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Change of the electrical properties in Fe-Al_2O_3 granular films

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A systematic study of the electrical resistance as a function of the temperature was performed in Fe-Al_2O_3 granular thin films. Our findings revealed a nonlinear dependence of the current versus voltage in the low field regime at low temperature. The variable range hopping mechanism is the best description of the behavior of our samples. A change of the electronic properties can be observed depending on the direct current applied to the sample's plane, and is related to different localization lengths. © *2004 American Institute of Physics*. [DOI: 10.1063/1.1775890]

Metal/insulator granular systems are composites which consist of metallic grains embedded in an insulator matrix.[1–3] Many magnetotransport effects have been discovered in these systems, such as the tunnel magnetoresistance[4,5] and giant Hall effect,[6] showing that the granulars are interesting systems to study. To better understand these effects, it is necessary to know the electronic characteristics, and many studies about this subject have been realized.[1–3] However, the investigation of the possibility of electronic changes when the injected current increases is not common. This letter reports on the modification of the transport mechanism when the injected current or applied bias is varied.

The Fe-Al_2O_3 granular samples were obtained by coevaporation of Fe and Al_2O_3 onto previously oxidized Si substrates, maintained at room temperature and in the presence of a base pressure better than 1×10^{-8} mbar. The thickness and the rate of deposition were controlled by means of a quartz balance. The use of the Rutherford backscattering spectrometry (α particles of 1.5 MeV) permitted the determination of 1000 Å for the samples thicknesses, and 0.27, 0.33, 0.41, and 0.48 for the average metal volume fractions (x) of the four samples discussed in this letter, respectively. X-ray diffraction measurements on the samples showed that Fe arranged itself in grains of bcc structure and 4.3 nm mean size within an amorphous Al_2O_3 matrix.

The electrical resistance experiments were performed using the four-point method with the direct currents ranging from 500 nA to 25 μA flowing in the sample's plane. Resistance (R) as a function of the temperature (T) (ranging from 4.2 to 300 K) measurements were performed in order to verify the influence of the current and the bias potential on the transport mechanisms. The estimated bias potential between grains is such that our system behaves as it does in the low field regime[2] for the near neighbor grains, but it can be high enough for the more distant grains in order to destroy their Coulomb blockade.

It is accepted that for metal insulator granular thin films, the temperature dependence of the resistance can be written as

$$R = R_0 \exp(T_0/T)^{\alpha}, \quad (1)$$

where $\alpha=1/4$ represents the variable range hopping regime,[7] and $\alpha=1/2$ the thermal activated regime.[1,2]

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Using this description to determine the predominant transport mechanism in our samples, one can see (Fig. 1) from the ln R $T^{-1/4}$ plot of the experimental data and the fitting curve that the transport via variable range hopping is a better explanation than the thermal activated one.

In the case of the variable range hopping, the parameter T_0 is given by $T_0=18.1/(k_B g_0 \xi^3)$,[8] where g_0 is the constant Mott density of states, ξ is the localization length, and k_B is the Bolzmann constant.

For different direct currents (I) one can perceive a change in the electronic properties of the samples, as shown in Fig. 2 for the case of $x=0.33$ and for T varying from 20 to 300 K. All resistances extrapolate to the same value for temperatures above 100 K and to another value below 20 K. On the other hand, between 20 and 100 K, the values are very different. These results lead us to conclude that below 20 K the Coulomb blockade is strongly present as denoted by the fast increase of the resistance. To better visualize the behavior of the electronic system for temperatures above 20 K and how it deviates from the $T^{-1/4}$ regime, a plot of the ln R $T^{-1/4}$ is shown in Fig. 3 for increasing injected currents. As seen in the figure, the curve for $I=500$ nA can be associated to electronic conduction being mediated via the variable range hopping mechanism with $T_0^{1/4}=22.86$ $K^{1/4}$. Increasing the injected current one can see two clear plateaus that can be attributed to variable range hopping mechanisms of different

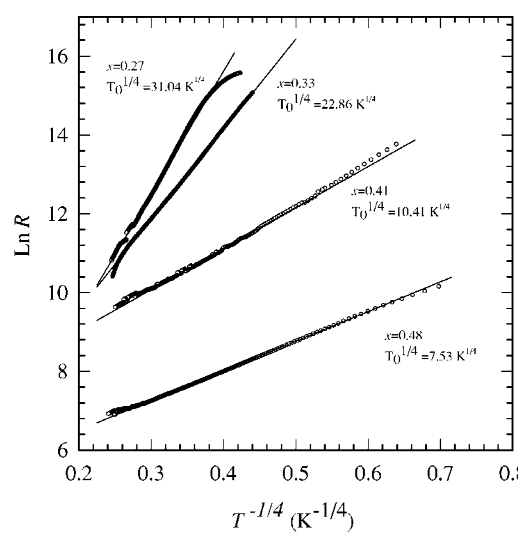

FIG. 1. ln R as a function of $T^{-1/4}$ for samples with $x=0.27$, 0.33, 0.41, and 0.48.

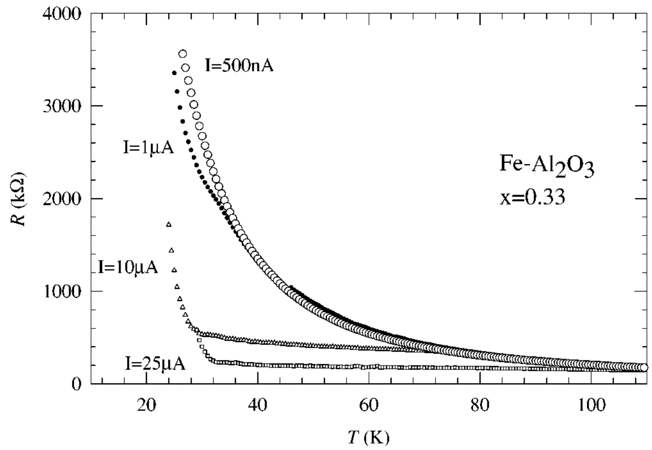

FIG. 2. Resistance as function of the temperature for the Fe-Al_2O_3 granular system with $x=0.33$ for injected direct currents I of 500 nA, 1 μA, 10 μA, and 25 μA.

T_0 such that $T_0^{1/4}=4.52$ $K^{1/4}$ for $I=10$ μA and $T_0^{1/4}=2.69$ $K^{1/4}$ for $I=25$ μA. These plateaus probably indicate that the electronic transition occurs in variable range hopping regime but with different ξ, which reduces the electric resistance of the sample.

At sufficiently low temperatures, all resistance curves of different applied currents return to the same value (see Figs. 2 and 3). This behavior is associated with the coulomb blockade between the grains when the thermal energy is decreased ($E_C > k_B T$).

A qualitative explanation of this behavior can be given by associating the increase of the localization length ξ with the hopping between more distant grains when the bias potential is increased. Therefore, there is strong evidence that for low bias potential, the tunneling is realized between relatively near neighbor grains, and that for higher bias potential, the tunneling occurs between more distant grains.

Taking the ratios of T_O, that is, T_0 (for I)/T_0(for 500 nA), even with g_0 unknown, we can obtain information about the ξ behavior. In fact, the localization length increases by a factor of 8.64 when the current increases from $I=500$ nA to $I=10$ μA and by a factor of 17.34 when the current increases from $I=500$ nA to 25 μA.

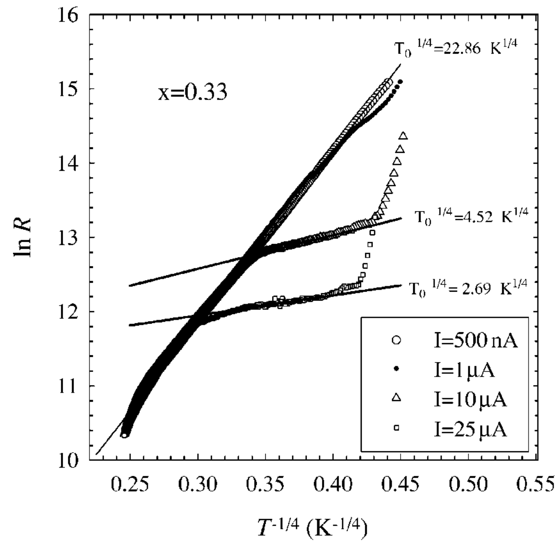

FIG. 3. ln R as a function of $T^{-1/4}$ for the Fe-Al_2O_3 sample with $x=0.33$ for injected direct currents I of 500 nA, 1 μA, 10 μA, and 25 μA.

We conclude that our Fe-Al_2O_3 granular thin films with average bcc metal volume fraction of 0.27 to 0.48 have nonohmic behavior that depends on the temperature. The electronic transport properties can be associated to variable range hopping mechanism with localization lengths values varying from low to high, as one increases the injected current or bias potential.

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