Spin-torque transfer in batch-fabricated spin-valve magnetic nanojunctions
(invited)

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A two terminal spin-injection device is fabricated using a nanostencil process with a Co–Cu–Co stack. The stack can be deposited both by sputtering and by electron-beam evaporation. A better edge definition is observed in evaporation-deposited films under cross section transmission electron microscopy. Both methods succeeded in producing junctions with sub-100 nm lateral dimensions and show spin-injection-induced magnetic switching. © 2003 American Institute of Physics. [DOI: 10.1063/1.1538170]

I. INTRODUCTION

Spin-polarized transport in ferromagnets less than 100 nm in size has made the effect of spin-angular momentum transfer-driven magnetic reversal a directly observable process.1–6 The efficient fabrication of low contact resistance, sub-100 nm current perpendicular (CPP) spin valves, however, remains a technological challenge. A batch-processable stencil–substrate approach was recently developed7 to address this fabrication issue. In this article, we describe in more detail the materials and magnetotransport properties of magnetic nanojunctions fabricated using this approach.

II. EXPERIMENT

Details of the stencil process are described in Ref. 7. Figure 1 gives a brief summary. It starts with a metal–insulator–metal trilayer, with the bottom metal responsible for electrical transport and providing an chemically inert surface for subsequent film deposition. The insulator is typically sputtered SiOx. It supports the top metal stencil and gives a controlled amount of undercut around the junction. The top metal stencil is made of platinum, and the sub-100 nm patterns are defined using electron-beam lithography and subsequent ion milling for pattern transfer into the Pt layer. This approach allows batch fabrication of the stencil substrate with electron-beam lithography. It simplifies the fabrication process and ensures high-quality edges in the final device.

FIG. 1. Schematic of the stencil-mask process: (a) Electron-beam lithography and pattern transfer into the Pt stencil; (b) Wet etch to open up the insulator spacer and creating a controlled amount of undercut; (c) Deposition of magnetic stack followed by metallic filling that gives top electrode contact; and (d) Optical lithography for the definition of wiring.

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process between magnetic film stack deposition and final device testing, thus enabling rapid turnaround in sample preparation.

As examples, in this article, two sample sets are discussed in detail. Sample A is made using magnetron sputtering, with a spin-valve stack sequence of \([3 \text{ Co}[10 \text{ Cu}] 12 \text{ Co}[200 \text{ Cu}][10 \text{ Pt}]]\), and sample B is made with thermal evaporation, with a stack sequence of \([3 \text{ Co}[10 \text{ Cu}][12 \text{ Co}[300 \text{ Cu}][10 \text{ Pt}]]\). Numbers represent layer thickness in nanometers. \(||\) represents vacuum break during growth. The stencil used for sample B turned out to have a final feature size about 0.04 \(\mu\)m larger in linear dimensions than nominal, which led to some nonideal behavior, discussed next.

A cross section view of the resulting junction is shown in Fig. 2, comparing film stack deposited using planar magnetron sputtering (sample A) and using electron-beam evaporation (sample B). Cross section samples were prepared using focused ion beam etching (FIB). As expected, a steeper better defined junction edge is observed for film stacks deposited using evaporation.

In all transport results, unless otherwise specified, the junction resistance refers to the dynamic resistance \(dV/dI\) measured using an ac lock-in circuit (operating at 331 Hz) on top of the dc bias current. The ac excitation amplitude is set to 100 \(\mu\)A root-mean-square.

Examples of the transport behavior are shown in Fig. 3. The magnetoresistance (MR) of the junctions for this particular stack range from 2% to 3.5%. This is true both for sputtered and for evaporated films. The junction resistance versus field curve \([R(H)\) curves\] show a characteristic knee structure near zero field. This is probably related to the micromagnetic coupling between the junction pillar situated inside the stencil and the extended magnetic film above.

Current-induced magnetic switching is observed for both types of films. The size difference of junctions due to lithography variation largely accounted for the difference in junction resistance as well as in the magnitude of switching threshold current shown in Fig. 3.

The threshold current depends on the applied field. This is illustrated in Fig. 4 using data from one of our better junctions. The gray scale describes the junction resistance. The bias current of the junction is swept from \(I_{\text{min}}\) to \(I_{\text{max}}\) and back under a constant bias field. The bias field is then stepped through from \(H_{\text{min}}\) to \(H_{\text{max}}\) and back, covering the four directions of sweeping as shown in the four panels of Fig. 4.

The current-switching threshold depends on the value of the bias field but is independent of the bias-field history, as seen in Fig. 4. It has a hysteretic dependence on current sweep. This can be seen by comparing the boundary position between the current up-sweep and current down-sweep graphs [Figs. 4(a) and 4(b) versus 4(c) and 4(d)]. These boundaries trace out the bias-field dependence of the threshold current \(I_{\text{c}}(H)\). The hysteresis region of the current-induced switching coincides with the bistable state in MR of the junction.

For bias fields outside the bistable region, the current-induced excitation becomes nonhysteretic, as depicted in Fig. 5. Such nonhysteretic dependence of \(R(I)\) appears in the dynamic resistance as a peak, whose sharpness and height depend on the sharpness and magnitude of the dc resistance jump and the ac measurement conditions such as the driving current amplitude. Such peaks in dynamic junction resistance appear in the gray-scale plot of Fig. 4 as bright streaks in the lower left- and right-hand side corner of Fig. 4, for example. For a well-behaved junction such as the one shown in Figs. 3(a) and 3(b), the contour plot shows simple switching boundaries with simple dependence on magnetic fields. For junctions with more complex switching characteristics, such as the one shown in Figs. 3(c) and 3(d), a more complex switching contour is seen. Although the details of switching for junctions larger than 0.05\(\times\)0.10 seems to show more complexity, the two main features remain, namely the hysteretic switching within the field range supporting a hyste-
etic magnetic state, and a series of nonhysteretic resistance peak features that show systematic magnetic field dependence.

III. DISCUSSION

The phenomenon of spin-angular momentum transfer-induced magnetic reversal has been examined in many previous works.\(^1\)--\(^6,9\)--\(^13\) In essence, when transport current passes through a ferromagnet, the ferromagnet polarizes the transport current along its magnetization axis. When the incoming current carries spin polarization in a direction different from that of the magnetization axis of the ferromagnet, this repolarization causes a net change in the angular momentum flow in the transport current. The difference in angular momentum per unit time is absorbed in the ferromagnetic electrode. The detailed process of angular momentum transfer from the electronic transport of view is currently the focus of many theoretical efforts.\(^14\)--\(^19\) Phenomenologically, the absorbed angular momentum change exerts a precessional torque on the magnetization of the electrode, providing a driving force for possible magnetic excitation.\(^10,12\)

The central role of this precessional torque is to counter the Landau–Lifshiz–Gilbert (~LLG~) damping,\(^20\) and for current levels above a certain threshold, to create a negative damping—or effectively, an amplification of spin precession. When the size of the electrode is small enough, and the net flow of angular momentum is large enough, the resulting magnetic excitation in the electrode can cause large-amplitude spin-wave excitation, even a coherent reversal of the magnetization of the nanomagnet electrode.

A magnetic moment reversal is by definition a large-amplitude process. Since large amplitude magnetic excitation is highly nonlinear, a general analytical solution of the problem is difficult. Numerical simulation is perhaps the only realistic way of grasping the large-amplitude behavior. For the understanding of the essential physics, however, it is possible to study the stability boundaries of such systems in a small-amplitude excitation limit.\(^10,21,22\) One needs to bear in mind, however, that crossing the small-amplitude stability boundary does not necessarily result in a magnetic reversal, as nonlinearity can stabilize certain large-amplitude orbits without incessitating a global magnetization reversal.

The magnetic dynamics of a thin-film nanomagnet can be well represented by the phenomenological LLG equation.\(^20\) One linearized solution to the LLG equation was presented by Slonczewski\(^23\) for extended films with a point–contact current injection and an uniaxial anisotropy potential.
Table I. A list of measured slope, intercept, and ISR for junctions with different sizes from sample A. For comparison, one data point from the work of Katine et al. (Ref. 5) is also included.

<table>
<thead>
<tr>
<th>Size ($\mu m^2$)</th>
<th>Slope (A/Oe)</th>
<th>Intercept (mA)</th>
<th>ISR (Oe)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.07x0.14</td>
<td>6.46x10^6</td>
<td>7.34</td>
<td>1136</td>
</tr>
<tr>
<td>0.07x0.14</td>
<td>6.39x10^6</td>
<td>5.87</td>
<td>918.6</td>
</tr>
<tr>
<td>0.05x0.20</td>
<td>7.81x10^6</td>
<td>3.83</td>
<td>490.4</td>
</tr>
<tr>
<td>0.05x0.10</td>
<td>8.63x10^5</td>
<td>7.14</td>
<td>827.3</td>
</tr>
<tr>
<td>0.05x0.10</td>
<td>2.82x10^6</td>
<td>7.81</td>
<td>2769.5</td>
</tr>
<tr>
<td>0.05x0.10 (300 K)</td>
<td>1.31x10^5</td>
<td>5.63</td>
<td>429.8</td>
</tr>
<tr>
<td>0.05x0.10 (300 K)</td>
<td>1.05x10^5</td>
<td>13.6</td>
<td>1255</td>
</tr>
<tr>
<td>0.08x0.16 (300 K)</td>
<td>1.96x10^5</td>
<td>17.6</td>
<td>898.2</td>
</tr>
<tr>
<td>0.08x0.16 (13.4 K)</td>
<td>5.98x10^5</td>
<td>10.8</td>
<td>1809</td>
</tr>
<tr>
<td>0.06x0.12 (13.4 K)</td>
<td>2.62x10^6</td>
<td>3.44</td>
<td>1314</td>
</tr>
</tbody>
</table>

*For $I_c$ only.

*Data from Katine et al. in Ref. 5.

The film.

The imaginary term of Eq. (2) gives a stability threshold (in cgs units) of

$$I_c = \alpha \frac{2e}{h \eta} \left( \ell_m a b M_s \right) \left( H_k + 2 \pi M_s + H + \frac{Dk^2}{2\mu_B} \right),$$

(2)

which is similar to Eq. (18) in Ref. 10 that is a special case for $k=0$, representing a coherent rotation. In Eq. (2), $\alpha$ is the LLG damping coefficient, $\ell_m$ is the thickness of the nanomagnet element $a$ and $b$ its length and width. $\eta$ is the spin-polarization factor. The real part of Eq. (1) gives the frequency dependence of the spin wave on the applied field. In cgs units, this reads

$$\hbar \omega = 2\mu_B \sqrt{(H + H_{eff})(H + H_{eff} + 4\pi M_s)},$$

(3)

where $H_{eff} = H + Dk^2/2\mu_B$. Equations (2) and (3) describe in good approximation the small-amplitude behavior of spin-wave excitation under spin-current injection. The stability boundary prediction of Eq. (2) especially can be compared with experimental results (which admittedly is from large-amplitude observation).

Two aspects of Eq. (2) can be compared with experiment. One is to quantify the slope at which $I_c$ depends on applied field, namely to measure $dI_c/dH$ and compare with the value of $\alpha (2e/\hbar \eta) (\ell_m a b M_s)$. This comparison involves several not-so-well-known parameters such as $\alpha$ the LLG damping coefficient, usually in the range of 0.005 to 0.01 for relatively thick magnetic films, and the spin-polarization factor $\eta$. The other, perhaps more robust way, is to compare the ratio of $I_c(H=0)/(dI_c/dH)$, or the intercept-to-slope ratio (ISR) of $I_c(H)$. This ratio from Eq. (2) is independent of many details of the spin-current interaction, and should give a net value close to $2\pi M_s + H_k + Dk^2/2\mu_B$. It can be readily done using data such as those presented in Fig. 4. The values thus measured from several of the junctions from sample A are tabulated in Table I. The conclusion from these data is, while the experimentally determined slope $dI_c/dH$ for these junctions lies within reason from those predicted by Eq. (2), the ISR falls systematically below what is expected from Eq. (2). For cobalt, $2\pi M_s$ alone should be around 9050 Oe, while the intercept-to-slope ratio obtained in Table I is on average an order of magnitude below.

Experimentally, it was observed that the value of ISR increases with decreasing temperature. A comparison of the values obtained at ambient temperature and that at 13 K for two junctions is given in Table I. This may suggest the role of thermal excitation as one cause for the deviation of ISR from Eq. (2).

The question that remains is the way the magnetic system distributes the input energy from the spin-injection-induced magnetic excitation. In other words, what is the coupling strength of various spin-wave modes to the excitation of spin injection. In a monodomain model, the only mode available is the $k=0$ uniform rotation. When internal degrees of freedom of the nanomagnet are included in the excitation process, we need a way to analyze and compare the energy distribution among the different spin-wave modes. This remains to be done theoretically. We speculate from these experimental results that the energy distribution problem is likely to be complex and has to include inputs from the materials, magnetic, and magnetotransport properties of the nanomagnet and its environment, as well as the specific transport and magnetic boundary conditions the nanomagnet is subject to.

In conclusion, a model substrate-based process is developed for the fabrication of low contact-resistance CPP spin-valve nanojunctions. These junctions are good candidates for systematic investigation of spin-current-induced magnetic excitation. Our preliminary study reveals a rich set of behavior in the response of such a junction to spin-current excitation. Two main processes in competition for spin-current excitation energy are observed: The magnetic reversal and the magnetic, and magnetotransport properties of the nanomagnet and its environment, as well as the specific transport and magnetic boundary conditions the nanomagnet is subject to.

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