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Negative magnetoresistance in NbSi amorphous alloys

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Abstract. Results are presented for the temperature and magnetic field dependence of the resistivity of a number of $Nb_{1-x}Si_x$ amorphous alloys in the variable-range hopping regime ($x = 0.89, 0.90, 0.91$). The magnetoresistance is negative and proportional to B in low magnetic fields. Analysis of the magnetoresistance presented is based upon theories of the recent model of an 'oriented path' mechanism.

The magnetoresistance (MR) of amorphous alloys has been studied in the weak-localization region for a number of years providing valuable information regarding the spin–orbit and inelastic relaxation times (Howson and Gallagher 1988). Recently the magnetotransport properties have been investigated in the variable-range hopping (VRH) regime. Nguen *et al* (1985) first predicted a negative MR which would be proportional to the magnetic field, using a logarithmic averaging technique for the interference between the different paths an electron can take as its hops between sites. Ovadyahu (1986) has measured the MR of indium oxide thin films revealing this negative component, while Ye *et al* (1990) have studied a gallium arsenide system and observed a negative MR at low fields. Ye *et al* (1990) analysed this negative MR using a model for the oriented path mechanism developed by Schirmacher (1990). This model is based upon an interference triangle between three hopping sites and agrees with the effects predicted by Nguen *et al* (1985) in their earlier model. A positive MR proportional to B^2 due to 'wavefunction shrinkage' is also expected and often observed (Shklovskii and Efros 1984).

We have been investigating the MR in the VRH regime using the a-NbSi system previously studied by Bishop *et al* (1985) and shown to have a metal–insulator transition at an atomic concentration of 88.7% Si. Our NbSi samples were sputtered onto soda glass substrates using an RF magnetron from a pie target consisting of segments of the two components. For the samples with very high silicon content a niobium base was used with only silicon segments. The spaces between them allowed the niobium to be sputtered. The samples were typically 0.8 μm in thickness and were analysed using an EDAX microprobe and the resistance measured using a standard four-probe technique with sputtered copper contacts. The accuracy of the microprobe means that we can only estimate the composition to within 1%. The measurements were taken in a helium-3 cryostat in magnetic fields up to 8 T.

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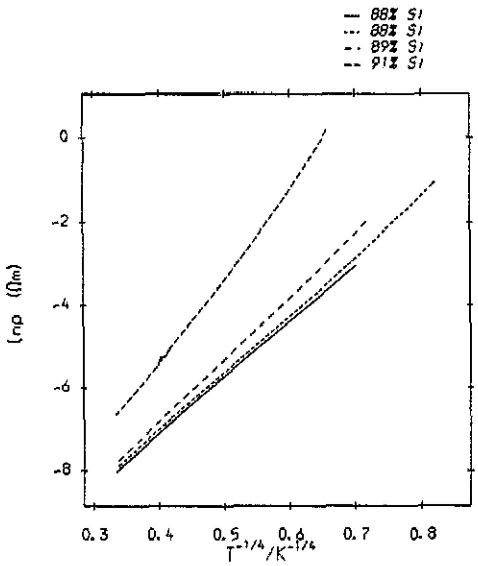


Figure 1. ln ρ versus $T^{-1/4}$ for the samples analysed demonstrating VRH and conduction due to the presence of a Coulomb gap.

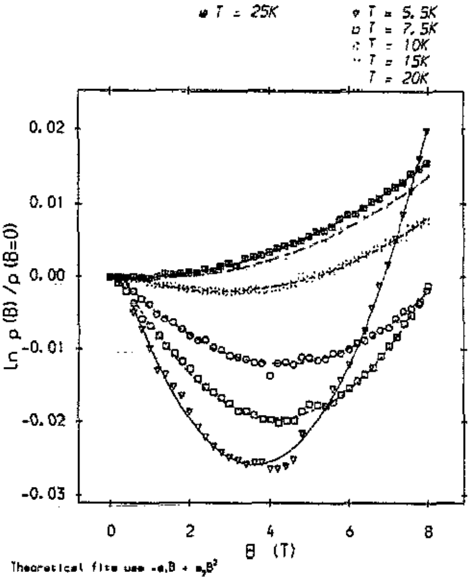


Figure 2. Magnetoresistance together with the theoretical fits for $Nb_{12}Si_{88}$.

Table 1.

Sample	T_0 (K)†	T_1 (K)‡	ξ_{a_1} (Å)	ξ_{a_2} (Å)
88% Si	39795	—	2.2	47.7
88% Si	—	116	3.3	78.5
89% Si	—	157	3.0	70.3
91% Si	—	375	2.4	25.7

† Determined from the slope of ln ρ versus $T^{-1/4}$ for VRH.
‡ Determined from ln ρ versus $T^{-1/2}$ for the Coulomb gap mechanism.

When the alloy passes through the metal–insulator transition the resistivity, in the absence of a field, is found to be described by Mott's variable-range hopping law (Mott and Davis 1979)

$$\rho(T) = \rho_0 \exp[(T_0/T)^{1/4}] \tag{1}$$

in three dimensions where ρ_0 and T_0 can be determined from the experimental measurements. Figure 1 shows a plot of ln ρ versus $T^{-1/4}$. The sample closest to the metal–insulator transition shows a temperature dependence consistent with VRH through the entire temperature range. The dependence in the other samples tends towards $T^{-1/2}$ at the *lowest* temperatures where the Coulomb repulsion between electrons leads to a hopping resistivity described by

$$\rho(T) = \rho_0 \exp[(T_1/T)^{1/2}]. \tag{2}$$

This behaviour is the result of a decrease in the density of states at the Fermi energy known as the 'Coulomb gap'. T_0 and T_1 can be determined from the temperature dependence and the values obtained are shown in table 1.

It has been suggested that the magnetoresistance in the VRH regime has two components. At low fields, a linear dependence on B has been proposed by Nguen *et al* (1985). This involved a numerical simulation of electrons within this region undergoing hops much greater than the average distance between nearest-neighbour sites, in conjunction with impurity scattering. By consideration of the interference of various paths between two states and the logarithmic averaging of the scattering amplitudes they found a negative magnetoresistance linear in B. This theory has been described as an 'oriented path mechanism' because of the limited number of scattering paths available between two sites. Schirmacher (1990) has also investigated the negative MR in the limit of a low concentration of scatterers. He finds an expression for this mechanism of the form

$$\ln(\rho(B)/\rho(B=0)) = N(r\xi)^{3/2}r^2(e/\hbar)B \tag{3}$$

where N is the concentration of scatterers, and r is the hopping distance. r is related to ξ by

$$r(T) \simeq \xi(T_0/T)^{1/4} \tag{4}$$

for variable-range hopping, and

$$r(T) \simeq \xi(T_1/T)^{1/2} \tag{5}$$

in the presence of a Coulomb gap. This negative magnetoresistance is followed by a crossover to a positive MR at higher fields resulting from the shrinkage of the electron wave function in both the longitudinal and transverse directions. This gives rise to a smaller overlap of the wavefunction tails which determines the probability of hopping between states. This 'shrinkage' leads to a positive B^2-dependence to the MR:

$$\ln(\rho(B)/\rho(B=0)) = (5e^2/2016\hbar^2)\xi r^3 B^2. \tag{6}$$

The suggestion of wavefunction shrinkage as an explanation for the rapid increase in resistance at higher fields has led to a discussion of a further mechanism for the negative-MR contribution (Raikh 1990). In a magnetic field, the overlap of the exponential tails of the wavefunction decreases, causing a reduction in the probability of a hop, but the activation energy of the hop also becomes smaller, making a hop more favourable. However, this mechanism is expected to be important only at very high fields. The $-B$-dependence we observe is at lower fields than the $+B^2$-dependence so this cannot be the origin of the negative MR.

We have analysed our data using a combination of the 'oriented path' and 'wavefunction shrinkage' mechanisms. We fit our data to

$$\ln(\rho(B)/\rho(B=0)) = -a_1 B + a_2 B^2 \tag{7}$$

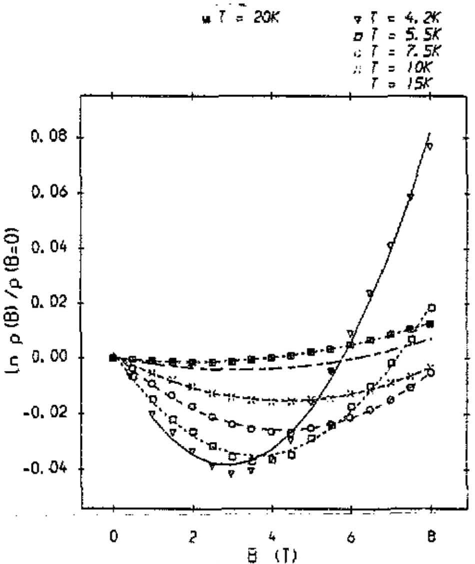
where

$$a_1 = N\xi^5(T_0/T)^{7/8}\, e/\hbar \qquad a_2 = (5e^2\xi^4/2016\hbar^2)(T_0/T)^{3/4} \tag{8}$$

for conduction by VRH, and

$$a_1 = N\xi^5(T_1/T)^{7/4}\, e/\hbar \qquad a_2 = (5e^2\xi^4/2016\hbar^2)(T_1/T)^{3/2} \tag{9}$$

when the conduction is affected by the Coulomb gap at low temperatures. In figures 2



Theoretical fits use $-a_1B + a_2B^2$

Figure 3. Magnetoresistance together with the theoretical fits for $Nb_{11}Si_{89}$.

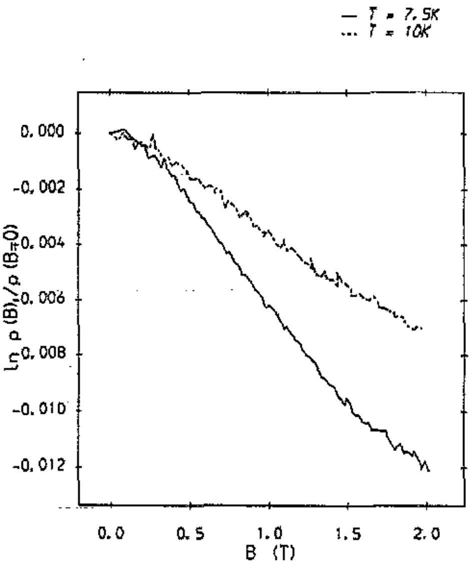
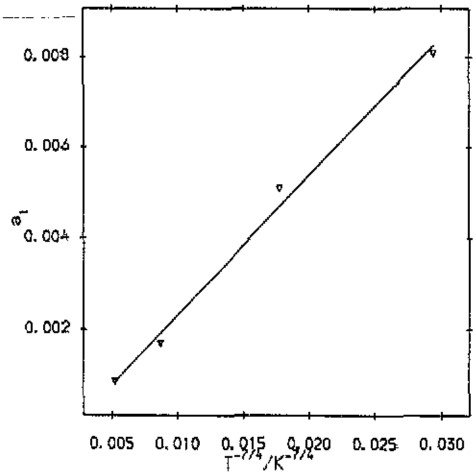
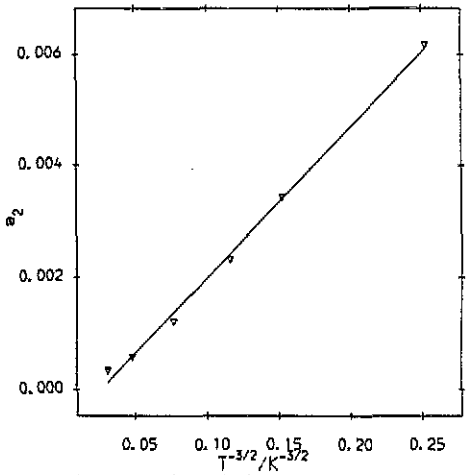


Figure 4. Low-field magnetoresistance indicating a linear B-dependence for $Nb_{12}Si_{88}$.



Line is a least squares fit to the data points

Figure 5. a_1 versus $T^{-7/4}$ confirming the temperature dependence associated with the Coulomb gap regime for $Nb_{11}Si_{89}$.



Line is a least squares fit to the data points

Figure 6. a_2 versus $T^{-3/2}$ confirming the temperature dependence associated with the Coulomb gap regime for $Nb_{11}Si_{89}$.

and 3 we present the magnetoresistance as a function of field between 0 and 8 T with the full curve displaying the fit. The fits are excellent, but at fields below about 0.5 T, a small $-B^2$-region is apparent (figure 4). Nguen *et al* (1985) do suggest the oriented path mechanism may have a B^2-dependence at very low fields. The temperature dependences of a_1 and a_2 should be $T^{-7/8}$ and $T^{-3/4}$ respectively for VRH conduction, but should be $T^{-7/4}$ and $T^{-3/2}$ in the presence of a Coulomb gap. Figures 5 and 6 show the two coefficients plotted for the 89% Si sample together with least-squares fits. Within the experimental error the data appear to confirm the dependences for the Coulomb gap case. Similar fits were obtained for the sample displaying VRH. It is difficult to compare our results with those of Ye *et al* (1990) as their data were collected between 1.2 K and 4.5 K. At temperatures below 4.2 K we observe no negative linear region in the magnetoresitance because of a dominant B^2-dependence. As the temperature rises this falls to reveal the linear region.

Equations (8) and (9) can be used to determine the localization length, ξ, using the values of T_0 and T_1 determined from the temperature dependence of the resistivity. All these values are shown in table 1. The values of ξ from a_2 are physically reasonable and follow the expected trend of decreasing ξ with increasing Si concentration. The coefficient a_1 depends on both ξ and the number density of scatterers N. A reasonable order of magnitude of N is $10^{28}\,\mathrm{m}^{-3}$ but this produces values for ξ an order of magnitude smaller than those from a_2. However, the model of Schirmacher (1990) is only strictly correct in the limit of a low density of scatterers, i.e. where there are only a few intermediate centres between hopping sites. In our case the density of scatterers is high and there are many intermediate scattering centres between hopping sites. Thus it is not too surprising that the model does not accurately predict the magnitude of the effect, although the T-dependence seems to be correct.

The magnetoresistance for the Nb_9Si_{91} sample was measured in both the longitudinal and transverse directions. In the indium oxide thin films the MR data in the perpendicular direction were 30% higher than in the parallel direction (Ovadyahu 1986), but we detected no anisotropy in our sample. This confirms the 3D character of our films.

In conclusion we have fitted the theories of wavefunction shrinkage and the oriented path mechanism for the MR of NbSi amorphous alloys, from which the localization length has been extracted. We confirm that our samples show a negative MR proportional to B at low fields with a crossover to a positive contribution proportional to B^2 at higher fields. There is some evidence for a $-B^2$-dependence at very low fields. We have not seen any anisotropy in the magnetoresistance measured in the parallel and perpendicular directions, which seems reasonable for these bulk 3D samples.

References

Bishop D J, Spencer E G and Dynes R C 1985 *Solid State Electron.* **28** 73

Howson M A and Gallagher B L 1988 *Phys. Rep.* **170** 5

Mott N F and Davis E A 1979 *Electronic Processes in Non-Crystalline Materials* (Oxford: Clarendon)

Nguen V L, Spivak B Z and Shklovskii B I 1985 *Zh. Eksp. Teor. Fiz.* **89** 1770 (Engl. Transl. 1985 *Sov. Phys.–JETP* **62** 1021

Ovadyahu Z 1986 *Phys. Rev.* B **33** 6552

Raikh M E 1990 *Solid State Commun.* **75** 935

Schirmacher W 1990 *Phys. Rev.* B **41** 2461

Shklovskii B I and Efros A L 1984 *Electronic Properties of Doped Semiconductors* (*Springer Series in Solid-State Science 45*) (Berlin: Springer)

Ye Qiu-Yi, Shklovskii B I, Zrenner A, Koch F and Ploog K 1990 *Phys. Rev.* B **41** 8477