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Metal-insulator transition in nanocomposites of glass and RuO_2

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Abstract. We report on studies of interplay between percolation and quantum localization in mixtures consisting of glass grains and RuO_2 metal particles of average diameters 550 and 10 nm, respectively. A weak temperature dependence of conductivity $\sigma(T) = a + bT^{\alpha}$, where $\alpha \cong 0.20$, is found in the temperature region $0.04 < T < 1$ K. Similarly, an anomalously small magnitude of magnetoconductivity is observed in the studied magnetic field range up to 5 T. These observations demonstrate that percolation nature of electron transport leads to a significant modification of quantum corrections to conductivity at the localization boundary. The conductivity at criticality obeys a dynamic scaling equation with the conductivity exponent $\mu = 1.65$ as expected for one-electron Anderson localization.

Keywords: RuO_2-glass mixtures, Anderson localization, percolation, dynamic scaling
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1 Introduction

RuO_2-glass nanocomposite consists of two randomly mixed phases: metallic RuO_2 grains of size $d \cong 10$ nm and insulating glass particles of much greater dimensions $D \cong 0.55$ μm. In order to describe charge transport in such a medium, percolation phenomena [1] specific to systems with macroscopic disorder as well as effects characterizing quantum localization, such as interference of scattered waves and disorder-modified electron-electron interactions [2, 3], have to be taken into account on equal footing [4]. Two transition points have been identified [5] as a function of the RuO_2 volume fraction v. In addition to the classical percolation threshold at $v_c \cong 0.035$, there is a second critical point at v_q in the range 0.12-0.16, in which the temperature coefficient of resistance at room temperature (RT TCR) changes its sign [6]. The latter, v_q, has been interpreted as a borderline of quantum percolation [4, 7, 8], which separates a system with localized states for $v < v_q$ from a system with extended states for $v > v_q$.

In this paper, we present millikelvin studies of conductivity in a series of films spanning the range of v making it possible to examine the scaling behavior [2, 9, 10] of

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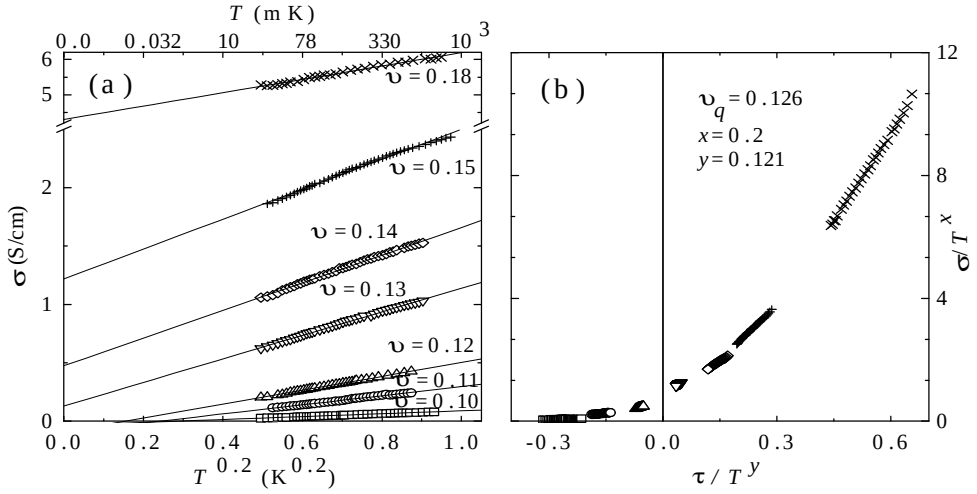

Fig. 1 (a) Low-temperature conductivity versus temperature to the power of $\alpha = 0.20$ for different values of RuO_2 concentrations in the vicinity of the MIT. The straight lines represent the least square fit to the data. (b) Data from figure (a) arranged in scaling plot. Vertical line at $\tau = 0$ is the transition point.

the conductivity in the vicinity of the quantum critical point v_q. The values of dynamic scaling exponents $\mu = 1.65$ and $z = 5.0$ determined here are markedly different from $\mu \cong 1.0$ and $z \cong 2.0$ observed [11, 12] for non-percolative media, in which spin-rotation symmetry is broken so that the Anderson-Mott transition driven by disorder-modified interactions can occur [2, 9]. Actually, the value of $\mu \cong 1.65$ is close to that expected [8, 13] for one-electron Anderson localization. At the same time, both μ and z we observe are close to those obtained for some systems with unbroken spin-rotation symmetry [10, 11]. This opens an interesting question about the role of long range fluctuations in the latter.

2 Samples

The studied samples have been prepared from laboratory made RuO_2-glass pastes consisting of RuO_2 and lead borosilicate glass powders having mean size of particles $d \cong 10$ nm and $D \cong 0.55$ μm, respectively. The pastes were deposited on alumina substrates by using printing and firing technique [5]. Experimental results for a series of samples with RuO_2 volume fraction $0.10 \square v \square 0.18$ are presented here.

3 Results and discussion

Figure 1a presents the temperature dependence of the conductivity between 0.04 and 1 K. Following the common approach we fit the conductivity versus temperature data

to the equation $\sigma(\upsilon, T) = \sigma(\upsilon, 0) + bT^{\alpha}$. According to Fig. 1a, this procedure implies the presence of the MIT for $0.12 < \upsilon_q < 0.13$. Furthermore, the exponent α is found to be rather small, $0.30 \geq \alpha \geq 0.12$ for $0.1 \square \upsilon \square 0.18$, respectively. In order to estimate the exponent α representative for the whole range of the studied samples dynamic scaling approach [2, 9] has been employed. According to this theory, the conductivity at criticality is a function of $\tau \equiv \upsilon/\upsilon_q - 1$ and T only, i.e. $\sigma(\tau, T) = b^{-\varepsilon} g\left(b^{1/\nu}\tau, b^z T\right)$, which predicts $\sigma(0, T) \propto AT^{\varepsilon/z}$ and $\sigma(\tau, 0) \propto \tau^{\mu}$ with $\mu = \varepsilon\nu$. Choosing $b = T^{-1/\nu}$as suggested in [10] we arrive at the following form $\sigma(\tau, T) = \sigma_q(T) f(\tau/T^y)$, where $\sigma_q(T) \equiv \sigma(0, T) = AT^x$, $x = \varepsilon/z$, $y = 1/(\mu z)$, which enables involving all data taken at all temperatures and values of τ in the critical regime to determine the exponents. Figure Fig. 1b presents our data arranged in scaling plot with parameters $\upsilon_q = 0.126$, $y = 0.121$ and $x = 0.20$, which, with $\varepsilon = d - 2 = 1$ in 3D case, lead to $\mu = 1.65$ and $z = 5$. The above values of z and μ are close to those reported for the Hubbard-Mott transition studied in $NiS_{2-x}Se_x$[14] and for studies of the MIT in elemental semiconductors in the absence of the magnetic field [10]. On the other side, the values of z and μ obtained here are markedly different from those for both classical percolation[16] and the Anderson-Mott transition in the cases when spin-rotation symmetry is broken either by spin-flip scattering or the magnetic field [11, 12]. Furthermore, the value of μ found here is in agreement with numerical estimates of this exponent for one-electron Anderson localization of noninteracting electrons [8, 13]. It is also worth noting that the value of $\upsilon_q = 0.126$ used to construct the scaling plot agrees with that at which RT TCR crosses zero for the studied material [5].

Figure 2a shows the influence of the magnetic field on conductivity, $\Delta\sigma(B) = \sigma(B) - \sigma(0)$, as determined for five selected RuO_2-glass samples at $T = 4$ K. The magnetoconductivity is seen to be negative. While it changes to positive below 300 mK, its magnitude remains smaller than 1%. This means that the quantum effects are suppressed comparing to the case of homogeneous systems. To explain this observation we have considered a model of Khmelnitskii [4], in which percolation is taken into account by allowing for a spatial dispersion of the diffusion coefficient, D is large at short length scale of metallic grains but small at distances comparable to percolation length scale. We have repeated Kawabata's calculations of magnetoresistance for the 3D case in the limit $\tau_{\phi} \to \infty$ by assuming $D(q)$ in the form $D(q) \propto 1 + (qL_c)^{t/\nu_p}$, where $t = 2.0$, $\nu_p = 0.89$ are classical percolation exponents [16]. The results for three values of $\upsilon = 0.10$, 0.15, 0.20, are shown as dashed lines in the Fig. 2b. It is seen that inhomogeneities on the mesoscopic scale can suppress quantum corrections to magnetoconductivity.

4 Conclusions

Our results demonstrate that quantum corrections to conductivity are modified in systems with inhomogeneities at the mesoscopic scale. Nevertheless the MIT with dynamic scaling is observed with the value of critical exponent z encountered in some nominally homogenous systems with spin-rotation symmetry conserved. The value of μ is close to that numerically predicted for one-electron Anderson localization. A possible scenario is, therefore, that inhomogeneities on the mesoscopic scale reduces

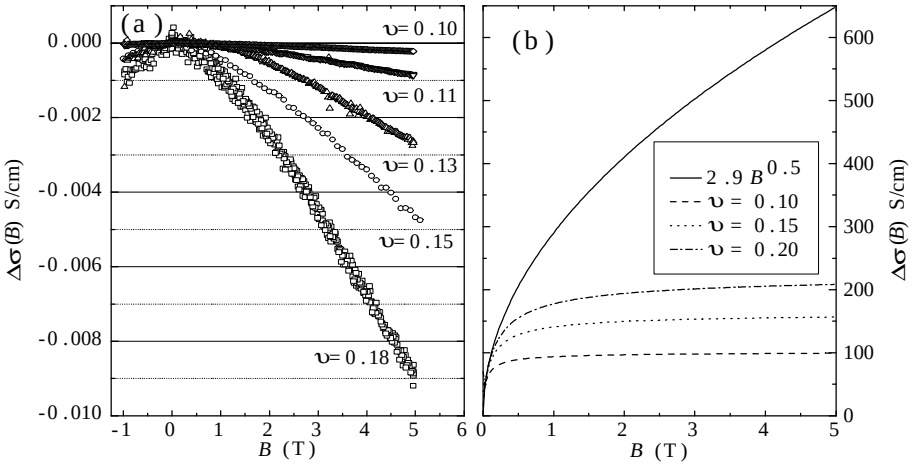

Fig. 2 (a) $\Delta\sigma$ of five RuO_2-glass samples studied at $T = 4$K. (b) Magnitude of quantum corrections to conductivity calculated according to Kawabata [15] (solid line). Inclusion of q-dependent diffusion coefficient according to Khmelnitskii [4] suppresses $\Delta\sigma$ (dashed lines).

localization effects of electron-electron interactions, so that the Anderson localization *per se* occurs.

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