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Doubly exchange-biased NiCoO/NiFe/Cu/NiFe/NiCoO spin valves

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A new type of doubly exchange-biased $Ni_{50}Co_{50}O$/NiFe/Cu/NiFe/$Ni_{30}Co_{70}O$ spin-valve structure, with two ferromagnetic layers exchange biased in opposite directions by two different antiferromagnetic layers is demonstrated. By field cooling in magnetic fields of opposite directions, the resultant hysteresis loop consists of two loops shifted in opposite directions from the zero magnetic field. The NiFe layers are in the antiparallel state in zero magnetic field, and the switching to the parallel state can be tuned by varying the exchange bias. The modified spin valves also show potential for suppressed Barkhausen noise.
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Spin valves are the most important devices that brought the giant magnetoresistance (GMR) effect to applications.[1] In prototype GMR systems with multilayers[2] or granular solids,[3] a magnetic field of at least a few kilo-oersteds is needed to realize a significant GMR. It is the spin-valve structure that enables the GMR effect to be achievable in a small magnetic field of less than 100 Oe, thus making it useful for applications, such as in the new generation of GMR read heads. Intense research efforts on the improvement of spin valves have centered on the enhancement of the GMR effect size, currently about several percent. These efforts have primarily focused on improving sample preparation conditions,[4] adjusting the interfacial scattering between layers,[5] and optimizing post annealing treatments.[6] In addition, new developments such as the dual spin-valve structures[7] have shown promising results with GMR values of 25%.[4] While the GMR value has continued to increase due to the aforementioned efforts, less attention has been given to the development of other potential device structures with new attributes. In this work, we explore a new type of spin-valve structure that exhibits good field sensitivity and low Barkhausen noise. Furthermore, this spin valve is a prototype magnetic switch that can be tuned for use in different field ranges.

A conventional spin valve is a four layer structure consisting of two ferromagnetic (FM) layers sandwiching a nonmagnetic (NM) spacer layer, and an antiferromagnetic (AF) layer used to pin one of the FM layers through exchange bias. The NM spacer layer separates the two FM layers from any interlayer coupling. Hence the pinned FM layer is magnetically hard while the unpinned FM layer is soft and free to switch in a small external field. The general principle for operating this device is to obtain two distinct spin states where in the first state the FM layers are aligned antiparallel to each other, and in the second state parallel to each other. The switching between the two magnetic states is realized by an external magnetic field, which simultaneously produces a change in the device resistance. However, in this configuration, since the resistance change is dictated by the reversal of the unpinned FM layer, the useful range of field sensing is restricted by the coercive field (H_c) of the unpinned FM layer. This constraint limits the usefulness of the spin-valve devices. In this work we describe a device with a second antiferromagnetic layer, along with a specific post annealing process, allowing the establishment of the antiparallel state in zero magnetic field. The switching of the states now no longer directly depends on H_c of the FM layers and the thickness of the NM spacer layer.

Our modified spin-valve structure is shown in Fig. 1(a), consisting of two pinned FM layers on both sides of the Cu spacer layer. We denote entities associated with the top AF/FM and the bottom FM/AF bilayer with the subscripts 1

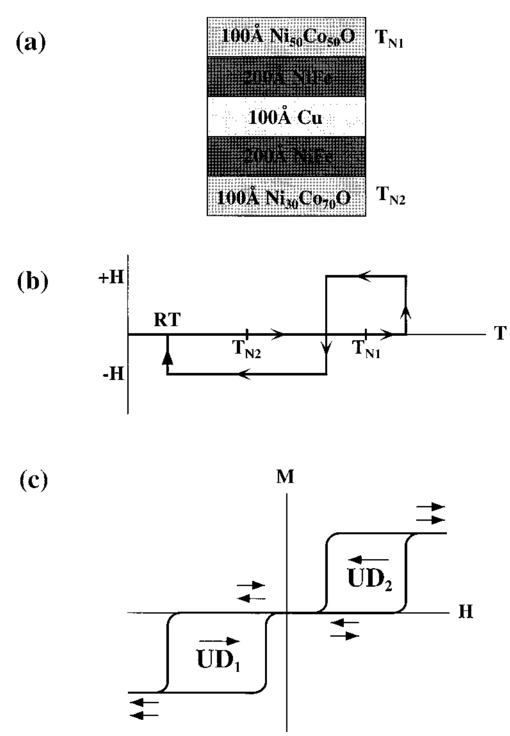

FIG. 1. (a) Modified spin-valve structure with two different Néel temperatures (T_{N1} and T_{N2}), (b) a schematic representation of the post annealing sequence used to establish exchange biasing, and (c) the expected hysteresis loop consisting of two loops shifted in opposite directions from zero magnetic field.

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and 2, respectively. The most distinct feature is that top AF layer possesses a different Néel temperature (T_N) from that of the bottom AF layer. We chose the $Ni_xCo_{100-x}O$ as the AF layers due to the ease of altering T_N by the composition.[8] In the structure shown in Fig. 1(a), the top AF layer has a Néel temperature ($T_{N1} \sim 135\,°C$) higher than that of the bottom AF layer ($T_{N2} \sim 80\,°C$). These features allow for cooling through two T_N's with magnetic fields in opposite directions.

The sample was grown by magnetron sputtering onto a Si (100) substrate at room temperature in a 5 mTorr Ar atmosphere. The substrate was mounted on a computer-controlled platform allowing for deposition from four sputtering sources. The two AF layers (100 Å $Ni_{50}Co_{50}O$ and 100 Å $Ni_{30}Co_{70}O$) were grown by radio frequency sputtering from cold pressed composite targets at a power of 75 W. The NiFe layers, deposited in an external magnetic field of 200 Oe, and the Cu layer were grown using direct current sputtering.

In Fig. 1(b), the post annealing sequence is graphically shown. Starting from room temperature (RT), the spin valve is first heated to a temperature above both T_N's. A positive magnetic field is then applied and the sample is cooled to an intermediate temperature between T_{N1} and T_{N2}. This establishes a unidirectional (UD_1) anisotropy in the top FM layer. The magnetic field is then switched to the negative direction and the sample is cooled through T_{N2} down to RT. The bottom FM layer now has a unidirectional (UD_2) anisotropy opposite in direction to that of UD_1.

As a result of the two exchange-biased FM layers, we can expect the hysteresis loop shown in Fig. 1(c), where both layers exhibit individual hysteresis loops shifted away from the origin along the field axis. Due to the nature of the exchange bias, the loop from the top FM layer is shifted to the left of the origin, while that from the bottom layer shifted to the right. The amount of shift is dependent upon the exchange bias, which can be varied in a number of ways. It has been shown that the deposition order of the layers,[9] the magnitude of the cooling field,[10] and the thickness of both the FM[11] and AF[12,13] layers contribute to the strength of the exchange bias. However, to simply illustrate the operation of this structure, we limit ourselves to varying only one parameter, the cooling field strength, to control the strength of the exchange bias. We demonstrate two different hysteresis loops which have been obtained from the same sample, but with different cooling fields.

We first show in Fig. 2 the hysteresis loop and the corresponding magnetoresistance (MR) curves of the modified spin-valve structure. The post annealing sequence was as follows. The sample was initially heated from RT to 140 °C in an Ar atmosphere. A positive field of 10 kOe was then applied and the sample was cooled down to 60 °C. At this point, the field was switched to a negative value of −40 Oe, at which the sample was further cooled down to RT. The entire annealing process lasted only a few minutes. After annealing, the sample was measured in a vibrating sample magnetometer at RT and the results are shown in Fig. 2(a).

In contrast to conventional spin-valve structures, the hysteresis loop in Fig. 2(a) clearly shows two loops shifted in opposite directions from zero magnetic field, the same as that depicted in Fig. 1(c). The coercivity H_c of the two subloops are about 15–20 Oe, much larger than the few oersteds seen in unpinned soft NiFe layers. The loop shift, known as the exchange field (H_E), and the enhanced coercivity H_c are signatures of the exchange bias. For this annealing sequence, the top FM layer has an exchange field (H_{E1}) of +35 Oe (shifted to the left) while the bottom FM layer has a H_{E2} of −25 Oe (shifted to the right). Although the top AF/FM bilayer was cooled in a field 250 times larger than that for the bottom FM/AF bilayer, the magnitude of H_E for both are similar.

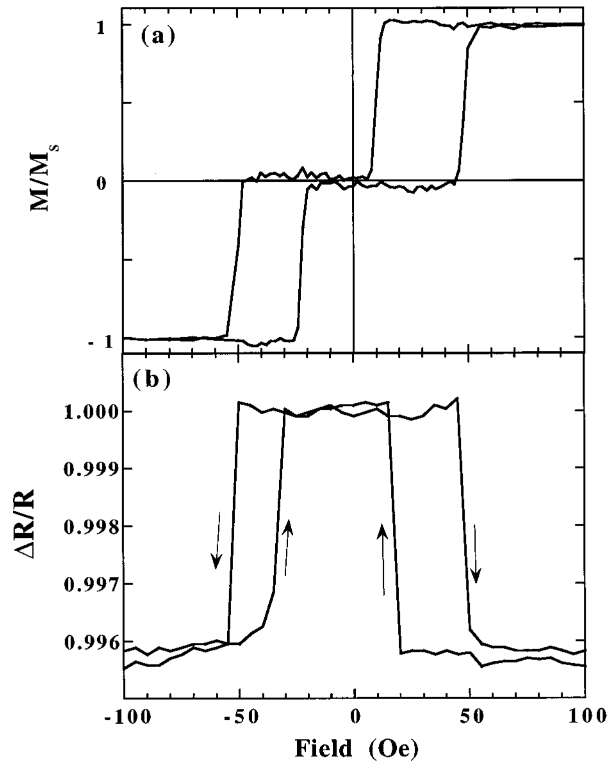

FIG. 2. (a) Magnetization and (b) magnetoresistance as a function of the applied magnetic field after the post annealing sequence of field cooling at 10 kOe from 140 to 60 °C, followed by field cooling at −40 Oe from 60 °C to RT.

An appropriate value of the second cooling field has to be judiciously chosen to maximize the relative shift between the two hysteresis loops. It is well known that in exchange-biased AF/FM bilayers, H_E vanishes at a temperature slightly below T_N known as the blocking temperature, T_B.[13] At a temperature near T_B, applying a large magnetic field in opposition to the unidirectional anisotropy can alter the exchange field.[14] In this work, the antiferromagnets, $Ni_{50}Co_{50}O$ and $Ni_{30}Co_{70}O$, have blocking temperatures around 80 and 45 °C, respectively. This difference in the blocking temperatures allows the establishment of the opposite exchange bias. The selection of AFs with relatively low values of T_B also avoids high temperature field annealing to establish the exchange bias, which may damage the layer structure. In our spin-valve structure, the second cooling field value of −40 Oe is small but adequate to shift the bottom FM layer a considerable amount without disturbing

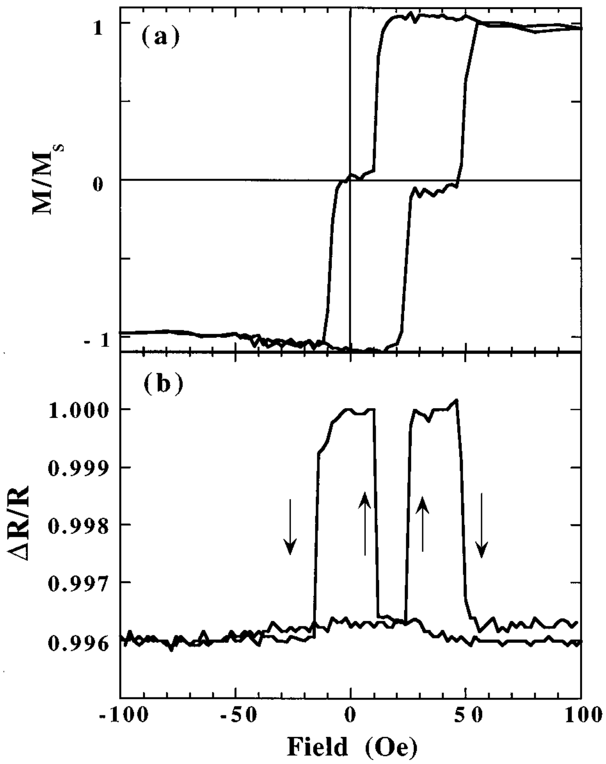

FIG. 3. (a) Magnetization and (b) magnetoresistance as a function of the applied magnetic field after the post annealing sequence of field cooling at 10 kOe from 140 to 60 °C, followed by field cooling at −100 Oe from 60 °C to RT.

the exchange field of the top FM layer. However, if the second cooling field value is increased from −40 to −100 Oe, for example, the resultant hysteresis loop is very much altered. This is shown in Fig. 3(a) where both loops are shifted to the right of the origin along the field axis. In this case, the top FM layer has an H_{E1} value of −8 Oe and the bottom FM layer has an H_{E2} value of −30 Oe.

The MR of the modified spin-valve structure with the above post annealing sequences has been measured at RT, using a standard four-probe method. As shown in Figs. 2(b) and 3(b), the high and low resistance states correspond to the antiparallel and parallel spin states of the FM layers. The expected MR characteristics are observed in both cases. Since the relatively thick FM layers were intended for magnetometry studies, they are not optimized for larger MR values. Nevertheless, all the essential MR properties have been illustrated.

Finally we mention some additional features in our modified spin valves. First, by varying the strength of the exchange bias in the two FM layers by means of the cooling field, one can dictate the spin valve to switch from a parallel to an antiparallel spin state at various field values including zero field. Therefore the same modified spin valve can be tuned to be more sensitive in specific magnetic field regions. Second, exchange bias of the FM layers stabilizes magnetic domains, which reduces the number of Barkhausen jumps associated with magnetization reversal, thereby reducing the overall noise in the device. Third, since both layers of the modified spin valve are exchanged biased, the switching between spin states is more abrupt, leading to a sharper resistive transition as well, or a higher field sensitivity.

In summary, we have demonstrated a new type of spin-valve structure with an additional AF layer. Using a specific post annealing sequence, the top and bottom FM/AF bilayers are cooled in opposite magnetic fields, establishing two opposite unidirectional anisotropies. The resultant hysteresis loop is made up of two individual loops which are shifted along the field axis but in opposite directions. In this configuration, we can obtain an antiparallel spin state at zero magnetic field. These results also show potential for increased field sensitivity and reduced device noise due to the doubly exchange-biased FM layers.

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[1] B. Dieny, V. S. Speriosu, S. S. P. Parkin, B. A. Gurney, D. Wilhoit, and D. Mauri, Phys. Rev. B **43**, 1297 (1991).
[2] M. N. Baibich, J. M. Broto, A. Fert, F. N. V. Dau, F. Petroff, P. Etienne, G. Crevzet, A. Friederich, and J. Chazelas, Phys. Rev. Lett. **61**, 2472 (1988).
[3] A. E. Berkowitz, J. R. Mitchell, M. J. Carey, A. P. Young, S. Zhang, F. E. Spada, F. T. Parker, A. Hutten, and G. Thomas, Phys. Rev. Lett. **68**, 3745 (1992); J. Q. Xiao, J. S. Jiang, and C. L. Chien, *ibid.* **68**, 3749 (1992).
[4] W. F. Egelhoff *et al.*, J. Appl. Phys. **79**, 5277 (1996).
[5] H. Kano, K. Kagawa, A. Suzuki, A. Okabe, K, Hayashi, and K. Aso, Appl. Phys. Lett. **63**, 2389 (1993).
[6] R. D. McMichael, P. J. Chen, and W. F. Egelhoff, IEEE Trans. Magn. **34**, 897 (1998).
[7] T. C. Anthony, J. A. Brug, and S. Zhang, IEEE Trans. Magn. **30**, 3819 (1994).
[8] M. Takano, T. Terashima, Y. Band, and H. Ikeda, Appl. Phys. Lett. **51**, 205 (1987).
[9] T. Ambrose and C. L. Chien, Appl. Phys. Lett. **65**, 1967 (1994).
[10] T. Ambrose, K. Leifer, K. J. Hemker, and C. L. Chien, J. Appl. Phys. **81**, 5007 (1997).
[11] C. Tsang, N. Heiman, and K. Lee, J. Appl. Phys. **52**, 2471 (1981).
[12] P. J. Van der Zaag, A. R. Ball, L. F. Feiner, R. M. Wolf, and P. A. A. van der Heiden, J. Appl. Phys. **79**, 5103 (1996).
[13] T. Ambrose and C. L. Chien, J. Appl. Phys. **83**, 6822 (1998).
[14] V. S. Speriosu, D. A. Herman, Jr., I. L. Sanders, and T. Yogi, IBM J. Res. Dev. **34**, 884 (1990).