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The temperature dependence of the inelastic scattering time in metallic n-InP

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Abstract. The weak localization near the metal–insulator transition in doped semiconductors is due to quantum interference effects, which can be observed when the inelastic scattering time τ_e is greater than the elastic scattering time τ_0. τ_e is considered to be an important parameter in the physics of submicrometre electronic devices. In this work we have determined τ_e for n-InP from negative-magnetoresistance measurements at low temperature. Three methods based on weak-localization theory have been used for low and moderate magnetic fields. In the temperature range 2 K–15 K, τ_e varies like T^{-1}, which agrees to some extent with the theory of Isawa. Theory and experiment give values of τ_e that have the same order of magnitude.

1. Introduction

Negative magnetoresistance in doped semiconductors at low temperature was first observed by Fritzsche and Lark-Horovitz (1955) some years after the observation of impurity band conduction. Since then, this negative magnetoresistance has been observed in various doped semiconductors and appears to be characteristic of different kinds of disordered systems of electrons. It was also observed in the case of localized electrons. However, most of the experimental results have been obtained with samples exhibiting metallic behaviour and impurity concentrations higher than the critical value n_c defined by the Mott criterion for the metal–insulator transition, i.e. $n_c^{1/3}a_H = 0.25$.

Several models, such as the localized magnetic moments model of Toyozawa (1962), have been proposed to explain the negative magnetoresistance. However, although the concept of localized spins in disordered systems without magnetic impurities has often been put forward and considered realistic, the recent development of microscopic theories for localization and the metal–insulator transition has led to the most convenient models for explaining the experimental results.

All these theories assume that the diffusion of electrons is accompanied by quantum interference between wave functions. A weak magnetic field introduces a phase shift and destroys the quantum interference; this leads to a negative magnetoresistance which varies as B^2 at very low magnetic fields and as $B^{1/2}$ for moderate magnetic fields. In this latter case $\Delta\sigma = AB^{1/2}$ and A ranges in value between 1 and 10 for metallic systems having impurity concentrations in a wide range between 10^{14} cm^{-3} and 10^{20} cm^{-3}; these values of A are comparable to the theoretical value of 2.9 used by several authors.

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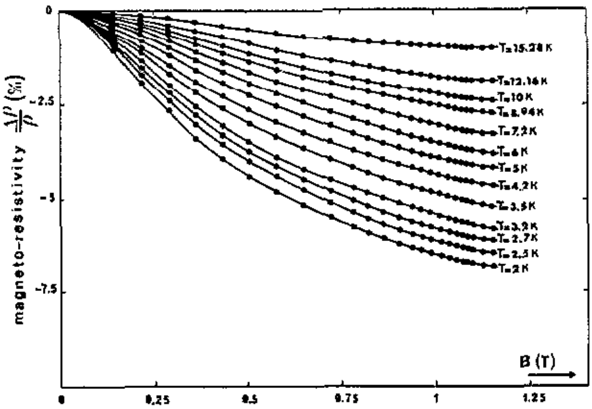

Figure 1. The variation of the negative magnetoresistivity $\Delta\rho/\rho$ with the magnetic field for temperatures between 2 K and 15 K.

This negative magnetoresistance is found to vary with temperature. This variation arises from the temperature dependence of the inelastic scattering time τ_e, the mean time between two inelastic collisions with another electron or a phonon; these scattering processes destroy the phase coherence of the electron wave functions. τ_e is temperature dependent and the negative magnetoresistance technique is the only method available for obtaining τ_e when $\tau_e > \tau_0$, where τ_0 is the elastic mean free path.

2. Experimental details

The n-type indium phosphide sample used in our experiment had an impurity concentration $n = 8 \times 10^{16}$ cm^{-3}, which is nearly twice the critical concentration for the metal–insulator transition: $n_c \simeq 4.8 \times 10^{16}$ cm^{-3}. The compensation was determined from the temperature dependence of the mobility between 1.5 K and 50 K. It was found to be $K = 0.5$ by use of the Brooks–Herring model (Brooks 1955) in a regime of scattering by ionized impurities. The negative magnetoresistance was measured between 2 K and 15 K for magnetic fields varying between 0 and 1.25 T.

3. Results and discussion

Figure 1 shows the magnetic field dependence of the magnetoresistivity between 0 and 1.15 T. It is negative and increases in magnitude at the lowest temperatures by up to 7%. It is more convenient to analyse the magnetoconductivity; it can be seen in figure 2 that the magnetoconductivity $\Delta\sigma$ varies as B^2 for weak magnetic fields. The highest magnetic field in this regime is 0.225 T at 12 K. As the temperature is decreased, $\Delta\sigma$ becomes larger, and the range of magnetic field where the magnetoconductivity varies as B^2 is reduced; the lowest value is 0.15 T at 2 K.

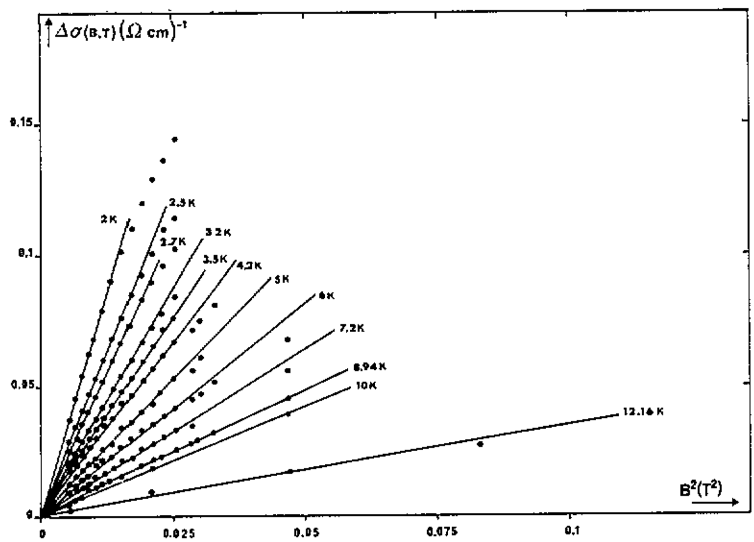

Figure 2. The magnetoconductivity $\Delta\sigma(B, T)$ as a function of the squared magnetic field, in the region of lowest magnetic fields, for temperatures between 2 K and 12 K.

Using the theory of weak localization, and neglecting electron–electron interactions, Kawabata (1980) showed that the magnetoconductivity can be given by the expression

$$\Delta\sigma = 4.8\, B^{1/2} F(\delta) \tag{1}$$

where

$$\delta = \hbar/4eDB\tau_e \qquad F(\delta) = \sum_{N=0}^{\infty} [2(N+1+\delta)^{1/2} - (N+\delta)^{1/2} - 1/(N+\tfrac{1}{2}+\delta)^{1/2}]. \tag{2}$$

Here D is the diffusion constant and τ_e is the inelastic scattering time. In fact, relation (1) is valid under the conditions

$$k_f l_0 > 1 \qquad eB\tau_0/m^* < 1 \qquad l_0 < \lambda$$

where eB/m^* is the cyclotron frequency, l_0 the elastic mean free path, τ_0 the elastic scattering time, $\lambda = (\hbar/eB)^{1/2}$ the magnetic length and k_F the wave vector at the Fermi energy.

For weak magnetic fields, relation (1) has a simple form; the Kawabata function $F(\delta)$ becomes $F(\delta) = 0.002\,08\, \delta^{-3/2}$, and the magnetoconductivity varies as B^2 and is given by the relation

$$\Delta\sigma = \frac{\sigma_0}{12(3^{1/2})} \left(\frac{\tau_e}{\tau_0}\right)^{3/2} \left(\frac{eB\tau_0}{m^*}\right)^2. \tag{3}$$

This relation has been used by many authors to obtain values of τ_e.

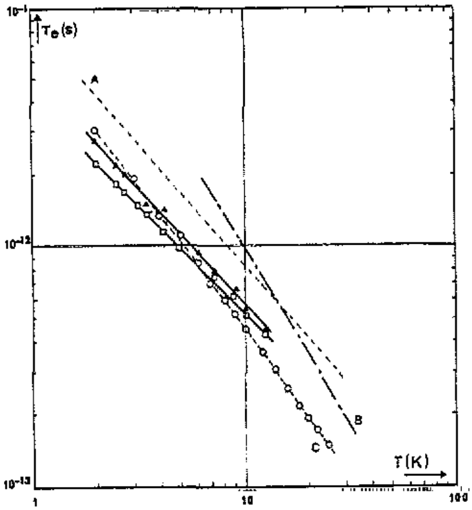

Figure 3. The variation of the inelastic scattering time τ_e with temperature. □: values obtained by the first method in weak magnetic fields; ▲: values obtained by the second method using the Kawabata formula—A: first term of the Isawa relation (8); B: second term of the Isawa relation (8); C: values of τ_e calculated using the total rate in the Isawa relation (8).

For very low values of the parameter δ, relation (2) becomes $F(\delta) = 0.605$, and the magneto-conductivity varies as $B^{1/2}$ and is given by the relation

$$\Delta\sigma = 2.9\, B^{1/2}. \tag{4}$$

A first set of values for τ_e has been obtained using expression (3) for $B < 0.2$ T. τ_e is deduced from the slope of the straight lines observed in the dependence of $\Delta\sigma$ on B^2 in figure 2. The values of τ_0 can be obtained from the conductivity at $T = 0$. $\sigma_0(T = 0)$ is generally equal to the Boltzmann conductivity

$$\sigma_B = ne^2\tau_0/m^*. \tag{5}$$

However, as the sample is in the vicinity of the MIT, $k_F l_0$ is of the order of 1 and we have to include corrections to the zero-temperature conductivity, which can be obtained from perturbation theory (Mott and Kaveh 1985):

$$\sigma_0 = \sigma_B[1 - C/(k_F l_0)^2] \tag{6}$$

where C is a constant between 1 and 3. Equation (5) gives $k_F l_0 = 1.15$ while equation (6) with $C = 3$ gives $k_F l_0 = 2.39$. As $n \cong 2n_c$ we can consider $k_F l_0 = 2.39$ to be the best value, and τ_0 has to be obtained from relation (6).

Figure 3 shows that τ_e varies like T^{-1}; the exact temperature dependence is given by the relation

$$1/\tau_e = 2.41 \times 10^{11}\, T^{0.88}. \tag{7}$$

This is to be compared with the theoretical curves in figure 3. These curves were obtained from the results of Isawa (1984) who found two terms in the total rate:

$$1/\tau_e = 1.7 \times 10^{11}(\hbar/E_F\tau_0)^2 T + 3.189(\hbar\tau_0)^{1/2}(kT)^{3/2}/(E_F\tau_0)^2. \tag{8}$$

Experimental values of τ_e are distributed in the range 10^{-12} s to 10^{-11} s. They are comparable to values given by theory except at the lowest temperatures. Finlayson and Mehaffey (1985) found the same temperature dependence for metallic samples. However, if we take $C = 0$ in equation (6), relation (8) gives values for τ_e that are one

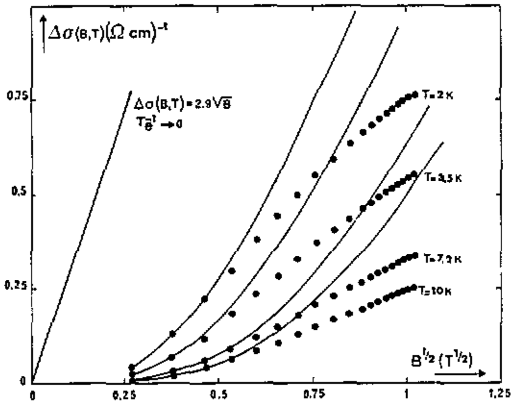

Figure 4. Comparison between experimental data for $\Delta\sigma$ and Kawabata results in the region of moderate magnetic fields, as functions of $B^{1/2}$.

quarter of our experimental values for the whole temperature range of the experiment; this is an additional argument for the existence of corrections to the conductivity near the MIT.

The value for the inelastic scattering time τ_e has also been obtained by a second method. The data were fitted using the Kawabata expression (1) in which τ_e is considered as an adjustable parameter. In our experiments δ varies from 0.02 to 40 and, as the function $F(\delta)$ does not have a simple analytical form, we calculated $F(\delta)$ for many values of δ^{-1} between 0.01 and 40 with an accuracy better than 10^{-6}. The best fits were obtained for magnetic fields $0 < B < 0.2$ T at the lowest temperatures and for $0 < B < 0.4$ T for the highest temperature.

The values of τ_e obtained by this method are shown in figure 3. They are slightly higher than the values obtained with the first method and their temperature dependence is given by the relation

$$1/\tau_e = 1.84 \times 10^{11}\ T^{0.98}. \tag{9}$$

We also observed a quite good agreement with theoretical values in the lower-temperature region; however, the temperature dependence of τ_e seems to be that given by the first term in the Isawa expression (equation (8)).

A third method can be used to obtain τ_e. As the sample is close to the MIT, and $k_F l <$ 3, the conductivity at finite temperature can be expressed in terms of relevant length scales (Mott and Kaveh 1985):

$$\sigma = \sigma_B\{1 - [c/(k_F l_0)^2](1 - l_0/L)\} \tag{10}$$

where $L^{-1} = (\lambda^{-4} + L_i^{-4})^{1/4}$; $L_i = (D\tau_e)^{1/2}$ is the inelastic diffusion length and λ the magnetic length. The only good fit with equation (10) was obtained for a very low magnetic field, $B = 0.072$ T, and the temperature dependence of τ_e is given by

$$1/\tau_e = 4.18 \times 10^{11}\ T^{0.94}. \tag{11}$$

The exponent of T is still close to unity; however, the values of τ_e are half of those obtained by other methods.

4. Conclusions

Figure 4 shows a comparison between experimental values of $\Delta\sigma$ and theoretical values calculated using the Kawabata formula (1) in which we included values of τ_e obtained by the second method.

A large discrepancy is observed between experimental data and equation (4); this means that the approximation of very large inelastic scattering times is not realistic. Data and theory are not shown for $B^{1/2} < 0.25$, since a good agreement is still found in this region. Figure 4 shows that there is a good agreement between experiment and the Kawabata model for moderate magnetic fields ($B \simeq 0.5$ T). However, this model should be improved for the highest magnetic fields. The model proposed by Mott (equation (10)) led to very poor fits for moderate magnetic fields, $B \simeq 0.2$ T, and for the highest magnetic field used in the experiment, $B = 1$ T. The only acceptable agreement with equation (10) when B was varied at a finite temperature was found for low magnetic fields, $0 < B < 0.2$ T.

The models proposed by Kawabata, Mott and co-workers are based only on localization theory, so it would be worthwhile to include electron–electron interactions in these models in order to reduce the discrepancies between the values of magnetoconductivity and inelastic scattering time obtained by theory and those from experiment, mainly in the regions with the highest magnetic fields and lowest temperatures.

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