

Thermal evolution of magnetic behavior in MBE-grown [50 Å ErFe₂/150 Å YFe₂]₂₀ superlattice

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In this letter, we report the thermal evolution of magnetic behavior of MBE-grown YFe₂-dominated [50 Å ErFe₂/150 Å YFe₂]₂₀ multilayers. The evolution from an exchange-spring magnet, to a two-phase-type magnet and eventually into a single-phase-type magnet is revealed in this multilayer from cryogenic to room temperature. In the low temperature region the loops with a negative coercivity and a vertical exchange-spring developed in the soft YFe₂ layers are presented. At the medium temperature, magnetic re-orientation occurs and the loops with a two-phase-type feature are observed, in line with a spin-flop transition driven by exchange-spring (Martin *et al*, *Appl. Phys. Lett.* 89,132511, 2006). Particularly, at room temperature a single-phase-type magnet is witnessed. The slanted loops observed in this joined switching agree with the behavior of predominated magnetically soft YFe₂ layers in this case. A magnetic phase diagram based on temperature is successfully established, serving as a guide for the application of magnetic devices based on such materials.

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Rare-earth-transition-metal (RE-TM) magnetic superlattice with Laves phase structure have been a hot topic due to their novel application such as permanent magnets, magnetic exchange springs, magnetic sensor and so on [1-2]. Many works have been conducted on the epitaxial in-plane Laves DyFe₂/YFe₂ systems [3-7]. Very recently, the magnetic properties of a series of (110) ErFe₂/YFe₂ multilayers, grown by molecular beam epitaxy (MBE), were investigated in our group. Out-of-plane magnetization direction of ErFe₂, close to the [110] growth axis of the multilayers, are presented due to the contribution from a cubic crystal field of Erbium ions and a growth-induced shear strain. Particularly, it was shown that novel vertical magnetic exchange springs can be developed in the soft YFe₂ layers of this multilayer [8], which can be used in exchange-spring media to achieve high density perpendicular recording [9]. In this article the temperature dependent magnetic property of the YFe₂ dominated multilayers of [50 Å ErFe₂/150 Å YFe₂]₂₀ is systematically investigated. Our finding reveals that three different magnet features can be formed from cryogenic to room temperature.

The (110) Laves phase ErFe₂/YFe₂ superlattice samples were grown by MBE (Balzers UMS 630 UHV facility) at Oxford. The samples were grown on epi-prepared (1120) sapphire substrates with a 100 Å (110) Nb buffer and a 20 Å seed layer of Fe. The magnetic measurements were performed from 10 to 310 K using a

vibrating sample magnetometer (VSM, Oxford Instruments Aerosonic 3001). All the measurements were carried out with the magnetic field, up to 12 T, along the out of plane [110] axis of the multilayers.

Fig. 1a shows the magnetization measurements at temperatures below 120 K. A hysteresis with a negative coercivity, once witnessed in in-plane DyFe₂/YFe₂ multilayers [10,11], is observed in this low temperature region and this unusual feature can be ascribed to an unwinding of magnetic spring driven by the built-in high-energy status. In case of a saturation state under a high field case, the magnetizations of ErFe₂ and YFe₂ layers are well aligned along the field direction to minimize the large Zeeman energy. Meanwhile, a magnetic spring is created inside the magnetically soft YFe₂ layers due to antiferromagnetic coupling between the hard/soft layers [8]. On reducing the external field, the pressure on the magnetic spring weakens and spring will unwind rapidly to lower the accumulated energy from spin spiral in this meta-stable state. This process, which is marked by the double arrows in the figure, is completely reversible [8]. As the moment of the soft layers moves to follow the field direction, the total magnetization drops rapidly. Here, a negative sign of coercivity is presented when the total magnetization crosses zero. This feature implies the instability of the magnetic spring status in this multilayer unless an enough high field is applied. Further increasing the field to an opposite maximum will give rise

to an irreversible reversal of the hard ErFe_2 layers, i.e., the occurrence of a sharp step in high field region in the loops.

Fig. 1b shows the results of the magnetization measurements at the temperature ranged from 150 K to 230 K. An inner loop, together with two symmetric outer loops in the first and third quadrants, is displayed. For the outer loops, the amplitude falls gradually and the shift goes further with the temperature increases. This type of loop with two-phase features was previously found in the in-plane Laves $\text{DyFe}_2/\text{YFe}_2$ systems [6]. It arises from the re-orientation of magnetic moment of hard layers, which is confirmed by our work, both experimentally and theoretically [12,13].

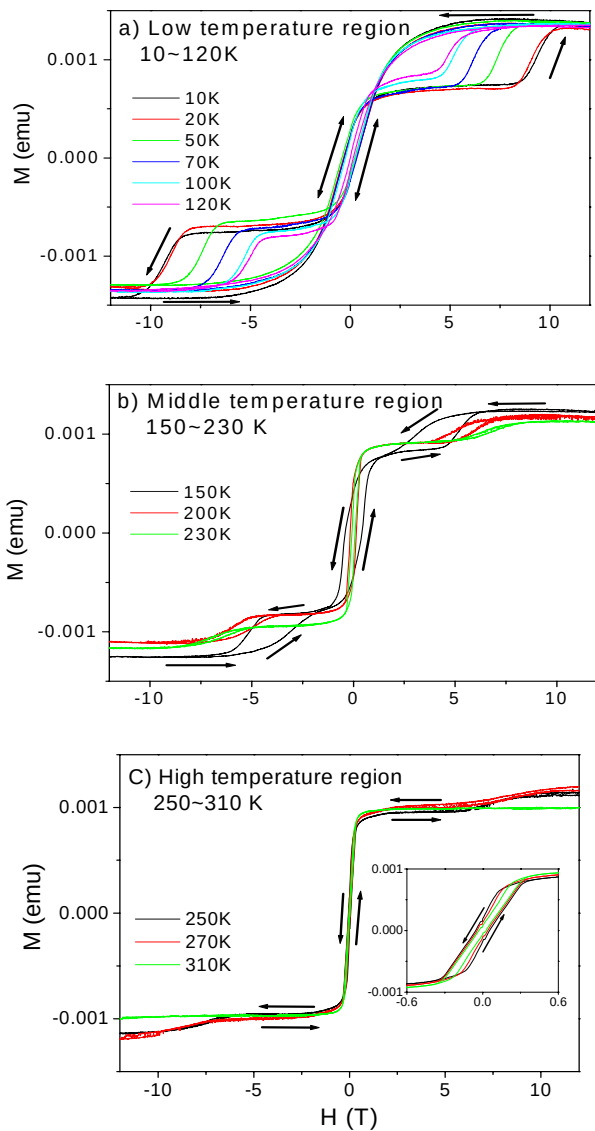


Fig. 1. (Color on-line) Magnetization measurements on a $[50 \text{ Å ErFe}_2/150 \text{ Å YFe}_2]_{20}$ multilayer at different temperatures. a) 10~120 K. b) 150~230 K, c) 250~310 K.

Inset shows the low field region.

Fig. 1c shows the results of the magnetization measurements from 250 K up to room temperature. At

250 K, the outer loops almost vanish while the upturnings around the position of exchange bias field are still visible. At room temperature, the outer loops completely vanishes and a single-unit-type switching behavior is demonstrated indicating a strong exchange coupling interaction. The inset in Fig. 1c shows that all the inner loops are highly slanted and the softness of the multilayers promotes, i.e. the coercivity falls with an increase in temperature. These observations agree with the in-plane YFe_2 -dominated case at high temperatures. In addition, a feature of a small kink in the magnetization near the zero-field was witnessed and possible explanations were listed before [5].

The magnetic phase diagram based on the thermal evolution is summarized in Fig. 2. Inside this diagram three types of magnet are denoted. The negative-coercivity feature in the exchange-spring magnet, shown at low temperature, is correlated with the spontaneous unwinding of the magnetic exchange spring to minimize the total energy. When the sign of the coercivity turns from negative to positive, a magnet correspondingly, goes from an exchange-spring type to two-phase type. At room temperature, the two-phase-type magnet further goes into a special form of single-phase-type magnet indicating a strong coupling interaction. The physical mechanism of the discontinuous change of sign in coercivity from negative to positive is revealed to correlate with a spin re-orientation from a co-planar to a non co-planar configuration [8]. The falling coercivity and low remanence, demonstrated at high temperatures, are consistent with the predominated magnetically soft YFe_2 layers in the multilayer. This rich set of features can be ascribed to different spin configurations arising from the temperature dependent energy competition. The magnetic phase diagram might serve as a guiding map for the potential development and application of magnetic Laves RE-TM multilayered devices.

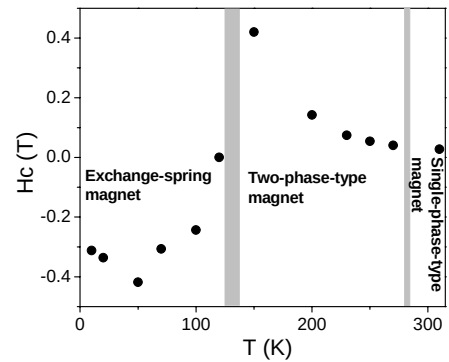


Fig. 2. The experimentally determined coercivity and feature evolution from cryogenic to room temperature. Inside this magnetic phase diagram three regions can be clearly separated.

We would like to make a final comment on this hard/soft RE-TM superlattice material. We should emphasize that this room-temperature single-phase-type magnet presented in the YFe_2 -dominated superlattice is

particularly useful for the device application due to its magnetically soft property at room temperature. Until now, we have demonstrated that not only coercivity in both single-phase-liked and exchange-spring magnet can be engineered [14], but also magnetic exchange-springs can be suppressed [15] in in-plane $\text{DyFe}_2/\text{YFe}_2$ superlattices by patterning. Work on patterning $\text{ErFe}_2/\text{YFe}_2$ superlattice with vertical magnetic spring is ongoing.

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