# Characterization of CZT Crystals with Using of the Time-of-Flight Method


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## Introduction

Conventional Time-of-Flight method (TOF) is used for measurement of charge carrier mobilities. It was widely used by many workers for various detectors materials characterization including CdTe and CdZnTe. Some of the first results on a high resistive CdTe were obtained by K. Zanio et al. in 1968 [1]. By this method the transit time of charge carriers generated close to one of electrodes is measured. Charge carrier can be produced by a pulsed electron beam, a fast laser pulse or by α-particles. Charge carrier mobility can be calculated by formula *(1)*.

In addition to the mobility, $\mu$, mean free drift time, $\tau$, of charge carries can be calculated with using of the Hecht relation [2] for a charge collection efficiency $\eta$. For a single charge collection in the planar detector, uniform electric field distribution and with ignored detrapping of charge carries this relation will be *(2)*.

$$\mu = \frac{d^2}{U * t_d} \quad (1)$$

$U$ - is the applied bias voltage;
$d$ - is the detector thickness;
$t_d$ - is the carrier drift time.

Free drift length $\lambda$ is equal to $\mu\tau E$, where $E$ - is the uniform electric field intensity, $E = U/d$.

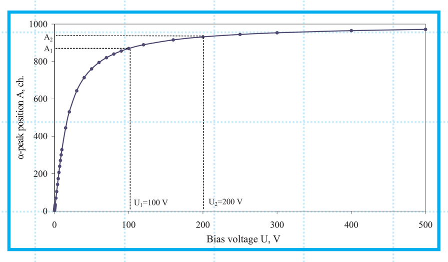
$$\eta = \frac{d}{\lambda}\left[1 - \exp\left(\frac{d}{\lambda}\right)\right] \quad (2)$$

$\eta$ - is the induced charge collection efficiency;
$d$ - is the detector thickness;
$\lambda$ - is the free drift length.

## Measurement techniques

The carrier drift time is usually measured by the rise time of the pulses from the charge sensitive preamplifier output. Presence of a ramp or a smoothly increased with one characteristic time output signal front can testify to presence of an uniform electric field distribution in the detector volume. Distorted output waveform can be a result of various nonuniformities inside of the detector volume.

Usually used method to estimate the value of *(μτ)* product is to measure charge collection efficiency as a function of the applied bias voltage *η(U)* [3]. In practice can be measured α-peak position in channels as a function of the applied bias voltage *A(U)*. *(μτ)* product can be obtained from the measurement data by a curve fitting procedure.

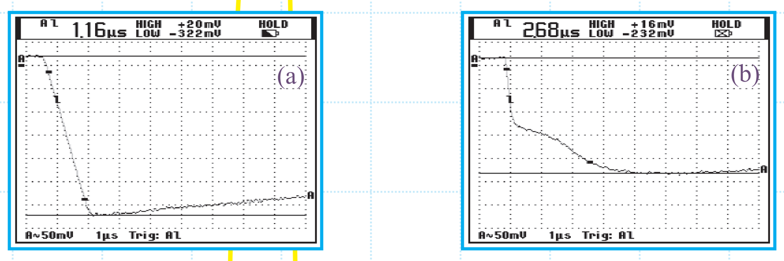


*Maximum α-peak position depending on applied bias voltage.*

There is other way of more simple direct calculation. It is can show that with using of the Hecht relation (2) *(μτ)* value can be calculate as *(3)*:

$$(\mu\tau) = \frac{d^2}{2U_1 \ln\left(\frac{A_2}{2A_1 - A_2}\right)} \quad (3)$$

$U_1$ - is the bias voltage;
$A_1$ - is the α-peak position in channels at bias voltage $U_1$;
$A_2$ - is the α-peak position in channels at bias voltage $U_2=2U_1$;
$d$ - is the detector thickness.



*Output induced charge signal waveforms for uniform detector (a) and nonuniform detector (b). α-particles illuminate negative contact.*

## Influence of the (μτ) product nonuniformity

Shall consider only nonuniformity of the *(μτ)* product dispersed by the detector area, single charge collection and uniform electric field distribution. Also we assume, that the distribution of values of *(μτ)* by the detector area submits to the normal Gaussian law of distribution *(4)*.

$$\phi(\mu\tau) = \frac{c}{\sigma_{\mu\tau}} \exp\left[\frac{\left((\mu\tau) - (\overline{\mu\tau})\right)^2}{2\sigma^2_{\mu\tau}}\right] \quad (4)$$

$(\overline{\mu\tau})$ - is the average value of *(μτ)* scattered by the detector volume, $0 < (\mu\tau) < \infty$;
$c$ - is the normalizing factor;
$\sigma_{\mu\tau}^2$ - is the dispersion of $(\mu\tau)$, $\sigma_{\mu\tau} < (\overline{\mu\tau})$.

A distribution of drift lengths $\lambda$ by the detector area will also submit to the normal law of distribution with dispersion of drift lengths $\sigma_\lambda^2$, $\sigma_\lambda = \sigma_{\mu\tau} E$. Let the value $\sigma_\lambda$ will be $\sigma_\lambda = b\overline{\lambda}$, where $b$ - is the nondimensional parameter and $\overline{\lambda}$ - is the average value of drift lengths. Parameter $b$ will define a degree of nonuniformity of drift lengths. Such replacement of variable allows to keep a given degree of nonuniformity at variation of values $\overline{\lambda}$ or $(\overline{\mu\tau})$.

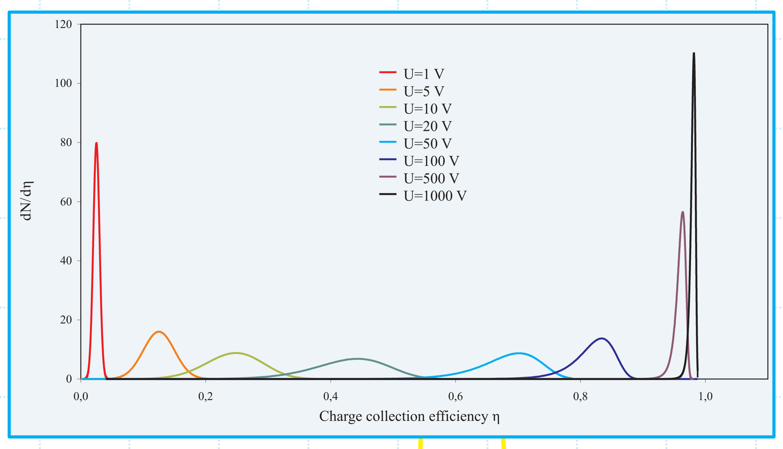
For the uniform electric field distribution, charge collection efficiency $\eta$ will be described by the Hecht equation for single charge collection *(2)*. As the charge collection efficiency $\eta$ is a function of a normal distributed random value $\lambda$, it is possible to determine density of function of the charge collection efficiency.

There is a maximum of the peak width bias voltage dependence. This maximum is observed then the free drift length $\overline{\lambda}$ becomes comparable with the detector thickness. The presence of this maximum can be used for an estimation of *(μτ)* values. Can show that with the assumption of a small value of the parameter $b$, the *(μτ)* can be calculated as *(5)*:

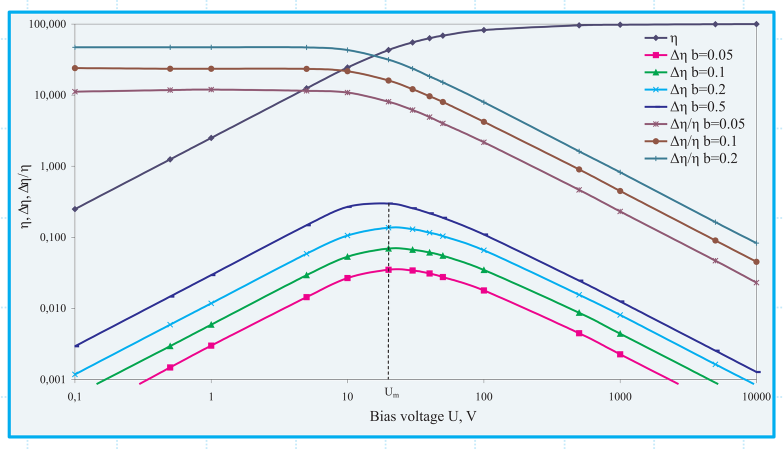
$$(\mu\tau) \approx K \frac{d^2}{U_m} \quad (5)$$

$U_m$ - is the bias voltage corresponding to the maximal peak width;
$K$ - is the non-dimensional parameter, depending on a kind of nonuniformity distribution by the detector volume; for the normal Gaussian law of distribution $K \approx 0.7$.

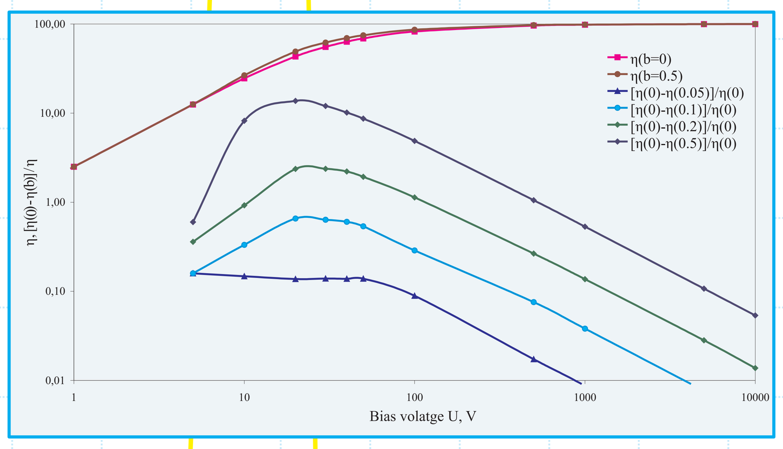
Energy resolution at low bias voltages is not dependent on voltage and is defined by the degree of nonuniformity $b$. Also this simple calculation show that presence of *(μτ)* nonuniformity will result in some changes in dependence *η(U)* in comparison with Hecht equation (2). This difference is the more noticeable the more nonuniformity of *(μτ)* is presented and can be a reason of a great miscalculation of *(μτ)* calculation.



*Calculated spectra for $(\mu\tau)_e$=1*10-3 cm/V*s, d = 0.2 cm, b = 0.2.*



*Calculated charge collection efficiency η, peak width (FWHM) Δη and energy resolution Δη/η depending on bias voltage U for $(\mu\tau)_e$=1*10-3 cm/V*s, d = 0.2 cm and various b.*



*Difference between calculated charge collection efficiency without (b=0) and with nonuniformity of (μτ) value depending on bias voltage U for $(\mu\tau)_e$=1*10-3 cm/V*s, d = 0.2 cm.*

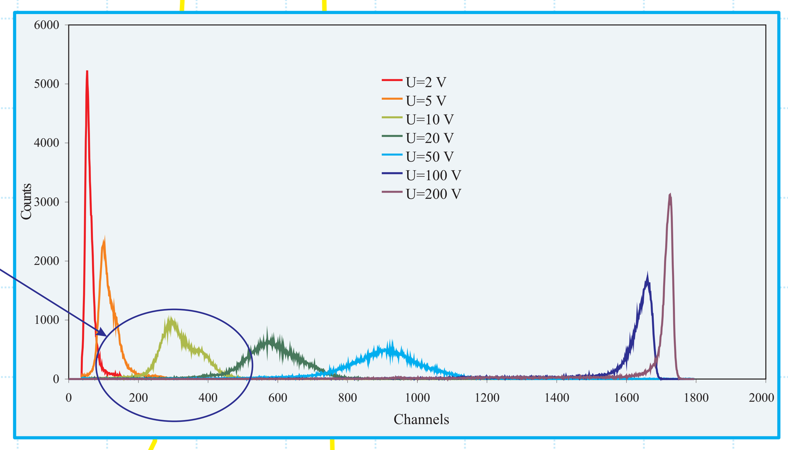
## Measurements

At measurements a negative electrode was irradiated by α-particles of 5.5 MeV ($Am^{241}$).

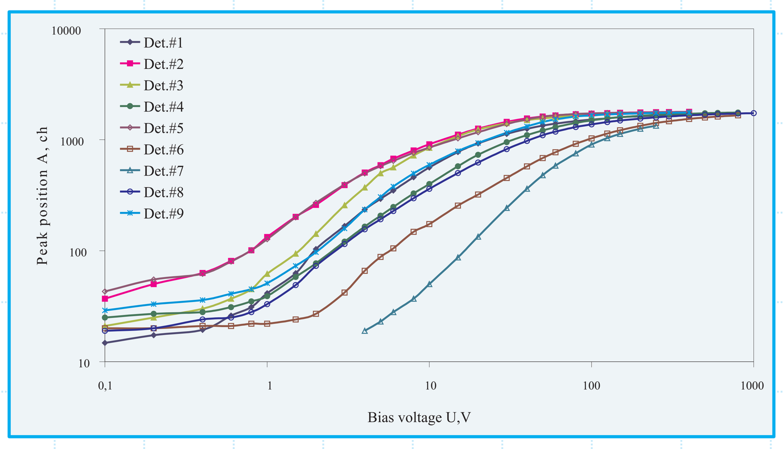
*Table. Calculated (μτ) values with using of measured data and expressions (3) and (5).*

| Detector No. | Area, cm | Thickness, cm | $(\mu\tau)_e$, $10^{-3}$ $m^2/V$ calculated by A(U) | $(\mu\tau)_e$, $10^{-3}$ $m^2/V$ calculated by $U_m$ | $\mu_e$, $cm^2/V*s$ |
|---|---|---|---|---|---|
| Det. #1 | 0.7x0.7 | 0.34 | 3.6 - 4.2 | 3.5 | 936 |
| Det. #2 | 1.0x1.0 | 0.21 | 2.5 - 4.2 | 2.4 | 862 |
| Det. #3 | 0.5x1.0 | 0.20 | 2.0 - 3.0 | 2.2 | 793 |
| Det. #4 | 1.0x1.0 | 0.48 | 4.9 - 6.5 | 4.3 | 863 |
| Det. #5 | 1.0x1.0 | 0.20 | 1.6 - 5.0 | 1.3 | 708 |
| Det. #6 | 1.2x1.2 | 0.61 | 3.0 - 8.0 | 5.2 | 681 |
| Det. #7 | 1.0x1.0 | 0.32 | 0.4 - 0.6 | 0.6 | 586 |
| Det. #8 | 1.5x1.5 | 0.50 | 4.2 - 7.0 | 3.7 | 862 |
| Det. #9 | 1.0x2.0 | 0.31 | 2.5 - 6.3 | 2.6 | 939 |

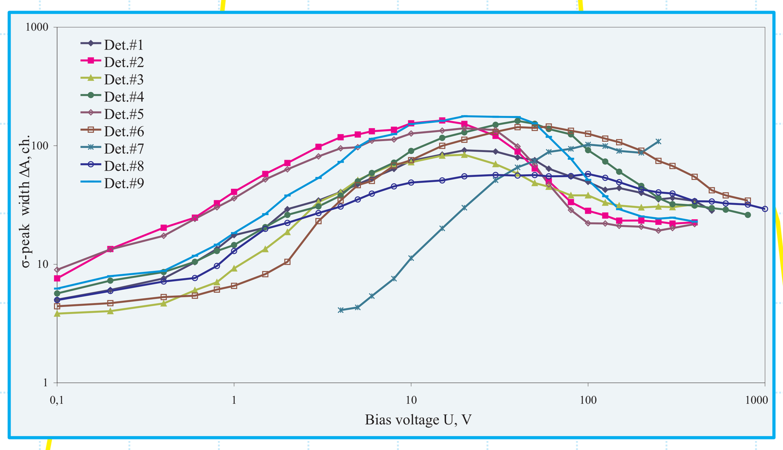
*Measured α-spectra at different bias voltages. Detector #9. Dimensions of the detector area 1x2 cm, thickness 0.31 cm.*



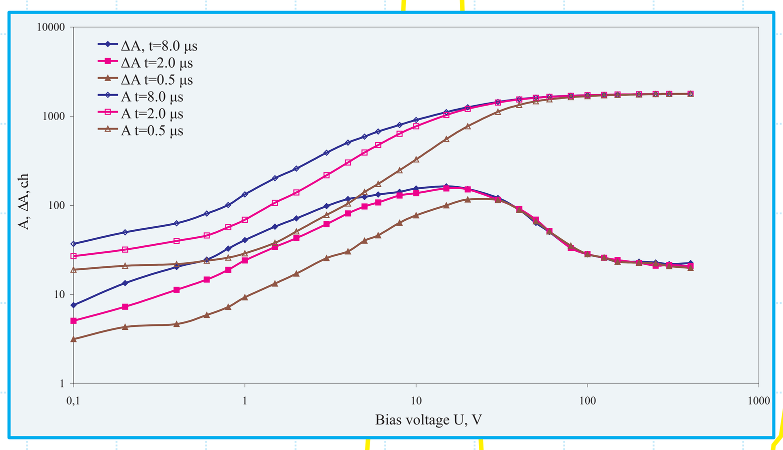
*Distored α-peak is an evidence of nonuniformity presence.*



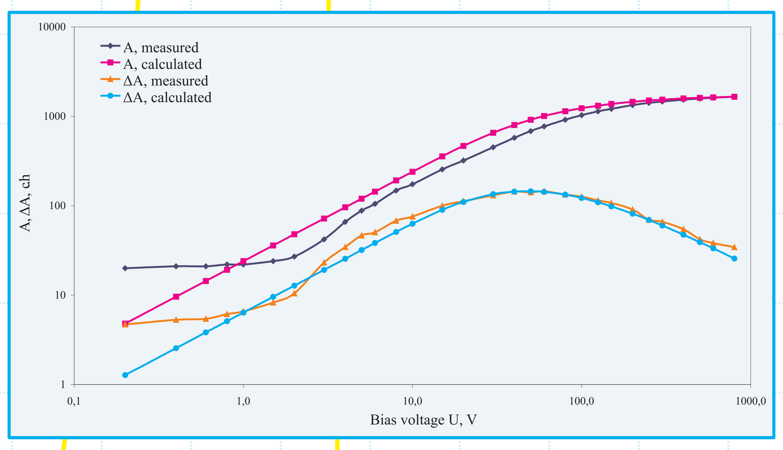
*Measured α-peak position in channels v.s. bias voltage for various CZT detectors.*



*Measured α-peak width in channels v.s. bias voltage for various CZT detectors.*



*Detector #2. Measured α-peak position in channels and peak width v.s. bias voltage for different shaping times.*



*Detector #6, area 1.2x1.2 cm, thickness 0.61 cm. Measured and calculated α-peak position and peak width in cannels v.s. bias voltage*

## Main results and conclusions

- Suggested modified methods for *(μτ)* product values calculation from the measurements data of *A(U)* and $U_m$.
- Some $(\mu\tau)_e$ values calculated from the measurement data of *A(U)* by a curve fitting procedure as well as by using of expression *(4)* are depending of applied bias voltage. It can be caused by a presence of nonuniformities inside of the detectors. False peaks presented in the measured α-spectra testify to presence of the nonuniformity.
- Coincidence of $(\mu\tau)_e$ product values calculated by two methods may be evidence of the data verification.
- Use of too small shaping time leads to an additional error with using measured data of *A(U)* especially at low bias voltages.
- At very low bias voltages charge collection is provided by the presence of a contact voltage drop.
- At high bias voltages there are influence of increased noise.
- Others possible unaccounted sources of errors can effects to the *(μτ)* calculation:
  - ✓ Not uniform electric field distribution inside of the detector volume. Uniform electric field distribution corresponds linear output signal front.
  - ✓ Not uniform detector's input window. It must be uniform, sufficiently thin and does not depend on the applied bias voltage.
  - ✓ Too small shaping amplifier shaping time. It must be longer then the charge carrier drift time. Otherwise correction for the ballistic deficit must be performed.
  - ✓ Too short preamplifier output signal fall time constant. It must be much longer then the charge carrier drift time.
  - ✓ Unaccounted charge carriers detrapping process.
  - ✓ Plasma effects connected with the high density of electron-hope pairs along the -particle tack especially at low bias voltages.


References

1. K. R. Zanio, W. M. Akutagava, R. Kikuchi, J. Appl. Phys., vol. 39, p. 2818, 1968.
2. K. Hecht, Z. Phys, vol. 77, p. 235, 1932.
3. J. W. Mayer, J. Appl. Phys., vol. 38(1), p. 296, 1967