# *Modeling Neutron-Irradiated Transistors: From Atomic Collisions to Carrier Flow*

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**Motivation**—Shutdown of Sandia's SPR-III pulse reactor necessitates the qualification of electronics for transient neutron exposure via irradiation testing less representative of threat conditions. New qualification protocols are the objective of the Qualification Alternatives to the Sandia Pulsed Reactor (QASPR) program. Central to this program is the development of science-based modeling to bridge the now greater differences between accessible testing and threats. Such modeling must encompass multiple physical processes, beginning with the generation and propagation of irradiation particles, followed by the creation and time-evolution of defects and their interactions with carriers, and culminating in the altered operation of devices and circuits. Silicon bipolar transistors are most sensitive to displacement damage and hence a focus of QASPR. The greatest scientific challenge, and the subject of this brief, is the treatment of defect and carrier reactions within the Si matrix.

**Accomplishment**—We are developing three computational procedures to model the chain of events within the Si transistor following the creation of primal vacancies (V) and self-interstitials ($Si_I$) by neutron irradiation. The starting point is illustrated in Fig. 1, which shows the distribution of defects produced within a representative micrometer cube by a maximum SPR pulse, as calculated by Philip Cooper using the binary-collision Monte-Carlo code MARLOWE. The defects are concentrated in collisional cascades rather than randomly distributed, with consequences both for the time-evolution of the defects and for their interactions with carriers. Pursuant to modeling of the local behavior near such clusters, the first of the aforementioned computational procedures is to develop statistically averaged, radially symmetric concentration profiles of V and $Si_I$ extending out to R ~ 0.5 µm. This is done by, first, evaluating V-V and $Si_I$-$Si_I$ spatial pair correlation functions from the output of the Monte-Carlo MARLOWE code, and then devising radial concentration profiles with the same correlation functions. This exercise is exemplified in Fig. 1, which shows the correlation functions associated with the adjacent defect map. The resulting strongly peaked radial concentration profiles provide the basis for the second computational procedure, a continuum-model treatment of the local diffusion and reactions of the defects and the influx of carriers. The array of defect reactions is summarized in Fig. 2. The results are compared with parallel calculations for uniformly distributed defects, thereby quantifying differences that can be used to adjust the computationally much simpler uniform case. Finally, the macroscopic bipolar device is modeled for the same reaction set but without local clustering, and the above corrections for clustering are applied. These procedures are currently being refined through comparison with a wide range of QASPR model-development data. Interim results for an n-p-n transistor exposed in the fast-burst reactor at White Sands Missile Range are shown in Fig. 2, where the consistency between modeling and experiment is seen to be good. Similarly satisfactory comparisons have more recently been made for irradiations in SPR.

**Significance**—Sandia's modeling of neutron damage in bipolar devices was previously limited to empirical fits unsuitable for extrapolation beyond testing. The present work is a promising first step toward prediction.

**Sponsor for various phases of this work include:** Nuclear Weapons

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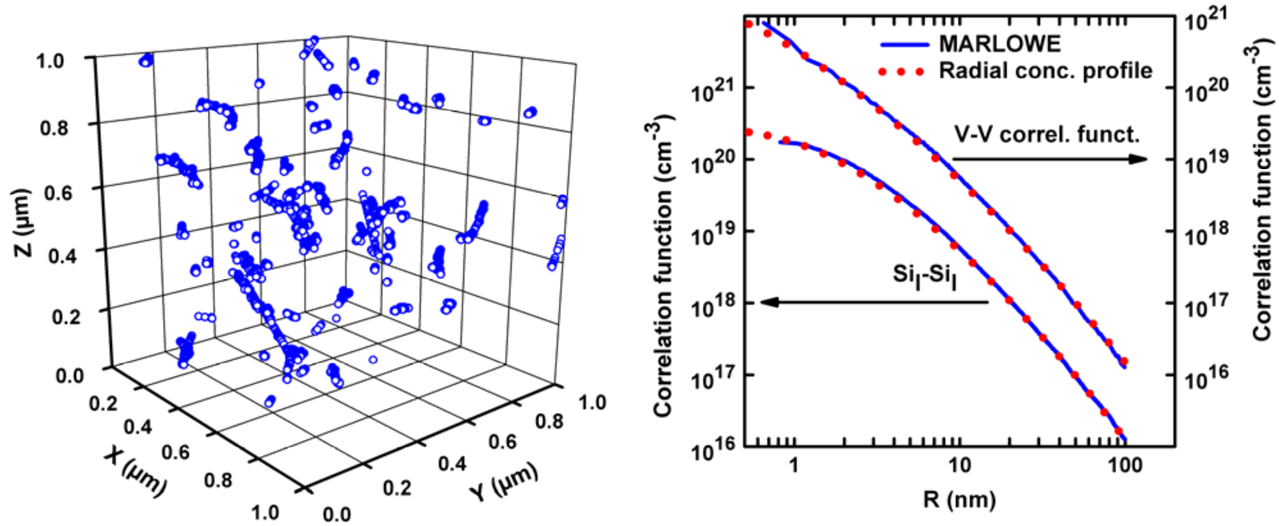


**Figure 1**. *Left panel*: Vacancy distribution from the MARLOWE code for the irradiation conditions of a maximum SPR pulse; the micrometer cube contains 11,330 Frenkel pairs. *Right panel*: Defect pair correlation functions from MARLOWE output and from the radial concentration profiles used to model cluster behavior; in the absence of clustering, the correlation functions are horizontal lines.

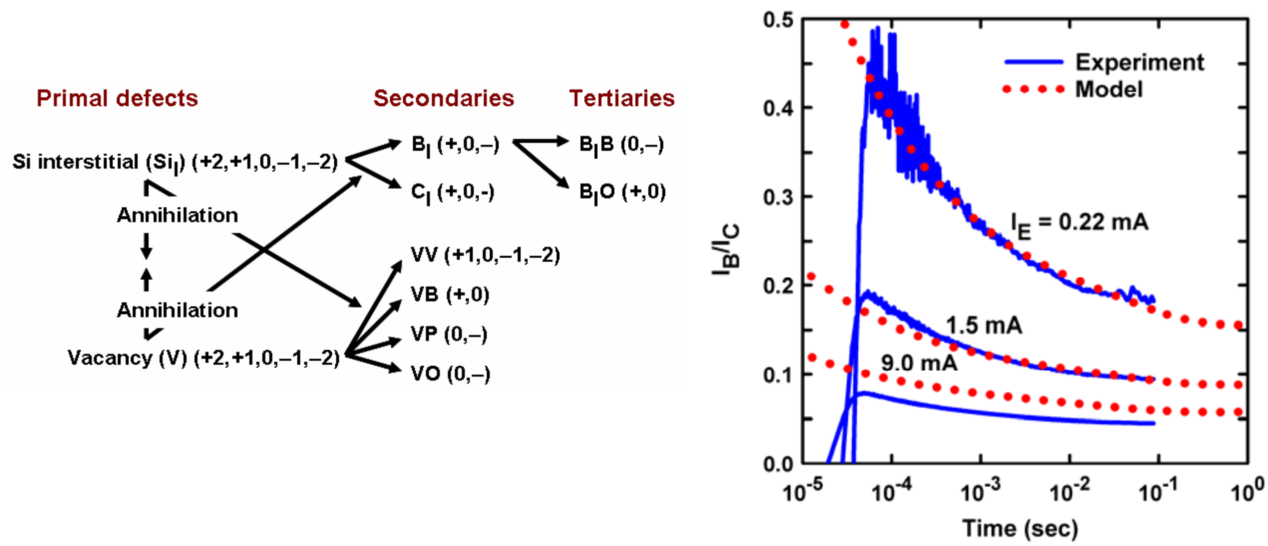


**Figure 2**. *Left panel*: Principal defect reactions active in Si up to room temperature, as taken from the literature and from Sandia calculations using density-functional theory; charge states are indicated in parentheses. *Right panel*: ratio of base current to collector current versus time in an n-p-n transistor following a 50 μs neutron pulse from the fast-burst reactor at White Sands Missile Range, as obtained from measurement and from the theoretical model for three emitter currents; two poorly known carrier-capture cross-sections in the model were adjusted to improve the agreement with the uppermost experimental data.