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Magnetoresistances in $Ni_{80}Fe_{20}$-ITO granular film

Chunhong Gao [a], Ke Chen [b], Yanxia Yang [a], Yuanqiang Xiong [a], Peng Chen [a,*]

[a] School of Physical Science and Technology, Southwest University, Chongqing 400715, China
[b] Chongqing Electric Power College, Chongqing, China

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ABSTRACT

The magnetic properties, electrical properties and magnetoresistance are investigated in $Ni_{80}Fe_{20}$-ITO granular film with various volume fractions V_{NF} of $Ni_{80}Fe_{20}$. The room temperature magnetization hysteresis of sample with V_{NF} = 25% shows superparamagnetic behavior. Current-voltage curve of sample with V_{NF} = 25% at 175 K shows typical tunneling-type behavior. The magnetoresistances of samples with low V_{NF} are positive at high temperature, and are negative at low temperature. The temperature-dependent magnetoresistances result from the competition among ordinary magnetoresistances, the granular-typed tunneling magnetoresistance and the spin-mixing induced magnetoresistances.

1. Introduction

The granular metal film has been extensively studied by Abeles et al. in 1970s, because of their high resistivities and low temperature coefficients of resistivity, which can be used as electrical resistors [1,2]. However, it has not been used as main component in information storage device till the discovery of a giant magnetoresistance (GMR) in the Fe/Cr multilayers [3], which initiated spintronic research and resulted in the first generation spintronic devices in the form of multilayered structures, which are now widely used in information storage device [4,5]. In particular, the metal-semiconductor hybrid systems have been extensively examined because of their potential application in electronics [6–8]. Researches on metal-semiconductor hybrid structure are mainly focused on silicon based, germanium based, ZnTe based, and diluted magnetic semiconductor (DMS) based systems. And the origin of the antiferromagnetic (AF) coupling and magnetoresistance (MR) are intensively investigated [9–21]. The temperature-dependent sign-changed MR was found in DMS systems, such as V-doped ZnTe [15], Cr-doped ZnTe [16], (Mn,Co)-co-doped ZnO films [17,18], Cr-doped tin-doped indium oxide (ITO) films [19], and Co/Si multilayers [20,21]. ITO is an n-type degenerated semiconductor. Recently, the FM-ITO system has attracted more and more attention. GMR in Fe/ITO [22] and Co/ITO [23] multilayer and tunneling magnetoresistance in CoFe/ITO sandwich [24] was reported. However, there are a few reports on the FM-ITO granular system. Moreover, the research on Fe-ITO granular film only discussed the GMR at room temperature, while the temperature dependent MR has not been investigated [25]. Here we focus our work on metal-semiconductor hybrid $Ni_{80}Fe_{20}$-ITO granular film, in which the temperature-manipulated sign-changed MR is found and the mechanism is discussed.

2. Experiment

$Ni_{80}Fe_{20}$-ITO granular films with various volume fraction (V_{NF} = 12%, 18%, 25%, 33% and 40%) of $Ni_{80}Fe_{20}$ were grown by sequential deposition of super thin $Ni_{80}Fe_{20}$ layer and ITO layer on Si ⟨1 1 1⟩ substrate at room temperature. The base chamber pressure for deposition was 3×10^{-5} Pa and the deposition pressure was 3 Pa. During the deposition, high-purity argon gas was used as sputtering gas and no oxygen was introduced. The deposition rates were 1.3 Å/s for $Ni_{80}Fe_{20}$ and 1.7 Å/s for ITO. A vibrating sample magnetometer from ADE was employed to examine the magnetic properties. Electrical properties and MR were measured in bar-shaped sample by the conventional four-terminal technique with temperature varying from room temperature to 15 K. All the measurements of MR curves were processed with the applied magnetic field parallel to the sample plane and perpendicular to the applied current.

* Corresponding author. Tel.: +86 23 68254612; fax: +86 23 68254608.
E-mail address: pchen@swu.edu.cn (P. Chen).

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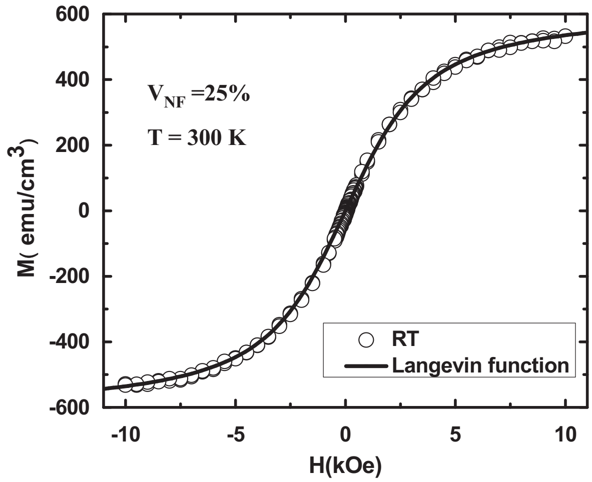

Fig. 1. Magnetization hysteresis loop of sample with V_{NF} = 25% and the fitting at room temperature.

3. Results and discussion

The magnetization hysteresis loop of sample with V_{NF} = 25% at room temperature (RT) shows superparamagnetic behavior (Fig. 1), which could be fitted by the Langevin function $M = M_s[\coth(\mu H/k_BT) - (k_BT/\mu H)]$, where M_s is the saturation magnetization, μ the magnetic moment of magnetic cluster, T the temperature, and k_B the Boltzmann constant. The FC-ZFC temperature-dependent magnetization for sample with V_{NF} = 25% indicates the blocking temperature about 98 K (Fig. 2). The superparamagnetic behavior indicates that $Ni_{80}Fe_{20}$ particle is small. The magnetization hysteresis loops at room temperature show superparamagnetic behavior for sample with $V_{NF} \geqq 25\%$ and ferromagnetic behavior for sample with $V_{NF} \geqq 33\%$ (Inset to Fig. 2).

Fig. 3 shows the *I–V* curve of sample with V_{NF} = 25% at 175 K, which shows tunneling-type behavior, where I is current and V is applied voltage. *I–V* curves of samples with high volume fraction of $Ni_{80}Fe_{20}$ (V_{NF} = 33% and 40%) show tunneling-type behavior, and *I–V* curves of samples with low volume fraction of $Ni_{80}Fe_{20}$ (V_{NF} = 12% and 18%) show linear behavior (not shown here). The temperature dependence of resistivity shows semiconductor behavior with negative temperature coefficient of resistivity and a sudden change around 120 K for sample with V_{NF} = 25% (Inset to Fig. 3). This may be caused by the temperature dependent magnetic state transition in the FM-ITO granular film.

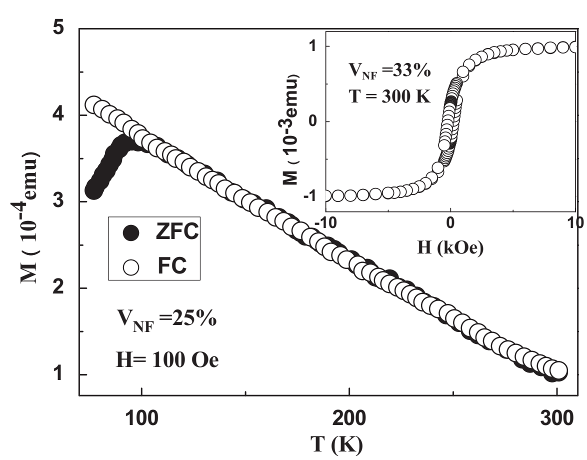

Fig. 2. The FC-ZFC temperature-dependent magnetization for sample with V_{NF} = 25%. Inset: magnetization hysteresis loop of sample with V_{NF} = 33%.

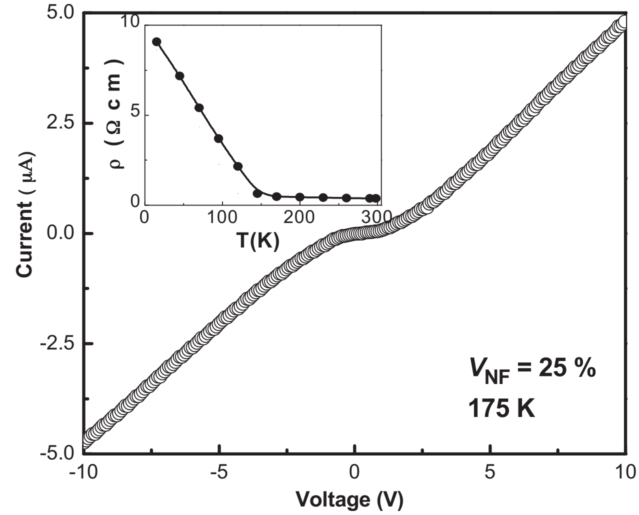

Fig. 3. *I–V* curve of sample with V_{NF} = 25% at 175 K. Inset is the temperature dependence of resistivity of sample with V_{NF} = 25%.

The MR is defined as $MR = (R_H - R_0)/R_0$, where R_0 and R_H were the resistance at zero magnetic field and maximum applied field. Fig. 4 shows the temperature dependences of MR of all samples. MR of samples with low volume fraction of $Ni_{80}Fe_{20}$ (V_{NF} = 12%, 18% and 25%) is positive at high temperature and increases with temperature decreasing, then is negative at low temperature. MR of samples with high volume fraction of $Ni_{80}Fe_{20}$ (V_{NF} = 33% and 40%) is negative in all scanned temperature. For the sample with V_{NF} = 25%, the MR increases from 0.36% at room temperature to 2.24% with temperature decreasing to 120 K, then the MR changes sign and is −0.78% at 15 K. The MR-temperature curve shows a discontinuity around 120 K, which is in accordance with the resistivity-temperature curve that shows abruptly change in this region. The total MR for $Ni_{80}Fe_{20}$-ITO granular films should be composed of three parts: (1) the positive ordinary magnetoresistance (OMR), which is proportional to the squares of applied field and fits well with the parabola equation $OMR \propto B^2/B_0^2$. (2) The positive spin-mixing magnetoresistance (SMR) due to magnetic disorder triggered by the temperature [22,24,26,27] and the current applied to the sample, which shows a response given by $SMR \propto (|B|/B_0^*)^{1/2}$ [28]. (3) The negative granular-typed tunneling magnetoresistance (TMR), which shows a response given by $TMR \propto -(M/M_s)^2$ [29].

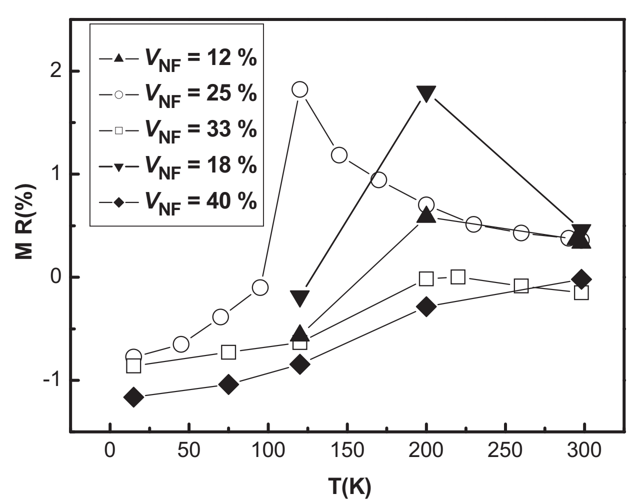

Fig. 4. The temperature dependences of MR of all samples.

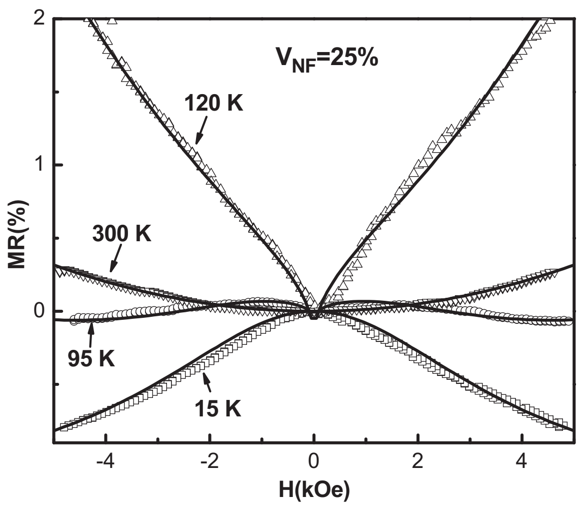

Fig. 5. The applied magnetic field dependence of MR curves and the fitting at various temperatures for sample with V_{NF} = 25%. Fitting: parabola fit at 300 K, parabola fit + spin-mixing fit at 120 K, parabola fit + $(-(M/M_s)^2)$ fit + spin-mixing fit at 95 K, $-(M/M_s)^2$ fit at 15 K.

The total MR for $Ni_{80}Fe_{20}$-ITO granular films is resulted from the competition among the three kind of MRs at different temperature. Fig. 5 shows the applied magnetic field dependence of MR and the fitting at various temperature for the sample with V_{NF} = 25%. It only shows OMR at room temperature and the MR curve fits well with the parabola equation MR $\propto B^2/B_0^2$. It is well known that semiconductors usually show relatively large OMR. The total MR at 120 K is composed of OMR and SMR, and the MR curve can be fitted by the parabola equation B^2/B_0^2 and spin mixing equation $(\left|B\right|/B_0^*)^{1/2}$. The total MR at 95 K is composed of OMR, SMR and TMR, and the MR curve can be fitted by the parabola equation B^2/B_0^2, spin mixing equation $(\left|B\right|/B_0^*)^{1/2}$ and $-(M/M_s)^2$. At 15 K, only TMR was observed, and the MR curve fits well by MR $\propto -(M/M_s)^2$. It should be noted that the temperature-dependent MRs for samples with low volume fraction of $Ni_{80}Fe_{20}$ (V_{NF} = 12%, 18% and 25%) show same characteristic (Fig. 4). At high temperature, $Ni_{80}Fe_{20}$ clusters are superparamagnetic, so the OMR in the semiconductor ITO dominates in total MR. As the temperature decreases, the magnetic spin disorder increases, and the OMR and the SMR appear simultaneously in the granular film. As the temperature decreases further, $Ni_{80}Fe_{20}$ clusters change from superparamagnetism to ferromagnetism step by step, and the TMR arises and dominates in the total MR at 15 K. That is to say, the OMR dominates at high temperature and the TMR dominates at low temperature while three kinds of MR are comparable in the middle temperature range. However, samples with high volume fraction of $Ni_{80}Fe_{20}$ (V_{NF} = 33% and 40%) only show negative MR in all scanned temperature, which should be due to larger $Ni_{80}Fe_{20}$ particles.

4. Conclusion

The magnetic properties, electrical properties and MR are investigated in $Ni_{80}Fe_{20}$-ITO granular film with various volume fractions V_{NF} of $Ni_{80}Fe_{20}$. The room temperature magnetization hysteresis of sample with V_{NF} = 25% shows superparamagnetic behavior. *I–V* curve of sample with V_{NF} = 25% at 175 K shows typical tunneling-type behavior. The magnetoresistances of samples with low V_{NF} are positive at high temperature, and are negative at low temperature. The temperature-dependent magnetoresistances result from the competition among ordinary magnetoresistances, the granular-typed tunneling magnetoresistance and the spin-mixing induced magnetoresistances.

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