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Positive Magnetoresistance in Hydrogenated Amorphous Alloys Silicon Nickel a-Si$_{1-y}$Niy:H at Very Low Temperature with Magnetic Field

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ABSTRACT

We present results of an experimental study of magnetoresistance phenomenon in an amorphous silicon-nickel alloys a-Si$_{1-y}$Ni$_y$:H (where y = 0.23) on the insulating side of the metal-insulator transition (MIT) in presence of magnetic field up to 4.5 T and at very low temperature. The electrical resistivity is found to follow the Efros-Shklovskii Variable Range Hopping regime (ES VRH) with $T^{-1/2}$. This behaviour indicates the existence of the Coulomb gap (CG) near the Fermi level.

Keywords: Amorphous Silicon-Nickel Alloys a-Si$_{1-y}$Ni$_y$:H; Variable Range Hopping Conductivity; Metal Insulator Transition; Positive Magnetoresistance

1. Introduction

In Variable Range Hopping (VRH) of the three dimensional disordered systems, like doped semiconductors, The resistivity ρ was shown by Mott [1,2] to behave like $\exp(T_0/T)^{1/4}$. This dependence was obtained by optimizing the hopping probability and assuming a slowly varying Density of State (DOS) in the vicinity of the Fermi level.

On the contrary, Efros and Shklovskii (ES) [3,4] have predicted that range electron-electron interaction reduces the DOS at the Fermi level and creates a soft Coulomb Gap (CG), which takes the form $N(E) = A \cdot (E - E_F)^{\nu}$, A is a constant and $\nu = 2$. The existence of the CG leads to the ES VRH regime of the resistivity, which behaves like $\exp(T_0/T)^{1/2}$.

The VRH regime leads to the following temperature behaviour of resistivity:

$$\rho = \rho_0 \exp\left[\left(T_0/T\right)^p\right] \text{with } p = \frac{\nu+1}{\nu+4} \quad (1)$$

Equation (1) remains quite universal since when $\nu = 0$, the DOS is constant and p = 0.25 corresponding to the Mott regime. But when $\nu = 2$, the DOS varies in the vicinity of the Fermi level and p = 0.5. The experimental situation has been confusing for some times, with both values being observed. Mott VRH and ES VRH have been widely observed in many doped semiconductors [5-9].

The metal-insulator transition in amorphous alloys has been an active field of experimental investigations over recent years, particularly in alloys of silicon and germanium [10-13].

Experimental results on resistivity in amorphous alloy a-Si$_{0.77}$Ni$_{0.23}$:H at low temperature and with magnetic field, have been analyzed in the insulating side of the metal-insulator transition (MIT). The positive magnetoresistance (PMR) measurements were obtained in the range of temperature 1 - 4.2 K and with magnetic field up to 4.5 T.

The sample was prepared by radio-frequency sputtering from silicon target. The substrate (Corning 7059 glass) was at room temperature during deposition and the sputtering gas was a 90% Ar and 10% H$_2$. The hydrogen was added to saturate silicon dangling bonds that might caused by the disorder.

Film thickness which was about 1 µm, was measured to an accuracy of 0.1 µm using a Talysurf stylus. The amorphous nature was demonstrated by electron diffrac-

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tion measurements in a transmission electron microscope.

The electrical resistivity was measured using standard four-terminal AC techniques.

In **Figure 1**, we plot the magnetoresistance ($\Delta\rho/\rho_0$) versus magnetic field. We noticed that it is positive and increases when the temperature decreases. ρ_0 is the resistivity at $B = 0$ T.

2. Theoretical Models of Positive Magnetoresistance in the VRH Regime

The theory, both for a constant density of states at the Fermi level and also for an arbitrary power-law dependence of $N(E_F)$, has been developed by Shklovskii and Efros [3] for weak magnetic field and by Tokumoto *et al.* [14] for high magnetic field. The criterion for the transition between low and high magnetic field regimes is given by:

$$\frac{\lambda^2}{a_H} = d \tag{2}$$

where d is the mean distance between impurities, $\lambda = (\hbar/eB)^{0.5}$ is the magnetic length, and a_H is the electron effective Bohr radius at zero magnetic field. The latter can be calculated using the formula $a_H = a_0 \cdot \varepsilon_r \cdot m_0/m^*$, where $a_0 = 0.53$ Å and ε_r is the relative permittivity of the medium.

When $(\lambda^2/a_H) \gg d$ (low magnetic field), Shklovskii and Efros [3] give the following equation of positive magnetoresistance in VRH regime:

$$\ln\left[\frac{\rho(B)}{\rho(0)}\right] = t^{(\nu)}\frac{a_H{}^4}{\lambda^4}\left(\frac{T_0}{T}\right)^{3p} \tag{3}$$

where $t^{(\nu)}$ is a constant depending on the form of the density of states and $p = (\nu+1)/(\nu+4)$. The parameter ν is known to be equal to zero (*i.e.*, $p = 0.25$) when the DOS $N(E_F)$ is constant near the Fermi level [1,2], whereas, $\nu = 2$ when $N(E_F)$ varies, creating the Coulomb gap [3]. The parameter T_0 depends on $N(E_F)$ and on the localization length ξ [13,15].

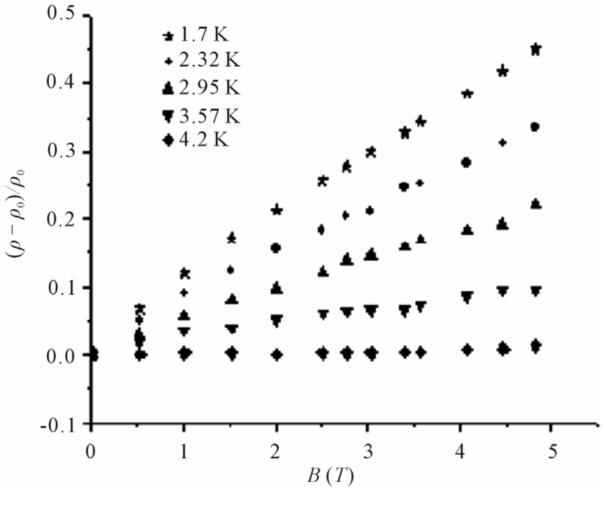

Figure 1. Positive magnetoresistance ($\Delta\rho/\rho_0$) versus magnetic field *B* for several values of temperature.

Equation (3) can be simplified as:

$$\frac{\rho(B,T)-\rho(0,T)}{\rho(0,T)} = \exp\left(\beta B^2\right) - 1 \tag{4}$$

The parameter β is dependent on the temperature in the VRH regime.

When $(\lambda^2/a_H) \ll d$ (high magnetic field), Tokumoto *et al.* [14] give a positive magnetoresistance expression, of the form:

$$\frac{\rho(B,T)-\rho(0,T)}{\rho(0,T)} = \exp\left[\frac{C^{(\nu)}}{a_B\lambda^2}\left(\frac{T_0}{T}\right)^{(S+1)}\right]^{1/(S+3)} - 1 \tag{5}$$

$C^{(\nu)}$ is also a constant depending on the form of the density of states, and a_B is equal to $a_H/\ln\left[(a_H/\lambda)^2\right]$.

Equation (5) can be simplified to:

$$\ln\left(\frac{\rho(B)}{\rho(0)}\right) = A\left(\frac{T_0}{T}\right)^{(S+1)/(S+3)} \tag{6}$$

where A is a constant independent of S, but varying like B.

3. Results and Discussion

Taking ε_r in vicinity of 14 [16], λ^2/a_H is found to be of order of 10^{-7} m for $B = B_{\max} = 4.5$ T, Whereas the mean Ni-Ni distance $d \approx 0.3\times10^{-9}$ m, so that $(\lambda^2/a_H) \gg d$ throughout the interval of magnetic field 0 - 4.5 T. Thus we can use Equation (3) to study the behaviour of the positive magnetoresistance.

In **Figure 2** we plot $\ln\left[\rho(B,T)/\rho(0,T)\right]$ against B^2 for different temperature. Straight lines with various slopes corresponding to different values of $\beta\left(T^{-2}\right)$ are observed.

We have a satisfactory result, if using Equations (3) and (4) for the variation of $\ln(\beta)$ against ln(T). Indeed we obtain a straight line with a slope near the value $-3p$.

In **Figure 3** we plot $\ln(\beta)$ against $\ln(T)$. We find a straight line with negative slope equal to −1.59. This value is to close to −1.5 and we can conclude that we have a ES VRH regime corresponding to $\nu = 2$ and $-3p = -3\left[(\nu+1)/(\nu+4)\right] = -1.5$.

The VRH conduction depends essentially on the relative magnitude of the hopping energies of Mott Δ_M, of ES Δ_{ES}, and of CG Δ_{CG}. Very close to the MIT, Iqbal *et al.* [17] showed that the CG becomes so narrow that the temperature range where the ES regime occurs cannot be reached and only the Mott regime is expected. The origin

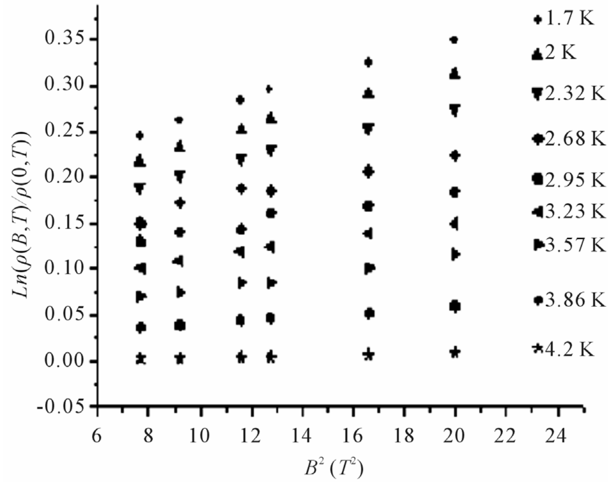

Figure 2. Variation of $\ln\left[\rho(B,T)/\rho(0,T)\right]$ against B^2 for several values of temperature.

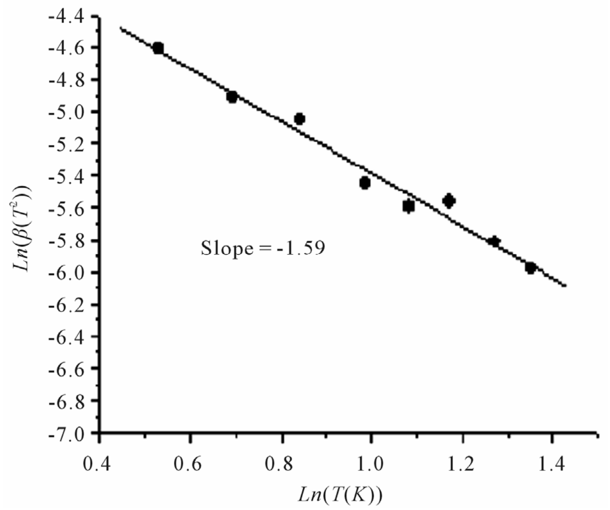

Figure 3. $\ln(\beta)$ in Equation (4) against $\ln(T)$.

of the disagreement with our results is quite difficult to explain. Therefore, VRH theories should be developed in the systems that are situated near the MIT.

4. Conclusions

The study of the positive magnetoresistance behaviour can help us to assume an accurate imagination about the density of states in vicinity of the Fermi level by highlighting the VRH regime that governs the electron hopping.

At very low temperature (T < 4.2 K), the electrical conductivity of Si$_{0.77}$Ni$_{0.23}$:H shows Efros-Shklovskii VRH that corresponds to nonzero constant density of states at the Fermi level, and demonstrates a positive magnetoresistance at low magnetic field.

The electron-electron interactions still significant even if the Coulomb Gap is narrow near the MIT. No crossover from Efros-Shklovskii to Mott is observed.

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