EFFECTS OF HIGH PROTON FLUENCES ON CZT DETECTORS*

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Abstract

The effects of high fluences of energetic charged particles on CdZnTe (CZT) detectors have been studied and are reported in this paper. Specifically, 200-MeV protons generated by the Brookhaven National Laboratory Linac were used to bombard a set of CdZnTe detector crystals to fluences as high as 2.6 10^{16} protons/cm^2. Following exposure a set of post-irradiation analyses were conducted to quantify the effects. These include: (a) gamma-ray spectra analysis using a high-purity germanium detector in an effort to assess both the peak position shifting as a function of fluence and the spectral content, (b) resistivity and leakage current measurements, and (c) manifestation of radiation damage in the crystal microstructure. In addition, and based on the irradiation parameters used, a numerical prediction model was formulated aiming to benchmark the observed isotopes.

INTRODUCTION

CdZnTe crystals have been rigorously pursued in recent years for their potential application as γ-ray detectors in a number of areas including space and nuclear nonproliferation. In the process of development and characterization it has become apparent that their performance is inhibited by material non-uniformity, crystal quality and excessive concentration of Te inclusions. The role, however, of these shortcomings in the performance of CdZnTe crystals in a radiation-harsh environment associated with either space or active, high-fluence interrogation is not known. Previous efforts focusing on the use of such detectors in space applications [1] have addressed the radiation damage caused by energetic particles and concluded that fluences as few as 10^8-10^9 p/cm^2 are sufficient to cause shifting of γ-ray peaks and resolution degradation.

In order to explore the effects of high radiation fluences on CdZnTe crystals and in particular the degradation of some of their key functions, an experimental effort has been launched at BNL. This effort aims to complement the on-going activities of growth and characterization of these crystals using x-rays at the BNL light source. It utilizes particle accelerator proton beams to induce radiation damage on these crystals and is augmented by post-irradiation analysis as well as benchmarking simulations for the identification of isotopes.

Discussed in this paper are five distinct steps that characterize the overall effort, namely, (a) radiation exposure of CZT crystals using the 200-MeV protons of the BNL Linac, (b) crystal structural damage visualization, (c) isotope identification using spectral analysis, (d) radiation damage effects on resistivity of crystals, and (e) numerical simulation of the radiation exposure and benchmarking against isotopes identified in spectral analysis.

The CdZnTe post-irradiation analysis revealed interesting cascade phenomena and observable defects as a result of the interaction with high energy particles which in turn translated into degradation of the leakage current. Also, the appearance of preferential energy levels within the band-gap is observed in irradiated crystals. The spectral analysis revealed a wealth of generated isotopes, which may inhibit the identification of source-borne signatures. These findings are discussed in the subsequent sections.

IRRADIATION

Using the 200-MeV proton beam of the BNL Linac and the target station of the Isotope Production Facility (BLIP) shown in Fig. 1, three CZT detectors were exposed to fluences ranging from 2.5·1015 p/cm2 to 7.3·1016 p/cm2. Figure 2 depicts one of the CZT detectors prior to irradiation as well as the configuration under the proton beam. Also seen in Fig. 2 are SiO2 quartz fibers situated upstream of the CZT detectors and responsible for scattering some of the primary 200 MeV protons. Fig. 3 depicts the proton beam profile obtained via radiography of a thin Ni film placed upstream of the crystals.

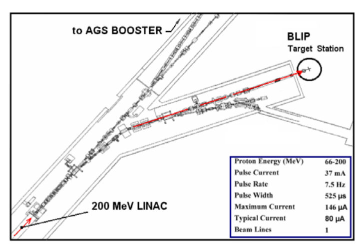

Figure 1: BNL accelerator schematic and target station used for CZT crystal irradiation.

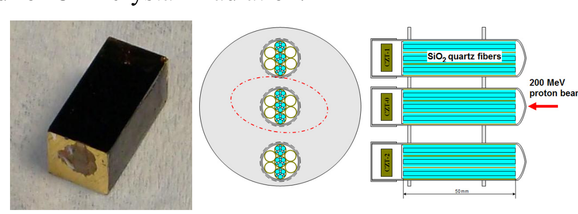

Figure 2: CdZnTe bar detector and irradiation configuration under 200 MeV proton beam.

Following the irradiation exposure it was observed that the CZT detector (CZT-0) situated within 1-σ of the beam, which was irradiated at a peak fluence of 7.3·1016 p/cm2, experienced total structural disintegration. The remaining detectors, CZT-1 and CZT-2, were intact.

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To enable post-irradiation examination outside the hot laboratory, the detectors "cooled-down" for a period of 12 months.

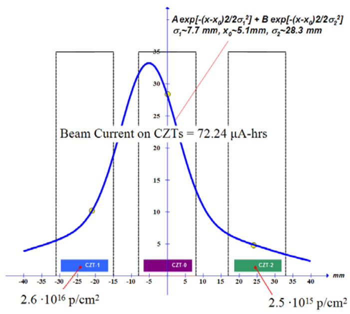

Figure 3: Proton beam profile and corresponding fluence.

CZT POST-IRRADIATION ANALYSIS

Following "cool-down", irradiated CZT crystals were characterized through spectral analysis, isotope identification, microscopic radiation damage and leakage current degradation. Findings are presented below.

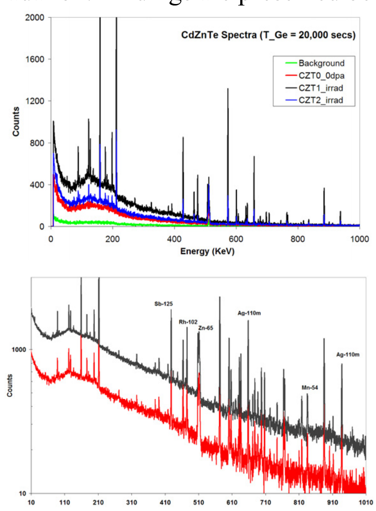

Figure 4: Measured CZT photon spectrum (Ge detector).

Spectral Analysis

To identify isotopes that resulted from the exposure of the CZT crystals to irradiation, a spectral analysis was performed using a high-purity Ge detector (ORTEC Solid-State Photon Detector, GEM30P4-83). Short and long Ge-detector exposures were implemented to ensure the validity of the findings. Figure 4a depicts a spectral comparison between the background, the un-irradiated detector and the two exposed detectors. Figures 4b and 4c show comparisons between different duration exposures of the same detector as well as identification of isotopes.

Damage Visualization

Radiation damage manifests itself through the formation of vacancy-interstitial atom pairs and for detector materials through the generation of energy levels within the band-gap as a result of lattice defects. It has also been observed [3] that irradiation damage of Ge detectors causes preferential hole trapping. Damage induced on the CZT detectors by the energetic protons was observed under an optical microscope.

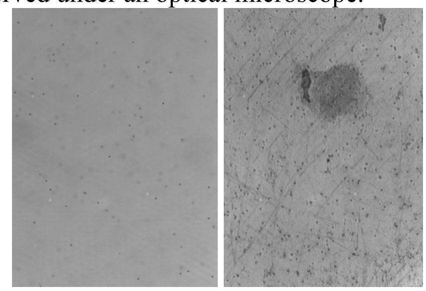

Figure 5: CZT surface of un-irradiated (left) and following irradiation (right) both showing Te inclusions.

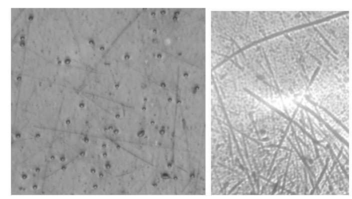

Figure 6: CZT surface following irradiation showing furrows produced by spallation fragments and pronouncement of Te inclusions.

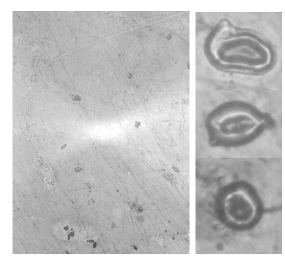

Figure 7: Radiation damage on the surface of CZT crystal and thermal spike effects near impurities or Te inclusions.

The aim was to assess if the damage characteristics observed in other crystals and non-metals, manifested in the form of thermal spikes, fragment tracks, etc. are observable in these crystals as well. Fig. 5 depicts the surface of a CZT detector prior to irradiation. Visible are the Te inclusions. Figure 6 is the image of one of the irradiated CZT crystals clearly depicting fragment tracks (result of spallation products displacing atoms of the lattice at the surface), and thermal spike (interaction of highly charged, massive, energetic fragment with electrons). Shown also in Fig. 6 is the pronounced nature of Te inclusions as a result of irradiation, which may be the result of interaction of the heavier Te atoms with radiating particles of spallation fragments. More pronounced "thermal spikes" are shown in Fig. 7 with remarkable similarity in the way they form on the CZT surface.

Resistivity Effects

I-V characteristics of the irradiated CZT detectors were measured using the set-up shown in Fig. 8 and compared with those of un-irradiated crystals. Fig.9 depicts the leakage current of a detector with no radiation exposure. Leakage current was seriously decreased as a result of irradiation. Fig. 10a compares the two irradiated crystals (CZT-1 experienced much higher fluence than CZT-2 during irradiation). Shown in Fig. 10b is the intriguing *I-V* characteristic exhibited by CZT-2. To ensure that the behavior is indeed real, the measurements were repeated three times and with different measurement resolution. All three measurements confirmed the behavior. The authors do not yet have a clear explanation of this, although it appears consistent with a type of damage-induced electrical breakdown at the contacts or within the crystals.

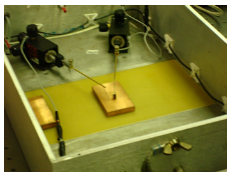

Figure 8*:* *I-V* measurement set-up.

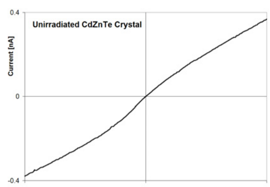

Figure 9*:* Un-irradiated CZT crystal *I-V* characteristic.

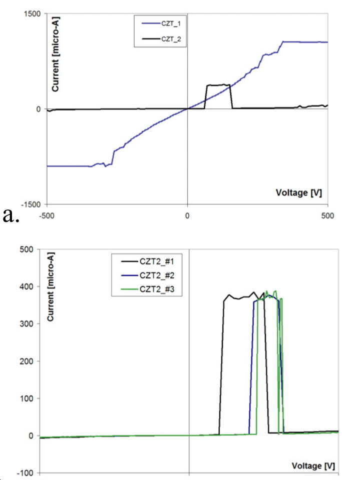

Figure 10*:* *I-V* characteristic of irradiated CZT crystal.

Simulation

A simulation study seeking to mimic the actual CZT irradiation conditions and set-up has been undertaken using the MCNPX general purpose Monte Carlo radiation transport code with ENDF/B-VII cross sections. The initial goal is to benchmark the calculation against the experiment by generating the γ-spectrum and comparing it with the one deduced from the Ge detector following irradiation. Success in such endeavor will establish a validated process through which the "design" of the crystal/detector can be influenced such that the signatures of source-induced isotopes and detector-induced isotopes are clearly delineated. Fig. 11 depicts the preliminary model used in the MCNPX analysis. Fig. 12 is a preliminary comparison of photon spectra between simulation and experimental test. The results are very encouraging. Several isotope γ energies match despite the fact that the MCNPX cross section library has not been enhanced to include isotopes that are of interest in the detector area. The decay time (~12 months) along with the actual proton fluence on one hand and the refined energy calibration of the Ge detector on the other are parameters that, if implemented, could lead to an even better photon energy peak correspondence.

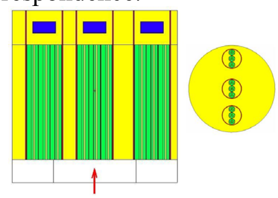

Figure 11*:* MCNPX model for CZT irradiation.

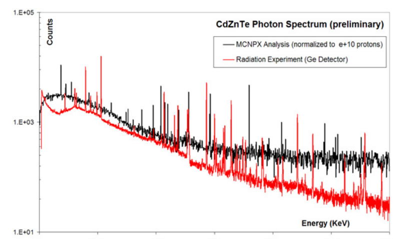

Figure 12*:* "Preliminary" comparison of photon spectra between irradiation test and MCNPX simulation.

SUMMARY

The effect of elevated high-energy proton radiation exposure of CZT crystals on key properties and damage characterization was studied at BNL. While the post-irradiation analysis showed severe degradation of leakage current, it also revealed unique I-V characteristics over a narrow voltage band. The examination of radiation damage under the microscope showed fragment tracks and thermal spikes. Finally, an ambitious simulation model revealed its potential as a tool for predicting detector spectral response following irradiation by energetic particles.

REFERENCES

[1] E. L. Hull, et al., "The Effects of 199 MeV Radiation Damage of CdZnTe Photon Detectors," IEEE Trans. Nucl. Sci., Vol. 44 (3), pp. 870-873, 1997

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