/cm^2 .

The primary and secondary photocurrent waveforms were predicted for the case of a rectangular pulse of ionizing radiation having a duration of 10 ns and doses of 0.05, 0.5 and 5.0 Rad(Si). The time and dose parameters were chosen so that the ionization occurred in a time which was short compared to the device response time and the resulting secondary photocurrent density was (a) much less than, (b) somewhat greater than, and (c) very much greater than the quiescent collector current density.

The secondary and primary photocurrent waveforms for the 0.05 rad (Si) case are shown in Figs. 10a and 10b, respectively. The secondary photocurrent waveform for this case is very similar to those predicted by classical analysis; the collector current reaches a maximum shortly after the ionization pulse terminates and then decays exponentially with time. The calculated emitter and collector contributions to primary photocurrent are shown in Fig. 10b. The magnitude and waveshape of the collector component is again consistent with classical predictions. Note also that the emitter component amplitude is only one-quarter that of the collector component and tends to zero very rapidly. Consequently, the frequently used assumption that this component is negligibly small is valid for this case.

When the dose is increased from 0.05 to 0.5 Rads(Si), however, many of the common assumptions, such as the charge neutrality of the collector and base regions, are no longer valid and substantial deviations from the classical waveforms are observed. For prompt doses of the order of 0.5 Rad(Si), the collector photocurrent

is many times larger than the quiescent bias current and substantial electric fields are produced in the bulk collector region. These fields are in the direction to cause minority collector carriers to drift toward the collector junction where they contribute to the primary photocurrent. Thus, as the collector current increases toward its peak value, there is a corresponding increase in the electric field and, therefore, the collector component of primary photocurrent. Since the primary photocurrent is a majority current in the base, this increase in primary photocurrent further increases the collector current, the electric field, primary photocurrent, etc.; that is, the coupling between the primary and secondary photocurrent is regenerative. This regenerative process gives rise to an unstable buildup of collector current which is ultimately quenched by recombination or depletion of excess minority carriers from the collector region.

The effect discussed above is very evident in Fig. 11 which shows the secondary and primary photocurrent waveforms for the 0.5 Rad(Si) case. Figure 11b shows that as the collector current increases (e.g., at 60 ns), there is a corresponding increase in the collector primary photocurrent. The instability discussed above is evidenced by the fact that in the time interval prior to the collector current peak, the collector current increases at an increasing rate, i.e., the collector current waveform is concave upward. After 90 ns, a large fraction of the excess collector minority carriers have either recombined or been swept into the base region and the unstable buildup can no longer be sustained. Consequently, the primary current and, subsequently, the collector current begin to decay toward their quiescent values.

Typically, the transient radiation models used in large scale circuit analysis programs do not consider this regenerative mechanism and simply assume that the collector primary photocurrent waveform is constant. A comparison of 10b and 11b shows very clearly that this assumption is not necessarily valid since the primary photocurrent waveform changes radically as the dose is increased. Moreover, the secondary photocurrent data indicates that a dose change of a factor of 10 causes the peak secondary photocurrent to increase by a factor of 20. This superlinear dependence of peak collector current on dose is a direct result of the collector regeneration process and, therefore, it is not predicted by the usual Ebers-Moll⁽²⁰⁾ or charge control⁽²¹⁾ device model. In order to predict this effect, it is necessary to employ a more exact model which includes coupling between the primary and secondary photocurrents. This refinement can be obtained either by using a multilump Linvill model⁽²²⁾ or by adding the appropriate corrections to the Ebers-Moll model.

The response of the assumed transistor to a large (5.0 Rad(Si)) dose of ionizing radiation is shown in Fig. 12. In this case, the photocurrents are very large and the device is driven into a saturated condition. In the saturated state, the collector current density is limited primarily by the bias voltage to collector bulk resistivity ratio and is essentially constant throughout the saturation period. After approximately 0.6 μ s, the primary photocurrent decays to a value where it can no longer hold the transistor in the saturated state and the secondary photocurrent decays to its quiescent value.

In addition to the normal saturation phenomena discussed above, early portions of the waveform shown in Fig. 12 illustrate another effect, conductivity modulation of the collector region. Since the carriers produced by ionizing radiation are free to take part in conduction process in exactly the same manner as those carriers introduced intentionally by impurities, ionization can temporarily increase the conductivity of the collector region.

In the saturated case, this increased conductivity is evidenced by the temporary collector current overshoot shown in the first 30 ns of the collector current waveform. The magnitude of this overshoot typically scales as about the one-half power of the dose.

Additional insight into the adequacy of contemporary device models can be obtained by examining the distribution of collector minority carriers at various times after the ionizing exposure. Fig. 13 shows the hole distributions which correspond to the saturated collector current waveform shown in Fig. 12. Immediately after the ionization pulse, the hole density in the collector is essentially uniform and equal to the density generated. As time increases, the electric field rapidly moves the holes toward the collector junction and, after only 60 ns, has collected nearly all of the carriers generated in the entire collector region. This result is further evidence of the general need to include the influence of the collector electric field in the models used for circuit and system analysis.

Displacement Damage

In addition to transient analyses, a second major use of the device analysis program is for the prediction of displacement damage effects in devices. During the last few years, significant progress has been made toward modeling the electrical properties of point defects and, to a lesser degree, cluster defects in silicon and germanium. Although it would be premature to claim that the accuracy of these recombination and trapping models is sufficient for accurate device analysis, some of the important bulk properties of the semiconductor, e.g., lifetime, have been successfully described in terms single and double level Shockley-Hall-Read models and, therefore, it is appropriate to determine which, if any, of the observed properties of irradiated semiconductor devices can be predicted directly from such models.

The device used for this analysis is a silicon NPN double diffused epitaxial transistor with the doping profile shown in Fig. 14. The doping profile has been selected to match the junction depths, base sheet resistivity and collector resistivity of the epitaxial 2N914 device. The general shape of the doping profile was determined from the theoretical shape of the diffusion processes used in the device fabrication.

Recombination in the unirradiated device is modeled by a two-level SRH model. Since the experimental devices used in the study were gold doped, a background density of 2.5×10^{14} gold centers per cm^3 was assumed. Donor and acceptor energy levels of 0.54 and 0.35 eV above the valence band and capture cross-sections of 1.7×10^{-16} , 1.1×10^{-14} , 6.3×10^{-15} and $2.4 \times 10^{-15} \text{ cm}^2$ for electron and hole capture on the donor and acceptor levels⁽²³⁾ were used to determine the recombination properties of the gold center.

Messenger⁽²⁴⁾ has described recombination in neutron irradiated materials by using two single-level SRH models, an acceptor level located 0.41 eV above the valence band and a donor level located 0.31 eV below the conduction band. These centers have hole and electron capture rates of 0.68×10^{-5} and 0.76×10^{-6} and 0.37×10^{-6} and $0.40 \times 10^{-5} \text{ (sec)}^{-1}$ per incident neutron/ cm^2 ($E > 0.01 \text{ MeV}$).

Using the recombination models discussed above, the characteristics of the 2N914 were predicted for two cases: (a) no neutron induced defects, and (b) a neutron fluence of $5 \times 10^{13} \text{ cm}^{-2}$. The emission crowding correction discussed earlier was applied to predict collector and base current density vs base emitter voltage characteristics for the case when the base-collector voltage is zero.

The experimental and predicted data for a typical 2N914 device are shown in Figs. 15 and 16, respectively. A comparison between these figures indicates reasonable correlation between experiment and theory. The predicted collector current curve has the proper slope and emission crowding bendaway. However, the predicted values are approximately a factor of two less than the measured values, presumably because of uncertainties in the emitter and/or base doping levels. The predicted pre-irradiation base current is consistent with the predicted collector current in that it has the correct curve shape but it also is low by a factor of two. This agreement is about as expected because of uncertainties in the doping profile, the gold cross-section and density parameters and the possible errors introduced by neglecting the emitter-base space charge recombination at or near the surface.

After neutron irradiation, there is again general agreement in the curve shapes. Except for the enhanced emission crowding deviations

both predicted and experimental collector current curves are essentially the same as in the pre-irradiated case. The predicted base current curve has the same general shape as the experimental curve and approximately the correct amplitude. The predicted change in base current density at a base-emitter voltage of 0.5 v and a neutron fluence of $5 \times 10^{13}/\text{cm}^{-2}$ is about $5 \times 10^{-3} \text{ ma/cm}^2$. This value is almost exactly the same as the value obtained by Goben and Smits⁽²⁵⁾ and agrees reasonably with the value of $3 \times 10^{-3} \text{ ma/cm}^2$ obtained from Fig. 15. Also note that in the low current regime, the neutron induced change in base current predicted on the basis of the Messenger model is approximately characterized by an expression of the form

$$\Delta I_b(V_{be}) = K \Phi \exp\left(\frac{q}{\eta kT} V_{be}\right)$$

where K is approximately 1.3×10^{-22} (a) and η is 1.4. It should be noted that these values are also in agreement with the values of 3.3×10^{-22} a and 1.5 measured by Goben and Smits.⁽²⁵⁾

At the higher current levels, the predicted and measured data both evidence similar "bendaway" characteristics which result from high injection and emission crowding effects. The relative importance of these two effects is shown in Fig. 16 by the comparison of the predicted characteristic prior to the emission crowding correction (the dotted curves) and the fully corrected curve.

Since these data indicate general agreement between theory and experiment, there is reason to look more closely at the calculated behavior and draw tentative conclusions concerning the relative importance of specific damage mechanisms. Rather than examine the total base current, it is instructive to examine the recombination current in each major region of the device. For the discussion here,

four base current components are considered: (1) the back injection of holes into the emitter region, (2) recombination in the emitter transition region, (3) recombination in the bulk base region and (4) recombination in the collector transition or Kirk region.^(26,27) The latter component becomes important at high injection levels where the carriers in transit through the collector transition region become more dense than the net impurity concentration and the effective collector junction moves into the collector region.

The predicted magnitude and bias dependence of these four components in the case of a $5.0 \times 10^{13} \text{ cm}^{-2}$ fluence is shown in Fig. 17. As postulated by Goben and Smits, recombination in the emitter transition region dominates at low current levels and has a voltage dependence of approximately $\exp(q V_{be} / 1.4 kT)$ over most of the bias range. Components 1 and 3, which are due to recombination in the bulk emitter and base regions, have an ideal Boltzman voltage dependence of $\exp(q V_{be} / kT)$ and, although small at low current levels, become significant for base-emitter voltages of the order of 0.7 v. Note also that the component due to recombination in the Kirk region, component 4, increases very rapidly at high current levels and is dominant for currents in excess of about 70 ma. The magnitude of this component is enhanced by having a collector-base voltage of 0 volts but even for nominal bias levels this component is significant at current densities of the order of 1000 a/cm^2 . Although devices do not normally operate at this high level, emission crowding is greatly enhanced by displacement damage and after irradiation such densities are achieved around the emitter periphery at reasonably low bias levels.

On the basis of these calculations, one would conclude that recombination in the emitter transition region and the Kirk region are the dominant damage mechanisms while bulk base recombination and emitter efficiency play secondary roles. However, it should be recognized that these conclusions are strongly dependent upon the lifetime models assumed. These models are based upon the characteristics of bulk silicon and could be grossly in error in space charge regions where there are large fields and small carrier densities. This possibility could easily account for the small discrepancies found in this analysis.

IV. Conclusion

This paper describes a device analysis program which automatically solves Poisson's Equation and the continuity equations over a one-dimensional region. The program automatically includes nonlinear mobility, impact ionization and SRH recombination models and should predict the electrical properties of devices with considerable accuracy.

The utility of the program is demonstrated by the results obtained from three examples. First, the transient analysis of the PIN diode indicates that field collapse occurs at relatively low radiation levels, e.g., 6 Rad(Si). Although this prediction has not been confirmed experimentally, it indicates that this device should not be used indiscriminately as a radiation detector, especially in applications demanding nanosecond time resolution at high ($> 10^9$ Rad/sec) dose rates. Second, the predicted transient response of the transistor emphasized the role of the collector electric field and indicated the shortcomings of several models now used in circuit analysis applications. In addition, the effect of conductivity modulation was predicted. Finally, the displacement damage calculations predict that in the 2N914 device both transition region recombination and Kirk effect are the dominant gain degradation mechanisms. Naturally this result is based upon the lifetime model assumed and is subject to considerable error. However, the agreement between the experimental and calculated device characteristics is very good and lends a measure of credibility to the predictions.

There are clearly many additional applications for analysis programs of this type. The radiation characteristics of the silicon controlled rectifier, the silicon controlled switch, and the standard diode could be predicted with no alterations of the program. The junction FET could also be analyzed by using the program to predict the depletion characteristic of a section of the channel. In addition, the program computes the small signal parameters and can be used directly to predict junction capacitance and other parameters required for the more approximate device models used in circuit analysis applications.

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APPENDIX I

Definition of Symbols

p, n	hole and electron concentrations $(\text{cm})^{-3}$
E	electric field intensity volts/cm
q	electronic charge (1.602×10^{-19} coulombs)
J_p, J_n	hole and electron current densities amperes/cm ²
g_p, g_n	hole and electron generation-recombination rates carriers/cm ³ -sec
g_{pR}, g_{nR}	ionization generation rates for holes and electrons carriers/cm ³ -sec
g_{pI}, g_{nI}	impact ionization generation rate for holes and electrons carriers/cm ³ -sec
g_{pd1}, g_{nd1}	hole and electron generation-recombination rates through a single level trapping center carriers/cm ³ -sec
g_{pd2}, g_{nd2}	hole and electron generation-recombination rates through a two-level trapping center carriers/cm ³ -sec
K	relative dielectric constant for silicon (11.5)
ϵ_0	permittivity of free space (8.85×10^{-14} farads/cm)
k	Boltzman Constant (1.38044×10^{-23} Joules/°K)
T	Absolute temperature °K
N_{Dt}	total ionized impurity concentration $(\text{cm})^{-3}$
N_D, N_A	concentration of donor and acceptor impurity atoms $(\text{cm})^{-3}$
μ_p, μ_n	hole and electron mobilities cm ² /volt-sec

μ_{po}	low field, low doping, hole mobility in silicon ($480 \text{ cm}^2/\text{volt-sec}$)
μ_{no}	low field, low doping, electron mobility in silicon ($1350 \text{ cm}^2/\text{volt-sec}$)
v_p, v_n	drift velocity for holes and electrons cm/sec
$\alpha_p(E), \alpha_n(E)$	ionization coefficients for holes and electrons carriers/carrier-cm
N_T	concentration of trapping centers $(\text{cm})^{-3}$
N_T^0, N_T^+, N_T^-	concentration of neutral, positive and negative charged trapping centers $(\text{cm})^{-3}$
N_{Ti}^+	net concentration of positively charged trapping centers for the trap level "i"
σ_p, σ_n	hole and electrons capture cross-sections for a single level trapping center
σ_p^0, σ_n^+	hole and electron capture cross-sections for donor level traps $(\text{cm})^{-3}$
σ_p^-, σ_n^0	hole and electron capture cross-sections for acceptor level traps $(\text{cm})^{-3}$
v_{tp}, v_{tn}	thermal velocity of holes and electrons cm/sec
p_1, n_1	hole and electron concentrations in the conduction band when the Fermi level coincides with the energy level of the single level trap
p_{1A}, n_{1A}	hole and electron concentrations in the conduction band when the Fermi level coincides with the acceptor trap energy level $(\text{cm})^{-3}$
p_{1D}, n_{1D}	hole and electron concentrations in the conduction band when the Fermi level coincides with the donor trap energy level $(\text{cm})^{-3}$

V_{be}	base-emitter voltage (volts)
I_b	base current (amperes)
I_e	emitter current (amperes)
I_c	collector current (amperes)
$\rho(V_{be})$	base sheet resistivity as a function of base-emitter voltage (ohms)
r	radius (cm)
R_c	radius of emitter
K	damage constant (amperes/cm ²)/(neutrons/cm ²)
ϕ	neutron fluence
η	slope correction constant used in the function $\exp(qV/\eta kT)$

Figure 1. Hole and Electron Impact Ionization Coefficients versus Reciprocal Electric Field Intensity for Silicon.

Figure 2A. Drift Mobilities in Silicon

Figure 2B. Carrier Drift Velocity as a Function of Electric Field Intensity

Figure 3. Impurity Doping Profile for Pin Diode

Figure 4A. Hole Distribution in a Pin Diode as a Function of Reverse Bias Voltage.

Figure 4B. Electric Field Distribution in a Pin Diode as a Function of Reverse Bias Voltage.

Figure 5A. Steady-State Electric Field Distribution in a Pin Diode for Several Ionization Rates.

Figure 5B. Steady-State Hole Distribution in a Pin Diode for Several Ionization Rates.

Figure 6. Ideal Transient Photocurrent Response for a 300μ Fully Depleted Pin Diode.

Figure 7A. Hole Distribution in a Pin Diode at Several Times

Figure 7B. Electron Distribution in a Pin Diode at Several Times

Figure 7C. Electric Field Distribution in a Pin Diode at Several Times.

Figure 8. Transient Photocurrent Response of a Pin Diode at Two Ionization Levels

Figure 9. Impurity Doping Profile for Transient Transistor Calculations

Figure 10A. Secondary Photocurrent versus Time for a Dose of 0.05 Rads (Si)

Figure 10B. Primary Photocurrent Response for a Dose of 0.05 Rads (Si)

Figure 11A. Secondary Photocurrent versus Time for a Dose of 0.5 Rads (Si)

Figure 11B. Primary and Secondary Photocurrent versus Time for a Dose of 0.5 Rads (Si)

Figure 12. Secondary Photocurrent as a Function of Time for a Dose of 5.0 Rads (Si)

Figure 13. Hole Distribution at Several Times After a Prompt Exposure of 5.0 Rads (Si)

Figure 14. Impurity Doping Profile for the 2N914 Transistor

Figure 15. Base and Collector Current as a Function of Base-Emitter Voltage (Experimental).

Figure 16. Predicted Base and Collector Current as a Function of Base-Emitter Voltage.

Figure 17. Predicted Base Current Components versus Base-Emitter Voltage