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Multiprobe perpendicular giant magnetoresistance measurements on isolated multilayered nanowires

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Abstract

By combining electrochemical deposition into nanopores with electron-beam lithography, we developed an experiment setup to probe the giant magnetoresistance effects with current perpendicular to the plane (CPP–GMR) on isolated nanowires. Here we present four-probe magnetotransport measurements on multilayered Co (55 nm)/Cu (5 nm) nanowires of 100 nm diameter. The multiprobe technique allowed us to measure high GMR ratio on wire segments as short as 500 nm, without any additional contact resistance. We present different magnetic behaviors and GMR ratios depending on the measured segment and the applied field orientation. Results are discussed in terms of the CPP–GMR theory.

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Multilayered nanowires are ideal structures to study giant magnetoresistance (GMR) in the current perpendicular to the plane geometry. They have been very useful to determine the spin diffusion length (SDL) of various materials [1,2], using the Valet–Fert (VF) model [3]. Up to now, all magnetotransport measurements on multilayered nanowires have been performed with the nanowires embedded in the membrane. For this purpose, a thin conductive layer is evaporated at the top of the membrane and electrical contact is established during the electrodeposition process when the first wire emerges at the membrane surface [4,5]. This method has the advantage of being quick and easy, but does not allow four-probe measurements. The contact resistance at the extremities of the wires cannot be eliminated as the measurements are performed in a two probes

configuration. Moreover, the wire remains inside the membrane, so we cannot determine exactly its diameter by scanning electron microscopy (SEM) or perform complementary magnetic observations such as magnetic force microscopy (MFM). Here we first report on magnetoresistance measurements on isolated nanowires of sub-micron scale length with a multiprobe technique. In this study, we focus on nanowires with thick magnetic layer, i.e. of the order or larger than the SDL in Co, and thin non-magnetic layer, i.e. much smaller than the SDL in Cu. We also determine the influence of the external magnetic field direction on the GMR properties.

Multilayered Co/Cu nanowires were electrodeposited using a pulse deposition technique in track-etched polycarbonate membrane with pore diameter smaller than 100 nm. The electrolyte used for this experiment is a sulphate bath containing Co^{2+} at high concentration (1 M) and Cu^{2+} at very low concentration (5 mM). Details of the electrodeposition process are described in the previous paper [6]. We obtained an array of 22 μm

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long multilayered nanowires with about 350 repetitions of the Co (55 nm)/Cu (5 nm) sequence. By dissolving the polycarbonate membrane in dichloromethane, we extracted the nanowires from the array in liquid solution and spread them over a silicon substrate. Isolated nanowires up to 10 μm long are located and selected by SEM. Electron beam lithography is then performed after spin coating a 4000 Å thick layer of PMMA. After development, a 1000 Å thick Al layer is evaporated and lifted off. More details on sample preparation are given elsewhere [7]. The micrograph in Fig. 1 shows the final multiprobe connection of a Co/Cu nanowire obtained with this technique. The separation between the contacting electrodes can be modulated down to 500 nm, thus, allowing to investigate the magnetoresistive effects locally on short wire segments containing a reduced number of bilayer repetition.

For comparison, magnetotransport measurements were also performed directly at the end of the electrodeposition process by contacting wires that emerged at the surface of the membrane with silver paste. Fig. 2 shows room temperature MR measurements obtained on ~ 10 multilayered wires embedded in the membrane. $R(H)$ curves show a bell shape with little hysteresis. When cycling with the field perpendicular to the wire axis, an MR ratio of 4.1% is measured, while it decreases down to 2.6% when the field is oriented parallel to the wire. The difference between parallel and perpendicular saturation resistance of 1% is due to the anisotropic magnetoresistance within the Co layers [8]. With this method, we have only access to the GMR on the entire nanowire length, and thus on 350 Co/Cu bilayers. In contrast, when measuring resistance of one isolated nanowire with the four-terminal system described previously, we can probe only a few bilayers with

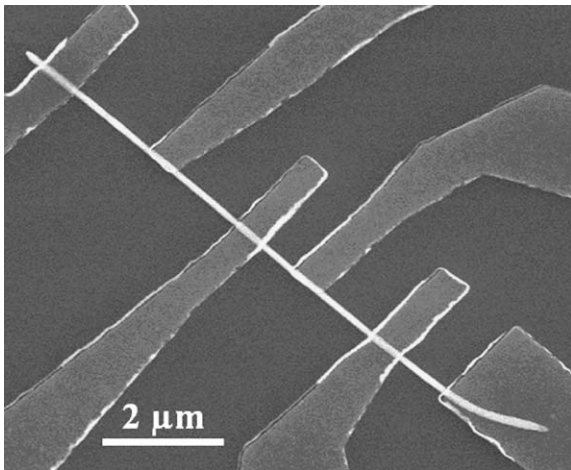


Fig. 1. SEM micrograph showing an isolated multilayered nanowire with multiprobe connections made by electronic lithography and lift-off process.

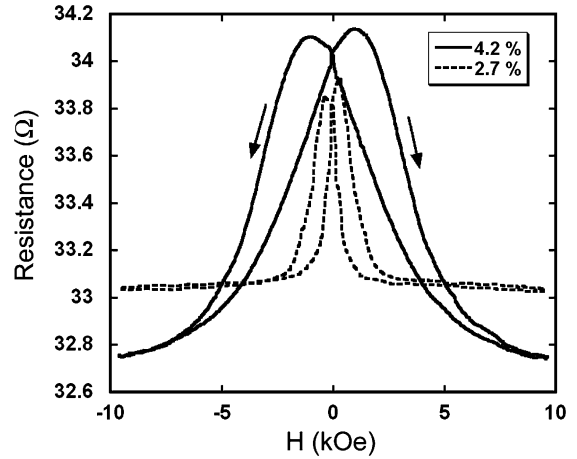


Fig. 2. MR measurements on several nanowires in parallel embedded in the membrane. Field loops run with external field H oriented parallel (dashed line) and perpendicular (full line) with respect to the wire axis.

no additional contact resistance and thus measure the GMR signal coming from this local Co/Cu stacking. Fig. 3 presents GMR measurements on two selected wire segments with different lengths that exhibit significantly different magnetic behavior and GMR amplitude. Fig. 3a shows the MR measurements on a 2.1 μm long segment with a total resistance of 30 Ω . The magnetic loop leads to a GMR ratio of 4.2% when the field is parallel to the wire axis and 10.2% when the field is perpendicular to the wire axis. In contrast, Fig. 3b shows the MR measurements of a 1.2 μm long segment where GMR ratios of 5.8 and 5.5% are obtained for perpendicular and parallel fields, respectively. The difference in the GMR ratio between samples can be explained in terms of CPP–GMR theory and micro-magnetic considerations.

As Co layers are thicker than the spin diffusion length (SDL) in Co, and Cu layer much thinner than SDL in Cu, the GMR ratio can be expressed with the VF model [3] as

$$\frac{\Delta R}{R^p} = \frac{2p\beta^2 I_{sf}^{Co}}{(1 - \beta^2) t_{Co}}$$

with β (~ 0.31) the bulk scattering spin asymmetry coefficient at 300 K, I_{sf} the SDL in Co (~ 38 nm at 300 K, [9]), t_{Co} the Co layer thickness (55 nm) and p the proportion of antiparallel orientations (180°) between magnetizations of two consecutive Co layers. As a consequence, the $R(H)$ curves reveal the degree of antiferromagnetic ordering of consecutive magnetic layers during the field cycle. Assuming a degree of antiparallelism $p = 1$, we find a maximum value of 14% for the CPP–GMR ratio. However, this upper value cannot be achieved experimentally because the Co layer

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