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Wide Bandgap Semiconductor Detector Optimization for Flash X-Ray Measurements

C. Roecker and R. Schirato

***Abstract*—Charge trapping, resulting in a decreased and spatially dependent electric field, has long been a concern for wide bandgap semiconductor detectors. While significant work has been performed to characterize this degradation at varying temperatures and radiation environments, this work concentrates upon examining the event-to-event response in a flash X-ray environment. The following work investigates if charge trapping is a problem for CZT detectors, with particular emphasis on flash X-ray radiation fields at cold temperatures. Results are compared to a non-flash radiation field, using an Am-241 alpha source and similar temperature transitions. Our ability to determine if a response change occurred was hampered by the repeatability of our flash X-ray systems; a small response change was observed with the Am-241 source. Due to contrast of these results, we are in the process of revisiting the Am-241 measurements in the presence of a high radiation environment. If the response change is more pronounced in the high radiation environment, a similar test will be performed in the flash X-ray environment.**

I. Introduction

Wide bandgap (WBG) semiconductor radiation detectors have been considered and utilized by many groups in recent years for X-ray and gamma-ray detection [1], [2]. These detectors have many advantages when compared to conventional semiconductor detectors: room and/or high temperature operation, low leakage current, thick depletion layers, high density, and large atomic number yielding higher detection efficiencies. Despite these advantages, trapping and/or charge freeze-out, contributing to a decreased electric field, has long been a concern for Cadmium Zinc Telluride (CZT) detectors [3], [4].

For most single-particle counting or spectroscopic applications, high electric field strengths and optimized contact and substrate geometries are used to improve limited charge collection. While these techniques work for single-particle applications, flash X-ray measurements, like those observed in X-ray free-electron laser [5] and flash radiography facilities, introduce a new challenge: energy deposition from a near instantaneous flash generates a large concentration of free carriers, typically over a much larger volume of the detector. Charge carrier movement in the detector applied field allows for measurement of the signal, but the separation of this relatively large carrier concentration also produces a time-dependent space charge field in the middle depth region of the detector which partially cancels the applied field, as described in Fig. 1. However, initial calculations suggest that subsequent to a large X-ray flash, the electric field strength may actually increase near the electrodes for a short duration, especially for the incident-side cathode in the case of poor hole mobility.

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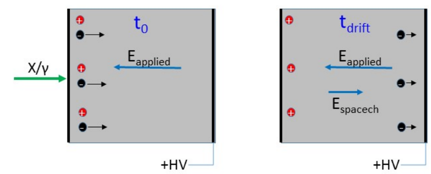

Fig. 1. Space charge from charge transport reduces the total electric field in the middle depth of the detector possibly resulting in sub-linear measurements.

This space charge induced field may result in a decreased amplitude measurement due to increased recombination, trapping, and ballistic deficit. Additionally, the increased charge trapping may degrade the response of subsequent signals, if thermal activation does not liberate the trapped charge. While many papers exist detailing the charge trapping and energy resolution characteristics as a function of temperature, flux, and time [6]–[11]; no comprehensive document has explored the dependence between temperature and the incident radiation flux in a flash X-ray environment on an event-to-event basis. In the rest of this summary, the term "event-to-event" is used to describe the response change due to multiple flash x-ray events, each individually composed of many photons interacting nearly instantaneously in the detector.

The work described here has investigated the effects of charge trapping in CZT detectors as a function of temperature in a flash X-ray environment on an event-to-event basis. Flash X-ray events deposit large amounts of charge, in an energy dependent depth profile, across the whole detector; this is in stark contrast to the standard energy spectrscopic measurement scenario in which single photons interact in a small volume of the detector depositing a relatively small amount of charge. In Sec. II, we describe our method and two experimental setups for measuring the signal degradation due to charge trapping. In Sec. III, we present preliminary results indicating that any response change is difficult to observe in the flash X-ray environment but an effect has been observed in a non-flash scenario. We propose a method to determine if the effect from the non-flash scenario is due to the detector physics. Finally in Sec. IV, we summarize the paper.

II. Method

To measure the charge trapping induced signal degradation in CZT we constructed two experimental setups: 1) a CZT detector inside a temperature controlled vacuum chamber which houses an Am-241 alpha source, and 2) a CZT detector and a temperature controlled enclosure with a flash X-ray system. To maintain the similarities between both experiments, the same

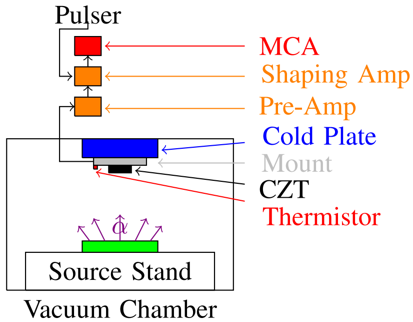

Fig. 2. Schematic of the Am-241 alpha source measurement setup. The source was placed far enough from the detector to minimize oblique angle transitions of the detector dead layer. The cathode of the detector was facing the source.

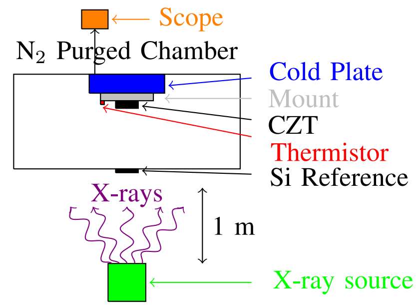

Fig. 3. Schematic of the flash X-ray source measurement setup. The X-rays were provided by either a Golden model 200 [12] or a L3-HP [13] X-ray source. Both sources had an endpoint energy of 150 kV; the Golden is a small hand-held source while the L3-HP is a relatively larger and higher flux source.

CZT detector with dimensions ∼4 mm×4 mm×2.3 mm was used in both experiments. To ensure electronic drift was not contributing to our alpha measurements, a pulser was used to normalize the response. For the flash X-ray environment the largest systematic is the pulse-to-pulse variation of the X-ray sources. Here we attempted to normalize this variation by using a small Si reference detector placed slightly below the CZT detector, but still near the beam center line.

The first experiment was designed to allow us to observe the effects of charge trapping in a slow and easily observable manner. The lessons from the first experiment[1] were applied to the more difficult operating environment of the second flash X-ray experiment. Before the first measurement was performed, the detector temperature was held at 30 C for roughly an hour to liberate thermally trapped charge. The detector was transitioned, at the maximum rate possible limited by the cooling elements, to -30 C and the Am-241 alpha energy response was monitored in hour long measurements for 180 hours. During these measurements a constant pulse rate pulser was used to verify that any shift in the energy response was due to the detector, not the electronics. We should also note that all electronics are physically located outside the vacuum chamber and should be at or near room temperature. Results from the first experiment are presented in Sec. III. A schematic of the Am-241 alpha setup is shown in Fig. 2.

The second experiment was designed to ascertain the relationship between flash X-ray event-to-event measurements as a function of temperature. A similar temperature transition was performed: the detector was warmed to remove any hysteresis effects, then the detector was rapidly transitioned to -25 C [2]. Shortly after the temperature transition, a flash X-ray system was used at roughly fixed intervals and the pulses were recorded. A schematic of the flash X-ray measurement is shown in Fig. 3. We used two flash X-ray sources: a Golden model 200 [12] and an L3-HP [13]. Both sources have a 150 kV end point energy. The Golden is a small hand-held unit, while the L3-HP is relatively large and our version delivers 20 J per shot. The predicted X-ray flux for both the L3-HP and Golden 200 is shown in Fig. 4. This flux was predicted using SpekCalc v1.0 [14], [15] with 32 mm of Cu equivalent shielding at 1 m from the detector with a 13 deg target angle.

[1]For instance: electronic noise elimination, operating characteristics of this batch of CZT, expected response, etc.

[2]Due to the N_2 environment we could only cool the detector to -25 C, not the -30 C used in the alpha experiments.

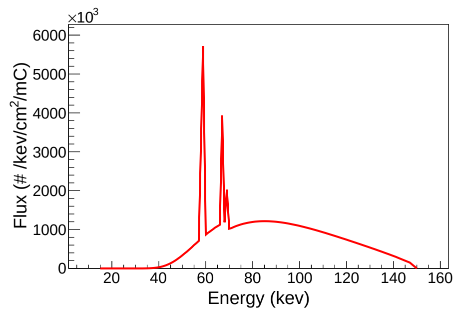

Fig. 4. The SpekCalc v1.0 predicted X-ray flux assuming 32 mm of Cu equivalent shielding at 1 m from the detector with a 13 deg target angle.

III. Preliminary Results

Using the experimental alpha setup presented above, an example energy spectra from experiment 1) at 10 hours after the temperature transition is displayed in Fig. 5. The Am-241 alpha response is observed at channel ∼3500. The constant pulser response is observed at channel ∼6200. We did not observe any significant drift in the pulser peak over the measurement period.

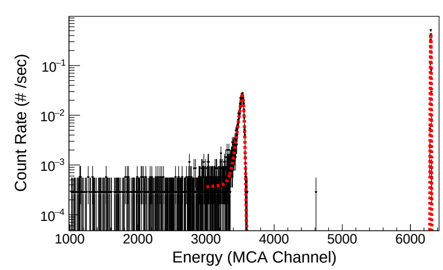

Fig. 5. The Am-241 alpha and pulser spectra 10 hours after the temperature transition.

The Am-241 peak in Fig. 5 was fit with two exponential distributions convolved with a Gaussian distribution described by,

$$f(x) = \sum_{i=0}^{i<2} \Bigg(A_i \frac{\lambda_i}{2} exp^{\frac{\lambda_i}{2}\left(2\mu + \lambda_i \sigma^2 - 2(2\mu - x)\right)} * Erfc\left(\frac{\mu - \lambda_i \sigma^2 - (2\mu - x)}{\sigma\sqrt{2}}\right)\Bigg), \quad (1)$$

where σ is the Gaussian standard deviation, μ is the Gaussian mean, A_i is the exponential amplitude, and λ_i is one of the exponential distribution rate parameters. This function was used to account for the typical charge carrier tailing observed in CZT as well as the charge trapping induced effects.

To determine the time-dependent CZT response to the alpha particles, the Gaussian mean was normalized to the pulser peak mean. As observed in Fig. 6, the Am-241 alpha response decreases as a function of time, indicating that charge trapping has an impact on the alpha response.

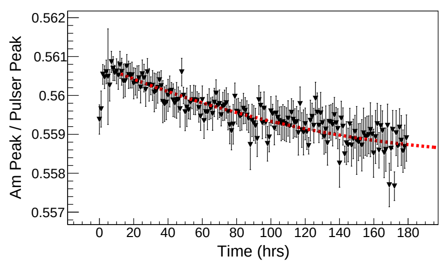

Fig. 6. The Am-241 peak normalized to the pulser peak as a function of time after a transition from room temperature to -30 C. The quoted uncertainty is the uncertainty of the Am-241 peak centroid not the FWHM of the peak. The accompanying fit is a double exponential function.

In addition to Fig. 6, we provide Fig. 7 where the uncertainty in each measurement is the Full Width Half Max (FWHM) of Am-241 peak distribution. This figure indicates how the low energy side of the peak spreads out as a function of time at -30 C.

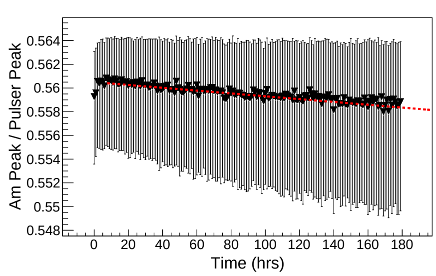

Fig. 7. The Am-241 peak normalized to the pulser peak as a function of time after a transition from room temperature to -30 C. The quoted uncertainty is the FWHM of the Am-241 peak distribution not the uncertainty of the peak centroid.

In the flash X-ray environment of experiment 2), we were not able to observe or induce the same response change, as observed in the alpha measurements, when the detector was kept at cold temperatures. The data from the Golden 200 flash

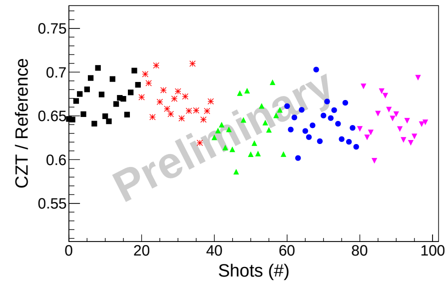

Fig. 8. The CZT detector response normalized to the Si reference detector as a function of the number of Golden 200 pulses. The black square and red star data were taken at 25 C. The green upward triangle, blue circle, and purple downward triangle were taken at -25 C at the following times respectively: immediately after the temperature transition, ∼100 hrs after the transition, and ∼100 hrs after the transition and after applying 10 shots from the L3-HP system. No significant event-to-event variation was observed. However, a variation was observed as a function of temperature.

X-ray source can be observed in Fig. 8. Each series of shots consisted of 20 pulses from the Golden 200 with a <1 minute separation between pulses. The black square and red star data were taken at 25 C; the green upward triangle, blue circle, and pink downward triangle data were taken at -25 C in the following sequence: immediately after the temperature transition, ∼100 hrs after the temperature transition, and 100 hrs after the temperature transition and after applying 10 shots from the L3-HP respectively. We initially thought the change would be easier to observe given the amount of charge deposited on the detector during an X-ray pulse. However, the Golden X-ray source was not consistent enough for us to observe small changes in the detector response at -25 C as a function of time, even when using a reference detector.

An attempt was made to use the much stronger L3-HP X-ray source at 30 cm from the detector without the thick shell of the chamber [3]. With this source no event-to-event response change was observed, but the detector started to show signs of breakdown as evidenced by significantly increased leakage current several seconds after each X-ray pulse. This increase leakage current was possibly caused by a short duration increase in the electric field near a contact subsequent to the X-ray flash. In this higher flux scenario we were able to observe a response and pulse shape change in the transition from room temperature to -25 C as observed in Fig. 9.

The above mentioned breakdown and the pulse-to-pulse variation of the Golden 200 X-ray source present problems for our flash X-ray experiments. While not being able to observe any event-to-event response change, the Am-241 alpha measurements indicate that the response might be slowly changing. Under the assumption that the effect might be larger when a larger current is running through a detector, we are in the process of performing the alpha measurements again, but this time in a conjunction with a high radiation field. If the rate of change of the response increases, we claim that the effect is real and may be a concern for CZT detectors operating in cold

[3] A piece of aluminum foil was used in place of the chamber door to contain the N_2 and block the room light.

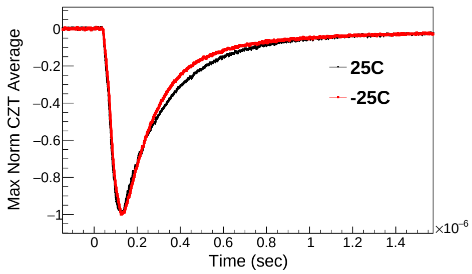

Fig. 9. The average CZT detector response normalized to the Si reference detector and scaled to the peak maximum for 10 L3-HP shots at 25 and -25 C. We did observe a pulse shape change, and subsequent decrease in the integral, at -25 C compared to 25 C. If charge trapping were a significant problem in this detector and shot configuration the pulses should have elongated at -25 C.

temperatures. Should this response change be observed, it will necessitate more careful and thorough flash X-ray experiments.

IV. Conclusion

While well suited to single particle counting or spectroscopy, CZT detectors may be particularly susceptible to space charge induced charge trapping in flash X-ray radiation environments. Here, we describe an effort to characterize this charge trapping with an alpha source and separately in a flash X-ray radiation environment, in an operating environment between -25 and -30 C. We have presented preliminary results of charge degradation in CZT after a rapid temperature transition from room temp to -30 C for the alpha source; here, we observed a slow degradation of the signal. However, we were not able to observe a significant and discernible event-to-event variation in the flash X-ray environment, which we attribute to the limitations of our setup. A pulse shape response change was observed in the flash X-ray environment as a function of the temperature. These contrasting results motivate additional measurements. We are currently in the process of repeating the alpha measurements in the presence of a high radiation field. If we observe a more pronounced response change between these new alpha measurements and the initial measurements, we claim it would indicate the effect is real and it would motivate a more careful set of flash X-ray measurements.

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