Effect of spin reorientation transition in $NdCo_5$/Fe bilayers

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Abstract

Exchange-coupled hard / soft magnetic phases are candidates for permanent magnets with enhanced energy densities [1]. As a suitable hard phase, various ferromagnetic rare-earth / transition-metal alloys like $SmCo_5$ and $NdCo_5$ offer high magnetocrystalline anisotropy together with decent saturation magnetization [2]. Besides, $NdCo_5$ (including thin films [3]) exhibits a temperature driven spin reorientation transition (SRT), in which the magnetization easy direction rotates from the hexagonal c-axis ($T>T_2$) to the basal plane ($T<T_1$).

In this work, a $NdCo_5$ (37 nm) / Fe (22 nm) bilayer has been grown by pulsed laser deposition on Cr-buffered MgO (110) substrate (Fig. 1) and investigated by vibrating sample magnetometry (VSM) and ferromagnetic resonance (FMR, measured at ~9.4 GHz). At 350 K (Fig. 2a) the c-axis is the magnetization easy axis. With the temperature decreasing to 290 K (Fig. 2b), hysteresis appears both along the a- and c-axes, as a consequence of the magnetization easy-direction rotation away from the c- to the a-axis. Below 255 K (Fig. 2c) the rotation is complete. Remanence values (Fig. 2d) also indicate $T_1 \cong 255$ K and $T_2 \cong 350$ K. The Fe layer’s influence is seen by the rounding of hysteresis loops vertices and by the S-shape of the hard-axis curves. Fitting a macrospin model to the results, we estimated a coupling energy of 1.4 $erg \cdot cm^{-2}$ at 350 K and effective coupling fields, H_{ex}, on each layer, of a few hundred Oe.

FMR modes were simulated for uncoupled and coupled layers (Fig. 3a). The FMR response of two ferromagnetically coupled FM layers is described by two normal modes: the acoustic-mode, A-M, of lower-frequency and in-phase precession of the moments in each layer; and the optical-mode, O-M, of a higher frequency and out-of-phase precession. In case of the strong coupling, A-M gives the information about averaged magnetic parameters of the bilayer, while O-M allows one to estimate the interlayer coupling strength [4]. In our case, however, the layers are quite thick, which results in weak effective coupling fields in both layers, and the resonance response in each layer is not modified strongly by the existing coupling. Thus, we can identify the FMR signals in the sample as those originating mainly from the individual responses of the Fe and $NdCo_5$ layers. In $NdCo_5$, the high internal anisotropy dominates over H_{ex}, so that the high-frequency FMR peak resembles that of a single $NdCo_5$ layer. Moreover, in most cases the precession frequency is much higher than the working frequency of the spectrometer, i.e. the FMR signal is unobservable. At the same time, the Fe layer is magnetically soft, its FMR frequency is much lower and more easily detectable. The Fe moment’s precession in the exchange field of $NdCo_5$ layer gives rise to partial transfer of magnetic anisotropy from the latter, similarly to the exchange bias effect. The anisotropy transferred from the $NdCo_5$ to the Fe layer is measurable, allowing one to follow the SRT in $NdCo_5$ by tracking the Fe FMR peak field variation with temperature, which constitutes the novelty of this work.

The Fe FMR peak field variation with temperature (Fig. 3c,d) depends on the applied field direction. With decreasing temperature, the FMR signal undergoes a shift to higher fields for $\mathbf{H} \parallel c$, while for $\mathbf{H} \parallel a$ the peak goes deeper into negative values below 350 K. This temperature dependence is qualitatively the same as that we measured and simulated (Fig. 3b) for a single $NdCo_5$ layer. It also agrees with the SRT temperature range as determined by VSM. This is an indirect observation of SRT through the Fe signal, as a result of the interaction between the layers. Through the magnetic coupling between the Fe and $NdCo_5$ layers, the anisotropic behaviour of the latter is transferred to the former, thus allowing a control of the anisotropy direction in Fe, which may find use in novel magnetic devices.

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References

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Figures

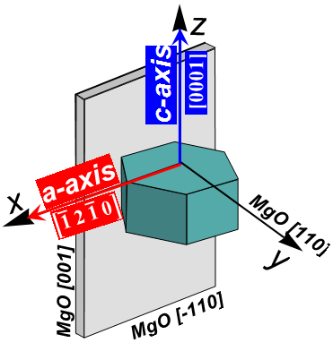

Figure 1: Sketch of the texture relation NdCo$_5$ film - MgO (110) substrate.

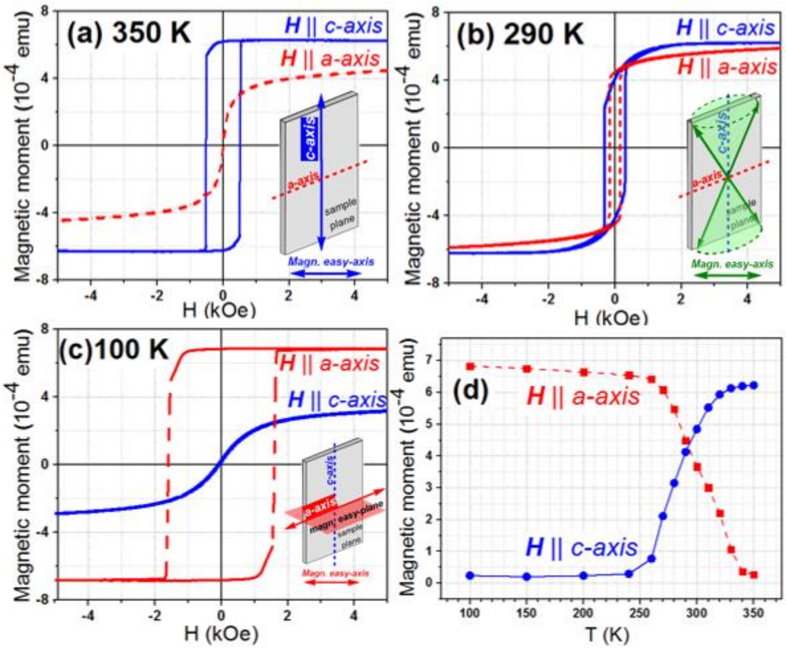

Figure 2: (a-c) Hysteresis measured along NdCo$_5$'s c- (solid line) and a-axis (dashed line) at different temperatures. The SRT is observed in: (a) easy c-axis regime; (b) easy-cone (biaxial) regime and (c) easy-plane (easy a-axis) regime. (d) Remanence values taken from hysteresis loops were used to estimate the SRT temperatures as 255 K and 350 K.

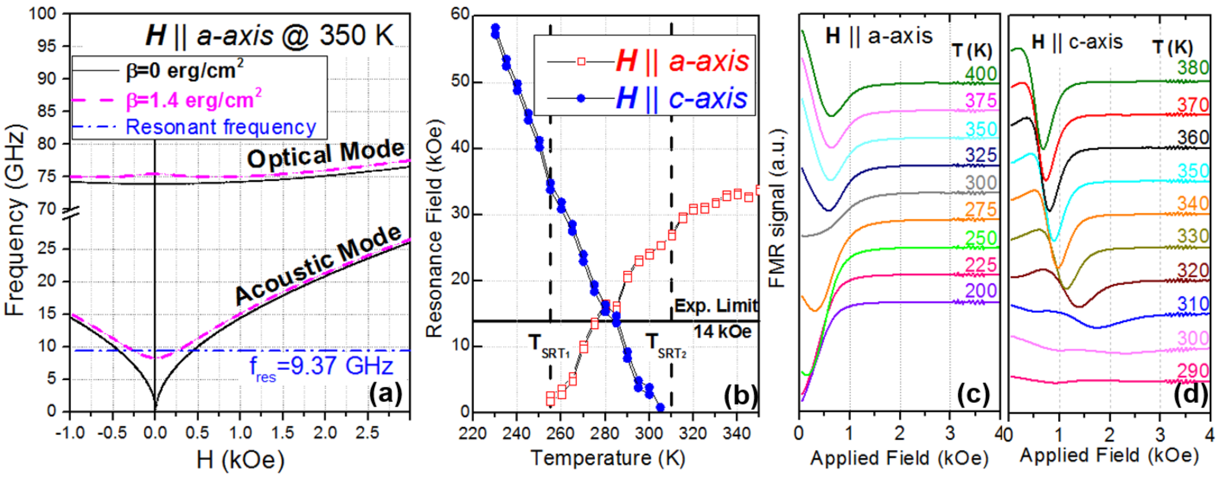

Figure 3: (a) Simulated FMR modes for uncoupled (solid line) and coupled (dashed line) NdCo$_5$/Fe bilayers. Horizontal dashed line is the microwave frequency (9.37 GHz). (b) Simulated peak position with varying temperature for a single NdCo$_5$ layer with **H** ∥ a (open squares) and **H** ∥ c (solid circles); (c-d) FMR signal of Fe with **H** ∥ a (b) and **H** ∥ c (c), showing the same qualitative temperature dependence as that of a NdCo$_5$ single layer.