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AN EXAMINATION OF THE 1-MeV EQUIVALENT SILICON DAMAGE METHODOLOGY*

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ABSTRACT

The assumptions, approximations, and uncertainty in the 1-MeV equivalent silicon damage methodology are reviewed. A new silicon displacement kerma function, based on ENDF/B-VI cross sections, is presented and its shape is experimentally confirmed. The issue of an associated 1-MeV equivalent reference kerma value is discussed.

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SUMMARY

1. INTRODUCTION

In the testing and design of radiation-hardened electronics, neutron fluence requirements are quoted in terms of a 1-MeV equivalent silicon damage. Sections 2 and 3 examine the assumptions, approximations, and uncertainty in the calculated silicon damage function, which is usually equated to the silicon displacement kerma (Kinetic Energy Released in MAterials). Sections 4 and 5 examine how this calculated displacement kerma function is related to measured damage in silicon devices. This examination serves to emphasize the importance of ensuring that reactor test facilities and radiation-hardness specifications reflect the same energy-dependence in the silicon damage function.

2. DISPLACEMENT KERMA

Figure 1 compares the current recommended silicon displacement kerma function from the ASTM E722-85 Standard Practice [1] with that based on the Si ENDF/B-V [2] and ^{28}Si ENDF/B-VI cross sections [3]. The ENDF/B displacement kerma function is based on the NJOY89 [4] methodology. The ENDF/B-V data is for elemental silicon whereas the ENDF/B-VI data is based on the ^{28}Si isotope. ENDF/B-VI data for the ^{29}Si and ^{30}Si components of elemental silicon are not yet available. The differences between the ENDF/B-V and ASTM displacement kerma have been previously reported [5] and shown to result in a difference of 10% in the spectrum averaged kerma from fission and degraded fission spectra. The ENDF/B-VI displacement kerma is seen to be virtually identical to the ENDF/B-V results for energies below 8 MeV. Inclusion of the ^{29}Si and ^{30}SI displacement kerma components is not expected to change this observation.

A detailed comparison of the ENDF/B-V and ENDF/B-VI cross sections and recoil energies shows that the differences above 8 MeV result primarily from changes in the recoil energy of the neutron-induced charged-particle reactions. ENDF/B-VI contains the new File 6 information that provides detailed energy/angle data for the reaction products. This enables a much higher fidelity analysis of the recoil energy imparted to the primary knock-on atom (PKA). Figure 2 compares the ENDF/B-V and ENDF/B-VI PKA recoil spectrum from a 14-MeV neutron.

The displacement kerma is produced by partitioning the PKA recoil energy into a displacement and an ionization term. The NJOY code uses the Lindhard partition function [6], which is based on the Thomas-Fermi potential. Figure 3 shows the effect other potentials can have on the displacement partition function. Use of different electronic potentials results in a normalization and a shape change in the displacement partition function. When the partition functions are normalized at 37 keV, the average PKA recoil energy from a 1-MeV neutron, the damage efficiency of a 1 MeV PKA can change by 20% depending upon the potential used.

3. SILICON DAMAGE MODEL

In order to convert the silicon displacement kerma into a number of displacements per recoil atom (dpa), a displacement model must be used. Several models [7,8,9,10] exist in the radiation effects and material damage community. NJOY uses the Kinchin-Pease model [11] with a displacement energy of 25 eV. The 25 eV is a community convention [12] for materials in which detailed displacement information is not known. Experimental data on silicon indicates that the lattice displacement energy is 13-15 eV [13]. The use of a different displacement energy results in a change in the normalization of the silicon 1-MeV damage but not in the shape of the curve. The use of other displacement models tends to affect the damage normalization and the behavior/shape of the low energy (<200 eV) partition function. The shape of the high energy damage response is not significantly affected by the choice of the model.

Work by M. Robinson [14] has shown that inconsistencies between the assumptions in the damage model and in the partition function can result in changes in the predicted damage. Figure 3 shows that use of the Robinson threshold-corrected formalism for combining the Lindhard partition function and the Kinchin-Pease damage model results in a 10% change in the normalization of the damage but does not change the shape of the damage response.

4. EXPERIMENTAL MEASUREMENTS

Experimental measurements [15] of the relative 14-MeV and fission damage in 2N2222 n-p-n devices have confirmed the predictions of the ENDF/B-VI displacement kerma when it is used in a Kinchin-Pease displacement model to predict damage in silicon. Using the latest ENDF/B-VI dosimetry cross sections, preliminary analysis of the measured ratio of 14-MeV to fission damage shows a 4% deviation from the NJOY calculations. This is well within the limits imposed by uncertainty in the reaction cross sections used in the fluence dosimetry.

Measurement of the 14-MeV/fission silicon damage ratio after a 24-hour bakeout at 180°C shows a 13% increase in the relative 14-MeV damage. This effect can be explained by the presence of multiple defect types (divacancy and vacancy-impurity, typically oxygen, defects) that anneal at different rates. Figure 4 shows that the defect density is strongly affected by the energy of the PKA recoil. It is hypothesized that the increased defect density from fission neutron irradiation results in a higher fraction of divacancies relative to vacancy-impurity defects. The divacancy defects in silicon have been shown [16] to anneal out at a lower temperature than vacancy-oxygen defects. MARLOWE [17] calculations are currently underway to test the consistency of this explanation.

5. 1-MeV EQUIVALENT NORMALIZATION

The number of factors, both experimental and calculational, affecting the normalization of the 1-MeV damage response function indicates that this normalization is set by community convention and not by rigid analysis. The analytic analysis and the experiments have indicated that shape changes on the order of 10-20% may result from defect annealing considerations as well as from the choice of the electronic potential. When the shape of the displacement kerma function changes, the question arises whether the reference 1-MeV normalization value should also change.

The new ENDF/B-VI displacement kerma, presented in section 2, is being considered by the ASTM 10.07 subcommittee as an update to the E722 standard. Adoption of a new displacement kerma curve is coupled with the issue of the 1-MeV normalization value. The normalization adopted in the new standard will affect system specifications and test levels. The current community standard for a 1-MeV silicon displacement kerma is 95 MeV-mb [18,19]. The ENDF/B-VI displacement kerma at 1.0 MeV is 93.8 MeV-mb. Since an energy of 1 MeV corresponds to a resonance in the silicon displacement kerma function, various 1-MeV kerma values can be obtained using different averaging/weighting schemes around this energy. Efforts are underway to repeat the previous weighting scheme [18] for determining this value. Variations of 10% in the reference kerma value are expected to result from the use of different reactor spectra weighting functions. The new ENDF/B-VI kerma data does not provide sufficient reason to modify the current standard reference 1-MeV displacement kerma value of 95 MeV-mb. The full paper discusses the implications of various methods for updating the 1-MeV reference silicon kerma value and makes a recommendation. The methods examined include:

1. Elimination of the 1-MeV methodology and use of displacement dose equivalent.

2. Duplication of the previous methodology [18] involving fitting the spectrum weighted damage to a specified functional form.

3. Defining a reference 1-MeV or fission spectrum on which the reference kerma is based.

4. Adjusting the 1-MeV reference kerma to preserve the 1-MeV equivalent fluence from the "average" test reactor.

5. Retaining the current community standard 1-MeV silicon displacement kerma.

The spectrum-averaged kerma for a typical fission and degraded fission reactor configuration will decrease between 7% and 12% if the ASTM displacement kerma is replaced with the ENDF versions. Therefore, the 1-MeV equivalent fluence will also decrease by this amount if the 1-MeV reference silicon damage of 95 MeV-mb is retained as a community standard. The value of the reference 1-MeV silicon damage is not important for simulation fidelity. What is important is that radiation-hardness requirements and the facility-testing community use a common value. Difficulties may result during the transition to a new standard if the radiation-hardness requirements are not traceable to a specific version of the E722 standard.

6. CONCLUSION

This paper has reviewed the assumptions in the 1-MeV silicon damage methodology. The latest (pre-released) version of the ENDF/B-VI cross sections has been used to provide the most current description of the silicon PKA recoil spectrum and the displacement kerma function. Experimental verification has been provided to validate the use of this new displacement kerma for radiation-hardness electronic testing. The importance of the new changes in the energy-dependence of the silicon 1-MeV damage response is presented. A recommendation is made on the choice of a 1-MeV reference silicon damage and the implications for the radiation effects community are examined.

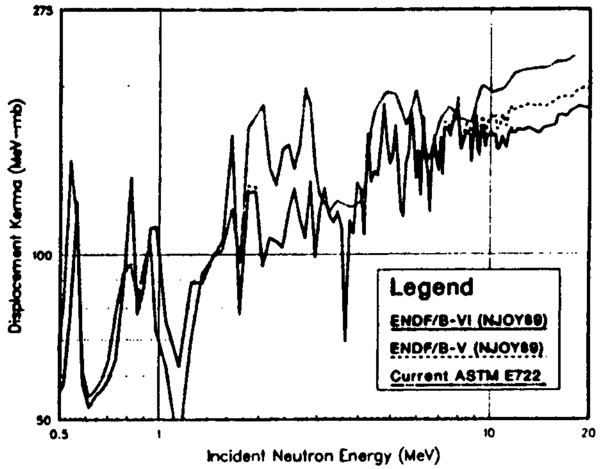

Figure 1
Comparison of Silicon Kerma Functions

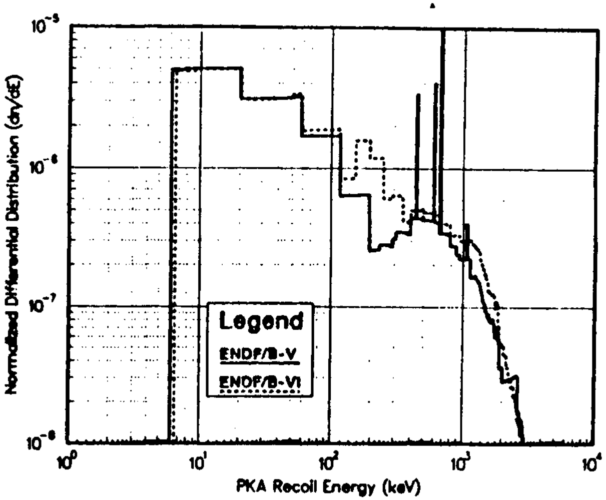

Figure 2
NJOY Silicon 14 MeV PKA Spectrum

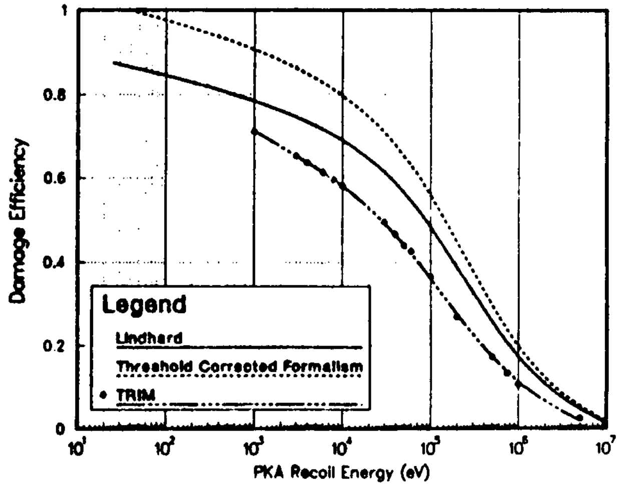

Figure 3
Comparison of Silicon Displacement Partition Functions

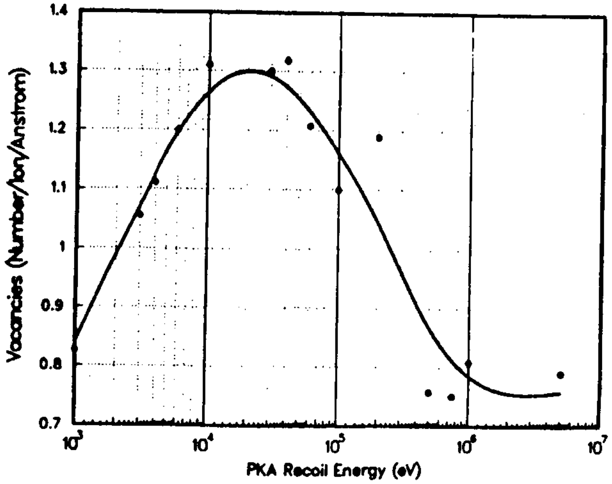

Figure 4
TRIM Estimate of Silicon Vacancy Density

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