Exchange coupling between Cr and ferromagnetic thin films

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Exchange bias has been observed in $Ni_{81}Fe_{19}$/Cr bilayers. The exchange bias field for Cr thickness t_{Cr} larger than 62 Å increases with t_{Cr} and levels off at $t_{Cr}=150$ Å, whereas coercivity increases without saturation. The blocking temperature increases with the Cr thickness. Due to the presence of commensurate spin density waves in the thicker but strained Cr layers, blocking temperature as much as 425 K has been observed. Exchange bias has also been observed in Co/Cr bilayers. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1544473]

The antiferromagnetism in chromium (Cr) was first predicted by Néel in 1936, but not confirmed by neutron diffraction until 1953.[1] Since its discovery, there has been persistent interest in the study of Cr. Unlike the antiferromagnetic (AF) ordering of the localized moments in common antiferromagnets, such as CoO and MnO, Cr is an itinerant antiferromagnet with spin density waves (SDW). Neutron diffraction and other studies have revealed a wealth of fascinating properties, among them, the propagation of longitudinal and transverse SDW along special crystal directions.[2,3] The Néel temperature of bulk Cr has been found to be $T_N=311$ K.

The antiferromagnetism in Cr thin films and Cr surfaces also exhibits many interesting properties. Although measurements more sensitive to thin films are required. For example, domain imaging of ferromagnetic (FM) layers on top of Cr, hysteresis measurements of FM/Cr heterostructures, and very recently, AF domain imaging using x-ray microdiffraction, have been reported.[4] In a different context, Fe/Cr multilayers have been featured prominently in recent years because of the realization of oscillatory interlayer coupling, a phenomenon that led to the discovery of giant magnetoresistance (GMR) effect first observed in Fe/Cr multilayers.[5–8]

The exchange bias in FM/AF layer systems has been intensely studied in recent years driven by the intriguing physics and its central role in spin-valve based devices.[9,10] A wide variety of AF layers, such as CoO, NiO, FeMn, PtMn, etc., have been employed in exchange bias. Conspicuously lacking are the studies of exchange bias in FM/Cr bilayers despite numerous studies exploring the interlayer coupling and the GMR in FM/Cr multilayers. Previously, Berger and Hopster observed a change of coercivity in Fe films on Cr(100) substrate near $T=130$ K due to the transition from longitudinal to transverse SDW AF.[11] In this work, we report the studies of exchange bias in FM/Cr bilayers. Exchange bias can not only be well established in FM/Cr despite the itinerant nature of Cr, the results also suggest that exchange bias can be profitably exploited to explore the rich phenomena of the SDW antiferromagnetism in Cr thin films.

Most of the studies involve Py(100 Å)/Cr bilayers with Py$=Ni_{81}Fe_{19}$ made on Si substrates using magnetron sputtering with a base pressure better than 7×10^{-8} Torr. The substrate temperature was kept at room temperature. Several wedge samples were made to cover the thickness range of the Cr layer (t_{Cr}) up to 350 Å in order to investigate the dependence of exchange bias on the thicknesses of Cr. We have also studied samples of Py(t_{Py})/Cr(350 Å), in which the Py thickness t_{Cr} has been varied. Finally, a few samples of Co/Cr bilayers were also made to confirm the exchange coupling between Cr and Co. Vibrating sample magnetometry was used to measure the hysteresis loops. During the measurement, the samples were cooled from 373 to 100 K in an in-plane magnetic field of 1 T.

Three representative hysteresis loops for a Py(100 Å)/Cr(250 Å) bilayer at $T=100$, 200, and 325 K are shown in Fig. 1. These hysteresis loops are rather square. The magnetic switching occurs in a narrow field range, indicating that exchange bias axis is along the field cooling direction. As expected, the values of the exchange bias field H_E and coercivity H_C decrease with increasing temperature. These results clearly demonstrate that exchange bias has been established in Py/Cr, even though Cr is a SDW antiferromagnet.

We next investigate the onset of exchange bias and its dependence on the Cr layer thickness t_{Cr}. At 100 K, no measurable exchange bias field H_E was observed for t_{Cr} up to about 60 Å. Exchange bias field appears at $t_{Cr}=62$ Å with a magnitude of -0.47 Oe (shift to the left) at $T=100$ K. The value of H_E of thicker Cr layers increases and levels off to about -10 Oe at $t_{Cr}\approx150$ Å as shown in Fig. 2(a). The observed dependence of H_E on the AF thickness is similar to those of Py/FeMn and Py/CoO bilayers. However, the critical AF thickness of 62 Å for Py/Cr at $T=100$ K is considerably larger than the value of 25 Å in Py/FeMn at room temperature and 32 Å in Py/CoO at $T=100$ K.[12,13] This may be

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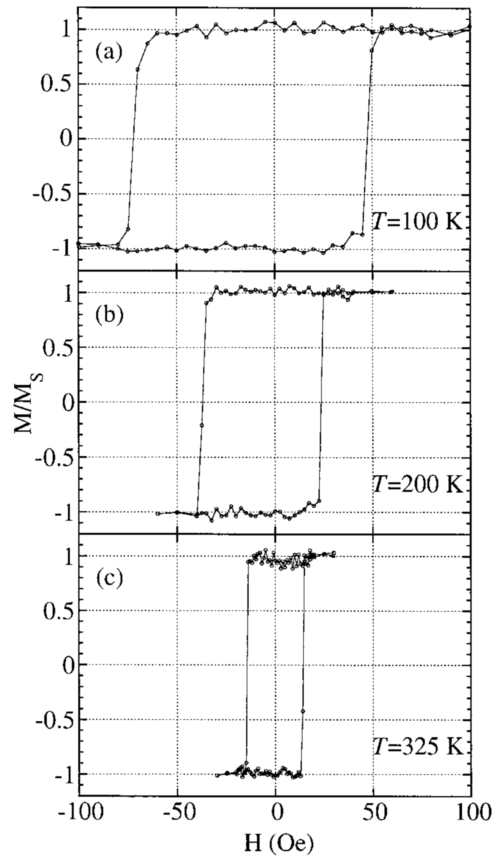

FIG. 1. Representative hysteresis loops of Py(100 Å)/Cr(250 Å) bilayer at $T=$(a) 100 K, (b) 200 K, and (c) 325 K.

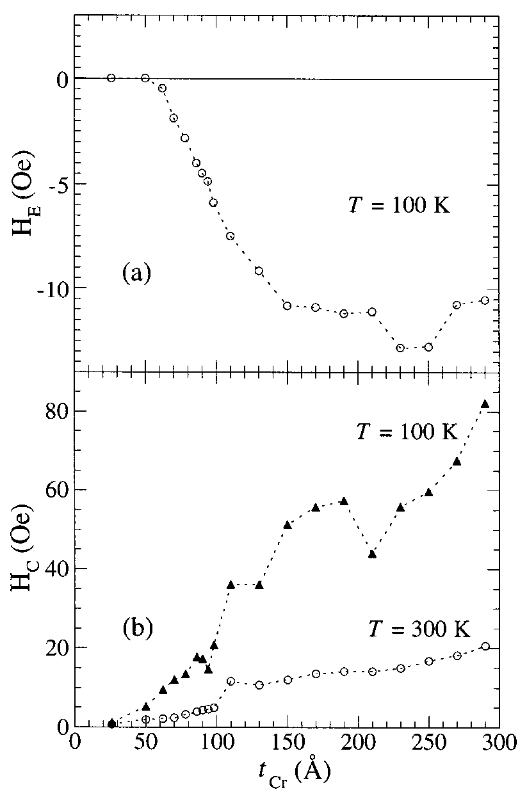

FIG. 2. The values of (a) exchange bias field (H_E) and (b) coercivity (H_c) of Py(100 Å)/Cr(t_{Cr}) bilayers at various Cr thicknesses t_{Cr} at 100 K [open circles (○)] and 300 K [solid triangles (▲)].

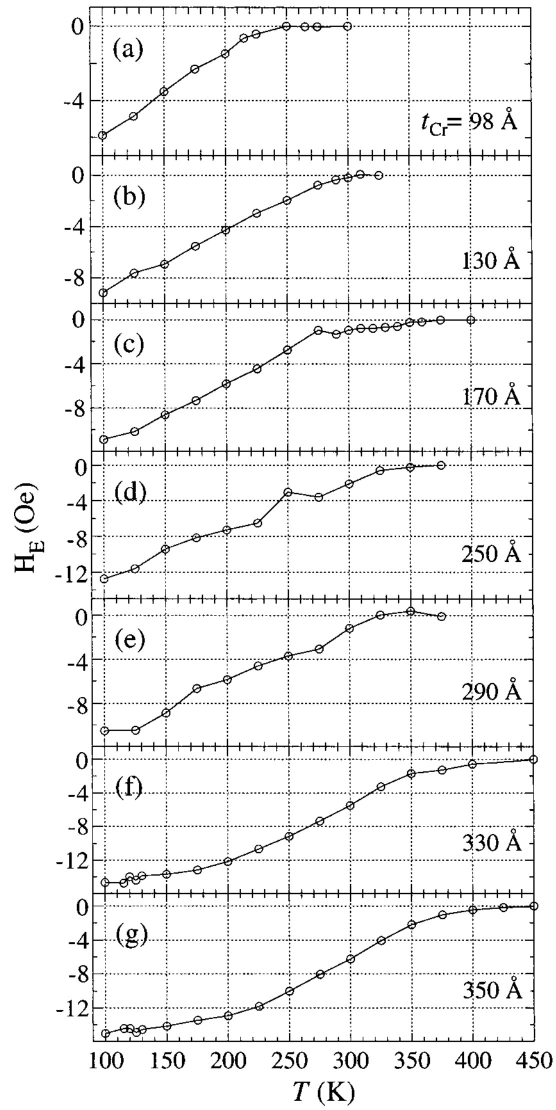

FIG. 3. Temperature dependence of H_E for Py(100 Å)/Cr(t_{Cr}) bilayers with $t_{Cr}=$(a) 98 Å, (b) 130 Å, (c) 170 Å, (d) 250 Å, (e) 290 Å, (f) 330 Å, and (g) 350 Å.

the result of the SDW antiferromagnetic ordering and a weaker antiferromagnetic anisotropy in Cr.

Another important consequence of exchange bias is the enhancement of coercivity.[9] The coercivity H_C of a free Py(100 Å) is about 0.5 Oe. The value of H_C increases monotonically with t_{Cr} starting at about 50 Å, as shown in Fig. 2(b). At $t_{Cr}=300$ Å, the value of H_C has increased to about 20 Oe at $T=300$ K and 80 Oe at $T=100$ K. Within the thickness range studied, the value of H_C increases with no sign of saturation even after H_E has leveled off. The data shown in Fig. 2 were taken using samples from three wedged specimens covering approximately the thickness range of 0–100 Å, 100–200 Å, and 200–300 Å of t_{Cr}. While the consistency of H_C within each wedge specimen is preserved, there are differences between the wedged specimens.

The temperature dependence of H_E for samples with various t_{Cr} is shown in Fig. 3. For all the samples, the magnitude of H_E monotonically decreases with increasing temperature and becomes zero at a temperature commonly known as the blocking temperature T_B. As shown in Fig. 3, the value of T_B increases with the Cr thickness t_{Cr}, from $T_B \approx 250$ K at $t_{Cr} = 98$ Å to $T_B \approx 425$ K at $t_{Cr} = 350$ Å. This variation of T_B may be related to the finite size effect of the AF layers.[13] However, the more unusual result is the fact that the values of T_B of the bilayers with thick Cr layers have exceeded the Néel temperature of 311 K of bulk Cr.

It is well known that the SDW AF ordering in Cr, particularly in Cr thin films, is highly susceptible to strain. The AF ordering in Cr can be driven from incommensurate SDW to commensurate SDW by strain.[2,3] The commensurate AF phase of Cr has a Néel temperature of 475 K, much higher than the value of 311 K for the incommensurate SDW AF phase. In the present studies of exchange bias in Py/Cr, we have observed T_B as high as 425 K for $t_{Cr} = 350$ Å. Since strains commonly exist in thin polycrystalline films, the thin Cr layers in Py/Cr bilayers probably include both incommensurate SDW AF phase and the commensurate AF phase, hence a higher value of T_B. These results also suggest exchange bias may be exploited to reveal characteristics of SDW in antiferromagnetic Cr.

To further establish exchange bias in Py/Cr bilayers, we have also studied the dependence of exchange bias on the FM thickness. For Py/Cr(350 Å) bilayers with various Py thicknesses, H_E is inversely proportional to the thickness of Py layer, with the values of −18.8, −11.0, and −8.0 Oe at 100 K for Py thicknesses of 44, 108, and 188 Å, respectively. The coercivity of these Py/Cr(350 Å) bilayers also decreases with increasing FM thickness. These characteristics on the FM thickness have been observed in many other FM/AF bilayer systems. We have also observed exchange bias in Co/Cr bilayers. For example, Co(94 Å)/Cr(350 Å) and Co(46 Å)/Cr(350 Å) exhibit exchange bias field of −8.6 and −12.0 Oe at 100 K, respectively. The dependence of H_E on the magnetization of the FM, M_{FM}, and the thickness, t_{FM}, of the FM layer follows the relation $H_E \propto [M_{FM} \cdot t_{FM}]^{-1}$, which is generally realized in most of the FM/AF exchange-coupled systems. The coercivity in the Co/Cr bilayers is much larger due to the larger magnetic anisotropy in Co. Thus, it appears that exchange bias in FM/Cr can be generally accomplished,

In summary, despite the fact that Cr is an itinerant antiferromagnet with spin density wave ordering, exchange bias has been established in a number of Py/Cr and Co/Cr bilayers. The onset of exchange bias at 100 K occurs at a Cr thickness of $t_{Cr} = 62$ Å. The magnitude of H_E increases with t_{Cr} and levels off at $t_{Cr} = 150$ Å, whereas that of the coercivity H_C increases with t_{Cr} without showing sign of saturation. The blocking temperature has been found to increase with the Cr thickness to as high as 425 K for $t_{Cr} = 350$ Å, probably due to the appearance of commensurate AF phase in strained Cr layer.

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