



# Diffusion length of minority carriers in (CdZn)Te and (HgCd)Te single crystals measured by EBIC method

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## Abstract

Diffusion length of minority carriers was determined in not intentionally doped  $\text{Cd}_{0.93}\text{Zn}_{0.07}\text{Te}$  and  $\text{Hg}_{0.8}\text{Cd}_{0.2}\text{Te}$  single crystals by the EBIC method at temperatures 80–300 K using an evaporated Au Schottky barrier ((CdZn)Te) or a P–N junction produced by ion milling or plasma etching ((HgCd)Te). The  $L$  values in P-(CdZn)Te were longer, than those of the binary CdTe and some showed a steep increase with decreasing temperature. The correlation of the diffusion length measurement with photoluminescence for the (CdZn)Te was observed. © 1999 Elsevier Science B.V. All rights reserved.

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## 1. Introduction

(HgCd)Te is a material frequently used for fabrication of infrared detectors. With a development of epitaxial technologies the detectors are produced by LPE or MBE, when (CdZn)Te is normally used as a substrate. One of the parameters which indicate the material quality of both (HgCd)Te and (CdZn)Te is the diffusion length of minority carriers  $L$ . The aim of the present paper is a study of  $L$  at temperatures 80–300 K using the electron beam induced current method (EBIC). Room tem-

perature results for (CdZn)Te samples were published in Ref. [1].

The EBIC method for measurement of  $L$  in (HgCd)Te was used in Refs. [2–4]. However, no data dealing with measurement of  $L$  in the N-type material produced by ion milling were found in the literature. Concerning the material (CdZn)Te measurement of  $L$  by EBIC was referred to in Refs. [4–10] for pure CdTe and in Ref. [1] for (CdZn)Te.

## 2. Experimental procedure

$\text{Cd}_{1-x}\text{Zn}_x\text{Te}$  ( $x \approx 0.07$ ) single crystals were produced in the Institute of Physics (Prague) by the

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vertical gradient freezing method (VGF). As-grown single crystals were mostly P-type with a concentration of holes  $5 \times 10^{13}$ – $5 \times 10^{16} \text{ cm}^{-3}$  and a mobility 30–70  $\text{cm}^2/\text{V s}$  at 300 K.

$(\text{Hg}_{1-x}\text{Cd}_x)\text{Te}$  ( $x \approx 0.2$ ) single crystals were produced by modified Bridgman method from the melt of constant composition. As-grown single crystals were P-type with a carrier concentration  $10^{15}$ – $10^{16} \text{ cm}^{-3}$  and a mobility 250–700  $\text{cm}^2/\text{V s}$  at 77 K [11].

We use low-temperature photoluminescence measurements as a standard characterization of the grown crystals. Before the measurements, crystals are cut into 1–3-mm-thick slides, mechanically ground, polished and finally, the surface is etched in a solution of bromine in methanol or bromine in lactic acid.

The structure used for a separation of electron–hole pairs in the EBIC method was the Au Schottky barrier evaporated on a part of sample surface in the case of  $(\text{CdZn})\text{Te}$  and a deep (100–200  $\mu\text{m}$ ) P–N junction produced by ion milling or plasma etching [12] in the case of  $(\text{HgCd})\text{Te}$ .

The determination of  $L$  was accomplished from EBIC measurements in the JEOL-50 scanning electron microscope (SEM) [13]. A standard formula

$$I(x)/I(0) \sim \exp(-x/L) \quad (1)$$

was used for evaluation of  $L$ . Here  $I$  is the EBIC signal,  $x$  is the distance of the generating electron beam from the edge of the Schottky barrier or the P–N junction located at position (0). The whole experimental arrangement is described in detail in Ref. [1].

### 3. Results and discussion

#### 3.1. $(\text{CdZn})\text{Te}$

The results of  $L$  together with other galvanomagnetic data measured at 300 K are given in Table 1. The values of  $L$  are longer in comparison with those published for pure CdTe (typically around 1  $\mu\text{m}$ ). It remains an open question, whether this fact is connected with the addition of Zn, which is used to stabilize the crystal lattice or with the method of growth itself. It should be noted that room temperature data of samples 1 and 2 were published in Ref. [1] (under Nos. 4 and 5). The values given in the present paper were measured after nine months and exhibit a decrease. This fact could be connected either to an increased surface recombination or to some aging effects due to rearrangement of point defects in the bulk. Fig. 1

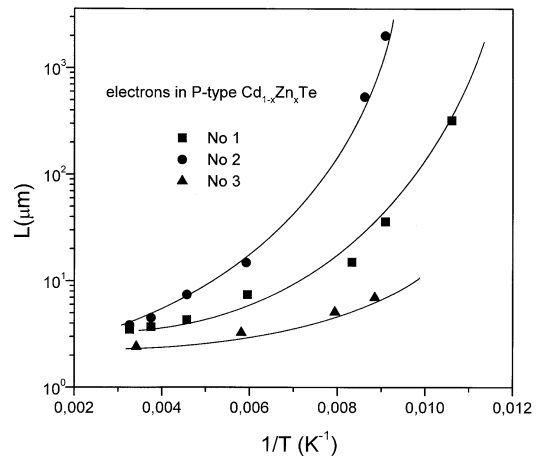


Fig. 1. Temperature dependence of  $L$  of electrons of  $(\text{CdZn})\text{Te}$  samples.

Table 1  
Electrical parameters of P- $(\text{CdZn})\text{Te}$  samples at 300 K

Sample	Resistivity ( $\Omega \text{ cm}$ )	Conc. ( $\text{cm}^{-3}$ )	$\mu$ ( $\text{cm}^2/\text{V s}$ ) (majority holes)	$L$ ( $\mu\text{m}$ )	$\mu\tau$ ( $\text{cm}^2/\text{V}$ ) (minority electrons)
1	2.8	$5 \times 10^{16}$	45	3.2	$4.2 \times 10^{-6}$
2	2.3	$3.5 \times 10^{16}$	77	3.8	$4.8 \times 10^{-6}$
3	625	$1.2 \times 10^{14}$	84	2.2	$1.9 \times 10^{-6}$

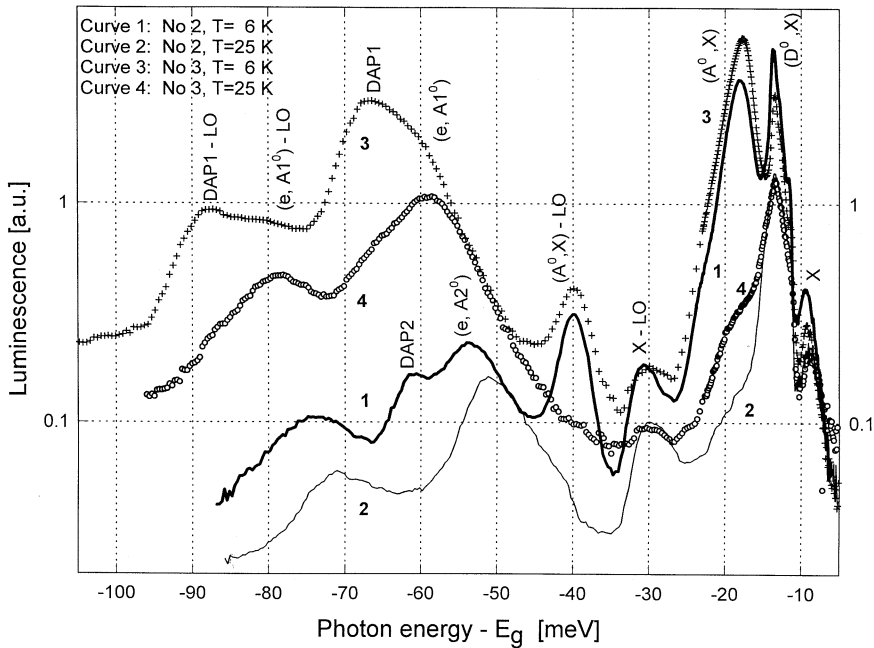


Fig. 2. Luminescence spectra of two (CdZn)Te samples at 6 and 25 K.

shows the temperature (90–300 K) dependence of  $L$  for electrons in P-type for three samples listed in Table 1. A step increase of  $L$  and of the corresponding mobility–lifetime product ( $\mu\tau$ ) is observed with a decreasing temperature. Very long  $L$  was observed in the case of sample No. 2 (2 mm at 110 K) and No. 1 (300  $\mu\text{m}$  at 90 K). This fact could be of some interest from the point of view of a possible application of a not intentionally compensated (CdZn)Te as a gamma ray detector.

Photoluminescence spectra from the two types of bulk (CdZn)Te samples included in this study are shown in Fig. 2 in a semilogarithmic plot. Structures related to recombination of free excitons (X), donor-bound excitons ( $D^0, X$ ), acceptor-bound excitons ( $A^0, X$ ) and their phonon replicas are observed as usual in good quality crystals. The gap energy and corresponding composition  $x$  of the samples can be deduced from these peaks using the formula [14]

$$E_g(T \rightarrow 0) = 1.606 + 0.322x + 0.463x^2 \quad (\text{eV}). \quad (2)$$

We obtained  $x = 0.076$  for sample No. 1,  $x = 0.085$  for sample No. 2 and  $x = 0.079$  for sample No. 3.

Various types of recombination involving shallow acceptors are observed in the spectral range  $(\hbar\omega/2\pi) < E_g - 40 \text{ meV}$ . Energy of zero-phonon line (ZPL) of free-to-bound recombination ( $e, A^0$ ) is determined by acceptor binding energy  $E_A$ , while ZPL of donor–acceptor-pair (DAP) recombination has a lower energy; for low doping concentration

$$E(\text{DAP}) \approx E_g - E_A - E_D + e^2/(4\pi\epsilon r), \quad (3)$$

where  $E_D$  is the donor binding energy, and  $r$  the Coulombic term in donor–acceptor space separation. Two spectral regions can be distinguished.

(1)  $E_A \geq 57 \text{ meV}$ : Acceptor created by substitutional impurities (e.g.  $\text{Na}_{\text{Cd}}$ ,  $\text{Li}_{\text{Cd}}$ ,  $\text{As}_{\text{Te}}$ ,  $\text{Sb}_{\text{Te}}$ ) [15,16]. The limit value 56.8 meV corresponds to the calculated effective mass acceptor.

(2)  $E_A < 57 \text{ meV}$ : These structures have been explained either by donor-cadmium vacancy-donor complex defects (e.g.  $\text{V}_{\text{Cd}}\text{-}2\text{Cl}$  Bell acceptor [17]) often observed in Cl-doped CdTe with  $E_A = 48 \text{ meV}$  [14] or by isoelectronic impurities (e.g. oxygen [18,19], perhaps selenium [20]).

The composition dependence in the system  $\text{Cd}_{1-x}\text{Zn}_x\text{Te}$  of shallow acceptor binding energies

can be expressed as [14]

$$E_A(x) = E_A(\text{CdTe}) + 8.2x \quad (\text{meV}), \quad (4)$$

i.e. for our composition is the difference

$$E_A(x) - E_A(\text{CdTe}) < 1 \text{ meV}. \quad (5)$$

In our samples with low diffusion length at 90 K (No. 3 in Fig. 1) DAP1 recombination prevails. On the contrary, in high diffusion length samples (Nos. 1 and 2 in Fig. 1, No. 1 not shown in Fig. 2) conduction band to type 2 acceptor recombination ( $e, A_2^0$ ) dominates this part of spectra even at low temperature. In both types of samples the luminescence was low in deeper acceptor region ( $200 \text{ meV} < (\hbar\omega/2\pi) - E_g < 120 \text{ meV}$ ), where, for example, recombination at A-centers  $V_{\text{Cd}}$ -donor appears.

We suppose that more convenient arrangement of point defects into complexes with low binding energy causes slower recombination through deep levels. This is manifested by long diffusion length (at 90 K) and observation of band-acceptor even at low temperature and a relatively low excitation level.

### 3.2. (HgCd)Te

In the case of (HgCd)Te, a P–N junction produced by ion beam milling was used for a separation of electron–hole pairs in the EBIC method. The interval of temperatures in which  $L$  can be measured depends on the temperature, when the P–N junction disappears as a result of activation of intrinsic conductivity. This temperature is basically determined by the composition  $x$  corresponding to the energy gap. The highest temperature for which reliable data could be measured is 130 K for composition  $x \approx 0.2$ .

The diffusion length of the minority holes in the N-type samples (see Fig. 3) varies between 20 and 120  $\mu\text{m}$  at 80 K decreasing with increasing temperature to 8–35  $\mu\text{m}$  at 130 K. The diffusion length of electrons in P-type on the same samples (Fig. 4) varies between 6 and 12  $\mu\text{m}$  at 80 K and is increasing with increasing temperature.

Analysis of these results is connected with the knowledge of temperature dependences of minority

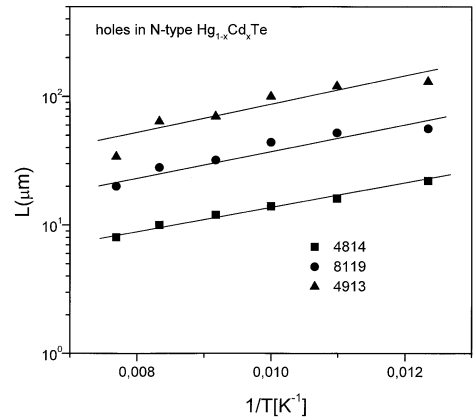


Fig. 3. Temperature dependence of  $L$  of holes in N-(HgCd)Te samples.

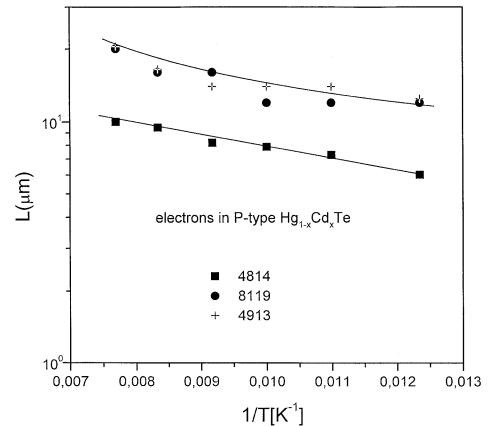


Fig. 4. Temperature dependence of  $L$  of electrons in P-(HgCd)Te samples.

carrier mobility or steady-state lifetime. The evaluation of temperature dependences (4.2–300 K) of Hall effect  $R_H$  and conductivity  $\sigma$  on P-type samples listed in Table 2 yields values of mobilities of minority electrons and majority holes. While the mobility of majority holes can be evaluated directly, the mobility of minority electrons at temperatures 80–130 K was extrapolated from higher temperatures, when they dominate the transport due to their high mobility. This extrapolation to lower temperatures may be questionable and the electron

Table 2  
Electrical parameters of P-(HgCd)Te samples

No	$x$	$p_{77\text{ K}} (\text{cm}^{-3})$	$\mu_{77\text{ K}} (\text{cm}^{-3})$ (holes)	$\mu_{77\text{ K}} (\text{cm}^{-3})$ (electrons)	$L_{80\text{ K}} (\mu\text{m})$ (electrons)	Lifetime (ns) (electrons)
4814	0.203	$8 \times 10^{16}$	365	21 000	6	1.4
4913	0.200	$2.5 \times 10^{16}$	850	18 000	12	8.1
8119	0.217	$2.9 \times 10^{16}$	600	14 000	12	6.2

lifetime  $\tau$  calculated from formula  $L = (kT\mu\tau/e)^{1/2}$  (here  $k$  is the Boltzmann constant,  $T$  is the absolute temperature and  $e$  is the electron charge) should be understood as a raw estimate only. The values of  $\tau$  are in good agreement with data published in Ref. [21] for steady-state measurements.

Contrary to P-type material, mobility of minority holes in N-type material is not well known. Therefore no calculation of lifetime was done in this case.

Although a more detailed theoretical evaluation of the measured temperature dependences is complicated by the relatively narrow temperature interval in which  $L$  could be measured, some qualitative description of  $L(T)$  can be given. As was mentioned above, an increase of  $L$  with increasing temperature was observed in the case of electrons in P-type, while  $L$  of holes in N-type was decreasing. The mobility of both minority electrons and holes is supposed to be decreasing with increasing temperature in the range 80–130 K due to domination of scattering on optical phonons. Concerning the behavior of lifetime of electrons an increase is observed at 80–140 K [22,23]; therefore the  $\mu\tau$  product and the corresponding  $L$  can be increasing with  $T$ . In the case of lifetime of holes, a decrease was measured at temperatures  $T > 90$  K [24], therefore the  $\mu\tau$  product and the corresponding  $L$  is expected to be decreasing with  $T$ , which is in agreement with our data in Fig. 3.

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