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Spin dependent tunneling junctions with reduced Neel coupling

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A new structure of spin dependent tunneling (SDT) junctions has been demonstrated to have a much reduced Neel coupling field between the free and pinned ferromagnetic layers comparing with conventional SDT structures. The new structure consists of a modified synthetic-antiferromagnetic composite layer as the pinned layer with two Ru spacer layers and three ferromagnetic layers. The Neel coupling field is much reduced for both top- and bottom-pinned SDT structures using this new composite pinned layer. Furthermore, the net magnetic moment is kept at zero for the composite pinned layer to minimize the fringe field after patterning. The coupling reduction can be understood by considering the additive contribution from the first two interfaces with Ru in the composite pinned layer, which cancels that from the pinned layer interface with the barrier. By properly spacing these three most important interfaces, reducing the coupling to basically zero is realized. The coupling reduction allows the elimination of an on-chip bias coil used to correct the coupling, therefore simplifying the electronics and reducing the power to operate the SDT sensors. The new SDT structure has potential impacts on many SDT and spin valve devices such as magnetoresistive sensors, galvanic isolators, magnetic logic, and MRAM devices. *© 2003 American Institute of Physics.* [DOI: 10.1063/1.1556982]

INTRODUCTION

Neel coupling exists in all practical ferromagnetic sandwiches such as spin dependent tunneling (SDT)[1] and spin valve structures.[2] Neel coupling is also called ‘‘orange peel’’ coupling,[3] which is caused by the magnetostatic interactions between the free poles at the two ferromagnetic interfaces next to the nonmagnetic barrier in a SDT junction. The coupling associated with a conformal roughness of the two interfaces causes a shift in the magnetic field response of the free layer magnetization, and therefore the magnetoresistance. In many applications especially at low field,[4] it is desirable to reduce or eliminate the Neel coupling for better device performance and simpler fabrication process. Synthetic antiferromagnetic (SAF) structure[5] has been applied to many device applications. It uses the extremely strong antiparallel exchange coupling of two ferromagnetic layers via a thin Ru layer of 0.4–0.9 nm. This exchange coupling can only be overcome under several kOe of magnetic field that is far above the operating magnetic field in our applications. In other words, the antiparallel configuration remains during the normal operation of the SDT device. A new SDT structure using a modified SAF structure as the pinned layer is realized to have a much reduced Neel coupling field. The new SDT structure allows the elimination of an on-chip bias coil, thus simplifying the electronics and reducing the power to operate a magnetoresistive sensor made of such new SDT junctions. The new SDT structure can be extended to many SDT and spin valve devices used in many applications.[6,7]

EXPERIMENT

SDT wafers were deposited using dc magnetron sputtering in a Shamrock system with a base pressure lower than 1.0×10^{-7} Torr. A typical conventional SDT wafer has a basic structure of Si(100)–200Si_3N_4–12$Ni_{65}Fe_{15}Co_{20}$–1.5Al_2O_3–5.0$Ni_{65}Fe_{15}Co_{20}$–35$Cr_{45}Mn_{45}Pt_{10}$ (in nm). The Al_2O_3 barrier was formed by depositing a layer of metallic Al then oxidizing it in a plasma containing Ar/O_2. A magnetic field of 50 Oe was applied during deposition to induce the easy axes in the magnetic layers. Annealing was done in forming gas at a temperature of 250 °C for 1 h with a magnetic field applied to the pinning direction. Magnetic properties of bulk samples including the coupling fields are measured using a shb-109A B-H loop tracer at room temperature. Magnetoresistive properties were measured using an automated magnetic probe station.

RESULTS AND DISCUSSION

A hysteresis loop is given in Fig. 1(a) for a conventional SDT structure of 12NiFeCo–1.5Al_2O_3–5.0NiFeCo–35CrMnPt (in nm) with a single pinned layer of NiFeCo. It is noted that there is a coupling field of 2.2 Oe as defined by the horizontal shift of the center of the hysteresis loop. When a SAF structure[5] (5.0NiFeCo5/0.9Ru/5.0NiFeCo) is used as the pinned layer, the coupling field is reduced to 1.2 Oe. The reduction is likely due to the introduction of the two new interfaces next to the Ru layer inside the composite pinned layer, as will be explained later. Further reduction could be achieved by making the ferromagnetic pinned layer next to the tunnel barrier thinner. However, it is also desirable to have a zero effective fringe field from the composite pinned layer after the SDT stack is patterned. Therefore the two

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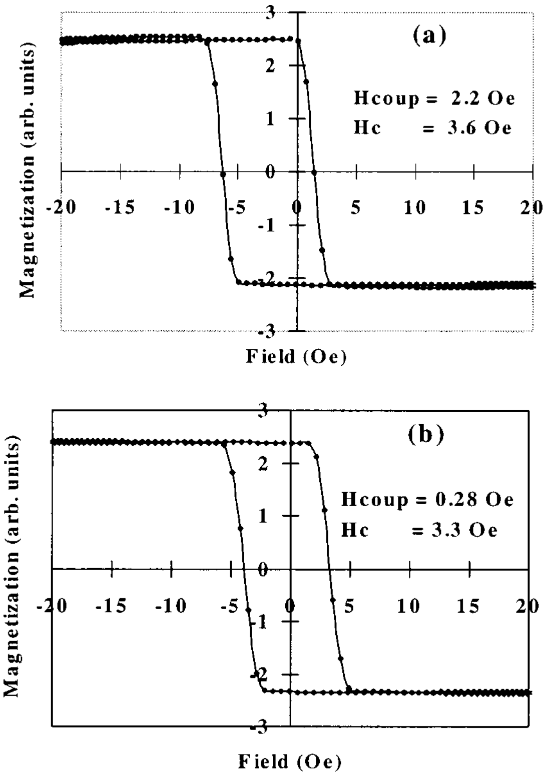

FIG. 1. Magnetic hysteresis loops for a top-pinned (a) regular SDT structure of 12NiFeCo–1.5Al$_2$O$_3$–5.0NiFeCo–35CrPtMn (nm) and (b) an improved SDT structure of 12NiFeCo–1.5Al$_2$O$_3$–1.5NiFeCo–0.9Ru–6.5NiFeCo–0.9Ru–5.0NiFeCo–35CrPtMn.

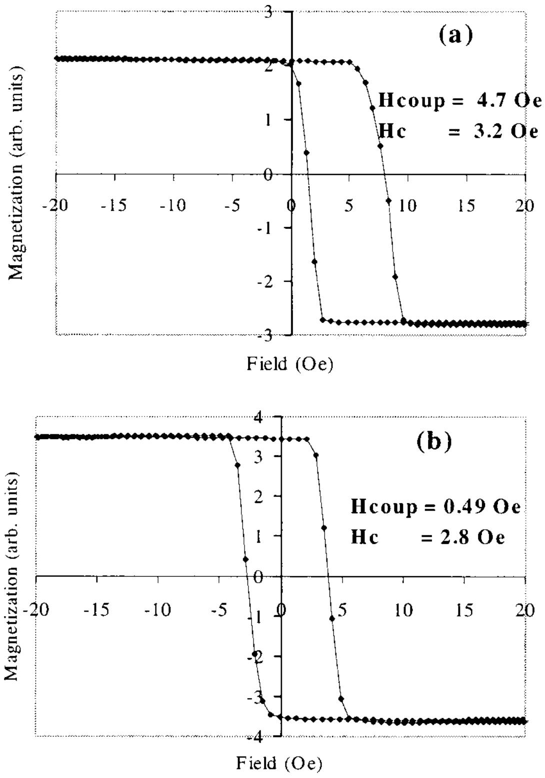

FIG. 3. Hysteresis loops of bottom-pinned (a) regular SDT structure of wafer–4.0NiFeCo–35CrPtMn–5.0NiFeCo–0.9Ru–5.0NiFeCo–1.5Al$_2$O$_3$–12NiFeCo–20Al and (b) improved SDT structure of wafer–4.0NiFeCo–35CrPtMn–5.0NiFeCo–0.9Ru–6.5NiFeCo–0.9Ru–1.5NiFeCo–1.5Al$_2$O$_3$–12NiFeCo–20Al.

NiFeCo layers need to be equal on both sides of the Ru layer, namely a regular SAF structure is needed. Furthermore, there is another requirement of large grains for the antiferromagnetic (AF) layer to have adequate pinning.[8] Large grains for the AF layer can be most readily achieved by using an appropriate buffer layer with enough thickness. This means that the composite pinned layer needs to be thick enough in the case of a top pinned SDT junction. By introducing another Ru/NiFeCo to the conventional SAF pinned layer, all three above-mentioned requirements can be satisfied simultaneously. As a result, the coupling field is reduced to 0.28 Oe for this top pinned SDT structure, as shown in Fig. 1(b). The final SDT structure now becomes wafer–12NiFeCo–1.5Al$_2$O$_3$–1.5NiFeCo–0.9Ru–6.5NiFeCo–0.9Ru–5.0NiFeCo–35CrMnPt, with a schematic shown in Fig. 2. It is noted that in the new SDT structure the FM-$p2$ layer is the same thickness as the sum of the FM-$p1$ and FM-$p3$ layers as shown in Fig. 2, thus achieving a zero net magnetic moment because the adjacent layers are antiparallelly aligned. It is also noted that the ferromagnetic material NiFeCo used can be replaced by any other suitable ferromagnetic materials without changing the discussions here.

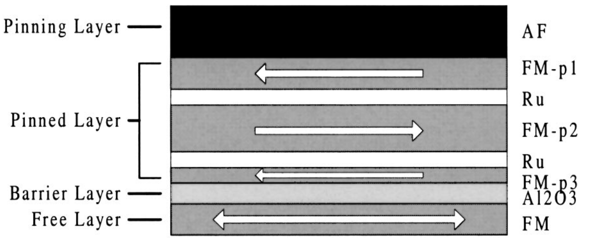

FIG. 2. Schematic of the new SDT structure having a composite top-pinned layer of a modified SAF.

For a bottom pinned SDT structure, the coupling is also reduced using the new structure of wafer–4.0NiFeCo–35CrMnPt–5.0NiFeCo–0.9Ru–6.5NiFeCo5–0.9Ru–1.5NiFeCo–1.5Al$_2$O$_3$–12NiFeCo–20Al. Figure 3 shows the hysteresis loops for such a structure, in comparison with another SDT structure of wafer–4.0NiFeCo–35CrMnPt–5.0NiFeCo–0.9Ru–5.0NiFeCo–1.5Al$_2$O$_3$–12NiFeCo–20Al. The coupling field is reduced from 4.7 to 0.49 Oe using the new structure.

In the following, we will analyze this coupling field reduction using the Neel's coupling model. A schematic is given in Fig. 4(a) depicting such coupling between two ferromagnetic slabs semi-infinitely thick each having an interface with the spacer. The coupling energy density J of the two ferromagnetic layers (saturation magnetization M, M'), separated by a nonmagnetic spacer with thickness t which has a two-dimensional sinusoidal waviness with an amplitude h and a wavelength w, is given in Eq. (1):

$$J=\frac{\pi^2}{\sqrt{2}}\frac{h^2}{w}(\mu_0 M M')e^{-(2\pi\sqrt{2}/w)t}. \tag{1}$$

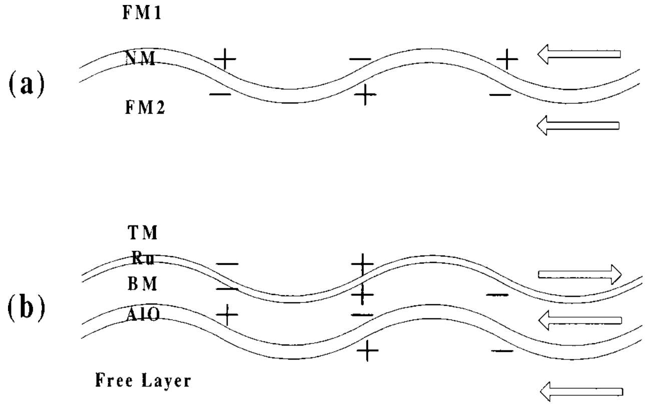

FIG. 4. Schematic of Neel coupling with (a) two semi-infinitely thick ferromagnetic layers FM1 and FM2 and (b) one with a Ru spacer inside the pinned layer.

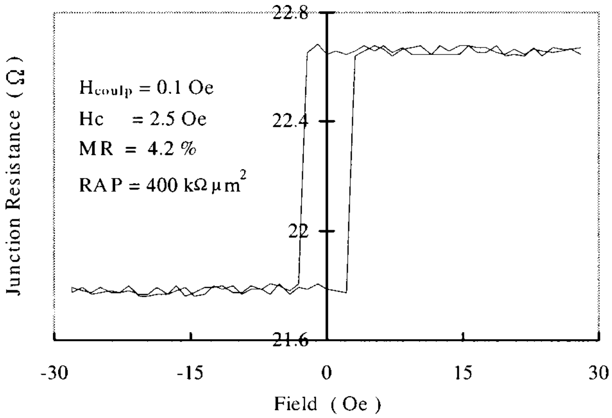

FIG. 5. Magnetoresistance trace of a SDT junction with the improved pinned layer structure of water–12NiFeCo–1.5Al_2O_3–1.5NiFeCo–0.9 Ru–6.5NiFeCo–0.9Ru–5.0NiFeCo–35CrPtMn (in nm).

Here we assume a finite thickness t_{free} for the free layer, the coupling field from the pinned layer interface can be defined by $H_{\mathrm{coup}} = J/(\mu_0 M' t_{\mathrm{free}})$:

$$H_{\mathrm{coup}} = \frac{\pi^2}{\sqrt{2}} \frac{h^2}{w} \frac{M}{t_{\mathrm{free}}} e^{-(2\pi\sqrt{2}/w)t}. \qquad (2)$$

Counting the interactions from the three interfaces in the composite pinned layer closest to the barrier to the top interface of the free layer, as shown in Fig. 4(b), the total coupling field for the new structure can be obtained by superposition $H_{\mathrm{coup}}(t)$ using the three t values. Interactions from other interfaces are ignored because the equivalent t values are much greater, leading to a much smaller effect based on Eq. (2).

Using nominal values of 1000 emu/cc for M, 12 nm for t_{free}, 1.5, 3.0, and 3.9 nm for t for the three interfaces, and forcing the calculated H_{coup} values to be 2.2 and 0.28 Oe as observed in Fig. 1, the two fitting parameters h, w are found to be 0.14 and 20 nm, respectively.

It is noted that Eq. (2) is from an oversimplified model. Two-dimensional sinusoidal contour, single wavelength, and conformal roughness for all interfaces are far from reality. It is also noted that the magnetic roughness may be different from the physical roughness actually observed from the TEM images. Nevertheless, Eq. (2) provides a qualitative guidance in reducing the Neel coupling field considering the inevitable interface roughness for a given SDT structure/material system.

Other magnetoresistive properties of the new structure are expected to be similar to the regular SDT structure, as that only a few atomic layers of ferromagnetic material at the barrier are needed to sustain a high magnetoresistance value.[9] Figure 5 gives a MR plot for a SDT junction with a modified pinned layer structure of 12NiFeCo–1.5Al_2O_3–1.5NiFeCo–0.9Ru–6.5NiFeCo–0.9Ru–5.0NiFeCo–35CrPtMn. It is noted that the coupling field is only 0.1 Oe, within the resolution of field measurement, though the MR value is relatively low for junctions on this wafer. It underlines the importance of depositing thin ferromagnetic (FM) layers with high quality in achieving the best MR properties.

In conclusion, we have demonstrated that it is practical to reduce the coupling field to be less than 1 Oe using a modified SAF structure of FM/Ru/FM/Ru/FM as the pinned layer while still canceling the magnetic moment for the composite pinned layer to achieve low fringe field. This reduction of coupling field can be explained semiquantitatively using Neel's magnetostatic coupling model with a conformal interface roughness.

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