Inverse Gain Comparison between Experimental and Simulation Results for Ion Beam Irradiations in Silicon Bipolar Junction Transistors

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Motivation—Late-time damage equivalence between the alternative facilities of the QASPR program makes use of the Messenger-Spratt damage factor to provide a comparison metric across the facilities. There are, however, many instances where we are interested in the transient behavior of the device on short time scales after the irradiation. For this early-time behavior we compare the inverse gain degradation across facilities, as defined by equation (1),

$$\Delta(1/G) = 1/G(t) - 1/G_0 \qquad (1)$$

where $G(t)$ is the time dependent gain measured during and after the irradiation and G_0 is the pre-irradiation gain. It is in this early-time regime that the ion beam irradiations are of particular importance. While no one alternative facility can replicate fast burst reactor testing (high neutron flux, short pulse width and uniform test volume) the combination of modeling and experimental results will allow parameter space exploration. As summarized in Table 1, comparison of the QASPR fluence values (in 1 MeV neutron equivalent fluence) and pulse lengths for the QASPR relevant facilities, testing in the Ion Beam Laboratory (IBL) will achieve the desired damage creation rates.

Accomplishment—We have previously demonstrated the ability to use the Messenger-Spratt damage factor as a means of late-time comparison across the QASPR relevant facilities and as a method of rescaling of the ion fluence to an effective 1 MeV equivalent neutron fluence. Furthermore, we have demonstrated the ability to match the temporal profile and the damage creation rate of SPR-III irradiations using Si ions in the IBL. Here we turn our attention to a comparison between experimental and simulation results for ion beam irradiations.

Figure 1 compares experimental and simulation results for a series of 4.5 MeV Si irradiations, spanning the critical QASPR fluence values. The simulation results are based on an atomistic model for the static and dynamic changes in gain of a silicon bipolar transistor due to energetic particle irradiation. The model is calibrated to SPR fast neutron data by adjusting the values of the carrier cross-sections within independent experimentally determined bounds. This provides a physics-based approach to simulate these effects and the resulting transient changes in transistor gain. We observe excellent agreement between the time-dependent shape and fluence dependence of the gain response (Figure 1). Similar results were found for the comparison between 36 MeV Si irradiation and simulation. The systematic offset between the simulation and experimental results is of great interest, as it indicates either an error in the measured ion or neutron fluence or a fundamental issue in the simulated defect creation rates for ion or neutron irradiations.

Significance—We have shown excellent agreement between the experimental results and 1D simulation for the shape and fluence dependence of inverse gain. The systemic offset on the order of 2x is an excellent result given the complexity of the calculations from incident ion fluence to the initial configuration of interstitials and vacancies after irradiation.

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Facility	QASPR Fluence	QASPR Pulse Length
SPR-III	~4E14 n/cm^2	~100 µs
IBL (Si EOR 4.5 MeV)	~4E14 n/cm^2	~10 µs
ACRR	~4E14 n/cm^2	~30 ms
IBL (Si Uniform 36 MeV)	~1E14 n/cm^2	~100 µs
WSMR FBR	~1E13 n/cm^2	~50 µs
LANSCE	~2E12 n/cm^2	~150 ns

Table 1. QASPR alterative facilities with QASPR relevant fluence levels (in 1 MeV equivalent neutron fluence) and pulse lengths. The Si End-of-Range (EOR), i.e., 4.5 MeV, corresponds to energies targeting the base-emitter (BE) junction directly, while Si Uniform refers to high energy Si irradiations, i.e., 36 MeV, that produce uniform damage levels throughout the emitter and base diffusion.

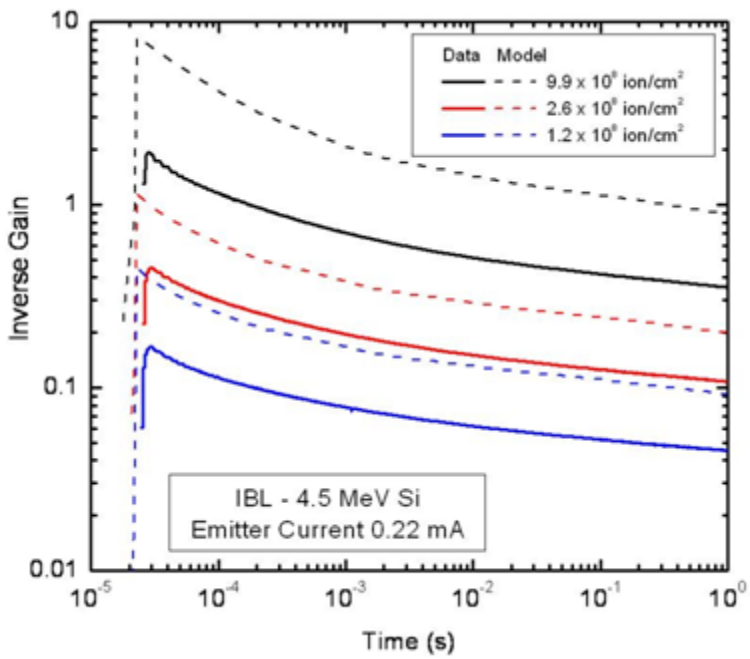

Figure 1. Inverse gain for both experiment and 1D simulations. There is excellent agreement in the shape and fluence dependence. The observed systematic offset (~ factor of two) is currently under investigation. This is an excellent result considering the computational chain for the calculation which starts with the number of interstitials and vacancies (IVs) produced from the initial irradiation (taking recombination and clustering effects into account) and then transports the initial IVs through higher order defect formation (VV, VP, etc..) and reactions which ultimately determine the final device performance. In addition, this calculation is complicated by the device geometry and nature of the ion beam irradiation.