Title

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Noise in CdZnTe Detectors

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Abstract

Noise in CdZnTe devices with different electrode configurations was investigated. Measurements on devices with guard-ring electrode structures showed that surface leakage current does not produce any significant noise. The parallel white noise component of the devices appeared to be generated by the bulk current alone, even though the surface current was substantially higher. This implies that reducing the surface leakage current of a CdZnTe detector may not necessarily result in a significant improvement in noise performance. The noise generated by the bulk current is also observed to be below full shot noise. This partial suppression of shot noise may be the result of Coulomb interaction between carriers or carrier trapping. Devices with coplanar strip electrodes were observed to produce a 1/f noise term at the preamplifier output. Higher levels of this 1/f noise were observed with decreasing gap widths between electrodes. The level of this 1/f noise appeared to be independent of bias voltage and leakage current but was substantially reduced after certain surface treatments.

I. INTRODUCTION

An important advantage of CdZnTe gamma-ray detectors is their ability to operate at room temperature. The problem of poor hole collection as well as electron trapping in CdZnTe materials can be ameliorated to a large extent through preferential electron sensing such as that achieved with coplanar-grid [1], strip electrode [2] or pixel electrode [3] detection techniques. Good energy resolution for high-energy gamma-ray detection has been achieved for detector sizes of 1 cm^3 or more using the coplanar-grid technique. While the energy resolution for such detectors at high energy is still largely determined by material uniformity, detector noise contribution usually dominates the energy resolution at lower energies. Even at high energies, detector noise can lead to a significant loss in the overall energy resolution for detectors made from highly uniform materials. As an example, Fig. 1 shows a Cs-137 spectrum taken using a 1 cm^3 coplanar-grid detector. For this detector, the noise as measured by the width of the pulser peak contributes more to the gamma-ray line width than the detector's intrinsic resolution. Without the effect of noise, the gamma-ray line width would have decreased to 1.3% FWHM.

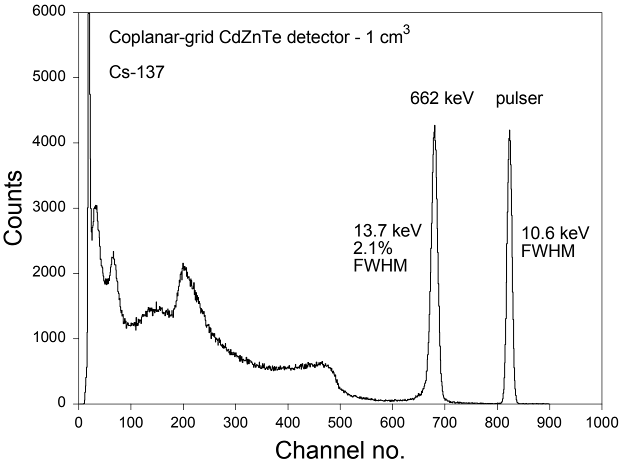


Fig. 1. A spectrum obtained from a Cs-137 gamma-ray source using a 1-cm^3 coplanar-grid CdZnTe detector.

The problem of noise is particularly acute in coplanar-grid detectors due to the use of fine-pitched interdigital electrode structures and the need to apply a bias voltage between the electrodes. Other CdZnTe detector configurations often employ fine-pitched electrodes as well, and some of them also require the application of bias voltage between coplanar electrodes [4][5]. It is therefore important to understand the origin of noise in these types of devices so that methods to minimize their adverse effects on detector performance can be developed. There are only a small number of publications concerning the detailed investigation of noise behavior in CdZnTe [6] and CdTe [7][8]. In these publications, the noise measurements are presented in terms of spectral distributions, which makes interpretation in terms of energy resolution less direct. In this paper, we present noise measurements made on CdZnTe devices with different electrode geometry using conventional nuclear electronics. The results are presented in terms of equivalent noise charge (ENC) versus amplifier peaking time so that the effects of noise on detector performance can be readily seen. Techniques to determine the noise parameters of detectors on the basis of ENC versus signal processing time are available in the literature [9].

II. MEASUREMENT SYSTEM

Noise measurements were made using a low-noise charge-sensitive preamplifier. The input stage of the preamplifier makes use of an Interfet NJ14 JFET, which has been removed from its original packaging to reduce dielectric related noise. The JFET was installed in a Teflon mount, which also housed the feedback components. The preamplifier utilized conventional resistive feedback with a feedback resistor of 2.4×10^8 ohms and a feedback capacitor of 0.5 pF. The preamplifier output was fed to either one of two variable time-constant pulse-shaping amplifiers. Two separate pulse-shaping amplifiers were used in order to cover the wide peaking time range of 0.25 μs to 28 μs. The shaping amplifiers utilize two-stage integration (CR-RC^2). The actual value of each of the selectable peaking times of the amplifiers was measured using

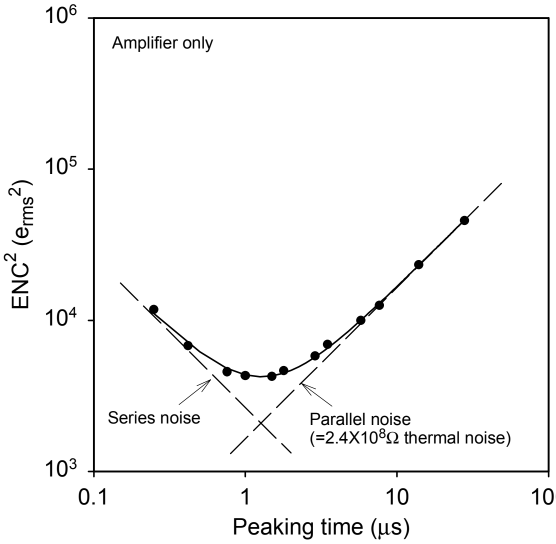


Fig. 2. Measured ENC^2 versus peaking time for the amplifier system used in this study with nothing connected at the input. The solid line is a fitted curve to the data. The dashed lines are the noise components extracted from the fit.

a digital oscilloscope. Noise levels were measured at the output of the pulse-shaping amplifiers using a wide-band rms voltmeter. The charge gain of the system was calibrated using a reference test capacitor and an electronic pulse generator.

Figure 2 shows the measured noise as a function of amplifier peaking time for the measurement system with nothing connected to the input. Plotting the square of the ENC (electrons rms) versus peaking time on a log-log scale allows the easy identification of various noise sources. In such a graph, series white noise such as that due to the input JFET's channel thermal noise will exhibit a decreasing contribution with increasing peaking time with a slope of –1. Parallel white noise such as shot noise due to leakage currents and thermal noise of resistance parallel to the input will exhibit an increasing contribution with increasing peaking time with a slope of +1. The noise that appears at the preamplifier output with an 1/f spectrum will typically give a flat contribution with little or no dependence on peaking time. The 1/f noise comes from two sources. One is the 1/f noise in the channel current of the input JFET. The other is the parallel f-type noise, which, when integrated on the feedback capacitance of the preamplifier, results in an 1/f spectrum at the output. From Fig.2, the noise behavior of the test system can be readily seen. The dashed lines are the series and parallel white noise components obtained by fitting to the data. The parallel white noise component was found to be virtually identical to the calculated thermal noise of the feedback resistor. Such a good agreement indicates that the noise coefficients that were employed in the calculation describe the behavior of the actual shaper quite accurately. Shot noise due to the gate leakage current of the FET, which is expected to be no more than several pA, is negligible. The 1/f noise component was too low to be accurately determined from the fit (ENC < 20 e rms).

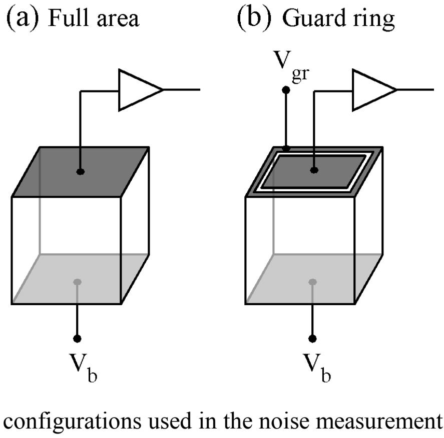
III. RESULTS

A. *Parallel White Noise*

Two high-pressure Bridgman grown CZT crystals were used in the measurements presented here. Each crystal is in the form of a cube 1 cm on a side, with no visible grain boundaries or twins. The crystals were acquired from eV Products, and they were cut from different boules. The electrodes on the devices were all formed using gold evaporation in vacuum. Prior to gold evaporation, the surfaces were etched in a 5% bromine-methanol solution, rinsed in methanol, and then blown dry using nitrogen gas. The surfaces not covered by electrodes were either left untreated or etched again with bromine-methanol solutions while the electrodes were protected with an etch-resistant wax.

Initial measurements were made using a planar detector structure with full area electrodes on opposing sides of the crystal. The amplifier was connected directly to one electrode, while a bias voltage was applied to the other, as shown in Fig. 3a. Figure 4 shows the noise measurement taken from crystal #1 (labeled "Full area"). The device was first operated at V_b=0 V and then at V_b=1000 V. The leakage current was measured by monitoring the change in the output DC voltage of the preamplifier. The measured current for this device at 1000V was 25 nA. The noise measurements show that the parallel white noise increased with the application of bias voltage as expected. However, the magnitude of the noise is much lower than that expected if one assumes that the leakage current of 25 nA generates full shot noise.

The measured leakage current of the full-area planar device consisted of surface leakage current and bulk leakage current. To separate these two current contributions, a guard ring electrode structure was formed on this device by etching a gap in one of the full-area contacts. This resulted in a center contact with an active area of ~0.75 cm^2 surrounded by a thin guard-ring electrode. Noise measurements were then made with the center electrode connected to the preamplifier (Fig. 3b). The guard ring was maintained at the same DC potential as that of the preamplifier input (-0.23 V) so that no surface current flowed between the center electrode and the


(a) Full area

(b) Guard ring

Fig. 3. Device configurations used in the noise measurements: (a) full area planar and (b) with a guard ring structure on one side. V_{gr} was kept at the same potential as the preamplifier input during the noise measurements.

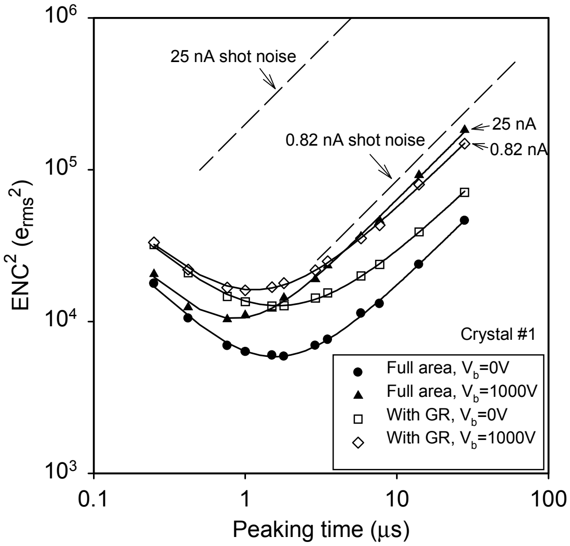


Fig. 4. Measured ENC^2 versus peaking time for crystal #1 in full-area planar and guard ring (GR) configurations at V_b=0V and 1000V. The dashed lines are the calculated full shot noise from the respective currents, including the contribution from the thermal noise of the feedback resistor.

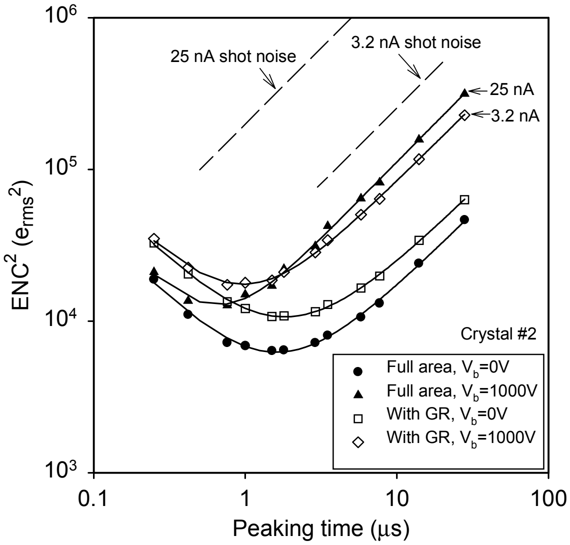


Fig. 5. Measured ENC^2 versus peaking time for crystal #2 in full-area planar and guard ring (GR) configurations at V_b=0V and 1000V. The dashed lines are the calculated full shot noise from the respective currents, including the contribution from the thermal noise of the feedback resistor.

guard ring, and it was AC bypassed to the signal ground. Noise measurements were made at V_b=0 V and V_b=1000 V, and the results are included in Fig. 4. The leakage current at the center electrode, which must be the current flowing through the bulk of the device, was 0.82 nA at V_b=1000 V. Despite the elimination of the relatively large surface current, the parallel noise component was only slightly below that of the full-area device. This decrease in parallel noise can be attributed to the smaller bulk current at the center electrode compared to that of the full area device. It is therefore reasonable to conclude that the observed parallel noise was due entirely to the bulk current. The surface current, although much larger than the bulk current, apparently did not contribute any significant noise. The suppression of shot noise in surface leakage current has also been reported in earlier publications [6][7].

The apparent absence of noise from surface leakage current can be explained if the surface conduction is resistive in nature and therefore does not generate shot noise, leaving only a thermal noise contribution. Assuming the bulk current scales with the active area, the bulk current in the full-area device would amount to 1.1 nA, leaving a surface current of 23.9 nA at V_b=1000 V. This gives an equivalent resistance of 42 Gohm. The thermal noise of this resistance is equivalent to the shot noise from a current of only 1.2 pA, which gives a negligible contribution to the total noise of the device.

A similar set of measurements was carried out for crystal #2, and the results are shown in Fig. 5. Again, the surface current of this device did not appear to generate significant shot noise. The bulk current was higher than crystal #1, resulting in a higher parallel noise component. The results obtained from these two crystals are quite consistent, and they imply that reducing the surface leakage current of a CdZnTe detector may not necessarily provide any significant improvement in detector performance.

Another interesting observation is that even the bulk currents of these devices do not appear to generate full shot noise. The measured parallel noise component is only about 70% of full shot noise calculated for the bulk current for crystal #1, and only about 50% for crystal #2. Shot noise is generated as a result of the random injection of charged carriers in a junction or vacuum device. One expects full shot noise to be generated if the injection of individual carriers is totally uncorrelated and each carrier moves between the electrodes unimpeded. There are at least two possible explanations for the observed suppression of shot noise: Coulomb interaction between carriers and carrier trapping [10]. Coulomb interaction among carriers introduces a certain degree of correlation between carrier injection events, thus reducing the randomness of carrier injection and the resulting shot noise. A higher degree of shot noise suppression is then expected if the carrier concentration within the device is higher. In the situation where there are trapping centers in the device, an injected carrier can be trapped before reaching the other electrode. A trapped carrier will contribute less than the full charge pulse to the external circuit. Therefore, for a fixed current, there are more carrier injection and possibly detrapping events compared to the case where there is no trapping. This reduces the statistical fluctuations and as a result the shot noise. Qualitatively, it can therefore be expected that devices exhibiting a higher carrier concentration or lower carrier lifetime will show a higher degree of shot noise suppression. For the present devices, the carrier density N can be calculated using $N = 1/\mu e \rho$ where μ is the carrier mobility, e the electronic charge, and ρ the material resistivity obtained from bulk I/V measurements. Ignoring the hole contribution and using the measured electron mobility of 8.9×10^2 cm^2/Vs and 7.7×10^2 cm2/Vs, N was found to be 7.8×10^3/cm^3 and 3.2×10^4/cm^3 for crystal #1 and #2, respectively. The electron lifetime was measured to be 9.6 μs for crystal #1 and 3.7 μs for crystal #2. Crystal #2 exhibited both higher carrier concentration and lower carrier lifetime compared to crystal #1. While this is consistent with the above explanation of shot noise suppression, additional studies are needed to determine if this can quantitatively explain the observed effects and whether other mechanisms are responsible.

B. 1/f Noise at Preamplifier Output

Many types of CdZnTe detectors utilize closely spaced coplanar electrodes either for position sensing or for preferential electron sensing. To investigate the noise behavior of such configurations, strip electrodes with different gap widths as shown in Fig. 6 were fabricated on the two crystals. By connecting different pairs of electrodes to the preamplifier input and an adjustable DC voltage source (AC signal ground), the effects of gap widths on noise can be observed. In the following, a V_s of “0V” refers to an applied DC voltage that equals the input voltage of the preamplifier thereby eliminating any current flow between strips. The back full-area contact was left unconnected (floating).

Figure 7 shows the measured noise between strips 1 and 2 as a function of peaking time. At V_s=0 V, a significant 1/f noise component of ~80 e rms can be seen at the preamplifier output, as shown by the dashed line obtained by fitting to the data. Increasing the bias voltage caused the leakage current between the strips to increase thus raising the parallel white noise component. In this case, the surface current and bulk current cannot be separately measured. Nevertheless, it is reasonable to assume that the leakage current is dominated by surface conduction while the parallel white noise is mainly due to the bulk current as observed in the planar devices. In any case, the 1/f noise component appears to be unaffected by the increase in bias voltage and leakage current. Adding a capacitor (2 pF) at the input increased the series noise component as expected, but again the 1/f noise remained constant. This indicates that the observed 1/f noise at the preamplifier output originates as a f-type noise source in parallel to the amplifier input, i.e., between the two strips. This preamplifier-output referred 1/f noise must be distinguished from the 1/f noise discussed in some of the publications, which refers to the current noise generated at the device [6][7]. If integrated on a charge sensitive amplifier, such 1/f current noise source would produce a $1/f^3$ type noise at the output. This was not observed in our results, possibly because our measurements did not extend to a sufficiently long peaking time.

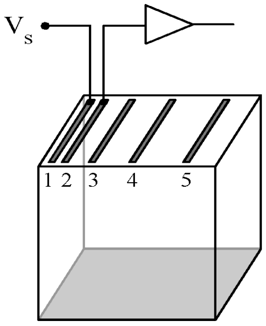


Fig. 6. Strip electrode configuration used in the noise measurements. The strips are each 9 mm long and 0.25 mm wide. The gaps between adjacent strips are 0.25 mm, 0.75 mm, 1.25 mm and 1.75 mm, respectively.

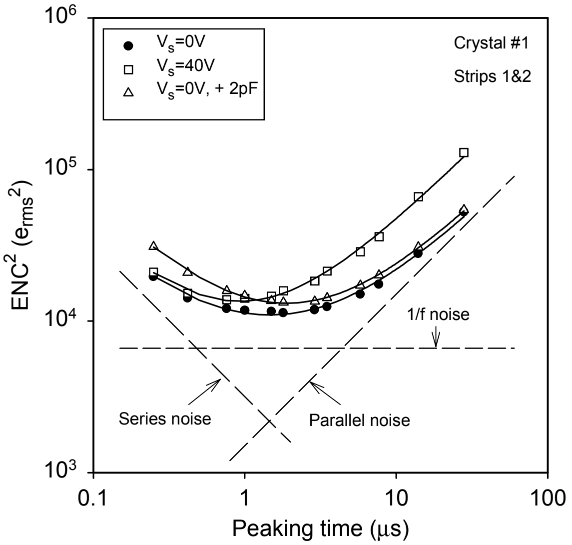


Fig. 7. Measured ENC^2 versus peaking time for crystal #1 with strips 1 and 2 connected. The dashed lines are the noise components obtained by fitting to the data for the case of V_s=0V with no capacitance added.

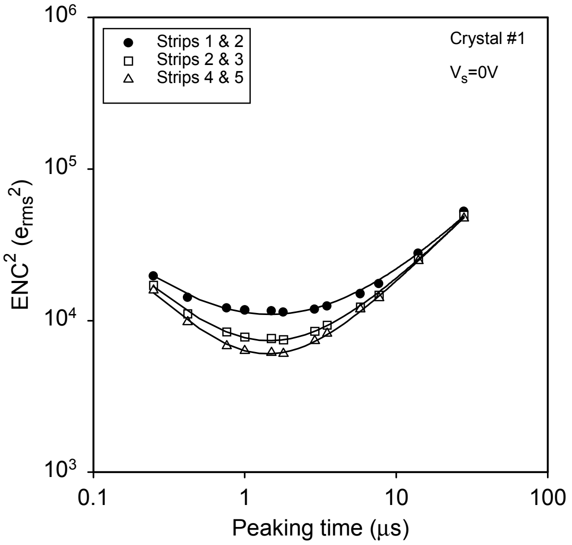


Fig. 8. Measured ENC^2 versus peaking time for crystal #1 with different pairs of strips and V_s=0V.

Figure 8 shows the measured noise between different pairs of strip electrodes with different gap widths. The 1/f noise component is seen to decrease with increasing gap width, from ~80 e rms for strips 1 and 2 to ~35 e rms for strips 4 and 5. This behavior is very similar to 1/f noise arising from lossy dielectric materials. However, in the present situation, the 1/f noise originated from the surface and not the bulk of the device. This can be concluded based on the following observations. First of all, the full-area planar device has a higher capacitance (1 pF) than the strip electrode device

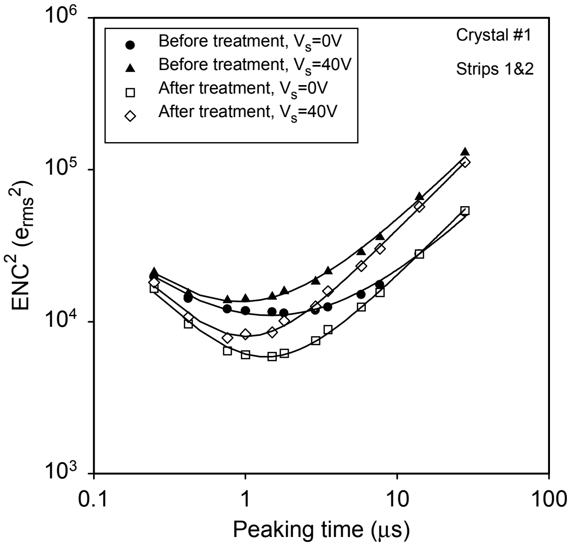


Fig. 9. Measured ENC^2 versus peaking time for crystal #1 with strips 1 and 2 connected before and after surface treatment.

(0.5 pF), yet the planar device showed a much lower 1/f noise level (Fig. 4) than the strip electrode device. The 1/f noise level was also observed to differ significantly in the strip device after different processing runs. Further evidence that the 1/f originates from the surface can be seen in Fig. 9, which shows the effects of chemical surface treatment. The magnitude of the 1/f noise was observed to diminish substantially (from ~80 e rms to ~25 e rms or less) after the surface treatment, which consisted of a brief (5 seconds) etch in 1% bromine-methanol solution followed by a soak in H_2O_2 for 1 minute. The electrodes on the device were also exposed to the chemicals during this treatment, but no visible changes of the electrodes could be seen and we do not expect the treatment to affect the electrical properties of the electrodes.

IV. CONCLUSIONS

Noise measurements made on CdZnTe devices with full-area planar geometry and with a guard-ring electrode structure showed that surface leakage currents do not generate any significant shot noise. The observed parallel noise component can be attributed entirely to bulk leakage currents. While it is certainly possible that excess noise be generated from the surface when using different surface treatments, it appears that surface leakage current per se is not the important parameter determining noise in CdZnTe detectors. This means that reducing the surface leakage current of a detector may not necessarily result in any improvement in detector noise. To effect a reduction in the parallel white noise, the bulk current needs to be reduced, and this requires increasing the bulk resistivity of the material. It was also observed that the bulk current does not generate full shot noise. The presence of Coulomb interactions between carriers and carrier trapping in the CdZnTe devices are two possible mechanisms that can lead to the observed partial suppression of shot noise. However, further studies are needed to determine which of these mechanisms or whether a different mechanism is responsible for the observed effect. 1/f noise was observed in devices with strip electrodes of different gap widths. The level of 1/f noise was found to increase as the gap between electrodes was reduced. The 1/f noise was not affected by the application of bias voltage or leakage current, but it could be greatly reduced through surface treatments.

V. ACKNOWLEDGMENTS

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