Giant magnetoresistance of new macroscopic ferrimagnets in the system Co-TbN

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Abstract

We first report the GMR effect of new macroscopic ferrimagnet, Co-TbN. The Co-TbN system demonstrates typical macroscopic ferrimagnet properties which are a magnetic compensation point and negative giant magnetoresistance (GMR) which is caused by the spin scattering contribution quite different from those of ordinary GMR materials. The Co-TbN system with 32 % TbN composition showed 0.72 % GMR in fields up to 8 kOe at room temperature and 9 % GMR at 250 K in 40 kOe. The GMR effect in the Co-TbN system increases with increasing temperature, which is due to the increase of ferromagnetic alignment of the Co and TbN in a field caused by the decrease of exchange coupling by temperature.

Key words : Macroscopic ferrimagnet, Giant magnetoresistance, antiparallel exchange coupling.

1. Introduction

Macroscopic ferrimagnets are a new class of phase separated magnetic materials which have been recently discovered[1]. The macroscopic ferrimagnets consist of two magnetic phases with a negative magnetic exchange at the phase boundary. A prototypical example is the Co-EuS system which has 100 particles of EuS in a cobalt matrix. The EuS is exchange coupled antiferromagnetically to the cobalt at least at the Co/EuS interface. In the Co-EuS system, the small size of the EuS particles provide a large fraction of the EuS in close proximity to the interface which is influenced by the strong Co/EuS exchange. It has been found that these materials display unusual magneto-optical[2] and magneto-transport[3],[4] properties. Magnetization and Kerr hysteresis loops have confirmed the macroscopic ferrimagnetic model for these systems. In measurements of the optical and magneto-optical properties of Co-EuS thin films, polar Kerr rotations of up to 2° have been observed in Co rich films at photon energies of 4.5 eV[5]. Transport measurements show that the magnetoresistance of Co-EuS behaves like that of the widely studied granular GMR materials[6] which consist of particles of a ferromagnetic metal in a conductive, nonmagnetic matrix. In contrast, Co-EuS consists of semiconducting, ferromagnetic particles in a conductive, ferromagnetic matrix of cobalt. As a consequence, the temperature dependence of the

magnetoresistance is very different in the Co-EuS system as compared to the ordinary granular GMR materials. With respect to the magnitude of the effect, the magnetoresistivity changes ($\Delta\rho$) of the Co-EuS system is 8 x 10-5 Wcm which is larger than other magnetoresistive materials. Even though the magneroresistivity change of this system is large, the magnetoresistance defined as $\Delta\rho/\rho$ is small, typically 2 3 %, because of the high resistivity of the material caused by a large volume fraction of semiconducting EuS phase.

A new macroscopic ferrimagnet, Co-TbN, was proposed in this study. The Co-TbN system has TbN precipitates in a Co matrix. The TbN has the same atomic magnetic moment as pure Tb and the rock salt structure[7], the same as EuS. The TbN precipitates also provide the higher Curie temperature and thus stronger antiparallel exchange coupling with the Co matrix than EuS. These stronger exchange effects are caused by conduction electron mediated exchange of the RKKY type[8] which is weak in semiconducting EuS. Another difference is the single ion anisotropy of the Tb atom which is a non-S-state ion. In contrast, EuS contains divalent europium which is a S-state ion and thus has zero single ion anisotropy. Furthermore, the TbN is a conductor rather than semiconductor so the resistivity of Co-TbN is much less than that of Co-EuS, which can improve the magnetoresistance, $\Delta\rho/\rho$. The Co-TbN differs with the granular GMR materials in that both phases are magnetic and also differs from the Co-EuS in that both phases are conductors.

2. Experiments

Amorphous TbxCo1-x thin films were prepared with the compositions of 25 32 % of Tb by FTMS with a composite target. The film compositions were controlled by changing the Ar sputtering gas pressure (5 15 mTorr). Nitrogen was introduced into amorphous TbCo thin films by annealing 650 °C for 12 hours with a continuous flow of 10 % H2-balance N_2 gas mixture in order to induce the phase separation of Co and TbN. Phase analysis was made with x-ray diffraction and with secondary electron images on a field emission SEM. The magnetization loops and magnetization vs temperature in high field up to 30 kOe were measured at temperatures from 20 K to 300 K using a SQUID magnetometer. Magnetoresistance at room temperature was made up to 8.5 kOe with a DC electromagnet using Van der Pauw geometry. Contacts were made with fine wires attached with silver paint at the corners of a square sample. The magnetoresistance with temperature has been done up to 40 kOe at temperature from 20 K to 250 K in a superconducting coil cryostat.

3. Results and Discussion

Various features of the magnetic and magneto-transport properties obtained from the Co-TbN with 32% TbN composition are shown in Fig. 1 to Fig.3. These data are typical of the magnetic behavior for all compositions from 25 % to 32 % TbN. The increase in magnetization with temperature and the broad minimum in magnetization in a field of 1 kOe are clear indications of ferrimagnetic behavior (Fig. 1). The small jump in the magnetization curves in fields of 10, 20 and 30 kOe at 50 K indicate that at these high fields the magnetic moments of TbN precipitates are ferromagnetically alligned with the Co matrix. The Curie temperature of TbN can be estimated as about 75 K by extrapolating from the break in the magnetization curve at 30kOe field. Fig. 2 (a) and (b) show the resistivity (ρ) and magnetoresistivity (Δ) changes of $Co_{0.68}$-$(TbN)_{0.32}$ as a function of the magnetic field at room temperature. The curves show a cusp type negative magnetoresistance at room temperature which is the decrease of resistivity with increasing applied field. Considering that the

electrical properties of the rare-earth nitrides DyN, HoN, and ErN are all metallic9, the TbN has the same electronic structure with those nitrides and thus it can be expected that the TbN precipitate is also an ordinary resistivity metal. The magnetoresistivity ($\Delta\rho$) and magnetoresistance ($\Delta\rho/\rho$) of $Co_{0.68}$-$(TbN)_{0.32}$ are about 1.12 x 10^{-7} Wcm and 0.72 % at room temperature up to 8 kOe field, respectively, where the sign of the magnetoresistance is negative (Fig. 3).

The GMR effect of Co-TbN macroscopic ferrimagnet can be described in terms of the scattering of spin polarized conduction electrons by the antiparallel exchange coupled spins at the phase boundary between TbN precipitates and Co matrix[3]. In the Co-TbN system the matrix and precipitate are both metallic. the matrix is ferromagnetic and the precipitates are magnetically ordered through the exchange with the Co matrix. In Co-EuS system, the Co matrix is metallic but the EuS in the particles is a semiconductor. Therefore, the carriers are mainly confined to the Co matrix, which is the main difference between Co-EuS and Co-TbN systems. In the Co-EuS system the conduction electrons are scattered mainly off the Co-EuS interface whereas in the Co-TbN system scattering can occur both at the Co/TbN interface and in the TbN precipitates. That scattering depends on the magnetic alignment of EuS with respect to the cobalt. In the Co-TbN system, when the carriers pass through the phase boundary between the two metallic phases, Co and TbN, they are scattered by the antiparallel exchange coupled spin and the resistivity is high in zero or low field. In high fields with the Co and TbN ferromagnetically aligned, this spin scattering contribution is expected to disappear. The GMR of $Co_{0.68}$-$(TbN)_{0.32}$ in the high field of 40 kOe is around 9 % at 250 K, which is due to the increase of the ferromagnetic alignment between the Co and TbN by the high field. The GMR of Co-TbN shows an increase with temperature. These data were obtained from the temperature dependence of resistance. Based on the magnetization curve with temperature in 1 kOe field in Fig. 1 , the magnetization decreases with decreasing temperature, which can be explained by the increase of magnetization of antiparallel exchange coupled TbN phase. The antiparallel exchange coupling between the Co and TbN with different magnetic moments may also become stronger with decreasing temperature. As a result, the ferrimagnetic behavior between the two different magnetic moments increases with decreasing temperature thus the magnetization decreases.

When the temperature increases above 150 K, the antiparallel exchange coupling of the Co and TbN decreases with increasing temperature and the Co and TbN are more easily aligned ferromagnetically in a field. Therefore, the spin scattering contribution is expected to decrease in high field with increasing temperature thus the magnetoresistivity , $\Delta\rho$, increases and the GMR, $\Delta\rho/\rho$, increases with increasing temperature.

4.Conclusions

The new macroscopic ferrimagnet, Co-TbN, consisting of TbN precipitates in a cobalt matrix, is formed by the transformation of amorphous TbCo to crystalline Co and TbN phases induced by annealing in N2 gas atmosphere. The fully transformed films, annealed at 650 ℃ demonstrate typical macroscopic ferrimagnet properties previously observed in Co-EuS which are a magnetic compensation point and negative giant magnetoresistance. The antiparallel exchange coupling at the phase boundary between TbN precipitates and Co matrix can explain both of these observations. The magnetization decreases with decreasing temperature in 1 kOe which indicates that the TbN magnetization and/or the ferrimagnetic exchange coupling at the phase boundary increases with decreasing temperature. The temperature dependence of resistivity of the macroscopic ferrimagnet $Co_{0.68}$-$(TbN)_{0.32}$ shows the typical temperature dependence of a metal. The GMR effect increases with increasing temperature in the range 30 to 230 K, which is

due to the increase of ferromagnetic alignment of the Co and TbN in a field caused by the decrease of exchange coupling by temperature.

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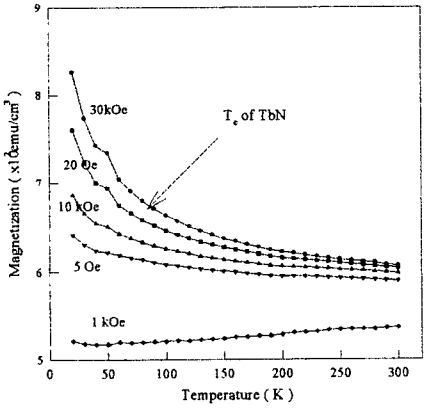

Fig. 1 Magnetization, M, of $Co_{0.68}$-$(TbN)_{0.32}$ with temperature at various applied fields.

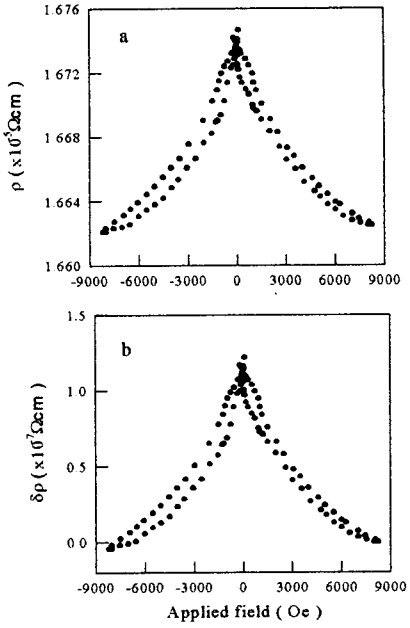

Fig. 2 The resistivity (a) and magnetoresistivity (b) changes of Co0.68-(TbN)0.32 films as a function of the magnetic field at room temperature.

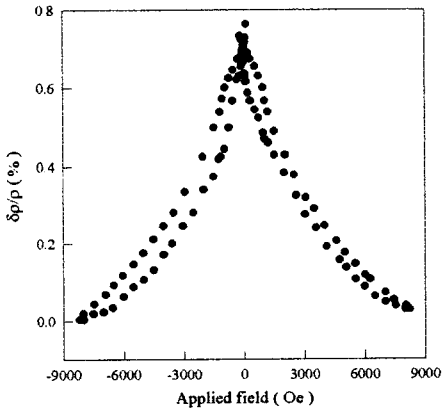

Fig. 3 The GMR($\delta \rho / \rho$) at room temperature $Co_{0.68}$-$(TbN)_{0.32}$ film as a function of the magnetic field.