SESSION D:

MODELING AND CHARACTERIZATION
OF RADIATION EFFECTS
NUMERICAL SIMULATIONS OF NEUTRON EFFECTS ON BIPOLAR TRANSISTORS†

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Abstract  

A detailed device model that has been verified by comparisons with experimental measurements on unirradiated, state-of-the-art bipolar devices has been modified to include the effects of neutron radiation on carrier lifetimes, concentrations, and mobilities. Numerical experiments on the degradation due to neutron fluences in the dc common emitter gains for bipolar transistors with submicrometer emitter and base widths are given and compared in general terms with the few published measurements.

I. Introduction  

This paper demonstrates that it is feasible to include the degradations due to neutron irradiation in detailed device models of the electrical performance of submicrometer bipolar transistors. It also contains numerical simulations of the degradation in dc common emitter gains for VLSI bipolar transistors. These simulations include variations of gain versus collector current with neutron fluence, with empirical and first-principles device physics, and with base Gummel number. The simulations for unirradiated devices have been verified by comparisons with measurements of the current-voltage characteristics and of the dc common emitter gain. The simulations for the irradiated devices have not been verified because consistent sets of data on devices and their associated test structures for doping profile and geometric configurations are not available.

The semiconductor industry depends on numerical simulations of device characteristics to identify trade-offs between the physical structure of a device and its performance. These simulations contain parameters that describe the effects of several physical mechanisms, such as the effects of high concentrations of dopant ions and carriers on carrier transport. In addition, neutron-induced changes in the electrical properties greatly affect the performance of submicrometer bipolar silicon devices. For neutron fluences between $10^{18} \text{cm}^{-2}$ and $10^{19} \text{cm}^{-2}$, these changes decrease carrier lifetimes, concentrations, and mobilities by as much as an order of magnitude from their respective unirradiated values.\textsuperscript{1,2}

There are three classes of numerical simulations for devices: equivalent circuits (Class 1), compact device models (Class 2), and detailed device models (Class 3). This paper pertains to detailed device models. Such models allow for the explicit description of the device physics associated with doping profiles and carrier lifetimes, concentrations, and mobilities. Numerical simulations that are based on detailed models include numerical solutions to the coupled nonlinear semiconductor device equations with appropriate boundary conditions. The semiconductor equations are solved self-consistently by either a finite element or finite difference procedures and include Poisson's equation for conservation of charge, continuity equations for holes and electrons, and several constitutive equations. The latter include the current-density equations for holes and electrons.

II. Approach  

In this paper, the improved device physics (IDP) based on the first-principles approach for high concentration effects\textsuperscript{3} and the measured effects of neutron exposure on carrier lifetimes, concentrations, and mobilities\textsuperscript{1,2} are combined in a modified version of a detailed device model that has the acronym SEDAN.\textsuperscript{4}

Figure 1 shows the stable degradations in minority carrier lifetimes, majority carrier concentrations, and majority carrier mobilities for n-type, bulk silicon with a resistivity of 2 $\Omega \text{cm}$. If the temperature is 300 K and the dopant ion is phosphorus, then this resistivity corresponds to an impurity concentration of about $2 \times 10^{15} \text{cm}^{-3}$. These curves have been digitized and included in SEDAN. Interpolation procedures for look-up tables also were added.

These curves for stable degradation due to neutron irradiation are strictly valid only for the concentration given. But, because degradation data do not exist for the highest concentrations in submicrometer bipolar devices, they are used here by necessity in the following numerical simulations for all concentrations greater than $2 \times 10^{15} \text{cm}^{-3}$ in both n-type and p-type silicon. Figures 36, 37, and 40 of reference 1 suggest that since the degradation coefficients vary only slightly with resistivities below 2 $\Omega \text{cm}$, using the degradation curves in Figure 1 for modeling submicrometer devices may be acceptable. In addition to the above dependences on material type, resistivity, temperature, impurity species, and concentration, stable damage depends also on injection level or bias conditions. Again, the data in Figure 38 of reference 1 suggest that neglecting the dependence on injection level is acceptable for the heavily doped regions of submicrometer bipolar transistors.

In conventional or empirical device physics (CDP), the parameters to describe high concentration effects are determined by interpretations of electrical measurements on the devices being modeled or on similar devices. Ambiguous results may occur when extracting such parameters from electrical measurements on devices. Such extractions for model parameters usually are based on a lower level device model and hence become dependent on the lower level device model itself. Empirical procedures give acceptable predictions for the effects of small variations in processing and in device geometry and dimensions. However, models built in this way may not lead to a fundamental understanding of the physical mechanisms responsible for the performance of the device.

Even though the above empirical parameters may predict or play back measured current-voltage characteristics of unirradiated devices, they are not necessarily the physically correct ones. Using them to simulate radiation effects is very questionable. Hence, the alternatives given below are recommended.

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when modeling the effects of neutron radiation on the electrical behavior of VLSI bipolar transistors that have regions with high concentrations of carriers and dopant ions.

When possible, it is preferable to obtain parameters for high concentration effects by first-principles calculations that are verified by alternative measurements such as optical absorption or luminescence. The latter measurements do not require device models for their interpretation. First-principles procedures give acceptable results for larger changes in fabrication processes and in device geometry and dimensions than do conventional procedures. First-principles procedures relate carrier concentrations directly to band structure changes and use scattering theory to calculate separate values for minority and majority carrier mobilities. These calculated values for mobilities may differ by factors of 2 at the same doping density. First-principles procedures also give the variations of minority carrier lifetimes with doping density that differ by factors of 3 from the variations given by empirical procedures.

Table I summarizes the major differences between the CDP and IDP approaches for the physical quantities that are needed in numerical simulations. In CDP, the effective intrinsic carrier concentrations, , , , and lifetimes are obtained from the interpretation of electrical measurements. The mobility of holes in n-type material is assumed equal to the mobility of holes in p-type material at the same dopant density. A similar equality is assumed for electrons. And the minority carrier lifetime due to Shockley-Read-Hall (SRH) processes is a three-parameter (, , and ) fit to electrical data, where and denote the doping density and reference density, respectively. Whereas in IDP, the equilibrium electron and hole concentrations, and , respectively, are calculated from first-principles in terms of a self-consistent distorted band structure (bandgap narrowing). The latter is verified by comparison with measurements of optical absorption coefficients for heavily doped materials. The minority mobilities are calculated from scattering theory and are found to be greater than majority mobilities. And the SRH lifetime is given by first-principles calculations as a function of the Fermi energy, . The major physical quantities presented in Table I for IDP and CDP should be considered as a single unit and not separately. That is, subsets of these quantities from CDP must not be combined with quantities from IDP in numerical simulations and vice versa.

III. Results

The first-principles device physics and the neutron effects then are included in numerical simulations of VLSI bipolar transistors. Several numerical experiments are performed to show the usefulness of methods based on first-principles device physics and detailed device models. However, caution in making definitive and quantitative conclusions is required since the neutron effects used in this work were extracted by interpreting measured data in terms of either class 1 or 2 models with empirical device physics. Extracting neutron effects by interpreting measured data in terms of class 3 simulations with first-principles device physics remains to be done. One purpose here is to demonstrate that it would be feasible to do this. The procedures for extracting the neutron effects self-consistently with first-principles device physics are analogous to the procedures for extracting the interface trap densities in the presence of arbitrary doping profiles. Namely, the neutron damage coefficients would be varied until acceptable agreement with measured current-voltage characteristics is achieved.

As a starting point, numerical simulations belonging to class 3 are applied to a device for which the conventional or empirical parameters give wrong predictions for the unirradiated device and for which the essential input doping profiles measured by secondary ion mass spectroscopy (SIMS) are available. This is the device discussed in reference 3. It has a 0.16-μm emitter-base junction depth, a 0.2-μm base width, and an emitter doping density near its surface (ohmic contact) of . Its net doping density profile from SIMS and spreading resistance data is given in Figure 2. The arsenic-doped emitter and boron-doped base profiles are modified SIMS profiles and the collector is a spreading resistance profile. The SIMS emitter profile near the surface is changed so that the measured and calculated sheet resistances agree. The scatter in the SIMS boron profile for the base is reduced by fitting the boron profile to a complementary error function. Reducing the scatter is necessary for numerical stability in the Poisson solver. The solid curve in Figure 2 contains the above two changes in the SIMS data and gives the net doping density profile used in the detailed model.

The verification of the improved device physics for the unirradiated device is shown in Figure 3. The minority carrier lifetime due to the Shockley-Read-Hall process is a variational parameter for the predicted curves. It is μs for the IDP and μs for the CDP. Varying the lifetime for CDP from 0.1 μs to 100 μs does not decrease the disagreement between the measured and predicted curves. Values near 1 μs give the closest agreement that is possible.

The simulations of the effects of neutrons on gain for the above device are shown in Figure 4. The device in reference 3 does not necessarily represent the optimum design for minimizing the effect of neutrons. It is used here only as an illustrative example since the unirradiated device has been characterized very well. The degradation of gain shown in Figure 4 is greatest at low collector currents and decreases with increasing collector current. This is consistent with the measured effects of neutrons on lifetimes, concentrations, and mobilities. Lifetimes decrease much more rapidly than the neutron dose than do carrier concentrations and mobilities. Because the gain at low currents is dominated by lifetimes, whereas the gain at higher currents is influenced also by carrier concentrations and mobilities, the curves shown in Figure 4 are qualitatively in agreement with what one would expect from experiment.
such as SEDAN do not consider the effective resistance in the base between the base contact and the active region under consideration, i.e., extrinsic base resistance. Modeling the latter requires two- or three-dimensional profiles, mask layouts, and sheet resistances of the bases. These are not available.

Figure 5 compares the predictions given by CDP and IDP at two neutron fluences. The pre-irradiation lifetime for CDP is given in parentheses and that for IDP is 0.1 μs. Observe that CDP suggests a much larger shift with neutron fluence in the value of the collector current at which the gain has a maximum value.

Figures 6 and 7 give an example of a sensitivity analysis on base Gummel number for the unirradiated device and show that input parameters, such as base widths and doping density profiles, must be accurate if detailed device models are to be useful for engineering purposes. In Figure 6, the SIMS profile (solid line) is approximated by Gaussian distributions for the emitter and base. This is done to facilitate changing the diffusion length, W, for the Gaussian distribution of the base, and thereby to change the base Gummel number. The approximate profile is indicated by the short-dashed curve with a diffusion length of 0.16 μm. The remaining two curves are profiles composed of Gaussian distributions with diffusion lengths of 0.15 μm (curve with long dashes) and 0.17 μm (curve with dot-dashes). Figure 7 shows that a 6% change in diffusion length leads to a factor of more than 2 change in the gain. The foregoing sensitivity analysis shows that the diffusion length and thereby the base Gummel number are key parameters to control in fabricating thousands of devices with the same gain characteristics.

IV. Conclusions

The above discussion shows that it is possible to include neutron effects in detailed device models and that the effects of modifications in physical structure on device performance when exposed to neutrons may be explored by using numerical simulations based on detailed device models. The experimental verification, which is analogous to that shown in Figure 3, remains to be accomplished for the neutron-irradiated cases. Such verification requires a set of test structures for determining by SIMS the doping profiles and for measuring the performance of the bipolar transistors. Both the transistor and its corresponding SIMS test structure should be fabricated next to each other on the same chip.

Acknowledgments

The author thanks K. F. Galloway for suggesting the challenges of understanding neutron effects on transistors. The author also thanks J. R. Sour for permission to reproduce Figure 26 in reference 1, C. H. Ellenwood for providing published data on neutron effects in machine-readable formats, and J. R. Sour, T. J. Russell, G. C. Messenger, and C. L. Wilson for helpful discussions.

References


4. Semiconductor Device Analysis, Stanford University, Stanford, CA, October 1979 version. This identification does not imply recommendation or endorsement by the National Bureau of Standards nor does it imply that the computer code identified is necessarily the best available for the purpose.


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Table I: Comparison of Conventional and Improved Device Physics

<table>
<thead>
<tr>
<th>Physical Quantity</th>
<th>Conventional Device Physics (CDP)</th>
<th>Improved Device Physics (IDP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>n_ie or bandgap narrowing</td>
<td>electrical measurements</td>
<td>first-principles calculations</td>
</tr>
<tr>
<td>minority mobility</td>
<td>$\mu_{min} = \mu_{maj}$</td>
<td>$\mu_{min} \neq \mu_{maj}$</td>
</tr>
<tr>
<td>SRH lifetime</td>
<td>$1 + \left( \frac{N}{N_{SRH}} \right)^{1/\alpha}$</td>
<td>$\tau_0 F(E_F)$</td>
</tr>
</tbody>
</table>

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Figure 1: The stable-degradation ratios for lifetimes $\tau_r$, carrier concentrations $n_i$, and mobilities $\mu$ as functions of neutron fluence. The subscripts 0 denote the pre-irradiated values. This Figure is reproduced from reference 1 with the permission of J. R. Sour.
Figure 2. Net doping density profile based on secondary ion mass spectroscopy and spreading resistance data for the npn bipolar transistor investigated in this paper.

Figure 3. DC common emitter gains as functions of the collector current. The long-dashed, short-dashed, and solid curves give the measured values, the values predicted by conventional device physics, and the values predicted by the improved device physics.

Figure 4. Numerical simulations of the degradations in gain versus collector current for several neutron fluences. These predictions are based on improved device physics that has been verified for the pre-irradiated transistor.

Figure 5. Comparisons of gain versus collector current for two values of neutron fluence. Conventional device physics is denoted by CDP and improved device physics is denoted by IDP.

Figure 6. Doping profiles for a sensitivity analysis for the gain to variations in Gummel number. Gaussian diffusion lengths are denoted by W.

Figure 7. Gain versus collector current for three values of Gaussian diffusion lengths. The corresponding doping profiles are given in Figure 6.