Gain Changes in Silicon Bipolar Transistors Due to Atomic Displacements: Theory and Experiment

by **W. R. Wampler and S. M. Myers**

Motivation—Irradiation of semiconductor devices by energetic neutrons or ions produces vacancies and interstitials which migrate and annihilate or react to form more stable defect complexes. These defects capture electrons and holes which increase carrier recombination and decrease the gain of a bipolar junction transistor (BJT). Thus, irradiation by a brief pulse causes a decrease in gain, which partially recovers with time after the pulse. We have developed a defect physics model to simulate these effects, which is based on known defects in silicon. This model is used in CHARON, a multi-dimensional diffusion-reaction device simulation code, to capture effects of radiation damage on device operation for the Qualification Alternatives to the Sandia Pulsed Reactor (QASPR) project. The fidelity of the model is a central issue for QASPR, since this influences the accuracy of predictions.

Accomplishment—We are undertaking model development, calibration, and validation by comparing simulations with measurements of gain versus time after a pulse for 2N2222 npn transistors irradiated with neutrons in SPRIII (Sandia Pulsed Reactor) and ACRR (Annular Core Research Reactor), and with silicon ions at the Sandia IBL (Ion Beam Laboratory). The model uses dopant profiles from secondary ion mass spectrometry (SIMS) measurements scaled to give measured gain. The calibrated model agrees closely with experiment as shown in Fig. 1 which plots the normalized inverse gain modified to reduce nonlinear dependence on irradiation dose. The simulation shown in Fig. 1 utilizes a one dimensional device model developed by one of us (Myers) as a platform for defect physics model development which agrees with CHARON. Between one millisecond and one second, the RMS deviation between the model and SPR cavity data is less than 1%. Model calibration is necessary because many of the defect properties are known only approximately. The parameter values (vacancy diffusivity and carrier capture cross sections) needed to achieve agreement with experiment are within their range of uncertainty. In the model, the principle physical process causing transient gain recovery is the diffusion of vacancies and their reaction with phosphorus dopants to form the vacancy phosphorous (VP) complexes near the base emitter junction. This is consistent with the presence of VP in this region of the device observed by deep-level transient spectroscopy (DLTS). As Fig. 1 shows, the time dependence of the transient gain change is nearly the same for irradiation by neutrons or by silicon ions for which the damage peak is at the emitter base junction (4.5 MeV for the Microsemi 2N2222). Model simulations have been compared with experiments over a broad range of conditions, including irradiation by neutrons and ions, wide ranges of damage levels and device currents, and both npn and pnp silicon BJTs. In general, the model gives the correct trends, though the extent of quantitative agreement varies and is still under investigation.

The magnitude of the gain change depends on the defect concentration. Figure 2 shows measured inverse gain change at one second after the pulse, modified to reduce non-linear dependence at high defect concentrations, plotted versus Frenkel pair concentration calculated using MARLOWE[1] and the measured irradiation doses. The modified inverse gain change varies linearly with defect concentration for each facility, but we see small offsets between the various irradiation facilities.

Significance—This work demonstrates that the device model used in QASPR can accurately simulate gain changes in silicon BJTs. This enables a critical test of the QASPR process in which the gain change from irradiation in SPR will be predicted for a device which differs from the one used in model development. This test will use the model together with measurements of transient gain change from irradiation with short ion pulses at the IBL and long time gain change from neutron irradiation in ACRR.

[1] *Computer Simulation of Atomic-displacement Cascades in Solids in the Binary-Collision Approximation*, M. T. Robinson and I. M. Torrens, Physical Review **B9**, 5008 (1974).

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Contact: William R. Wampler, Radiation-Solid Interactions, Dept. 1111
Phone: (505) 844-4114, Fax: (505) 844-7775, E-mail: wrwampl@sandia.gov

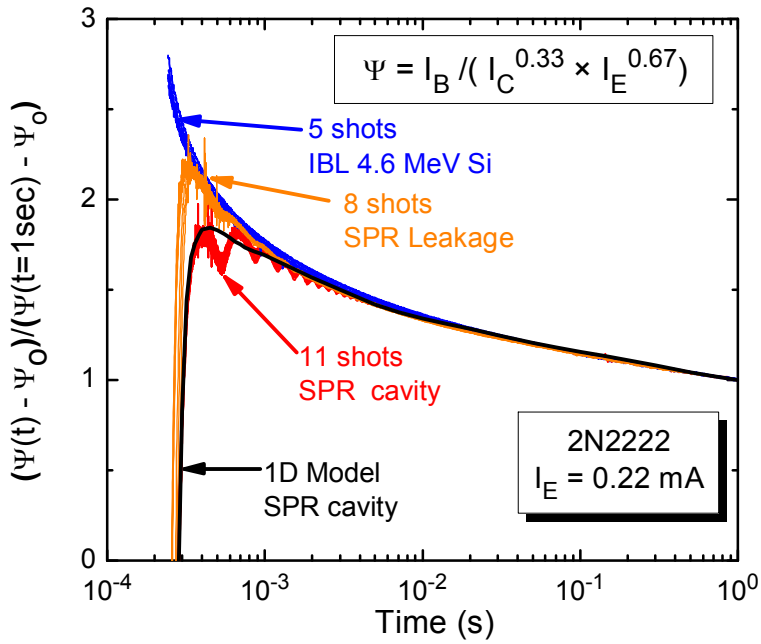

Figure 1. Inverse gain change normalized to the value at one second. The plotted quantity Ψ includes a correction to remove nonlinear transient response at high damage mainly from the constant emitter current configuration used in the experiment. At low damage $I_C \approx I_E$ and $\Psi \approx I_B/I_C$. The calibrated model (black) agrees closely with data from neutron irradiation in SPR central cavity (red) and with data from irradiation with 4.5 MeV ions (blue). For this plot, the origin of the time scale is chosen to put the center of the pulse at 0.2 millisecond. Ψ_o is the inverse gain of the device prior to irradiation.

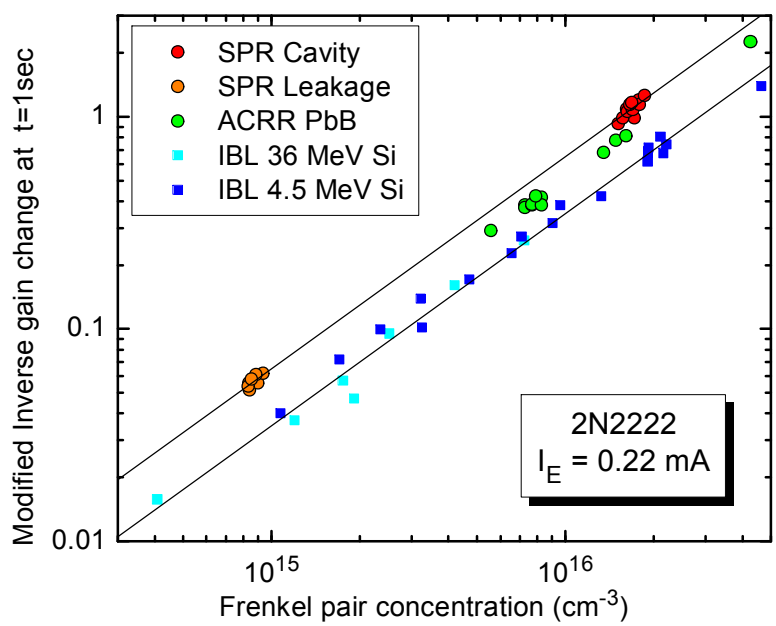

Figure 2. Inverse gain change one second after the pulse, modified to reduce non-linear dependence at high defect concentrations, plotted versus Frenkel pair concentration calculated using MARLOWE with measured irradiation doses. Black lines indicate linear dependence on defect concentration.