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Resolution degradation of semiconductor detectors due to carrier trapping

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Abstract

Incomplete charge collection in semiconductor X-ray detectors due to carrier trapping is recognized as an important source of signal broadening. In this paper we show the results of calculations of energy resolution for a TlBr detector using an analytic approach developed in our earlier work in which fluctuations in the distribution of photon absorption sites are related to fluctuations in the collected charge. Using measured values of transport parameters for electrons and holes in the detector material we obtained excellent agreement with experiment in the X-ray energy range 6–660 keV.

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Keywords: Semiconductor X-ray detector; Carrier dynamics; Energy resolution

An ideal spectroscopic detector has a theoretical resolution (Fano-limit), which is determined by statistical fluctuations in the number of generated electron–hole pairs after photon absorption. In real semiconductors however, there are several mechanisms leading to incomplete charge collection and resulting in resolution degradation, the major ones of which are carrier diffusion [1] and carrier trapping [2,3]. Trapping is a particularly serious problem affecting resolution for almost all compound semiconductors. Until recently the usual approach to modelling the detector resolution ΔE was by assuming an empirical relation for the variance of the contribution due to carrier trapping (trapping noise) of the form [3,4]

$$\Delta E = 2.355\sqrt{F\varepsilon E + (\Delta E_{\mathrm{el}}/2.355)^2 + a_1 E^{a_2}}, \qquad (1)$$

where E, ε and F are photon energy, energy required to produce one electron–hole pair and

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Fano factor respectively, ΔE_{el} is the electronic noise, and a_1 and a_2 are arbitrary fitting parameters describing the contribution due to trapping noise.

In our recent work [4] we have shown that the variance due to trapping noise can be written in an exact form $G(E)E^2$, so that

$$\Delta E = 2.355\sqrt{F\varepsilon E + (\Delta E_{el}/2.355)^2 + G(E)E^2}. \tag{2}$$

The trap factor $G(E)$ in this expression depends in addition to photon energy, on detector thickness L, pixel size R, lateral coordinate of the absorption site beneath the pixel, and electron and hole mean drift paths l_e and l_h, respectively. However, $G(E)$ exhibits universal behaviour at low photon energy $L/L_0(E) \gg 1$ where $L_0(E)$ is the photon absorption length. For this energy range

$$G(E) = \left(\frac{L_0(E)}{l_e}\right)^2. \tag{3}$$

Expression (3) is written for the situation when electrons move towards a pixelated plane of a detector. The photon absorption length above 1 keV is usually a strong function of photon energy varying as $\sim E^{1.7}$ if K- and L-edge absorption discontinuities are disregarded. In the opposite limiting case $L \ll L_0(E)$ the trap factor does not depend on photon energy, but still depends on detector thickness, pixel and beam geometry, carrier transport parameters, bias voltage and temperature. A typical $G(E)$ dependence is shown in Fig. 1 for $l_e/L = 15, l_h/L = 0.7$ and the two different pixel sizes $R/L = 0.05$ and $R/L = 1$. The photon absorption coefficient was chosen here in a general form as a smooth function of energy in units of E_0 defined as the energy at which mean photon penetration depth coincides with the detector thickness L, hence $L_0(E) = L(E/E_0)^{1.7}$. This dependence accurately reproduces the variation of the absorption coefficient with photon energy in the range above 1keV. The only features lacking are the individual L- and K-absorption edges. From Fig. 1 we see that saturation of G occurs at an energy below E_0, reflecting the exponential profile of distribution of absorption sites, most of which fall closer to the illumination surface.

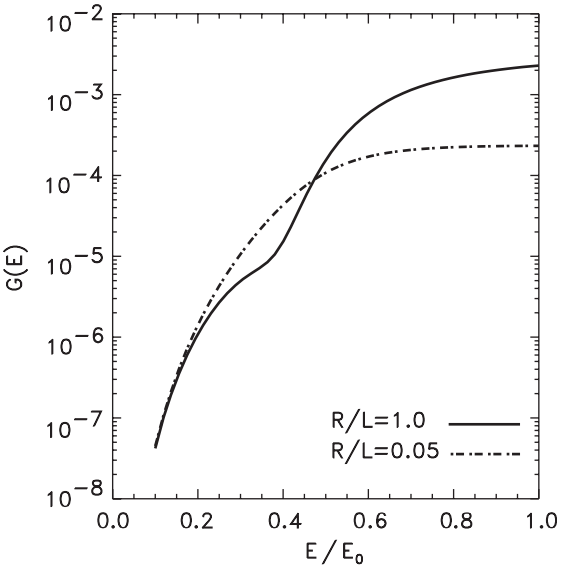

Fig. 1. Trapping factor dependence on pixel size.

The small pixel effect is clearly seen to result in a considerably smaller absolute value of trap factor $G(E)$ over broad range of energies. However, it is also seen that the small pixel effect is not a universal and immediate cure for poor hole transport. There exists a broad range of photon energies, in which the spectroscopic performance of a small pixel device turns out to be worse than that having larger pixels. Whilst above $\simeq 0.5E_0$ the $G(E)$ for small pixel is nearly two orders of magnitude smaller than $G(E)$ for the larger pixel, below $0.5E_0$ it becomes significantly larger than the latter. The whole behaviour depends on the interplay between statistical fluctuations of collected charge in the spectral range of interest, the extent of near field region and carrier transport parameters [4].

Now we will compare theoretical results with experimental data on TlBr. The details of detector design and all relevant experimental data can be found in [5]. The detector was 1 mm thick with a 3×3 pixel structure on the anode and planar electrode surface on the cathode. The pixel dimensions were $350 \times 350\,\mu m^2$. The initial characterisation was carried out using ^{55}Fe, ^{57}Co,

^{137}Cs, and ^{241}Am, radioactive sources. The bias voltage was maintained at $V_b = -400\,V$, the amplifier shaping time $\tau = 6\,\mu s$. X-ray measurements were also carried out at the X-1 beamline at the HASYLAB synchrotron radiation facility covering the energy range 12 to 100 keV.

The energy resolution function of pixel 2–2 under full area illumination together with the results of modelling are shown in Fig. 2.

Modelling was based on formula (2) with the following parameters: $\varepsilon = 6.5\,eV$, $F = 0.12$, $\Delta E_{el} = 1.7\,keV$, $\mu_e\tau_e = 5 \times 10^{-4}\,cm^2/V$, $\mu_h\tau_h = 3 \times 10^{-5}\,cm^2/V$. Whilst the product $\mu_e\tau_e$ was measured for this material independently, no such direct measurement was made for holes. Theoretical curves for energy resolution are very sensitive to the magnitude of $\mu_h\tau_h$ with even a slight variation resulting in a strong shift of the resolution curve at high energies. This sensitivity is illustrated in the Fig. 3, where we show the calculated trap factor dependence on photon energy for same detector configuration but for different values of l_h. As is seen the transition from the low to high photon energy limits for this detector occurs at $E_0 = 200\,keV$. Thus, as expected, in the photon energy range below 100 keV the results are relatively insensitive to the exact value of l_h. On the other hand above E_0 the situation reverses. Therefore laboratory experiments with ^{137}Cs radioactive source provide valuable data which allows the accurate evaluation of $\mu_h\tau_h$.

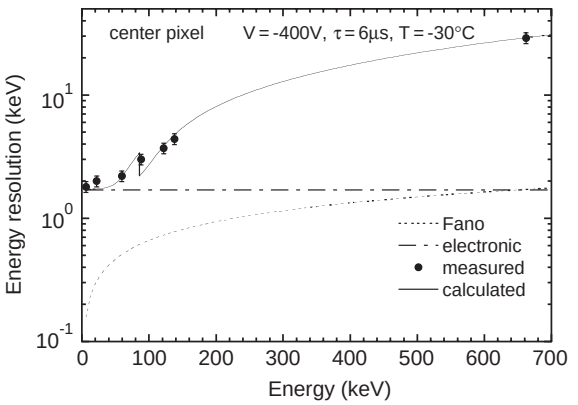

Fig. 2. The energy resolution of pixel 2-2 measured from soft X-ray to γ-ray energies.

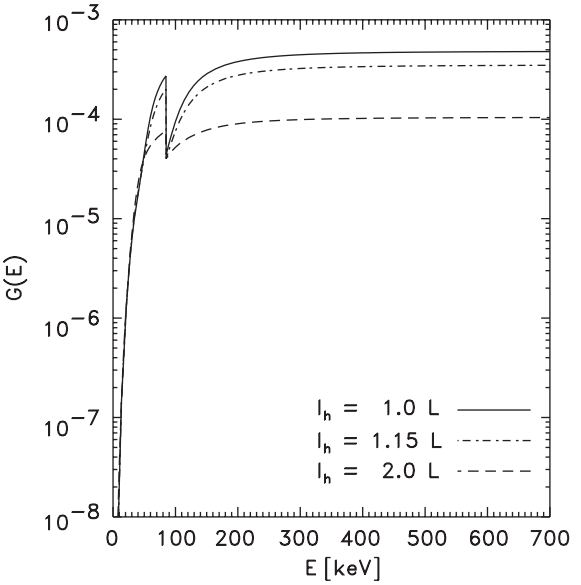

Fig. 3. Trapping factor dependence on hole drift path. $R/L = 0.175$.

Onodera et al. measured the energy resolution of their best TlBr detector to be 9.7 keV at 662 keV and $T = -20\,K$ [6]. Taking their detector configuration and their transport data for electrons and holes at room temperature $R = 570\,\mu m$, $L = 1.8\,mm$, $V_b = 1800\,V$, $\mu_e\tau_e = 1.7 \times 10^{-4}\,cm^2/V$ and $\mu_h\tau_h = 6.4 \times 10^{-5}\,cm^2/V$ we obtain $\Delta E = 34.3\,keV$. The most likely explanation of the discrepancy is that the actual values for the $\mu\tau$ parameters in their detector were different from the measured bulk values, perhaps due to lower temperature or inhomogeneity of the material. The resolution of 9.7 kev at 660 keV could have been obtained for the detector with the same $\mu_h\tau_h$ as reported, but with $\mu_e\tau_e$ of $5 \times 10^{-4}\,cm^2/V$, which falls well within the expected range for this material.

In summary, we have shown that the trapping noise results in the resolution degradation described by the $G(E)E^2$ signal variance. $G(E)$ has a universal low energy asymptotic with no dependence on pixel geometry. In the opposite limit of high photon energies G is a constant depending on both pixel geometry and carrier transport parameters. Theoretical modelling shows excellent agreement with experiment for TlBr detectors in the range 6–660 keV.

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