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A Physics-based Device Model of Transient Neutron Damage in Bipolar Junction Transistors

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***Abstract*—To simulate effects of neutron-induced damage on bipolar circuit performance, a new compact model has been developed using a physics-based approach. The model compares well to experiment, for all modes of bipolar operation.**

***Index Terms*—Annealing, bipolar junction transistor, displacement damage, neutron radiation effects, circuit modeling.**

I. Introduction

The simulation of time-dependent behavior of neutron-irradiated circuits, which include various Si devices, is difficult for a number of reasons. Detailed atomistic level modeling of single devices is challenging in and of itself, but distilling all the relevant physics into a compact model, typically used by circuit simulators, is even more difficult, as the behavior is very complex and nearly impossible to adequately describe with only a handful of ordinary differential equations. As a result, compact modeling of neutron effects has been previously limited to empirical approaches [3] [8], which require a relatively high degree of calibration and are generally only useful for longer-term post-anneal transient behavior.

The purpose of the present work has been to develop a predictive, physics-based, compact bipolar junction transistor (BJT) model of transient neutron effects for Si devices. This model is being developed in the Xyce [5] [6] [7] parallel circuit simulator, a production simulator under development within Sandia National Laboratories. The approach taken for this model is somewhat non-traditional, in that our model is not truly "compact", requiring several hundred equations. However, it is substantially more efficient than equivalent TCAD calculations, and as such still represents a substantial reduction in computational cost.

This paper is organized as follows. In section II, a brief description of neutron effects in Si devices is given, as well as a description of previous neutron modeling work. In section III, our new model is described in detail. In section IV, results from the model are presented, and compared with experimental data as well as other modeling approaches. Section V contains the final summary for the paper.

II. Background

A. Regimes of BJT Behavior

Bipolar junction transistors (BJT) are generally considered to have four regimes of behavior, when operating in the normal environment [12]. There are two PN junctions in a BJT; the base-emitter (BE) junction, and the collector-base (BC) junction. Each of these junctions can be either forward or reverse biased, and the four regions of operation correspond to all the possible combinations of junction bias:

- Forward Active: BE junction forward-biased, BC junction reverse biased.
- Inverted Active: BE junction reverse-biased, BC junction forward biased.
- Saturation: both junctions forward biased.
- Cutoff: both junctions reverse biased.

In general, neutron damage will have the greatest impact in junctions that are forward biased. As a result, an effective compact model needs to account for neutron damage effects in both junctions to be of practical use.

B. Effect of Neutrons

Incident neutrons damage a semiconductor lattice, by creating crystalline defects such as vacancies, divacancies, and interstitials. These defects, reduce carrier lifetimes, by adding recombination centers in the energy band structure of the material. As such, any device characteristic that is dependent upon carrier lifetime is affected by neutron damage. This has the potential to affect many aspects of device behavior [1], [4], [8], [9].

The most dominant effect of neutron damage is reduction of transistor gain, $\beta = I_C/I_B$ (the ratio of collector current to base current). Gain reduction is the result of enhanced recombination in key regions of the transistor, including the base-emitter depletion region. However, in addition to gain degredation, Fjeldly [3] and Hajghassem [4] have both identified other potential impacts on device behavior, including minority carrier lifetimes, Forward and reverse gain, saturation (intercept) current, generation/recombination current, high-injection knee current, series (terminal) resistances, and depletion/diffusion capacitances.

III. Neutron Model Description

In order to improve upon previous models, a new model of neutron effects in silicon BJTs is proposed. The new model consists of several components, which are illustrated by the flowchart in fig. 1. This includes a localized reaction model, a carrier model, and an integration term, as well as a normal environment transistor model. For the present work, the normal environment model used is the Gummel-Poon BJT model, but other models can be used.

The use of a global reaction module is based on several assumptions, which are partially based on observations from device (TCAD) simulation:

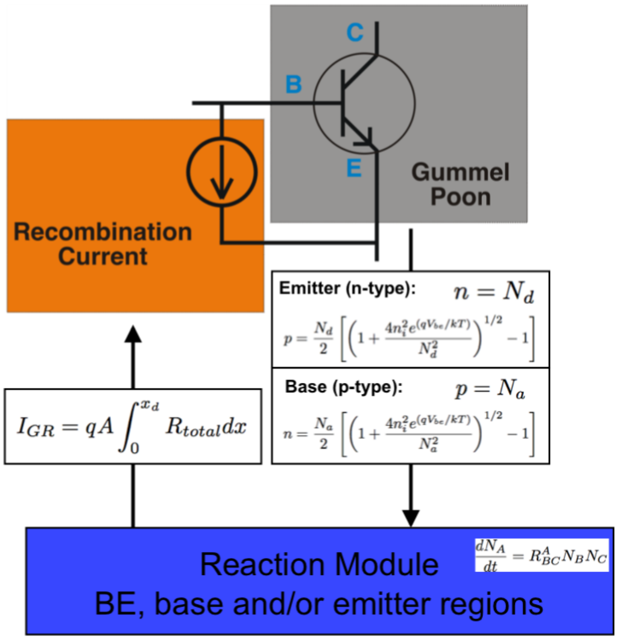

Fig. 1. Neutron model flowchart. In this example, the "core" transistor model is a Gummel-Poon (level=1) BJT, but other transistor models can be used at the discretion of the user. The defect reaction module is applied to the base-emitter junction, but the model can be applied to the other junction as well. The model needs to be applied to any junction that is foward-biased. So, a device in saturation would need the model applied to both junctions.

- Neutron damage-induced recombination is localized to relatively small volumes surrounding forward-biased depletion regions. This assumption is also made in compact models to approximate Shockley-Read-Hall(SRH) recombination current. [13].
- Defect evolution is dominated by reactions and not transport.
- Carrier densities are primarily a function of local electrostatic potential.
- Defect time scales differ from carrier time scales, allowing for quasi-static approximations of carrier densities.
- Doping impurities maintain their original doping profiles.

A. Reaction Module

Neutrons affect BJT performance primarily by creating crystalline defects, which can dramatically increase carrier recombination rate. Our new neutron model is primarily based on a detailed "reaction module", which solves a set of coupled ordinary differential equations with respect to time, for the full system of crystalline defect reactions. The reactants of the model are the set of Silicon defect species (vacancies, divacancies and interstitials).

Carrier emission and capture reactions are included in the model, but are not completely self-consistent, as the electron and hole densities are computed are analytically determined as functions of the junction bias used by the Gummel-Poon model. (The details of this analytic calculation are explained in section III-B.) They are considered inputs (from the carrier model) to the reaction module, and this relationship is illustrated in figure 1. The calculated emission and capture rates are used to produce a dynamic recombination current, which is applied in parallel to the Gummel-Poon, as depicted in figure 1.

Most of the equations of the global model are of the form:

$$\frac{dN_A}{dt} = R_{BC}^A N_B N_C \tag{1}$$

where N_A is the concentration of a defect that is produced by a reaction between species N_B and N_C. Defect transport is excluded, but the module can be applied at multiple device locations to capture some spatial defect non-uniformity. The model provides carrier emission and capture rates and lifetimes, which can be applied in a variety of ways to the Gummel-Poon BJT. Alternately, one can calculate the recombination current directly from the capture and emission rates of the global model.

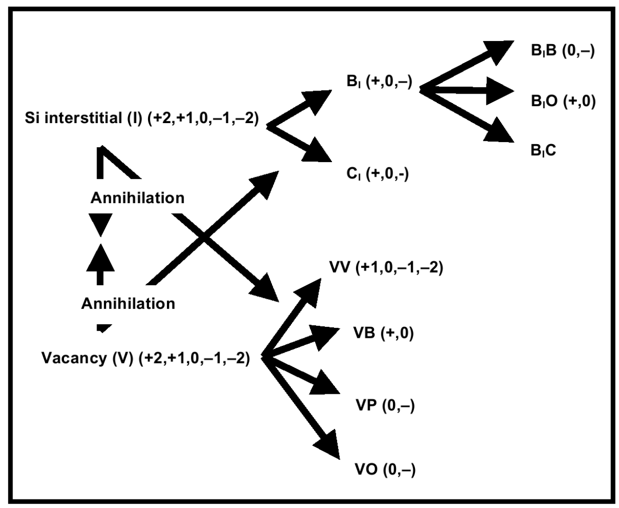

Fig. 2. Defect reaction diagram. Based on the reactions described in Myers [11].

A typical reaction network for neutron-induced defects is depicted in figure 2. The defect reaction module consists of a set of defect species (vacancies, divacancies and interstitials) and reactions between those species. The specific reaction set can be specified from an input file. To date, the reaction networks have been specific to Silicon devices, but other materials, such as Galium Arsenide could be handled in theory. The reaction network for Silicon has been presented in [11].

B. Carrier Model

The reaction module needs electron and hole densities, as they are reactants in the emission and capture reactions. Typical compact models, such as the Gummel-Poon, do not calculate carrier densities directly, but instead only use currents and voltages as model variables. To approximate the carrier densities needed by the reaction model, a set of analytic expressions and approximations are used, which are computed throughout the integration volume to determine densities as a function of spatial location. It has been observed that the electron and hole densities in the irradiated case will be similar to those of the normal scenario, even during the radiation pulse. As such, one can approximate electron and hole densities with standard analytic expressions.

The electron and hole densities at various locations in the device are determined by a combination of approximations. These are illustrated in figures 3 and 4.

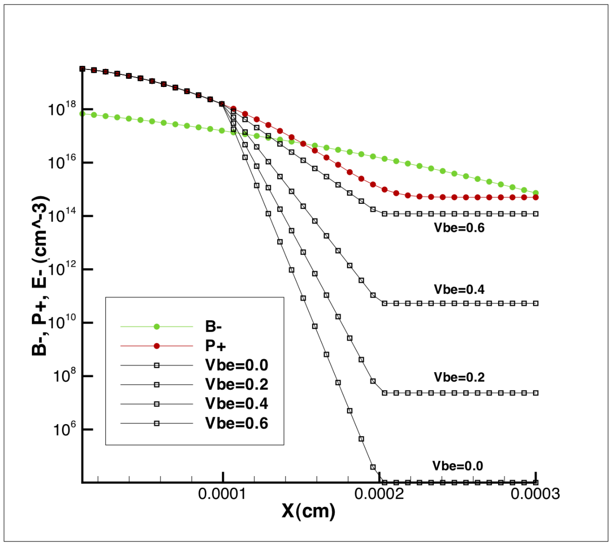

Fig. 3. Electron calculation result. This is from the base-emitter region of a 2N2222. The dopants are Boron and Phosphorus. On the emitter N-side of the junction, the electron density is pinned to the majority dopant, Phosphorus. On the base P-side of the junction, the electrons are the minority carrier, and thus are computed based on the formula given by equation 2. In the middle of the junction, the density is approximated as a logarithmic interpolation between the minority and majority values at the junction edges. The location of the junction edges is specified by the user.

To obtain the electron and hole densities the emitter or base region, one simply assumes that the majority carrier density will be approximately equal to the doping density. The minority carrier density can be determined from bias-dependent analytic expressions. Thus the minority carrier density in an p-type region (the base of an NPN transistor), at the junction edge, will be ([10], p. 331):

$$n = \frac{N_a}{2}\left[\left(1 + \frac{4n_i^2 e^{(qV_{be}/kT)}}{N_a^2}\right)^{1/2} - 1\right] \tag{2}$$

Equation 2 is derived for the high-injection case, but defaults to a simpler expression for low-injection. A similar expression for the minority carrier density in an n-type region (the emitter of an NPN transistor), at the junction edge, will thus be:

$$p = \frac{N_d}{2}\left[\left(1 + \frac{4n_i^2 e^{(qV_{be}/kT)}}{N_d^2}\right)^{1/2} - 1\right] \tag{3}$$

In the base region of the 2n2222, $N_a = 4.0e + 16$ cm^{-3}, so according to equation 2, the electron density, n is approximately $n = 1.89e + 12$ cm^{-3}.

In the middle of the junction, both electron and hole densities are approximated by performing a logarithmic interpolation between the values of each carrier at the junction edges. This can be observed in figures 3 and 4.

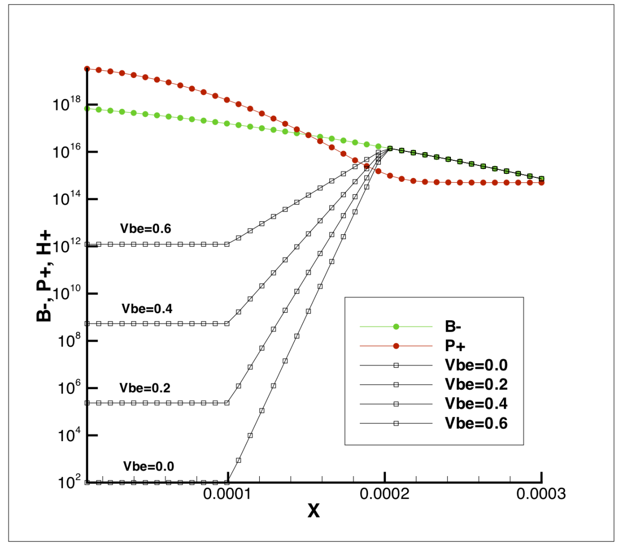

Fig. 4. Hole calculation result. This is from the base-emitter region of a 2N2222. The dopants are Boron and Phosphorus. On the base P-side of the junction, the hole density is pinned to the majority dopant, Boron. On the emitter N-side of the junction, the holes are the minority carrier, and thus are computed based on the formula given by equation 3. In the middle of the junction, the density is approximated as a logarithmic interpolation between the minority and majority values at the junction edges. The location of the junction edges is specified by the user.

C. Calculation of Recombination Current

The generation-recombination current is determined by using the calculated emission and capture rates for electrons and holes, and integrating over the area of interest:

$$I = qA\int_{x_p}^{x_n} R_{total}dx \tag{4}$$

$$R_{total} = \sum_{m=1}^{N_{cap}} R_m^n - \sum_{m=1}^{N_{emit}} R_m^n + \sum_{m=1}^{N_{cap}} R_m^p - \sum_{m=1}^{N_{emit}} R_m^p \tag{5}$$

where the integrand contains the calculated emission and capture rates for electrons and holes from the reaction model.

D. Numerical Considerations

The proposed model is somewhat unusual, in that the number of equations is considerably larger than is typically expected for compact models. However, there is some precedent for this approach, particularly in the area of total dose modeling [2], where small discretized regions are incorporated into compact models, to handle spatial nonuniformities which are unresolvable via analytic closed form expressions. The result is that the proposed model is more computationally expensive than typical compact models. However, the neutron model has been developed to mitigate this extra expense as much as possible. In particular, the defect evolution is isolated only to regions of the device which are likely to produce substantial recombination current, and regions which do not meet this criteria are excluded. Additionally, by computing carrier densities from analaytic expressions, rather than partial differential equations, the set of equations is far less numericall stiff than one would get from a full TCAD treatment. The time stepping only has to be on the defect evolution time scale, and can exclude time scales for electron and hole transport.

IV. Results and Discussion

A result from the new model is given in figure 5, in which the new model is compared against the model from reference [3]. For convenience, the model from reference [3] will be referred to as the "RPI model". This comparison focuses on dependence on the base-emitter voltage, which is known to have a significant impact on annealing rate. In general, increasing foward bias will lead to faster annealing, because defect reaction chemistry is driven in part by the electron and hole densities. The two biases used in the figure are $V_{be} = 0.2V$ and $V_{be} = 0.6V$.

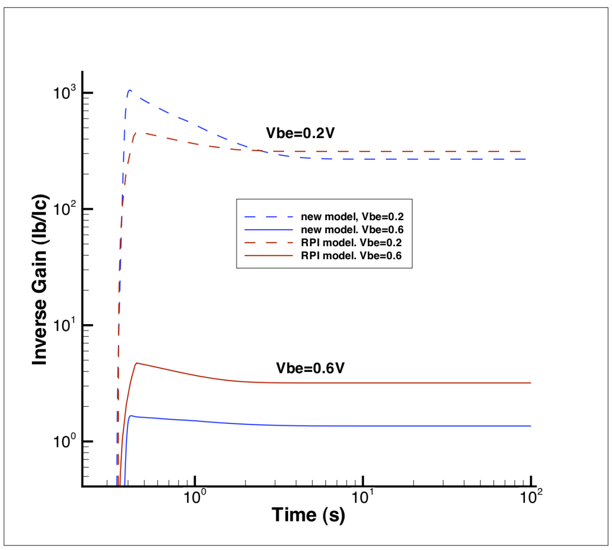

Fig. 5. Neutron model comparison. The new model is compared to the compact model from reference [3]. The simulated device is an NPN 2N2222 in forward active mode.

There are two features of interest in figure 5. First of all, we found that it was impossible to calibrate the RPI model to match the new model at both values of V_{be}. Additionally, the shape of the RPI model annealing curve is constant for both values as well. The RPI model assumes a single time constant, which is not dependent upon applied bias. The new model, in constrast, has a strong bias dependence that is enforced through the carrier model. As such, the shape of the new model annealing curve is substantially different for both biases. This has also been shown to be consistent with TCAD simulation.

V. Summary

A new approach to neutron-aware compact modeling of bipolar junction transistors has been described. The new model is based on the evaluation of a detailed reaction model, coupled to a bias-dependent carrier model. The model can be applied to either junction of a bipolar transistor, depending on the biasing. Comparisons to a previous modeling approach demonstrates advantages of the new model, in particular bias-dependent annealing.

VI. Acknowledgements

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