Proceedings of the 47th International School and Conference on the Physics of Semiconductors "Jaszowiec 2018"

Magnetoconductivity of a Mercury Cadmium Telluride Resonant THz Detector

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Magnetoconductivity tensor $\hat{\sigma}$ of a THz detector made of a $\mathrm{Hg}_{1-x}\mathrm{Cd}_x\mathrm{Te}$ epitaxial layer was determined at a few temperatures T between 2 K and 100 K for magnetic fields B up to 0.5 T. At all temperatures the sample exhibited n-type conductivity. The observed dependence of $\hat{\sigma}(B)$ could be reasonably approximated with a one-carrier model at the highest T, but this model cannot be used to describe data at the lowest temperatures. We show that optical transitions at THz frequencies occur at magnetic fields characterized by strong changes of conductivity. That is why response of the detector working in a photoconductive mode must be corrected by taking into account its $\hat{\sigma}(B)$ dependence.

DOI: 10.12693/APhysPolA.134.973

PACS/topics: magnetoconductivity, THz spectroscopy, mercury cadium telluride

1. Introduction

Mercury cadmium telluride has been studied for more than 50 years now, but only recently there have been fabricated crystals of a high enough quality to reveal fascinating phenomena like observation of the Dirac fermions in bulk crystals [1, 2] and topological transitions in quantum wells [3]. Thus, a very well known material which has been used during last decades for fabrication of low-energy photons' detectors, has appeared now to serve for a new type of research. On the other hand, more standard properties of HgCdTe can be studied nowadays on a high-quality material which leads to more refined analysis of known phenomena.

The motivation of this work has come from recent THz spectroscopy experiments carried out on an InSb THz detector [4]. A usefulness of narrow band-gap semiconductors in THz spectroscopy comes from a strong tunability of a resonant response (due to a cyclotron resonance transition) with magnetic field. At excitation with a monochromatic radiation of frequency ω, the cyclotron resonance occurs at magnetic field satisfying $\omega = eB/m$ and the smaller is m, the stronger is tunability of the resonant response. Narrow band-gap materials like InSb and HgCdTe are characterized by a small electron effective mass. In the case of HgCdTe with the cadmium concentration of about 17%, the band-gap is close to zero, so the effective mass is also close to zero (see Fig. 5 in a recent review by Zawadzki [5]), and is even smaller than in InSb, one of the best known THz detector.

Terahertz detectors are very often used in a photoconductive mode, i.e., a photocurrent is the measured signal generated by interaction of the detector with THz photons. Typically, this method of measurements offers the highest signal-to-noise ratio when compared with other techniques, like absorption or photovoltage measurements. However, there is a serious drawback in using such detectors as THz photoconductors which is related to magnetoresistance of the detector. This comes from the fact that in measurements of a photoconductive response, one observes a result of two processes: first, there occurs an absorption of the photon which can be generally described as a heating of the electron system, second, an increased temperature of the electron system transforms into changes of a dc conductivity. This two-step mechanism which leads is valid both at a resonant and non-resonant heating.

Our experience in application of InSb as a magnetic-field-tuneable THz detector shows that a correct interpretation of spectroscopic photoconductive results requires taking into account the magnetoresistance of the detector. In other words, as it hs been explained in detail in [4], it is only the conductivity and not photocurrent which has to be analysed to give the correct signatures of optical transitions. As it has been shown in [4], when using a THz detector with a low effective mass of electron, one has to take into account two factors. First, a response of the detector, even at high magnetic fields (i.e., quantizing, when the Landau quantization has occurred) can be non-resonant. In such a case, heating of the electron system is not related to the cyclotron resonance transition but is rather caused by intra-Landau-level absorption of THz quanta by electrons with energies close to

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the Fermi energy. Such a heating occurs when a detector is subject to radiation with photon's energy less than the cyclotron resonance energy. Second, it may happen that at magnetic fields corresponding to a resonant excitation, detector's conductivity shows some features related to the quantum Hall effect or the Shubnikov–de Haas oscillations which interfere with variations of a dc current caused by THz photons. A superposition of these two effects makes the spectroscopic interpretation difficult and one has to be sure how to discriminate between them in a photoconductive measurements. This directly leads to the necessity to determine the magnetoconductivity tensor of the detector.

Thus, the present paper is devoted to determination of the conductivity tensor of a HgCdTe THz detector. We show that at the working temperature of the detector, equal to 2 K, it exhibits a very strong magnetoresistance of about two orders of magnitude at magnetic fields below 0.1 T. Due to a very small effective electron mass and a high quality of the sample, resonant transitions are observed at such small B for photon's energy of the order of a meV. We indicate that appliaction of such a detector in the photoconductive THz experiments requires taking into account the magnetic field dependence of its conductivity tensor.

2. Results and discussion

We studied an MBE-grown HgCdTe epitaxial layer on a semi-insulating GaAs substrate. The thickenss of the epitaxial layer was equal to 11 μm and the concentration of Cd was equal to about 17%. The epitaxial layer was not intentionally doped. A scheme of the sample is shown in Fig. 1.

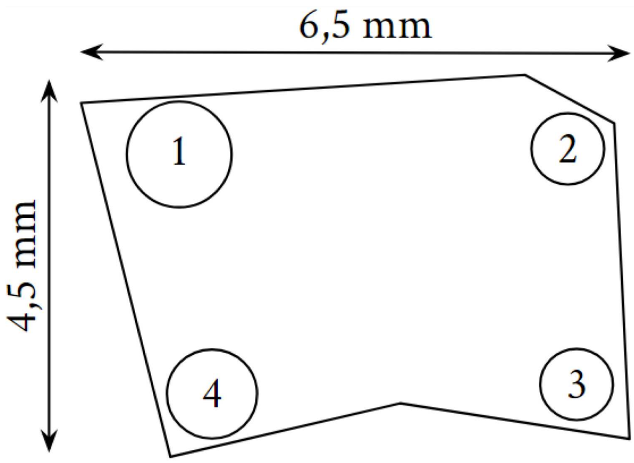

Fig. 1. A scheme of the sample studied. Numbered circles denote soldered indium contacts.

The sample was cooled down and the Hall effect measurements by the van der Pauw method [6] were carried out at a few temperatures between 2 K and 100 K with magnetic field up to 0.5 T. The measurements were done for two directions of current and two directions of the magnetic field. Results of the measurements are shown in Fig. 2 where resistances presented are proportional to corresponding voltages measured at the current set to 1 μA. Transmission spectra were obtained with a monochromatic excitation from a backward wave oscillator or a molecular laser. Transmission signal was registered as a photocurrent on a carbon resistor placed behind the sample.

Measured voltages were combined according to the standard procedure which allows to eliminate most of parasitic effects influencing the Hall effect. Strictly speaking, this procedure eliminates parasitic effects which are characterized by the symmetry with respect to the direction of current and direction of magnetic field different from that of the Hall effect. However, it preserves parasitic effects of the same symmetry as the Hall voltage, like the Ettingshausen effect [7]. These parasitic effects are caused by temperature gradients appearing in the sample and were not specifically addressed in the experiments described in this paper. We would like to notice, however, that at tempeature below 4.2 K the sample was immersed in liquid helium and the dissipated power $I^2 R_{ij,kl}$ was of the order of 10^{-9} W with $I = 1$ μA and $R \approx 10^3$ Ω. The cooling efficiency of the system used was equal to 30 mW. Thus, we assume that temperature gradients in the sample are not important in the present study.

Comparison of resistance values shown in the left and central columns indicate that the sample is not homogeneous or indium contacts are not identical. Depending on temperature, resistance $R_{12,34}$ is about 10 to 40 times bigger than $R_{23,14}$ and this difference cannot be explained by the geometry of the sample (see Fig. 1). Nevertheless, resistances $R_{12,34}$ and $R_{23,14}$ shows a very similar dependence on magnetic field. All the curves presented in Fig. 2 indicate a strong magnetoresistance which is particularly pronounced at 2 K and 20 K. The resistance $R_{13,24}$ presented in the right column in Fig. 2 is an analog of the Hall voltage measured in a Hall-bar geometry. In the ideal case of the Hall bar geometry, the Hall voltage probes are positioned perpendicularly to the current lines and in such a way that a contribution of the voltage drop along the current flow to the Hall voltage is negligible. This is not the case in the present study since the shape of the sample does not allow for a uniform distribution of the current (see Fig. 1) and the "Hall contacts" 2 and 4 are not positioned face to face with respect to the current flowing between contacts 1 and 3. It appears that in such a configuration, the parasitic voltage coming from contribution of the voltage drop along the current lines to the Hall voltage constitutes the dominant part of $R_{13,24}$ and makes $R_{12,34}$ and $R_{13,24}$ quite similar. This is one of the reasons why measurements had to be carried out for two directions of the current and magnetic field — by taking an appropriate combination of measured voltages, one can eliminate this parasitic effects as much as possible.

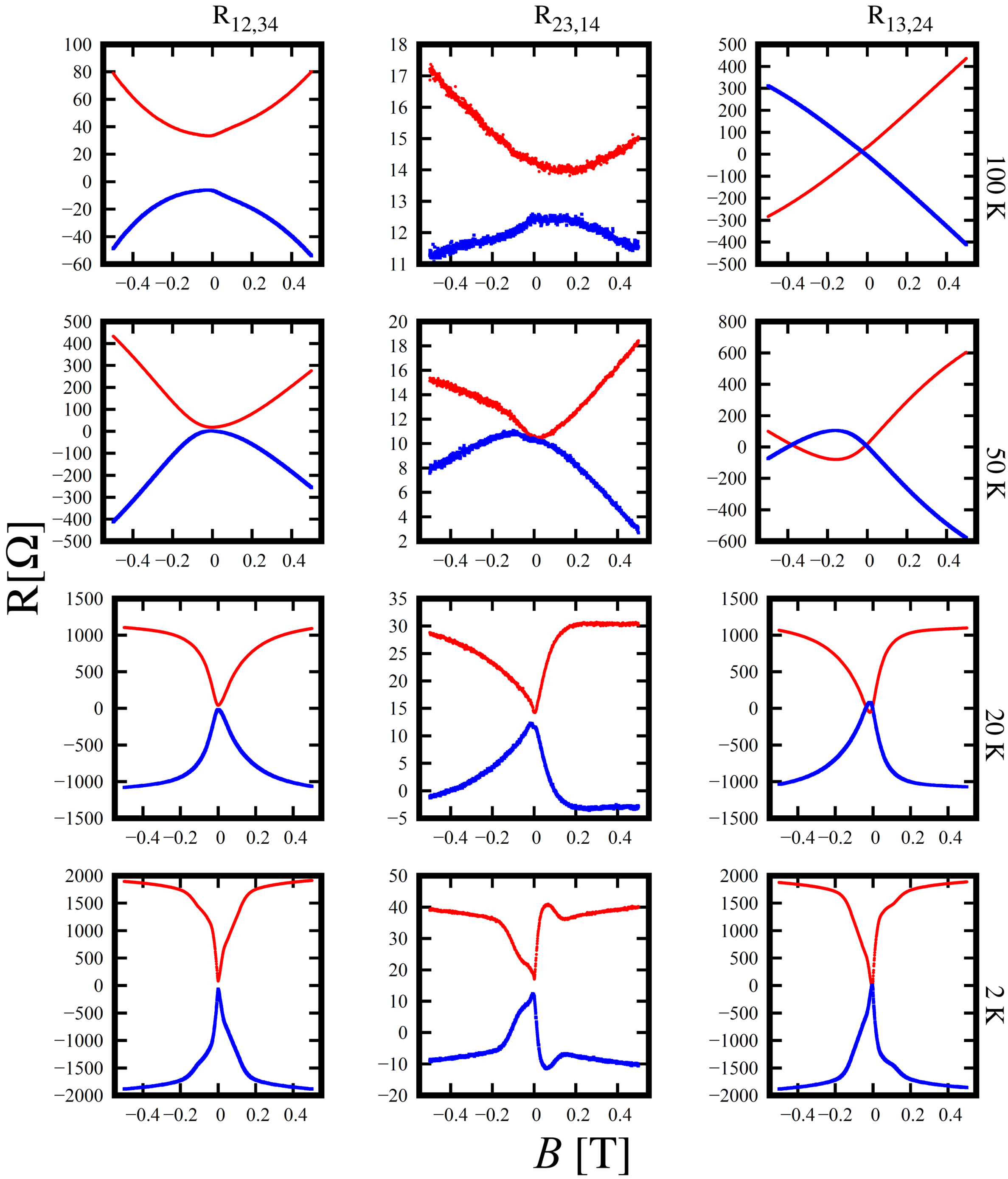

Fig. 2. Magnetic field dependence of resistances measured according to the procedure described in Ref. [6]. Resistance $R_{ij,kl}$ denotes measurements of the voltage between contacts k and l while the current is flowing between contacts i and j. Upper (red) and lower (blue) curves in each graph correspond to positive and negative current, respectively. Temperature of measurements leading to graphs in the same row is shown at the right. The horizontal scale of the magnetic field is the same for all graphs.

Facing the problem of similarity of $R_{12,34}$ and $R_{13,24}$ we repeated measurements at 2 K for all possible configurations of contacts consistent with the van der Pauw method (in the case of the left and middle columns in Fig. 2 this means taking cycling permutations of indexes (12, 34) and (23, 14); indexes in the right column are changed accordingly). This procedure was taken in order to avoid as much as possible an influence of sample's inhomogeneity. Next, obtained resistances were averaged. This led to the result of the same character

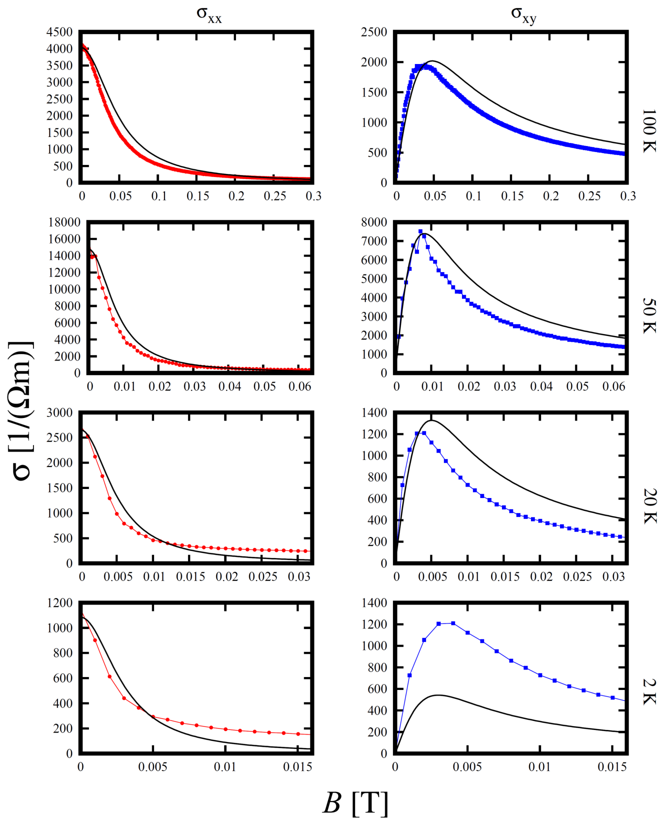

Fig. 3. Components σ_{xx} (left) and σ_{xy} (right) of the conductivity tensor calculated from resistances presented in Fig. 2. Dots — experimental data, solid lines — the one-carrier conductivity model. Note different scales of magnetic field at plots referring to different temperatures.

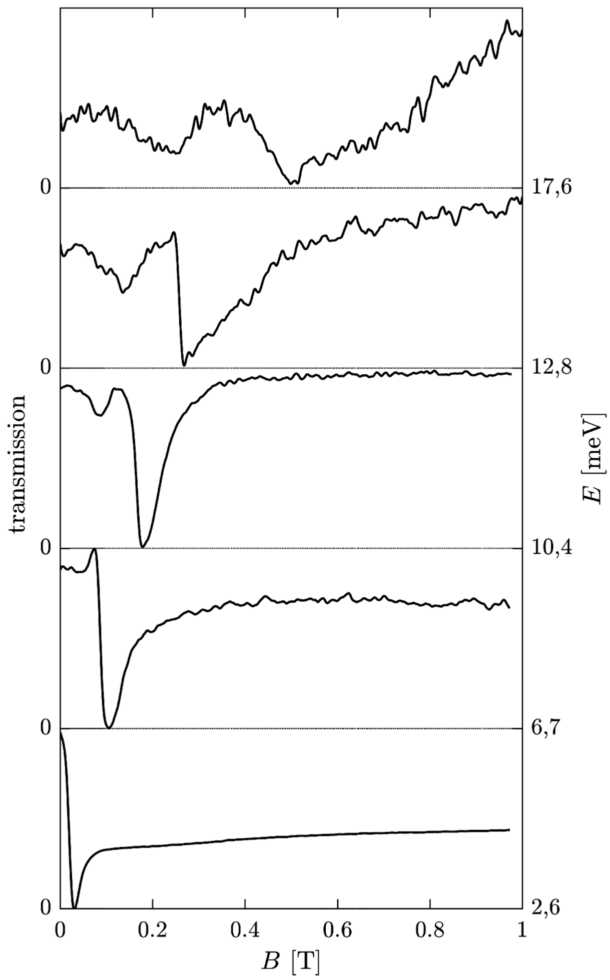

Fig. 4. Transmission spectra of a monochromatic radiation as a function of magnetic field.

as shown in Fig. 2. This leads us to conclusion that a very strong magnetoresistance of the sample at low temperatures is the property of material studied and not caused by sample's inhomegeneity.

With the resistances presented in Fig. 2 and the procedure described in [6], we calculated conductivity tensor which components at four temperatures are shown in Fig. 3. One can notice that strong variations of the conductivity occur at lower at lower magnetic field when temperature decreases. This clearly corresponds to an increase of the mobility of electrons. Since the conductivity was of n-type at all temperatures, we started the analysis of $\hat{\sigma}(B)$ with the simplest model given by Eq. (1) with $N = 1$:

$$\sigma_{xx} = \sum_{i=1}^{N} \frac{n_i e \mu_i}{1 + (\mu_i B)^2},$$
$$\sigma_{xy} = \sum_{i=1}^{N} \frac{n_i e \mu_i^2 B}{1 + (\mu_i B)^2}. \tag{1}$$

In these formulae e is the electron charge, n_i and μ_i is the concentration and mobility of charges of type i, respectively, and N is the number of types of charges taken into account. Results of the fit are presented in Fig. 2 with solid lines. One can notice that description with the simplest model assuming one-carrier conductivity is reasonable at 100 K (with $n = 9.4 \times 10^{14}$ cm^{-3} and $\mu = 2.7 \times 10^5$ cm^2/(V s)) but fails at lower temperatures. We tried to describe the data taking $N = 2$ (electrons and heavy holes) or $N = 3$ (electrons, light, and heavy holes), but the agreement with the experimental data was not satisfactory. A large discrepancy between experimental data and the fit visible in Fig. 3 at lower temperatures is caused by the fact that the fitting was carried out for all the magnetic field range (0–0.5 T) so a small range of B when the discrepancy is large does not influence essentially the overall quality of fit which is optimized in the fitting procedure.

Facing these difficulties, it is evident to indicate that magnetotransport measurements should be repeated on a sample with the Hall-bar geometry and in a broader range of magnetic field. This could allow to eliminate a large contribution of magnetoresistance to the Hall voltage and to influence a possible contribution to conductivity from carriers of the mobility lower that that of electrons (see Eq. (1)).

From the point of view of application of this HgCdTe layer as a THz detector, the most important are properties of the sample at 2 K. Unfortunately, their estimation with the above conductivity model is the least satisfactory. Thus, the values of electron mobility and concentration at the lowest temperature resulting from the $N = 1$ model can serve only as a crude estimation of real values (at 2 K one gets $n = 2.2 \times 10^{13}$ cm^{-3} and $\mu = 2.5 \times 10^6$ cm^2/(V s)). Nevertheless, we think that presented experimental data give a direct evidence of a rapid changes of the layer's conductivity at very small B of about 10–20 mT which is a signature of presence of carriers with mobility of the order of 10^6 cm^2/(V s).

Figure 4 shows a few spectra of transmission of a monochromatic radiation with photon energies between 2.6 meV and 17.6 meV (indicated in the figure). One can easily see that the sample really behaves as a magnetic-field tunable THz detector. It is of a possible great potential for applications that for photon energies of the order of 1 meV, sharp resonant structure appears at magnetic fields of a few tens of mT. Let us note that just in this range of B, conductivity of the layer changes strongly. This is an indication that interpretation of THz spectroscopic data obtained with such a detector working as a photoconductor must be treated with a special care.

In conclusion, we determined a conductivity tensor of a HgCdTe epitaxial layer at a few temperatures between 2 K and 100 K and showed that the sample can be used as a magnetic-field tunable THz detector. We showed that strong variations of conductivity occur at magnetic fields were a resonant optical response is present. That is why magnetoconductivity characteristics of a detector must be taken into account when one wants to use it in a photoconductive mode.

Acknowledgments

A financial support from ERA.Net RUS Plus – TERASENS project, Foundation for Polish Science through the Grant No. TEAM/2016-3/25, Polish National Science Centre UMO-2015/17/B/ST7/03630 through the grant and Russian Ministry for Science and Education is acknowledged.

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