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Current-perpendicular-to-plane giant magnetoresistance in submicron pseudo-spin-valve devices

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We measured the transport behavior of $Ni_{80}Fe_{20}$(Py)/Cu/Py current-perpendicular-to-plane (CPP) submicron spin-valve devices with Cu spacer thickness up to 530 nm, fabricated directly from as-grown heterostructures using a three-dimensional focused-ion beam etching technique. The work bridged the gap between existing conventional CPP giant magnetoresistance measurements and lateral type spin-valve experiments. By fitting the data with the Valet-Fert model, we determined the spin asymmetry ratio of 0.80 ± 0.01 and spin diffusion length of 600 ± 245 nm in Cu at 77 K. The magnitude of resistance change obtained in this work was comparable with conventional CPP measurements, but was about two orders of magnitude larger than those of lateral spin-valve devices. The results implied that any success in exploiting the lateral type spintronic devices for practical uses would rely critically on improving the size of the measured signals.

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I. INTRODUCTION

The recent interest in exploring the spin degree of freedom in charge carriers lies in their potential for device structures and quantum computations. Successful exploitation of the phenomenon relies on the ability to inject carriers of a particular spin orientation and their subsequent detection; these have been demonstrated by both electrical and optical means. The pioneering works of Johnson and Silsbee demonstrated the possibility of observing such effects in metallic systems.[1–3] A simpler spintronic device is the giant magnetoresistive (GMR) multilayer structure, in which the resistance changes according to the relative magnetization orientation of the magnetic layers separated by the nonmagnetic (NM) spacers. In fact, it has been shown that in some spin injection device geometries there exist simple relations between the GMR and spin injection signals.[4–6]

However, the results obtained from the spin injection experiments were not consistent with those in the GMR measurements. In particular, the magnetoresistance (MR) signal size of the so-called lateral spin valve (LSV) spin injection devices was much lower than those in the GMR multilayers measured in the current-perpendicular-to-plane (CPP) geometry.[5–8] In LSV two problems are always present that complicate the analysis: the formation of *ex situ* interfaces and the anisotropic magnetoresistive (AMR) effect.[9,10] There are even doubts on the validity of the "quasi-one-dimensional" model used in the analysis of data in LSV.[11] On the other hand, Kimura *et al.* noted that the proximity of two ferromagnets (FM) can significantly alter the electrochemical potential in the NM.[12]

Fabrication difficulties meant that there were few CPP GMR experiments with thick NM spacers,[13] nor any LSV with spacing between the two FM electrodes less than 100 nm.[8] Here we studied the transport behavior of $Ni_{80}Fe_{20}$(Py)/Cu/Py pseudo-spin-valve structures, with the thickness of Cu spacer spanning up to 530 nm, by measuring three-dimensional focused-ion beam (FIB) fabricated devices.[15] Through such measurements we bridged the gap between the two different types of GMR geometries. Our results suggested that in lateral type spintronic devices one has to overcome the weak signal sizes before the advantage of long spin diffusion length can be exploited.

II. EXPERIMENTAL

We used UHV sputter-deposited structures of Cu/Py 20/Cu(t_{Cu})/Py 40/Cu (units in nm) for the experiment, with t_{Cu} varying between 10 and 530 nm. The deposition chamber was cooled with liquid nitrogen throughout the deposition process.[14] Devices were fabricated by FIB etching as described in a previous publication.[15] To facilitate the switching of the Py layers, devices were fabricated with large in-plane aspect ratios (1.5 to 2.5). The dimensions of the devices ranged from 120 nm to 500 nm, which were measured by scanning electron microscopy (SEM) after processing in the FIB. Transport measurements were made at a temperature of 77 K with a low frequency (15 Hz) current up to 500 μA. A SEM micrograph of a device with 530 nm Cu spacer is shown in Fig. 1.

III. RESULTS AND DISCUSSION

Figure 2 illustrates the MR measurement results of devices with t_{Cu} of 10, 100, and 390 nm. Since the devices had

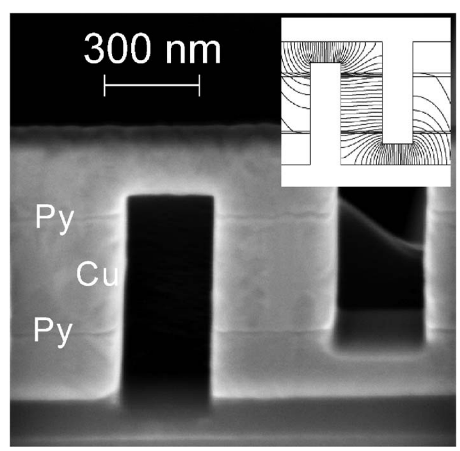

FIG. 1. SEM micrograph (at 45°) of a Py/Cu/Py pseudo-spin-valve device with 530 nm of Cu spacer. Inset: finite element simulation of equipotential lines across the device.

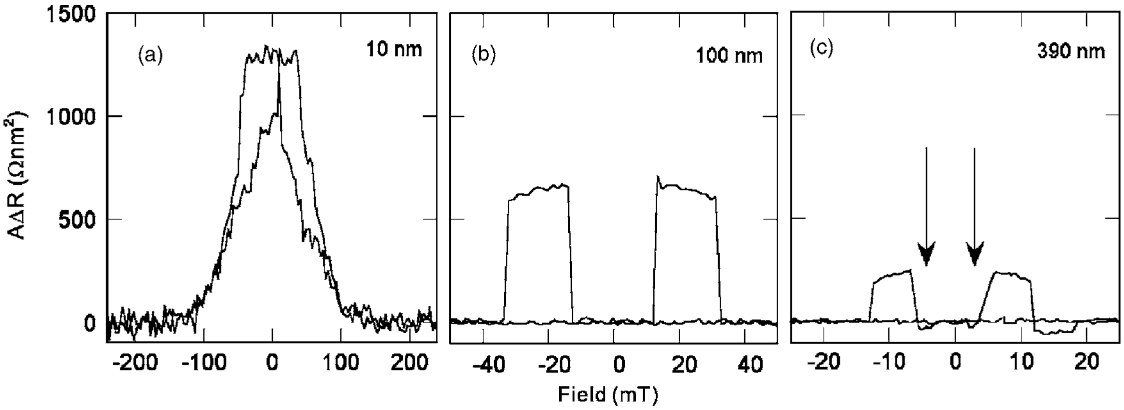

FIG. 2. CPP GMR measurements of pseudo-spin-valve devices with (a) 10 nm, (b) 100 nm, and (c) 390 nm of Cu spacer thickness. Arrows in (c) indicate the resistance dips as mentioned in the text.

different lateral sizes, we plotted the product of the device area (A) and the resistance change (ΔR) versus field to allow a direct comparison of the results. The presence of two different resistance states was clearly visible in all of the devices. In the $t_{\mathrm{Cu}}=10$ nm sample, strong magnetostatic coupling across the edges of the nanomagnets caused a large degree of coherent rotation of the FM layers before they come to saturation. The flat region around zero fields suggested the occurence of the antiparallel alignment of the FM magnetizations; such a region was absent in the MR measurement measured in the orthogonal direction. The antiparallel alignment was assisted by the large aspect ratio of the device. With an increasing spacer thickness, the magnetostatic coupling between two Py layers became weaker and they switched independently. In some devices which had small lateral dimensions, single domain-type switching was possible, as shown by the very sharp transition between parallel and antiparallel states in the device with $t_{\mathrm{Cu}}=100$ nm [Fig. 2(b)].

In Fig. 3 we show the $A\Delta R$ product of all devices measured. An exponential decay of $A\Delta R$ was observed, which was reduced by an order of magnitude when t_{Cu} increased from 10 nm to 530 nm. To study the results quantitatively, we employed the CPP model developed by Valet and Fert (VF model) to extract the spin asymmetry ratio α and spin diffusion length in $\mathrm{Cu}(\lambda_{\mathrm{Cu}})$,[16] assuming infinitely thick Py layers [since $\lambda_{Py}\sim 5$ nm (Ref. 17)] and did not include any Py/Cu interfacial resistances. As we expected t_{Cu} to span from the regime $t_{\mathrm{Cu}}\ll\lambda_{\mathrm{Cu}}$ to $t_{\mathrm{Cu}}\sim\lambda_{\mathrm{Cu}}$, we solved the complete VF equation without any assumptions on t_{Cu}, which read as[23]

$$A\Delta R=\frac{4\alpha^2\rho_{\mathrm{Cu}}\lambda_{\mathrm{Cu}}}{\left[1+\left(\frac{\rho_{\mathrm{Cu}}\lambda_{\mathrm{Cu}}}{\rho^{\star}_{Py}\lambda_{Py}}\right)\right]\sinh\left(\frac{L}{\lambda_{\mathrm{Cu}}}\right)+\frac{2\rho_{\mathrm{Cu}}\lambda_{\mathrm{Cu}}}{\rho^{\star}_{Py}\lambda_{Py}}\cosh\left(\frac{L}{\lambda_{\mathrm{Cu}}}\right)}, \tag{1}$$

where $\rho^{\star}_{Py}=\rho_{Py}/(1-\alpha^2)$ refers to the normalized Py resistivity.[16] We used resistivity values of $\rho_{Py}=63\ \mathrm{n}\Omega\ \mathrm{m}$, $\rho_{\mathrm{Cu}}=19\ \mathrm{n}\Omega\ \mathrm{m}$ (as measured from ~ 100 nm thick films deposited under identical conditions), yielding $\alpha=0.80\pm 0.01$ and $\lambda_{\mathrm{Cu}}=600\pm 245$ nm. The value of α was comparable with that obtained in typical CPP GMR measurements,[17] but was about four times larger than that obtained in LSV experiments (~ 0.2).[6] The fitted λ_{Cu} also matched with the values of 350 nm at room temperature and 1 μm at 4.2 K for LSV, as well as ~ 450 nm at 4.2 K for Nb-sandwiched repeated bilayers.[18] We also noted that our measured λ_{Cu} was longer than that obtained in electrodeposited nanowires (140 ± 10 nm at 77 K),[13] possibly due to the differences in the structural quality and purity of the samples.

Anisotropic magnetoresistance (AMR) is a concern in many of the spin injection experiments.[6,8,19] Indeed, we have observed small resistance dips in the devices with large t_{Cu} in the small field region (an example is shown in Fig. 2). In our devices there were two possible sources of AMR contributions: (i) from the Py layers within the electrodes that connected the devices with the current/voltage probes; and (ii) from the nonperpendicular current flow within the device pillars. To estimate the effect of (i), we measured the current-in-plane MR of a thin (170 nm) membrane in a $t_{\mathrm{Cu}}=50$ nm sample (i.e., thinning down a track without the three-dimensional etching to define the CPP geometry). The changes, if any, were so small that we could not detect them within the noise limit ($<0.06\%$), possibly due to the strong shunting effect by the Cu electrode layers. For the later one (ii), we prepared CPP devices with the spin valves replaced

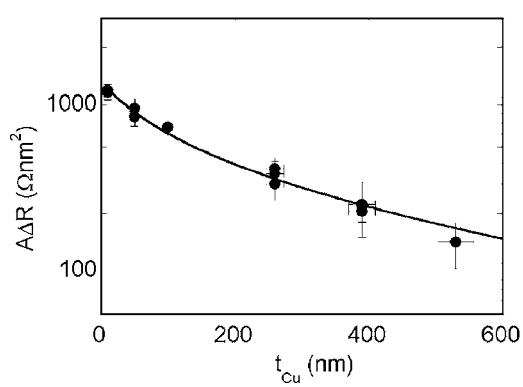

FIG. 3. Compiled MR results of the devices measured. Solid line is a fit using the VF model.

by a single Py layer of 30 nm. Care was taken to prevent any LSV-type GMR effect by defining very long (~ 1 μm) bottom and top electrodes. Small resistance dips similar to that of Fig. 2(c) were obtained; however, no changes in the MR sign were observed when the in-plane field was applied in orthogonal directions. These results ruled out the possibility of AMR effects. The assertion was further supported by two-dimensional finite element simulation of current flow in the devices (inset of Fig. 1). We have no clear explanations for the resistance dips at the moment, but they may arise from the complex domain structures within the Py nanomagnets in the devices.

The most comprehensive CPP GMR data were obtained from multilayers sandwiched between superconducting electrodes[20] and in nanowires electrodeposited through nanopores.[13] In both cases, $A\Delta R$ values in the range of 10 to $1000 \sim \Omega\ \mathrm{nm}^2$ were observed for $t_{\mathrm{Cu}} \ll \lambda_{\mathrm{Cu}}$. Simple extrapolation by the VF model should yield resistance changes of about one-tenth of this order of magnitude for t_{Cu} of the order 100 nm. This was also observed in the results shown here. A direct scaling of the spin injection results of Jedema *et al.* into GMR signals (a resistance change of 1.6 mΩ with spacer length of 250 nm and cross-sectional area of $5 \times 10^{-15}\ \mathrm{m}^2$), however, showed that their signals were two *orders of magnitude* smaller than ours for the same FM electrode separation, even though their results were obtained at 4.2 K and our measurements were performed at 77 K.[6] It is evident that there is a fundamental difference between the two different device geometries which led to the observed discrepancies between the signal sizes.

Here we discuss some possibilities for explaining the differences between the CPP GMR measurements and the LSV signals. In the latter case, there is enhanced surface scattering in the NM tracks due to the small Cu thickness, as well as the current shunting by the NM electrodes overlapping with the FM ones, which complicated the definition of the spacer length. However, one should expect a significant drop in the measured λ_{Cu} if surface scattering was the reason for the small signal sizes.[13,21] Current shunting can lead to difficulty in defining the separation between the FM spacers, which can affect the estimated α value. However, the current flow in all the devices with different FM separation would be identical around the FM electrodes as long as the Cu bridge was long enough, effectively causing a constant shift in the estimated spacing between FM electrodes.[20] Even taking the worst-case scenario into account (assuming all current being injected from the furthest end of the NM edge overlapping with the FM finger), the signal obtained by Jedema *et al.* was still an order of magnitude smaller than most GMR measurements.

Another possibility for the small signal in LSV devices may be related to the spin suppression effect by the Py electrodes in the LSV, which was shown by Kimura *et al.* recently.[12] In CPP GMR devices, current flows away from the FM/NM interfaces immediately after leaving the FM electrodes, so the supppression of the spin signal could be reduced. The hypothesis can be tested by fabricating and measuring CPP-type spin injection devices. One can either insert a thick layer of NM between the FM electrode and the NM bridge in a typical LSV; alternatively, a Kelvin-bridge type of structure can well be adapted for such measurements.[22]

In our calculations, we have explicitly neglected the contributions from interfacial resistances. The main reason was that all of the interfaces in our samples were prepared *in situ*, and so there were no contamination issues. A large interfacial resistance, possibly due to the formation of *ex situ* interfaces, would lead to strong confinement of spin accumulation within the N layer, leading to a divergent $A\Delta R$ (constant $t_{\mathrm{Cu}} A\Delta R$)[4] when $t_{\mathrm{Cu}} \ll \lambda_{\mathrm{Cu}}$, a feature which apparently appeared in Jedema's and Johnson's data.[3,5,6]

Interdiffusion at the interfaces, on the other hand, can also introduce additional electron scattering and should be considered in the calculations. In this work, the degree of interdiffusion across interfaces was minimized by deposition at low temperatures. Critical x-ray reflectivity analysis of exchange-biased spin-valve (SV) samples without the thick Cu electrode layers showed a maximum possible *chemical* roughness (arising from interdiffusion) of 0.5 nm at the Py/Cu interface.[14] This value was comparable with those listed in the literature,[17] and similar value is expected for the samples deposited in this work. In fact, we have attempted to take into account the possible interfacial resistances in the VF model calculations.[4] Our results showed that such contributions, if present, have to be comparable with $\rho^{\star}_{Py}\lambda_{Py}$ (of the order 500 $\Omega\ \mathrm{nm}^2$) for fitting our data. This range of interfacial resistance was consistent with the experimental values in the literature obtained from sputtered spin-valves.[17]

The low signal strength in LSV devices has important consequences for developing lateral spintronic devices: While a large spin diffusion length can be obtained in such structures with the right choice of material, the signal strength ($A\Delta R$) is prohibitively small for measurements. Assuming a resistance change of $100\ \Omega\ \mathrm{nm}^2$ and a cross-sectional area of $100\ \mathrm{nm}^2$, and with a current density of $10^6\ \mathrm{A\ cm}^{-2}$, the voltage change would be only 1 μV; higher current densities would run into the regime where electromigration becomes significant. This means that lateral devices, at least with the present geometry and materials combination, are unlikely to be employed for applications. A similar remark has been made by George *et al.*.[19]

In summary, we fabricated submicron pseudo-spin-valve devices with thick Cu spacers, bridging the gap between the existing CPP GMR measurements and LSV-type experiments. The measurement results were consistent with the existing CPP GMR measurements and gave $A\Delta R$ values in the range of 100–1000 $\Omega\ \mathrm{nm}^2$ for t_{Cu} up to 530 nm, which was distinctly different from those obtained in LSV devices. Our results have important consequences for the development of spintronic devices. Discrepancies between our data with other measurements were discussed. Further experiments comparing GMR in LSV and typical CPP GMR devices with refined geometries may shed light on the issue.

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