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Influence of the annealing field strength on exchange bias and magnetoresistance of spin valves with IrMn

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We report on field annealing effects in spin valves with an IrMn pinning layer and spin valves with a synthetic antiferromagnet. The exchange bias field and magnetoresistance of spin valves with an IrMn/CoFe bilayer at the bottom improve drastically upon annealing in large magnetic fields. The evolution of the exchange bias field with annealing field strength shows a rapid increase up to an applied field of 0.5 T, which is followed by a more gradual improvement up to an annealing field of 5.5 T. The increase of the exchange bias field in large magnetic fields indicates that the interfacial spin structure of the IrMn layer is directly influenced by the annealing field strength. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1895474]

I. INTRODUCTION

For read head and other magnetic sensor applications, magnetic spin-valve stacks with large exchange bias field (H_{ex}) and high magnetoresistance (MR) values are required. Spin valves with a CoFe/IrMn top layer usually exhibit good magnetotransport characteristics in the as-deposited state, whereas spin valves with an IrMn/CoFe bottom layer normally require magnetic-field annealing to establish a large exchange bias. After magnetic annealing, however, the exchange bias field of bottom-pinned films often exceeds that of top-pinned films.[1–3] The reasons for this discrepancy and, more generally, the origin of the exchange bias effect have been studied in detail. While many groups found a strong correlation between H_{ex} and the degree of crystalline texture,[1–5] others did not find any and they attributed their exchange bias results to the influence of grain size,[2,6–8] interface roughness,[2,9] or magnetic effects[10,11] instead. The magnetic-field annealing experiments in most of these studies focused primarily on the optimization of the annealing time and temperature. On the other hand, the influence of the annealing field strength on exchange bias and MR is less well studied. In fact, it is common practice to anneal spin-valve stacks in relatively small magnetic fields of several hundred mT. In a report on annealing field effects in IrMn systems, van Driel *et al.* showed that the exchange bias field of an IrMn/CoFe bilayer is considerably enhanced after field cooling in 2.5 T instead of 19 mT.[3] Although similar annealing field effects were found for NiFe/CoO bilayers,[12] it is more generally believed that exchange bias is predominantly determined by the magnetization state of the ferromagnetic layer.[13,14]

In this paper we report on the influence of the annealing field strength on the exchange bias and MR of four different types of spin valves. The annealing field in our experiment ranges from 0.05 to 5.5 T. In particular, we find that annealing fields of several tesla improve the magnetotransport properties of spin valves with an IrMn-pinned ferromagnetic layer at the bottom.

II. EXPERIMENT

The spin valves were grown at room temperature by dc magnetron sputtering on SiO_2 substrates in a Shamrock deposition system (base pressure $<10^{-7}$ mbar). To establish exchange bias, the substrates were placed in an in-plane magnetic field of 5 mT during deposition. The deposition rate was determined by x-ray reflectivity measurements on single-layer calibration films. The four different spin-valve structures under investigation are shown in Fig. 1. After

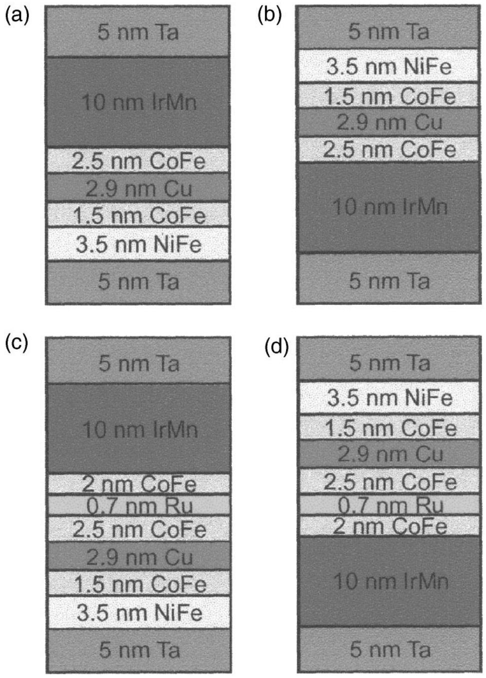

FIG. 1. Spin-valve structures: (a) top spin valve (TSV), (b) bottom spin valve (BSV), (c) synthetic anitiferromagnetic top spin valve (SAFTSV), and (d) synthetic anitiferromagnetic bottom spin valve (SAFBSV).

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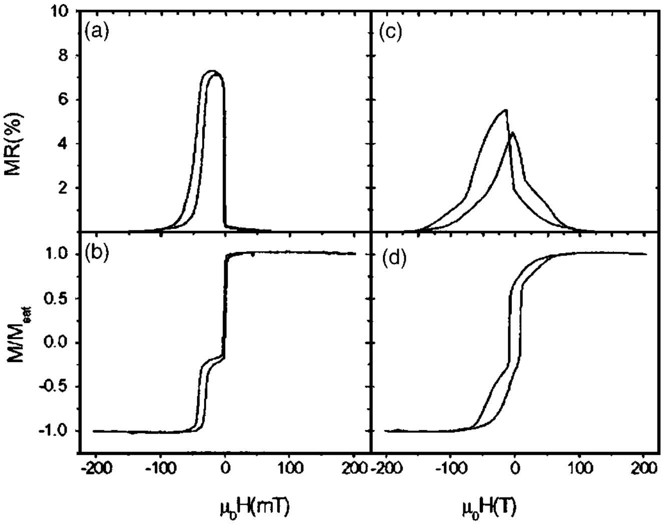

FIG. 2. Magnetotransport and SQUID magnetization curves for the as-deposited TSV [(a) and (b)] and BSV [(c) and (d)] structures.

deposition the samples were annealed in a vacuum furnace (pressure $<10^{-6}$ mbar), which was specifically designed to fit into a superconducting magnet. The annealing temperature and annealing field were varied from 180 to 300 °C and 0.05 to 5.5 T, respectively. The typical temperature and field ramp-up time was 30 min, after which the samples remained at the annealing temperature for 1 h. Thereafter, the samples were field-cooled to room temperature. The annealing field was aligned parallel to the growth-induced exchange bias direction. In-plane magnetoresistance measurements were conducted in standard four-point geometry and magnetization curves were obtained with a superconducting quantum interference device (SQUID) magnetometer. The transport measurements were repeated several times (initial and subsequent hysteresis loops). In all experiments the exchange bias field and coercivity remained constant, i.e., no exchange bias training effects were observed. The crystalline structure of the spin valves was characterized by x-ray diffraction (XRD).

III. RESULTS

The magnetotransport and SQUID data for the as-deposited top spin-valve (TSV) and bottom spin-valve (BSV) structures are shown in Fig. 2. After deposition the top-pinned spin valve exhibits a MR of 7.4% and an exchange bias field of 34 mT. The coercivity of the free NiFe/CoFe bilayer is about 0.25 mT. For the BSV structure the exchange bias field is only 23 mT and the coercivity of the free layer is 7 mT. The drastically smaller difference between H_{ex} and H_C for the bottom-pinned spin valve leads to simultaneous magnetization reversal in the free and pinned ferromagnetic layers and hence to a reduced MR effect of only 5.0%.

Field annealing for 1 h. in a magnetic field of 5.5 T changes the MR and the exchange bias field of both the TSV and BSV structures. Figure 3 shows the dependence of H_{ex} and MR on the annealing temperature. Both the exchange bias field and the MR of the top-pinned spin valve decrease upon magnetic-field annealing. While the exchange bias field is approximately independent of the annealing temperature ($\mu_0 H_{\mathrm{ex}} \approx 25$ mT), the MR decreases monotonically with increasing annealing temperature from 7.3% at 180 °C to 3.5% at 300 °C. Contrary to the TSV structure, the exchange bias field and MR of the bottom-pinned spin valve increase upon magnetic-field annealing. For the BSV structure $\mu_0 H_{\mathrm{ex}} = 40$ mT after annealing at 180 °C, which is larger than the exchange bias field of the TSV structure before annealing. However, above 180 °C the exchange bias field decreases monotonically with increasing temperature and finally it becomes smaller than its preannealing value when the annealing temperature is larger than 270 °C. The MR of the BSV structure is about 8.5% independent of the annealing temperature and the coercivity of the free CoFe/NiFe bilayer is 7 mT.

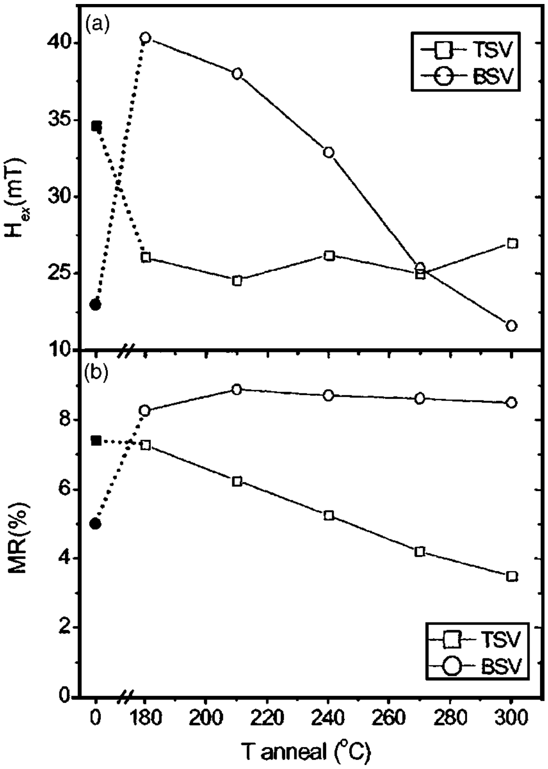

FIG. 3. Annealing temperature dependence of the exchange bias field (a) and MR (b) of the TSV and BSV structures. The annealing field was 5.5 T. The filled symbols indicate the as-deposited values.

To study the influence of the annealing field strength on the exchange bias and MR of spin valves, we fixed the annealing temperature at 210 °C. Figures 4 and 5 compare SQUID magnetization curves and magnetotransport loops for the TSV and BSV structures before and after magnetic-field annealing. The exchange bias field and MR of the top-pinned spin valve decrease upon annealing and the deterioration of the spin-valve properties is similar for annealing in a 0.5 T and 3 T field. The magnetotransport properties of the annealed bottom-pinned spin valve, however, depend strongly on the magnetic-field strength. Although annealing in a field of 0.05 T already improves the MR from 5.0% to 7.8%, it only slightly increases the exchange bias field. The exchange bias field of the BSV structure improves rapidly

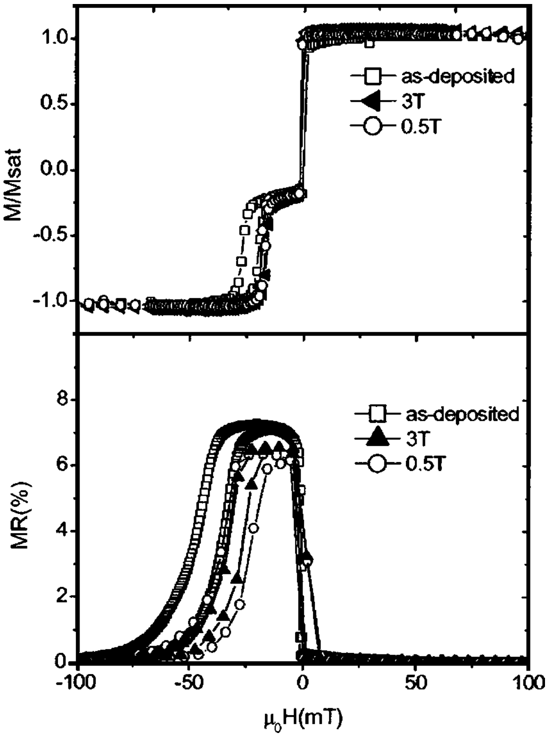

FIG. 4. Normalized magnetization and magnetotransport curves for the TSV structure before and after annealing in different magnetic fields.

with increasing magnetic-field strength up to a field of about 0.5 T. Above 0.5 T the exchange bias field increases more gradually with annealing field and so does the MR. The influence of the annealing field strength on the exchange bias field and MR of TSV and BSV structures is summarized in Fig. 6.

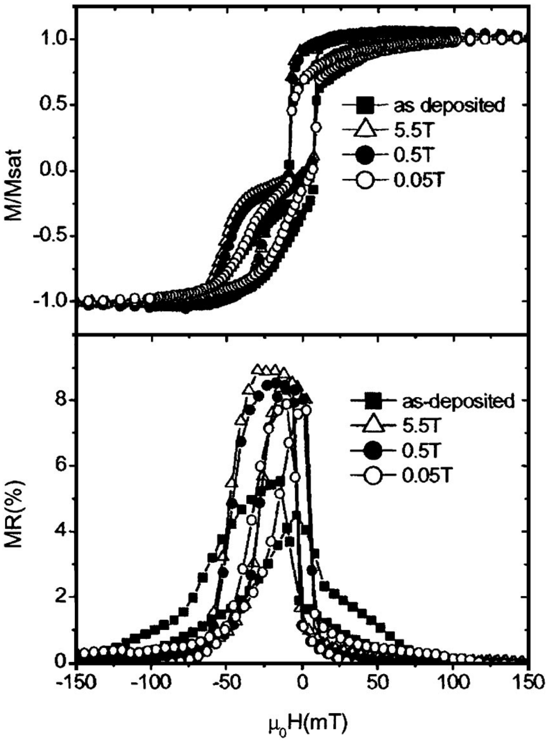

FIG. 5. Normalized magnetization and magnetotransport curves for the BSV structure before and after annealing in different magnetic fields.

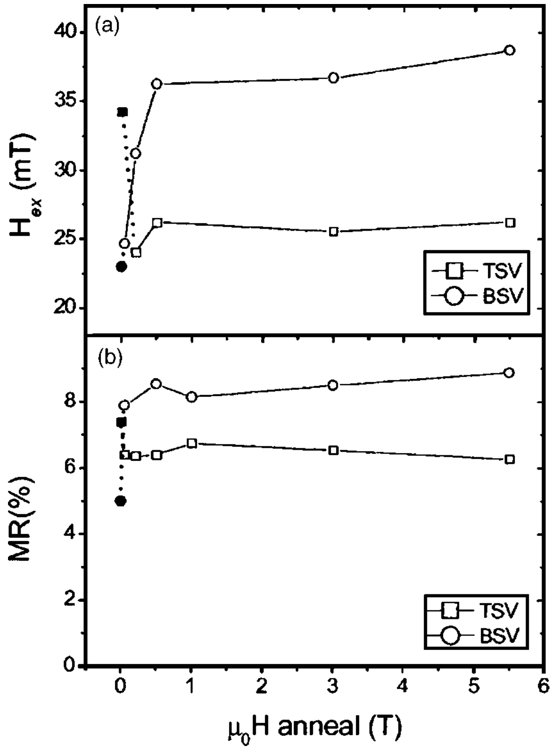

FIG. 6. Annealing field strength dependence of the exchange bias field (a) and MR (b) of the TSV and BSV structures. The annealing temperature was 210 °C. The filled symbols indicate the as-deposited values.

The synthetic antiferromagnet top and bottom spin valve structures were annealed under the same conditions as the spin valves without a synthetic antiferromagnetic layer. The annealing results for different magnetic-field strengths are summarized in Fig. 7. Although the exchange bias field of the top configuration decreases and the MR of the bottom configuration increases upon annealing at 210 °C, the measurements do not reveal any clear annealing field effects.

IV. DISCUSSION

The experiments reveal that the exchange bias field and the MR of the BSV structure are larger than that of the TSV structure after magnetic-field annealing. Although the difference in exchange bias between IrMn bottom-pinned and IrMn top-pinned bilayers has often been attributed to the degree of (111) film texture,[1–5] we found no evidence for this in our experiments. XRD measurements on the annealed samples reveal that the IrMn layer in the TSV structure is (111) textured, but no (111) peaks were measured on the BSV films. This clearly indicates that a (111) crystalline film texture is not a necessary prerequisite for large exchange bias fields. The magnitude of the exchange bias in the TSV and BSV structures is more likely determined by grain size, interface roughness, and defects at the CoFe/IrMn interface and in the IrMn bulk.

Another remarkable difference between the TSV and BSV structures is the dependence of the MR on the annealing temperature. While the MR of the bottom-pinned spin valve is approximately constant for annealing temperatures between 180 and 300 °C, the MR of the top-pinned spin valve decreases rapidly with temperature. Since the MR

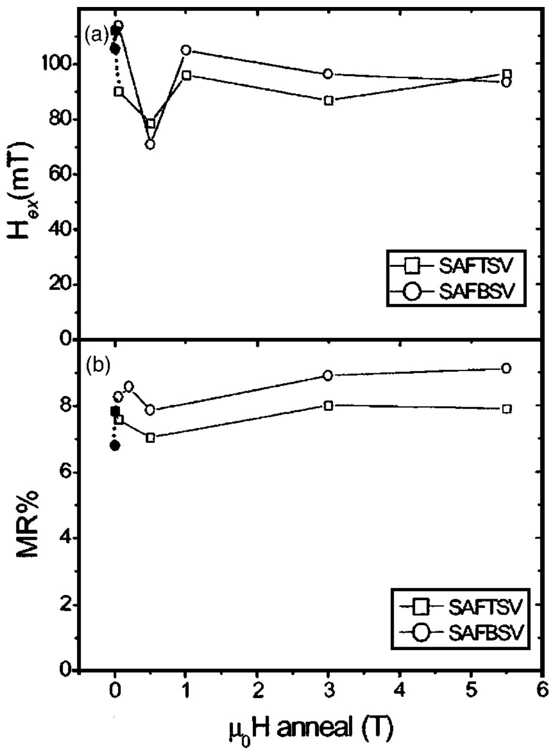

FIG. 7. Annealing field strength dependence of the exchange bias field (a) and MR (b) of the SAFTSV and SAFBSV structures. The annealing temperature was 210 °C. The filled symbols indicate the as-deposited values.

originates predominantly from spin-dependent electron scattering at the CoFe/Cu interfaces, any change in MR indicates a thermal modification of these interfaces. The diffusion of Mn atoms from the IrMn layer to the CoFe/Cu interfaces is a thermally activated process that is different for TSV and BSV structures. Top-pinned CoFe/IrMn interfaces have been found to be less stable against Mn outdiffusion than bottom-pinned IrMn/CoFe interfaces.[15] The decrease of MR for the TSV structure above annealing temperatures of 180 °C can therefore be due to Mn diffusion towards the CoFe/Cu interfaces. A similar Mn-diffusion-related deterioration of the MR has been measured on magnetic tunnel junctions with a CoFe/IrMn top electrode.[16,17]

While the thermal deterioration of the magnetotransport properties dominates any possible magnetic-field effects for the TSV structure, the exchange bias of the BSV structure clearly depends on the annealing field strength. The exchange bias field initially increases rapidly from 23 mT in the as-deposited state to 36 mT after annealing in a field of 0.5 T and this is followed by a more gradual increase to 39 mT for annealing in a field of 5.5 T. The influence of the annealing field strength can be understood by considering the microscopic origin of exchange bias in IrMn/ferromagnetic bilayers. The exchange bias effect in these systems depends on the uncompensated interfacial spin structure in the IrMn layer.[18,19] Spin reversal in the antiferromagnetic layer is thermally activated and therefore it depends critically on the experimental conditions (temperature and field sweep rate) and the energy barrier distribution. At room temperature and at low-field sweep rates only some of the uncompensated spins are pinned, i.e., they do not rotate in an external magnetic field. The coupling between these spins and the spins in the ferromagnetic layer results in a shift in the hysteresis loop. The majority of the uncompensated interfacial spins, however, are not pinned. These spins are dragged along with the magnetization reversal process in the ferromagnetic layer and although they do contribute to an enhanced coercivity, they are not responsible for the exchange bias effect.

The pinned spins are most likely located at the interface defects or grain boundaries, which act as pinning sites for domain walls in the IrMn layer. Consequently, the number of pinned interfacial spins depends critically on interface roughness and grain size.[2,6–9] In addition, dilution and irradiation experiments have shown that the number of defects in the antiferromagnetic layer also influences the domain structure and the exchange bias effect.[20–23] Since the magnitude of the exchange bias field is directly proportional to the pinned uncompensated moment along the bias direction, magnetic-field annealing can change the bias field by modifying the number of pinned spins or realigning the orientation of the spin moment. Thermally activated diffusion changes the number of defects in the IrMn bulk and at CoFe/IrMn interface during annealing at elevated temperatures. This alters the number of pinned uncompensated interfacial spins and therefore the exchange bias field. The annealing field, on the other hand, does not change the number of pinned spins but it can influence the alignment of the spin moment.

Although it is generally found that the antiferromagnetic spin structure is determined mainly by the local moment on the ferromagnetic interface,[13,14] this cannot explain the dependence of the exchange bias field on the annealing field strength. If the ferromagnetic moment determines H_{ex}, saturation of this moment during field cooling would result in maximum exchange bias. Since the saturation field of the CoFe layer is considerably smaller than 0.05 T, annealing in this field would already maximize the exchange bias field. As can be seen in Fig. 6, this is clearly not the case for the BSV structure. Obviously, the application of a larger magnetic field during cooling directly influences the alignment of the uncompensated interfacial spins in the IrMn layer. The component of the interfacial spin moment along the annealing field direction increases with increasing field strength and after freezing some of these interfacial spins during the field cooling procedure it results in an enhanced exchange bias field.

For the spin valves with a synthetic antiferromagnet the exchange bias field depends on the antiferromagnetic coupling between the two CoFe layers that are separated by the Ru spacer and not on the exchange coupling at the CoFe/IrMn interface. Changes in the spin structure of the IrMn layer do not therefore affect the exchange bias and hence no dependence of H_{ex} on the annealing field strength is measured (see Fig. 7).

V. CONCLUSION

We have shown that magnetic annealing in large fields enhances the exchange bias and MR of IrMn bottom-pinned spin valves. The dependence of the exchange bias field on the annealing field strength can be split into two regimes: For annealing fields up to 0.5 T the exchange bias field increases rapidly from 23 to 36 mT. Above 0.5 T the enhancement is more gradual and the exchange bias field reaches 39 mT after annealing in a field of 5.5 T. The annealing field effects for the IrMn bottom-pinned spin valves are attributed to a realignment of the pinned interfacial spins in the IrMn layer. The application of a large magnetic field during cooling increases the component of the pinned interfacial moment along the field direction and this results in a larger exchange bias. For IrMn top-pinned spin valves and spin valves with a synthetic antiferromagnet no clear magnetic-field effects were measured. For top-pinned spin valves the study on the annealing field effects is complicated by a thermal deterioration of the magnetotransport properties during annealing and for spin valves with a synthetic antiferromagnet the pinning strength does not depend on the spin structure in the IrMn layer.

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