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RESISTANCE SCALING IN INHOMOGENEOUS MEDIA IN THE VICINITY OF A METAL-INSULATOR TRANSITION

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Scaling relation between residual R_0 and temperature-dependent R_1 parts of the sample electrical resistance in the vicinity of a metal-insulator transition can be a guide in examining the structure of the material. In the relation $R_1 \propto (R_0)^{\nu}$ the exponent value $\nu=1$ is typical for a random mixture of metallic and insulating domains, $\nu=0$ for granular metals. A special case $\nu=0.75$ has been observed recently. It corresponds to a fractal structure of the insulating phase with the classical size effect governing the conductivity of the metallic channels. Experimental data on Zn-Sb and Al Ge alloys are presented.

1. INTRODUCTION

Transport phenomena in inhomogeneous media are usually considered by applying the percolation theory (1). However, the material science has at its disposal a lot of geometrical patterns which are not of a simple random nature. For instance, granular metals contain in essence a correlated system of rather regularly alternating metallic and insulating regions. Much more complicated structures may occur when the solid mixture arises as a result of a phase transition in some parts of the sample. If these two phases have different conductivities, for instance, when a metal-insulator transition takes place, one should describe conducting network and the total conductance of the sample.

In this content the term "metal-insulator transition" has two meanings: "point transition" when a small volume becomes dielectric, and "sample transition" when the conductance of the whole sample drops to zero. We shall concern ourselves only with studying the metallic side of the sample transition. The main idea is that while analyzing scaling relations for the sample resistance one can judge what type of the structure is realized in the sample and distinguish, for example, a fractal pattern from a random one.

2. RESISTANCE SCALING

Let's represent the resistance R as a product of a resistivity ρ by a geometrical factor φ

$$R = \rho(T)\varphi = [\rho_0+\rho_1(T)]\varphi = \frac{p_F}{ne^2}\left(\frac{1}{l_0}+\frac{1}{l_T}\right)\varphi \qquad /1/$$

(p_F is the Fermi momentum, mean free path $l^{-1}=l_0^{-1}+l_1^{-1}$). When the changes in the resistivity are controlled by the carrier density n as well as when the resistance changes are due only to the alternation in the shape of the conductive channels, i.e. of the factor φ, then relation

$$R_1 \propto R_0 \equiv [R_0]^1 \qquad /2/$$

holds. The latter case apparently takes place during approaching the transition in a random mixture of two phases. Indeed, when approaching the threshold, what alters is the size of the cells of the conductive backbone in the infinite cluster, i.e. the factor φ.

Insulating films in an ideal granular metal are connected in series with metal volumes. As the tunnel resistance of the films does not depend on T one gets

$$R_1 = const \propto [R_0]^0. \qquad /3/$$

3. FRACTAL PATTERN OF THE Zn-Sb ALLOY STRUCTURE

The exponent values $\nu=1$ from Eq./2/ and $\nu=0$ from Eq./3/ are not the only possible ones. Below follows an example with $\nu=0.75$: an inhomogeneous structure created in the course of a special phase transition, namely, the amorphization of the metastable phase of alloy Zn-Sb quenched under pressure (2,3). The initial state is crystalline and metallic while the final one is amorphous and insulating. The amorphization process could be led slowly by the low temperature annealing. It could be repeatedly interrupted by returning to nitrogen temperatures.

This transition to the amorphous state has the following important features:

1. the specific volume increases significantly during the transition ;

2. the sample resistance R increases by orders of magnitude while the sample remains metallic at low temperatures, i.e. while it retains $\partial R/\partial T>0$;

3. the large increase of the resistance is accompanied by a very small decrease of the temperature T_c of the superconducting transition. This point contains the evidence that the sample is macroscopically inhomogeneous in the intermediate states of the transition (2) .

A fractal-like model of the intrinsic structure of the sample was proposed in (3). It supposes the growing insulating amorphous inclu-

sions to be cactus-like with leaves branching many times. These leaves, or sheets, are supposed neither to intersect each other nor to merge. This maintains the existence of current paths, at the far-gone stages of the transition, in contrast with the percolation model.

The development of the "cactus" structures can be described by a parameter d, mean distance between the leaves. According to (3), the current paths are located at the surface with fractal dimension three which separates two "cactuses"; from the mathematical point of view the current paths are similar to trajectories of brownian particles. The fractal dimension of such a trajectory is two: its length is proportional to squared radius R of the domain it occupies.

So, as far as electrical resistance is concerned, the conductive channels are conductive brownian trajectories. Now d becomes the step length of the random walk and, with the distance between the contacts L being constant, we have the channel length $\lambda \propto d^{-1}$. Supposing in addition that the cross-section of the channel is d^2 we obtain $\varphi \propto d^{-3}$.

To get an exponent in Eq./2/ different from $\nu=1$ we need some dependence of φ on d. Such dependence can exist due to the dc size effect. For a wire with diameter $d \ll l_0$ the mean free path l_0 can be, within a rather good accuracy, replaced in Eq./1/ by d (5). Then, with whatever relation between l_T and d, one has

$$\rho_0(d) \propto d^{-1}, \quad \rho_1(d) \propto d^0, \qquad /4/$$

Combining this with $\varphi \propto d^{-3}$ we finally get

$$R_0 \propto d^{-4}, \quad R_1 \propto d^{-3}, \quad R_1 \propto [R_0]^{0.75} \qquad /5/$$

That is just what follows from the experiment (Fig.1). Note, in passing, that in the percolative system the links between the nodes of its backbone always contain so called red bonds, regions with minimal possible cross-sections (1). This means that the dc size effect cannot influence the ν value.

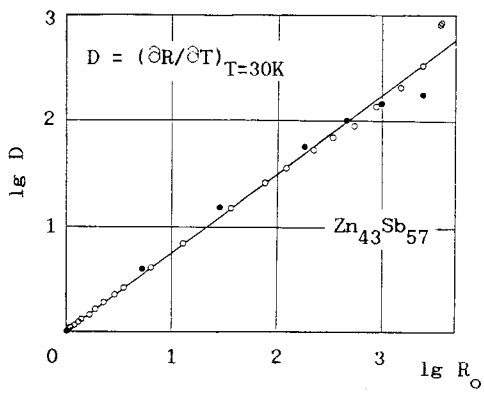

FIGURE 1

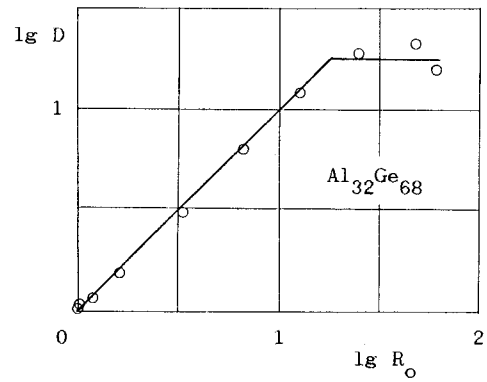

FIGURE 2

4. Al-Ge DATA

The experiment with the Al-Ge alloy was performed similarly to those with Zn-Sb. The differences were only quantitative. However, the results are quite different, as it can be seen from the comparison of Figs.1 and 2. Note that Fig.2 demonstrates the exponent $\nu=1$ instead of $\nu=0.75$. Similarity of the processes in the both alloys gives reason to suggest that the structures in both are the same and that the relation between l and d is the main source of the difference.

Exponent 0.75 is the result of the combination of a fractal structure of the insulating phase and a rather long mean free path l. If, instead, $l \ll d$ holds one will find $\nu=1$.

CONCLUSIONS

In conclusion, the scaling relations between the parts of the resistance in the vicinity of the metal-insulator transition contain information about the macrostructure of the sample. Eqs /2/ and /3/ express the two limiting cases which correspond to a random mixture of phases and to a granular metal. The exponent ν can be changed by the dc size effect. The Zn-Sb experimental data give such an example.

REFERENCES

(1) D.Stauffer. Introduction to percolation theory (Taylor and Fransis, London, 1985).

(2) O.I.Barkalov, I.T.Belash, V.F.Gantmakher, E.G.Ponyatovskii and V.M.Teplinskii, Pis'ma JETF 48 (1988) 561 [JETP Letters 48 (1988) 609].

(3) V.F.Gantmakher, S.E.Esipov and V.M.Teplinskii. Zh. Eksp. i Theor. Fiz. 97 (1990) 373 [Sov. Phys. JETP 70, No 1 (1990)].

(4) J.Feder. Fractals (Plenum Press, New York, 1988).

(5) R.G.Chambers in : The Physics of Metals. 1.Electrons, ed. J.M.Ziman, (Cambr. Univ. Press, 1969).