Semicond. Sci. Technol. 8 (1993) S352–S355. Printed in the UK

Magnetic-field-induced localization in $Pb_{1-x}Sn_xTe(In)$

D R Khokhlov†, I I Ivanchik†, A de Visser‡ and A V Nikorich§

† Physics Department, Moscow State University, Moscow 119899, Russia
‡ Van der Waals–Zeeman Laboratory, University of Amsterdam, Valckenierstraat 65–67, 1018 XE Amsterdam, The Netherlands
§ Institute of Applied Physics of Moldavian Academy of Sciences, Grosula 5, Kishinev, Moldova

Abstract. 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 an increase in magnetoresistance with time (localization) for a relatively low concentration of non-equilibrium electrons n. The characteristic time for localization τ depends exponentially on H and linearly on T. The possible origins of the effect are discussed.

1. Introduction

Lead–tin tellurides doped with indium have received a lot of attention over recent years because of a number of unusual effects observed in this material, for example Fermi level pinning [1] and persistent photoconductivity [2]. These effects originate from unusual features of the impurity states in $Pb_{1-x}Sn_xTe(In)$ [3]. The low-field galvanomagnetic properties of $Pb_{1-x}Sn_xTe(In)$ have been extensively studied [3], and some new interesting effects, such as a giant negative magnetoresistance [4], 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 K $< T <$ 4.2 K.

2. Experiment

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 were in the dielectric state [5]. The indium concentration (N_{In}) varied from 0.2 to 0.5 at.%. External infrared illumination allowed the free electron concentration to be changed smoothly [2].

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

The measurements were 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 $Pb_{0.75}Sn_{0.25}Te(In)$ samples has well-known characteristics [5]: there are two pronounced activation parts, one (70–300 K) corresponds to the thermal electron–hole generation via the bandgap, another (15–50 K) corresponds to the activation from impurity centres. For 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 number of 'frozen' electrons depends on N_{In} and on the cooling rate [6]. 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 [5]. The effects we observe do not depend on whether the non-equilibrium electrons are photogenerated or 'frozen'.

Some typical magnetoresistance and magnetic field versus time profiles are shown in figure 1. It was found that if ρ_0 is high enough, the resistivity of the sample increases exponentially in time after the moment t_0 of magnetic field stabilization

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

Our earlier measurements have show that this rise in resistivity is due to a decrease of free electron concentration, i.e. to the localization effect [7].

For every fixed ρ_0 the characteristic time τ depends exponentially on the applied magnetic field (figures 2, 3)

$$\tau = \tau_{(H=0)} \exp(H/H_0). \qquad (2)$$

0268-1242/93/01S352+04 $07.50

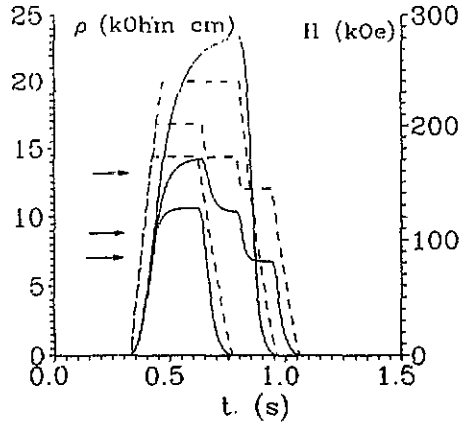

Figure 1. Magnetoresistance (full curves) and magnetic field (broken curves) versus time for $Pb_{0.75}Sn_{0.25}Te$ + 0.2 at.% In at $T = 4.2$ K, $\rho_0 = 25\,\Omega$ cm. The arrows indicate the moment of magnetic field stabilization to the different $\rho(H)$ curves.

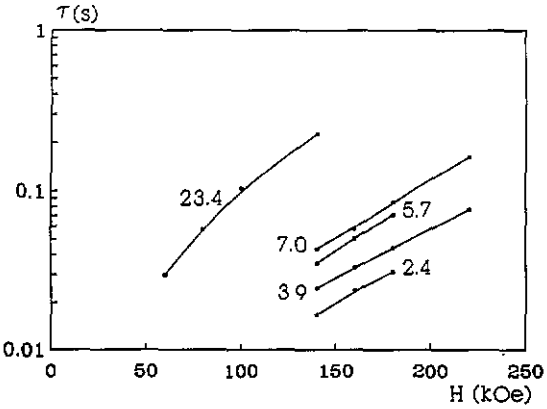

Figure 2. Dependence of the characteristic time τ on magnetic field H for $Pb_{0.75}$ · $_{\sim 5}$Te + 0.4 at.% In at $T = 4.2$ K for the different degrees of photoexcitation. Figures near the lines are ρ_0 in Ω cm.

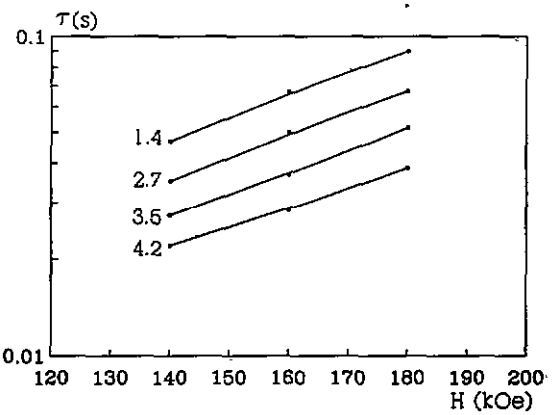

Figure 3. Dependence of the characteristic time τ on magnetic field H for $Pb_{0.75}Sn_{0.25}Te$ + 0.4 at.% at the different temperatures for ρ_0 ($T = 4.2$ K) = 2.3 Ω cm. Figures near the lines are T in K.

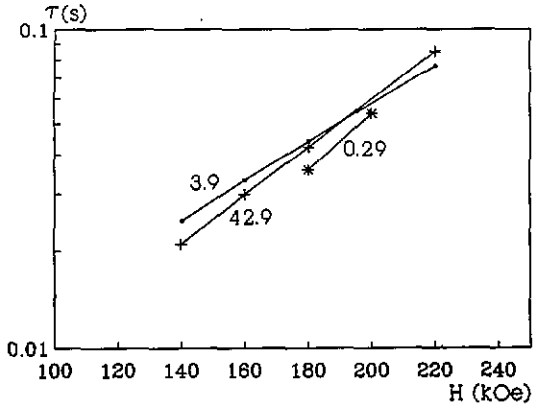

Figure 4. Field variation of the characteristic time τ at $T = 4.2$ K for samples with values of N_{In} of 0.2 at.% (+), 0.4 at.% (•), and 0.5 at.% (*). Figures near the lines are ρ_0 in Ω cm.

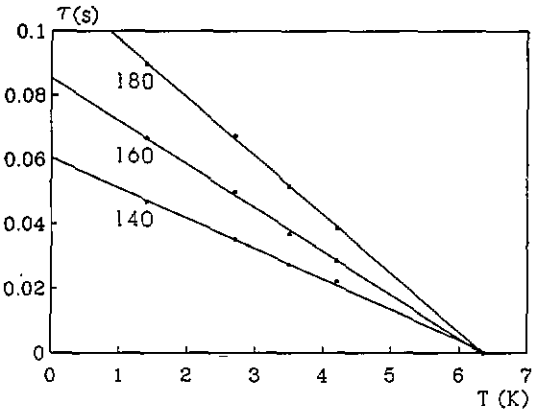

Figure 5. Dependence of the characteristic time τ on the temperature T for different magnetic fields H. Figures near the lines are H in kOe; $\rho_0 = 2.3\,\Omega$ cm, $N_{In} = 0.4$ at.%.

The characteristic field H_0 does not depend on temperature, or on the degree of the photoexcitation (i.e. the ρ_0 value) for magnetic fields exceeding 80 kOe (figures 2, 3). H_0 depends only slightly on N_{In} (figure 4). It should be noted, however, that the smaller N_{In} is, the lower the photoexcitation (higher ρ_0) needed to reach the same τ in comparable magnetic fields (figure 4). In relatively low fields ($H < 80$ kOe) the $\tau(H)$ dependence becomes non-exponential (figure 2). This non-exponential behaviour is only observed for very small degrees of photoexcitation.

The temperature dependence of τ at fixed H is close to linear (figure 5)

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

where T_0 does not depend on the applied magnetic field, and is defined only by the non-equilibrium electron concentration n. T_0 drops with increasing n. One can see that if the photoexcitation is strong enough, i.e. if T_0 becomes less than the sample temperature T, then the effect is no longer observed.

The dataset we have does not allow us 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 a magnetic field might originate from a range of different mechanisms.

4.1. Localization due to energy band modulation (EBM)

The EBM amplitude $E_{EBM} \sim 1$–2 meV in the $Pb_{1-x}Sn_xTe(In)$ alloys has been estimated in [8] from the analysis of Shubnikov–de Haas oscillation data.

The strongest argument providing evidence for such a connection is the following. One can see from figure 2 that, for every fixed magnetic field, τ drops with increasing n, and if the free electron concentration is high enough, then the value of τ becomes smaller than the characteristic time of the magnetic field increase. Experimentally it looks like a shift of the localization region to higher fields for a higher degree of photoexcitation. The non-equilibrium free carriers screen the inhomogeneities, so if the value of τ is defined by E_{EBM}, then E_{EBM} and τ decrease as ρ_0 drops. Furthermore, lowering of the indium content in the sample should lead to a decrease of E_{EBM}, then for a smaller N_{In} a lower photoexcitation (higher ρ_0) is needed to reach the same τ in comparable magnetic fields. This effect is observed experimentally (figure 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 increasing with 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

$$\tau = \tau_0 \exp[(E_p - E_F)/kT]. \tag{4}$$

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

$$H_0 = kT/\alpha \tag{5}$$

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

One could suppose that the conductivity is defined by tunnelling through the drift barriers. This might explain the absence of a 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, T_0 first becomes smaller for a higher degree of photoexcitation. Besides this, T_0 is of the same order of magnitude as E_{EBM}, estimated from an analysis of the Shubnikov–de Haas oscillation data 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 an external factor.

Also, 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 $\tau_m = \varepsilon\varepsilon_0\rho \sim 10^{-5}$ s, which is much lower than the observed values of τ.

4.2. Localization due to magnetic freeze-out on the shallow impurities

It is known that, due to the high value of the dielectric constant in $Pb_{1-x}Sn_xTe$, $\varepsilon \sim 10^4$ [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 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 this, the linear character of the $\tau(T)$ dependence contradicts this assumption.

4.3. Localization on the deep impurity level E_0 in a magnetic field

If E_0 is initially empty, lies higher than the quasi Fermi level E_F and shifts down in energy in a magnetic field, one could observe a transition of electrons from the conduction band to the impurity level when E_0 crosses E_F. It is likely that E_0 is a metastable impurity state revealing itself in a range of other effects [4, 11, 12].

First of all, the metastable impurity state is separated by a barrier $W \sim 1$ meV in the configuration-coordinate space from the extended and the ground impurity states [12]. This can easily explain the dynamics of the process. Indeed, the barrier height of ~ 20 meV between the ground impurity and the extended states provides the characteristic recombination time of photoconductivity $\sim 10^3$ s at $T = 4.2$ K [2], so the observed range of τ values for the transitions from E_F to E_0 is reasonable. Next, 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 [2]. Usually this process is associated with a recombination to the metastable impurity states [11]. Finally, independence of the parameter H_0 from any external factor indicates that the localization process is defined by the internal structure of the metastable impurity centre.

On the other hand, motion of the metastable impurity level in the low magnetic field $H < 0.5$ T for a small degree of photoexcitation seems to lead to the delocalization of electrons, resulting in a giant negative magnetoresistance effect [4]. The delocalization effect in high magnetic fields has also been observed for very high degrees of photoexcitation, when there is no localization [7]. If the same metastable impurity state is responsible for all these effects, then its motion in a

magnetic field should depend on the level filling factor in a very unusual way.

5. Summary

In summary, we have observed the localization effect in high magnetic fields in $Pb_{1-x}Sn_xTe(In)$ and discussed its origin in terms of (i) energy band modulation, (ii) magnetic freeze-out on a shallow level and (iii) localization on a metastable deep impurity level. None of these origins seems to offer a complete explanation, and more experimental and especially theoretical efforts are needed to elucidate this discrepancy.

Acknowledgment

We are grateful to Professor A V Dmitriev from the Moscow State University and to Dr P Frings from the University of Amsterdam for helpful discussions.

References

[1] Averkin A A, Kaidanov V I and Mel'nik R B 1971 *Fiz. Tekh. Poluprov.* **5** 91
[2] Akimov B A, Brandt N B, Klimonskiy S O, Ryabova L I and Khokhlov D R 1982 *Phys. Lett.* **88A** 483
[3] Kaidanov V I and Ravich Yu I 1985 *Sov. Phys.–Usp.* **28** 31
[4] Akimov B A, Nikorich A V, Khokhlov D R and Chesnokov S N 1989 *Fiz. Tekh. Poluprov.* **23** 668
[5] Akimov B A, Zhlomanov V P, Ryabova L I, Chudinov S M and Yatsenko O B 1979 *Sov. Phys.–Semicond.* **13** 759
[6] Akimov B A, Albul A V, Nikorich A V, Ryabova L I and Khokhlov D R 1984 *Sov. Phys.–Semicond.* **18** 1112
[7] Khokhlov D R, de Visser A, Ivanchik I I and Nikorich A V 1992 *Physica* B **177** 491
[8] Akimov B A, Brandt N B, Ryabova L I, Sokovishin V V and Chudinov S M 1983 *J. Low Temp. Phys.* **51** 9
[9] Nishi S, Kawamura H and Murase K 1980 *Phys. Status Solidi* b **97** 581
[10] Bauer G, Burkhard H, Heinrich H and Lopez-Otero A 1976 *J. Appl. Phys.* **47** 1721
[11] Romchevich N, Popovich Z V, Khokhlov D, Nikorich A V and Konig W 1991 *Phys. Rev.* B **43** 6712
[12] Zasavitskiy I I, Matsonashvili B N, Pankratov O A and Trofimov V T 1985 *Sov. Phys. JETP Lett.* **42** 1