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Current-driven switching of exchange biased spin-valve giant magnetoresistive nanopillars using a conducting nanoprobe

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An array of exchange biased spin-valve giant-magnetoresistance nanopillars was fabricated and the current I dependence of the resistance R was investigated using an electrically conducting atomic-force microscope (AFM) probe contact at room temperature. We observed current induced switching in a MnIr/CoFe/Cu/CoFe/NiFe nanopillar using the AFM probe contact. Current-driven switching using nanoprobe contact is a powerful method for developing nonvolatile and rewritable magnetic memory with high density. © *2004 American Institute of Physics*.
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I. INTRODUCTION

From both technological and fundamental viewpoints, the realization of future nonvolatile magnetic memory devices with higher density requires new approaches to reading and writing data because conventional magnetic data storage is rapidly approaching the limit of data writing. As the magnetic elements become smaller, a larger external magnetic field will be required to write magnetic data into them. Electrical switching by injection of a spin-polarized current, which was theoretically predicted by Slonczewski[1] and Berger,[2] has attracted attention because it would enable magnetic data to be written without an external magnetic field. In a Co/Cu/Co nanostructure, the hysteretic behavior of electrical switching when a current is applied has been experimentally demonstrated,[3–10] the electrical switching is caused by the magnetic momentum reversal of the thinner Co layer due to the spin-polarized current injected from the thicker Co layer.

An alternative approach to ultrahigh density memory and data storage systems has been proposed[11] in which data are written on a nonmagnetic polymer medium using a heating process and an atomic-force microscope AFM probe technique. Although reading and writing data electrically using proven magnetic technology it is more versatile and desirable, electrical magnetic recording using a probe contact in patterned magnetic elements has yet to be demonstrated. This paper reports the first observation of current-driven switching using a AFM nanoprobe contact on an exchange biased spin-valve giant magnetoresistance (GMR) nanopillar.

The nanopillar structure was an exchange biased spin-valve $Mn_{80}Ir_{20}$ (12 nm)/$Co_{90}Fe_{10}$(3 nm)/Cu(6 nm)/$Co_{90}Fe_{10}$ (1 nm)/$Ni_{81}Fe_{19}$(5 nm) [MnIr/CoFe/Cu/CoFe/NiFe] GMR film, in which the bottom CoFe/NiFe acts as a magnetically soft layer, and the top CoFe layer acts as a magnetically hard layer. We selected this structure for two reasons.

(1) Using an array of a nanometer-scale pillars may enable the production of higher density magnetic memory device, although the shape of the pillars makes it difficult to control their magnetic anisotropy.
(2) Current-driven switching has been mainly observed in Co/Cu/Co-based magnetic multilayered nanostructures[3–10] containing thick and thin Co layers. In previous experiments by others,[6,10] an antiparallel configuration of the magnetization in two Co layers was produced using the difference in the coercive force H_c of two Co ferromagnetic layers which is due to shape magnetic anisotropy. In our experiment, an exchange bias coupling using an antiferromagnet MnIr was employed to induce unidirectional magnetic anisotropy in the top layer to CoFe ensure either parallel or antiparallel magnetization of the CoFe/NiFe and CoFe layers regardless of the pillar shape.

II. EXPERIMENT

We first prepared an Au(10 nm)/$Mn_{80}Ir_{20}$(12 nm) $Co_{90}Fe_{10}$(3 nm)/Cu(6 nm)/$Co_{90}Fe_{10}$(1 nm)/$Ni_{81}Fe_{19}$(5 nm)/

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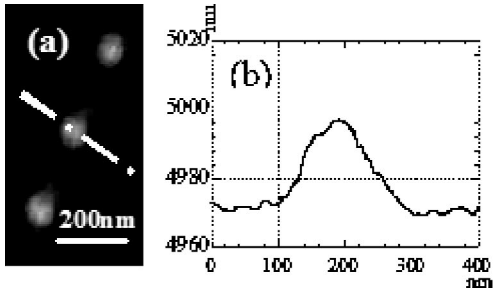

FIG. 1. (a) (SEM) image of an array of MnIr/CoFe/Cu/CoFe/NiFe nanopillars after ion milling; (b) AFM image of profile of a typical MnIr/CoFe/Cu/CoFe/NiFe pillar. Schematic view of cross section of nanopillar using an AFM apparatus.

Ta(50 nm) film on a thermal-oxidized Si substrate using an ultrahigh vacuum sputtering apparatus. We fabricated the nanopillars using lithography with an AFM cantilever and ion milling. The milling step was timed to stop when the surface of the bottom NiFe layer appeared. The MnIr/CoFe/Cu/CoFe/NiFe nanopillars (100 nm diameter) formed in a uniform array with a 200 nm pitch. Figure 1(a) shows a scanning electron microscopy (SEM) image of an array of MnIr/CoFe/Cu/CoFe/NiFe nanopillars after ion milling. Figure 1(b) shows an AFM profile of a typical pillar; it shows that the pillar was 30 nm high and that the ion milling stopped when the surface of the bottom CoFe or NiFe layer appeared. Figure 2 shows our experimental setup. The dc current-voltage (*I*-*V*) curve was measured using a conductive AFM (C-AFM) apparatus at room temperature, where the applied atomic force was from 5 to 10 nN. To establish ohmic contact between the probe and the pillar, we examined the *I*-*V* characteristics of the Au film using four kinds of probes, Pt, PtIr, W, and B-doped C. The bias current direction was defined as positive when spin-polarized electrons flowed from the bottom CoFe/NiFe layer to the top CoFe layer. The *I*-*V* curve measurement was done under a zero magnetic field.

III. RESULTS AND DISCUSSION

Figures 3(a) and 3(b) show the *I*-*V* curve for a contact on a separately prepared 50 nm Au film. The ones in (a) were measured using a Pt- and PtIr-coated Si cantilever while the ones in (b) were measured using B-doped C- and W-coated Si cantilevers. The curves in (a) showed a resistance of ~100 Ω, while those in (b) exhibited diodelike characteristics, suggesting that an oxidized layer had formed on the surface of the probe. A nonlinear *I*-*V* curve like a tunnel contact was observed for the C-coated probe. The contact between the Au film and Pt or PtIr probe ensured an ohmic contact, which is why we used Au for both a protection cap and electrical contact for the nanopillars.

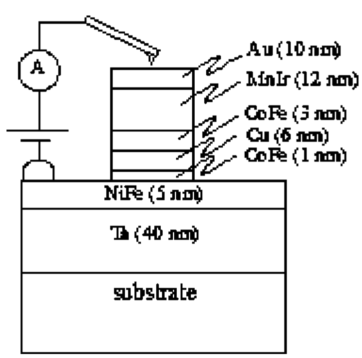

FIG. 2. Schematic view of cross section of experimental setup.

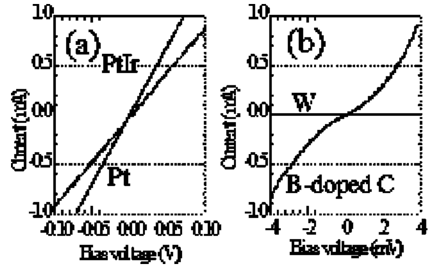

FIG. 3. (a) *I*-*V* curves measured using Pt- and PtIr-coated Si cantilevers; (b) *I*-*V* curves measured using B-doped C- and W-coated Si cantilever.

Figure 4 shows the typical *I* dependence of *R* in the Au(10 nm)/MnIr(12 nm)/CoFe(3 nm)/Cu(6 nm)/CoFe(1 nm)/NiFe(5 nm) nanopillars when we used a Pt-coated probe. Clear hysteretic switching behavior was observed in these pillars with good reproducibility. We confirmed that no hysteretic behavior was present in an unpatterned GMR film. In the measurements in this study, when the current was flowing from the thinner top CoFe layer to the thicker bottom CoFe/NiFe layer, the resistance changed from a higher state to a lower one. The observed $\Delta R/R$ was 2.7%, which is in line with the spin-transfer torque-driven switching reported elsewhere[5–10] for Co/Cu/Co nanopillars, as predicted by Slonczewski's model.[1] The critical current values are $Ic_{+} \sim 6.5$ mA and $Ic_{-} \sim -7$ mA which correspond to $Jc_{+} = 8.3 \times 10^{7}$ A/cm^{2} and $Jc_{-} = 8.9 \times 10^{7}$ A/cm^{2}, respectively.

Using the four kinds of probes, we examined the magnetic field *H* dependence of *R* for a different nanopillar having the same structure and dimensions. Figure 5 shows the *R*-*H*curves when the magnetic field was applied parallel to the direction of the unidirectional anisotropy of the top CoFe layer, as induced by the MnIr layer. The current was 1 μA; its geometry is shown in the inset. A typical *R*-*H* loop of an exchange biased spin-valve GMR device was observed with $\Delta R/R$ of 2.5% between 0.1 and 0.25 kOe, which is in good agreement with the *R*-*I* measurement using probe contact (Fig. 4). This result suggests that the electrical switching produced using a probe contact is caused by current-driven magnetization reversal.

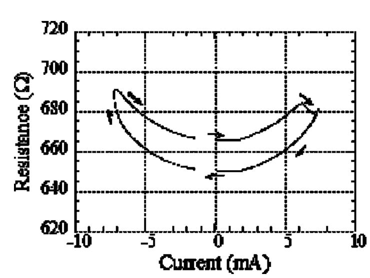

FIG. 4. Resistance as a function of current in a MnIr/CoFe/Cu/CoFe/NiFe Nanopillar measured using Pt- coated probe. Arrows show current sweep direction during measurement.

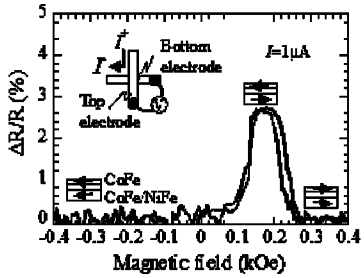

FIG. 5. Resistance as a function of magnetic field in MnIr/CoFe/Cu/CoFe/NiFe nanopillar using the four-probe method. Schematic shows geometry of current during measurement.

As the current is increased, there is a symmetric gradual rise in resistance with respect to the current direction, as shown in Fig. 4. When we applied a current of 10 mA, the point of the PtIr-coated probe started to melt, as shown in the SEM images in Fig. 6. Because the probe point had an area of less than 50 nm, application of a 10 mA current resulted in a current density of 1×10^9 A/cm^2. An *I-V* curve measured using the melted probe exhibited a nonlinear response, suggesting that the Si surface of the cantilever was exposed.

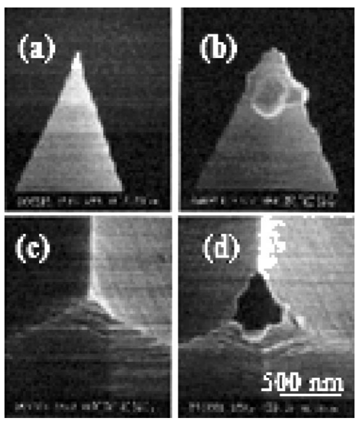

FIG. 6. SEM images of the point of a PtIr-coated cantilever; (a,c) initial image and (b,d) images after 10 mA current was applied. (a) and (b) show side view, and (b) and (d) show top view.

IV. CONCLUSION

In conclusion, we have observed current-driven hysteretic switching using AFM probe contact in an exchange biased spin-valve MnIr/CoFe/Cu/CoFe/NiFe nanopillar. This probe contact technique, incorporating current-driven switching, is promising for production of magnetic memory devices with ultrahigh areal densities.

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