Measurements of Defects in Neutron-Irradiated Silicon Bipolar Transistors Using Capacitance Spectroscopy

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Motivation—A central concept of the Qualification Alternatives to the Sandia Pulsed Reactor (QASPR) program is to establish a "damage equivalence" that allows one to model a device's response to fast neutrons from the Sandia Pulsed Reactor (SPR) by measuring its response in alternative radiation sources, e.g., ion beams. The development of high fidelity models requires input from experimental measurements of displacement-defect levels in devices irradiated in all facilities, both SPR and alternative sources. The requirements of QASPR are particularly challenging in that data are needed at short times after neutron irradiation, data on actual devices (here silicon bipolar transistors) with high neutron damage levels that produce clusters of damage rather than uniform damage. To meet these challenges we have developed a suite of measurement and analysis techniques used after in-situ, low-temperature irradiation including deep-level transient spectroscopy (DLTS), thermally stimulated capacitance spectroscopy (TSCAP) and capacitance-voltage (CV) measurements.

Accomplishment—An experimental measure of the number of defects as a function of time after neutron damage is not possible on the desired time scales. We mitigate this difficulty by performing isochronal anneals after neutron irradiation at 5 K, using the changes in defects as a function of annealing temperature to understand the time dependence at room temperature. An example of an isochronal annealing sequence of an npn 2N2222 collector after neutron irradiation at SPR is shown in Fig. 1 where we show several DLTS spectra (proportional to the numbers of defects) after annealing steps between 130 K and 500 K. Each peak in the DLTS spectrum corresponds to a trap within the silicon band gap with deeper traps appearing at higher temperatures. The di-vacancy trap (VV), which has two charge states and peaks at both 134 and 233 K, and the vacancy-phosphorus (VP) trap at 233 K are prominent. Note that the 134 K VV trap shows growth, particularly after the 353 K anneal, that we ascribe to changes in the amount of charge within a cluster. Models have indicated that VP traps at the base/emitter junction are particularly important in understanding gain degradation since they act as recombination centers and increase the base current. We have measured the base current in operating transistors (both npn and pnp irradiated at the same time) following isochronal anneals above room temperature. The results are shown in Fig. 2 along with a normalized plot of the number of VP defects measured in the collector of an npn transistor. The scaling of the base current recovery with the measured number of VP defects confirms the modeling results and indicates that much of the gain degradation of a silicon bipolar transistor can be ascribed to VP defects.

Significance—These data represent some of the first attempts to describe device performance starting at an atomistic level, taking into account defect clustering that is characteristic of neutron damage. The technique is a significant expansion of the DLTS technique that includes measurements at low temperature on actual devices at high damage levels. These data provide a level of detail heretofore unavailable that will enable a description of the damage equivalence between various types of radiation sources.

Sponsor for various phases of this work include: Nuclear Weapons/Qualification Alternatives to the Sandia Pulsed Reactor

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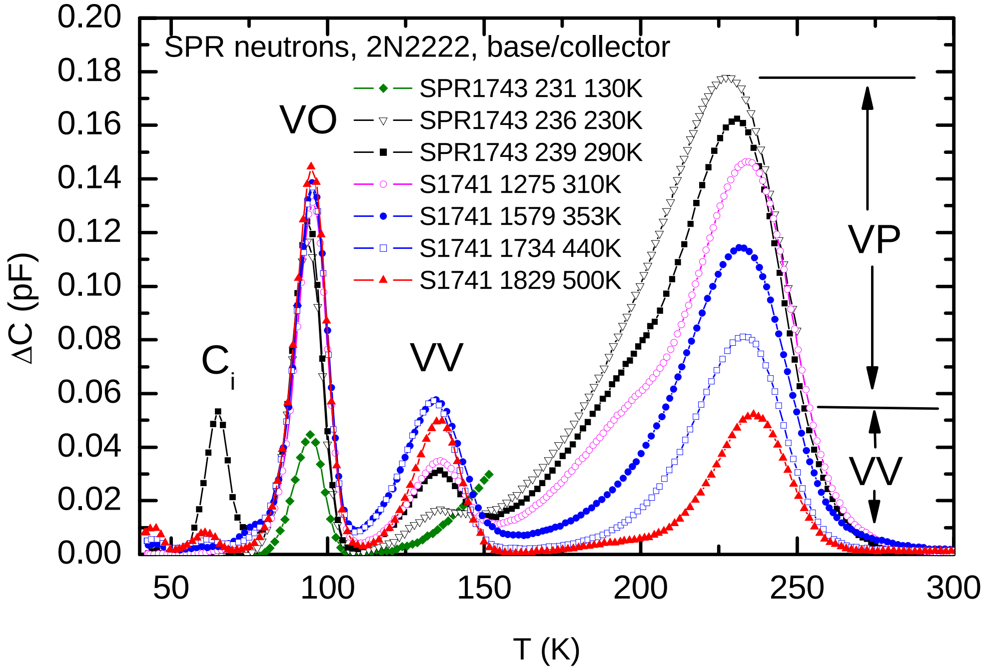

Figure 1. DLTS following 5K irradiation and isochronal anneals at the temperatures indicated. Peaks resulting from the carbon interstitial, vacancy-oxygen, vacancy-vacancy and vacancy-phosphorus defects are shown. As the device is annealed, a major change is the loss of the VP defect.

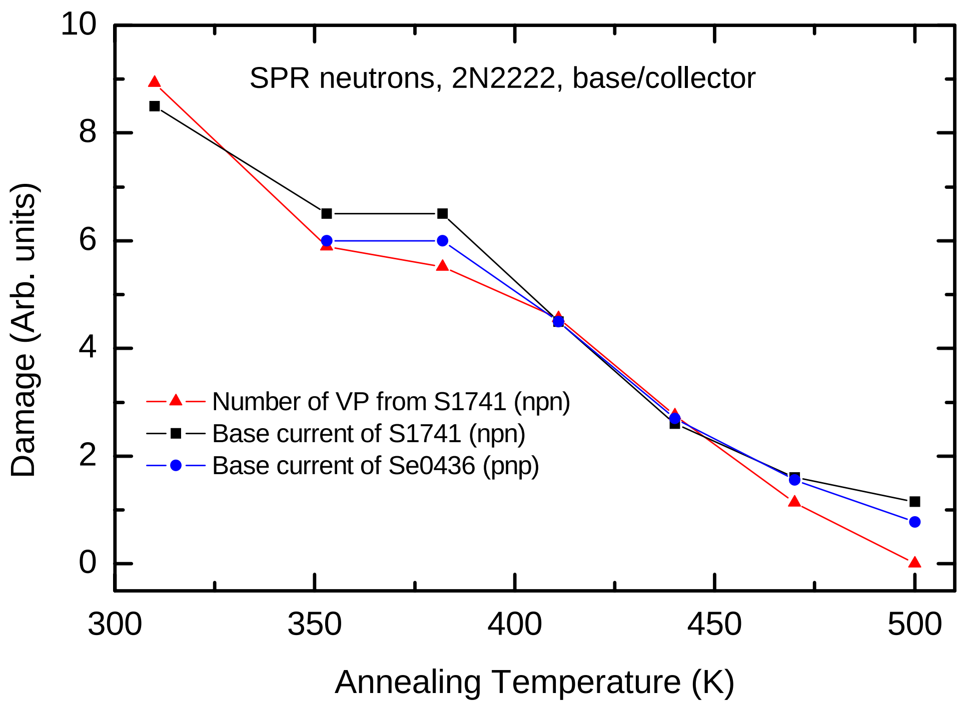

Figure 2. Damage as measured by the number of vacancy-phosphorus defects from DLTS of an npn collector as a function of annealing temperature. This indicates that the vacancy-phosphorus is a key component of gain degradation in these devices.