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Ultra-low-temperature conductivity in silicon doped with antimony

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Abstract. We measure to low temperatures (10 mK) the conductivity behaviour in high magnetic fields of an Sb-doped Si sample of just-metallic character. The sample had previously been assessed by Long and Pepper as showing evidence for a new electronic phase. Our measurements further highlight the anomalous low-temperature behaviour, and we discuss the results in the context of a recently published theory of the effect, and in comparison to other magnetoresistance data on silicon-based doped semiconductors. A further possibility emerges from this discussion, in that the anomaly may be appearing under experimental conditions such that the usual limiting mechanism on the conductivity is 'frozen-out' by the high magnetic fields used.

There continues to be interest in the metal–non-metal transition in doped semiconductors [1], with the focus of attention residing in the scaling properties of the conductivity with doping density n. The scaling theory of Abrahams *et al* [2] was developed in terms of $g(L)$ which can be thought of as the conductance of a cube of size L. In three dimensions this conductance increases with L for $g > g_c$ (metallic region) and decreases with L for $g < g_c$ (insulator region) where g_c is the critical conductance. A scaling function β defined as $\beta = \mathrm{d} \ln g(L)/\mathrm{d} \ln L$ equals zero at the metal–insulator transition where $n = n_c$. Scaling theory shows that the conductivity in the critical region is then given by $\sigma = \sigma_c(n/n_c - 1)^\nu$ where the critical exponent ν is the inverse slope of β versus ln g. In particular, in the silicon-based systems, the critical exponent of $\frac{1}{2}$ is well established in Si : P [3, 4] and Si : As [5], whereas in Si : Sb [6] there is some ambiguity in the experimental results.

When a magnetic field is applied it seems that the scaling exponent should revert to the value of unity. It does so in Ge : Sb [7]. In uncompensated Si : As [8], however, there is some evidence in metallic samples that the critical exponent is unchanged in fields up to 15 T. For Si : Sb, at a just-metallic density, a simple re-plot of the data of figure 3 of [5] is shown in figure 1. For the sample coded L2/3 we plot the values of $\sigma(0)$, obtained from an extrapolation of the linear $\sigma(T) \propto T^{1/2}$ regions back to the $T = 0$ axis, against field B, in T. In the terminology of Long and Pepper this analysis operates on the A-state. This follows the procedure of Thomas [7], and establishes that the scaling with field in Si : Sb, at least for this sample, has a critical exponent of unity. Furthermore, from the graph, we see that the critical field for this sample is 12.5 T. Given that the sample density is 3.1×10^{18} cm^{-3} and the critical doping density is 2.9×10^{18} cm^{-3}, then,

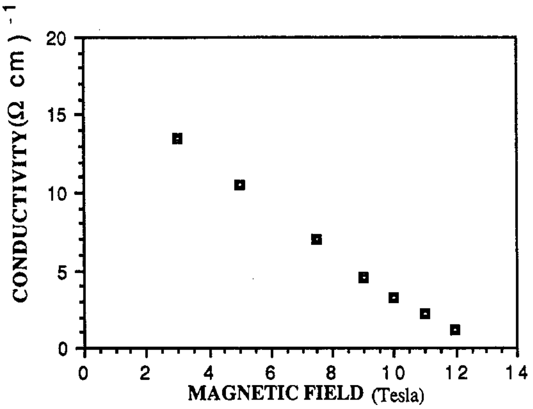

Figure 1. The extrapolated conductivity at zero temperature from straight line σ–T plots (plots obtained at temperatures greater than those at which the low-temperature anomaly appears), against B, the magnetic field.

following Shafarman *et al* [8], we deduce that the coefficient η in $N_c(B) = N_c(0)(1 + \eta B^2)$ must have a value of about $4 \times 10^{-4}\ \mathrm{T}^{-2}$ which fits quite well with the value of 2×10^{-4} quoted for Si:As. This approach assumes that the magnetic field affects the critical concentration N_c. For this sample the density of $3.1 \times 10^{18}\ \mathrm{cm}^{-3}$ is taken from a room temperature Hall coefficient R, and use [9] of $R = 3\pi/8ne$. The room temperature conductivity of the sample we found to be $87\ \Omega^{-1}\ \mathrm{cm}^{-1}$.

Si : Sb also exhibits highly unusual ultra-low-temperature behaviour, where the conductivities of several samples close to the metal–non-metal (MNM) transition appear to exhibit transitions to a more conducting state as the temperature is lowered. Kaveh and Mott [10] have hypothesised that the driving mechanism for this two-transition behaviour, which has not been found in the other silicon-based systems, lies in the enhanced spin–orbit interaction associated with Sb donors, as compared to P and As donors. Since the possible difference in scaling behaviour at zero field near the MNM transition, between on the one hand Si:P and Si:As, and on the other Si:Sb, is also thought to be due to the symmetry-breaking property of the spin–orbit interaction, we have undertaken some further ultra-low-temperature measurements on the L2/3 sample of Long and Pepper [6], kindly lent to us by Professor Pepper.

Before presenting our data, a few comments are apposite on the measurement techniques we employed. We used a simple lock-in detection technique, with a frequency of 30 Hz, and the contact resistances were roughly a few ohms at helium temperatures. Power dissipation was about 10^{-12} W. The sample is basically rectangular in shape, of length 15 mm, breadth 2.09 mm and thickness 287 μm. However, along each long side, three side-arms are positioned with equal spacing, each side-arm being thin ($\simeq\frac{1}{2}$ mm) and ending in a pod to which solder contacts can be made. The separation between adjacent voltage probes (side-arms) was 3 mm. For our measurements we used the two current contacts and two outer voltage probes on one side. The Long and Pepper measurements employed the centre and one outer voltage probe on one side. We quote these geometries because there is a constant disagreement, from room temperature downwards, in the absolute values of conductivities; where the measurements overlap in temperature, our values of σ, the conductivity, are always 15% lower than those of Long and Pepper. To eliminate any possibility of inhomogeneity a check at room temperature was undertaken on the 'centre to side-arm' resistivity readings, revealing a difference between the two side-arms of about 3%, explicable on the basis of slightly different current paths near the two ends of the bar. We believe that the discrepancy

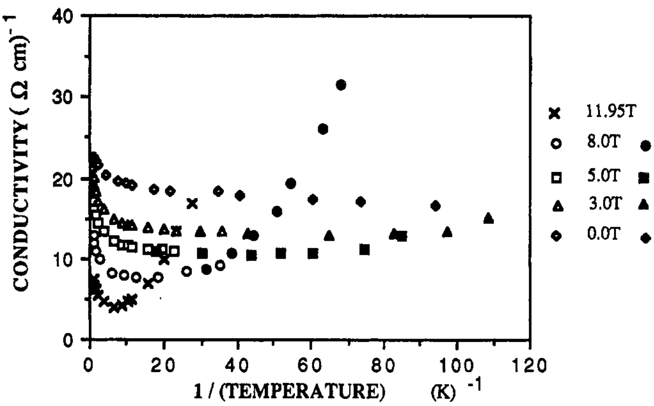

Figure 2. Conductivity against $1/T$ for several field values. The units of σ are $\Omega^{-1}\,cm^{-1}$ and of $1/T$ are K^{-1}. Open symbols and crosses are Long and Pepper data; full symbols are from this work.

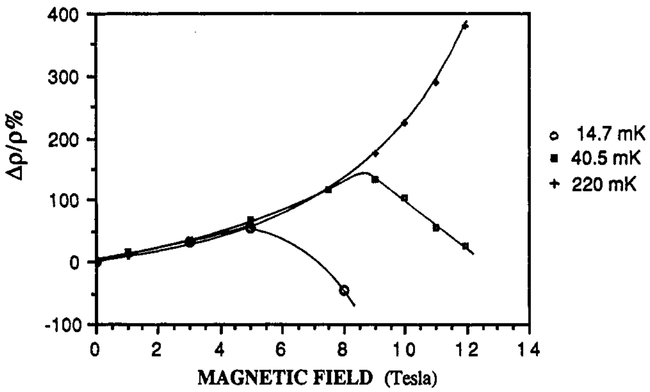

Figure 3. The change of resistance, $\Delta\rho$, on application of a magnetic field $\boldsymbol{B}$, divided by the zero-field resistance and the fraction expressed as a percentage, plotted against B for three different temperatures. Here the two highest temperatures involve only Long and Pepper data, whilst the lowest temperature involves only our data.

between our conductivities and those of Long and Pepper reflects, therefore, an error by them either in a current calibration or in a measurement of sample geometry. In presenting data in figures 2, 3 and 4, then, we have scaled the Long and Pepper measurements by the factor 0.85. Our maximum magnetic field is 8 T, whereas the Long and Pepper results were taken up to 11.95 T.

We note the following new information that these figures reveal.

(i) The strong rise in conductivity as T is decreased does not seem to freeze out on moving down to 10 mK (figure 2). The new low-temperature points make it clear that a low-temperature rise in conductivity is present at all fields except $B = 0$.

(ii) The initial rise in $\Delta\rho/\rho(0)$ is a positive magnetoresistance effect, with a $\Delta\rho/\rho(0) \propto B^2$ dependence (figure 3). This B^2 dependence is very strong at 220 mK,

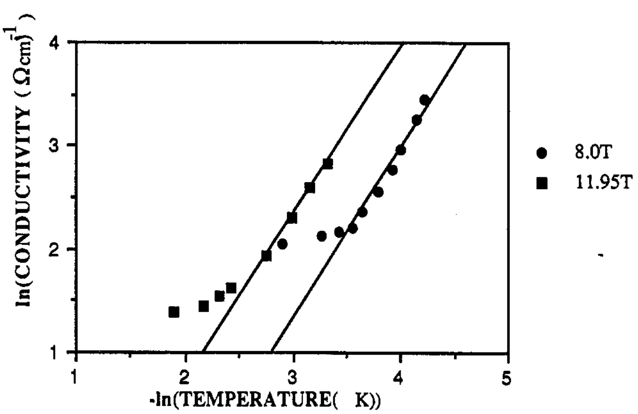

Figure 4. Log–log plots of conductivity σ against temperature for the two fields at which the anomalous behaviour is most marked.

and, as the temperature drops, it remains of approximately the same magnitude but is apparently truncated at smaller and smaller magnetic fields by the appearance of a strong downward trend in the magnetoresistance. This change in sign of slope takes over at a field of about 3 T at 11 mK, a field of about 9 T at 40.5 mK and, if it exists at all, at a field of greater than 12 T at 220 mK. There is a clear correlation, in both figures 2 and 3, between low temperature and low field for the change in sign of the slope in the magnetoresistance. There is also a convincing demonstration in figure 3 that the initial positive magnetoresistance is relatively independent of temperature. From both figures it seems that the highly conducting states that are accessed by the application of a magnetic field are easily washed out by temperature effects.

In discussing the results we address first the question of the generality of the result. In particular, do recent experiments in a very similar system [8], Si : As, exhibit any indication of such an anomaly in the low-temperature conductivity? Here, the base temperature is about 60 mK, and similar relative densities (8.67×10^{18} cm^{-3} for one sample when $N_c(0) = 8.55 \times 10^{18}$ cm^{-3}) and similar fields (~10 T) have been measured. A positive magnetoresistance effect is observed (figure 1 in [7]), up to 8 T, quite similar to the 220 mK curve of figure 3 above. Both the shape of the curve and the magnitude of the positive magnetoresistance for Si : Sb (220 mK) and Si : As (60 mK) accord rather well. At 40.5 mK in Si : Sb, figure 3 shows that the down-turn in $\Delta\rho/\rho(0)$ occurs at a field of about 9 T. It seems that the Si : As results have been taken in a range of temperature and field just outside the experimental conditions needed to observe any low-temperature, high-field anomaly in the conductivity. Low-temperature results [11] for Si : P have only explored the low-field region going up to 1 T. A positive magnetoresistance is measured in the 30 mK, 1 T experimental region with a magnitude similar to the Si : Sb (figure 3) results. Thus it seems that the requisite experimental conditions for corroboration of the low-temperature, high-field anomaly in Si : Sb have not so far been attained in other silicon systems.

On the theoretical side, Kaveh and Mott [10] have published an article that they believe can provide a plausible basis for the Long and Pepper [6] results. We now turn to an examination of this theory, particularly in the context of our own extension of those results.

The theory relies on spin–orbit interaction and weak-localisation and anti-localisation corrections. It predicts that as the magnetic field is increased from zero, the conductivity at zero temperature should first decrease, then, when the magnetic length becomes approximately equal to the spin–orbit scattering length, start to increase towards an asymptotic value equal to the Boltzmann conductivity, σ_B. If we fit the low-field drop in σ (figure 3) to a B^α power law dependence, the zero-temperature asymptote for α is 0.62 from our data with an error of $\pm 2\%$. This corresponds rather well with the theoretical prediction of $\alpha = 0.5$. (Unfortunately our data are not sufficiently closely spaced in field to verify that the high-field rise in σ has a similar asymptotic power law dependence at zero temperature.)

However, the magnitude of the low-temperature effects as observed experimentally, and the sizes of the fields involved, seem to us to be incompatible with the basis of the theory. For example, at 8 T (figure 2), the conductivity improves by a factor of five as the temperature is lowered from 50 mK to 14.7 mK. Similarly, at 11.95 T, the conductivity rises by a factor of greater than four on cooling from 160 mK to 32 mK. An important feature is that, in each case, the conductivity at the lowest temperature is substantially greater than its value at 1 K, indicating that the improving conductivity at low temperature is not limited by the value of the Boltzmann conductivity. The theory [10] makes clear that this latter conductivity should be the low-temperature limit. Again at, for example, 14.7 mK, it is possible to deduce (figure 3) that the conductivity first decreases by a factor of two from 0 to 5 T, then rises by a factor of more than three when the field increases to 8 T. These effects all have magnitudes measured in the hundred per cent range. It is hard to believe that such huge effects are associated with the appearance and disappearance of weak-localisation and weak-anti-localisation correction terms.

We feel compelled on these orders-of-magnitude arguments to reject the theory of [10]. Alternative models are by no means obvious. The field/temperature correlation for the change in sign of the slope of magnetoresistance (figure 3) is not related to any onset of localised spin order, since, for example, the 8 T and 40.5 mK relation (figure 3) would predict a g-factor, in $g\beta B \sim k_B T$, of about 0.01, a magnitude not usually connected with electronic g-factors!

The inelastic scattering time τ_i is a most important parameter in the neighbourhood of the metal–insulator transition for both localisation and interaction components. In the weak-localisation regime, quantum interference can only occur if the inelastic scattering time is significantly longer than the elastic scattering time.

In the interaction regime, the conductivity is normally controlled by the interaction length $L_T = (hD/kT)^{1/2}$ which gives the well known $\sigma \propto T^{1/2}$. However, Kaveh *et al* [12] have shown that, close to the metal–insulator transition, the inelastic diffusion length L_i becomes shorter than the interaction length L_T and so the former then determines the temperature dependence of the conductivity. Our sample is well within the Kaveh *et al* criterion $k_F l < 2.3$. At low temperature the shortest inelastic scattering time is that due to electron–electron scattering. Schmid [13] obtained a relation $1/\tau_i \propto T^{3/2}$ for disordered metals. More recently Isawa [14] obtained $1/\tau_i \propto T$ at low temperatures. This has been confirmed by experimental measurements on InP by Finlayson and Mehaffey [15], on GaAs by Morita *et al* [16] and on InGaAs by Maliepaard *et al* [17]. From Isawa, the inelastic diffusion length $L_i = (D\tau_i)^{1/2}$ then gives $\sigma \propto T^{1/2}$ at sufficiently low temperatures. Note that the $T^{1/2}$ behaviour is now controlled by the inelastic L_i. From [14] equation (7), we can calculate the inelastic scattering rate $1/\tau_i = T \times 1.7 \times 10^{11} h/E_F\tau_0$. Substituting the appropriate parameters we find $1/\tau_i = 1.7 \times 10^{13} T$ from which we can calculate $L_i = (D\tau_i)^{1/2}$.

Turning now to figure 3, we note that the 15 mK curve departs from the high-temperature form at about 5 T. At 15 mK we find $L_i = 1.2 \times 10^{-8}$ m which equals the magnetic length $L_H = (h/Be)^{1/2}$ at 5 T. The equivalent numbers for 40 mK and 8 T are $L_i = 0.7 \times 10^{-8}$ m and $L_H = 0.9 \times 10^{-8}$ m. The conductivity therefore begins to increase when the magnetic length becomes shorter than the dominant inelastic diffusion length. The process can continue, by 'freezing out' the interaction process where 'freezing out' simply implies the replacement of a particular scattering mechanism by another of shorter characteristic length.

At this stage the field has reached a value where the magnetic length is comparable with the inter-impurity distance, and so impurity scattering is in turn frozen out. Straight-line fits to the two curves of figure 4 in their low-temperature portions produce slopes of 1.6 for both the 8 T and 11.95 T data, given $\sigma \propto T^{-1.6}$, with an error bar on the exponent of 0.3.

We now require a mechanism capable of carrying a current that, in the high-field region, exceeds the zero-field value. We make a tentative suggestion following along the lines proposed for 2D systems by Buttiker [18]. He discusses the suppression of both elastic and inelastic scattering in high magnetic fields leaving the electron current to be carried out by skipping orbits along the sample edge. For this to occur the essential requirement of specular reflection at the sample edge is relatively easy to obtain in 2D structures. In our 3D structure we may note that the Fermi wavelength is much greater than the lattice spacing. Pippard [19], discussing related problems in metals, remarks that in the semiconductor case, roughness on an atomic scale may be of minor importance and partial specular reflection may become a real possibility. We speculate therefore that skipping orbits may be the controlling influence on conductivity once the usual scattering mechanisms have been suppressed by the magnetic field.

The particular sample, L2/3, on which we have made measurements is just metallic and shows evidence for a field-driven transition at 12.5 T. At low temperatures, and high fields, a strong anomalous conductivity component emerges, apparently correlated with the shrinking of the magnetic length below the elastic and inelastic scattering lengths. We believe that no other silicon-based samples have been explored under similar conditions, and therefore that the effect may be general. We adduce some experimental evidence from the field dependence of the conductivity in favour of a recently published theory [10], but believe that the effects measured are really too large to be explained by that theory.

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