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Low-Noise Electronics for High-Resolution CdZnTe and CdTe X-Ray Detection Systems

A. Niemelä⁽¹⁾

Metorex International Oy, Riihitontuntie 7 C, P.O. Box 85, 02201 Espoo, Finland

Abstract

CdZnTe and CdTe detector performance can be significantly improved with low-noise electronics. The main sources of noise that broaden the spectrum peaks in a room-temperature system are incomplete charge collection and leakage current of the detector, and the feedback resistor of the preamplifier. The detector leakage current can be reduced by cooling the detector to about -30°C. Normally, at these temperatures the leakage current of a small detector crystal drops to the picoampere level which enables the use of low-noise, pulsed-optical feedback preamplifiers instead of noisier resistive feedback preamplifiers. Also, because of lower leakage currents, it is possible to use higher bias voltages at low temperatures which is important for more efficient charge collection. This reduces spectrum background and peak tailing. Applying rise time discrimination circuitry to the linear amplifier reduces the tailing effect even further, especially at higher energies. By employing all these methods a number of Cd_{0.9}Zn_{0.1}Te, Cd_{0.8}Zn_{0.2}Te and PIN-structure CdTe detector crystals were tested at temperatures between -20°C and -40°C, and at best FWHM energy resolutions of 240 eV at the 5.9-keV line of ⁵⁵Fe, 600 eV at the 59.5-keV line of ²⁴¹Am, and 4.4 keV (0.7 %) at the 662-keV line of ¹³⁷Cs were obtained. These energy resolutions measured at room temperature with conventional methods are typically about 4 to 10 times poorer.

1. INTRODUCTION

The total energy resolution (FWHM) of an X-ray or gamma-ray detection system at a known radiation energy can be divided in three major contributors, which sum quadratically:

$$\text{FWHM}^2 = \text{FWHM}_E^2 + \text{FWHM}_X^2 + \text{FWHM}_D^2 \quad (1)$$

where FWHM_E is the electronics noise contribution measured as the pulser resolution; FWHM_X is the detector noise contribution, or the "tailing factor", due to incomplete charge collection and other non-ideal effects in the detector crystal; and FWHM_D is the detector crystal statistical noise contribution, given by:

$$\text{FWHM}_D^2 = 2.35^2 F \varepsilon E \quad (2)$$

where F is the Fano factor, ε the average energy required to produce an electron-hole pair in the detector material, in eV, and E the radiation energy in eV. The Fano factor is usually 0.10 to 0.12 for good quality silicon and germanium detectors but slightly higher for currently available compound semiconductor detectors.

⁽¹⁾ Present address: Massachusetts Institute of Technology, Room 26-552, 77 Mass. Ave., Cambridge, MA 02139, U.S.A.

When one wants to improve the energy resolution FWHM of an X-ray detection system, one must concentrate on minimizing the electronic noise contribution FWHM_E because there are no means to reduce the statistical noise contribution FWHM_D and methods to affect FWHM_X are limited. The various contributors of the electronics noise FWHM_E are discussed in detail in the next chapter.

II. ELECTRONIC NOISE

The noise due to electronics, i.e. the preamplifier front end and the shaping amplifier, is conveniently calculated with equivalent noise charge (ENC, in rms electrons) which can be divided into three separate contributors:

$$\text{ENC}^2 = \text{ENC}_{\text{SER}}^2 + \text{ENC}_{1/f}^2 + \text{ENC}_{\text{PAR}}^2 \quad (3)$$

where ENC_{SER} is the "series noise" contributor including noise sources due to the input FET white voltage noise e_n and the detector and FET capacitances [1]:

$$\text{ENC}_{\text{SER}}^2 = 2kT a_1 \Gamma C_D (m^{1/2} + m^{-1/2})^2 / (\tau_M \omega_0) \quad (4)$$

where k is Boltzmann's constant ($1.38 \cdot 10^{-23}$ J/K); T is absolute temperature in K; a_1 is a noise parameter of the shaping amplifier; Γ is related to the voltage noise of the FET by: $e_n^2 = 4kT/g_m$ with a theoretical and typical value of $\Gamma = 0.67$ (however, for short-channel FET's the value can be higher than unity); $m = C_D/C_g$ is the mismatch coefficient for the FET gate capacitance C_g and the detector capacitance C_D which is assumed to contain all stray capacitances including the feedback capacitor C_f ; τ_M is the measurement time, or peaking time of the shaping amplifier (directly proportional to the Gaussian shaping time constant τ by: $\tau_M = 2.2\tau$); and $\omega_0 = g_m/C_g$ is the cut-off, or transition frequency of the FET.

The second term in Eq. (3) ENC_{1/f} describes the noise due to the FET 1/f noise:

$$\text{ENC}_{1/f}^2 = a_2 H_f (m^{1/2} + m^{-1/2})^2 C_D \quad (5)$$

where a_2 is another noise parameter of the shaping amplifier, and $H_f = A_f C_g$; with A_f related to the 1/f-noise spectral density $S(f) = A_f/f^\alpha$ and α being close to unity. A_f is strongly dependent of the operating temperature of the FET [2].

The third term ENC_{PAR} is the "parallel noise" component due to shot noise in the reverse leakage currents of the FET (I_G) and the detector (I_L), and to the thermal noise of the feedback resistor R_f if one is used in the preamplifier:

$$\text{ENC}_{\text{PAR}}^2 = a_3 \tau_M [q(I_G + I_L) + 2kT/R_f] \quad (6)$$

where q is the charge of an electron ($1.60 \cdot 10^{-19}$ C). To minimize the effect of the feedback resistor R_f its value must be maximized. However, large value resistors (in the order of GΩ's) act as sources of noise far larger than would be expected theoretically in Eq. (6). This is due to the fact that there is some capacitive and sometimes inductive parasitics in large value resistors, and the absolute value of the resistance is often strongly dependent of frequency, voltage and temperature.

The noise parameters (a_1 , a_2 and a_3) of the shaping amplifier vary according to the shaping function used. For instance [1], values of $a_1 = 8/3$, $a_2 = 3.6$, $a_3 = 0.77$ can be used for the most commonly used and wide-spread type of nuclear spectroscopy linear shaping amplifier, the Gaussian one.

The effect of the mismatch coefficient $m = C_D/C_g$ is at its minimum when the FET gate capacitance equals the detector capacitance. Therefore, the input FET should be chosen so that it is firstly as low-noise as possible, and secondly matches the detector capacitance as closely as possible. Selected devices like Motorola 2N4416 ($C_g = 3.5$ pF, $g_m = 7$ mA/V, $e_n = 1.3$ nV/ $\sqrt{\text{Hz}}$), InterFET NJ14 ($C_g = 2.5$ pF, $g_m = 6$ mA/V, $e_n = 1.5$ nV/ $\sqrt{\text{Hz}}$) and Moxtek MX10 ($C_g = 0.8$ pF, $g_m = 7$ mA/V, $e_n = 1.3$ nV/ $\sqrt{\text{Hz}}$) have been found to be suitable for operation with low-capacitance detectors at room temperature, and at lower temperatures.

There are other sources of noise present in an X-ray detection system than the ones described above, for example, "microphonics" due to mechanical vibration of the FET gate lead or components operated at high-voltage, $1/f^2$ noise and gate-coupled thermal noise of the FET, and dielectric noise due to, for instance, dielectric losses in the materials that are physically in connection with the detector or the FET gate. Care must be taken when mounting the detector crystal and the FET on a substrate or package. High-purity Teflon, sapphire, boron nitride and alumina have been found to be good mounting materials for the front end. For instance, if optimally high resolution is required, the FET should be removed from its original can or package and mounted on low-loss, low-leakage material. The dark glass-like material found underneath a metallic FET can is a relatively high source of excess noise. Similarly, the feedback capacitor C_f should be made of good, low-loss dielectric. Also, care must be taken not to add any unwanted parasitic stray capacitance in parallel with the detector-FET node when designing the front end. If these precautions are taken into account, the noise sources mentioned above are not important in a real-life system and are not considered mathematically here. However, a more detailed discussion of some of these additional sources of noise can be found in Ref. [1] or [2].

The ENC formula (3) gives the electronic noise of the system in "rms electrons". However, usually it is clearer and more convenient to give the electronic noise in eV with the help of FWHM_E , which is called the "pulser resolution" of the system:

$$\text{FWHM}_E = 2.35 \text{ ENC } \varepsilon/q \quad (7)$$

where ε is the average energy required to create an electron-hole pair in the detector material and q is the charge of an electron. For example, for $\text{Cd}_{0.8}\text{Zn}_{0.2}\text{Te}$ ε is assumed to be 5.0 eV, for CdTe the value is 4.43 eV, and for silicon 3.61 eV at room temperature.

As a mathematical example we can calculate the electronic noise, or pulser resolution FWHM_E of a good-quality, low-leakage current CdZnTe X-ray detection system at various shaping time constants. Let us assume that the detector size is $2 \times 2 \times 2 \text{ mm}^3$ ($C_D = 0.4$ pF, $I_L = 500$ pA) and it is used at room temperature with a resistive feedback preamplifier employing a 2N4416-type FET ($C_g = 3.5$ pF, $g_m = 7$ mA/V, $\omega_o = g_m/C_g = 2 \cdot 10^9$ rad/s, $I_G = 0.2$ pA, $A_f = 10^{15} \text{ V}^2$, $H_f = A_f C_g = 3.5 \cdot 10^{27} \text{ V}^2\text{F}$) and a feedback resistor $R_f = 10$ G Ω . The calculated FWHM_E with its contributors are displayed graphically in Fig. 1, where the minimum electronic noise of 700 eV is achieved at 0.25- μs shaping time constant. As can be seen, the parallel noise contributor FWHM_{PAR} totally dominates the noise behavior of the system. Let us consider another case where the same system as above is used with a pulsed optical feedback preamplifier with the FET and detector cooled to -30°C ($T = 243$ K). The numerical values for this case are the same, except for: $I_L = 2$ pA, $I_G = 0.02$ pA and $R_f = \infty$, all present in the same contributor ENC_{PAR} . The calculated values are presented in Fig. 2. Now the minimum electronic noise is only 166 eV and it is obtained with 5- μs shaping time constant due to the drastically reduced effect of the parallel noise contribution FWHM_{PAR} .

To demonstrate the effect of reduced temperature in real life, the pulser resolution FWHM_E of a $2 \times 2 \times 2 \text{ mm}^3$ $\text{Cd}_{0.8}\text{Zn}_{0.2}\text{Te}$ detector crystal was measured at -20 , -30 and -40°C with an optical FB preamplifier and a semi-gaussian linear amplifier operated at various shaping time constants. The results are presented in Fig. 3. Note that the parallel noise contribution FWHM_{PAR} is reduced a great deal as we go down in temperature, but only a slight reduction is seen in the series noise FWHM_{SER} at shorter shaping

time constants. The reduction in FWHM_{SER} is due to the presence of temperature T in Eq. (4), and to the fact that the transconductance g_m of a typical JFET is increased by some 10 to 20 % as the temperature is reduced from room temperature to -30°C .

III. SPECTROMETRIC RESULTS

Fig. 4 shows an ^{55}Fe and pulser spectrum obtained with a $2\times 2\times 2\text{ mm}^3$ $\text{Cd}_{0.8}\text{Zn}_{0.2}\text{Te}$ detector crystal and a pulsed optical FB preamplifier operated at -40°C . The bias voltage was -1000 volts, and the shaping time constant was $6\text{ }\mu\text{s}$ [3]. The FWHM of the 5.9-keV line is 240 eV, and the FWHM_E of the pulser peak is 187 eV. For comparison, the ^{55}Fe FWHM measured at room temperature is typically above 1 keV.

To test the accuracy of the noise formulas presented in the previous chapter, Fig. 5 shows measured and calculated energy resolutions at ^{55}Fe for the CdZnTe X-ray detection system that was used as a numerical example. The measured values are a bit higher than the simulated ones due mainly, we believe, to underestimation of the tailing factor FWHM_X . The measured and simulated values agree better at -40°C than at -20°C where the tailing factor contribution is larger due to the lower bias voltage used in the measurement. A Fano factor of 0.14 was used in the calculations [3].

The tailing factor FWHM_X is a strong function of the bias voltage across the detector [4]. The bias voltage must be raised as high as possible to create a strong enough electric field inside the detector. This minimizes the trapping of the holes as they are swept to the negative electrode. Nevertheless, as seen in Fig. 4, for instance, there is still some tailing visible at the foot of the 5.9-keV peak, although the high bias voltage of 1000 volts produces a very strong electric field of 5 kV/cm.

Another advantage of cooling, besides lowering electronic noise, is that the detector leakage current is smaller so that much higher bias voltage can be used while maintaining the detector leakage current at an acceptable noise level. The effect of higher bias voltage can be seen clearly in Fig. 6 obtained with a 16-mm^2 , 3-mm thick $\text{Cd}_{0.9}\text{Zn}_{0.1}\text{Te}$ crystal operated at -28°C and 2- μs shaping. The tailing factor is reduced from 135 eV to 38 eV as the bias is increased from 200 to 600 volts. The peak to background ratio is also improved at higher bias voltages. Note also that the pulser resolution becomes worse as the bias is increased because of linearly increased leakage current. For this reason, there is always an optimum value for the bias voltage to obtain the best energy resolution. In Fig. (6) the optimum bias voltage is 400 volts, yielding a FWHM of 320 eV at 5.9 keV.

The tailing effect becomes more severe at higher radiation energies because of the fact that when a high-energy X- or gamma-ray photon enters the detector crystal, the ionization can take place deeper in the detector volume, and the holes have to travel a long distance and are more likely to become trapped. One way to reduce this tailing effect is to use rise-time discrimination circuitry in the shaping amplifier when higher energies are to be measured. Namely, the photon events that are affected by long time constant hole-trapping mechanisms are the ones that only give raise to the spectrum background and peak tailing. Also, some kind of collimation in front of the detector crystal should be employed to reduce the edge effects which also contribute to the tailing and background.

Fig. 7 shows three ^{241}Am spectra taken with a 16-mm^2 , 3-mm thick $\text{Cd}_{0.9}\text{Zn}_{0.1}\text{Te}$ detector crystal at different conditions: (a) shows a spectrum taken at room temperature using a resistive feedback preamplifier, +300 V bias and 0.5 μs shaping time constant (the optical feedback preamplifier could not be used at room temperature due to excess detector leakage current); (b) shows a spectrum taken at -30°C using an optical feedback preamplifier, -600 V bias and 2 μs shaping time; and (c) shows a spectrum taken as in (b) but with a rise-time discriminator [5]. In all cases the bias voltage and the linear amplifier shaping time constant were chosen for optimum energy resolution. There is a drastic improvement in energy resolution and tailing effect as we go from (a) FWHM 2500 eV to (b) 900 eV

to (c) 600 eV. However, the photopeak counting efficiency dropped to about 50% from (b) to (c) because of the counts rejected by the rise-time discriminator. Note that rise-time discriminator can also correct some more serious charge collection problems, like a localized trap center producing doublet peaks in the energy spectrum [5].

The rise-time discrimination circuitry that was used in the measurements was built around a commercially available gated integrator, in which the voltage pulses with fast rise times reach the flat-top level in a shorter time than pulses that have experienced charge trapping. The pulses with slow rise times are thus gated out of the amplifier output by the control logic. However, the system can also be operated in a correction mode where the slow rise-time pulses are analyzed and placed to the correct channel in the energy spectrum by correction logic circuitry. The operation of the rise-time discriminator is discussed in more detail in Ref. [6].

To demonstrate the high-energy gamma-ray detection performance of the system a ^{137}Cs spectrum was measured with the rise-time discriminator turned off, Fig. 8 (a); and on, Fig. 8 (b). The FWHM of the 662-keV peak was improved from 35 keV to 4.4 keV by the rise-time discriminator. The detector was a 16-mm², 3-mm thick $\text{Cd}_{0.9}\text{Zn}_{0.1}\text{Te}$ detector operated at -30°C, -800 V of bias, and 1-μs shaping time constant.

Fig. 9 shows two ^{241}Am spectra taken at -28°C with a 16-mm², 0.5-mm intrinsic layer thickness PIN-structure CdTe detector. The spectrum in Fig. 9 (a) was taken without the rise-time discriminator and Fig. 9 (b) with it. In both measurements the detector bias voltage was -140 volts and the linear amplifier was operated at 2-μs shaping time constant. The ^{241}Am 59.5-keV line FWHM improved from 1.1 keV to 700 eV, and once again, there is a clearly visible improvement in the peak tail.

IV. CONCLUSIONS

The performance of CdZnTe and CdTe detectors can be significantly improved by low-noise electronics and by cooling the detector and first stage of the preamplifier to a temperature around -30°C which is easily achieved, for example, with commercially available miniature Peltier coolers.

Currently available CdZnTe and CdTe material suffers from charge trapping/detrapping mechanisms and low hole mobility-lifetime product. Because of this, there is a lot of rise time variations at the preamplifier output, and the slow rise-time pulses are seen lower than correct amplitude at the A/D converter input. This increases background and peak tailing in the energy spectrum significantly. However, this effect can be corrected to some extent by applying a rise-time discriminator in the system, although a reduction in the counting efficiency is seen.

V. ACKNOWLEDGEMENTS

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Fig. 1. Calculated pulser resolution FWHM_E and its contributors for the room-temperature CdZnTe system used as an example. The minimum noise is 700 eV.

Fig. 2. Calculated pulser resolution FWHM_E and its contributors for the CdZnTe system operated at -30°C. The minimum noise is 166 eV.

Fig. 3. Measured pulser resolutions FWHM_E of a $2 \times 2 \times 2 \text{ mm}^3$ $\text{Cd}_{0.8}\text{Zn}_{0.2}\text{Te}$ detector crystal at -20°C , -30°C and -40°C .

Fig. 4. Measured ^{55}Fe and pulser spectrum taken at -40°C with a $2 \times 2 \times 2 \text{ mm}^3$ $\text{Cd}_{0.8}\text{Zn}_{0.2}\text{Te}$ detector crystal [3].

Fig. 5. Measured and calculated ^{55}Fe FWHM at -20°C and -40°C taken with a $2\times 2\times 2\text{ mm}^3$ $\text{Cd}_{0.8}\text{Zn}_{0.2}\text{Te}$ detector crystal. At -20°C , -600 volts of bias was used, and at -40°C it was -1000 volts.

Fig. 6. Measured values of ^{55}Fe FWHM, Pulser FWHM_E, Detector Contribution $\sqrt{(\text{FWHM}^2 - \text{FWHM}_E^2)}$, and "tailing factor" FWHM_X vs. bias voltage, [4].

Fig. 7. Three ^{241}Am spectra obtained with a 16-mm^2 , 3-mm thick $\text{Cd}_{0.9}\text{Zn}_{0.1}\text{Te}$ detector at (a) room temperature; (b) at -30°C ; and (c) at -30°C with rise-time discrimination [5].

Cs-137 at -30 C without RTD **Cs-137 at -30 C with RTD**

Fig. 8. Two ^{137}Cs spectra obtained with a 16-mm^2 , 3-mm thick $\text{Cd}_{0.9}\text{Zn}_{0.1}\text{Te}$ detector crystal at -30°C (a) without; and (b) with rise-time discrimination.

Fig. 9. Two ^{241}Am spectra obtained with a 16-mm^2 , 0.5-mm intrinsic layer thickness PIN-structure CdTe detector at -28°C , (a) without; and (b) with rise-time discrimination.