# Low-temperature conductivity and magnetoconductivity of neutron-transmutation-doped barely metallic GaAs in the vicinity of the metal-insulator transition



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# Low-temperature conductivity and magnetoconductivity of neutron-transmutation-doped barely metallic GaAs in the vicinity of the metal–insulator transition

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**Abstract.** Measurements of the temperature dependence of conductivity and magnetoconductivity are presented of barely metallic n-GaAs bulk crystals doped by the neutron-transmutation-doping technique resulting in medium-compensated samples of fixed compensation degree in the immediate vicinity of the metal–insulator transition at low temperatures. At $n \rightarrow n_c$ the temperature dependence in $\tau_\varphi$ (the phase-breaking time) disappears and therefore at low temperatures the temperature dependence of the conductivity is determined by the electron–electron interaction and necessarily $L_{int}$ is the smallest relevant length leading to a dependence $\sigma(T) = bT^{1/3}$.

The experimentally determined density of states at the Fermi level is quite different whether $n = n_c$ is reached by an exactly controlled impurity concentration or by magnetic tuning with $n = n_c(B) > n_c(0)$. This is interpreted by the influence of the magnetic field on the weak-localisation contribution and a change in the density of states at the Fermi level. When $n = n_c$ is reached by a controlled impurity concentration, the experimentally obtained density of states at the Fermi level is in good agreement with the value estimated from the impurity concentration and the energy spread of donor states in the gap.

## 1. Introduction

The great progress in the understanding of low-temperature conductivity and magnetoconductivity of disordered systems with metallic conductivity originates mainly from the development of the theory of weak localisation (WL) and electron–electron interaction (EEI) [1–4].

One of the most important questions in the low-temperature electrical transport is which quantum mechanical correction has the smallest length scale $L_{min}$: the correction $L_\varphi$ due to WL or the correction $L_{int}$ due to EEI. This smallest length dominates the quantum corrections to the conductivity

$$\sigma(T) = G_c e^2/\hbar L_{min} \tag{1}$$

where $G_c$ is the critical dimensionless conductance in the one-parameter scaling equation.

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If the effect of WL dominates the conductivity,

$$L_{\min} = L_\varphi = (D\tau_\varphi)^{1/2} \tag{2}$$

is valid and $\sigma(T)$ is determined by $\tau_\varphi(T)$. $D$ is the diffusion coefficient and $\tau_\varphi$ is the phase-breaking time at inelastic collisions of electrons. If on the other hand the effect of EEI dominates the conductivity,

$$L_{\min} = L_{\mathrm{int}} = (D\hbar/k_{\mathrm{B}}T)^{1/2} \tag{3}$$

is valid and neglecting the temperature dependence in $D$ we obtain $\sigma \sim T^{1/2}$.

In general, at free-carrier concentrations $n > n_c$, with $n_c$ the critical concentration of the metal–insulator transition (MIT), the effects of WL and EEI in $\sigma(T)$ are of the same order of magnitude. However, approaching the MIT at $n \simeq n_c$ these contributions can become significantly different.

In this case the smallest length scale determining the temperature dependence should be $L_{\mathrm{int}}(T)$ according to [5]. In [5] it is argued that in the case of statistically distributed impurities at the wavevector $k \neq 0$, the energy of Hubbard repulsion is greater than the Fermi energy $E_{\mathrm{F}}$. This gives rise to singly occupied impurity levels with localised spins at which the free electrons will be scattered. Then the phase-breaking time is modified by an additional term $\tau_s$ due to the scattering time at localised spins. According to [6] the phase relaxation time is then

$$\tau_\varphi^* = (1/\tau_\varphi + 1/\tau_s)^{-1}. \tag{4}$$

At $\tau_s \ll \tau_\varphi$ the phase relaxation time $\tau_\varphi^*$ is completely defined by $\tau_s$ which is assumed to have no temperature dependence, i.e. $\tau_\varphi^*$ also does not depend on temperature. In this case the temperature dependence of the conductivity is totally determined by $L_{\mathrm{int}}(T)$. By expressing $D$ in (3) by the Einstein relation

$$\sigma = (\partial n/\partial E_{\mathrm{F}})e^2 D \tag{5}$$

we obtain from (1) at $n \rightarrow n_c$, i.e. $\sigma(0) \rightarrow 0$, that

$$\sigma = (e^2/\hbar)[G_c^2(\partial n/\partial E_{\mathrm{F}})(k_{\mathrm{B}}T)]^{1/3} \tag{6}$$

with $\partial n/\partial E_{\mathrm{F}}$ the density of states at the Fermi level [7]. Consequently at $n = n_c$ a dependence $\sigma(T) \sim T^{1/3}$ should be obtained.

On the other hand, if $\tau_\varphi$ is governed by relaxation due to exchange interaction it has been shown that [8–10]

$$\hbar/\tau_\varphi = [A/(\partial n/\partial E_{\mathrm{F}})](k_{\mathrm{B}}T/\hbar D)^{3/2} \tag{7}$$

with

$$A = 2^{1/2}/6\pi^2. \tag{8}$$

In the case of the dependence $\tau_\varphi \sim T^{-1}$ theoretically predicted in a restricted low-temperature range by Isawa [10] and which is in metallic n-GaAs at $T < 1$ K experimentally found by a $\Delta\sigma(T, B) \sim T^{1/2}$ dependence in [11, 12] we obtain using (5) for the conductivity

$$\sigma(T) \sim (e^2/\hbar)[(\partial n/\partial E_{\mathrm{F}})k_{\mathrm{B}}T]^{1/3}. \tag{6a}$$

The result is that even in this case of temperature dependence in connection with $L_\varphi(T)$ as the smallest length a dependence $\sigma(T) \sim T^{1/3}$ should be obtained.

In the present paper we shall show that in compensated n-GaAs at $n \rightarrow n_c$ the temperature dependence in $\tau_\varphi$ disappears and therefore at low temperatures all temperature dependence of the conductivity is determined by the EEI and necessarily $L_{\mathrm{int}}$ is the smallest relevant length leading to (6).

**Table 1.** Main data obtained. $(\partial n/\partial E_F)^{theor}$ was obtained using $N_D - N_A$, (9) and (10). $b^{theor}$ was deduced from (6), (13) and $(\partial n/\partial E_F)^{theor}$. $(\partial n/\partial E_F)^{exp}$ was obtained from $b^{exp}$ using (6) and (13).

| Sample | $N_D - N_A$ ($10^{22}$ m$^{-3}$) | $\sigma(0)$ ($10^2$ S m$^{-1}$) | $B_c$ (T) | $(\partial n/\partial E_F)^{theor}$ ($10^{24}$ m$^{-3}$ eV$^{-1}$) | $b^{theor}$ (S m$^{-1}$ K$^{-1/3}$) | $b^{exp}$ (S m$^{-1}$ K$^{-1/3}$) | $(\partial n/\partial E_F)^{exp}$ ($10^{24}$ m$^{-3}$ eV$^{-1}$) |
|---|---|---|---|---|---|---|---|
| 1541 | 2.15 | 0 | 0 | 7.7 | 164 | 260 | 21.2 |
| 16601 | 2.4 | 1.8 | 4.7 | 8.0 | 166 | 127 | 3.57 |
| 9305 | 2.5 | 4.6 | 7.0 | 8.1 | 167 | 100 | 1.74 |
| 9303 | 2.7 | 4.6 | 7.5 | 8.3 | 168 | 139 | 4.67 |

Moreover it will be shown that the experimentally determined density of states at the Fermi level is quite different whether $n = n_c$ is reached by an exactly controlled impurity concentration or by magnetic tuning with $n = n_c(B) > n_c(0)$ and that its value in both cases differs significantly from the free-electron density of states determined from

$$\partial n/\partial E_F = mp_F/\pi^2\hbar^3 = mk_F/\pi^2\hbar^2 \tag{9}$$

with

$$k_F = (3\pi^2 n)^{1/3} \tag{10}$$

the wavevector at the Fermi level.

## 2. Experimental results and discussion

Semiconducting crystals doped with shallow impurities are up to now the most suitable material for verifying the predictions of the theory, because of the exact knowledge of all necessary crystal parameters, and in particular the effective masses. Additionally, the disorder as well as the electric properties can be influenced by a simple variation in the doping level and in the compensation degree, giving rise to dielectric or metallic conductivity. Our investigations are performed on n-GaAs crystals with barely metallic conductivity and a free-carrier concentration close to $n_c$. The main data on the samples are given in table 1.

The material GaAs has been used for the following reasons:

(i) In bulk material the method of neutron transmutation doping can be applied up to very high concentrations of the introduced donors, resulting in a remarkably more homogeneous impurity distribution than for chemically doped Czochralski crystals showing exact three-dimensional conduction. It has been shown by us [13] that with neutron transmutation doping by a simple variation of the neutron irradiation dose and the annealing procedure the impurity concentration and the compensation degree can be changed in such a way that the MIT with $n = n_c$ can easily be reached. At fixed annealing conditions all samples irradiated with different neutron doses have a constant compensation degree $K = N_A/N_D$.

(ii) n-GaAs is especially suitable for investigations of WL because the effect of negative magnetoresistance based on WL which is for $n > n_c$ quantitatively described by the theory [14–16] is considerably greater than for comparison in Ge and in Si.

(iii) Owing to the relatively large Bohr radius in n-GaAs doped with shallow impurities even at $n$ far from $n_c$ the MIT can be tuned by a relatively low magnetic field.

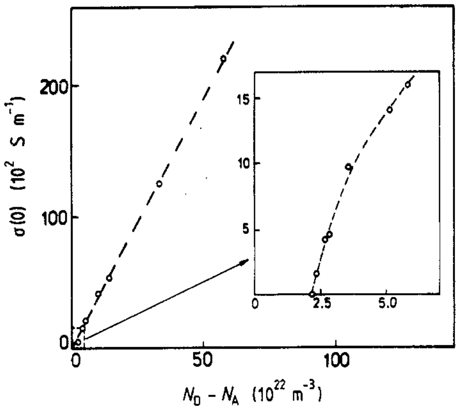


**Figure 1.** Dependence of the zero-temperature conductivity of metallic n-GaAs on the free-carrier concentration. The inset shows the immediate vicinity of the MIT.

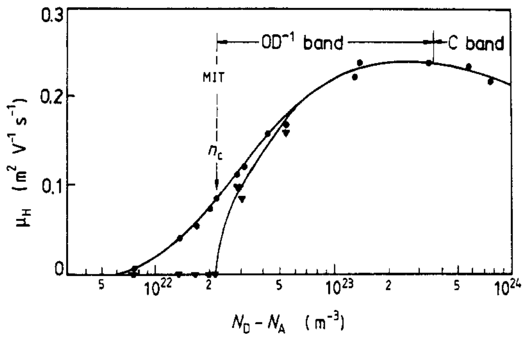


**Figure 2.** The Hall mobility of metallic n-GaAs versus the free-carrier concentration at $T = 1.5$ K (●) and $T = 0.3$–$0.05$ K (▼).

The measurements of the temperature dependence of the conductivity have been performed in a dilution refrigerator down to $T = 50$ mK and in a magnetic field up to $B = 2$ T in a four-terminal configuration with an AC bridge (Cryobridge model 103) at a low frequency. In the case of the magnetic-field-induced MIT the conductivity in the magnetic field up to $B = 14$ T has been investigated in the International Laboratory of High Magnetic Fields and Low Temperatures in Wrocław, Poland, at $T = 1.8$–$4.2$ K.

Recently it was shown [12, 13] that on the metallic side of the MIT at $n \to n_c$ the conductivity (figure 1) and the Hall mobility (figure 2) at low temperatures obey the scaling law

$$\sigma(0) = C\sigma_{MM}|n/n_c - 1|^{\nu} \tag{11}$$

with $\nu = 0.84 \pm 0.11$ and $n_c = 2.18 \times 10^{22}$ m$^{-3}$ (figure 3).

Therefore, as shown in table 1, sample 1541 with a free-carrier concentration $n$ of $2.15 \times 10^{22}$ m$^{-3}$ represents the case $n \simeq n_c$. The low-temperature conductivity of this sample in figure 4 shows even without an external magnetic field at $T < 1$ K the predicted relationship $\sigma \sim T^{1/3}$ in accordance with (6).

As mentioned above, this can be caused by the WL as well as by the EEI effect. In order to separate both contributions, we measured the temperature dependence of the magnetoconductivity in such low magnetic fields, where $\Delta\sigma \sim B^2$ holds.

We found that at $T < 1$ K where (6) is fulfilled, $\Delta\sigma(B)$ does not depend on temperature. Within the framework of the theory of the negative magnetoresistance [14–16] it

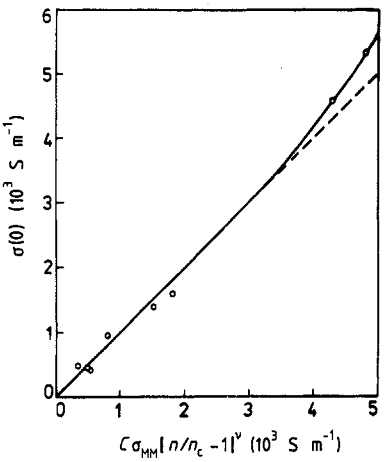


**Figure 3.** Scaling behaviour of the zero-temperature conductivity of metallic samples in the vicinity of the MIT: $\sigma(0) = C\sigma_{MM}|n/n_c - 1|^{\nu}$ with $\nu = 0.84 \pm 0.11$, $C = 6.6$, $\sigma_{MM} = 177\ \mathrm{S\ m^{-1}}$ and $n_c = 2.18 \times 10^{22}\ \mathrm{m^{-3}}$.

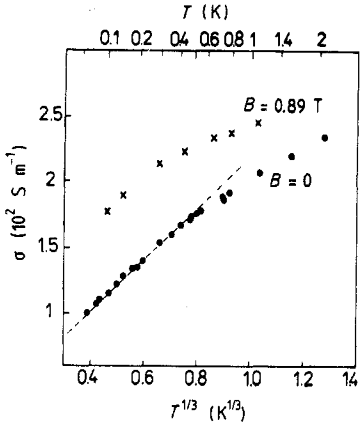


**Figure 4.** Low-temperature conductivity of sample 1541 with $n = 2.15 \times 10^{22}\ \mathrm{m^{-3}}$ in the $T^{1/3}$-representation.

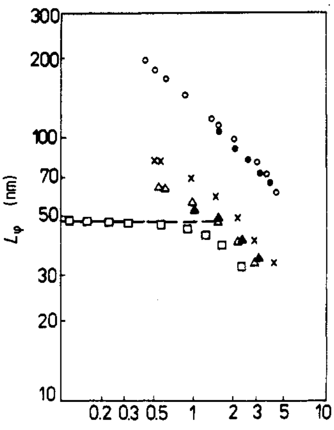


**Figure 5.** Temperature dependence of the phase-breaking length obtained from the magneto-conductivity $\Delta\sigma \sim B^2$ at WL for various $N_D - N_A$: □, $2.15 \times 10^{22}\ \mathrm{m^{-3}}$; ▲, $2.5 \times 10^{22}\ \mathrm{m^{-3}}$; △, $3.0 \times 10^{22}\ \mathrm{m^{-3}}$; ×, $3.6 \times 10^{22}\ \mathrm{m^{-3}}$; ●, $5.2 \times 10^{22}\ \mathrm{m^{-3}}$; ○, $5.9 \times 10^{22}\ \mathrm{m^{-3}}$.

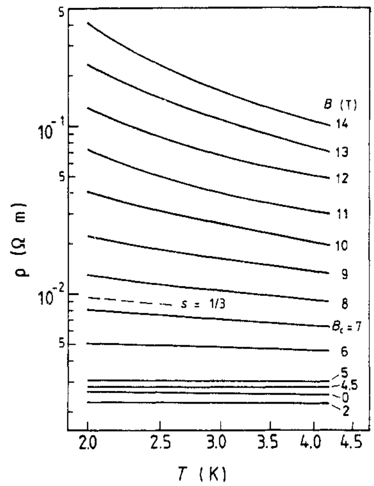


**Figure 6.** Double-logarithmic plot of the temperature dependence of the resistivity of sample 9305 with $N_D - N_A = 2.5 \times 10^{22}\ \mathrm{m^{-3}}$ at fixed magnetic field. The slope of the curve at $B_c = 7\ \mathrm{T}$ is $s = 0.32$.

can be understood that at $n \rightarrow n_c$, $\tau_{\varphi}$ and, due to (2), $L_{\varphi}$ both have no temperature dependence (figure 5). From this the following conclusions can be drawn.

(i) the temperature dependence of the conductivity at $T < 1$ K is totally an effect of the EEI.

(ii) $L_{\mathrm{int}}$ is the smallest length.

The vanishing temperature dependence in $\tau_{\varphi}$ can be explained by the appearance of localised spins at the phase transition from the metallic to the insulator side. In this case,

$\tau_\varphi$ must be replaced by $\tau_\varphi^*$ in accordance with (4), and $\tau_\varphi$ should be much greater than $\tau_s$, i.e. the phase-breaking time is controlled by the time of the encounter of localised spins and free electrons. The existence of localised spins is confirmed by the fact that only at relatively high $B$ does the contribution of the diffusion channel in the magnetoconductivity disappear. This contribution which is due to Zeeman splitting of free electrons is according to [4] not expected to appear in the case of strong spin–orbit as well as in spin–spin scattering. Strong spin–orbit scattering should result in an anomalous positive magnetoresistance. In the experiment, however, a negative magnetoresistance has been obtained. On the one hand this contribution is not essential, and on the other hand the disappearance of the diffusion contribution in the magnetoconductivity can be assumed to be the result of the interaction of free-electron spins with localised spins.

Another possibility which should be discussed is that the negative magnetoresistance originating from WL is superimposed by a negative magnetoresistance caused by the suppression of the spin-dependent scattering of free electrons on localised spins in a magnetic field as for example obtained in diluted magnetic alloys of Cu:Mn type (the Yosida–Toyozawa effect of s–d scattering [17, 18]).

In this case in a weak magnetic field the following relation should be found:

$$\Delta\rho/\rho \sim (B/T)^2 \qquad (12)$$

which saturates in higher magnetic fields.

In our experiments however, at $B \rightarrow 0$ such a dependence (12) has not been obtained and, in higher fields, $\Delta\sigma \sim B^{1/2}$ was found in agreement with the theory of negative magnetoresistance based on WL. Conclusively, even if a negative magnetoresistance due to s–d interaction exists, its influence is comparatively small and therefore can be neglected. From the slope $b$ in $\sigma = bT^{1/3}$ and using (6) a density of states at the Fermi level of $2.12 \times 10^{25}\ \mathrm{m^{-3}\ eV^{-1}}$ was observed for the sample with $n \simeq n_c$ (table 1).

For comparison with the experimental results in [19–21] we have in (6) used the value of $G_c$ from [22]:

$$G_c = 2/3\pi^3. \qquad (13)$$

The experimental value of $\partial n/\partial E_F$ has to be compared with theoretical expressions using realistic crystal parameters. One possibility which has been used in [19, 20] is the free-electron density of states (9), (10) giving with $m^* = 0.067\, m_0$ and $N_D - N_A$ the results for $b^{\text{theor}}$ and $(\partial n/\partial E_F)^{\text{theor}}$ shown in table 1. The value of $(\partial n/\partial E_F)^{\text{theor}}$ is about three times lower than that experimentally obtained. However, this estimate is for the following reasons not correct.

(i) The MIT in n-GaAs occurs not in the conduction band but in the impurity band of delocalised states ($D^-$ band) which is seen in figure 2 by the increase in the low-temperature Hall mobility with increasing impurity concentration up to a maximum at about $10^{23}\ \mathrm{m^{-3}}$. This was recently confirmed by far-infrared magnetotransmission measurements [23].

(ii) Immediately at the MIT the relation (9) is no longer fulfilled owing to the onset of the degeneracy at a much higher impurity concentration and the non-parabolicity of the conduction band.

In this case one can obtain a more realistic estimate of $\partial n/\partial E_F$ from the impurity concentration $N_D$ assuming an energy spread $\Delta E_{\text{imp}}$ of about 3–5 meV in the band gap due to the randomly distributed charged impurities given by

$$\partial n/\partial E_F \simeq N_D/\Delta E_{\text{imp}} \qquad (14)$$

and leading to $\partial n/\partial E_F = (10\text{–}20) \times 10^{24}\ \mathrm{m^{-3}\ eV^{-1}}$ which is close to $(\partial n/\partial E_F)^{\text{exp}}$ for sample 1541 with $n \simeq n_c$. The agreement between $\partial n/\partial E_F$ obtained from $b^{exp}$ and the estimate from the donor concentration and the energy range of donor distribution is sufficiently good if one takes into account that (14) underestimates the real $\partial n/\partial E_F$-value.

We now analyse the temperature dependence of the conductivity in samples with $n > n_c$ tuned by a magnetic field to the MIT. In this case, as follows theoretically, the WL contribution is depressed and the dependence $\sigma(T)$ is only due to the contribution from the EEI. Newson and Pepper [19] and Maliepaard *et al* [20, 21] recently investigated the MIT tuned by a magnetic field on epitaxial layers of n-GaAs with a free-carrier concentration somewhat exceeding $n_c$ and with different compensation degrees and found also a dependence (6), but most of their measurements showed a slope $b$ of the curves $\sigma = bT^{1/3}$ significantly smaller than in our case of $n \simeq n_c$.

For comparison with the results in [19–21] in table 1 the slopes $b$ of some samples with barely metallic conductivity magnetically tuned to the MIT are additionally shown. Figure 6 shows in double-logarithmic representation a typical dependence $\rho(T, B)$ at a fixed magnetic field. This representation serves for the determination of the critical magnetic field at which the sample passes the MIT as well as of $b^{exp}$ in table 1. The critical magnetic fields for different samples ranged from 4.7 to 7.5 T. However, the slope $b^{exp}$ of all magnetically tuned samples was significantly smaller in comparison with the value of sample 1541 with $B_c = 0$. Our results for $b^{exp}$ and $\partial n/\partial E_F$ of magnetically tuned samples are also in good agreement with those values shown as figures in [19, 20]. The reason for obtaining a $\partial n/\partial E_F$-value approximately one order of magnitude lower after (6) for magnetically tuned samples then in the case of $n \simeq n_c$ is possibly the changed density of states at the Fermi level in a magnetic field due to the shift of $E_F$ downwards on the energy scale.

In conclusion, we have demonstrated that in n-GaAs, at the MIT, localised spins exist, leading to suppression of the temperature dependence of the phase-breaking time due to WL. In this case the temperature dependence of the conductivity totally originates from the electron–electron part of the quantum corrections and the interaction length $L_{int}$ is the smallest relevant length which is in agreement with the model of Altshuler and Aronov [5].

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