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Status of Radiation Damage Measurements in Room Temperature Semiconductor Radiation Detectors

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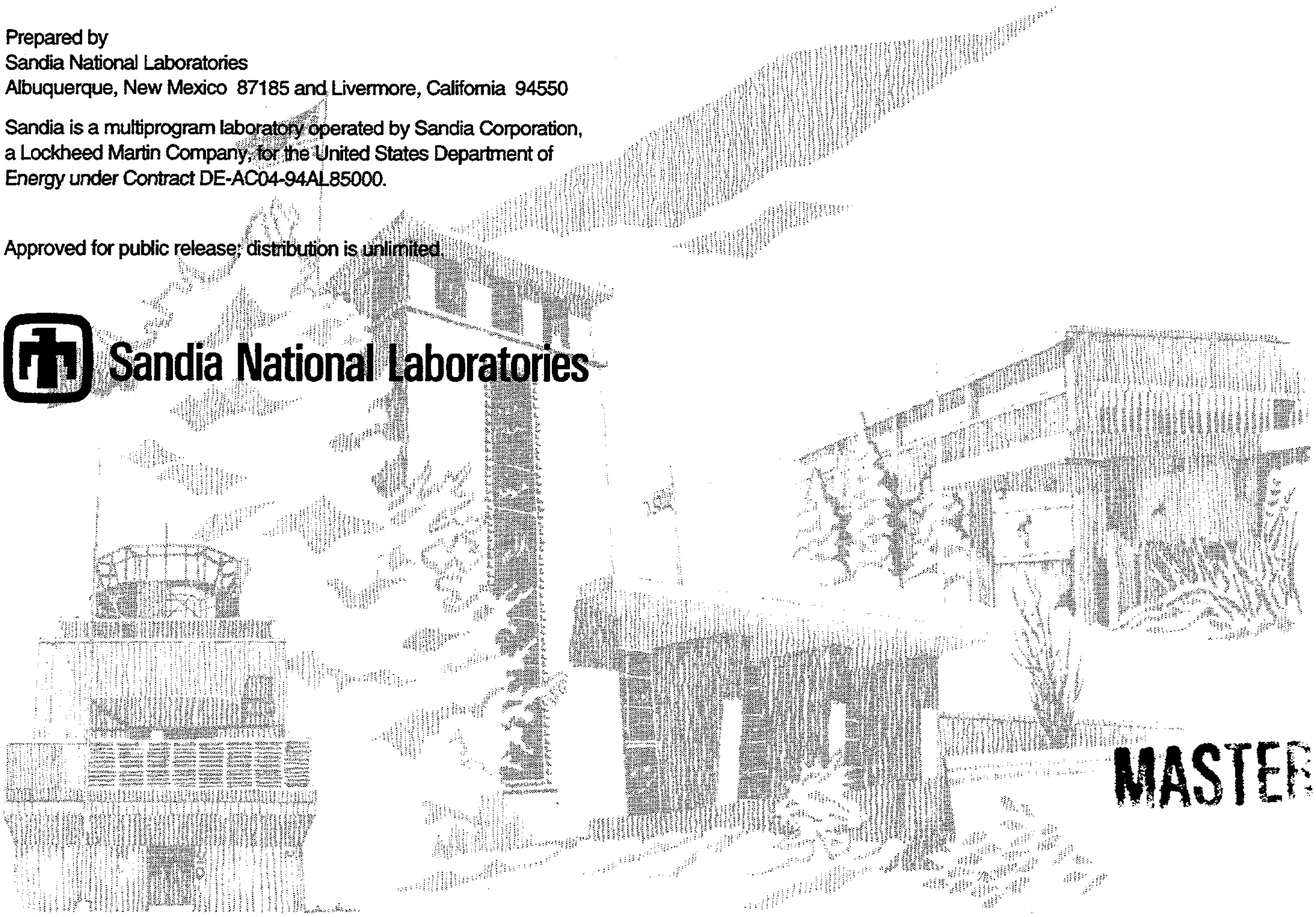

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STATUS OF RADIATION DAMAGE MEASUREMENTS IN ROOM TEMPERATURE SEMICONDUCTOR RADIATION DETECTORS

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Abstract

The literature of radiation damage measurements on cadmium zinc telluride (CZT), cadmium telluride (CT), and mercuric iodide (HgI_2) is reviewed for the purpose of determining their applicability to space applications. CZT strip detectors exposed to intermediate energy (1.3 MeV) proton fluences exhibit increased interstrip leakage after 10^{10} p/cm^2 and significant bulk leakage after 10^{12} p/cm^2. CZT exposed to 200 MeV protons shows a two-fold loss in energy resolution after a fluence of 5 x 10^9 p/cm^2 in thick (3 mm) planar devices but little effect in 2 mm devices. No energy resolution effects were noted from moderated fission spectrum neutrons after fluences up to 10^{10} n/cm^2, although activation was evident. CT detectors show resolution losses after fluences of 3 x 10^9 p/cm^2 at 33 MeV for chlorine-doped detectors. Indium doped material may be more resistant. Neutron exposures (8 MeV) caused resolution losses after fluences of 2 x 10^{10} n/cm^2. Mercuric iodide has been studied with intermediate energy protons (10 to 33 MeV) at fluences up to 10^{12} p/cm^2 and with 1.5 GeV protons at fluences up to 1.2 x 10^8 p/cm^2. Neutron exposures at 8 MeV have been reported at fluences up to 10^{15} n/cm^2. No radiation damage was found under these irradiation conditions.

Table Of Contents

Status of Radiation Damage Measurement in Room Temperature Semiconductor Radiation Detectors

Introduction

As part of its FY-97 PIDDP work scope, Sandia National Laboratories, California, was tasked to assess the status of radiation damage measurements for a group of wide-bandgap semiconductor materials being developed for use as x-ray and gamma-ray spectrometers. Interest in radiation damage in these materials stems from the growing interest in their application to space science and from the known susceptibility of cryogenic germanium and silicon to damage at relatively modest fluence levels.

Radiation damage in semiconductor radiation detectors is manifest in a number of ways including changes in energy resolution, leakage current, and peak position. Under certain conditions, activation may also occur. While the space environment contains a wide variety of high energy particles, damage to semiconductor detectors is due primarily to electrons, protons, and neutrons. Parameters affecting the response of materials to radiation fields include fluence level, flux, incident energy, detector bias, and detector temperature. Additionally, detector dimensions and impurities can also be of importance.

Methods

Radiation effects data were obtained through a literature search using the computer data bases INSPEC, CALPLUS, and COMPENDEX, together with DOE archives. In all, more than 300 abstracts were reviewed. The review was confined to the materials cadmium zinc telluride, (CZT), cadmium telluride (CT), and mercuric iodide (HgI_2), the most promising of the wide-band gap materials now under development.

Results

The radiation effect reported most frequently was the change in energy resolution although changes in the leakage current and peak position shifts were sometimes cited. Energy resolution (ΔE) was determined in most cases by recording the spectrum of a monochromatic photon or alpha particle before and after exposure. Detector energy resolution is reported in terms of the full width of a given spectral line at its half intensity point (FWHM). In general, neither the detector bias conditions nor the detector temperature were reported. Where available, this information is noted in this report. The results of this investigation are summarized in Tables 1-3. References are indicated in the final column of each table and listed in Appendix A.

Before discussing results of the current study, it is useful to note that significant energy resolution losses in silicon occur at about 10^{12} n/cm^2 for fast neutrons (Ewan, 1975) and leakage current and pulse height changes after 5 x 10^{11} protons/cm^2. Planar germanium detectors exhibit significant resolution losses after 10^9 n/cm^2. Coaxial (n-type) are significantly more resistant to neutrons (Pehl, 1979) than p-type. Coaxial (p-type) germanium detectors exhibit resolution losses at about 2 x 10^7 protons/cm^2 while in n-type coaxial (reverse electrode) detectors, resolution losses appear at about 2 x 10^8 protons/cm^2. Despite the susceptibility of germanium to radiation damage, thermal annealing methods have been developed to mitigate, if not reverse, the symptoms of high fluence exposures.

Mercuric Iodide

The results of this investigation are summarized in Table 1. Proton exposures at 10, 10.7, 33, and 1500 MeV have been reported. (Iwanczyk, 1996; Becchetti, 1983; Patt, 1990, and Nakano, 1976). Fluences ranged from 1.2 x 10^8 protons/cm^2 (1500 MeV) to 10^{12} protons/cm^2 (10.7 MeV). Also reported were 8 MeV neutron exposures at fluences up to 10^{15} n/cm^2. No evidence of radiation-induced damage was reported in HgI_2 under the exposure conditions cited. We note, however, that the 1500 MeV data did not extend beyond a fluence of 1.2 x 10^8 protons/cm^2 which is equivalent to only about one year in earth orbit.

TABLE 1.

Radiation Damage in HgI_2 Room Temperature Semi-Conductor Detectors

Material	Radiation	Effects	Reference
HgI_2	Proton/10.7 MeV	No ΔE loss @ 5.9 KeV after 10^{12} p/cm^2	1
	10.0 MeV	No effect on 5.5 MeV alpha pulse height up to 10^{10} p/cm^2	2
	1500 MeV	No ΔE loss @ 5.9 KeV up to 1.2 x 10^8 p/cm^2	3
	33 MeV	No ΔE loss @ 59.6 and 122 KeV up to 2.5 x 10^{10} p/cm^2	4
	Neutron/8 MeV	Little ΔE effect up to 10^{15} n/cm^2 in 5.3 MeV alpha spectrum.	2
	Photon	No data	--

Cadmium Telluride

Damage studies were found for proton, neutron, and photon irradiations. The results are summarized in Table 2. Proton exposures at 33 MeV were made on chlorine and indium-doped material. This energy was selected so that the beam passed through the thickest samples (2.8 mm) and thus contributed no Bragg peak in the test samples. In chlorine-doped samples, the energy resolution degraded sharply after about 3×10^9 protons/cm^2 at photon energies of 59.6 and 122 KeV. There was some evidence of a slight resolution improvement at lower fluences. Evidence of a detector thickness dependence in the resolution response was also noted. While quantitative data were not obtained for the single indium-doped device tested, the data suggests a higher degree of radiation resistance than with the chlorine-doped material. Neutron irradiations were reported at an energy of 8 MeV. Significant reductions in energy resolution were reported after about 2×10^{10} n/cm^2 in 5.5 MeV alpha spectra. Photon irradiations were reported using Co-60 (1.17 and 1.33 MeV) with the resolution monitored at 662 and 59.6 KeV. Marked changes in peak shape were reported at both energies after exposure of several times 10^5 R. No data were found at intermediate and low exposure levels.

TABLE 2.

Radiation Damage in CdTe Room Temperature Semiconductor Detectors

Material	Radiation/Energy	Effects	Reference
CdTe	Proton/33 MeV	Chlorine doped — ΔE degradation after ~3 x 10^9p/cm ^{2} @ 59.6 and 122 KeV in 0.9 mm thick sample Onset of ΔE loss in 1.75 mm sample @ 59.6 KeV near 3 x 10^8 p/cm^2 Indium doped — evidence of greater radiation resistance, no quantitative data	4
	Neutron/8 MeV	p-type — increasing ΔE loss (5.5 MeV alpha) @ > 2 x 10^{10} n/cm ^{2}	5
	Photon/1.25 MeV	Substantial ΔE loss @ 59.6 KeV after 10^5 R	6

Cadmium Zinc Telluride

Radiation damage studies on CZT have been conducted using both protons (1.3 and 200 MeV) and neutrons (moderated fission spectrum). The results of these studies are shown in Table 3. With 1.3 MeV protons, the bulk leakage was found to increase significantly after 10^{12} p/cm^2 in unbiased strip detectors (10 x 10 x 2 mm). The interstrip leakage increased significantly after about 10^{10} p/cm^2. No energy resolution data were reported (Bartlett, 1996).

Considerable work has been reported in the region of 200 MeV. Varnell (1996) irradiated 2 and 3 mm thick planar detectors with up to 5 x 10^9 p/cm^2 and found resolution losses in the thicker devices (3 mm). The initial (unirradiated) FWHM values at 59.6 and 122 KeV of 3.2 KeV and 3.9 KeV, respectively, degraded to 4.1 and 4.3 after 10^9 p/cm^2 and to 6.2 and 9.2 KeV after 5 x 10^9 p/cm^2. The thinner device (2 mm) showed no degradation at either energy after like exposures, however. A downward shift in peak channel with increasing fluence was reported for both thick and thin detectors. Varnell attributes the resolution degradation to increased electron trapping.

In a similar study, Bartlett (unpublished data), exposed both strip and planar detectors to 200 MeV protons. The strip detectors (15 x 15 x 2 mm) were exposed under bias to fluences from 10^8 to 5 x 10^9 p/cm^2. A small gain shift (3%) was noted after a fluence of 1 x 10^9 p/cm^2 and a significant shift (>25 %) after 5 x 10^9 p/cm^2. No consistent pattern of resolution degradation was found. The resolution of a single detector exposed to 5 x 10^9 p/cm^2 was unchanged at a photon energy of 59.6 KeV and significantly degraded at 122 KeV while small losses (and gains) were found at 1 x 10^8 and 1 x 10^9 p/cm^2. In this study, the outputs of three strips in each detector were summed; one detector was used for each fluence level (1, 10, and 50 x 10^8 p/cm^2). Two planar devices (10 x 10 x 2 mm and 15 x 15 x 2 mm) were exposed to a fluence of 5 x 10^9 p/cm^2, one under bias the other unbiased. Gain shift and energy resolution were measured at photon energies of 14.4, 17.8, 59.6, and 122 KeV. Gain shifts were found at all energies in both biased and unbiased cases. Significant (>45%) resolution losses were found at 59.6 and 122 KeV in the unbiased device. Minor changes (both positive and negative) were reported for the biased case.

Neutron irradiations with a moderated fission spectrum source (CF-252) at fluences up to about 10^{11} n/cm^2 on a single detector were reported (Bartlett, 1996). The detector (10 x 10 x 2 mm) was biased during exposure. No resolution degradation was found at photon energies of 14.4, 26.3, 59.6, and 122 KeV for fluences up to 10^{10} n/cm^2. Significant resolution losses were found after 7x10^{10} n/cm^2, however. It is interesting to note that the resolution losses were largely recovered after 12 weeks of annealing at room temperature. Evidence of neutron activation, in the form of gamma-ray lines from cadmium and tellurium isotopes, was apparent at fluences beyond about 10^{10} n/cm^2.

TABLE 3.

Radiation Damage in Cadmium Zinc Telluride (CZT) Room Temperature Radiation Detectors

Material	Radiation/Energy	Effects	Reference
CZT	Protons/199 MeV	3 mm thick detector — ΔE @ 59.6 and 122 KeV degrades starting at 10^8 p/cm^2, 2 fold increase in ΔE @ 5.x 10^9 p/cm^2 -- 2 mm thick detector — little ΔE change up to 5 x 10 p/cm^2 -- Downward peak shift proportional to fluence in 2 mm and 3 mm devices -- Effects attributed to increased e-trapping	7
	Protons/200 MeV	Strip detector (biased) — 2 mm thick -- Significant (>25%) gain shift @ 59.6 and 122 KeV from 5 x 10^9 p/cm^2 -- ΔE loss @ 122 KeV after 5 x 10^9 p/cm^2 — no ΔE effect @ 59.6 KeV Planar (biased) — 2 mm thick -- Small ΔE effects, both positive and negative found @ 14.4, 59.6, and 122 KeV Planar (unbiased) — 2 mm thick -- Large (>45%) ΔE losses at 59.6 and 122 KeV following 5 x 10^9 p/cm^2 exposure -- Gain shifts in both biased and unbiased detectors at 14.4, 17.8, 59.6, and 122 KeV	8
	Proton/1.3 MeV	2 mm thick strip detector (unbiased) -- Bulk leakage increases significantly after 10^{12} p/cm^2 -- Interstrip leakage increases after 10^{10} p/cm^2 -- No spectral data	9

TABLE 3. (continued)

Radiation Damage in Cadmium Zinc Telluride (CZT) Room Temperature Radiation Detectors

Material	Radiation/Energy	Effects	Reference
CZT	Neutron/Moderated Fission Spectrum	Planar detection — (10 x 10 x 2 mm) -- No ΔE effects @ 59.6 or 122 KeV for fluence up to 10^{10} n/cm^2 -- Measurable ΔE loss @ 10^{11} n/cm^2 -- Activation emission (γ) from cadmium and tellurium isotopes appear at 10^{10} n/cm^2 -- Thermal annealing reverses most of ΔE loss in 12 weeks	10

Conclusions

Knowledge of the radiation susceptibility of the leading room temperature semiconductor detectors CZT, CdTe, and HgI_2, is at best fragmentary. Factors known to be of significance in semiconductor radiation damage such as rate effects (flux), incident energy, and device temperature have not yet been examined. Moreover, the available data are from a very small sampling of detectors (sometimes a single device) and do not, in general, cover the complete fluence range of interest.

Despite these shortcomings, several interesting features emerge from the existing data. The most apparent is that HgI_2 appears to relatively immune to proton and neutron-induced radiation damage. No resolution degradation was found from intermediate energy protons at fluences up to 10^{12} p/cm^2. Similarly, no degradation was found from high energy protons although the effects of fluences significantly beyond 10^8 p/cm^2 have not been investigated and accordingly the suitability of HgI_2 for long-term space mission remains in question. Additionally, the material is apparently not susceptible to damage from intermediate energy neutrons.

The situation for cadmium telluride is less clear. No data were found for effects of high energy protons although the results at intermediate energy suggest vulnerability beginning in the region of 10^8 p/cm^2. Neutron data are also incomplete although at intermediate energies (8 MeV) the damage threshold for resolution degradation is relatively high (10^{10} n/cm^2). While no evidence of activation was reported, effects similar to those in CZT can be expected.

The radiation susceptibility of CZT is also in question. There is evidence of resolution degradation from 200 MeV protons beginning in the region of 10^9 p/cm^2 as well as a downward shift in peak channel proportional to the proton fluence. However, the resolution degradation was apparent only in a 3 mm thick device and not a 2 mm detector. There is also evidence that the resolution degradation is dependent on bias conditions although this is based on the results from a single detector. Detector response changes following high energy proton irradiation are consistent with increased electron trapping and the associated decreases in the mobility-lifetime product. With intermediate energy protons (1.3 MeV),bulk and interstrip leakage was evident but only at high fluence levels. Damage for moderated fission neutrons is evident only after 10^{10} n/cm^2. Neutron activation lines from cadmium and tellurium isotopes appear after about 10^{10}n/cm^2. It is interesting to note that annealing at room temperature was very effective in restoring resolution losses.

Recommendations

A substantial amount of work remains before an understanding of the radiation susceptibility of room-temperature, semiconductor detectors emerges. Because of the great interest in deploying CZT-based instruments (and the apparent resistance of HgI_2) it is suggested that initial efforts be confined to developing a working knowledge of CZT related effects. Several areas are in particular need of near-term attention. Of particular interest are high energy proton-induced resolution losses in the fluence region beyond 10^8 p/cm^2 where a larger number of detectors encompassing a wider range of detector types is required. Questions concerning the effects of device thickness and bias conditions also need to be resolved. Further measurements at low and intermediate proton energies should be carried out to determine the vulnerability of the contact-CZT interface and validate the promising results obtained on a single device. Because of the potential for resolution degradation at relatively modest fluence levels, a practical annealing procedure should be developed.

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