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Detector by Using a Pulse Shape Analysis***

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Performance studies of CdZnTe detector by using a pulse shape analysis

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ABSTRACT

Pulse shape analysis is proved to be a powerful tool to characterize the performance of CdZnTe devices and understand their operating principles. It allows one to investigate the device configurations, electron transport properties, effects governing charge collection, electric-field distributions, signal charge formation, etc. This work describes an application of different techniques based on the pulse shape measurements to characterize pixel, coplanar-grid, and virtual Frisch-grid devices and understand the electronic properties of CZT material provided by different vendors. We report new results that may explain the performance limits of these devices.

Keywords: CdZnTe, pulse-shape analysis, gamma ray detectors

1. INTRODUCTION

In the past, several experimental techniques have been proposed to investigate the performance of CdZnTe (CZT) detectors. The pulse shape analysis of the transient current signals is one of method that offers a simple way to evaluate CZT devices and understand the problems limiting their performances: device contact configurations, electron transport, effects governing charge collection, electric-field distributions, output signal formation, etc.

The transient current technique has being widely used in semiconductor device physics. In this technique, the excess charge carriers, produced by optical pulses, x-rays, energetic electrons, or other source of radiation, move under the influence of the electric field inside the semiconductor and generate the transient signal, which carries information about device performance. The transient current pulses are digitized and stored as waveforms for further analysis.

This work describes an application of this technique to characterize different types of CZT devices such as pixel, coplanar-grid, and virtual Frisch-grid detectors and measure the electronic properties of CZT crystals provided by different vendors. The waveform analysis technique is a powerful diagnostic tool that helps us to identify and solve the specific problems that result in poor performance of the CZT devices, which are currently under development in the Detector Development and Testing Division at Brookhaven National Laboratory. The waveform analysis algorithms

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used in this work were developed solely for device testing purposes and, because of this, were not optimized for digital pulse shaping or pulse shape corrections recently proposed for CZT detectors.

In these studies, we used three types of single charge carrier CZT detectors: coplanar grid (CPG), pixel, and virtual Frisch-ring (FR) detectors. The operation principles of these devices and their performance characteristics have been discussed in the literature, see, e.g., Refs. [1-8].

2. EXPERIMENTAL SETUP

Commercial $15 \times 15 \times 7.5 \text{ mm}^3$ CPG detectors with contact patterns comprised of $350\text{-}\mu\text{m}$ -wide strips located at a $700\text{-}\mu\text{m}$ pitch, and $10 \times 10 \times 10 \text{ mm}^3$ 4×4 pixel detectors with $100\text{-}\mu\text{m}$ gaps between the pixel contacts were purchased from eV-Products, Inc. The CPG detectors were mounted with two Teflon brackets on the ceramic substrates. The device electrodes (grids and cathode) were connected to the substrate's pins by using thin gold wires glued with a conductive epoxy. The pixel detectors were Z-bonded by the manufacturer to the ceramic substrates with 16-pin miniature connectors on the opposite sides. The $3 \times 3 \times 6$ and $6 \times 6 \times 11 \text{ mm}^3$ FR devices were fabricated by using CZT crystals acquired from Yinnel Tech, Inc. and from Freiburg University as previously described [9,10]. The original crystals were hand polished and etched briefly with a 2% bromine/methanol solution. Electroless Au contacts were applied only to the ends, thereby forming the anode and cathode contacts. Afterwards, the side surfaces were polished further to reduce side-surface leakage current. To improve the device performance, the side surfaces of some of the samples were treated with a $\text{NH}_4\text{F}/\text{H}_2\text{O}_2$ solution [11].

During the measurements, the CPG and pixel detectors were plugged inside a custom test box containing the eV-Products, Inc. hybrid preamplifiers. In the case of the FR device, we used the eV-Products device holder. The shielding electrode of the FR device was connected to the cathode and kept at zero potential, while the positive voltage was applied to the anode. The signals generated on device's electrodes, including the cathode, were digitized with a LeCroy 6050 Waverunner and stored for further analysis.

Uncollimated ^{137}Cs and ^{68}Ge sources were used to generate interaction events inside the devices. For the time resolved measurements, we employed a small, 3 cm^3 , BaF_2 detector and the 511-keV annihilation photons emitted by the ^{68}Ge source to produce coincidence signals in the CZT device under the test and BaF_2 detector. Fast signals generated by the BaF_2 detector were used as triggers to locate the interaction moment of an incident photon. In the case of CPG and pixel devices, we found that the leading edge of the cathode signals can also be used to identify the interaction moments with an accuracy of less than 20 ns.

In the case of CPG detectors, the typical bias applied to the cathode was 1000-1500 V, while the differential bias between the grids was varied between 0 and 80 V. In the case of pixel detectors, the bias applied to the cathode was higher at 1500-2000 V, since the pixel leakage current is small. We applied $\sim 2000 \text{ V}$ on the FR device.

We employed a highly collimated high intensity quasi-monochromatic X-ray beam available at BNL's National Synchrotron Light Source (NSLS) to study the uniformity of the device response. Depending on the type of measurements, we used either a 10 or $25 \text{ }\mu\text{m}$ diameter beam. The energy distribution of the incident photons had a Gaussian distribution centered at 75 keV with 10-keV spread. For each position of the beam, we collected a pulse-height spectrum generated by the x-ray interacting near the cathode, and we evaluated the position and full-width-at-half-maximum (FWHM) of the primary photopeak. The detectors tested in this work had modest energy resolution, typically $2.0\text{-}3.0 \%$ at 662 keV .

3. RESULTS AND DISCUSSION

3.1. Waveform analysis algorithm

For each acquired event, we used digitized waveforms to evaluate signal amplitudes and timing information. Fig. 1 shows typical waveforms measured for CPG, pixel, and FR detectors biased at 1500, 2000, and 1000 V, respectively. The following algorithm was employed in this work. It starts with analysis of the cathode signal to find the event arrival time. The first few data points of the cathode signal are used to calculate the waveform's baseline and the standard deviation of the noise. The event arrival time is approximately located as the sample number at which the signal reaches greater than two standard deviations of noise above the baseline. Then, a narrow points segment around this sample is selected for the linear backward interpolation of the pulse's leading edge. The intersection of the interpolation line with the baseline gives the event arrival time. We achieved a time resolution (FWHM) of $\sim 10 \text{ ns}$ estimated with respect to the

coincidence signals read out from a BaF₂ scintillator when annihilation photons from a ⁶⁸Ge source were used to generate signals in both detectors.

Fig. 1. Typical waveforms acquired for three detectors under the test: (a) CPG, (b) pixel, and (c) Frisch-ring.

Next, the algorithm determines the electron cloud's arrival time to the anode electrodes. For this purpose, the fast-rising signals from the collecting grid of the CPG device, pixel contact of the pixel detector, or anode of the FR device are used. We define this time as an intersection of two lines: one extrapolates forward a pulse's leading edge and the second extrapolates backward the pulse's saturated amplitude (see Fig. 1). To take into account the preamplifier delay time, we used the points located around the half amplitude of the grids' differential signal. The saturated part of the waveform is usually a slow-rising function resulted from the collection of the holes and depends on the interaction depth. Finally, the signals' amplitudes are calculated as the difference between the saturated part of a waveform (a pulse level) and the baseline. The baseline is calculated by averaging the points within the time window T adjacent from the left to the beginning of the pulse (event arrival time). The same size window located after the electron cloud arrival time and delayed by ΔT is used to calculate the pulse level. The delay is necessary to shift the averaging window to minimize the effect of the rounded top of the pulse. The actual values for T and ΔT are selected so as to minimize the electronic noise and ballistic deficit, typically $T \sim 200$ ns and $\Delta T \sim 150$ ns. It is important that for each event the locations of the averaging windows on both grids and cathode waveforms are the same. The algorithm's adjustable parameters, which depend on the oscilloscope's acquisition settings and electronic noise, require some tuning before application of the above algorithm for waveform analysis.

3.2. Coplanar-grid detector

Fig. 1 (a) shows typical waveforms measured from the cathode and grid anodes of the CPG device. The cathode signal has a linear rising negative slope similar to those generated by an electron cloud moving in a parallel plate ionization chamber. The grid signals have identical positive slopes (half the cathode's one) until an electron cloud approaches the grids. From this moment, the collecting grid signal starts rising exponentially and reaches the maximum value when electrons arrive to the grid. In contrast, the non-collecting grid signal changes slope and decays symmetrically to the collecting one. If the holes transport is neglected, then the amplitudes of the signals would reach their maxima when all the electrons arrived at the grids. After this moment, the amplitudes of the pulses would decay linearly with the slopes corresponding to the decay time of the preamplifiers, ~ 1 ms. Nevertheless, the pulses in Fig. 1(a) have slow-rising slopes indicating the charge transport of holes. In fact, Fig. 1(a) shows the waveforms corresponding to an interaction event close to the anodes; it was specifically selected to illustrate the contribution of holes. For the events interacting close to the cathode, the holes contribution is less pronounced. It should be mentioned, that after subtraction of the grid signals the contribution due to uncollected charges left in the device (including the holes) has little effect on the device response.

The amplitudes and time characteristics of the output signals were evaluated as described previously and used to plot correlations between the cathode, collecting and non-collecting grids signals. These plots, in which each interaction

event is represented by a point with the coordinates equal to the amplitudes of the signals measured from the grids, A_1 and A_2 , and from the cathode A_3 , represent the unique performance characteristics of a particular CPG device.

Fig. 2 (a,b) shows the correlations between the grids signals, A_1 vs. A_2 , measured for the CPG detector with the cathode biased at 1000 V and the differential voltages applied between the grids of: (a) 0 V and (b) 60 V. The detector was flood irradiated with gamma rays from a ^{137}Cs source located 2 cm above the cathode. There are three distinctive regions in the correlation plots. The continuum of dots between the positive axes represents the charge sharing events for which the total collected charge is divided between the two grids. These events give rise to the positive output signals generated on both grids. An important feature of this continuum is that its edge, which corresponds to the total energy absorption events interacting near the cathode, follows a straight line. The abrupt change of the dot density corresponds to Compton-edge-events interacting near the cathode, which also follow a straight line. These features illustrate the fact that the dots representing the single events interacting at the same depth (distance from the cathode) and depositing the same amount of charge concentrate along the line defined by the equation: $A_1 + A_2 = C$, where C is the constant. This statement follows from the charge conservation law: $A_1 + A_2 + A_3 = 0$.

Fig. 2. Correlations between the grids signals, A_1 vs. A_2 , measured for the CPG detector at two differential bias voltages applied between the grids: (a) 0 and (b) 60 V. The cathode bias is 1000 V.

If the deposited charge is collected by a single strip (it could be either one if no differential bias is applied between the grids), a positive signal will be generated on the collecting grid and a negative on the other. Such events produce two continuums symmetrically located in the upper left and bottom right quadrants. For these distributions, the total energy of the deposition events are represented by the track of the dots concentrated along the line $|A_1 - A_2| = Q_0$, where Q_0 is charge corresponding to the total absorbed energy. This equation illustrates the operation principle of coplanar-grid devices, i.e., the difference between collecting and non-collecting grid signals gives the total deposited energy. The Compton edge is also seen in this distribution as the line parallel to the photoabsorption track. For the events interacting close to the cathode, the photoabsorption tracks merge with the continuum distribution representing the charge sharing events. Moving along the track in the opposite direction corresponds to the events interacting deeper inside the device. As the differential bias between the grids is applied, the events (dots) move toward one of the quadrants depending on which of the grids is collecting (Fig. 2(b)).

As was already mentioned, the correlation plots can be also used as diagnostic tools to characterize the performance of the CPG devices, e.g., the plots shown in Fig. 2 reveal three problems related to the particular CPG device used in these measurements. These problems affect the energy resolution and photopeak efficiency of the devices.

First, the tracks of the dots, corresponding to the total energy absorption events, bend off the lines $|A_1 - A_2| = Q_0$, which indicates the charge loss in CZT bulk due to electron trapping. As seen in Fig. 2, the actual track's location follows a line $|A_1 - \alpha A_2| = Q_0$, where α is a numerical coefficient. These lines, whose orientations are slightly different from a 45-degree angle with respect to the coordinate axes, illustrate the standard approach used to correct the output signals from CPG devices due to electron trapping. The parameter α is assumed to be independent of the photon energy.

Second, the dots distribution in the tracks becomes wider as a dot position in the track goes below a halfway point toward the dots representing the events for which the interaction points lay deep inside the detector. It should be

remembered, however, that the distributions in Fig. 2 represents the superposition of many local correlation plots associated with all pairs of adjacent strips. This means that for limited areas of the detector, the global changes in the grids' responses cause the dots to shift upward or downward resulting in a symmetrical broadening of the track. Here, the track broadening indicates the global asymmetry between the grids weighting potentials. It is well known that these areas are located near the device's edges. This effect results in the long tails usually seen on the right and left wings of the peaks in the pulse-height spectra measured for CPG devices.

Third, the width of the dots distribution in the track above the threshold where it starts to broaden cannot be entirely explained by the anti-correlated electronic noises in the grids' signals. In the correlation plot (Fig. 2), the contribution of the electronic noise is represented by the asymmetrical dots distributions in the center of the coordinate system. As seen, the electronic noise can account for about half of the track's width. Another contributing factor could be the local variations in the grids' signals caused by the local dependences of the collected charge and the grids weighting potentials. We will discuss these effects in the next section.

To obtain more accurate data about the local variations of the device response, we completed 1-D scans with fine spatial resolution, $<10 \mu\text{m}$, across the adjacent strips in several locations. We plotted the dependence of the normalized differential signal $(A_{col}-A_{non})/(A_{col}+A_{non})$ vs. the beam position in the X-direction. For the events interacting near the cathode, the sum of grids' signals $A_{col}+A_{non}$ equals to the total deposited charge. We normalized the output signals in order to minimize the variations due to the energy spread of the beam. Fig. 3 shows the dependences of $(A_{col}-A_{non})/(A_{col}+A_{non})$ versus the beam position as measured at several differential biases applied between the grids. As seen in the figure, when the grids' differential bias increases from 0 to 40 V, the dips in the curves located above the non-collecting strips gradually reduce until no more improvements can be seen. To our surprise, the device response becomes almost flat (saturated) at the differential grid bias of 40 V, which is about 2.5 times smaller than the value calculated for the same device geometry under the assumption of no space charge inside the crystal. Moreover, the effective strip sizes and their locations, estimated from the response variations, do not precisely coincide with the actual strip positions. These two facts indicate that electric field inside the detector is not uniform in both the vertical and horizontal directions. The average electric-field strength decreases toward the anode (as if space charge existed inside the detector), resulting in a smaller differential grid bias required to steer all the electrons toward the collecting strips. This gives indication of a residual space charge in the CZT material. At the same time, the lateral field variations cause random changes in the apparent strip locations in the x-ray map.

Fig. 3. Dependences of $(A_{col}-A_{non})/(A_{col}+A_{non})$ vs. the beam position measured at several differential biases applied between the grids.

Fig. 4. The dependences of the normalized grid signal $A_{col}/(A_{col}+A_{non})$ and its FWHM vs. the beam position measured at a cathode voltage of 1000 V and three differential grid biases: 15, 30 and 40 V.

Since the charge losses on the surface in the gaps between the strips are not apparent in the correlation curves, we have attempted to find another way to characterize this effect in the case of CPG detectors. Fig. 4 shows the dependences of the normalized grid signal $A_{col}/(A_{col}+A_{non})$ and its FWHM vs. the beam position measured at 1000 V on the cathode and at three differential grid biases: 15, 30 and 40 V. As can be seen from Fig. 4, when the charge is shared between the collecting and non-collecting strips, the grids' output signals are very sensitive (change rapidly) to the x-ray position. At

15-V differential grid bias, when the x-ray beam is above the division line between the strips, $A_{col}/(A_{col}+A_{non})$ changes by 50-60% within a 10- μ m step. Since the size of the beam is 10 μ m (interaction points are randomly distributed within a 10- μ m spot), it results in the significant fluctuations in A_{col} , which is reflected in the dependences of the FWHM shown in Fig. 4. In contrast, at 30 V the dependence $A_{col}/(A_{col}+A_{non})$ still has a dip, while the dependence of the FWHM is almost flat. This suggests that at 30 V the charge is no longer shared any more between the collecting and non-collecting grids; all electrons are steered toward the collecting strips. However, $A_{col}/(A_{col}+A_{non})$ still has a dip that cannot be explained by the charge loss in CZT bulk. This means that some fraction of the charge reaches the surface in the gaps between the strips, where the trapping sites have a significantly higher density than in the bulk. As the grid bias increases above 40 V, the dips in the differential grids' signal on the bias voltage between strips either completely disappears or becomes very small. At some point, it becomes impossible to separate charge trapping at the surface versus charge trapping in the CZT bulk.

3.3. Pixel detector

The typical waveforms measured from the cathode and two adjacent pixels of the pixel device are shown in Fig. 1(b). The cathode signal is identical to that measured for the CPG device and is described in the previous section. The pixel signals rise slowly until an electron cloud approaches the anode side of the detector. From this moment, the signal from the pixel that collects charge rises rapidly while the signals from the adjacent pixels decay. Fig. 1(b) shows the case when the charge is shared between two adjacent pixels; both signals saturate to positive values proportional to the charge collected by the pixels. The pixel signal will saturate at the negative value if no charge is collected by the pixel contact. The negative amplitude is induced by the uncollected holes and depends on the interaction depth. In contrast to the CPG device, the holes transport cannot be seen due to the "small pixel effect". As a result, the saturated portions of the waveforms measured for the pixel device have relatively small negative slopes corresponding to the decay time of preamplifiers. By applying the waveform analysis, we evaluated the amplitudes of the cathode and pixels signals and the electron cloud's drift time, which for single interaction point events is the same as an interaction depth.

Fig. 5 (a,b) shows the correlation between amplitudes of the pixel signal and the drift time (the cathode signal could also be used to substitute for the drift time) measured for two representative pixels. As shown in Fig. 5(a), the total energy of the deposition events corresponds to the flat distribution of the positive amplitudes except for the region near the pixel, which indicates a nearly perfect compensation of the electron trapping by the depth dependence of the pixel response. In contrast, the distribution of the negative amplitudes induced by the holes when the electrons are collected by other pixels has a positive slope which can be used to estimate the electron lifetime in the region above the pixel: $\sim 5 \mu$ s in this case.

As in the case of the CPG detector, this correlation plot reveals information about the detector performance. For example, the plot in Fig. 5(b) shows a slight bending of the total energy deposition "track" at long drift times (events interacting close to the cathode) indicating incomplete compensation. This bending along with the bending in the short drift time region (events interacting close to the anode) results in the asymmetrical widening and low energy tailing of the peaks in the pulse-height spectra.

Fig. 5 (a,b). Correlation between amplitudes of the pixel signals and the drift time measured for two representative pixels. The cathode bias is 2000 V.

Another effect that can be seen in the correlation plot is the charge sharing between adjacent pixels. For example, the dots distributed between the total energy deposition “track” and Compton edge are caused by the charge sharing between the adjacent pixels. This effect can potentially contribute to the peak’s broadening if the pixel size is small while the gaps between the pixel contacts are large. To investigate this effect on the device performance, we evaluated correlations between the amplitudes of the signals readout from the central pixel and eight adjacent ones, acting like a single guard ring, connected in two groups, “gray” and “dark”, as shown in Fig. 6 (a). By taking the difference between the signals from these two groups, like in a CPG device, we were able to eliminate the contribution due to the uncollected charges (holes and trapped electrons) and ensure that the amplitude of the differential signal is proportional to the collected charge only. In this case, when the interaction events are triggered by the signal from the central pixel the nonzero differential signal (positive or negative) will indicate the charge sharing. Fig. 6 (b) and (c) show the correlation between the amplitudes of signals readout from the central pixel, A_3 , and differential signals measured from the two adjacent groups of pixels, A_1 and A_2 . The dots, distributed around a zero value of the differential signal, represent single pixel events without charge sharing (we neglected the multiple interaction point events for which the charge could be collected by other than the adjacent pixels). The negative signals correspond to the events for which the charge is shared between the central and one of the “gray” pixels, while the positive ones correspond to the charge sharing with the “dark” pixels. The total energy deposition events are represented by dots spot at zero of the differential signal (no charge sharing) and by the two symmetrically located “tracks” (charge is shared). Pay attention, that the maximum positive and negative amplitudes of the differential signals corresponding to the total energy deposition events above the “gray” and “dark” pixels are not equal, because we multiplied the signals from the “gray” group to make the weighting potentials of the both groups of pixels symmetrical.

Fig. 6. (a) Pixels arrangement. (b) Correlation between A_3 and A_1-A_2 . (c) Magnified region around a zero value of A_1-A_2 .

By selecting a narrow region around zero value of the differential signal, one can reject the charge sharing events readout from the central pixel. Fig. 7 shows the pulse-height spectra evaluated for the central pixel before and after rejection of the charge sharing events. From comparison of the spectra one can see that for the pixel geometry used in the tested device the charge sharing events, occurring near the pixel edges, contribute mainly to the continuum and have no or little affect on the shape of the peak. This is because only a small fraction of the edge events produce signals with the magnitudes slightly less than those signals that correspond to the peak position. Another helping factor is that the charge loss at the surface between the pixels does not affect the amplitude of the output signals. The latter effect depends on the pixel’s pattern geometry and how far the pixel contacts are located from the substrate grounding plate.

Fig. 7. (a) The pulse-height spectra evaluated for the central pixel before and after rejection of the charge sharing events. (b) Pulse-height spectra after rejection of charge sharing events with energy resolution indicated.

For example, strong signals losses were observed for the interaction points located above the pixel boundaries in Ref. [12]. In contrast, this effect was not seen with the devices tested here. Fig. 6(b) shows that the dots distributions (tracks) corresponding to the total energy deposition events follow the straight lines indicating no signal loss during the charge sharing between the central pixel and the surrounding ring of pixels. In other words, the sum of the signals from the adjacent pixels is conserved even though some fraction of the charge could be trapped at the surface between the pixels. To verify this, we carried a high resolution (20- μm step size) 1-D scan with a 10- μm diameter X-ray beam available at NSLS across several pixels of the pixel detector under test. As an example, Fig. 8 (a) and (b) show the amplitude dependence of the signals read out from two adjacent pixels vs. the x-ray beam position and the correlation of the pixel amplitudes evaluated for the same data points. Fig. 8 clearly demonstrates no signal loss during the charge sharing.

Fig. 8. (a) The amplitude of the signals read out from two adjacent pixels vs. the x-ray beam position. (b) The correlation between the amplitude of the signals evaluated for the same data points.

The right edges of the dots distributions shown in Fig. 5(a) and (b) corresponds to the electron drift time across the entire detector. This value gives an estimate for the electron mobility: $\sim 950 \text{ cm}^2/\text{V}\cdot\text{s}$ in this case. This value is slightly less than the commonly known $1000 \text{ cm}^2/\text{V}\cdot\text{s}$. The difference can be attributed to the field nonuniformity inside 1-cm thick detector. Measurements with greater accuracy can be performed by fitting the waveform read out from one of the central pixels with a theoretical curve. We would like to refer to the measurements conducted in Ref. [13] that used a fast

pulsed laser to generate free carriers near the cathode. In this work, the beginning of the pixel signals was determined by employing the electronic trigger supplied by the laser, while the end of the drift was evaluated by fitting the fast rising part of the pixel signals. To improved accuracy, the induced signal from the adjacent pixel was used to subtract out the slowly rising part of the transient signal read out from the central pixel. As an example, the results of the fitting procedure applied to the signals read out from a selected pixel for different biases are shown in Fig. 9.

Fig. 9. The results of the fitting procedure applied to the signals read out from the selected pixel at different cathode biases [13].

3.4. Frisch-ring detector

Waveform analysis helped us to better understand the operational principle of the FR detectors and factors limiting their performance. The typical waveform measured from the anode of the FR device is shown in Fig. 1(c). It is similar to shape generated on the pixel contact that collects charge in the case of a pixel device. From this point of view, the FR device can be considered as a “segment” of a pixel device. The operation principle of FR device is illustrated in Fig. 10 (a,b), which shows the correlation between the anode signal and drift time evaluated for a $5 \times 6 \times 11 \text{ mm}^3$ bar-shaped CZT detector before (a) and after (b) placing the copper shield on the side surfaces of the bar. These plots demonstrate how the shielding of the side surfaces provides the uniform response and excellent spectroscopic performance of the FR devices. It is interesting to mention, that estimated electron mobility based on these plots for the CZT crystals manufactured by Yinnel Tech, Inc. is $\sim 860 \text{ cm}^2/\text{V}\cdot\text{s}$. The negative slope of the correlation curve in Fig. 10(b) allowed us to evaluate the low estimate of the electron lifetime in the CZT sample used to fabricate this device: $>12 \text{ }\mu\text{s}$.

Fig. 10. The correlation between the anode signal and drift time evaluated for a $5 \times 5 \times 11 \text{ mm}^3$ CZT detector before (a) and after (b) placing the copper tape to shield the side surfaces of the device.

One of the problems, which we faced during the fabrication of the FR detectors, was that some of the devices had unpredictably poor performance that could not be related to the internal crystal defects. By applying waveform analysis to the output signal read out from the detectors with poor responses, we found that for the majority of the events, the measured pulses have two-rising slopes with a clearly seen knee separating the fast and slow parts. The duration of the slow rising part can be as long as several microseconds. Fig. 11 shows the examples of the normal and abnormal (two-rising slope) pulses. By identifying and rejecting the two-rising slope events, we were able to improve the device's spectral response.

Fig. 11. (a) Examples of the waveforms measured from the $3 \times 3 \times 6 \text{ mm}^3$ FR exhibiting poor performance: (a) normal vs. abnormal pulses, (b) a typical waveform indicating the fast and slow rising parts.

Fig. 12 shows the correlation between the amplitude of the signals and slow-rise-time portion of the pulse evaluated for $3 \times 3 \times 6 \text{ mm}^3$ FR detectors with good and poor performances. While the good detector shows no correlation, the poor performance device shows a strong correlation with the decay of the amplitude for the long rise times, which could be explained by the ballistic deficit effect. However, as shown in Fig. 12 (c), the track of the data points corresponding to the 662-keV peak gets wider as the slow rise time increases, which indicates that the slow-rising events are associated with electron charge losses. Both the ballistic deficit and electron losses associated with slow rising events result in a poor spectral response of the detectors.

Fig. 12. The correlation between the amplitude of the signals and slow-rise-time portion of pulse evaluated for $3 \times 3 \times 6 \text{ mm}^3$ FR detectors with (a) good and (b,c) poor performances.

The slow rising part seen in the waveforms can be attributed to the electron cloud drifting near the side surfaces of the device where electron mobility is smaller than in the CZT bulk. As discussed in Ref. [10], the electric field inside the

bar-shaped CZT device, such as a virtual Frisch-grid detector, depends on the boundary conditions (potential distribution) on the device side surfaces, which is mainly determined by the surface resistivity and the nature of the surface leakage current. If the surface potential decreases (in absolute values) more rapidly than linear function from the cathode level to zero, a substantial fraction of the field lines will intersect the side surfaces causing the electrons to drift along the surface with small velocities. This proposed phenomenon could generate the two-slope slow rising signals seen in poor performing FR devices.

This waveform analysis also helped us to explain and minimize the low energy tail seen in the pulse-height spectra acquired with FR detectors. This tail is due to the events interacting close to the anode where the shielding efficiency could be poor even when a small area of the surface is left unshielded. This is illustrated in Fig. 13, which shows the dependence of the device response vs. the drift time (a) and the pulse-height spectrum (b) evaluated for a $3 \times 3 \times 6 \text{ mm}^3$ FR detector with a 1-mm unshielded area left near the anode.

Fig. 13. The dependence of the device response vs. the drift time (a) and the pulse-height spectrum (b) evaluated for a $3 \times 3 \times 6 \text{ mm}^3$ FR detector with a 1-mm unshielded area left near the anode.

5. CONCLUSIONS

In this work we demonstrated the application of the pulse shape analysis to characterize the performance of CdZnTe devices. By using this technique, we investigated three types of CZT detectors: CPG, pixel, and Frisch-ring devices. We identified several effects limiting the performance of these detectors and illustrated how the application of the pulse shape analysis helped to overcome these problems.

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REFERENCES

- [1] T. E. Schlesinger and R. B. James, Semiconductors and Semimetals, in *Semiconductors for Room Temperature Nuclear Detector Applications*, Vol. 43, San Diego, CA: Academic, 1995.
- [2] G. F. Knoll, *Radiation Detection and Measurement*, 3rd Ed. (Wiley, New York, 2000).
- [3] J. D. Eskin, H.H. Barrett, and H.B. Barber, "Signals induced in semiconductor gamma-ray imaging detectors", J. Appl. Phys., vol. 85, pp. 647-659, 1999.

- [4] P.N. Luke, "Unipolar charge sensing with coplanar electrodes", *IEEE Trans. Nucl. Sci.*, vol. **42**, pp. 207-213, 1995.
- [5] P. N. Luke, M. Amman, and J. S. Lee, "Factors affecting energy resolution of coplanar-grid CdZnTe detectors", *IEEE Trans. Nucl. Sci.* Vol. **51**, pp. 1199-1203, 2004.
- [6] Z. He, G. F. Knoll, D. K. Wehe, and Y. F. Du, "Coplanar grid patterns and their effects on energy resolution of CdZnTe detectors", *Nucl. Instr. Meth. Phys. Res.* A411, pp. 107-113, 1998.
- [7] A. Shor, I. Mardor, and Y. Eisen, "Performance of $1 \times 1 \times 1 \text{ cm}^3$ pixel CdZnTe gamma detectors," *IEEE Trans on Nucl Sci*, Vol. **49**, pp. 1935-1940, 2002.
- [8] D.S McGregor, Z. He, H.A. Seifert, D.K. Wehe, and R.A. Rojas, "Single Charge Carrier Type Sensing with a Parallel Strip Pseudo-Frisch-Grid CdZnTe Semiconductor Radiation Detector," *Appl. Phys. Lett.* **72**, pp. 792-794, 1998.
- [9] W. J. McNeil, D. S. McGregor, A. E. Bolotnikov, G. W. Wright, and R. B. James, "Single-charge-carrier-type sensing with an insulated Frisch ring CdZnTe semiconductor radiation detector", *Appl. Phys. Lett.* **84**, pp. 1988-1990, 2004.
- [10] A. E. Bolotnikov, G. S. Camarda, G. A. Carini, G. W. Wright, D. S. McGregor, W. McNeil, and R. B. James, "New Results from Performance Studies of Frisch-Grid CdZnTe Detectors", *Proc. SPIE*, Vol. **5540**, pp. 33-45, 2004.
- [11] G.W. Wright, G. Camarda, E. Kakuno, L. Li, F. Lu, C. Lee, A. Burger, J. Trombka, P. Siddons, and R.B. James, "Effects of Surface Roughness on Large-Volume CdZnTe Nuclear Radiation Detectors and Removal of Surface Damage by Chemical Etching," *Proc. SPIE*, Vol. **5198**, pp. 306-313, 2004.
- [12] A. E. Bolotnikov, W. R. Cook, F. A. Harrison, A. S. Wong, S. M. Schindler, and A. C. Eichelberger, "Charge loss between contacts of CdZnTe pixel detectors," *Nucl. Instr. Meth. Phys. Res.* A432, pp. 326-331, 1999.
- [13] A. E. Bolotnikov, S. E. Boggs, W. R. Cook, F. A. Harrison, and S. M. Schindler, "Use of a pulsed laser to study properties of CdZnTe pixel detectors", *Proc. of SPIE*, Vol. **3769**, pp. 52-58, 1999.