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Variable-range hopping magnetoresistance in CdSe

D M Finlayson

Department of Physics and Astronomy, University of St Andrews, St Andrews, Fife KY16 9SS, UK

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Abstract. A negative magnetoresistance is reported for the variable-range hopping regime of a straightforward sample of CdSe. The behaviour is consistent with the theory of Nguyen *et al*.

When a fairly high concentration of Cr is added, the magnetoresistance becomes predominantly positive with a strong temperature dependence at low magnetic fields. This is attributed to the influence of the spin system associated with the added Cr. Anomalous behaviour in other systems may similarly be related to spin concentrations.

Quantum interference effects in the weak-localization regime of disordered metals have been studied extensively for over a decade and are now fairly well understood. Studies of quantum interference in the variable-range hopping (VRH) regime on the insulator side of the metal–insulator transition are of more recent date and this cannot be said to be well understood. Nguyen *et al* [1] first showed that the interference among various forward paths associated with hopping can be destructive. This destructive interference can be suppressed by a magnetic field, giving rise to a negative magnetoresistance. A somewhat different approach by Sivan *et al* [2] yielded similar results. The theoretical predictions are that

$$\Delta R/R \cong B^2 T^{-\alpha} \tag{1}$$

where $\alpha = \frac{3}{4}$ for a constant density of states or $\frac{3}{2}$ in the presence of a Coulomb gap.

An earlier theory by Shklovskii and Efros [3] considered the effect of a magnetic field on the donor wavefunctions but did not at that time consider interference. They predicted a positive magnetoresistance governed by the equation

$$\ln[\rho(H)/\rho(0)] = aB^2[T_0/T]^{\alpha} \tag{2}$$

where α again has the same values.

Experimental results are confusing in that, quite apart from minor details of temperature dependence etc, the sign of the magnetoresistance appears to be dependent on the system under investigation. Thus Zhang *et al* [4] for CdSe and Tremblay *et al* [5] for GaAs obtain a negative magnetoresistance while Dai *et al* [6] find only a positive magnetoresistance in all Si based semiconductors. By contrast Shlimak *et al* [7] observe a negative magnetoresistance in Ge above a temperature of 2 K.

Some time ago [8] we measured a set of samples of CdSe and obtained apparently good agreement with the Shklovskii–Efros theory of positive magnetoresistance (2). Negative magnetoresistance was also observed but in the absence of an appropriate theory this was not pursued at the time. The samples used covered a wide range of electron concentrations

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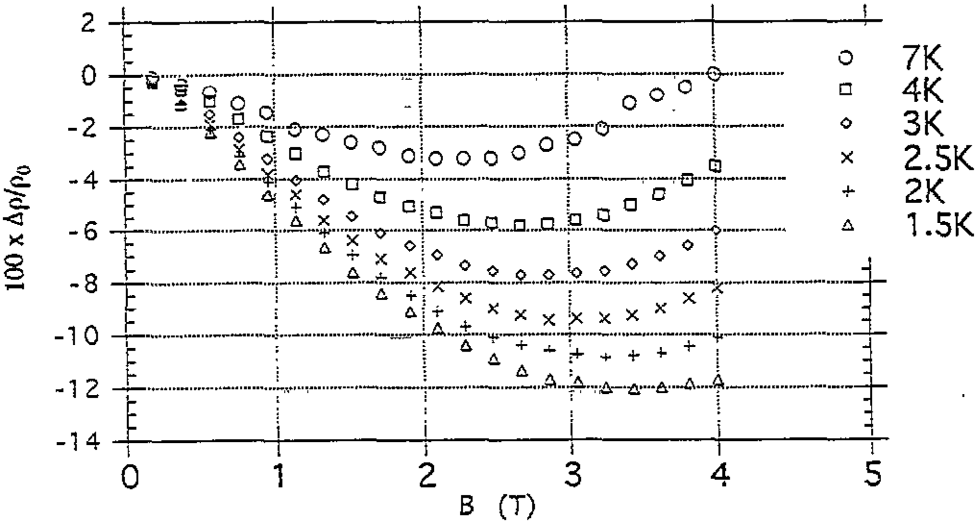

Figure 1. The magnetoresistance versus magnetic field at different temperatures for sample (iii).

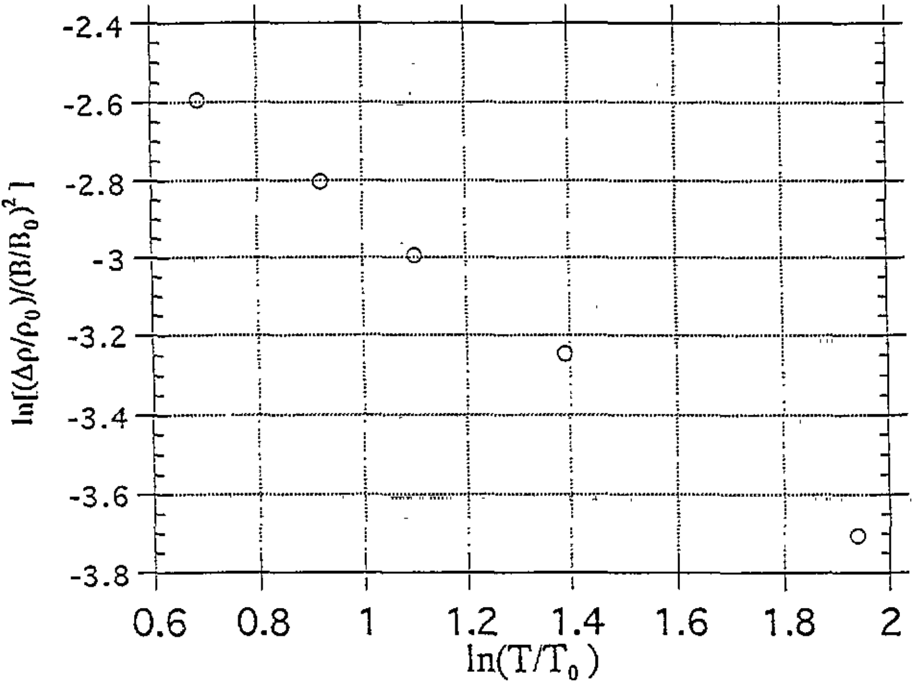

Figure 2. A double log plot of the magnetoresistance ratio divided by the square of the magnetic field versus temperature for sample (iii). $B_0 = 1$ T; $T_0 = 1$ K.

on both sides of the metal–insulator transition but were somewhat unusual in that some were heavily doped with Cr. This impurity turns out to be electrically neutral and so the addition of Cr allows one to add spins to the system without significantly changing the

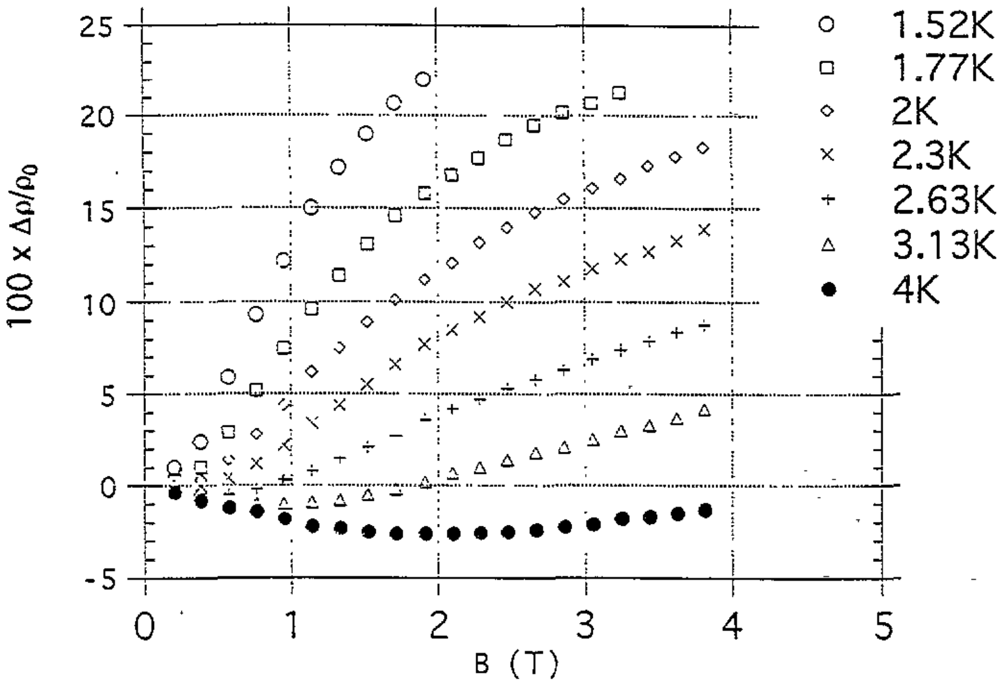

Figure 3. The magnetoresistance versus magnetic field at different temperatures for sample (i).

electron density. In zero magnetic field the resistivity–temperature curves yield a distribution appropriate to their measured electron density irrespective of Cr concentration. By contrast, there is a dramatic difference between the magnetoresistances of samples with and without Cr; the latter give a negative magnetoresistance similar to that obtained by Dai *et al* [6] while the former show a large positive magnetoresistance. These measurements are now presented in the hope that they will shed some light on the current rather confusing picture of magnetoresistance in the VRH regime.

Three samples were measured in the insulating range with electron concentrations ($\times 10^{17}$ cm^{-3}) of (i) 2.4, (ii) 1.2 and (iii) 0.36. The critical density in CdSe we take to be about 3×10^{17} cm^{-3} [4, 8]. All three samples were heavily compensated with $K \cong 0.75$. Samples (i) and (ii) were heavily doped with Cr at about 10^{19} cm^{-3}. These were provided by Dr J Baranovski (Warsaw); sample (iii) was provided by Professor J W Allen of this department.

A plot of magnetoresistance versus magnetic field at six different temperatures for sample (iii) is shown in figure 1. It will be seen that the magnetoresistance is entirely negative up to fields of 4 T. This is very similar to the behaviour reported by Zhang *et al* [4]. As predicted by theory, at low fields the magnetoresistance ratio varies as the square of the magnetic field. Writing (1) in the form

$$(\Delta\rho/\rho_0)/B^2 = T^{-\alpha}$$

and plotting on a log–log scale in figure 2 we find $\alpha = 0.9$ in not too bad agreement with the value of 0.75 derived from the $T^{-1/4}$ law.

Turning now to the Cr doped samples we see from figure 3 (sample (i)) and figure 4 (sample (ii)) that the magnetoresistance is now predominantly positive with a small negative

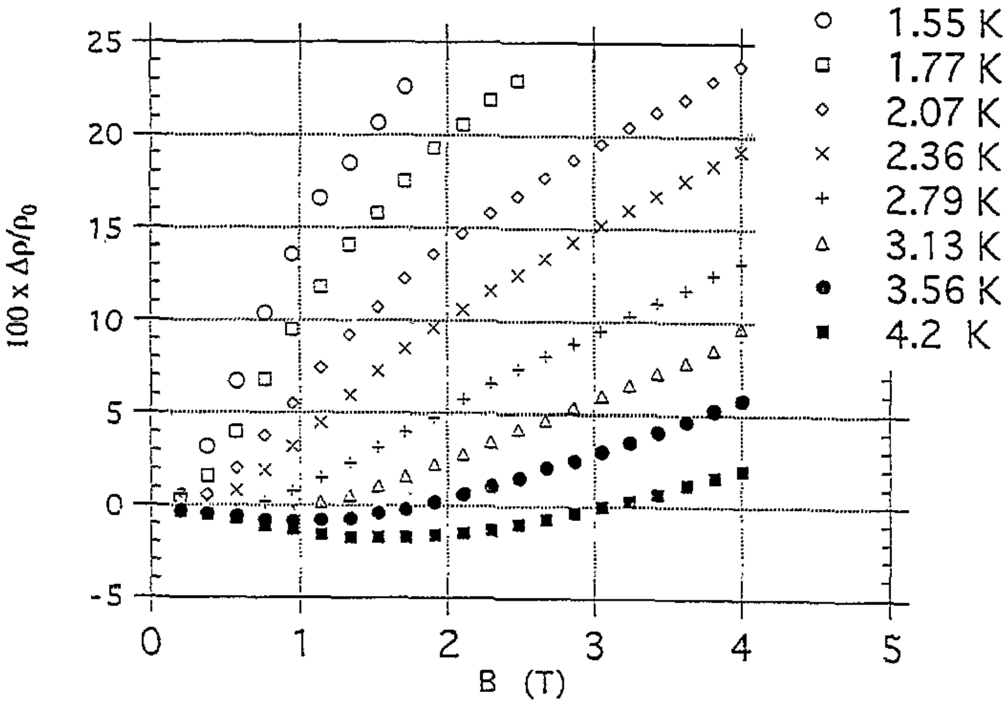

Figure 4. The magnetoresistance versus magnetic field at different temperatures for sample (ii).

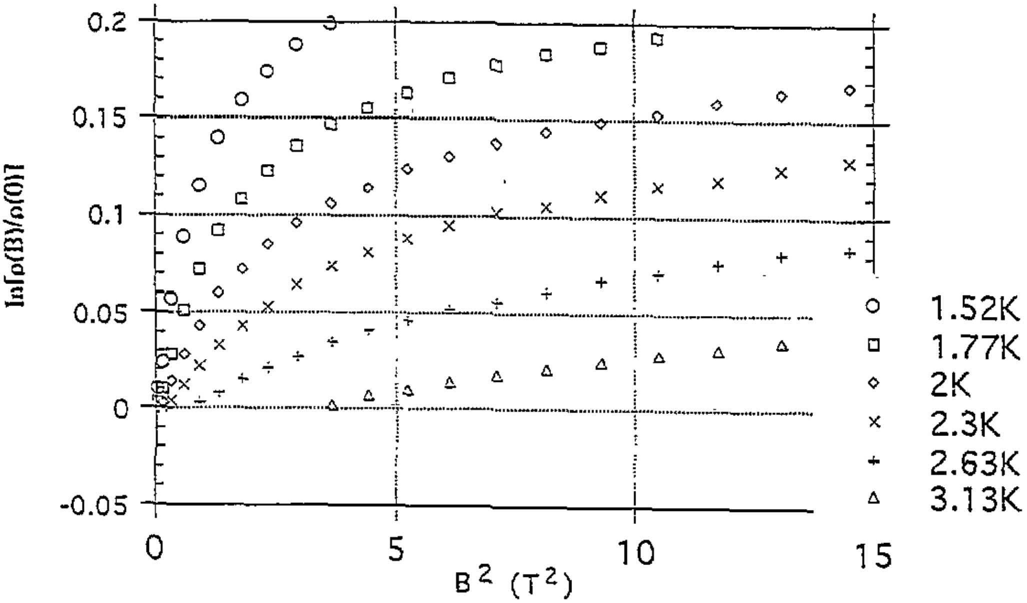

Figure 5. The log of the resistance ratio versus the square of the magnetic field at different temperatures for sample (i).

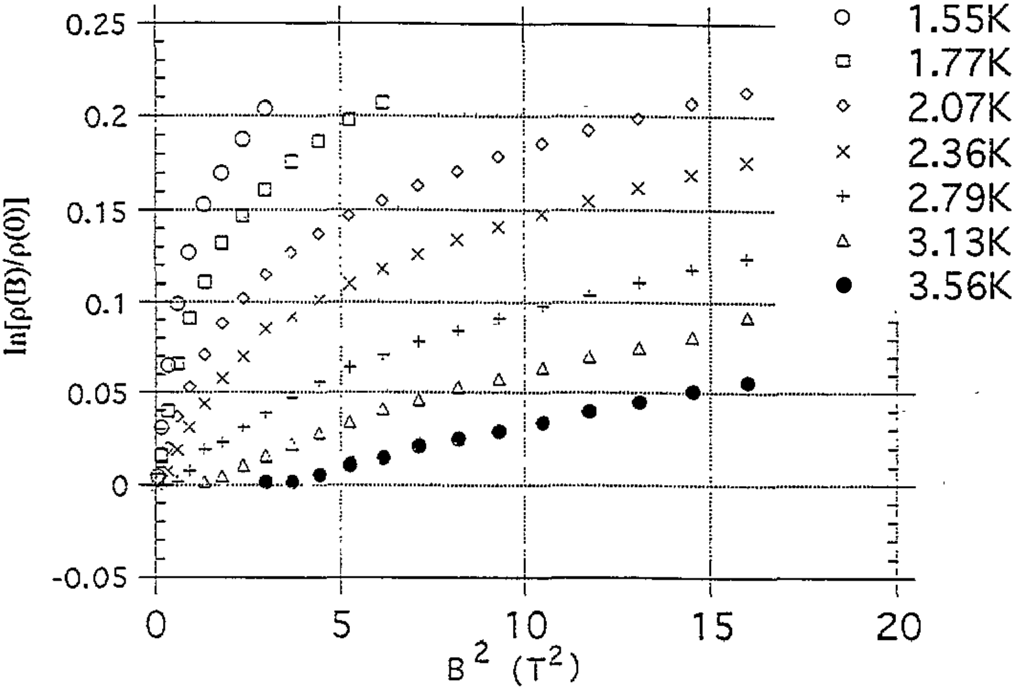

Figure 6. The log of the resistance ratio versus the square of the magnetic field at different temperatures for sample (ii).

value appearing at higher temperatures. Plotting $\ln[\rho(H)/\rho(0)]$ versus B^2 in figure 5 (sample (i)) and figure 6 (sample (ii)) we may observe in passing that the slope becomes independent of temperature at fields above about 2 T. From the slopes at low fields and log–log plots in figure 7 we obtain values for α in equation (2) of four for sample (i) and five for sample (ii). Thus although the predicted low-field B^2 dependence is obtained the temperature dependence bears little relation to that predicted by the theory of equation (2). Similar conclusions were reached by Dai *et al* [6] for Si.

We wish now to consider the suggestion made by Dai *et al* that the absence of a negative magnetoresistance in Si might be due to the relatively high density of spins in Si since we have an even higher density in the samples under consideration.

The theory of Nguyen *et al* [1] considers an electron tunnelling between two sites, the probability of tunnelling being determined by scattering and interference between the various forward going paths. Scattering is due to the fact that in VRH the typical hop distance is greater than the average interimpurity distance and so within the hop distance other sites will affect the hop probability. Nguyen *et al* showed that in zero field the interference is predominantly destructive, but when the phase coherence is broken by, for example, a magnetic field, the destructive interference is removed and a negative magnetoresistance results. If now some of the intermediate sites are spin occupied the phase coherence will be broken and no destructive interference will occur. Since in VRH the hop length increases as the temperature is lowered, the chance that a hop length will include a spin is increased and so, as the temperature is lowered in the presence of a spin system the negative magnetoresistance will tend to vanish. This is indeed what we observe in our CdSe samples.

The observed positive magnetoresistance requires some consideration. In our sample

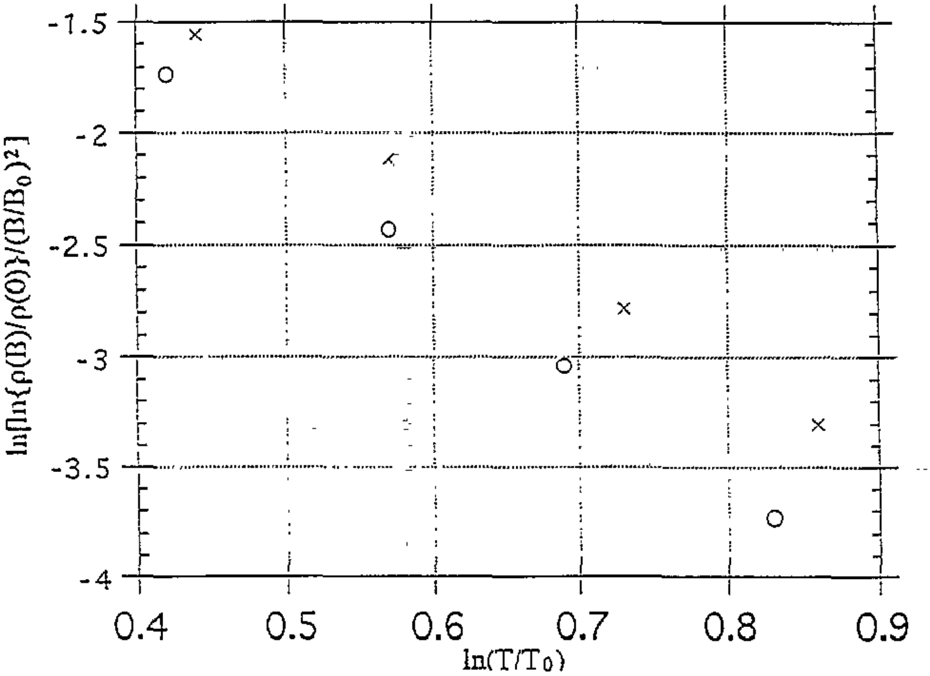

Figure 7. A double-log plot of the log of the resistance ratio divided by the square of the magnetic field versus temperature: o, sample (i); x, sample (ii); $B_0 = 1$ T; $T_0 = 1$ K.

(iii) the negative magnetoresistance saturates in a field of a few tesla depending on the temperature and only in fields greater than 4 T does the magnetoresistance become positive. This positive magnetoresistance may reasonably be attributed to the Shklovskii–Efros theory summarized in (2). It is difficult to see then how the large positive magnetoresistance shown in figures 3 and 4 at much lower fields can be attributed to the same source. We have noted earlier that the temperature dependence of this effect is very much greater than expected from the theory of (2). We suggest therefore that the low-field positive magnetoresistance is not due to the influence of magnetic field on the donor wavefunctions but relates to the interaction of magnetic field with the extra spin system.

Spivak [9] considered VRH in the presence of a spin system. He suggested that hops over paths containing impurities with spins of the same direction interfere whereas paths over different spins do not. Thus, in zero magnetic field interference is small since the spins are disordered. When a field is applied the spins tend to align, giving rise to a positive magnetoresistance. However the temperature change observed in figure 7 is much greater than that expected from the theory of Spivak. At sufficiently high fields we might expect the effect to saturate because most of the spins are aligned. To obtain an idea of the order of magnitude we write $g\mu B = kT$ to obtain $B = 1.5$ T. We have noted in figures 5 and 6 that at fields of this order no further change in slope with temperature is observed although the magnetoresistance continues to increase with field. We suggest that at this relatively high field, modification of the wavefunctions has become operative in the production of a magnetoresistance.

To summarize, in Si, which from other evidence contains about 10^{18} spins cm^{-3}, no negative magnetoresistance is observed. In Ge, with an order of magnitude of fewer spins, a negative magnetoresistance is observed only at temperatures above 2 K. In CdSe, a substantial negative magnetoresistance is observed both by Dai *et al* and ourselves. The addition of spins to the system suppresses the negative magnetoresistance and replaces it by a large low-field positive magnetoresistance, which saturates at higher fields. The high-field positive magnetoresistance is attributed to wavefunction shrinkage. We have not been able to explain the strong low-field temperature dependence and await with interest further developments of theory on positive mangetoresistance in the VRH regime.

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