Memory effects of exchange coupling in CoO/$Ni_{81}Fe_{19}$ bilayers

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By changing the field-cooling procedure, the value and even the sign of the exchange field H_E in CoO/$Ni_{81}Fe_{19}$ bilayers can be greatly altered. The value of H_E can be made to vanish at any temperature below T_N. We also show that the magnetization of the $Ni_{81}Fe_{19}$ is the crucial parameter in the field-cooling procedure. Changing the magnetization during field cooling shows that the exchange bias is an accumulative memory effect, dependent on the thermal and field history of the bilayer. The enhanced coercivity which accompanies the exchange bias, depends only on temperature and not on the field-cooling history. © *1999 American Institute of Physics.* [S0021-8979(99)38208-6]

An exchange coupling between an antiferromagnet (AF) and a ferromagnet (FM) in a FM/AF bilayer causes the hysteresis loop of the FM layer to shift from the $H=0$ axis by the amount known as the exchange field (H_E), after the bilayer has been field cooled below the Néel temperature (T_N) of the AF.[1] The exchange-coupled FM layer also exhibits a larger coercivity (H_c) than that of the uncoupled FM layer. Numerous experiments have shown that both the values of H_E and H_c decrease with increasing temperature.[2–7] The value of H_E vanishes, and that of H_c retains its uncoupled FM value at the so-called blocking temperature T_B. For some AF (e.g., CoO), the value of T_B and T_N are essentially the same, whereas in others (e.g., NiO) T_B can be significantly lower than T_N.[3]

In establishing the exchange coupling, it is necessary to cool the FM/AF layer in a magnetic field, most commonly in a dc magnetic field from $T>T_N$ to lower temperatures in order to establish a unidirectional anisotropy. We show in this work that the exchange bias can be greatly modified by altering the cooling process, in which the magnetization of the FM layer, and not the magnetic field, is of crucial importance. Most importantly, we show that the exchange coupling retains a memory of the field-cooling procedure.

Bilayer samples of CoO/Py, where Py=$Ni_{81}Fe_{19}$, were made in a magnetron sputtering system with a base pressure of 8×10^{-8} Torr. The samples were sputtered at room temperature in 6 mTorr Ar onto Si substrates. The constituent layers of the samples are Si/CoO(370 Å)/Py(175 Å)/Au(50 Å) with a [111] preferred orientation. The Py layer was deposited in a magnetic field to induce an easy axis. Magnetic hysteresis measurements were made in a vibrating sample magnetometer. The uncoupled Py layer displays a square loop with a small coercivity.

It is essential to specify the conditions with which the bilayer was cooled in establishing the exchange coupling. While a dc magnetic field would assure a full magnetization (M_s) of the FM layer during the field-cooled (FC) operation, the FM layer can have various values of magnetization (M) under the zero-field-cooled (ZFC) scheme, ranging from essentially M_s in the remnant state to $M=0$ when the FM has been demagnetized. We used three procedures for field cooling: (1) FC at 200 Oe with $M=M_s$, (2) demagnetize the FM layer at $T>T_N$ with $M=0$, and then ZFC, (3) FC in an ac magnetic field of 200 Oe oscillating at 1/4 Hz with a time-varying M averaged to 0.

To illustrate the importance of the cooling procedures, the CoO/Py bilayer was measured at 200 K under the three procedures mentioned above. Using the usual FC procedure (1) results in a shifted hysteresis loop ($H_E\approx100$ Oe) and an enhanced coercivity ($H_c\approx45$ Oe), as shown in Fig. 1(a). Uncoupled $Ni_{81}Fe_{19}$ has no exchange bias ($H_E=0$ Oe) and only a small coercivity ($H_c\approx3$ Oe). Under the ZFC procedure (2), after demagnetization and *zero*-field cooling, there are *two* loops shifted to opposite sides as shown in Fig. 1(b). This is because the FM layer has formed a closure domain structure with domain magnetizations in opposite directions. Although the sample was ZFC, it is as if two samples were FC with opposite magnetic fields. Under the procedure (3), when the bilayer was cooled in a 200 Oe *oscillating* field at 1/4 Hz, the resultant loop had *no* exchange field ($H_E\approx0$) and only an enhanced H_c, as shown in Fig. 1(c). Because the magnetization in the FM layer was changing, there was no preferred direction with which to induce a FM/AF exchange coupling. The oscillating field method can completely suppress the exchange bias. These results illustrate clearly that the state of the magnetization of the FM is of crucial importance during cooling.

To further explore the establishment of the exchange bias, the sample was first cooled in an oscillating field from 300 K (above T_N) to a temperature T_s, then field cooled in a dc field of 200 Oe from T_s to 200 K. The first part of the cooling process was designed to suppress, and the second part to introduce, exchange bias. A series of measurements were then made at increasing temperatures from 200 K. The results at various temperatures with different T_s are shown in Fig. 2. For example, when the sample was cooled to $T_s=260$ K in an oscillating field, and then field cooled in 200 Oe from 260 to 200 K, the exchange bias at 200 K is no longer zero. For increasing temperature, the exchange bias decreases and vanishes at 260 K, the *same* as that of T_s, and remains zero at $T>T_s$. Similar results for other values of T_s are also shown in Fig. 2. The bilayer exhibits exchange bias for $T<T_s$, but no exchange bias for $T_s<T$. When $T_s>T_N$, i.e., the usual field cooling condition, exchange bias exists at all temperatures less than T_N. These results demon-

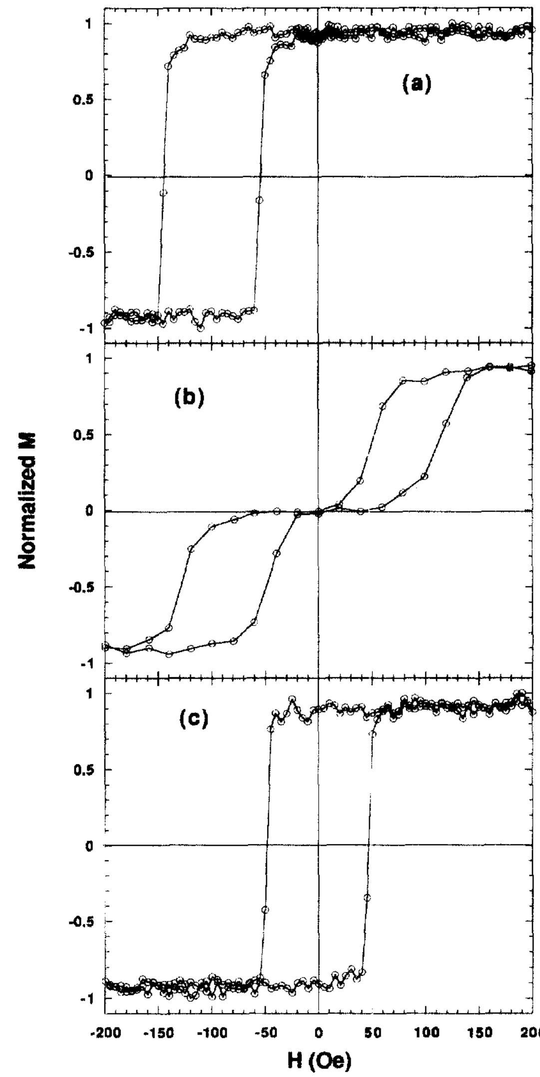

FIG. 1. Magnetic hystereses of a CoO/Py bilayer at 200 K; (a) after field cooling the sample from 300 K in a 200 Oe field; (b) after demagnetizing the sample at 300 K, and zero field cooling to 200 K, and (c) cooling the sample in a 200 Oe oscillating field (1/4 Hz) from 300 to 200 K.

strate that the bilayer sample has the *memory* of the cooling procedure and the temperature T_s at which the dc cooling field was switched on; *and* the memory that at $T>T_s$, there was no exchange bias.

It is also noted in Fig. 2 that the lower the value of T_s, the lower the value of the resultant exchange field H_E. This is just another manifestation of the memory effect of the exchange coupling. The full strength of the echange field requires field cooling throughout the entire temperature range from T_N. We have thus demonstrated that the exchange bias can be locked in and suppressed at *any* temperature below T_N, and furthermore, the value of exchange field can acquire *any* value less than the maximum allowed at that temperature by full field cooling.

To investigate the memory effect of exchange coupling in a different way, we have studied the consequence of reversing the direction of the dc field during cooling. The sample was cooled in +200 Oe field to a temperature T_q, at which the field was changed to −200 Oe, before cooling from T_q to 200 K, i.e., FC in a positive field at $T>T_q$, and

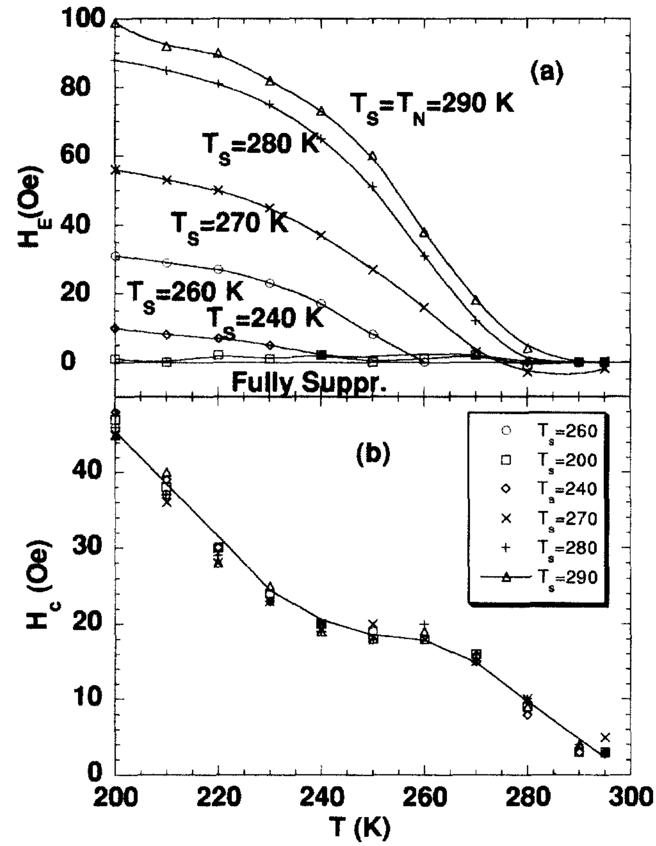

FIG. 2. Temperature dependence of (a) H_E and (b) H_c for a CoO/Py bilayer, after cooling in a 200 Oe oscillating field from 300 K to T_s and field cooled in a 200 Oe field from T_s to 200 K.

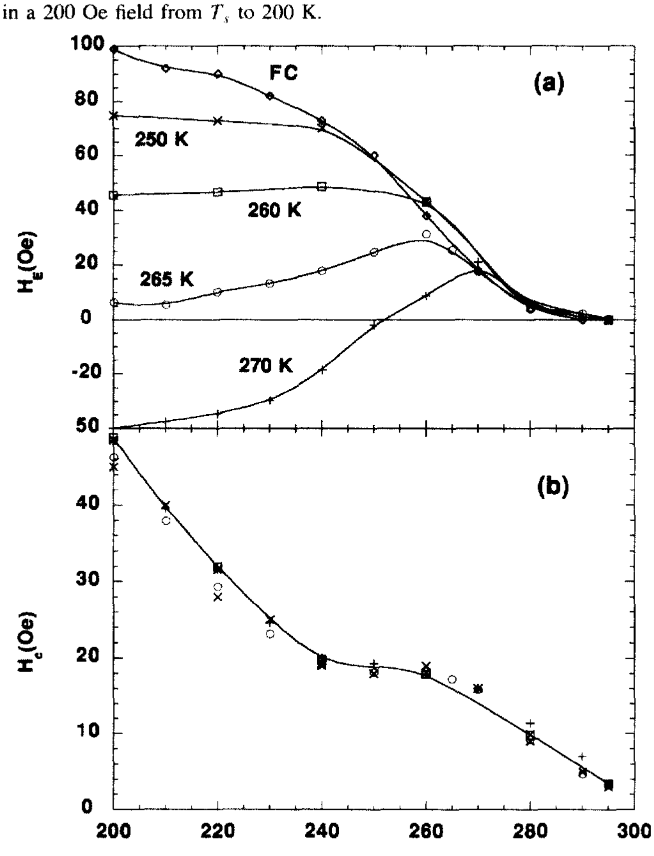

FIG. 3. Temperature dependence of (a) H_E and (b) H_c for a CoO/Py bilayer, after field cooling in a 200 Oe field from 300 K to T_q and in −200 Oe from T_q to 200 K. The numbers in the graph indicate T_q, the temperature at which the field was switched.

FC in a negative field at $T<T_q$. Measurements were then made at increasing temperature from 200 K. The results are shown in Fig. 3, where the data with a usual FC procedure with a positive field are labeled FC. Consider the case with $T_q=260$ K, for example. The value of H_E in the negative FC range ($200\,\mathrm{K}<T<T_q$) now *increases* with increasing temperature, before reverting to decreasing with temperature in the positive FC range ($T>T_q$). For a sufficiently high T_q (e.g., 270 K) the value of H_E can even change sign. These results again demonstrate clearly that the bilayer has the *memory* of a positive FC in $T>T_q$, followed by a negative FC in $200\,\mathrm{K}<T<T_q$.

Most remarkably, while the values of exchange field can be altered to such a great extent, the value of coercivity is *uniquely* defined at every temperature, regardless of the value of H_E, nor the different thermal and field cycles, as shown in Figs. 2(b) and 3(b). This indicates that the value of the coercivity is linked to the intrinsic exchange coupling, unaffected by the field cooling procedure which shifts the location of the loop, thus the value of H_E, but not the width of the loop, which is H_c.

The observed memory effect of the exchange coupling has both scientific and technological importance. Theoretical models of exchange coupling have focused on the interactions at $T<T_N$ among the magnetic moments, the spin structure, anisotropy, and the domain structures of the FM and AF layers.[8–10] We show that the resultant exchange coupling depends on the entire thermal and field history from T_N to the measurement temperature, not merely on crossing the Néel temperature in a magnetic field. The memory effect also has technological implications. We show that to lock in an exchange coupling, e.g., in spin-valve devices, it is not necessary to FC from above T_N. Instead, exchange coupling can be obtained by FC from any temperature, below which exchange coupling would occur.

In summary, we have shown that the state of the magnetization of the FM is the crucial parameter in establishing the exchange bias. The exchange bias can be modified greatly in its value and sign by changing the field-cooling procedure. Furthermore, the bilayer system retains a memory of the entire field-cooling procedure. While the exchange bias can be manipulated, the coercivity always maintains a unique value at a given temperature.

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