Perpendicular giant magnetoresistance of Co/Cu multilayers deposited under an angle on grooved substrates


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Perpendicular giant magnetoresistance of Co/Cu multilayers deposited under an angle on grooved substrates

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We propose a novel experimental technique for investigating the giant magnetoresistance effect measured with the current perpendicular to the layer plane (the so-called CPP geometry). Using holographic laser interference nanofabrication techniques and anisotropic etching the surface of semi-insulating InP substrates is patterned into V-shaped grooves of 0.2 μm width. Subsequently, a magnetic multilayer can be evaporated under an angle with the substrate normal, naturally resulting in a CPP-like magnetoresistance configuration. The technique is illustrated for Co/Cu multilayers, for which we present magnetization and magnetoresistance experiments. © 1995 American Institute of Physics.

Since the start of research on metallic superlattices, the artificial multilayer period induced anisotropic conductance has resulted in a number of new interesting resistance effects (see e.g. Ref. 1). Magnetic multilayers have been intensively studied, primarily because of their giant magnetoresistance (MR) effect² and its important industrial application potential. In most MR experiments the measuring current is in the plane of the multilayer, the so-called current-in-plane (CIP) geometry. Nevertheless, the great importance of experiments with the measuring current perpendicular to the multilayer plane (the so-called CPP geometry) has been emphasized in several theoretical papers.³⁻⁷ It took several years to realize these ideas experimentally, thanks to the development of ultra-sensitive SQUID-based voltage measuring techniques,⁸ by using microlithography to define “pillar” structures in the multilayers⁹ or, more recently, by electrodeposition of a multilayer into pores made in polycarbonate membranes.¹⁰

The latter two techniques might have application potential because room temperature operation of a CPP-MR sensor is feasible. Electrodeposition is an emerging technique and, so far, only resulted in room temperature MR values of the order of 10%. On the other hand, a remaining problem of the lithographic pillar microfabrication technique is that the perpendicular resistance is still very small and that processing is rather complicated.

In this letter, we propose a novel experimental technique for studying the CPP-MR effect in magnetic multilayers, enabling higher resistance values and which technologically is much simpler than the pillar microfabrication technique.⁹ By using holographic laser interference lithography and anisotropic etching techniques, we fabricate a V-groove pattern into the surface of semi-insulating InP substrates; subsequently a multilayer is evaporated under an angle with the substrate normal, giving rise to a CPP-like measuring configuration.¹¹ We demonstrate this technique for the widely studied Co/Cu multilayer model system.

The preparation of the grooved substrates is schematically shown in Fig. 1(a). We first cover a semi-insulating (100) oriented InP substrate with a thin (100 nm) photoresist layer (HPR 204). The resist is then exposed to a line pattern (period 201.4 nm), produced by a single-frequency holographically interfering Ar-laser beam (Spectra Physics 2045E). The photoresist is developed and the InP is anisotropically etched in a 60 H₂O: 30 HBr(47%):0.1 Br₂ solution. The result is the grooved substrate shown in Fig. 1(a). By evaporating a multilayer under an angle with the substrate normal onto just one of the two (111) side planes (with a width of 170 nm) of the groove, the structure of Fig. 1(b) can be grown. Before and after the multilayer deposition we deposit a well-conducting layer (Au or Cu), which redistributes the current I, so that predominantly a CPP-measurement configuration is obtained, as schematically shown in the figure.

The multilayer stacks were prepared in a multichamber MBE system (VG Semicon V80M). All depositions were carried out at room temperature, at a pressure of better than 10⁻¹⁰ mbar. Characterization of our samples by x-ray diffraction is not easy due to the intrinsic slope of the multilayers with respect to the substrate plane. However, we grew the Co/Cu multilayers on both Au buffer layers [which is known to result in (111) growth] and on Cu buffer layers [which results in (100) or mixed (100)–(111) growth] and did not observe important differences in MR for our choice of layer thicknesses. Figures 1(c) and 1(d) are scanning electron microscopy pictures of the top surface and the cross section of the complete structure (20 nm Cu+32×[1.5 nm Co+4.5 nm Cu]+20 nm Cu), respectively. It is obvious that the real structure is much more rounded than the schematic drawing of Fig. 1(b). A consequence is that the total layer thickness has to be chosen large enough to get a sufficiently low contact resistance between “neighboring” multilayer structures. Another consequence is that the non-magnetic layer thickness (Cu in our case) should be chosen large enough to prevent significant ferromagnetic coupling between the magnetic layers via pinholes or thickness fluctuations.

Room temperature magnetization experiments are shown...
in Fig. 2 for the case when the field is applied in the plane of the substrate along the direction of the grooves and perpendicular to the direction of the grooves. As expected, the direction parallel with the groove is the easy axis of magnetization; the relatively high remanent magnetization and the low saturation field indicate that the sample is not coupled antiferromagnetically, but rather uncoupled. The $H_{\parallel}$-curve does not show saturation on the same field scale, which is due to the fact that the field is not applied within the plane of the magnetic film itself, but parallel to the substrate so that a non-zero demagnetization factor is present.

For a correct interpretation of the experiment it is important to realize a uniform current distribution perpendicular or parallel to the direction of the grooves and not to get a mixed CIP-CPP geometry; to prevent the latter the length/width ratio of our samples in the measuring direction was chosen to be at least 4. The actual measuring configuration probably may be not “purely” CPP since, depending on the position in the multilayer, the current may have an angle of non-normal incidence to the multilayer plane. In Fig. 3(a) we show the CPP-like MR curves for a $[20 \text{ nm Cu} + 32 \times [1.5 \text{ nm Co} + 4.5 \text{ nm Cu}] + 20 \text{ nm Cu}]$ sample, measured both at room temperature and at 4.2 K with the field applied in the substrate plane in a direction parallel to the grooves and with the current perpendicular to the direction of the grooves [thus corresponding to the schematic current situation of Fig. 1(b)]. Due to the fact that the magnetic layers are uncoupled, a randomly oriented magnetization pattern is obtained around the resistance maximum and a hysteretic MR behavior is observed. The CPP-MR is about 37% at low temperature and 17% at room temperature. These measurements are to be compared with the CIP-MR data of Fig. 3(b) (measured with the current parallel to the grooves). We find that the MR is considerably smaller than for the CPP case. Of course, the CIP resistance is shunted by the Cu layers on top and below the multilayer, giving rise to a reduction of the measured CIP-MR effect. Taking this into account, the magnitude of the CIP-MR is of the same order as previous results on (111) oriented$^{12}$ or (100) oriented$^{13}$ Co/Cu multilayers. The CPP-MR effect at 4.2 K is in agreement with the literature results of Ref. 14. This suggests that our new CPP-MR measuring technique indeed is very promising for the future. In Fig. 4 we directly compare the CIP-MR with the CPP-MR data and demonstrate that, over the complete temperature regime, the CPP-MR is higher than the CIP-MR. The same behavior was observed for several other uncoupled samples (with relatively high Cu-thickness). We have found that,
when reducing the Cu-thickness, ferromagnetic coupling—probably via pinholes—can be present, giving rise to smaller MR values; this may be intrinsically related to the growth on a $\sim 111$ substrate plane\cite{12} or can be due to the round-off growth of the multilayer shown in Fig. 1\cite{d}. In the future we wish to explore this region of small non-magnetic layer thickness and investigate the effect in different material systems.

In conclusion, we demonstrate a new technique for studying the CPP-MR effect in magnetic multilayers. The magnetic multilayer is evaporated under an angle onto grooved substrates made by holographic laser interference lithography and anisotropic etching, naturally giving rise to a CPP-like measuring geometry. We illustrate this technique for Co/Cu multilayers.

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\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig3}
\caption{Magnetoresistance curves at room temperature and 4.2 K for a (20 nm Cu + $32 \times (1.5 \text{ nm Co} + 6.0 \text{ nm Cu}) + 20 \text{ nm Cu}$) multilayer measured (a) in the CPP-like geometry (L groove) and (b) in the CIP-like geometry (L groove).}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig4}
\caption{Temperature dependence of the CPP and CIP magnetoresistance for the multilayer of Fig. 3.}
\end{figure}

\begin{thebibliography}{11}
\bibitem{11} Resistance measurements on multilayers, deposited on structured substrates were already reported by T. Shinjo, T. Ono, and H. Yamamoto, in Colloquium Digest of the 14th International Colloquium on Magnetic Films and Surfaces (Heinrich-Heine Universität, Düsseldorf, 1994), p. 245; T. Ono and T. Shinjo (unpublished).
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