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Reduced magnetic coercivity and switching field in conetic-alloy-based synthetic-ferrimagnetic nanodots

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Abstract

The coercivity (Hc) and switching field (Hsw) of free layers increase remarkably with shrinking size, which reduces the sensitivity of spintronic devices. Conetic-alloy-based synthetic ferrimagnetic (SyF) trilayers are proposed to show reduced Hc and Hsw than single-layer in nanodots. The investigation on the thickness dependence reveals linear reliance of Hc and Hsw on amplification factor. Hc and Hsw are further reduced after field annealing at 200 °C. This work provides an approach to reduce the Hc and Hsw in nanomagnets.

Key words: synthetic-ferrimagnetic, nanodots, nanosphere lithography

Introduction

The development of spintronics has brought to various novel electronic devices such as magnetoresistance (MR) sensors, spin-torque oscillators (STO), and magnetic random access memories (MRAM). In these spin-valve based devices, ferromagnetic (FM) materials with low coercivity (Hc) and small switching field (Hsw) are required as free layers. However, the Hc and Hsw in nanostructures are typically much larger than that in the planar films due to the increased demagnetization field with shrinking size. By engaging synthetic-ferrimagnetic (SyF) free layer, the Hc of submicrometer magnetic tunnel junction can be reduced while high thermal stability is maintained [1]. Conetic alloy (Ni77Fe14Cu5Mo4) is an FM material with smaller Hc than traditional soft magnetic materials [2]. While the previous investigations on the magnetic properties of SyF are mainly based on NiFe, CoFe and CoFeB, whether smaller Hc and Hsw can be achieved in conetic-alloy-based SyF nanostructures remains unclear. Meanwhile, annealing is reported to be beneficial for reducing the Hc of MR sensor with conetic alloy free layer [3]. An experimental investigation on the magnetic properties and annealing effect of conetic-alloy-based SyF nanodots will be beneficial for evaluating the feasibility of engaging conetic-alloy-based SyF as free layers in nanometric spintronic devices. Besides, nanosphere lithography [4] is a cost-effective nanofabrication technique that is capable of parallel production of nanostructures on large area. Its high yield for sample fabrication made it an ideal method for this research. In this work, the Ru thickness in SyF planar films is firstly optimized to achieve small Hc and Hsw. Later, the magnetic properties of SyF nannodots with different FM thicknesses are compared with that of the single-layer nanodots. Finally, the SyF films and nanodots are field annealed to explore the annealing effect of Hc and Hsw.

Experimental

The SyF structures are Ta 5/Cu 5/ $Ni_{77}Fe_{14}Cu_5Mo_4$ tF/ Ru tRu/ $Ni_{77}Fe_{14}Cu_5Mo_4$ 3/Ru 5 (thickness in nanometers). The fabrication processes of nanodot arrays are schematically shown in Fig. 1. The films are sputtered on Si/SiO_2 substrate under in-plane magnetic field to define the easy axis (Fig 1(a)). Non-close-packed 120-nm polystyrene nanospheres are distributed on the surface by electrical static adsorption (Fig 1(b)). The nanodot arrays are formed after ion milling (Fig 1(c)) and cleaning to remove the residual spheres (Fig 1(d)). The vacuum annealing is conducted at 100 °C to 400 °C for 1 hour under 0.1 T magnetic field along the easy axis.

Results and discussions

The SEM images of the nanosphere masks and nanodot arrays are shown in Fig. 1(e) and (f), respectively. Non-close-packed spheres are uniformly distributed with average diameter of 120 nm and average center-to-center distance of 220 nm. The diameter of the dots are reduced to around 60 nm in the tilted ion milling process. The dot-to-dot interactions are relatively weak due to the large distances amongst the units. The thickness of Ru (tRu) in SyF planar films are varied from 0.5 to 1.1 nm while tF is maintained at 7 nm to investigate the influence of spacer thickness. Minimum Hc of 0.72 Oe and Hsw of 1.1 Oe can be achieved at Ru thickness of 0.5 or 1.3 nm (Fig. 2). In the following investigation, tRu = 1.3 nm is used. The magnetic properties are comparatively studied in SyF nanodots (tF = 5 – 11 nm) and single layer nanodots (6 nm). Curved hysteresis loops with low squareness are observed (Fig. 3 (a)), due to the increased demagnetization field in nanostructures [5]. The Hc (2.3 – 17 Oe) and Hsw (10 – 58 Oe) of the SyF nanodots are all smaller than the single-layer nanodot (Hc = 20 Oe and Hsw = 70 Oe). This is because the demagnetization field at the edges of the nanodots are reduced by the interlayer coupling between the two FM layers [6, 7]. The Hc of SyF nanodot can be interpreted as the combined contribution of anisotropy and in-plane demagnetization [8]: $Hc = 2Ku/Ms \times (t1+t2)/(t1-t2) + NdMs/d \times (t1-t2)$ (1) where Ku is the uniaxial anisotropy, Ms is the saturation magnetization, t1 and t2 are the thickness of two FM layer, Nd is the demagnetization factor in easy axis, d is the size of the dot. Since circular dot is discussed here, Nd equals to 0. The term $(t1 + t2)/(t1 - t2)$ is defined as the amplification factor (Ị). As shown in Fig. 3 (b), the measured Hc and Hsw exhibit linear relationships with Ị (Ị = (tF+3)/(tF-3)). The intercept is believed to be resulted from the demagnetization in the edges. These results indicates that smaller Hc and Hsw is expected at larger thickness difference between two FM layers. The minor hysteresis loops of as-deposited and field-annealed SyF nanodots and planar films are shown in Fig. 4 (a) and (b), respectively. The squarness ratio decreases at high annealing temperature (Ta > 300 °C), indicating the possible loss of ferromagnetism. The Hc of nanodots and planar films present similar annealing effect (Fig. 4(c)). The Hc reaches minimum as Ta increases to 200 °C. The reduced Hc is attributed to the enhanced crystalline fitness at interfaces [2]. However, further increasing Ta to 400 °C results in remarkable increase in Hc and Hsw, especially in nanodots. This is possibly resulted from the reduced crystallinity due to oxidization or inter-diffusion at high temperature. This inference is confirmed by the atomic form microscopy and X-ray diffraction characterization, which will be shown in the full paper.

Conclusions

Conetic-alloy-based SyF thin films and nanodot arrays are prepared by nanosphere lithography, and the dependence of Hc and Hsw on Ru thickness, FM layer thickness, and annealing temperature are investigated. Smallest Hc and Hsw are observed in SyF thin films when tRu = 0.5 or 1.3 nm. The Hc and Hsw of SyF nanodots are much smaller than that of single-layer nanodots, and exhibit linear relationship with Į. Minimum Hc of 4.1 Oe and Hsw of 16 Oe is achieved in SyF nanodots after 200 °C field annealing, while higher annealing temperature tends to increase Hc. This work has proved that Conetic-alloy-based SyF structure is capable of providing low Hc and Hsw in nanometer regime, thus holding some promise as free layers of nanometric spintronic devices.

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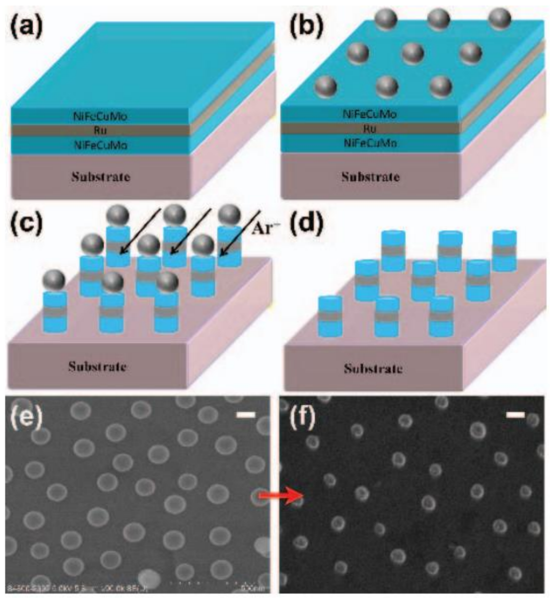

Fig. 1 (a)–(d) The fabrication processes of nanodots, and the SEM images of (e) nanosphere masks and (f) patterned nanodots

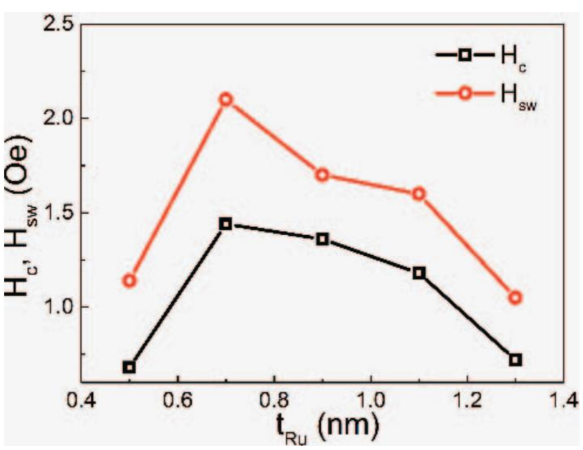

Fig. 2 Hc and Hsw of SyF planar films with different Ru thickness

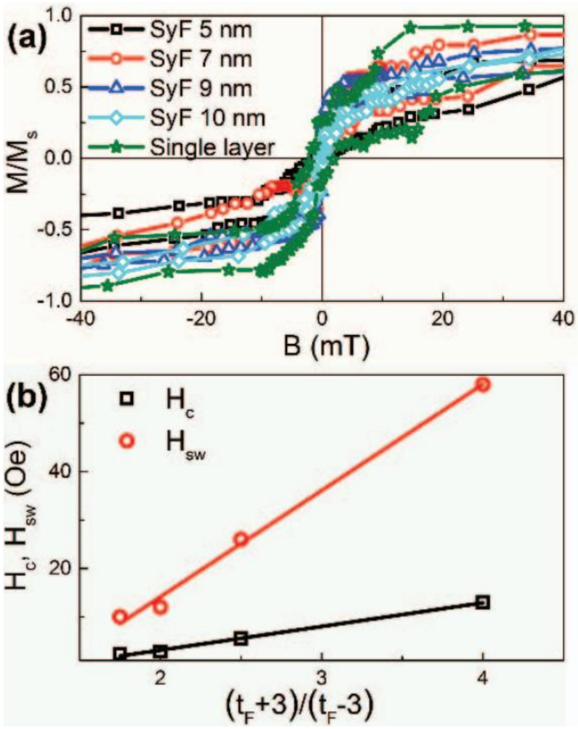

Fig. 3 (a) The minor hysteresis loop of nanodots of single layer and SyF at different tF. (b) Hc and Hsw as a function of amplification ratio.

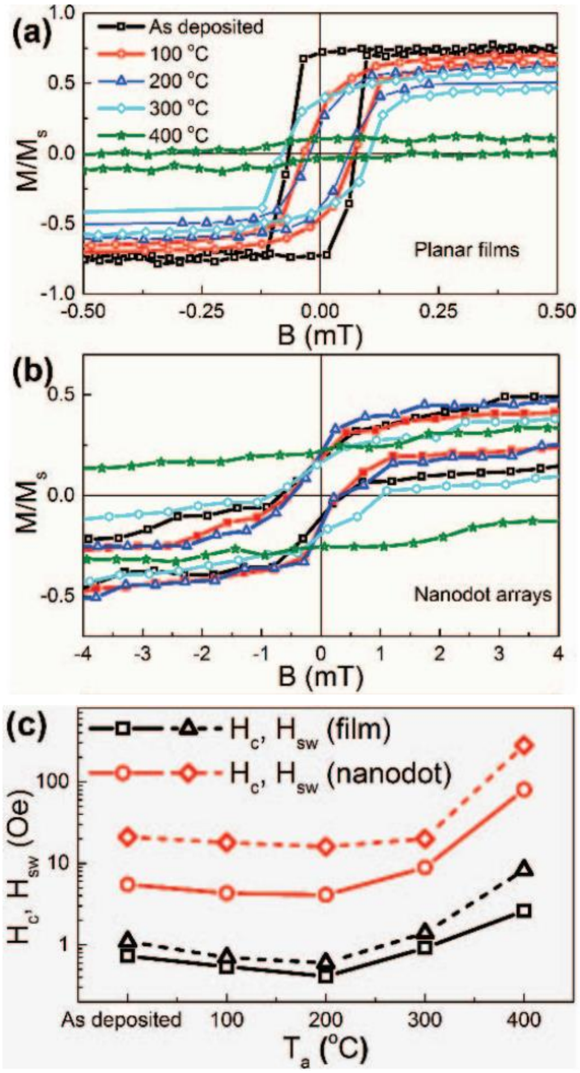

Fig. 4 The minor hysteresis loop of (a) nanodots and (b) planar films at different annealing temperature. (c) Hc and Hsw as a function of Ta.