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Thickness and Aspect Ratio Dependences of Magnetic Domain Structures in Patterned CoFe Thin Films on GaAs (001) Substrates

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Abstract

We characterize magnetic domain structures in patterned CoFe thin films, which are deposited on GaAs (001) substrates, using magnetic force microscopy (MFM) at room temperature under zero-field condition. We observe that the domain structures depend on the crystallographic orientations of GaAs substrates in the case of 20-nm-thick CoFe thin films with a relatively high aspect ratio, e.g., 2 x 0.5 μm^2. The MFM observation results suggest that the magnetic domains can be tuned by controlling aspect ratio and thickness of CoFe thin films.

1. Introduction

Recently, the research fields of semiconductor spintronics are attracting a tremendous amount of attention because the high performance of conventional electronic devices based on scaling laws is facing physical limitations. In such spintronic devices, efficient spin-polarized current injections into various types of III-V compound semiconducting materials, such as GaAs, AlGaAs, InAs, and InGaAs, from ferromagnetic thin film materials, such as CoFe and CoFeB, with and without insulating MgO thin film interlayers have been intensively investigated [1-3], as a high spin-injection efficiency into semiconductor is required.

We have grown vertical free-standing InAs nanowires and MnAs/InAs heterojunction nanowires on GaAs (111)B substrates by selective-area metal-organic vapor phase epitaxy, and characterized the magnetotransport properties in single InAs nanowires [4]. Our research target in the long term is to realize vertical nanowire spintronic devices consisted of semiconducting nanowires and ferromagnetic electrodes, such as CoFe. Thus, it is crucial to control the magnetic properties and the magnetic domain structures in ferromagnetic electrodes because the current through the nanowire devices depends on the magnetization direction of ferromagnetic electrodes. In the magnetic hysteresis (*M-H*) loops of CoFe and amorphous CoFeB thin films grown on GaAs substrates, in-plane uniaxial magnetic anisotropy was observed [5, 6]. However, to the best of our knowledge, it was only reported that direct observations of patterned Fe thin films, which have a circular or rectangular shape, grown on GaAs (001) and (110) substrates, by magnetic force microscopy (MFM), showed magnetic domain structures depending on the crystal orientations of Fe thin films [7]. In this paper, the magnetic domain structures in patterned CoFe thin films deposited on GaAs (001) substrates are characterized directly by MFM observations under as-deposition condition.

2. Experimental Procedures

Deposition of $Co_{0.8}Fe_{0.2}$ thin films with a thickness of 10 and 20 nm was performed by radio frequency magnetron sputtering at room temperature. Patterned CoFe thin films were prepared by conventional electron beam lithography and liftoff processes on GaAs (001) substrates. The domain structures in patterned CoFe thin films were observed by MFM. MFM measurements were carried out at room temperature under zero-field condition. Before patterning CoFe thin films, we have never observed any marked magnetic domains in the CoFe thin films (not shown here).

3. Results and Discussion

Figure 1 shows MFM images of patterned CoFe thin films with a thickness of 20 nm. All the patterns of CoFe thin films clearly show a spontaneous magnetization. In the case of the patterned films with an aspect ratio of unity, i.e., the square shape, the marked closure magnetic domain was mostly observed, as shown in Fig. 1(a). The percentage of the obtained single magnetic domain was increased with increasing the aspect ratio. In the case of patterned CoFe thin film with 0.5 x 2 μm^2, in which the elongated direction is parallel to the <110> orientation of the substrates, the single magnetic domain was observed, as shown in Fig. 1(b). Hereafter, this domain is defined to as “Type-A”. On the other hand, when the elongated direction is parallel to the <1-10> orientation of the substrates, a double magnetic domain, Type-B domain, was observed, as shown in Fig. 1(c). These results suggest that the domain structure in patterned CoFe thin films depends on the crystallographic orientation of GaAs substrates.

Figures 2, next, shows MFM images of patterned CoFe thin films with a thickness of 10 nm. In the case of the square-shaped patterns, similarly to the case of 20-nm-thick CoFe films, the closure magnetic domain was mostly observed, as shown in Fig. 2(a). In addition, in the case of patterned CoFe thin films with 2 x 0.5 μm^2, even if the elongated direction is parallel to the <1-10> direction of the substrates, the single magnetic domain, Type-C domain, was observed, as shown in Fig. 2(b). Type-A was observed in Fig. 2(c), similarly in Fig. 1(b). In the CoFe and amorphous CoFeB thin films on GaAs substrates, in-plane uniaxial magnetic anisotropy due to the crystallographic orientation of GaAs substrates have been observed [5, 6]. For example, the results show that the <1-10> orientation of CoFe thin films is the magnetic hard axis [5]. Therefore, the magnetic domain structure depended on the substrate orientation in the 20-nm-thick CoFe would be due to the in-plane uniaxial magnetic anisotropy.

To understand the stable magnetic domain structures, we roughly estimated the thickness dependence of total energy

E_{total} in the patterned CoFe thin films in Type-A, B, and C. The E_{total} was calculated by the sum of magnetostatic energy E_m, the energy of uniaxial magnetic anisotropy E_{ani}, and the domain wall energy E_{DW}, i.e., the total energy can be expressed as Eq. (1):

$$E_{total} = E_m + E_{ani} + E_{DW} = \frac{N}{2}\frac{M_s^2}{2}V + KV + 4\sqrt{AK}S \quad (1)$$

Here, N is the demagnetization coefficient, M_s is the saturation magnetization, K is the density of in-plane uniaxial magnetic anisotropy [5], A is the exchange stiffness constant, V is the volume of CoFe thin film, and S is the area of the domain wall. The shape of patterned CoFe thin films was approximated here as an ellipsoidal structure to use the demagnetization coefficient determined in Ref. [8] for the rough estimation. Figure 3 shows the calculation results of E_{total} as the function of CoFe thickness. E_{total} of Type-A is lower than that of Type-B and C for both of the film thicknesses of 10 and 20 nm. Therefore, when the elongated direction is parallel to the <110> orientation of substrates, a single magnetic domain, i.e., Type-A, is stable. In addition, E_{total} of Type-C is larger than that of Type-B for the film thicknesses thicker than 18 nm. Therefore, in patterned CoFe thin films with a thickness of 20 nm, when the elongated direction is parallel to the <1-10> orientation of substrates, a double magnetic domain, i.e., Type-B, is stable. These results suggest that the magnetic domains are tuned by controlling the aspect ratio, thickness, and orientation of patterned CoFe thin films.

4. Conclusions

In this paper, we characterized the magnetic domain structures in patterned CoFe thin films deposited on GaAs (001) substrates by MFM. The results obtained markedly show that the magnetic domain structures depend on the crystal orientation of GaAs substrates. In addition, the results indicate that the magnetic domains are tuned by controlling the aspect ratio and thickness of patterned CoFe thin films.

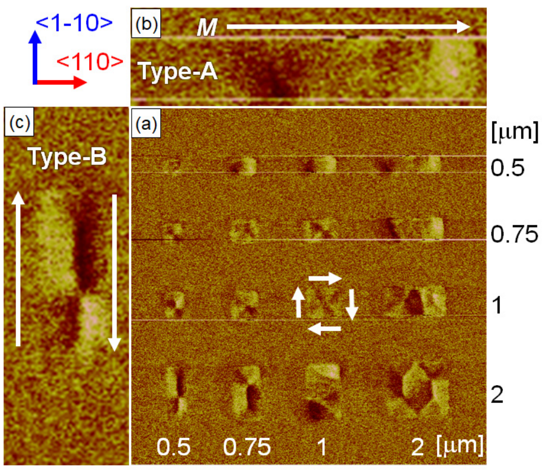

Figure 1 MFM images of patterned CoFe thin films with the thickness of 20 nm. (a) Whole images of the patterns, and the patterns with the size of 2 x 0.5 μm^2: (b) the elongated direction // <110> and (c) <1-10>.

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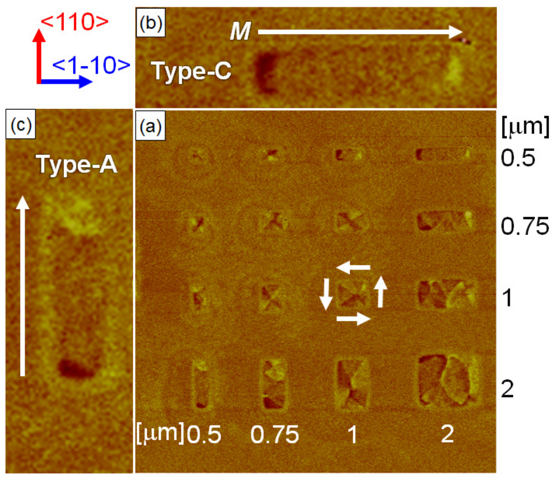

Figure 2 MFM images of patterned CoFe thin films with the thickness of 10 nm. (a) Whole images of the patterns, and the patterns with the size of 2 x 0.5 μm^2: (b) the elongated direction // <1-10> and (c) <110>.

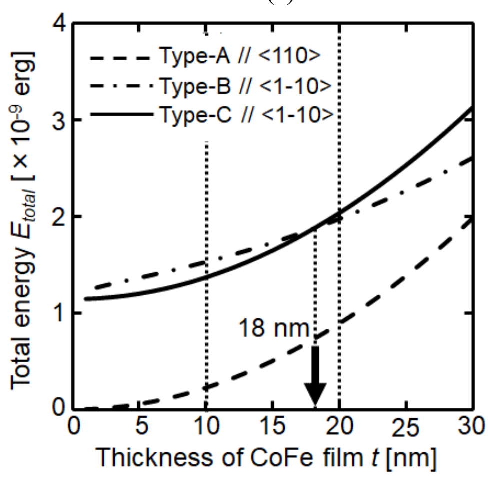

Figure 3 Thickness dependence of calculated total energies for the domains, Type-A, B, and C, in patterned films.