Magnetoresistance measurements in permalloy clusters electrodeposited on silicon

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Abstract. We have studied the magnetoresistive behaviour of permalloy clusters electrodeposited on silicon at temperatures ranging from 5 to 300 K. A giant magnetoresistive (GMR) contribution observed at low coercive fields (10 Oe) was attributed to large permalloy clusters, and a broad peak at 300 Oe to anisotropic magnetoresistive (AMR). The GMR effect is due to coherent spin injection from cluster to cluster through the Si matrix. This conduction mechanism was also checked by depositing a 2 nm Au layer on top of the surface of the substrate with the permalloy clusters.

1. Introduction

Giant magnetoresistive (GMR) like behavior has been observed recently in permalloy (Py) clusters electrodeposited on silicon substrates at room temperature and the effect was associated to a spin-polarized current flowing from ferromagnetic cluster to ferromagnetic clusters through the semiconducting substrate [1]. This system is analogous to realize a 2D-granular ferromagnet but using as intergranular material a semiconductor instead of having a 3D-granular ferromagnetic material with a non-magnetic metallic matrix [2, 3]. Similar MR effect on silicon substrates was observed in planar structures with different coercivities, i. e. in Ni/Si/Ni interfaces prepared through e-beam lithography [4].

In this work, we have measured the magnetoresistance (MR) of the permalloy/silicon system at low temperatures for a given density of non-percolative clusters on the surface of the single crystal substrate. Additionally, in order to distinguish univocally AMR from GMR and conductivity through Si or percolation, we put forward a method that consists in depositing a very thin film of gold, that open a new channel through clusters, that covers the surface of the magnetic cluster and Si and measured magnetoconductivity with and without the gold layer.

2. Experimental

The Py clusters were galvanostatic deposited on n-type (100) Si with resistivity of 1 - 10 Ohm.cm. An adhesive tape was used to mask off all the substrate surface except for a circular area of 0.50 cm² on which deposition was desired, that is the sample dimension. Electrical contact to each substrate was made through a GaIn back contact. Prior to deposition, the substrates were immersed in a 5% HF solution for 5–10 s, to remove native oxide from the surface. The potentials were measured against a
saturated calomel electrode, and the Pt foil counter-electrode was directly placed opposite the working electrode (substrate). FeNi deposits on Si were prepared from an aqueous electrolyte containing 30 mM FeSO₄, 700 mM NiSO₄, 20 mM NiCl₂, 16 mM saccharin, and 400 mM H₃BO₃, resulting in composition close to the permalloy alloy (80 at.% Ni and 20 at.% Fe) for current densities of 6.3 mA/cm², as determined previously [5].

In order to perform the measurements for the electrical and MR characterization we have used the four point probe technique. GaIn eutectic alloy was employed as ohmic contact on the top surface of the sample to inject unpolarized currents in the linear regime, similarly to the procedures of reference [1]. For the I-V and MR experiments, the GaIn back contact were removed after the electrodeposition of the Py to avoid any parallel contribution to the resistance of the system.

Scanning electron microscopy (SEM) with field emission gun was used to determine the surface morphology of the electrodeposited substrates.

3. Results

Figure 1 shows typical surface morphology of samples with permalloy clusters on the surface of the silicon substrate. The presence of isolated Py clusters or agglomerates of clusters is clearly seen. For low deposition times clusters with distribution size of 10 – 50 nm, separated by average distances of 20 nm, are observed. For long deposition times, the clusters and agglomerates grow forming continuous layers, as expected. That is, the formation through electrodeposition of a distribution of separated Py clusters on the surface of Si is controlled by the deposition time.

![Figure 1: Typical SEM image of electrodeposited permalloy clusters on the surface of silicon for low deposition times.](image)

Figure 2a - 2d presents a sequence of magneto resistive results obtained for temperatures of 5, 80, 180 and 300 K on samples with morphology similar to the one shown in Figure 1 for in-plane magnetic field and perpendicular to the electrical current (transversal configuration). The main characteristics of the MR curves are the existence of i) sharp peaks at low magnetic field, ascribed to the GMR response of the large clusters that have low coercivity (10 Oe), and ii) broad peaks at 300 Oe assigned to the anisotropic magnetoresistance of the clusters with a distribution of smaller sizes. The information about the existence of small and large clusters is obtained from SEM images and hysteresis loops with characteristic shape of a cluster size distribution (result not shown). Additionally, no significant GMR is expected from the small clusters since the distance between them is larger then the distance between the larger ones. By increasing the temperature, the relative contribution of the AMR is reduced and, consequently, the GMR is more evidenced. Another interesting feature of the MR curves at different temperatures appears for the temperature of 180 K, where the contribution of the ordinary magnetoresistance (OMR) of the semiconducting substrate is clearly seen through the parabolic behaviour at higher magnetic fields. That is, at this temperature the resistance of the silicon
is close to a minimum, since the resistance of the silicon substrate increase by reducing T, due to the 
recombination of the dopant carriers, and by increasing T, due to the presence of phonons. The results 
described above are explained if we consider that the injected current into the semiconductor flow 
through two channels, one being the semiconducting substrate, which contribution is evidenced at 180 
K, and the other being the path from cluster to cluster through the silicon substrate. This last case is 
supported by the presence of the GMR and AMR peaks. Moreover, the GMR effect is attributed to the 
presence of a spin-polarized current flowing through the two-dimensional network of ferromagnetic 
clusters in the semiconducting matrix.

Figure 2: Transversal MR measurements of electrodeposited permalloy clusters on Si, with and 
without a 2 nm covering of Au, for four different temperatures.

Figure 2e - 2h displays the MR curves of the samples shown in Figure 2a – 2d after covering the 
surface with 2 nm of Au. The purpose of the Au layer is to offer a third channel for the electric current 
and to bring additional information about the mechanism of the spin electron current transferred 
through the Si. The spin mean free path through a metal is much shorter than in semiconducting 
materials, especially for gold that has a strong scattering of spin orbit coupling and then GMR is 
strongly reduced [6]. In the sequence of MR curves from 2e – 2h it was evident the reduction of GMR 
peaks, when compared with samples without the Au layer, specially for the temperature of 5 and 80 K, 
where the resistance of the substrate is still relatively high forcing the current between the clusters 
through the Au channel. The AMR response that is not dependent of the Si or Au channel maintains 
the same magnitude of the effect when no Au channel is present. As T is increased, the current through
Si increases due to the ionization of the dopants, an effect much more strong than the phonon contribution, and the spin transfer between clusters is more effective, and a GMR recovering of the uncovered samples is observed. The physics of the experiments with the Au layer is consistent and the method permits to distinguish clearly between GMR and AMR and to control the relative magnitude between both contributions.

4. Conclusions
It was described the magnetoresistance of permalloy clusters electrodeposited on silicon substrates at temperatures ranging from 5 to 300 K. The MR curves showed GMR and AMR contribution that varied relatively their intensity with the increase of the temperature. The GMR effect from the large clusters, i.e. clusters with lower coercivity, was due to the presence of a spin-polarized current that flows from cluster to cluster through the semiconducting substrate. This mechanism of conduction was confirmed by evaporating a 2 nm Au layer on top of the samples with permalloy clusters on the silicon surface.

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