Neutron and Ion Induced Defects in Silicon in a Complex Damage Environment

by **R. M. Fleming**

Motivation—The Qualification Alternatives to the Sandia Pulsed Reactor (QASPR) program seeks to build a physics-based model of neutron damage in materials that begins with an atomistic description of damage and ends with a prediction of the performance of a complex circuit. The beginning of this process is an understanding of the science of defect formation and defect reactions. We have been seeking this understanding using deep level transient spectroscopy (DLTS) measurements from npn and pnp transistors following neutron and ion irradiation. These radiation sources are known to produce damage cascades rather than uniform point defects. The challenge here is to apply knowledge from a mature field (silicon radiation defects) to a complex problem (interacting defects in damage cascades). We have found that interacting defects produce a number of unexpected phenomena including changes in the electrical characteristics of the defects and changes in defect formation chemistry.

Accomplishment—Following ion and neutron irradiation we have made DLTS measurements on the collectors of npn transistors ($N_D \sim 10^{15}$ cm^{-3}) and the bases of pnp transistors ($N_D \sim 10^{17}$ cm^{-3}). We have applied a simple model[1] whereby clusters of defects raise the local energy levels of defects relative to the Fermi level and slow the rate of electron capture into these defects. We use a realistic simulation of the spatial and size distribution of these defect clusters and show that the model predictions agree very well with measurements of electron capture into the di-vacancy (V_2) defect between 300 and 500 K in the npn collector. Moreover, annealing studies used together with the model show that a well-known, but unexplained asymmetry in the DLTS spectrum after neutron damage in n-type silicon must result from interacting V_2 defects within the damage cascade. Damage cascades and asymmetric DLTS spectra occur only when the transistor are damaged by neutrons or ions at the end of range. When point defects are created uniformly (electron damage or early in the ion track), no interacting V_2 defects are produced. The result is symmetric DLTS spectrum with a larger vacancy oxygen (VO) defect signature.

In the highly doped pnp base, the reaction chemistry is different. All DLTS spectra are similar, regardless of whether damage cascades are present. The dominant defect is vacancy phosphorus (VP) after all types of damage.

Significance—This is the first quantitative model of band bending and slowed electron capture effect in neutron damaged silicon. The quantitative agreement of the model with the data has allowed us to prove that the large, unexplained DLTS peak near the single charge state of V_2 arises from the spatial region of damage cascade. The logical conclusion is that it comes from an enhanced number of V_2 defects located within strained regions of the lattice. These experiments are of interest to QASPR because they quantify the degree of clustering in agreement with more sophisticated QASPR models. They also show that in the transistor base, where defects directly affect the transistor gain, the dominant defect remains VP with few of the interacting V_2 defects.

[1] R. M. Fleming, C. H. Seager, D. V. Lang, P. J. Cooper, E. Bielejec, and J. M. Campbell, J. Appl. Phys. **102**, 043711 (2007).

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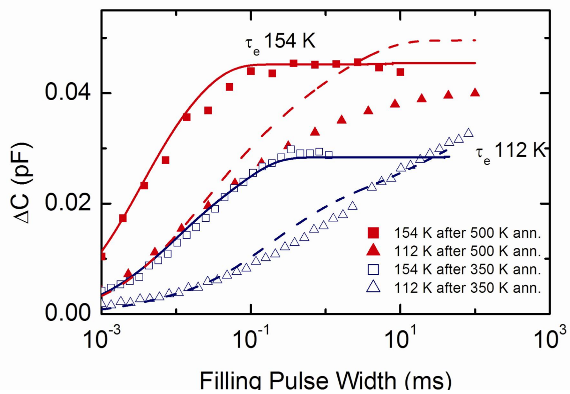

Figure 1. DLTS signal as a function of the filling pulse width shows a stretch out characteristic of electrostatic defect interactions and band bending. After annealing at 500K (solid symbols) there is less stretch out. Lines are fits to a model described above.

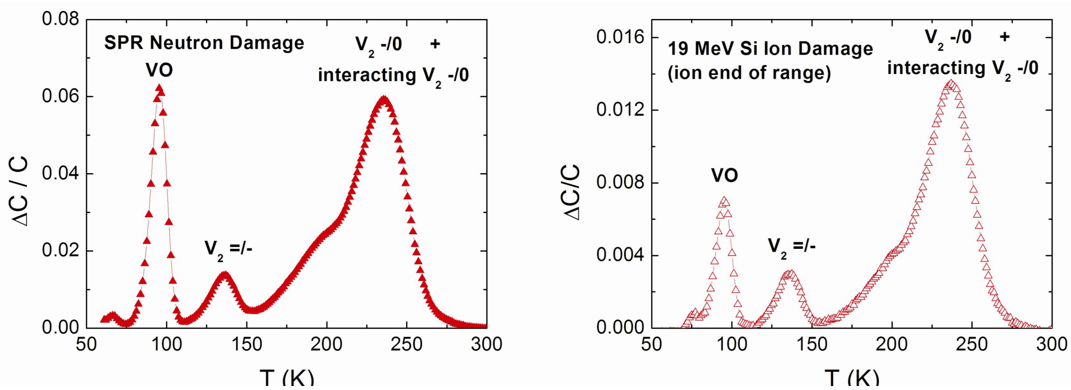

Figure 2. Neutrons and ions at end of range show asymmetric V_2 DLTS at 125 and 235K due to contributions from interaction V_2 defects within damage cascades.

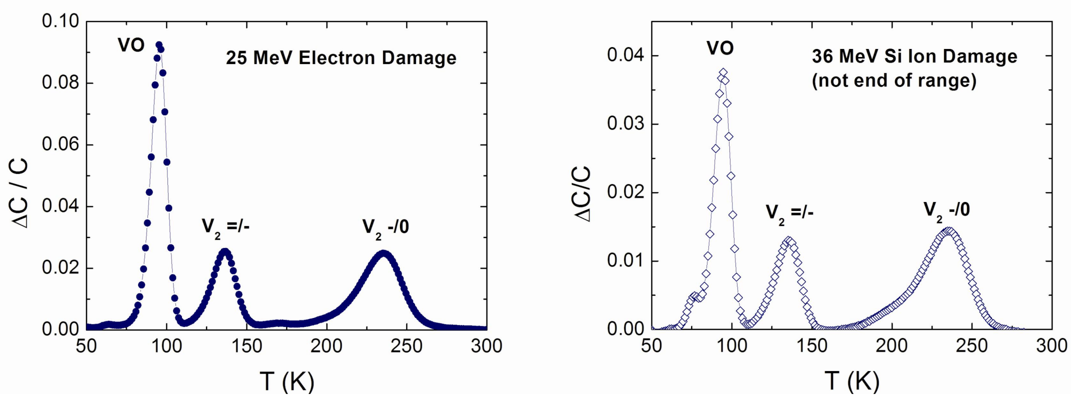

Figure 3. Electrons and ions before end of range show symmetric V2 DLTS and 125 and 235K and no defect clustering effects.