25 Temperature and Magnetic Field Dependent Transports in Granular Structures

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1. INTRODUCTION

We study the temperature and magnetic field dependent transports of a two-dimensional granular system near percolation threshold. We consider a model system that consists of ferromagnetic, metallic nano-sized particles randomly distributed on a 2D non-magnetic and insulating surface. The particles (grains) do not touch one another, but electrons can quantum tunnel from one grain to another. We assume a temperature range where phonon-assisted hopping is not important and quantum tunneling dominates the transports between the particles. However, the temperature is still high enough so that the phase coherence between different tunneling events is lost. In this case the whole system can be treated as a classical percolation network with resistance between grains determined by quantum tunneling. Spin-dependent scattering is also considered in our system.

To simulate such a system numerically, we start with a model of classical random resistor network in 2D. The conductance of each bond is assumed to have the following temperature dependence (Wong *et al.*, 1999):

$$\sigma_0(T) = Ae^{-\Delta E/k_B T} \tag{1}$$

where $\Delta E \sim \hbar^2/2m^* s^2$ is the energy level spacing within the particle, s is the grain size, T is the temperature, m^* is the effective mass of the electron and A is a constant. We note that in case when the grain size s is large enough so that Coulomb interaction is important, ΔE should be replaced by the Coulomb blockade form $\Delta E = e^2/\varepsilon s$. With this model, we calculate the bulk conductance of the network as follows: We write down the matrix equation of the local electric potential V of the network using Kirchhoff's law, and then

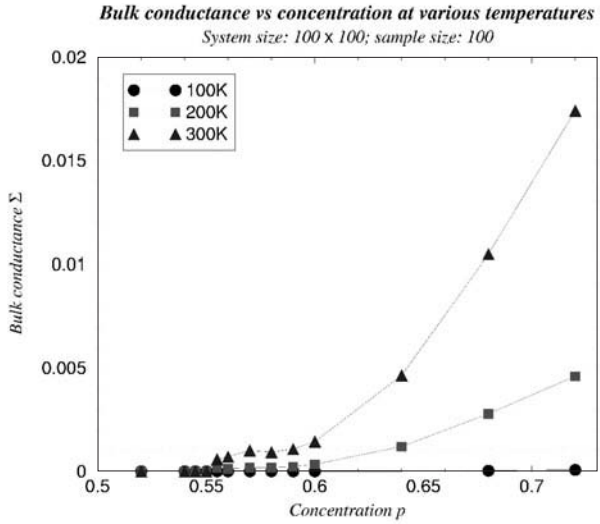

Figure 1 Bulk conductance vs concentration at various temperatures.

solve it numerically by successive over-relaxation (SOR). From V we can find the total current and hence the bulk conductance Σ of the whole network.

2. EFFECTIVE CRITICAL POINT

We first study the bulk conductance of a system with a particle size distribution proportional to s^{-4}, corresponding to an unannealed system in experiments by Jing *et al.* (1996). Figure 1 shows the plot of the bulk conductance Σ versus particle concentration p at various temperatures T, obtained numerically as described above. The curves obey the scaling relation between Σ and p as expected:

$$\Sigma \sim (p - p_c)^t \tag{2}$$

We now look at p_c and t more closely. Since temperature and particle size distribution affect only the values of the bond conductivities but not the connectivity, p_c should be identical to the geometrical critical point, which is 0.59 for site percolation in 2D. However, experimentally one may find a different p_c due to the limited precision of the measuring instruments. Consider in Figure 1 the dashed line representing the smallest possible reading $\varepsilon = 0.001$ of the measuring instrument. One would conclude from experiment that $\Sigma \sim 0$ for any $\Sigma < \varepsilon$. Then at 100 K, we find that $\Sigma = 0$ for all values of p we have considered, i.e. the system behaves as an insulator because of the overall smallness of the value of $\sigma_0(T)$. However, at 200 K and 300 K, we find metal-insulator transitions with *effective critical point* p_c = 0.64 and 0.59 respectively. Correspondingly, we also find *effective t -exponent* of 1.01 ± 0.06 at 200 K and 1.12 ± 0.08 at 300 K. We see that although the effective critical point is smaller at a higher temperature, the effective *t*-exponents are not too different from each other.

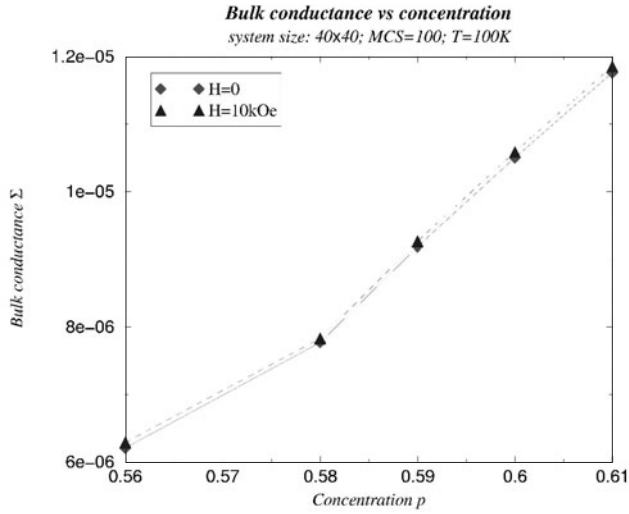

Figure 2 Bulk conductance vs concentration when spin-dependent scattering is taken into account. Σ is always slightly larger when a magnetic field exists.

3. MAGNETORESISTANCE

To include spin-dependent effect in our model, we assume that the ferromagnetic particles are single-domained, so that each of them is characterized by a dipole moment. An external uniform magnetic field H is applied perpendicular to the plane of the network, and the equilibrium spin configuration of the system is found by Monte Carlo method. The conductance of each particle is now modified as follows: (Altbir *et al.*, 1998)

$$\sigma^{-1}(H,T) = \sigma_0^{-1}(T) - \kappa \cos\theta_{ij}(H,T) \tag{3}$$

where $\sigma_0(T)$ is the original conductance that ignores the spin-dependent scattering, θ_{ij} is the angular difference between the dipole moments of the nearest neighbours particle i and particle j, and κ is a constant, taken to be $0.1\,\sigma_0^{-1}(T)$. By repeating the simulation using this new set of bond conductance, we found a negative magnetoresistance for all p at 100 K as shown in Figure 2. This is expected because with the magnetic field, the magnetic moments align more or less to the same direction, making $\cos\theta_{ij}(H,T)$ closer to 1 on average. In contrast, another analysis shows that at 300 K the negative magnetoresistance is almost unobservable. We believe that at this high temperature, thermal fluctuation has randomized the alignment of the magnetic moments to an extent that overrides the effect of the magnetic field, leading to a vanishing negative magnetoresistance.

In Figure 3 we also plot the magnetoresistance as a function of magnetic field H before saturation at 150 K and near the percolation threshold. We observe that magnetoresistance becomes more negative as H increases as expected. The magnetic field dependence is not linear in H at small H. The critical exponent is found to be larger than one.

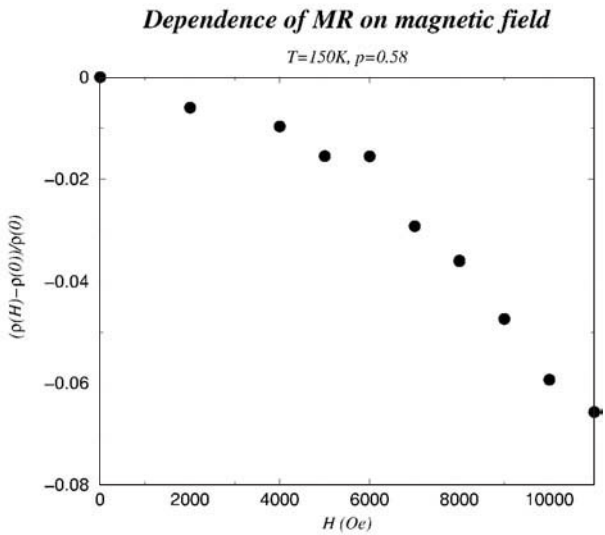

Figure 3 Graph of magnetoresistance vs external magnetic field. A stronger field leads to a more negative magnetoresistance. The power law dependence on magnetic field has an exponent bigger than 1.

4. CONCLUSIONS

We have shown that the percolation threshold determined experimentally may not reflect the true (geometrical) critical point of our system. Instead, it is an effective critical point arising from the limitation in the precision of the measuring instruments. The effective critical point and the corresponding critical exponent are temperature dependent, although the temperature dependence of the effective *t*-exponent is found to be very weak.

To consider the effect of magnetic field, we assumed that spin-dependent scattering changes the bond conductance of the system, and then found that it leads to a negative magnetoresistance at low temperatures. The magnetoresistance near the percolation threshold has a power law dependence on magnetic field with exponent bigger than 1.

ACKNOWLEDGEMENT

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REFERENCES

D. Altbir, P. Vargas, J. d'Albuquerque e Castro, 1998, *Dipola interaction and magnetic ordering in granular metallic materials*, Physical Review B, 57, 13604-9

X. N. Jing, N. Wang, A. B. Pakhomov, K. K. Fung and X. Yan, 1996, *Effect of annealing on the giant Hall effect*, Physical Review B, 53, 14032-5

S. K. Wong, B. Zhao, T. K. Ng, X. N. Jing, X. Yan, P. M. Hui, 1999, *A phenomenological model of percolating magnetic nanostructures*, European Physics Journal, 10, 481-485