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Critical behaviour of the conductivity in metallic n-type InP close to the metal–insulator transition

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Abstract. The metal–insulator transition (MIT) induced by a magnetic field, in barely metallic and compensated n-type InP has been re-examined. Using new analysis methods, we have determined the magnetic field for which the conductivity change from a metallic behaviour to a variable-range hopping regime. On the metallic side of the MIT, the electrical conductivity is found to obey $\sigma = \sigma_0 + mT^s$ down to 60 mK; the zero-temperature conductivity can be described by a scaling law with an exponent $\nu = 1$ and there is no evidence for a minimum metallic conductivity.

As the MIT is approached, we observe a clear crossover from a $T^{1/2}$ to $T^{1/3}$ temperature dependence of the conductivity, which is related to a competition between two length scales: the correlation length and the interaction length.

Mott (1972) introduced the concept of a minimum metallic conductivity σ_{min} in disordered metallic systems. In the case of doped semiconductors, this quantity was shown to be the pre-exponential σ_0 of the conductivity

$$\sigma = \sigma_0 \exp[-(E_C - E_F)/kT] \tag{1}$$

when the conduction mechanism is by excitation of the electrons from the Fermi level E_F to a mobility edge E_C.

In our earlier experiments on InSb and InP (Biskupski *et al* 1980) we found agreement with this model. Extending the experiments down to lower temperatures in the range of 40 mK and applying a magnetic field, Long and Pepper (1984) and our group (Biskupski *et al* 1984, Spriet *et al* 1986) have shown that in the case of InP the value of the conductivity σ was independent of temperature down to 40 mK, for different values of the magnetic field, below a critical value. Above this critical field, the conductivity was no longer metallic and some arguments were given (Dubois *et al* 1985) for a discontinuous metal–insulator transition (MIT), induced by the magnetic field.

During the same time, the scaling theory of Abrahams *et al* (1979) predicted that minimum metallic conductivity does not exist in non-interacting electron systems. This was confirmed by experimental results obtained for doped semiconductors such as Si : P (Rosenbaum *et al* 1980), which showed that the conductivity at $T = 0$ behaves like

$$\sigma = \sigma_c(n/n_c - 1)^\nu \tag{2}$$

with $\nu = 1$ or $\nu = 0.5$.

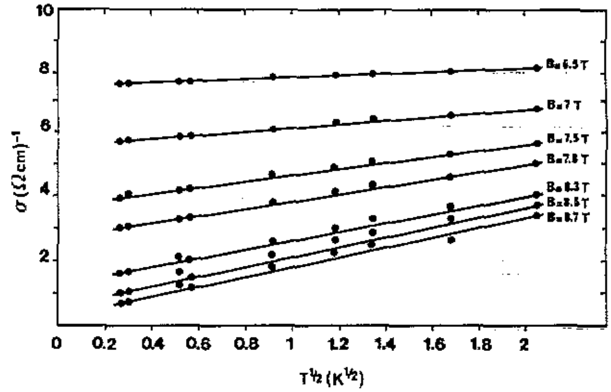

Figure 1. Conductivity versus $T^{1/2}$ for seven values of the magnetic fields between 6.5 and 8.7 T. The lines are the least-squares fits to the data.

During the same period, InP appeared to be a peculiar case. From electrical measurements in the presence of a magnetic field with an InP sample, on the metallic side of the MIT, Biskupski *et al* (1984) found that the conductivity was no longer metallic for $B > 7$ T, and Arrhenius plots of the conductivity versus T^{-1} gave some evidence for variable-range hopping (VRH) for $B > 7$ T. In another work, we (Dubois *et al* 1985) used Hall effect measurements to argue for a sharp MIT at $B = 7$ T. As the magnetic field is increased, three regimes could be observed.

(a) For 0 T < B < 7 T the conductivity is metallic and can be fitted with the equation

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

and the conductivity σ_0 at $T = 0$ is finite.

(b) For $B > 9$ T, the extrapolation of σ at $T = 0$ with equation (3) gives $\sigma_0 = 0$. On the other hand, Hall effect measurements and the presence of VRH were found to be consistent with the value $\sigma_0 = 0$. The slope m in equation (3) has nevertheless an unusual behaviour and its coexistence with variable range hopping was found to be 'puzzling'.

(c) For 7 T < B < 9 T we found that σ versus $T^{1/2}$ curves were straight lines with a positive slope m, and these lines could be extrapolated at $T = 0$, giving a non-zero value of $\sigma_0 < \sigma_{min}$. On the other hand, Arrhenius plots of σ versus $T^{-1/4}$ were also straight lines, giving arguments for σ_0 ($T = 0$) = 0. From Hall effect measurements we gave arguments for $\sigma_0 = 0$ and we have considered that the extrapolation at $T = 0$ was 'dangerous' since the result was dependent on the model which was used. Furthermore in this region the variation in m, which is the result of a competition between Hartree and exchange terms in the interaction, was not clear.

So in this work we have re-examined data obtained with the same n-type InP sample on the metallic side of the MIT. We have concentrated our attention on the results obtained for temperatures between 1 K and 60 mK and magnetic fields in the range 6.5–10 T where the 'puzzling results' mentioned previously, appear. In this range of magnetic fields, we plot the conductivity σ versus $T^{1/2}$ (figure 1) or versus $T^{1/3}$ (figure 2) and it can be seen that straight lines are obtained in each case; furthermore, good fits can be

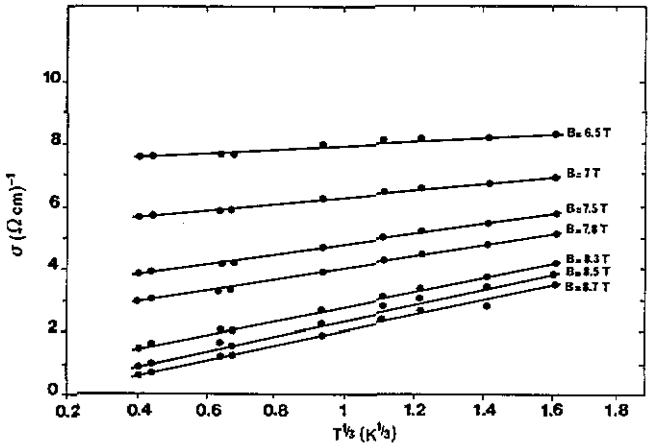

Figure 2. Conductivity versus $T^{1/3}$ for the same seven values of the magnetic field as in figure 1. The lines are also the least-squares fits to the data.

obtained with these two different models. In order to clarify this problem, the experimental values of the conductivity σ_i at different temperatures T_i were fitted to an expression of the form

$$\sigma = \sigma_0 + mT^s \tag{4}$$

using σ_0, m and s as adjustable parameters. The fitting procedure was as follows: s was varied from 0.01 to 1 with a step of 0.01; for each value of s the data were fitted to equation (4), and σ_0 and m were obtained by standard linear regression methods. The goodness of the fit was tested with the estimation of the percentage deviation

$$\mathrm{dev}(\%) = \left[\frac{1}{n}\sum_{i=1}^{n}\left(\frac{100}{\sigma_i}(\sigma_0 + mT^s - \sigma_i)\right)^2\right]^{1/2}. \tag{5}$$

In figure 3 we plot dev(%) against the exponent s for several values of the magnetic field. As in our previous work we believed that VRH could appear between 7 and 9 T, we used the same fitting procedure to find the magnetic field region, where VRH is the best model fitting with the experiment. In figure 4, we plot dev(%) against s for different magnetic fields in the range 7–9.5 T, when fitting the data with the expression for σ for VRH:

$$\sigma = \sigma_1 \exp[-(T_0/T)^s]. \tag{6}$$

It can be seen that the minimum for dev(%) is obtained only for $B > 9$ T; so, for these values of B, the sample behaves like an insulator and we can observe VRH which obeys the Mott law with $s = 0.25$; furthermore the conductivity at $T = 0$ is zero. For $B < 9$ T, figures 4 and 3 show that the conductivity is in agreement with equation (4) and the conductivity is metallic; the values of s will be discussed further. Now we can estimate the value of the magnetic field for which the MIT occurs by an analysis of the variation in σ_0 in equation (4) with the magnetic field for $B < 9$ T.

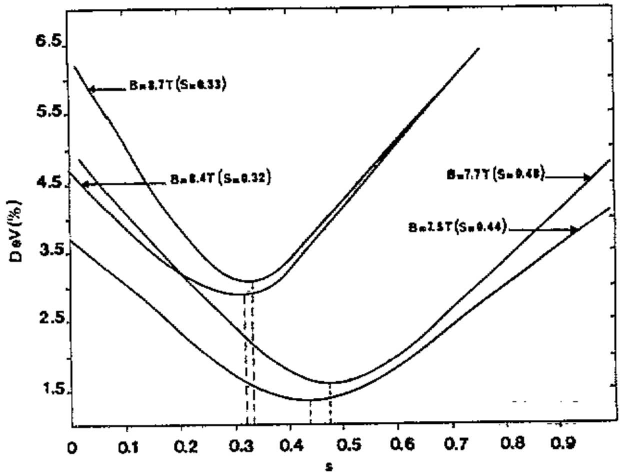

Figure 3. Percentage deviation dev(%) versus exponent s in equation (4) for different values of the magnetic field. Two sets of curves can be clearly distinguished: a first set with a minimum close to $\frac{1}{3}$, a second set with a minimum close to $\frac{1}{2}$.

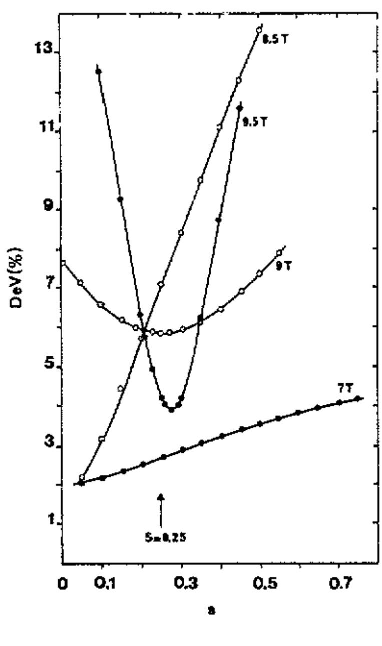

Figure 4. Percentage deviation dev(%) versus exponent s in equation (6) for some values of the magnetic field between 7 and 9.5 T. VRH is observed above 9 T.

If we plot σ_0 as a function of the magnetic field it can be seen in figure 5 that σ_0 decreases linearly to zero at a value of B close and just below 9 T which is in agreement with the onset of the VRH above 9 T. The best fits are obtained with the expression

$$\sigma_0 = \sigma_c(1 - B/B_c)^\nu \tag{7}$$

where $\sigma_c = 11.94\ \Omega\ \mathrm{cm}^{-1}$, $B_c = 8.6$ T and the exponent $\nu = 1.07 \pm 0.05$. This equation is in agreement with the scaling theory of Abrahams *et al* (1979) and the exponent is

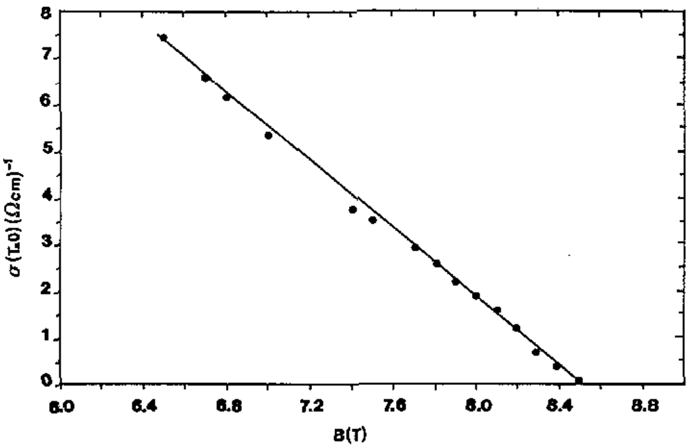

Figure 5. Zero-temperature conductivity deduced from equation (4) versus magnetic field. The full curve is the best fit of equation (7) to the data.

close to the value $\nu = 1$ predicted by Castellani *et al* (1987) in the case of a MIT driven by electron–electron interactions. With another n-type InP sample which is more metallic and with an impurity concentration $n = 1.24 \times 10^{17}\ \mathrm{cm}^{-3}$ we found the same behaviour of σ_0 with an exponent $\nu = 1.06 \pm 0.03$.

It should be stressed that, firstly, these results imply that the concept of minimum metallic conductivity no longer holds and, secondly, that we could not arrive at these conclusions with our previous Arrhenius plots of log σ versus T^{-1}.

To obtain more confidence in these new results which change our mind about the MIT, we compared our data with another form of the scaling law for the conductivity:

$$\sigma_0 = \sigma_c[(a_\perp^2 a_\parallel / a_{\perp c}^2 a_{\parallel c}) - 1]^\nu \tag{8}$$

where $a_\perp$ and $a_\parallel$ are the effective Bohr radii perpendicular and parallel to the magnetic field respectively, and $a_{\perp c}$ and $a_{\parallel c}$ their values at the MIT. Equation (8) is obtained from the scaling equation (2), using the Mott criterion in the case of a magnetic-field-induced transition:

$$n^{1/3}(a_\perp^2 a_\parallel)^{1/3} = 0.26. \tag{9}$$

Equation (8) has been used in the case of disordered semiconductors by Ishida and Otsuka (1977) and Mansfield *et al* (1985); the exponent ν was found to be close to the value $\nu = 1$ predicted by Castellani *et al* (1987).

When performing a fit of our data with equation (8), where $a_\perp$ and $a_\parallel$ are calculated with the model of Yafet *et al* (1956), it can be seen in figure 6 that there is good agreement with equation (8) and we find that $\nu = 0.92 \pm 0.03$ and $\sigma_c = 12.41$; these values of ν and σ_c are comparable with those that we have obtained with equation (7). So it seems now that, in the case of the MIT induced in InP by a magnetic field, the arguments for a continuous transition with a scaling behaviour of the conductivity on the metallic side are better than our previous arguments (Biskupski *et al* 1984, Dubois *et al* 1985). Thus we have to change our mind about the MIT in InP; however, this material remains a peculiar case as mentioned by Mott (1989); the constant m in equation (4) changes sign

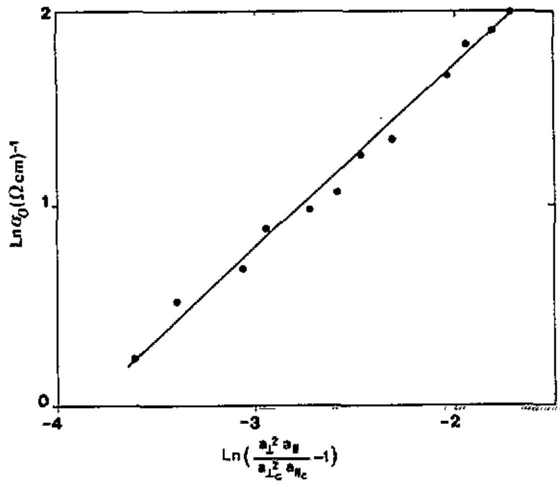

Figure 6. Zero-temperature conductivity deduced from equation (4) as a function of $a_\perp^2 a_\parallel / a_{\perp c}^2 a_{\parallel c}$. The full curve is the best fit of equation (8) to the data.

as the MIT is approached by increasing the magnetic field; this has already been noticed by Mott (1989) and will be the subject of a forthcoming paper.

Another original result is obtained from a detailed analysis of the temperature dependence of the corrections to the conductivity in equation (4), for magnetic fields in the range 6.5–9 T. Far from the MIT and below 7.9 T, a $T^{1/2}$ dependence is observed for σ and this is in agreement with quantum interference effects and electron–electron interactions. Close to the MIT and for magnetic fields in the range 7.9–8.7 T, the best fits are obtained with $T^{1/3}$. This $T^{1/3}$ correction to the conductivity was also observed in GaAs by Newson and Pepper (1986) and Maliepaard Pepper and Newbury (1988).

In this work it can be seen in figure 3 that we observe clearly the crossover from $T^{1/2}$ to $T^{1/3}$ as the MIT is approached. This was first predicted by Altshuler and Aronov (1983) who consider the conductivity given by the expression

$$\sigma = G_c e^2/hL + e^2/h\zeta \tag{10}$$

where G_c is the critical value of the dimensionless conductivity, ζ the correlation length and L a relevant length. In a system close to the MIT, in which the electron interactions are important, we have $\zeta \to \infty$. Altshuler and Aronov show that the relevant length in this case is the interaction length $L_T = (Dh/kT)^{1/2}$ and, according to the scaling hypothesis that they obtain for the conductivity and the interaction length, expressions which are valid when $\zeta > L_T$ are

$$\sigma = (e^2/h)[C(\partial N/\partial\mu)T]^{1/3} \qquad L_T = [(C/T)(\partial\mu/\partial N)]^{1/3} \tag{11}$$

where $C \simeq 1$ and $\partial N/\partial\mu$ is the density of states at the Fermi level.

A similar analysis was given by Kaveh *et al* (1989) who predicted the same crossover from $T^{1/2}$ to $T^{1/3}$ in a strong magnetic field which suppresses the Hartree term in the correction to the conductivity, in which case the MIT is induced solely by exchange interactions. In figure 7 we plot the interaction length L_T as deduced from equation (11) and the correlation length ζ deduced from the conductivity at $T = 0$ for different magnetic fields. It can be seen that

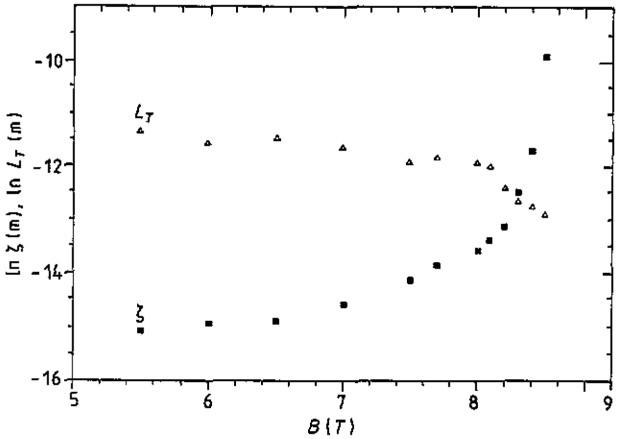

Figure 7. Correlation length ζ and interaction length L_T at $T = 66$ mK versus the magnetic field below and close to the MIT.

(i) far from the MIT, $\zeta < L_T$;

(ii) as the transition is approached, ζ diverges and becomes greater than L_T for a magnetic field in the vicinity of 8 T, which is in agreement with the value of 7.9 T for which the crossover from $T^{1/2}$ to $T^{1/3}$ is observed.

In summary we have determined with a more detailed and coherent analysis of experimental data the value of the magnetic field for which the MIT is induced and we have presented arguments for which we change our mind about the existence of a minimum metallic conductivity in InP.

A coherent ensemble of new results has been obtained; we have shown by different approaches that the zero-temperature conductivity has a scaling behaviour close to the MIT. There is also clear evidence for a change in the temperature dependence of the metallic conductivity which is due to competition between the correlation length which diverges at the transition and the interaction length which is the relevant length scale for the conductivity close to MIT.

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