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Modification of exchange bias by cooling field without changing the ferromagnetic magnetization

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ABSTRACT

In this work, cooling fields (H_{FC}) with different signs or magnitudes were applied on ferromagnetic (FM)/antiferromagnetic (AF) films [Pt(10 Å)/Co(4 Å)]$_4$/NiO(t_{NiO} Å) when FM magnetization of Pt/Co multilayers was kept in positive saturation state at room temperature. Compared to results at $H_{FC}=+5$ kOe, it is seen that $H_{FC}=-1$ kOe suppressed the exchange bias field (H_E) and enhanced the coercivity (H_C) at the same time. The phenomenon indicates that AF spins can be modified by cooling field without changing the FM magnetization. The experimental results are understood by the competition between the FM/AF interfacial exchange coupling and Zeeman energy in FM/AF systems with ferromagnetic interfacial coupling.

1. Introduction

Exchange bias refers to a shift of the hysteresis loop along the magnetic field axis [1]. It typically results from the interfacial exchange coupling between a ferromagnet (FM) and an antiferromagnet (AF). Exchange bias has been intensively studied for decades due to its intriguing physics and importance in technological application [2]. The two most widely recognized manifestations of this phenomenon are the loop shift, referred to as the exchange bias field (H_E), and the coercivity enhancement (H_C) [3–4]. Usually, exchange bias is initialized by cooling FM/AF bilayer through the blocking temperature (T_B) in the presence of a magnetic field. T_B is the critical temperature above which exchange bias vanishes. Furthermore, exchange bias is often accompanied by a gradual degradation of H_E as well as a reduction in H_C through consecutive hysteresis loops, which is known as training effect [5–6]. The training effect is quantified by H_E vs. n-dependence, where n labels the number of loops cycled after first setting exchange bias via field cooling. There is a qualitative consensus that the training effect reflects the rearrangement of AF spin structure toward the equilibrium configuration during the magnetization reversal process of FM layer [7].

Due to the essential role which cooling field plays in initializing exchange bias, its effect on exchange bias has been widely investigated [8–12]. It is found that field cooling procedure induces changes in the microscopic AF structure of NiO layers when exchange coupled to an FM layer. These changes have been related to the macroscopic value of H_E and considered as a key step in the establishment of exchange bias [8]. The magnitude of H_E is strongly affected by the magnitude of the cooling field (H_{FC}) at low values and levels off at high values [9]. Very large H_{FC} may lead to positive exchange bias in the FM/AF systems with antiferromagnetic interfacial coupling, such as FeF_2/Fe and MnF_2/Fe bilayers, due to the alignment of AF spins with the cooling field [10–11]. However, this kind of competition has not been reported in the FM/AF systems with ferromagnetic interfacial coupling and some authors claimed that it is the magnetization state of FM layer and not the cooling field which controls exchange bias [13]. Because FM layer hardly maintains a constant magnetization when H_{FC} varies from large to small, or from positive to negative, it is difficult to distinguish the contributions of the cooling field and the FM magnetization on exchange bias.

In this paper, cooling fields with different directions or magnitudes were applied on [Pt/Co]$_4$/NiO films to investigate the effect of cooling field on exchange bias while FM magnetization was kept in the saturation state above T_B. Pt/Co multilayers are often used as an FM component which own strong perpendicular-to-plane magnetic anisotropy below room temperature (RT) [14–16]. For optimum Co thickness value, Pt/Co multilayers exhibit several kilo-oersted of nucleation field (H_N) and H_C [17–19]. The field at which previously saturated FM spins cease to be aligned is defined as H_N. The unique characteristics of Pt/Co multilayers provide us a way to study exchange bias by manipulating cooling field in a wide range without changing the

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saturation state of FM magnetization. Experimental results indicate that AF spins can be manipulated by cooling field without modification of FM magnetization.

2. Experiments

A series of samples [Pt(10 Å)/Co(4 Å)]$_4$/NiO(t_{NiO} Å) were deposited on thermally oxidized Si substrates by dc and rf magnetron sputtering. For each film, 100 Å thick Ta and 100 Å thick Pt underlayers were deposited firstly to improve the perpendicular anisotropy of Pt/Co multilayers. The base pressure of the chamber was better than 3×10^{-7} Torr. During sputtering, only Ar gas was introduced in the chamber and the pressure was kept at 4×10^{-3} Torr. Commercial Pt, Co, NiO targets with 99.99% purity were used [20]. No external magnetic field was applied when samples were prepared. The polycrystalline NiO layer, which is weakly face-centered-cubic (111) textured, is used as the AF to exchange bias Pt/Co multilayers [21–23]. Magnetization measurements were carried out on a superconducting quantum interference device (SQUID).

3. Results

Square out-of-plane (circles) and S shaped in-plane (squares) hysteresis loops at RT are shown in Fig. 1(a) for [Pt(10 Å)/Co(4 Å)]$_4$/NiO(100 Å). The loops imply that the [Pt/Co]$_4$ multilayer exhibits a good perpendicular-to-plane easy axis. It is seen that H_N of the film is −1.1 kOe, thus cooling fields no less than −1.1 kOe were used to investigate exchange bias.

After being magnetized to positive saturation state at RT, the sample with $t_{NiO}=100$ Å was cooled to measurement temperatures at $H_{FC}=+5$ kOe(−1 kOe). The values of H_E and H_C are denoted as $H_E{}^+$ and $H_C{}^+$ ($H_E{}^-$ and $H_C{}^-$). It should be noted that H_{FC} would not affect the positive saturation state of FM magnetization and we always start our measurement field sweep from the direction of FM magnetization. Fig. 1(b) shows the representative hysteresis loops taken at 150 K at $H_{FC}=+5$kOe (circles) or −1kOe (squares). Both loops show negative exchange bias. The differences in the values of H_E and H_C are 12 Oe and 17 Oe, respectively. Fig. 1(c) shows the data of H_E as a function H_{FC} at 10 K. When H_{FC} decreases, a decline in H_E is observed and becomes more profound as H_{FC} approaches to H_N.

Fig. 2(a) represents the dependences of $H_E{}^+$ (circles) and $H_E{}^-$ (squares) on n at four measurement temperatures 10 K, 50 K,

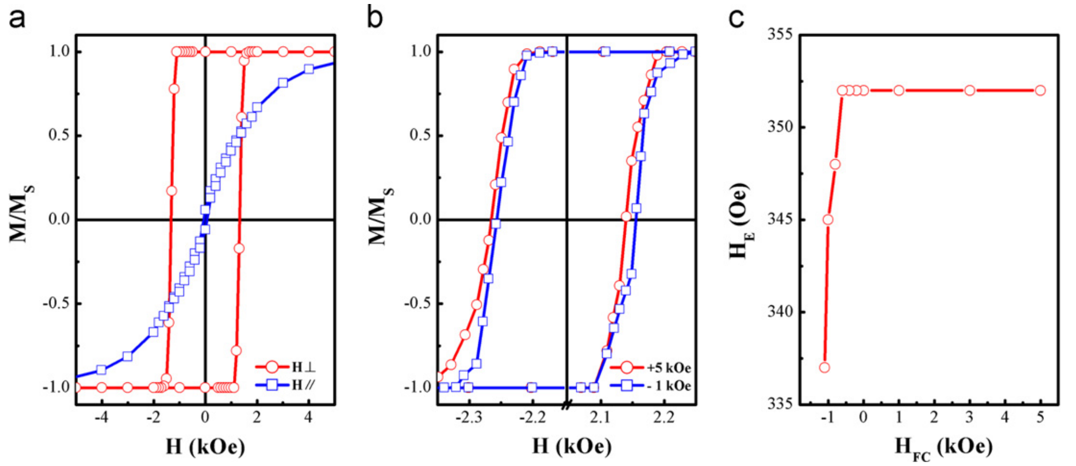

Fig. 1. (a) Out-of-plane (circles) and in-plane (squares) hysteresis loops at RT for [Pt(10 Å)/Co(4 Å)]$_4$/NiO(100 Å) film. (b) Hysteresis loops taken at 150 K at $H_{FC}=+5$ kOe (circles) or −1 kOe (squares) for the sample with $t_{NiO}=100$ Å. (c) Dependence of H_E on H_{FC} at 10 K.

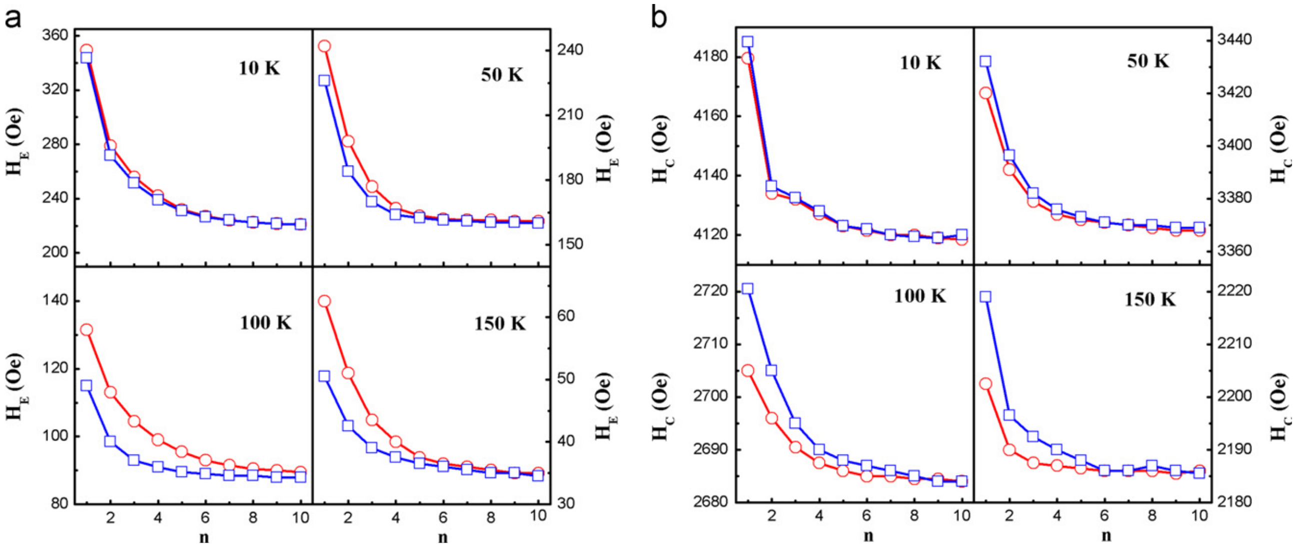

Fig. 2. Dependence of (a) H_E and (b) H_C on n when the sample was cooled at $H_{FC}=+5$ kOe (circles) or −1 kOe (squares).