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Tunable thermal hysteresis in CoGd alloys

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We show that tunable magnetic thermal hysteresis can be realized for a simple ferrimagnetic CoGd alloy. The magnetization of a $Co_{0.8}Gd_{0.2}$ alloy shows a bow-tie curve as a function of temperature, which indicates supercooled and superheated phase transitions. The width of the magnetic thermal hysteresis can be *tuned* by an external magnetic field, with values of 190 K at fields near 100 Oe and values of 20 K near 400 Oe. Experimental results are in reasonable agreement with theoretical calculations. © *2005 American Institute of Physics*. [DOI: 10.1063/1.2132530]

There have been a number of recent investigations into tunable thermal hysteresis in magnetic multilayer systems.[1–3] The thermal hysteresis occurs between two stable magnetic states and can be exceptionally large, spanning up to 200 K. In addition, the thermal hysteresis can be dramatically tuned or eliminated by changing a small external magnetic field. These studies have concentrated on multilayers made of alternating films of transition metals and the rare-earth metal Gd. Such a two-state tunable system could be employed in a nonvolatile magnetic memory, however the operational temperature in the previous studies centered around 200 K.

In this letter we report on tunable thermal hysteresis in a CoGd alloy.[4–10] Alloys can have a number of technological advantages over multilayer systems. First, multilayers systems often depend sensitively on the properties of the interfaces, for example the degree of intermixing or the smoothness of the interface.[11] Second, multilayer systems can be nonuniform since one film may be slightly thicker or thinner than an equivalent film in a different portion of the structure. Third, multilayer systems may have large surface effects,[12–14] since films at the surfaces do not have the same exchange coupling as those in the central portion. Finally, we note that the operational temperature for thermal hysteresis in the CoGd alloy is centered around room temperature, well above that found in the multilayer system. In fact, small changes in composition could easily move the operational temperature to 400 K.

The thermal hysteresis depends on the existence of two stable states at the same temperature. In the alloy, Co and Gd moments have strong antiferromagnetic exchange coupling and are arranged antiparallel to each other.[15,16] The first state is a Co-aligned state where the Co magnetization is aligned with the external field and the Gd is opposite. There is also a Gd-aligned state[17–24] where the Gd magnetization is aligned with the external field and Co is opposite. At high temperatures the system is in the Co-aligned state; the Gd moments, which are small, are oppositely directed to the field. As the temperature decreases the Gd moments increase in their thermal averaged magnitude and the net magnetic moment can actually be opposite to the external field if some anisotropy holds the spins in place. Eventually, however, this configuration becomes unstable and the structure reverses with the Gd moments along the field and the Fe moments antiparallel to the applied field. A similar situation occurs on heating the system from low temperatures.

Samples were prepared in a dc magnetron sputtering system at room temperature. They were deposited on Corning glass substrates and 20-nm-thick Ag layers were used as buffer and cap layers. Deposition thicknesses were monitored *in situ* using a quartz thickness monitor calibrated by a stylus profilometer. 20 nm $Co_{0.8}Gd_{0.2}$ alloy was created by codeposition from pure Co and Gd targets. Magnetization (thermal hysteresis) measurements in the temperature interval 10–390 K were taken using a superconducting quantum interference device magnetometer starting from 390 K under a constant in-plane external magnetic field (100–800 Oe). The temperature is first reduced to 10 K and then increased back to 390 K. The temperature sweep rate was 10 K/min.

In Fig. 1, magnetization versus temperature is shown for a 2-nm-thick $Co_{0.8}Gd_{0.2}$ alloy for different values of the external magnetic field. In Fig. 1(a) the system at 390 K is originally in a Co-aligned state at 100 Oe and remains in this state as the temperature is reduced to 160 K. Magnetic anisotropy stabilizes the structure so that a negative magnetization[25,26] is observed. Below 160 K, the structure switches from the Co-aligned to the Gd-aligned configuration. Positive total moment is attained around 120 K and becomes more positive as the temperature is reduced. On heating from 10 K, the Gd-aligned state is stable up to 340 K exhibiting a negative total moment above 300 K. Around 340 K, the system switches back to its initial Co-aligned configuration. The resulting "bow-tie" shape is characteristic for the thermal hysteresis. The thermal hysteresis width, defined as the temperature interval between the minima of the bow-tie curve, spans over 190 K for a 100 Oe external magnetic field. For 200 Oe and higher external magnetic fields the width decreases as the field increases, but retains the bow-tie shape as shown in Figs. 1(b) and 1(c). At 800 Oe, as shown in Fig. 1(d), the bow-tie vanishes.

The theoretical calculations are based on a mean field approach.[27,28] An individual Co spin feels a net effective magnetic field, $\vec{H}_{Co}$, which is produced by the external field,

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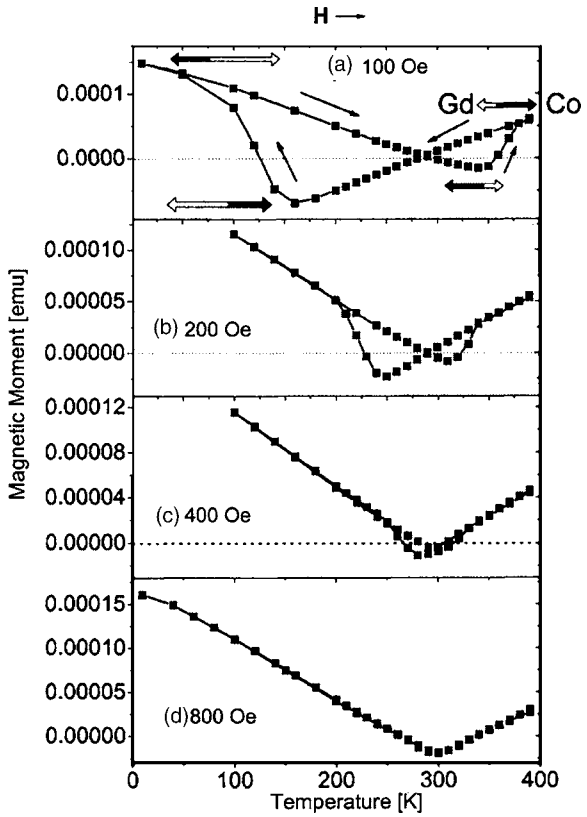

FIG. 1. Thermal hysteresis with increasing external magnetic fields for 2-nm-thick $Co_{0.8}Gd_{0.2}$ alloy. The Co and Gd magnetization directions are shown as black and white arrows, respectively. The external magnetic field, **H**, points to the right as shown.

H, the anisotropy field (assumed to be uniaxial), H_a, and the exchange field from neighboring Co and Gd spins.

$$\vec{H}_{\mathrm{Co}} = H\hat{z} + H_a\langle m^z{}_{\mathrm{Co}}\rangle/m_{\mathrm{Co}} + J_I\langle\vec{m}_{\mathrm{Gd}}\rangle n_{\mathrm{Gd}} + J_{\mathrm{Co}}\langle\vec{m}_{\mathrm{Co}}\rangle n_{\mathrm{Co}}. \tag{1}$$

Here J_I is the effective exchange coupling between a Gd and a Co spin, J_{Co} is the exchange coupling between Co spins, and n_{Gd} and n_{Co} given the number of nearest neighbor Gd and Co spins, assuming a random distribution. A similar equation is used to find the effective field acting on the Gd spins. The direction and thermal averaged Gd and Co moments, $\langle\vec{m}_{\mathrm{Gd}}\rangle$ and $\langle\vec{m}_{\mathrm{Co}}\rangle$, are then found by an iterative process. An initial direction is chosen for Co and Gd moments, the effective fields for each spin is calculated and then used to find the new directions of the magnetic moments and the thermal averaged moments through the Brillouin function, e.g., $\langle m_{\mathrm{Co}}\rangle = g\mu_B S_{\mathrm{Co}} B_S(g\mu_B S_{\mathrm{Co}} H_{\mathrm{Co}}/kT)$. These new thermal averaged moments are then used, in turn, to find new effective fields. The process continues until a self-consistent state evolves.

Exchange parameters for the calculation are chosen to match the bulk behavior of the individual materials. We take $g=2$, $S_{\mathrm{Co}}=0.63$, $S_{\mathrm{Gd}}=3.5$, $\mu_B J_{\mathrm{Gd}}=3.56\times10^4$ Oe, $\mu_B J_{\mathrm{Co}}=1.53\times10^6$ Oe and $\mu_B J_I=-1.51\times10^5$ Oe. The ratio of the exchange values is close to the values used by Mansuripur in earlier mean-field calculations[27] for CoGd alloys. Furthermore, the magnetic moment on the Co atoms is reduced to about 73% of its usual bulk moment, again in agreement with Mansuripur.[27] The anisotropy field is 19 Oe in the Co, a value close to numbers found in multilayer systems. The fraction of Gd is 22.8% and Co is 77.2%, close to experimental values. We note that changes of 1% in the composition may vary the compensation temperature by over 50 K in the theoretical calculations.

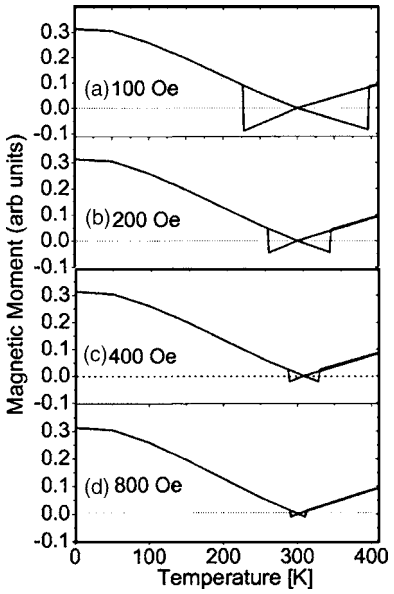

FIG. 2. Theoretical calculations for magnetization as a function of temperature for 2-nm-thick $Co_{0.772}Gd_{0.228}$ alloy. The theory is in good agreement with experimental results of Fig. 1.

As seen in Fig. 2, theoretical calculations are in reasonable agreement with experimental results. The compensation temperature, the temperature at which the net moment of the Gd spins is equal and opposite to that of the Co spins, is at 300 K in agreement with the experiment. In addition, the bow-tie shape, and the decrease in the width of the thermal hysteresis as the applied field is increased are all reproduced by the theoretical calculations. The differences between experiment and theory may be due to changes in anisotropy fields with temperature which are not included in the theory.

We note that we have also performed calculations where S_{Co} has its bulk value and J_I was about four times larger. In this case, the overall fit for M vs T does not match the experiment quite as well, but the general trends seen in Fig. 2 could be reproduced with this alternate parameter set. Thus we conclude that the appearance and behavior of the bow-tie is not an oddity of a particular parameter choice.

In Fig. 3, the width of the bow-tie curves for 2 nm $Co_{0.8}Gd_{0.2}$ alloy is shown as a function of external magnetic field. The width of the bow-tie decays exponentionally with increasing external magnetic field. In addition the theoretical results for $Co_{0.772}Gd_{0.228}$ alloy are also shown. Good agreement is seen between experiment and theory.

As shown in Fig. 4, the measured and the theoretical results for the coercive field, H_C, of 2 nm $Co_{0.8}Gd_{0.2}$ alloy show an asymptotic maximum as a function of temperature near T_{comp}. Coercive field measures how easy it is to reverse the magnetization. The field at which this reversal takes place depends on the competition between the anisotropy energy, which would like to hold the moments in their current positions, and the Zeeman energy of the net moment in the applied field. So as the net moment decreases (near the compensation point) the anisotropy energy wins out and it takes a larger field to reverse the spins. The agreement between experiment and theory is reasonable, especially con-

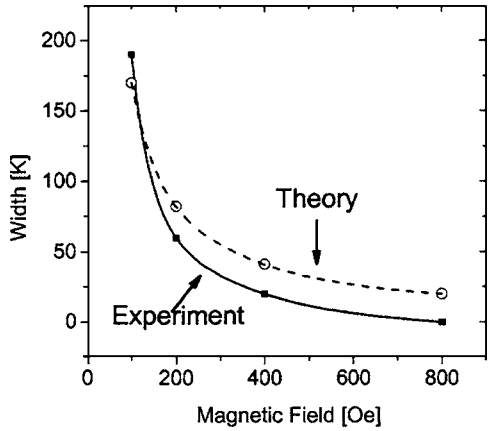

FIG. 3. Width (temperature interval between the minima) of the thermal hysteresis as a function of the external field for 2 nm $Co_{0.8}Gd_{0.2}$ alloy. The theory for $Co_{0.772}Gd_{0.228}$ alloy is shown by the dashed line.

sidering that coercive field can depend on domain wall motion and nucleation sites not included in this calculation.[29]

A single parameter used in the calculations for anisotropy, H_a, does a good job of explaining both the thermal hysteresis and the coercivity, indicating that one mechanism is responsible for both effects. This suggests that systems which show the coercive behavior seen in Fig. 4 could also show tunable thermal hysteresis as discussed here. However, it may not be that simple. In multilayer work it has been seen that thermal hysteresis occurs only for a narrow range of H_a values. If H_a is too large then the system remains in either the Gd-aligned state or the Co-aligned state as the temperature is changed. This can be seen, for example, in Fig. 1(a) of Ref. 2.

In conclusion, CoGd alloys show large thermal hysteresis. The width of the thermal hysteresis can be *tuned* to have values between 0 and 190 K by moderate changes in the applied external magnetic field. Experimental results are in reasonable agreement with theoretical calculations. The midpoint of the thermal hysteresis is at 300 K, but calculations and previous studies have shown that this can easily be adjusted by small changes in the composition of the alloy. The temperature dependence of the coercive field is also explained using the same theoretical model as is used for the thermal hysteresis.

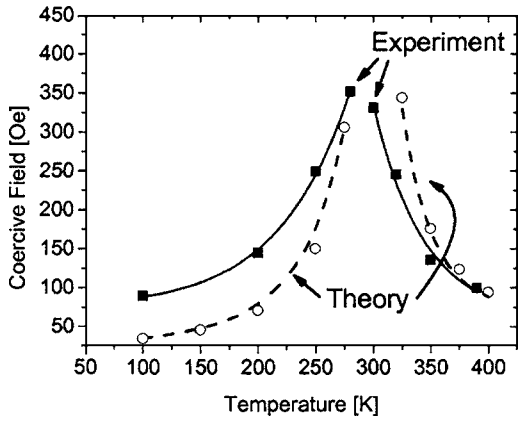

FIG. 4. Coercive field as a function of temperature for 2 nm $Co_{0.8}Gd_{0.2}$ alloy, experiment and theory ($Co_{0.772}Gd_{0.228}$) are both shown.

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