



## ELECTRON LOCALIZATION IN $Pb_{1-x}Sn_xTe(In)$ IN HIGH MAGNETIC FIELD

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We report on the high-field ( $H < 400$  kOe) magnetoresistance of initially dielectric  $Pb_{0.75}Sn_{0.25}Te(In)$ . The data taken at (1.4 - 4.2) K show a magnetoresistance increase in time (localization) for a relatively low concentration of nonequilibrium electrons. The characteristic time for localization  $\tau$  depends exponentially on  $H$  and linearly on  $T$ . The possible origins of the effect are discussed.

### 1. Introduction.

Lead-tin tellurides doped with indium received a lot of attention during recent years because of their promising candidature for photodetection in the far infrared. The nontrivial effects observed in these materials - Fermi level pinning<sup>1</sup> and persistent photoconductivity<sup>2</sup> - originate from unusual features of impurity states in  $Pb_{1-x}Sn_xTe(In)$ <sup>3</sup>. The low-field galvanomagnetic properties of  $Pb_{1-x}Sn_xTe(In)$  have been extensively studied<sup>3</sup>, and some new interesting effects, such as a giant negative magnetoresistance<sup>4</sup>, have been reported.

In this paper we report on high-field ( $H < 400$  kOe) magnetoresistance measurements of  $Pb_{0.75}Sn_{0.25}Te(In)$  in the photomemory regime for different levels of initial photoexcitation in the temperature interval  $1.4 \text{ K} < T < 4.2 \text{ K}$ .

### 2. Experimental.

All  $Pb_{0.75}Sn_{0.25}Te(In)$  samples we investigated were single crystals grown by the modified Bridgman technique. The tin content of an alloy  $x = 0.25$  was chosen in order to provide Fermi level pinning within the bandgap, so initially the samples are in the dielectric state<sup>5</sup>. The indium

concentration ( $N_{In}$ ) varied from 0.2 to 0.5 at.%. External infrared illumination allowed to change smoothly the free electron concentration<sup>2</sup>.

The samples were mounted into the special chamber that was cooled by liquid helium and screened completely the background radiation. An internal thermal source of infrared radiation provided a controlled change of free carrier concentration.

The measurements have been performed in the high-field facility of the University of Amsterdam. The maximum field that can be attained is 400 kOe. Different field profiles can be programmed and the pulse duration is of the order of 1 s.

### 3. Results.

The temperature dependence of the resistivity of all the  $Pb_{0.75}Sn_{0.25}Te(In)$  samples has the well-known characteristics<sup>5</sup>: there are two pronounced activation parts, one of them ((70 - 300) K) corresponds to the thermal electron-hole generation via the bandgap, another one ((15 - 50) K) corresponds to the activation from impurity centers. For the alloys with  $N_{In} < 0.4$  at.% lowering of the temperature below 15 K results in thermal "freezing" of electrons in the conduction band. The amount of "frozen"

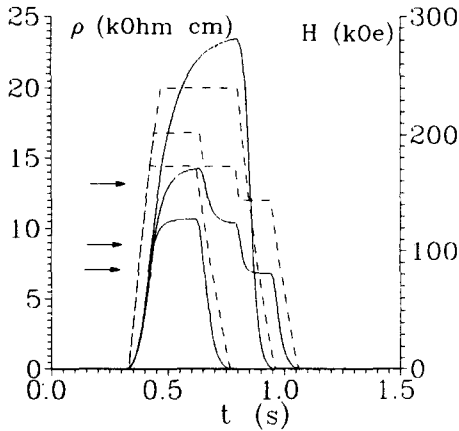


Fig. 1. Magnetoresistance (solid lines) and magnetic field (dashed lines) versus time for  $Pb_{0.75}Sn_{0.25}Te + 0.2$  at.% In at  $T = 4.2$  K.  $\rho_0 = 25$  Ohm cm. The arrows indicate the moment of magnetic field stabilization to the different  $\rho(H)$  curves.

electrons depends on  $N_{In}$  and on the cooling rate <sup>6</sup>. For the sample with  $N_{In} = 0.5$  at.% the "darkness" free electron concentration does not exceed  $10^6$   $cm^{-3}$  at  $T = 4.2$  K <sup>5</sup>. The effects we observe do not depend on whether the nonequilibrium electrons are photo-generated or "frozen".

Some typical magnetoresistance and magnetic field versus time profiles are shown in fig. 1. It was found that if  $\rho_0$  is high enough, the resistivity of the sample increases exponentially in time after the moment  $t_0$  of magnetic field stabilization:

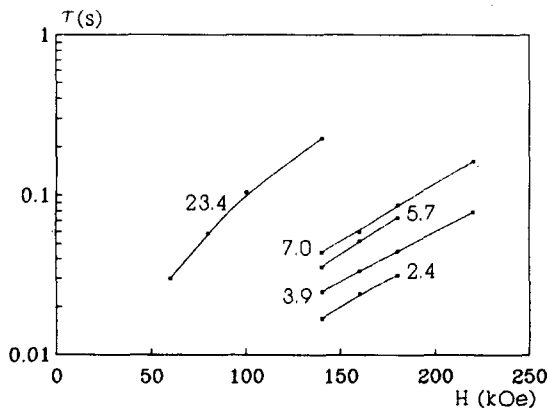


Fig. 2. Dependence of the characteristic time  $\tau$  on magnetic field  $H$  for  $Pb_{0.75}Sn_{0.25}Te + 0.4$  at.% In at  $T = 4.2$  K for the different degrees of photoexcitation. Figures near the lines -  $\rho_0$  in Ohm cm.

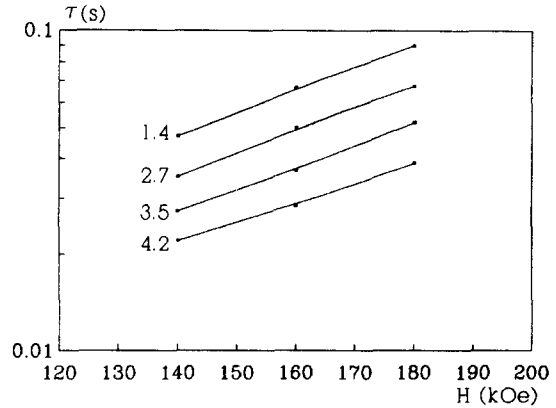


Fig. 3. Dependence of the characteristic time  $\tau$  on magnetic field  $H$  for  $Pb_{0.75}Sn_{0.25}Te + 0.4$  at.% In at the different temperatures for  $\rho_0(T=4.2K) = 2.3$  Ohm cm. Figures near the lines -  $T$  in K.

$$\rho = \rho(t=t_0) + \Delta\rho \{1 - \exp[-(t-t_0)/\tau]\} \quad (1)$$

Our earlier measurements have shown that this resistivity rise is due to the decrease of free electron concentration, i.e. to the localization effect <sup>7</sup>.

For every fixed  $\rho_0$  the characteristic time  $\tau$  depends exponentially on the magnetic field applied (fig. 2, 3):

$$\tau = \tau(H=0) \exp(H/H_0) \quad (2)$$

The characteristic field  $H_0$  does not depend on temperature, or on the degree of the photoexcitation (i.e. the  $\rho_0$  value) for magnetic field exceeding 80

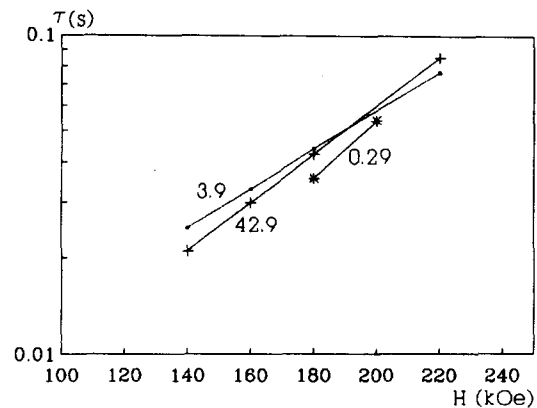


Fig. 4. Field variation of the characteristic time  $\tau$  at  $T = 4.2$  K for samples with values of  $N_{In}$  of 0.2 at.% (+), 0.4 at.% (·), and 0.5 at.% (\*). Figures near the lines -  $\rho_0$  in Ohm cm.

kOe (fig. 2.3).  $H_0$  depends only slightly on  $N_{In}$  (fig. 4). It should be noted, however, that the smaller is  $N_{In}$ , the lower photoexcitation (higher  $\rho_0$ ) is needed to reach the same  $\tau$  in comparable magnetic fields (fig. 4). In relatively low fields ( $H < 80$  kOe) the  $\tau(H)$  dependence becomes nonexponential (fig. 2). This nonexponential behavior is only observed for very small degree of photoexcitation.

Rising of the free electron concentration leads to the shift of a region, where the effect is observed, to higher magnetic fields (fig. 2). If  $\rho_0$  is small enough, the resistivity relaxation is not detected for the highest  $H = 380$  kOe and  $\partial H/\partial t = 800$  kOe/s that we have used in our experiment ( $\tau < 10^{-2}$  s).

The temperature dependence of  $\tau$  at fixed  $H$  is close to be linear (fig. 5)

$$\tau = \tau_0 (1 - T/T_0) \exp(H/H_0) \quad (3)$$

where  $T_0$  does not depend on the magnetic field applied, and is defined only by the nonequilibrium electron concentration  $n$ .  $T_0$  drops with increasing  $n$ .

The dataset we have does not allow to determine precisely  $\tau_0(N_{In})$ . We can only conclude that  $\tau_0 \sim 10^{-2}$  s.

#### 4. Discussion.

Generally, the effect of localization in magnetic field might originate from a range of different mechanisms.

##### 1) Localization on the deep impurity level $E_0$ in magnetic field.

If  $E_0$  is initially empty, lies higher than the quasiFermi level  $E_F$  and

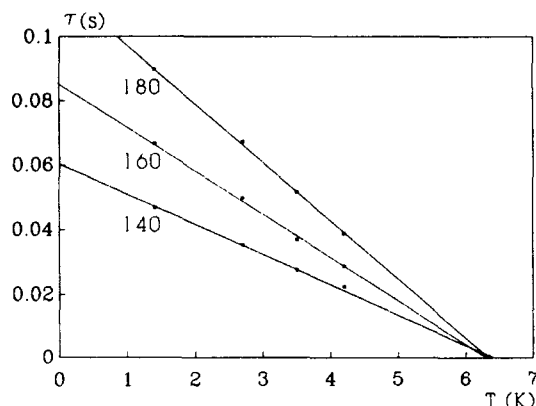


Fig. 5. Dependence of the characteristic time  $\tau$  on the temperature  $T$  for different magnetic fields  $H$ . Figures near the lines -  $H$  in kOe,  $\rho_0 = 2.3$  Ohm cm,  $N_{In} = 0.4$  at. %.

shifts down in energy in magnetic field, one could observe a transition of electrons from the conduction band to the impurity level when  $E_0$  crosses  $E_F$ . However in this case for a higher degree of photoexcitation,  $E_F$  should approach  $E_0$ , so the localization should shift to lower fields. Experimentally the opposite is observed.

##### 1) Localization due to the energy band modulation (EBM).

The EBM amplitude  $E_{EBM} \sim (1-2)$  meV in  $Pb_{1-x}Sn_xTe(In)$  has been estimated in <sup>8</sup> from the analysis of the Shubnikov - de Haas oscillation data. The shift of the localization region to higher fields for higher degree of photoexcitation is the most strong argument providing evidence for such a connection. Indeed, the nonequilibrium free carriers screen the inhomogeneities, and therefore  $E_{EBM}$  decreases as  $\rho_0$  drops. Furthermore, lowering of the indium content in the sample should lead to a decrease of  $E_{EBM}$ . If the value of  $\tau$  is defined by  $E_{EBM}$ , then for a smaller  $N_{In}$  a lower photoexcitation (higher  $\rho_0$ ) is needed to reach the same  $\tau$  in comparable magnetic fields. This effect is observed experimentally (fig. 4).

Let us consider now, how the EBM can lead to the localization effect. If we assume that for a relatively low degree of photoexcitation the sample conductivity is defined by the activation from  $E_F$  to the percolation level  $E_p$ , then the increase of the sample resistance may result from the activation energy rising in magnetic field. The latter is a consequence of the increase of the conduction band density of states. If the localization is an activation process, then

$$\tau = \tau_0 \exp[(E_p - E_F)/kT] \quad (4)$$

If  $(E_p - E_F)$  in a first approximation depends linearly on  $H$ :  $(E_p - E_F) = (E_p - E_F)_0 + \alpha H$ , then, comparing (3) and (4), one obtains

$$H_0 = kT/\alpha \quad (5)$$

i.e.  $H_0$  should be proportional to the sample temperature. We see however that  $H_0$  does not depend on  $T$  (fig. 3). This means that the localization is not the activation process.

One could suppose that the conductivity is defined by the tunnelling through the drift barriers. This might explain the absence of the strong temperature dependence of  $H_0$ , because the barrier thickness does not depend on  $T$ . In the framework of this hypothesis it is natural to suppose that the parameter  $T_0$  is just the measure of  $E_{EBM}$ . Indeed, first of all,  $T_0$  becomes smaller for the higher

degree of photoexcitation. Besides that,  $\tau_0$  is of the same order of magnitude as  $E_{FEM}$ , estimated in 8.

On the other hand, in this case there should exist a strong dependence of the barrier thickness, and, consequently, of the parameter  $H_0$ , on the free electron concentration. However we see that  $H_0$  is a sample parameter and does not depend on any external factor.

Besides that, it is not clear, how this mechanism can provide the dynamics of the process we observe. Indeed, the characteristic time of the free carrier concentration change is defined by the Maxwell relaxation time  $\tau_m = \epsilon\epsilon_0\rho \sim 10^{-5}$  s, that is much lower than the observed values of  $\tau$ .

#### iii) Localization due to the magnetic freeze-out on the shallow impurities.

It is known, that due to the high value of the dielectric constant in  $Pb_{1-x}Sn_xTe$ ,  $\epsilon \sim 10^4$  9, the shallow impurities have a very low binding energy, and do not form bound states even in rather high magnetic fields  $H \sim 80$  kOe 10. If the effect we observe is due to the magnetic freeze-out, then the shift of the localization region to higher fields for higher free electron concentration might originate from the amplification of the shallow impurity potential. On the other hand, as in the case with the EBM, the dynamics of the process is not clear. Besides that, the linear character of the  $\tau(T)$  dependence contradicts this assumption.

#### iiii) Others.

One cannot exclude that the localization of the nonequilibrium electrons in magnetic field has yet another microscopic nature. First of all, the parameter  $H_0$  does not depend on any external factor. Secondly, the value of  $\tau_0 \sim 10^{-2}$  s is close to the characteristic time of the initial fast photoconductivity drop after switching-off the radiation source 11. Usually this process is associated with a recombination to the metastable impurity states that reveal themselves in a range of other effects 4, 11, 12. However the motion of this metastable impurity level in the low magnetic field  $H < 0.5$  T seems to lead, in

contrary, to the delocalization of electrons resulting in a giant negative magnetoresistance effect 4.

#### 5. Summary.

In summary, we have observed localization effect in high magnetic fields in  $Pb_{1-x}Sn_xTe(In)$  and discussed its origin in terms of 1) localization on deep impurity level, ii) energy band modulation, iii) magnetic freeze-out on shallow level. No one of these origins seem to offer a satisfactory explanation, and more experimental and especially theoretical efforts are needed to elucidate this discrepancy.

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