Science-Based Modeling of Pulse-Irradiated Transistors in the QASPR Program

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Motivation—Impending shutdown of the Sandia Pulse Reactor (SPR-III) will require that electronics be qualified for fast-transient neutron irradiation by using alternative experimental facilities less representative of potential threat environments. QASPR (Qualification Alterna-tives to Sandia Pulse Reactor) was initiated in Oct. 2005 to establish the required new qualification protocols. Success will hinge upon the development of substantially improved, science-based models for neutron-irradiated Si bipolar devices that can bridge the greater gap between testing and threat conditions. This is challenging due to the numerous defect reactions occurring within irradiated Si and the fact that neutrons produce atomic displacements in clusters. In the present effort, we are carrying out modeling calculations to explore the defect behavior and its influence on bipolar devices, and are thereby determining how the physics will ultimately be implemented in QASPR models.

Accomplishment—Silicon bipolar transistors exposed to neutron irradiation were modeled using a new, 1-D finite-element code. The transistor base was treated by an approximation whereby the potential and majority-carrier concentration – but not the minority-carrier concentration – are constrained along a plane within the neutral region of the base. Explicit account was taken of the formation of vacancies (charge states -2,-1,0,+1,+2) and Si interstitials (-2,-1,0,+1,+2), their migration and field-drift, their recombination, and their reactions to form VV(-2,-1,0,+1), B_I(-1,0,+), VB(0,+1), VP(-1,0), VO(-1,0), B_IB(-1,0), B_IO(0,+1), and C_I(-1,0,+1). Here V is the vacancy, the subscript I denotes interstitial atoms, and P, B, O, and C are the dopants and principal impurities.

Figure 1 shows the time-dependent base current computed for a commercial N-P-N transistor (Microsemi 2N2222) exposed to a pulse of MeV neutrons in the fast-burst reactor at White Sands Missile Range. This calculation captures the principal features of the device response, including a positive photocurrent during the irradiation pulse that falls off as defect recombination centers accumulate; a subsequent negative current caused by electron-hole recombination at the defects; and a drop-off in the latter current arising from defect annealing.

The consequences of defect formation in clusters (not included above) were examined using a second new finite-element code. This program again included the aforementioned defect processes, but now treated a sub-micrometer sphere of Si containing a cluster, with radial symmetry assumed. These calculations reveal two key effects of the clustering: first, reactions among the vacancies and interstitials are much more rapid due to their proximity; and, second, local electrostatic fields (band-bending) arising from defect charging in the cluster alter the rates of capture for conduction electrons and holes. The latter effect is illustrated in Fig. 2, which shows how the steady-state flow of carriers into the defect-containing volume differs between the cases of clustered and randomly dispersed divacancies. Means of including these clustering effects in the device model are under investigation.

Significance—These exploratory calculations, along with comparisons to experiment, are providing the basis for design of the defect-physics package that will ultimately be used in QASPR device models.

Sponsors for various phases of this work include: Nuclear Weapons Program

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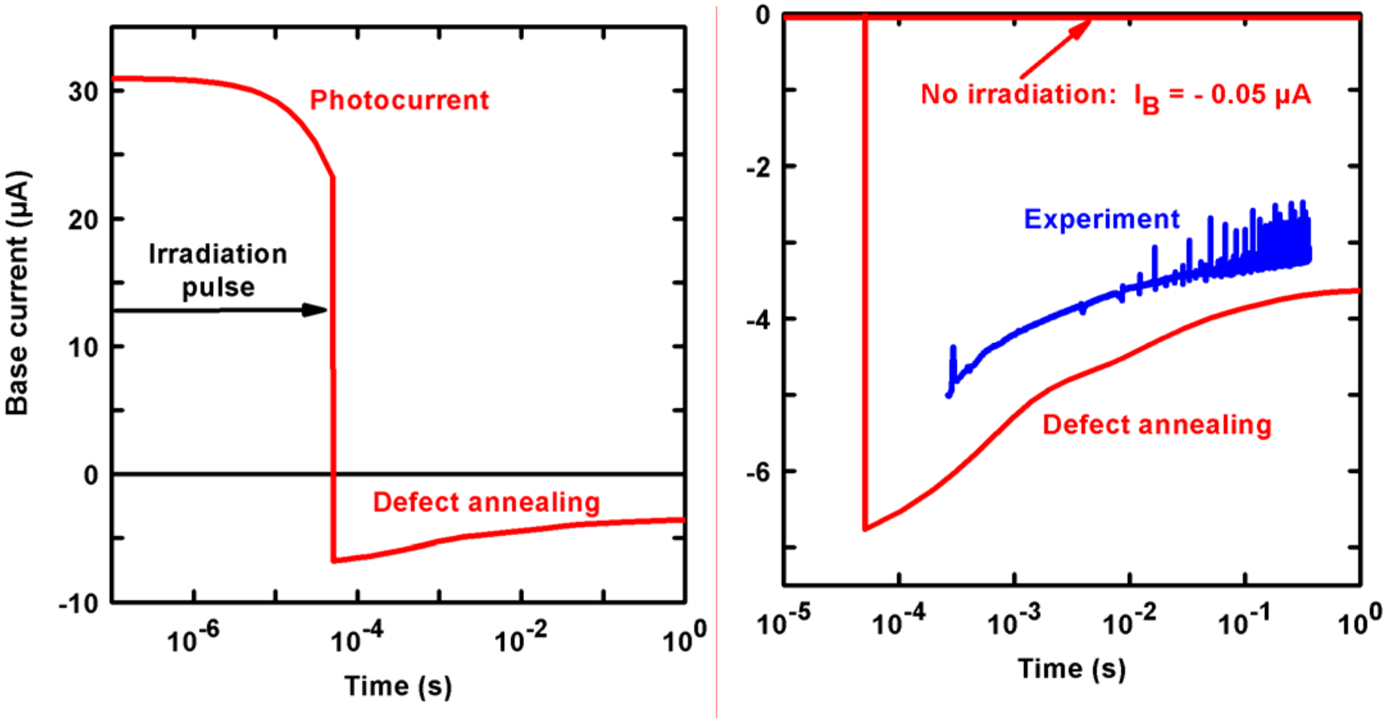

Figure 1. Model-predicted base current versus time (in red) for a Si N-P-N bipolar transistor subjected to a 50-µs burst of 6×10^{13} neutrons/cm^2 with V_{EB} = 0.5 volts and V_{BC} = 3.0 volts. The right-hand panel is expanded from the left. (The poorly known carrier-capture cross sections for the neutral vacancy were equated to 10^{-14} cm^2 for better agreement with experiment.)

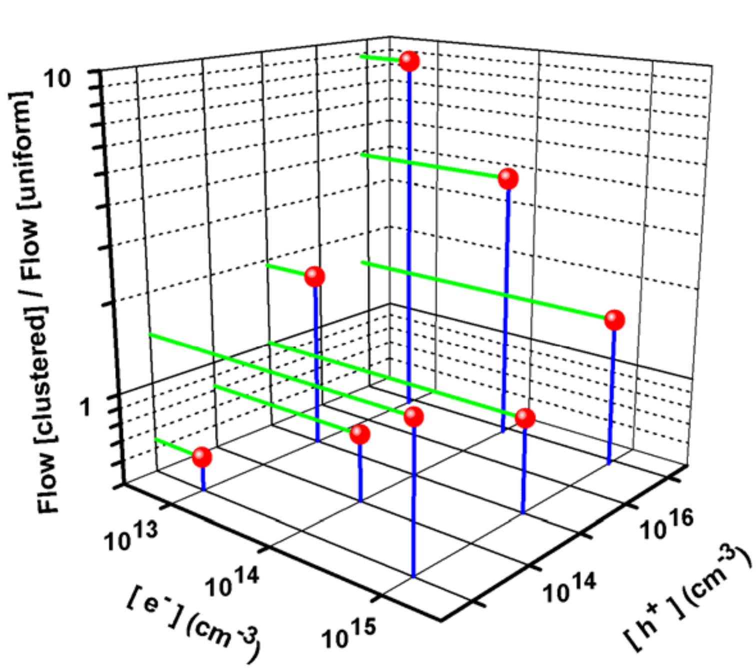

Figure 2. Ratio of carrier annihilation rates by a constant number of divacancies with and without clustering, for a range of local conduction-electron and hole concentrations typical of an operating N-P-N transistor. The clustering increases the local defect concentration by ×8000.