X-ray escape peak variations in diodes made from doubly travelling solvent grown p-type CdTe

H. Jäger, R. Thiel

X-RAY ESCAPE PEAK VARIATIONS IN DIODES MADE FROM DOUBLY TRAVELLING SOLVENT GROWN p-TYPE CdTe

H. JÄGER and R. THIEL

Battelle-Institut e. V., Am Römerhof 35, 6000 Frankfurt, R. F. A.

Résumé. — On a étudié la variation de l'intensité du pic d'échappement d'un compteur CdTe en fonction de la tension de polarisation appliquée. Les cristaux sont préparés par double croissance THM et dopés à l'indium à des concentrations de 2,1 $\times 10^{16}$ cm^{-3}, ils sont de type p et présentent une résistivité de 4 $\times 10^{6}$ Ω.cm. Lorsque la tension appliquée croît, l'intensité du pic d'échappement tend à saturer. Une étude théorique a permis de calculer la dépendance de la probabilité d'échappement des photons X en fonction de l'épaisseur de la zone de charge d'espace. Une méthode a été développée permettant d'accorder les résultats expérimentaux aux prévisions de notre modèle ; un accord satisfaisant a été obtenu en ce qui concerne l'épaisseur sensible et la densité de la zone de charge d'espace.

Abstract. — The dependence of the escape peak height on the applied diode voltage was measured at diodes made from doubly travelling solvent grown CdTe. The crystal was In-doped with a concentration of 2.1 $\times 10^{16}$ cm^{-3} and p-type with a resistivity of 4 $\times 10^{6}$ Ω.cm. The escape peak height saturates at higher voltages. The theoretical dependence of the X-ray escape probability on space charge layer depth was derived. A method for evaluating the experimental curve according to the thoeretical correlation was developped : it yields the actual space charge layer depth and the space charge density.

The X-ray escape peak is a well-known phenomenon in CdTe gamma detectors ; it is much more pronounced than, for instance, in silicon. The reason is the marked increase in the X-ray fluorescence coefficient ω with the atomic number Z of the absorbing element. For CdTe whose average Z is 50, ω_K amounts to about 0.85, for Si it is 0.04, for Ge and GaAs 0.54 (Fig. 1).

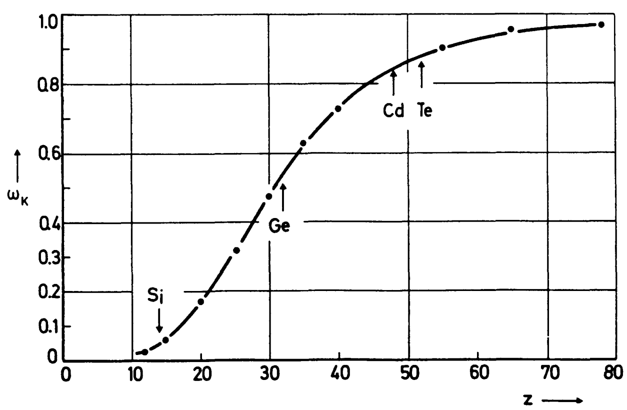
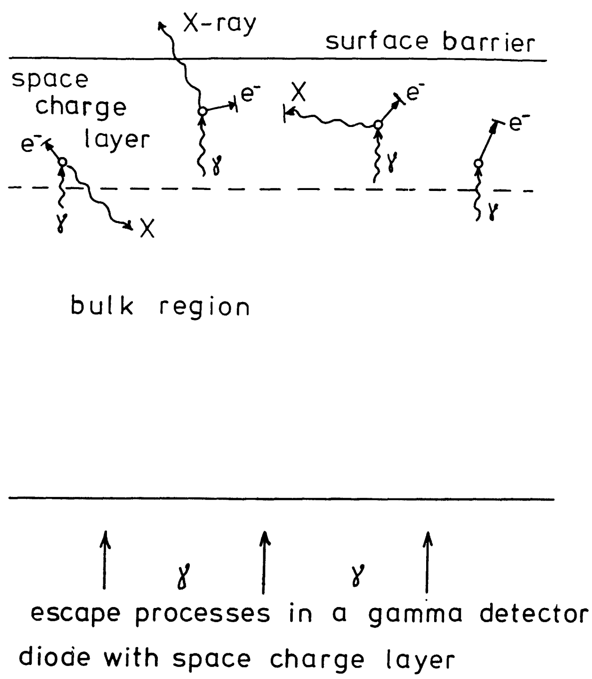


FIG. 1. — The K-shell X-ray fluorescence yield as a function of the atomic number Z (from Bambynek, [4]).

The process responsible for the occurrence of the escape peak in the gamma spectra of a CdTe detector is described (Fig. 2) in the following for a detector structure with a space charge layer : in each energy transfer from the gamma quantum to a K-shell electron, a K-X-ray quantum is formed simultaneous to the photoelectron. As shown in the diagram at the right-hand side of figure 2 the absorption length curves of photoelectrons and photons are rather different. The K-X-rays generated have larger absorption lengths than the electrons and hence will escape from the space charge layer to the outside or to the field-free bulk region with higher probability than the photoelectrons. The result is the well-known gamma spectrum with the full energy photopeak and when going to lower energies the escape peak at ($E_\gamma - E_K$) and finally the K-X-ray line. This X-ray peak is either due to X-ray fluorescence quanta coming from the bulk CdTe and absorbed in the space charge layer or due to events of electron escape from the space charge layer at simultaneous absorption of the X-ray quantum arising from the same γ-quantum. The relative peak heights in such spectra are changed when the space charge depth is modified by reverse voltage variations. Figure 3 shows two spectra taken at the lowest (5 V) and the highest voltage (200 V) with an In-doped doubly travelling solvent grown CdTe crystal.

This material was grown with zone temperature of about 800 °C at a speed of 4.3 mm/d. In was added to the Te-zone prior to the second growth in form of a Cd-0.5 ‰ In-alloy resulting in a 3.5 $\times 10^{17}$ cm^{-3} concentration of In in Te. According to Zanio [8], who gives a segregation coefficient for 880 °C growth

Article published online by EDP Sciences and available at http://dx.doi.org/10.1051/rphysap:01977001202029300



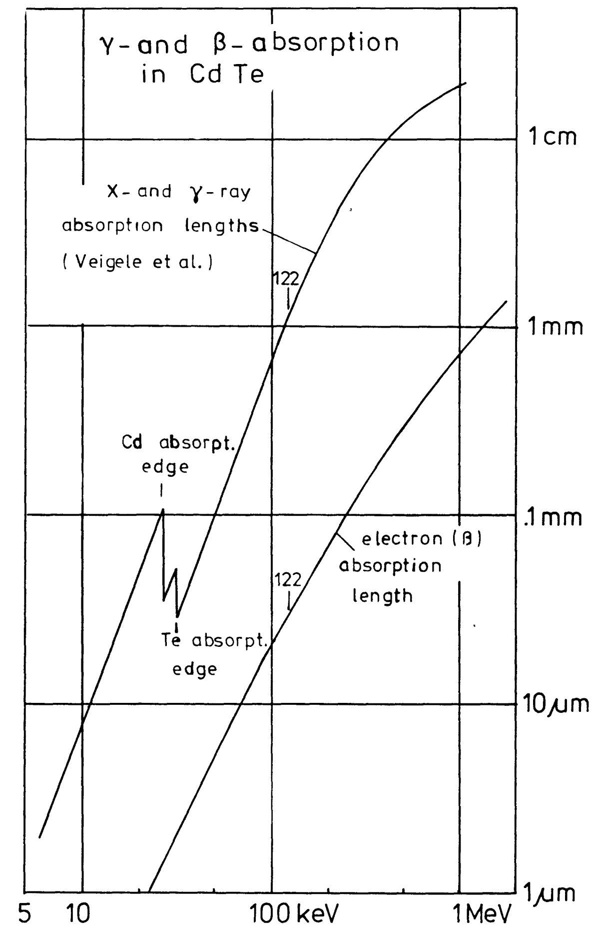


FIG. 2. — Left : principle of escape processes. Right : energy dependence of the absorption lengths of photons and photoelectrons in CdTe.

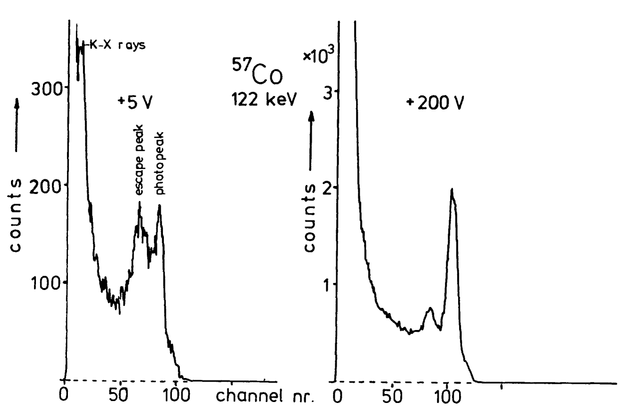


FIG. 3. — Experimental spectra of CdTe diodes at low and high voltages. Note the relative escape peak height.

of 0.06, we can estimate our CdTe to be In-doped to a concentration of 2.1×10^{16} cm^{-3}. The CdTe wafer, 14 mm in diameter and 1.22 mm thick, was contacted on one side with a whole area electroless silver contact, on the other side with a periodic field of 260 μ diameter gold dots evaporated through a metal mask. The ^{57}Co gamma radiation penetrates from the probably space-charge-layer-free silver contacted side. The spectra were taken with positive voltage applied to the gold dots ; they are reverse biassed by this and hence the space charge layer depth w increases with reverse voltage V_R. The wafer turned out to be inhomogeneous : only part of the diodes exhibited well resolved ^{57}Co spectra.

The escape peak intensity was not evaluated as product of width and height, because the width was poorly defined in these spectra. Hence, the height alone was taken as an index of peak intensity. This height was defined from the difference between counts in the channel and background counts in this channel. The background curve was graphically extrapolated from the regions beyond the escape peak, as schematically shown in the lower diagram of figure 4. This background seems to have been caused predominantly by the photoelectron escape continuum.

The escape peak heights are plotted against $V_R^{1/2}$ that is approximately proportional to the space charge layer depth w according to the well-known relations in abrupt semiconductor junctions. The photopeak height is shown in the same figure. This curve shows a superlinear increase while the escape peak height saturates as expected because of lack of additional escape events from deeper partial layers in the charge region.

For the evaluation of the escape peak height we need the theoretical relation between escape probability and space charge depth, which will be presented here without detailed derivation. The basic mathe-

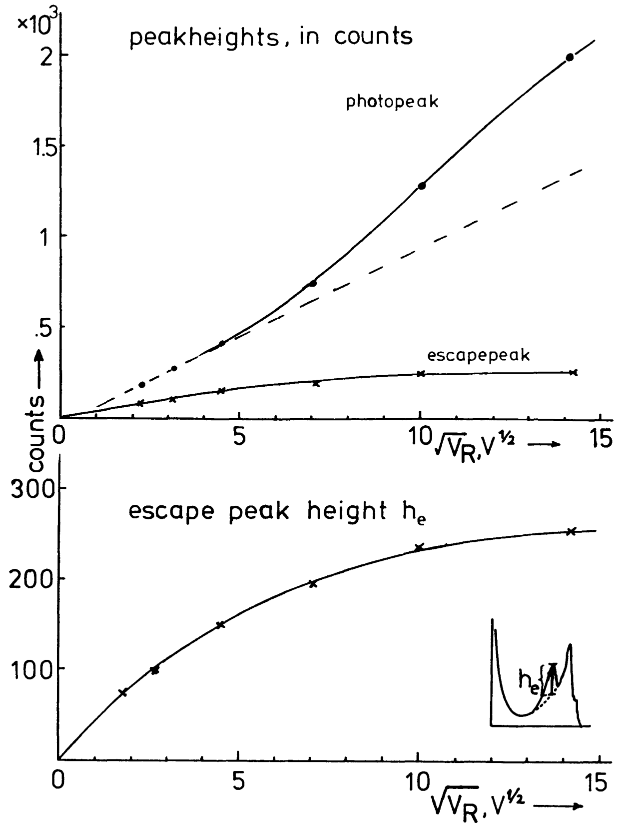


FIG. 4. — Top : absolute heights of photopeak and escape peak against V_R. Bottom : escape peak height and the way of evaluation from the spectra.

matics are described in a paper by Sherman 1955 [5]. If the space layer depth w is small compared with the absorption length $l_\gamma = 1/\mu_\gamma$ of the primary gamma radiation, and if w is furthermore markedly smaller than the diode contact dot diameter (i. e. we may apply the *semi-infinite model* or a one-dimensional electric field in the space charge layer), then the following relation holds :

$$N_e(w) = \omega_K N_0(\mu_\gamma/\mu_K) \exp(-\mu_\gamma D) \times \times [E_3(0) - E_3(\omega_K w)] \quad (1)$$

N_e is the number of escape events from the space charge region, μ_γ and μ_K are the attenuation coefficients (or the inverted absorption lengths) of the primary gamma radiation and the K-X-ray radiation respectively, N_0 is the number of primary gammas impinging on the silver-contacted side of the wafer per $cm^2 \cdot s$ and D is the thickness of the CdTe wafer. E_3 is one of the exponential integral functions, which are tabulated, e. g., in Abramovitz-Stegun [6] ; $E_3(0)$ is 0.5 ; $E_3(0) - E_3(w)$ marks the w-dependence of the escape peak height. It has in fact the same form as the measured curve in figure 4. For a CdTe detector the correct theoretical curve necessary for evaluating the experimental curve, by comparison, must be composed of four equations of type 1 each taking into account the ω_K and μ_K of the CdK_α, CdK_β, TeK_α and TeK_β X-rays in CdTe. The μ_K-values have been taken from Veigele *at al.* [7], the ω_K values from Bambynek *et al.* [4] (see Fig. 1).

	CdK_α	CdK_β	TeK_α	TeK_β
ω_K	0.692	0.148	0.699	0.158
μ_K, cm^{-1}	83.0	60.5	166.5	118.0

This curve normalized to $\varepsilon = N_e/N_0 \exp(-\mu_\gamma D)$ is synthesised by a computer programme. It is presented in the upper diagram of figure 5.

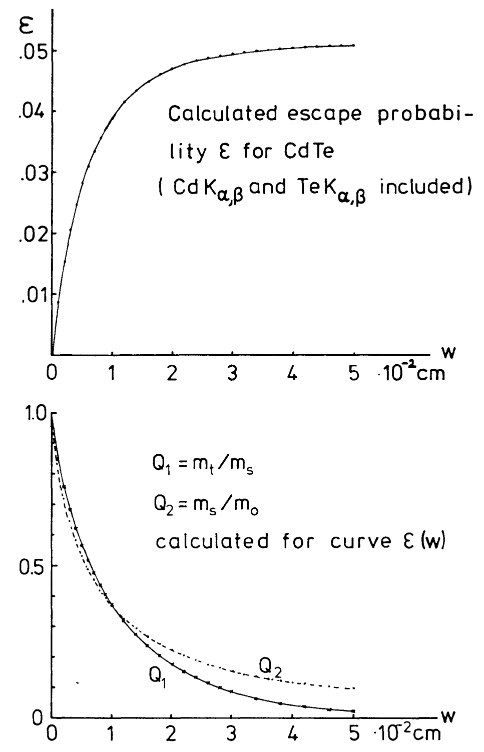


FIG. 5. — Top : The normalised theoretical escape curve $\varepsilon(w)$ for CdTe. Bottom : The theoretical curves of the dimensionless ratios Q_1 and Q_2 necessary for evaluation of experimental curves $h_e(V_R)$.

The evaluation of the curve $h_e(w)$ suffers from the fact that proportional factors for abscissa and ordinate are not known. Hence, values of the experimental curve normalised in both axis directions have to be formed for a comparison with the theoretical curve. Such normalised values are (see in the lower diagram of figure 4) :

$$\text{The ratio } Q_1 = \frac{m_t}{m_s} = \frac{\text{slope of the tangent}}{\text{slope of the secant}}$$

$$\text{the ratio } Q_2 = \frac{m_s}{m_0} = \frac{\text{slope of the secant}}{\text{slope in the origin}}.$$

The theoretical values of both ratios can be calculated for curve $\varepsilon(w)$ by a small expansion of the computer programme used for $\varepsilon(w)$. By substituting experimental Q_1 and Q_2 values (for individual $\sqrt{V_R}$ values) in the theoretical Q_1 and Q_2 curves we get w-values attributed to $\sqrt{V_R}$ values. In ideal cases all the pairs $\sqrt{V_R}$-w as drawn from Q_1 or from Q_2 yield straight lines through the origin, the slope of which characterizes the constant of the space charge layer-voltage expression

$$w = \left(\frac{2\,\varepsilon_d\,\varepsilon_0}{q_e\,p}\right)^{1/2} \cdot V_R^{1/2} \qquad (2)$$

of which only p is unknown.

Figure 6 presents the $\sqrt{V_R}$-w correlations obtained by comparison of experimental and theoretical Q_1 and Q_2 values. Q_1 leads to strong deviations from linearity at higher $\sqrt{V_R}$ values ; hence evaluation using Q_2 is more useful. From the straight line of Q_2 we find $w = 6.2 \times 10^{-4}\ \text{cm}/V^{1/2} . \sqrt{V_R}$. As can be seen in figure 6 w is 50 µm at about 65 V and does not exceed 100 µm at 200 V. Hence the *semi-infinite model* for the space charge layer is still valid, though an influence of the growing deviation is effective in curve $h_e(V_R^{1/2})$ at higher voltages as revealed by the curves in figure 6. With ε_d(CdTe) = 10.6 we come to an acceptor concentration in the space charge layer of $q = 3.0 \times 10^{13}\ \text{cm}^{-3}$.

Capacitive determinations of p are usually unreliable because of high series resistance of such diodes. Hence the method of investigating the voltage dependence of the escape peak height is a reliable tool to find out the real space charge depth and the acceptor concentration in travelling solvent-grown CdTe crystals.

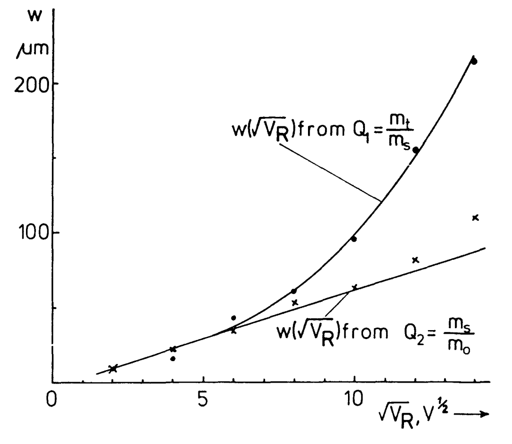


FIG. 6. — Results of the two evaluations using Q_1 and Q_2 respectively (see text) : The space charge layer thickness w as a function of V_R, V_R being the applied reverse voltage.

We thank Professor Langbein, Mr. R. Hartmann and Mr. B. Füssl for discussions and assistance. This work was sponsored by the German Federal Ministry of Research and Technology represented by the DFVLR/BPT.

References

[1] BELL, R. O. and WALD, F. U., *IEEE Trans. N. S.* **19** (1972) 334.

[2] TRIBOULET, R. *et al.*, *Nature Phys. Sci.* **245** (1973) 12.

[3] TRIBOULET, R. *et al.*, *J. Appl. Phys.* **45** (1974) 2759.

[4] BAMBYNEK, W. *et al.*, *Rev. Mod. Phys.* **44** (1972) 716-813.

[5] SHERMAN, J., *Spectrochim. Acta* **7** (1955) 283.

[6] ABRAMOVITZ, M. and STEGUN, I. A., *Handbook of Math. Functions* (Dover Publ. Inc., New York) 1965, p. 228 ff.

[7] VEIGELE, W. M. J. *et al.* *X-ray cross section compilation* Report No. KN-798-69-2 (R).

[8] ZANIO, K., *J. Electron. Mat.* **3** (1974) 327.