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Exchange coupling in ferromagnetic/antiferromagnetic/ferromagnetic $[Pd/Co]_n$/NiO/Co trilayers with different [Pd/Co] anisotropy

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ABSTRACT

Exchange coupling in NiO/Co bilayers and $[Pd/Co(t_{Co})]_n$/NiO/Co trilayers prepared by magnetron sputtering has been investigated. With decreasing thickness (t_{Co}) of the Co layers in [Pd/Co] multilayers (MLs) and increasing number of [Pd/Co] repeats (n), the ferromagnetic easy axis of the [Pd/Co] MLs switches from in-plane to out-of-plane direction. Ferromagnetic and non-collinear interlayer couplings between the [Pd/Co] MLs and the Co layer across the antiferromagnetic NiO spacer are found in trilayers. After cooling at in-plane and out-of-plane remanent state, respectively, for $t_{Co}=1$ nm and $n=2$, a larger in-plane exchange bias field of 724 Oe is observed which vanishes at temperatures above 90 K which is the same as the in-plane blocking temperature observed in the NiO/Co bilayer. For $t_{Co}=0.3$ nm and $n=7$, the in-plane blocking temperature in the trilayer enhances up to 210 K, which strongly depends on orientation and strength of the ferromagnetic [Pd/Co] ML anisotropy axis.

1. Introduction

The exchange bias (EB) effect [1], typically resulting from the exchange coupling at the interface between ferromagnetic (FM) and antiferromagnetic (AFM) materials, has attracted wide interest due to both the theoretical significance and the important role in spin-valve and magnetic random-access memories [2–5]. When a FM/AFM system is field cooled through the AFM Néel temperature T_N or deposited under the influence of an in situ magnetic field, a unidirectional exchange anisotropy can be established due to the exchange coupling at the interface between a FM and an AFM material. Experimentally, the EB effect manifests itself as a displacement of the hysteresis loop along the magnetic field axis and an increase in loop width. The magnitude of this displacement is frequently taken as a measure of the exchange field or exchange bias H_E. In the past decades, a large amount of experimental and theoretical work has been undertaken to discern the nature of the exchange coupling at the FM/AFM interface [6–8]. Although various theoretical models have been proposed to explain the EB effect, they are challenged by emerging experimental results.

So far, in the FM/AFM bilayers, exhibiting in-plane or out-of-plane anisotropy, the EB effects have been extensively studied [9–12]. The EB effects in more complex $FM_1/AFM/FM_2$ trilayers also have attracted much interest, mainly due to the presence of two FM/AFM interfaces [13–15]. In particular, interlayer coupling between two FM layers across an AFM spacer has been observed (ferromagnetic, antiferromagnetic, non-collinear), resulting in interesting phenomena [16–20]. A spiral spin structure across the AFM FeMn layer was observed in NiFe/FeMn/Co trilayers [16]. Also, propagation of the EB behavior between two FM_1/AFM and AFM/FM_2 interfaces across the AFM order in CoFe/FeMn/CoFe trilayer has been found [17]. In addition, an enhanced in-plane blocking temperature was observed in $FM_1/AFM/FM_2$ heterostructures with mutually orthogonal easy axes [18,19]. Although the EB effects in $FM_1/AFM/FM_2$ trilayers have been explored to some extent, the effect of varying the FM_1 layer anisotropy on the interlayer and interfacial exchange coupling in $FM_1/AFM/FM_2$ trilayers has not been systematically investigated.

In this work, $[Pd/Cot_{Co}]_n$/NiO/Co trilayers, with t_{Co} the thickness of the Co layers in the [Pd/Co] multilayer (ML) and n the number of [Pd/Co] repeats, have been prepared by dc and rf magnetron sputtering. The effects of varying the FM anisotropy of the [Pd/Co] ML on the interlayer and interfacial exchange coupling have been investigated in [Pd/Co]/NiO/Co trilayers.

2. Experimental details

Four samples have been prepared by dc and rf magnetron sputtering from separate commercial Ta, Pd, Co, and NiO targets with 99.99% purity on Si substrates. The Ar pressure during deposition was 4×10^{-3} Torr, and the base pressure before

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deposition was about 2×10^{-7} Torr.

Sample 1: Si/Ta(10)/Pd(10)/NiO(4)/Co(3)/Ta(10);
Sample 2: Si/Ta(10)/Pd(10)/[Pd(1)/Co(1)]$_2$/NiO(4)/Co(3)/Ta(10);
Sample 3: Si/Ta(10)/Pd(10)/[Pd(1)/Co(0.5)]$_4$/NiO(4)/Co(3)/Ta(10);
Sample 4: Si/Ta(10)/Pd(10)/[Pd(1)/Co(0.3)]$_7$/NiO(4)/Co(3)/Ta(10) (unit: nm).

In the [Pd(1)/Co(t_{Co})]$_n$/NiO/Co trilayer series, the [Pd/Co] ML was selected as the FM layer because the ferromagnetic easy axis can be tailored by varying the thickness of the Co layers (t_{Co}) and the number of [Pd/Co] repeats (n) [21–24]. The crystal structure was analyzed by X-ray diffraction (XRD) which revealed that the Pd and NiO layers are highly face-centered-cubic (FCC) (111) textured and that the Co layers are hexagonal-close-packed (200) textured. Magnetization measurements were carried out in a superconducting quantum interference device magnetometer (SQUID). The hysteresis loops were measured at different temperatures after cooling in the remanent state. The magnetization direction of the FM layer during field cooling determines the anisotropy axis of the AFM layer and the unidirectional exchange coupling. The samples are cooled at the remanent state in order to distinguish between the coupling conditions of the [Pd/Co]/NiO and NiO/Co interfaces. To obtain the remanent state, firstly, the samples were saturated in a positive magnetic field applied along the in-plane or out-of-plane direction, then the magnetic field was decreased to zero at room temperature (295 K). All hysteresis loops have been normalized to their saturation magnetization (M_s).

3. Results and discussion

The in-plane magnetic hysteresis loops of the NiO/Co bilayer at 295 K and 10 K after cooling in the remanent state from 295 K are shown in Fig. 1(a). It is clear that the hysteresis loop shows a good square shape with coercivity H_C of 20 Oe (inset), indicating that the easy axis of the FM Co layer lies in the in-plane direction. The hysteresis loop has a clear shift in the negative-magnetic-field direction and a strong FM coupling in the NiO/Co interface exists at low temperature. The shift in the hysteresis loop can be quantified through the exchange field $H_E = |H_L + H_R|/2$ and the coercivity H_C is defined as $H_C = |H_R - H_L|/2$, where H_L and H_R are the left and right coercive fields. A large exchange field H_E of about 290 Oe and a coercivity H_C of about 1500 Oe are observed. After cooling in the remanent state to low temperature, the interfacial microscopic magnetic structure of adjacent AFM NiO layers can be changed due to the interfacial exchange coupling. Net uncompensated moments are induced at the AFM NiO interface. For the interfacial magnetic moments of the Co layer, the interfacial exchange coupling J_{ex} with a fraction of frozen-in net interfacial uncompensated NiO moments exert a microscopic torque on the Co spins to keep them in the positive direction during magnetic reversal. The interfacial exchange coupling induces unidirectional anisotropy and leads to a shift in the loop. Meanwhile, most of the unpinned net interfacial uncompensated NiO moments would rotate with the FM Co spins in the external field due to the strong exchange coupling between the NiO and Co layers when $K_{AFM}\ t_{AFM} \le J_{ex}$, where K_{AFM} and t_{AFM} are the magnetocrystalline anisotropy and the thickness of AFM NiO layer, respectively, leading to the large coercivity H_C. The hysteresis loops as a function of temperature have been measured after cooling at the remanent state from 295 K. The temperature dependence of H_E for the NiO/Co bilayer is shown in Fig. 1(b). H_E decreases monotonically with increasing temperature, vanishing at the blocking temperature (T_B) of about 90 K which is much lower than the Néel temperature T_N (~520 K) of bulk NiO. Especially, H_E decreases rapidly from 290 Oe at 10 K to 35 Oe at 40 K. This can be ascribed to an increase of the magnetocrystalline anisotropy of the AFM NiO and the more and more frozen NiO spin moments with decreasing temperature.

Fig. 2(a) gives the schematic cross section of [Pd/Co(t_{Co})]$_n$/NiO/Co trilayers with different Co-layer thicknesses of 2, 4 and 7 units. The in-plane magnetic hysteresis loop at 295 K of [Pd(1)/Co(1)]$_2$/NiO(4)/Co(3) trilayer is shown in Fig. 2(b). It is seen that the in-plane hysteresis loop displays a square shape and the moment reversal of the FM Co layer and FM [Pd/Co]$_2$ ML at the same field is due to the FM interlayer coupling between two FM layers. The hard axis of the [Pd/Co]$_2$ ML is out-of-plane and the easy axis lies in-plane. Fig. 2(c) and (e) shows the out-of-plane loops at 295 K for the samples of [Pd(1)/Co(0.5)]$_4$/NiO/Co and

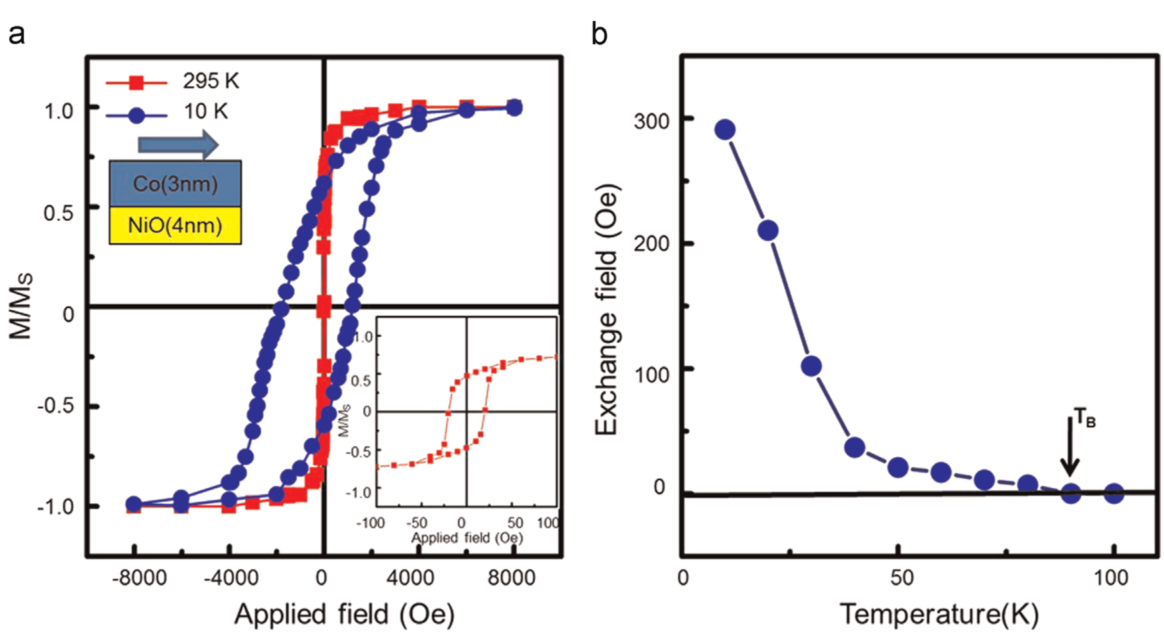

Fig. 1. In-plane magnetic hysteresis loops at 295 K and 10 K after cooling at in-plane remanent state from 295 K for a NiO/Co bilayer (a). The magnetization is normalized to the saturation value. Inset (a): enlarge in-plane magnetic hysteresis loop at 295 K. (b) Temperature dependence of the in-plane H_E for a NiO/Co bilayer.