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Low-temperature conductivity and weak-localization effect in barely metallic GaAs

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Abstract. Low-temperature measurements of the conductivity, the Hall effect and the magnetoresistance have been performed on an n-GaAs sample of impurity concentration close to its critical value for the metal–insulator transition.

The magnetoconductivity is analysed in the context of the weal-localization theory, and the inelastic scattering time τ_ϵ is deduced from the same model in two different ways for each temperature. It is found that τ_ϵ varies as T^{-1} in the whole temperature range. This behaviour is compared with the theoretical predictions.

Discrepancies are found between the weak-localization theory and the experimental data for magnetic fields larger than 0.4 T.

1. Introduction

The inelastic scattering time τ_ϵ is nowadays considered as an important parameter for submicron devices such as superlattices and mesoscopic systems. However, the determination of τ_ϵ in doped semiconductors remains a problem.

Yet in the weak-localization region, i.e. when $k_F l_0 \gg 1$ (k_F is the Fermi wavenumber and l_0 the elastic mean free path), models exist according to which the inelastic scattering time is deduced from negative-magnetoresistance measurements. These theories are based on the quantum interference of an electron with itself along a diffusion loop. The magnetic field shifts the phase of the electronic wavefunction and destroys the localization effect, giving rise to the negative magnetoresistance.

In systems without spin–orbit coupling and in the low-temperature limit, τ_ϵ will be equal to τ_φ, the time during which the phase is kept before being changed by an inelastic shock.

The simplest model for negative magnetoresistance in a three-dimensional system without interaction has been proposed by Kawabata (1980). It has also been the model most often used until now because of its practicality, especially in weak magnetic fields (Dynes *et al* 1983, Morita *et al* 1984, Ootuka *et al* 1987, Friedland *et al* 1990).

The purpose of this paper is to study the behaviour of the inelastic scattering time with the temperature near the mobility edge and to observe either the T^{-1} dependence predicted by Isawa (1984) or a saturation in the low-temperature limit, as reported by Friedland *et al* (1990).

2. Low-temperature conductivity in a zero magnetic field

In the impurity band of semiconductors, when the Fermi level E_F is higher than the mobility edge E_c, it is well known that conduction has a metallic feature but the classical Boltzmann conductivity σ_B is altered by localization and interaction effects. While weak localization is responsible for the reduction in the zero-temperature conductivity $\sigma(0)$, the electron–electron interaction influences the temperature dependence of σ.

Considering the decrease in the electronic wavefunctions as a perturbation of the free-electron model, Kaveh and Mott (1987) showed that, in the immediate vicinity of the metal–insulator transition (MIT), the zero-temperature conductivity is given by

$$\sigma(0) = \sigma_B g^2[1 - C/g^2(k_F l_0)^2] \tag{1}$$

where g is the reduction in the density of states (DOS) resulting from disorder and C is a constant between 1 and 3.

Here we take $g = \frac{1}{3}$ as evaluated by Mott (1972) at the MIT and $C = 1$ because of the Ioffe–Regel criterion ($k_F l_0 = \pi$ at MIT), in accordance with the scaling theory of localization (Abrahams *et al* 1979).

When we approach the transition on the metallic side, Altshuler and Aronov (1989) and then Kaveh and Mott (1981) explained that a dip appears in the DOS. This dip, which becomes the Coulomb gap in the insulating phase, leads in the metallic phase to the $T^{1/2}$ behaviour of the conductivity.

Another way to tackle the problem is to use the one-parameter scaling equation

$$\sigma = g_c e^2/\hbar L + e^2/\hbar\zeta \tag{2}$$

where g_c is the critical conductance of value 0.03 (Kaveh and Mott 1987), ζ is the correlation length and L must be replaced by the minimum length scale. According to Altshuler and Aronov (1983), near the MIT, the only relevant length scale is the interaction length $L_T = \sqrt{\hbar D/kT}$, so that

$$\sigma = \sigma_0 + mT^{1/2}. \tag{3}$$

Such behaviour has been widely observed in various semiconductors (Long and Pepper 1985). Moreover, in the critical regime, ζ is presumed to be much larger than L_T and the diffusion constant D varies with temperature. First-order derivation in $1/\zeta$, using the Einstein relation

$$\sigma = e^2 D N(E_F) \tag{4}$$

shows that

$$\sigma = \sigma_0 + mT^{1/3}$$

with

$$m = (e^2 g_c^{2/3}/\hbar)[kN(E_F)]^{1/3} \qquad \sigma_0 = \tfrac{2}{3}e^2/\hbar\zeta. \tag{5}$$

This relation was also obtained by Maliepaard *et al* (1988) and allows us to determine the DOS $N(E_F)$ at the Fermi level and the correlation length ζ.

In the same way, it is possible to demonstrate that

$$D = [g_c/N(E_F)]^{2/3}[(kT)^{1/3}/\hbar] + \tfrac{2}{3}[1/N(E_F)\hbar\zeta]. \tag{6}$$

Knowing $N(E_F)$ and ζ, it becomes easy to calculate this dependence.

3. Magnetoconductance due to weak localization

Kawabata (1980) expressed the correction to the conductivity in the weak-localization regime and in the weak-magnetic-field range, that is to say under the conditions

$$\hbar/m^* v_F \tau_0 \ll 1 \qquad eB\tau_0/m^* \ll 1 \qquad l_0/\lambda \ll 1 \tag{7}$$

where $\lambda = \sqrt{\hbar/eB}$ is the magnetic length and $\tau_0 = l_0/v_F$ the elastic scattering time.

Kawabata shows that

$$\Delta\sigma(B,T) = (e^2/2\pi^2\hbar\lambda) f_3(\delta) = 4.8\sqrt{B} f_3(\delta) \Omega^{-1} \mathrm{cm}^{-1} \tag{8}$$

where

$$\delta = \hbar/4DeB\tau_\epsilon$$

and

$$f_3(\delta) = \sum_{N=0}^{\infty} \left[2(\sqrt{N+1+\delta} - \sqrt{N+\delta}) - \frac{1}{\sqrt{N+\frac{1}{2}+\delta}} \right].$$

For quite weak magnetic fields, namely $\delta \gg 1$, equation (8) has the asymptotic form

$$\Delta\sigma(B,T) = [e^4 (D\tau_\epsilon)^{3/2}/12\pi^2\hbar^3] B^2 = 4.78 \times 10^{22} (D\tau_\epsilon)^{3/2} B^2 \ \Omega^{-1}\ \mathrm{cm}^{-1}. \tag{9}$$

This last relation has been used by many workers to determine the inelastic scattering time τ_ϵ.

4. Experiment

The sample used in this study is an n-type gallium arsenide bar with a free-carrier concentration $n(300\ \mathrm{K}) = 2.9 \times 10^{16}\ \mathrm{cm}^{-3}$, just above the critical concentration $n_c \simeq 2.2 \times 10^{16}\ \mathrm{cm}^{-3}$ for the MIT (Rentzsch *et al* 1986).

The conductivity has been measured in the temperature range 0.3–300 K with magnetic fields up to 5.8 T.

We have determined the compensation ratio using an original method proposed by Wolfe *et al* (1970). The ionized-impurity concentration N_i has been primarily calculated for all temperatures from the Brooks (1955) formula, giving the mobility μ as a function of the temperature T and the concentration n:

$$\mu = (2^{7/2}/300\pi^{3/2})[\kappa\epsilon_0^2 (kT)^{3/2}/m^{*1/2} e^3 N_i] \{1/[\ln(1+x) - x/(1+x)]\} \tag{10}$$

where $x = 6\kappa m^* k^2 T^2/\pi n\hbar^2 e^2$, κ is the dielectric constant and m^* is the effective mass of the electron.

On the assumption that N_i may be equal to $N_A + N_D$ in the considered temperature range and that $n(300\ \mathrm{K}) = N_D - N_A$, the donor and acceptor densities (N_D and N_A, respectively) have been found to vary with temperature. The minima observed in the $N_D(T)$ and $N_A(T)$ dependences are interpreted by Wolfe *et al* (1970) to be as required in the desired region. Indeed, equation (10) remains valid within the temperature range where ionized-impurity scattering is the dominant conduction process, corresponding to the common minima of $N_D(T)$ and $N_A(T)$. In the temperature interval that he found, namely 50–115 K, we can estimate that K=0.65.

Figure 1 shows the behaviour of the magnetoresistance in the whole range of fields. Nevertheless, concerning the dependence of $\Delta\sigma$ on the magnetic field, our analysis will be limited to $B = 1.5$ T so that the positive magnetoresistance and the Shubnikov–de Haas effect which arises at $B \simeq 2$ T are not taken into account.

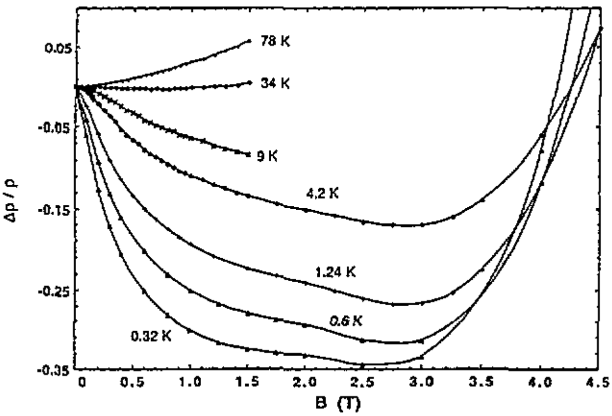

Figure 1. Negative magnetoresistance, Shubnikov–de Haas effect and positive magnetoresistance against the field B: ——, guides for the eyes.

5. Results and discussion

In order to analyse the conductivity at a low temperature and zero magnetic field, we have fitted the data in the range 0.3–4 K to the relation

$$\sigma(T) = \sigma_0 + mT^s \tag{11}$$

where s varies from 0 to 1 with a step of 0.1. For each value of s, the percentage of deviation between experimental and theoretical values of the conductivity has been calculated as

$$\mathrm{dev}\% = \sqrt{\frac{1}{i_{\max} - i_{\min} + 1} \sum_{i=i_{\min}}^{i_{\max}} \left(\frac{100}{\sigma_i} [\sigma(T_i) - \sigma_i] \right)^2} \tag{12}$$

and reported in figure 2. Here, $i_{\min}$ and $i_{\max}$ are the minimal and maximal index of values taken in the list of data. We observe a minimum of dev% for $s = 0.21$.

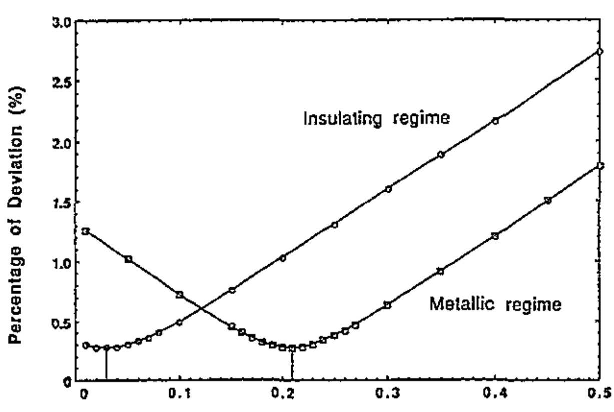

Figure 2. Percentage of deviation obtained in fitting the experimental conductivity data to equation (11) (□) or equation (13) (○) as a function of the exponent s, at zero magnetic field.

In the same figure 2, we have plotted dev% corresponding to the law

$$\sigma(T) = \sigma_0 \exp[-(T_0/T)^s]. \tag{13}$$

Here we find the minimum at $s = 0.03$, contradicting the hypothesis of a variable-range hopping behaviour.

Since the exponent $s = 0.21$ in equation (11) has no physical meaning, we assume that a $T^{1/3}$ dependence would be better than a $T^{1/2}$ regime, all the more so because the data in figure 2 are of the same order between $s = 0.2$ and $s = 0.3$. Further analyses have been carried out, combining the $T^{1/2}$ and $T^{1/3}$ dependences or taking into account both the interaction effects and the weak-localization corrections, but all of these make us believe that the single $T^{1/3}$ law is the most suitable. In figure 3, σ is reported against $T^{1/3}$ and is compared with its low-temperature expression

$$\sigma = 0.554 + 1.7975T^{1/3}\ \Omega^{-1}\ \mathrm{cm}^{-1}. \tag{14}$$

It enables us to calculate the experimental values of the DOS at the Fermi level $N(E_F) = 2.55 \times 10^{43}\ \mathrm{J}^{-1}\ \mathrm{m}^{-3}$ from the value of m. $N(E_F)$ is half of the theoretical value estimated in the free-electron approximation, certainly because localization and interaction effects decrease the DOS considerably.

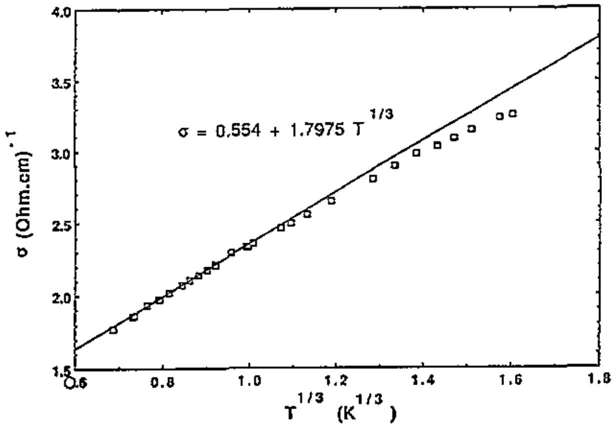

Figure 3. Variation in the conductivity with $T^{1/3}$ in the low-temperature limit.

Using equation (5) and the value of the parameter σ_0 obtained from equation (14), we can determine the temperature dependence of the diffusion constant which is given by the expression

$$D = 2.549 \times 10^{-4}T^{1/3} + 8.5 \times 10^{-5}\ \mathrm{m}^2\ \mathrm{s}^{-1}. \tag{15}$$

It is also important to evaluate the electron mean free path l_0. Solving equation (1), where $\sigma_B = ne^2 l_0/\hbar k_F$, we obtained a quadratic equation of unknown quantity l_0. The solution of this equation, taking into account $\sigma(0) = 55.4\ \Omega^{-1}\ \mathrm{m}^{-1}$, gives $l_0 = 3.51 \times 10^{-8}$ m, that is to say $k_F l_0 = 3.34$, which indicates that the sample is very close to the MIT.

A first set of values for the inelastic scattering time τ_ϵ has been obtained in the weak-magnetic-field limit from the slope of the straight lines obtained by plotting $\Delta\sigma$ versus B^2 in figure 4. The values of τ_ϵ have been obtained with equations (9) and (15). The range of magnetic fields in which a quadratic dependence is observed is reduced as the temperature

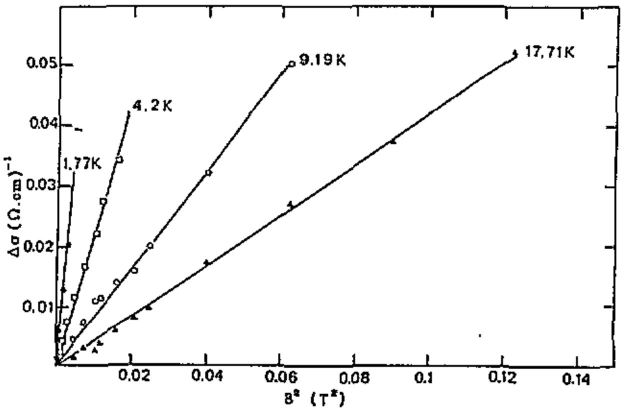

Figure 4. Variation in the magnetoconductivity with B^2 in the region of the lowest magnetic field.

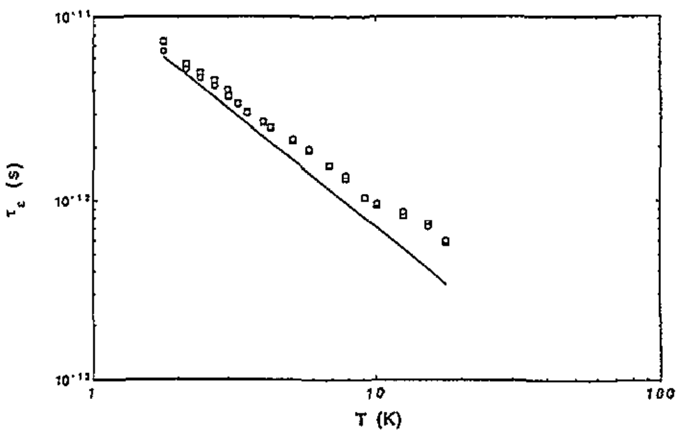

Figure 5. Variation in the inelastic scattering time with temperature: ○, values obtained from the slope of $\Delta\sigma(B^2)$; □, values obtained by the use of the total Kawabata formula (8); ——, values calculated using the Isawa relation (16).

decreases. Thus it was not possible to use this method between 0.3 and 1.8 K because very few data were available in this range of low magnetic fields.

The inelastic scattering times calculated using equation (9) are plotted against T on a logarithmic scale in figure 5 and are compared with the theoretical expression of Isawa (1984):

$$\tau_\epsilon^{-1} = 1.7 \times 10^{11}(\hbar/E_F\tau_0)^2 T + 3.189[\sqrt{\hbar\tau_0}/(E_F\tau_0)^2](kT)^{3/2}\ \mathrm{s}^{-1}. \tag{16}$$

According to Isawa, below the temperature $T_0 = 0.166\hbar/k\tau_0 \simeq 6$ K, the first term in equation (16) becomes dominant and then

$$\tau_\epsilon = 1.64 \times 10^{-11} T^{-1}\ \mathrm{s}. \tag{17}$$

In fact, the T^{-1} behaviour is observed in the whole temperature range since a linear fit of the values in figure 5 gives

$$\tau_\epsilon = 1.244 \times 10^{-11} T^{-1.08}\ \mathrm{s}. \tag{18}$$

Morita *et al* (1984) found the same temperature dependence for a GaAs sample doped deeper in the metallic regime ($n = 7.8 \times 10^{16}$ cm^{-3}).

Subsequently, τ_ϵ has also been deduced from the total expression of Kawabata (equation (8)) by a numerical fit where $f_3(\delta)$ has been replaced by a polynomial proposed by Baxter *et al* (1989):

$$f_3(\delta) = 2(\sqrt{2+\delta} - \sqrt{\delta}) - [(\tfrac{1}{2}+\delta)^{-1/2} + (\tfrac{3}{2}+\delta)^{-1/2}] + \tfrac{1}{48}(2.03+\delta)^{-3/2}. \tag{19}$$

The conditions (7) imply that we consider only fields below 0.5 T.

Figure 6 shows that this model is in good agreement with the weak-field magnetoconductivity but there exists a field $B_0 \leqslant 0.4$ T above which the theoretical curve diverges towards a $\sqrt{B}$ regime while the experimental curve bends downwards. Once again, this field B_0 decreases with increasing temperature. Unfortunately, the field step used in our measurements below 1.8 K was 0.1 T. At this temperature, B_0 is in the range of 0.1 T. So the number of data was insufficient to enable us to estimate τ_ϵ.

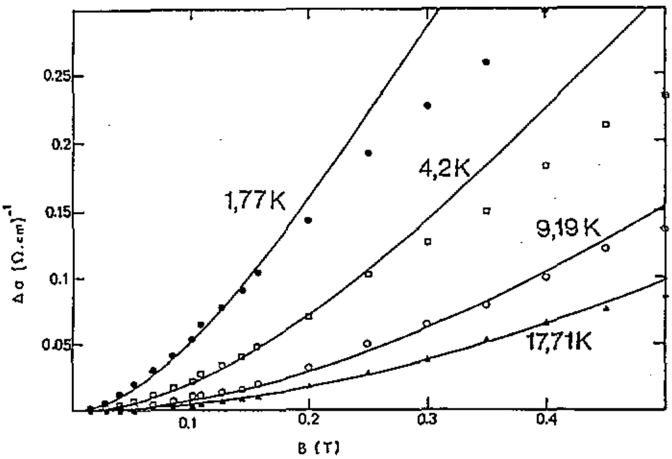

Figure 6. Variation in the magnetoconductivity with the magnetic field. Comparison with the fit to the Kawabata formula in weak and moderate magnetic fields.

The values of τ_ϵ deduced from this analysis, also reported in figure 5, are quite close to those calculated from the slope of $\Delta\sigma(B^2)$ and we obtain

$$\tau_\epsilon = 1.1594 \times 10^{-11} T^{-1.04} \text{ s}. \tag{20}$$

In fact, a few improvements were carried out to the first method and additional corrections have to be implemented if we wish to analyse the magnetoconductivity in higher magnetic fields.

6. Conclusion

We have pointed out that Kawabata's model can be used to fit our experimental magnetoconductance in weak magnetic fields and to evaluate the inelastic scattering time.

The values obtained for τ_ϵ are in quantitative agreement with the theory of Isawa (1984), taking into account both localization and Coulomb interaction effects. The behaviour of τ_ϵ seems to remain linear in T^{-1} in the whole range of temperatures.

There is a contradiction between this result and that of Friedland *et al* (1990). Indeed, Friedland *et al* found that τ_ϵ no longer has a temperature dependence when the concentration

n gets closer n_c in GaAs. This phenomenon has been explained by Hikami *et al* (1980) in terms of the effect of localized spins at the MIT. The phase coherence time is altered by a spin scattering time τ_s as

$$\tau_\epsilon^* = \tau_\epsilon \tau_S/(\tau_\epsilon + \tau_S). \tag{21}$$

At low temperatures, τ_ϵ increases and becomes much larger than τ_s, so that τ_ϵ^* is completely described by τ_s, which is supposed to be temperature independent.

To check this theory, we should carry on with our analysis of magnetoconductivity to the lowest temperatures. Unfortunately, we would have to consider higher magnetic fields and this is impossible with the model of Kawabata alone. As suggested by Biskupski and Bouattou (1991), it would be convenient to add some terms due to the enhancement of the interaction effects, in order to achieve a better fit in a wide range of fields and at lower temperatures.

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