Effects of proton-induced radiation damage on Cadmium Zinc Telluride pixel detectors

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ABSTRACT

Cadmium Zinc Telluride (CdZnTe) is a room temperature solid state material with many properties attractive to space-borne astrophysical instrumentation. Irradiation of monolithic CdZnTe detectors with 199 MeV protons shows that proton-induced radiation damage causes an increase in electron trapping in the material. Small-pixel and strip CdZnTe detectors which rely on efficient electron collection are particularly sensitive to changes in the electron mean free path, which can result in significant changes in the spectral response. Using a charge transport model, we calculate the effects of the observed radiation damage on spectral response for pixel detectors of several geometries. A degradation in spectral response is observed which is most pronounced for small-pixel detectors. The magnitude of the effects indicate that depending on pixel size and the desire for good spectral performance annealing may be necessary to maintain good detector performance after approximately 1 – 2 years in low-earth orbit.

1 INTRODUCTION

Recently, relatively good-quality CdZnTe has become commercially available for use as a detector material for hard X-ray and soft gamma-ray applications.[3,2] CdZnTe is produced by alloying ZnTe with CdTe to form the ternary alloy $Cd_{1-x}Zn_xTe$, where $x \leq 0.2$. This produces a wider bandgap than in CdTe. The high resistivity, on the order of $10^{11}\Omega$ cm,[2] and consequently low leakage current results in good spectral performance relative to CdTe. The high atomic number, high density, durability and stability of the material make it particularly attractive for space-borne hard X-ray and gamma-ray experiments. In addition, compact detectors with good spatial resolution ($\lesssim$100 μm) can be fabricated.[4,6]

Distinct from silicon and High-Purity germanium, where both electrons and holes are efficiently collected, the hole mobility in CdZnTe is low, and hole mean free paths are significantly smaller than typical 1 – 2 mm detector thicknesses. The electron mobility-lifetime product ($\mu_e\tau_e$) is over an order of magnitude higher than that for holes ($\mu_h\tau_h$), and characteristic electron mean-free paths are between 1 – 2 cm for bias voltages of 1000 V cm^{-1}. Gamma-rays with energies $\gtrsim$ 80 keV penetrate a distance into the detector significant compared to the detector thickness. For these photon energies, the variation in the contribution of hole trapping to the signal induced on the detector electrodes as a function of gamma-ray interaction depth results in 'tailing', or smearing of the pulse signal.

mobility-lifetime product as a result of the irradiation were not investigated in detail, however there is not a dramatic increase in the spectral 'tailing' which results from hole trapping, and therefore no evidence for a significant change in $\mu_h \tau_h$.

3 EFFECTS OF RADIATION DAMAGE ON PIXEL DETECTORS

3.1 Detector resolution model

The effect of changes in carrier mean free path on spectral response of a detector depends on the detector electrode geometry. For monolithic (slab) detectors and pixel detectors where the pixel size approaches the detector thickness both electrons and holes contribute to the measured signal over a significant fraction of the detector volume. Depending on the ratio of electron to hole mean-free path, the photopeak efficiency can in fact improve as the electron mean-free path decreases. For pixel detectors with large aspect ratios (ratio of detector thickness to pixel width) the signal is dominated by the electron collection over most of the detector volume, and the spectral response is quite sensitive to the electron mean free path.

To quantify the dose levels at which radiation damage has a significant effect on the spectral response of pixel detectors we employ a model to calculate the effect of increased electron trapping on the detector resolution. In general, the energy resolution of the detector can be expressed as

$$\Delta E = 2.35(\sigma_N^2 + \sigma_c^2 + \sigma_l^2 + \sigma_e^2)^{1/2}. \tag{1}$$

In this expression σ_N^2 is the statistical variance on the number of charge quanta collected, σ_c^2 is the contribution to the energy resolution due to the variation in the effect of trapped charge on the signal as a function of gamma-ray interaction depth in the detector, σ_l^2 is the contribution from leakage current, and σ_e^2 represents the contribution from electronic noise. The leakage current contribution will scale with pixel dimension.

The leakage current in CdZnTe detectors changes little as a result of proton radiation damage, and the primary effect on the detector resolution is from incomplete charge collection. To determine the magnitude of this contribution for pixel detectors of various geometries we use a charge transport model. The detector electric field is generated for arbitrary contact geometry using a finite difference method. In the case of the pixel detectors considered here the field is uniform throughout the detector. The model follows the electrons and holes created in a gamma-ray interaction through the detector, calculating the spatial distribution of charge as a function of time. The charge signal induced on the positive electrode is calculated for each time step. We calculate a spectrum for gamma-rays of a particular energy by generating the distribution of gamma-ray interaction positions in the detector and calculating the spectrum of collected charge corresponding to that distribution.

In this model we make several simplifying assumptions: (1) All the charge is created at a single point, so that finite photoelectron range, Compton scattering and the effect of K-shell photon escape or reabsorption are ignored. (2) Recombination and diffusion are ignored. (3) The trapping times are assumed to be significantly longer than the amplifier shaping time, so that detrapping is not considered.

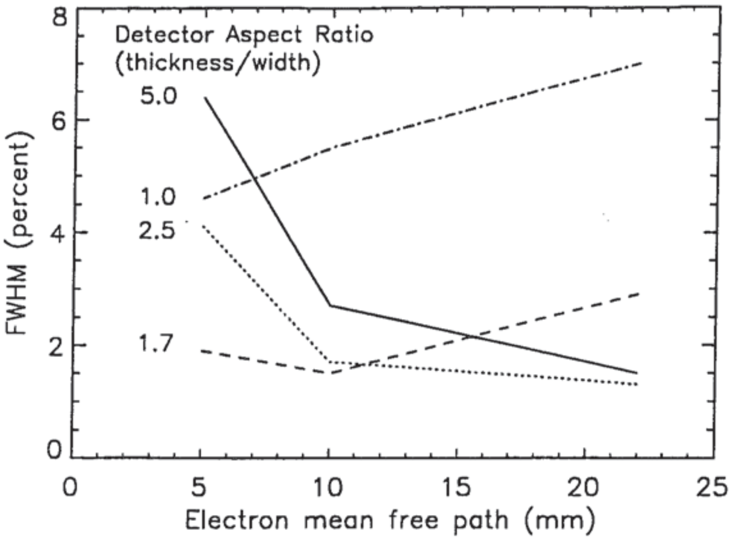

Figure 2: Calculated contribution to the energy resolution at 60 keV due to incomplete charge collection as a function of electron mean free path for detector pixel aspect ratios (ratio of thickness to pixel width) of 5, 2.5, 1.7 and 1.

The $\mu_h\tau_h$ is assumed constant. There is no evidence for a change in this quantity due to irradiation, however this was not investigated in detail in the radiation studies. We take the initial value for $\mu_e\tau_e$ as 2.2×10^{-3} cm^2 V^{-1}s^{-1}, intermediate in the $7 \times 10^{-4} - 7 \times 10^{-3}$ range measured for good-quality CdZnTe. We calculated the spectral contribution from incomplete charge collection (σ_c) for 60 and 122 keV gamma-rays incident on a 2 mm thick pixel detector with pixel sizes ranging from 200μm - 2 mm for a bias field of 1000 V cm^{-1}.

Figure 1 shows the model results for several pixel sizes for 60 keV gamma-rays incident on the top of the detector for proton fluxes of 0, 2.5×10^9, and 5×10^9 p cm^{-2}. The most notable effect of the decreased $\mu_e\tau_e$ is the downward shift in peak position due to charge loss. A change in the peak width and full-energy efficiency is also evident. For the small pixel sizes the peak width and tailing on the high-energy side of the peak is due to electron trapping. The charge collection efficiency is better for more penetrating gamma-rays, since the holes contribute negligibly to the positive electrode signal and more penetrating gamma-rays suffer less electron trapping. Thus the resolution degrades significantly for increased electron trapping. For large pixel sizes the hole trapping dominates the pulse tailing, and the tail appears on the low-energy side of the peak, as is usual with monolithic slab detectors. As $\mu_e\tau_e$ decreases the effects of electron trapping can begin to balance those of hole trapping, and the contribution to the resolution from incomplete charge trapping can actually decrease as a result of proton damage, as seen for the 1.2 mm and 2 mm pixel sizes.

Figure 2 shows the contribution to the energy resolution at 60 keV due to incomplete charge collection as a function of electron mean free path for various detector pixel aspect ratios. For optimized CdZnTe pixel detectors σ_c will dominate the resolution at energies $\sim$ 60 keV. The statistical limit at 60 keV is 0.7% FWHM (assuming a Fano factor of 0.1), and for pixel sizes of $\sim$400 μm and low-noise readout

4 CONCLUSION

Proton damage at dose levels of a few $\times 10^9$ p cm^{-2} can have significant effects on the electron trapping in CdZnTe which lead to pixel-size-dependent changes in the spectral response of pixel detectors. For response at low energies (10 – 80 keV) the effect on the spectral response is most significant for small pixel detectors, and results in a shift in the peak position and degradation in spectral resolution. At high energies (100 - 200 keV) the change in $\mu_e\tau_e$ results in a significant change in the shape of the detector response.

For low Earth moderately-inclined orbits the expected high energy proton dose levels are in the range $(1 - 2) \times 10^9$ p cm^{-2} yr^{-1} depending in on the inclination and level of shielding. Depending on the application and desire for spectroscopic performance the observed level of proton damage may be of concern after $1 - 2$ years on orbit. To some degree the effects of tailing and loss of full-energy efficiency at high energy can be compensated for by increased detector bias at the expense of higher leakage current and reduced low-energy resolution. Because of the change in ratio of $\mu_e\tau_e$ to $\mu_h\tau_h$, however, the shape of the detector response will change, possibly leading to calibration problems. Annealing of the CdZnTe material at temperatures of 100°C will therefore be required for mission lifetimes exceeding 1 – 2 years where spectroscopic performance is required.

We plan future tests to further quantify the effects of proton damage to CdZnTe detectors. These tests will include investigation of the dependence of electron trapping on material properties such as Zinc concentration, and a more accurate assessment of changes in hole trapping. Changes in the hole trapping are of particular importance for crossed strip detectors, which are more sensitive to changes in hole mobility and trapping times. We also plan to better characterize the changes in electron transport properties, including direct measurements of the electron mobility after irradiation.

5 REFERENCES

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