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WEAK-LOCALIZATION IN n- AND p-TYPE FILMS OF $Pb_{1-x}Eu_xTe$

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We investigated the magnetotransport properties of n- and p-type films of $Pb_{1-x}Eu_xTe$, grown by molecular beam epitaxy, with Eu concentrations close to the Metal-Insulator transition. The n-type sample shows a negative magnetoresistance which magnitude increases continually as the temperature is lowered. On the other hand, for the p-type sample, a negative magnetoresistance can be observed only for temperatures below 7 K. Comparing the magnetoresistance of both samples we show that the scattering mechanism should have a different origin.

Keywords: Weak localization; diluted magnetic semiconductors; magnetic scattering.

1. Introduction

$Pb_{1-x}Eu_xTe$ alloys are IV-VI diluted magnetic semiconductors (DMS) which have demonstrated important optical properties. The introduction of the Eu^{2+} ions into the binary PbTe causes an increase of its energy gap, that can be varied from 0.31 eV up to 2.0 eV.[1] Due to this characteristic these alloys can be used as basic materials for optical detectors and sensors devices, which can cover continuously the optical spectrum from the infrared to the visible range. Besides the increase of the energy gap, the introduction of localized magnetic moments of the Eu^{2+} ions can also modify the electrical and optical properties of the alloy. In general, DMS exhibit cooperative effects due to spin exchange interactions not present in nonmagnetic semiconductors.[2] As for any DMS the understanding of the interaction between the magnetic ions and the spin of the free carriers is of fundamental importance, particularly for the development of the spintronics.[3]

Another important consequence of the addition of the Eu^{2+} ions into the PbTe is the introduction of disorder which, due to short-range alloy scattering, causes a Metal-Insulator Transition (MIT). It has been shown by Prinz et al.[4] that the increase of the Eu content in n-type films of $Pb_{1-x}Eu_xTe$ doped with Bi induces a MIT for x about 0.10. A negative magnetoresistance has also been observed in these alloys at low magnetic fields indicating the presence of weak localization. A MIT has also been detected in p-type films of $Pb_{1-x}Eu_xTe$ for $x \sim 0.05$.[5]

2. Growth and Characterization

In this work we investigate the magnetotransport properties of n- and p-type films of $Pb_{1-x}Eu_xTe$ with Eu concentrations close to the MIT, i.e., $x \approx 0.10$ and $x \approx 0.05$ for n- and p-type samples, respectively. The n and p character of our samples is obtained by a careful control of its stoichiometry, since Pb (Te) vacancies in PbTe act as acceptor (donors). The samples were grown by molecular beam epitaxy (MBE) onto (111) BaF_2 substrates. Three effusion cells with PbTe, Eu and Te_2 were utilized to grow the samples. The flux variation of the Te_2 cell source is used to control the concentration and the type of carriers. All films have a thickness of about 2 μm. Samples were electrically characterized, as a function of temperature, through resistivity and Hall effect measurements from 10 K to 300 K. Its magnetoresistance was measured for magnetic fields up to 17 T and temperature ranging from 1.3 K up to 100 K. Samples with annealed In contacts in the van der Pauw geometry were used.

3. Results and Discussion

In Fig. 1 we show the resistivity (Fig. 1(a)) and carrier concentration (Fig. 1(b)) as a function of temperature for both n- and p-type films. For both films the resistivity shows an insulator behavior, i.e., an increase of the resistivity as the temperature is lowered. For the n-type sample this increase is monotonic, while for the p-type sample the resistivity shows a sharp increase for temperatures lower than 6 K. The decrease of the carrier concentration, as a function of temperature, has a similar behavior for both samples. The product $k_F l$, where k_F is the Fermi wave vector and l is the mean free path, diminishes as we decrease the temperature, varying from 1.20 to 0.61 for the n-type film and from 0.37 to 0.26 for the p-type film. This shows that our samples are in the limit between a metallic and insulator behavior ($k_F l \sim 1$).

The magnetoresistance measured for the n- and p-type samples is shown in Fig. 2(a) and 2(b), respectively. The n-type sample, obtained by lack of stoichiometry, presents a positive and a negative contribution to the magnetoresistance for temperatures as high as 40 K. A similar behavior has been observed by Prinz et al.[4] in $Pb_{1-x}Eu_xTe$ films doped with Bi. The positive component results from the field-induced redistribution of the electrons between the Landau levels corresponding to different valleys as well as, from the onset of the field-induced localization. The negative component is associated with a localization effect and it results from the destructive influence of the magnetic field upon interference of self-crossing trajectories. Its magnitude increases as the temperature is lowered in a smooth way.

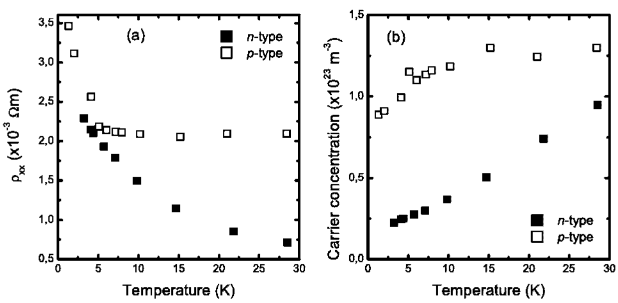

Fig. 1. Resistivity (ρ_{xx}) (a) and carrier concentration (b) as a function of temperature for n- and p-type films of $Pb_{1-x}Eu_xTe$.

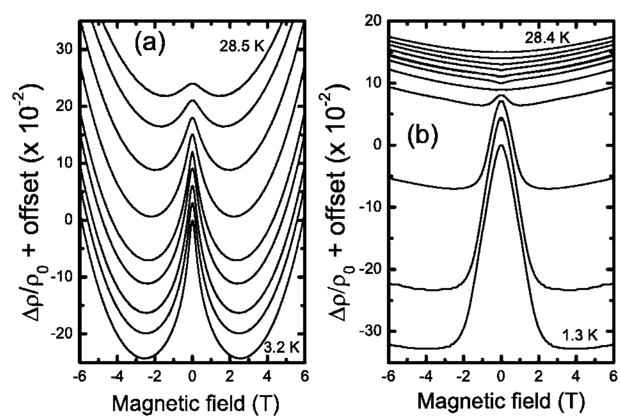

Fig. 2. Magnetoresistance for different temperatures for (a) n-type film (T = 3.2, 4.1, 4.4, 5.7, 7.1, 9.8, 14.7, 21.8, and 28.5 K) and (b) p-type sample (T = 1.3, 2.5, 4.1, 5.1, 6.0, 7.2, 7.9, 10.2, 15.2, 21.0, and 28.4).

For the p-type sample we observe only a positive contribution to the magnetoresistance for temperatures down to about 7 K. For lower temperatures a negative contribution shows up, which magnitude increases steeply as the temperature is lowered. This clearly shows that we cannot attribute the weak localization effects to the same scattering mechanisms.

We have used a model developed by Kawabata, for anisotropic surfaces of constant energies and $k_F l \gg 1$,[6] to describe the negative component of the magnetoresistance. The magnetoconductivity as a function of the magnetic field (H) is given by

$$\Delta\sigma = \sigma(H) - \sigma(0) = \frac{fe^2}{2\pi^2\hbar l_H} F(\delta)$$

where

$$F(\delta) = \sum_{N=0}^{\infty} \left[2\left(\sqrt{N+1+\delta} - \sqrt{N+\delta}\right) - \frac{1}{\sqrt{N+\frac{1}{2}+\delta}} \right]$$

with the cyclotron radios

$$l_H = \sqrt{\frac{\hbar}{eH}} \qquad \text{and} \qquad \delta = \frac{l_H^2}{4\tau_\varepsilon D}$$

where τ_ε is the inelastic scattering time and D the diffusion constant. f is a factor used to describe the anisotropy and the many valley contribution. We use f and τ_ε as fitting parameters.

The fitting obtained for the magnetoresistance of both n- and p-type samples are shown in Fig. 3(a) and 3(b), respectively. A good agreement can be observed for low magnetic fields. For the n-type film we obtain $\tau_\varepsilon \propto T^{-1.55}$ and $f = 0.83$ which are very closed to the values obtained by Prinz et al.[4] ($\tau_\varepsilon \propto T^{-1.72}$ and $f = 0.82$) for a $Pb_{1-x}Eu_xTe$ film doped with Bi. For the p-type sample a good agreement can be observed only for temperatures $T < 6$ K from which we obtain $\tau_\varepsilon \propto T^{-3.66}$ and $f = 0.7$. We obtain f smaller than one ($f = 1$ in the case of many valley systems provided that intervalley scattering time is shorter than the phase relaxation time) probably due to a fast intervalley scattering process. The temperature dependence obtained for the inelastic scattering time could be attributed to the electron-phonon scattering. In the metallic regime ($k_F l \gg 1$) a $\tau_\varepsilon \propto T^{-3}$ has been predicted[7] while in the insulator regime ($k_F l \ll 1$) the theoretical predictions are controversial. A $\tau_\varepsilon \propto T^{-4}$ (Ref. 8) as well as $\tau_\varepsilon \propto T^{-2}$ (Ref. 9) have been obtained. It is important to note that the model used was developed to systems where $k_F l \gg 1$, but even for our systems where $k_F l \approx 1$ a reasonable fitting could be obtained.

M. Csontos et al.[10] observed a large negative magnetoresistance in InMnSb diluted magnetic semiconductor. They found that the large negative magnetoresistance is dominated by the scattering between the holes and the Mn magnetic ions. They also performed experiments by applying pressure in the samples to increase the p-d coupling and had observed a increasing on the negative magnetoresistance. In the case of $Pb_{1-x}Eu_xTe$ no effect has been observed of the interaction between the electrons and the Eu magnetic ions in n-type samples. However, it is well known that in DMS the interaction between holes and the magnetic ions is stronger than for electrons. Hence, the scattering by the magnetic ions could probably explain the abrupt increase of the negative contribution to the magnetoresistance of our p-type samples. This is under investigation.

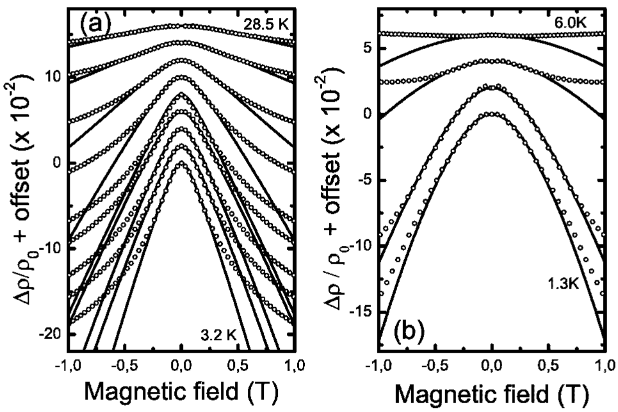

Fig. 3. Fit of the magnetoresistance using the model described in the text for (a) n-type and (b) p-type samples, respectively. Symbols are the measured curves and the solid lines the fitting.

4. Conclusions

We have studied the magnetotransport properties of n- and p-type films of $Pb_{1-x}Eu_xTe$, grown by molecular beam epitaxy, with Eu concentrations close to the Metal-Insulator transition. Our results for the n-type sample, obtained by lack of stoichiometry, confirm that the short-range scattering could be responsible by the weak localization. On the other hand, for the p-type sample, it seems necessary to include the scattering by the localized magnetic moments.

Acknowledgments

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References

1. A. Y. Ueta, Ph.D. Thesis, Johannes Kepler Universität, Linz, Austria (1997).
2. *Diluted Magnetic Semiconductors*, edited by J. K. Furdyna and J. Kossut, *Semiconductors and Semimetals* vol. 25 (Academic, Boston, 1986).
3. S. A. Wolf et al., *Science* **294**, 1488 (2001).
4. A. Prinz et al., *Phys. Rev. B* **59**, 12983 (1999).
5. J. A. H. Coaquira et al., *J. Superconductivity* **16**, 115 (2003).
6. A. Kawabata, *Solid State Commun.* **34**, 431 (1980).
7. P. Santhanam et al., *Phys. Rev. B* **35**, 3188 (1987).
8. J. Rammer and A. Schmid, *Phys. Rev. B* **34**, 1352 (1986).
9. D. Belitz and S. Das Sarma, *Phys. Rev. B* **36**, 7701 (1987).
10. M. Csontos et al., *Phys. Rev. Lett.* **95**, 227203 (2005).