

Magnetic Domain Structures Controlled by Patterned CoFe Nanolayer Thickness on GaAs (001) Substrates

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Abstract

We characterize the magnetic domain structures in patterned CoFe nanolayers, which are deposited on a GaAs (001) substrate, depending on a nanolayer thickness by magnetic force microscopy (MFM) under zero-field conditions at room temperature. We mostly observe closure domain structures in 35-nm-thick patterned CoFe nanolayers, possibly caused by fourfold anisotropy. On the other hand, single domains are mostly observed in the nanolayers with a thickness of thinner than 20 nm, which also depend on a crystal orientation of the substrate. All the results obtained by MFM show that the magnetic domains can be adjusted by controlling the thickness of the patterned CoFe nanolayers, as well as the crystal orientation of the substrates.

1. Introduction

In the research field of semiconductor electronics, although the performance of conventional electronic devices has been improved through miniaturization of electronic devices themselves, the technological limitation affecting the design of electronic devices makes semiconductor spintronics technology much attractive. In such spintronic devices, due to the need for high spin injection efficiency into the semiconductors, the spin injection from ferromagnetic nanolayer materials such as CoFe and CoFeB with or without insulating MgO nanolayer interlayer is effectively injected into various types of III-V compound semiconductor materials, such as GaAs, AlGaAs, InAs, and InGaAs [1-3]. We have grown vertical free-standing InAs nanowires on GaAs (111)B substrates by selective area metal-organic vapor phase epitaxy and characterized the magnetotransport properties in a single InAs nanowire [4]. We aim to use semiconductor nanowires with ferromagnetic electrodes (such as CoFe) to realize vertical nanowire spintronic devices. Therefore, controlling the magnetic properties and magnetic domain structures in the ferromagnetic electrodes becomes quite vital. In the hysteresis loop (M - H) of CoFe and amorphous CoFeB nanolayers grown on GaAs substrates, an in-plane magnetic anisotropy, which is a superposition of uniaxial and fourfold anisotropies, was observed [5, 6]. Uniaxial and fourfold anisotropies depend on the crystal orientation and the thickness of nanolayers, respectively. However, so far as we know, only the direct observation of circular or rectangular patterned Fe nanolayers grown on GaAs (001) and (110) substrates through magnetic force microscopy (MFM) has been reported [7]. In this paper, we are mainly characterizing the thickness dependence of magnetic domain structures in the patterned CoFe nanolayers deposited on GaAs (001) substrates directly by MFM under as-deposited conditions.

2. Experimental Procedures

Co_{0.8}Fe_{0.2} nanolayers with a thickness of 10, 20, and 35 nm were deposited by radio frequency magnetron sputtering at room temperature. After the deposition, patterned CoFe nanolayers were prepared on GaAs (001) substrates by a conventional liftoff process after electron beam lithography. For characterizing magnetic domains of patterned CoFe nanolayers, MFM was used at room temperature without any application of external magnetic field, neither before nor during the MFM observations.

3. Results and Discussion

Figure 1 shows MFM images of patterned CoFe nanolayers under as-deposited conditions, i.e., no application of B , with a thickness of 35 nm. All the patterns of CoFe nanolayers clearly show spontaneous magnetization at room temperature. From the observation, we mostly observe a multiple domain structure in all the patterned CoFe nanolayers. When the patterned nanolayers are square shape, i.e., the aspect ratio of patterns is unity, in particular, the closure domains were observed.

Figure 2, next, shows a comparison among MFM images for the nanolayer patterns with a thickness of (a) 35, (b) 20, and (c) 10 nm and a size of 0.50 x 2.0 and 0.75 x 2.0 μm^2 , in which the elongated direction parallel to the $\langle 110 \rangle$ orientation of the substrates. Figure 3 is for the corresponding case of the elongated direction parallel to the $\langle 1-10 \rangle$ orientation of the substrates. White arrows represent a possible magnetization direction, M , judging from the careful investigation of a magnetic response of the nanolayers by changing a magnetized direction of MFM tips used for observation. Depending on the crystallographic orientation of the substrates, a single or double magnetic domain was observed with a thickness of 10 and 20 nm, while we observed multiple magnetic domains for the 35-nm-thick patterns.

In the CoFe and amorphous CoFeB thin films on GaAs substrates, both in-plane uniaxial magnetic anisotropy due to the crystallographic orientation of GaAs substrates and fourfold magnetic anisotropy depending on a thickness of a CoFe nanolayer have been observed [5, 6]. In our previous study [8], to consider the stable magnetic domain structures, we roughly estimated the thickness dependence of total energy E_{total} in the patterned CoFe nanolayers with a size of 0.50 x 2.0 μm^2 . Ignoring the fourfold magnetic energy for a relatively thin CoFe nanolayer, the E_{total} was calculated by the sum of magnetostatic energy E_m , the energy of uniaxial magnetic anisotropy E_{anis} , and the domain wall energy E_{DW} , i.e., the total energy E_{total} can be expressed as Eq. (1):

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

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. [9] for the rough estimation. From the calculation in our previous study [8], a single magnetic domain is stable, in which the elongated direction of the patterns is parallel to the $\langle 110 \rangle$ orientation of the substrates, and a double magnetic domain is stable with nanolayer thickness thicker than 18 nm, in which the elongated direction of the patterns is parallel to the $\langle 1-10 \rangle$ orientation of the substrates [8]. For CoFe nanolayers with a thickness of 35 nm in the current study, since the contribution of a fourfold magnetic anisotropy increases, it is reasonable that a multiple magnetic domain becomes stable despite the crystal orientation of the substrates. These results suggest that a magnetic domain structure is tuned by the crystal orientation of the substrates because of in-plane uniaxial magnetic anisotropy, whereas the effect of a fourfold magnetic anisotropy prevails for relatively thick nanolayers.

4. Conclusions

In this paper, we characterized the magnetic domain structures in patterned CoFe nanolayers on GaAs (001) substrates by MFM. The results show that the magnetic domain structures depend on the crystal orientation of GaAs substrates mainly due to in-plane uniaxial magnetic anisotropy. For

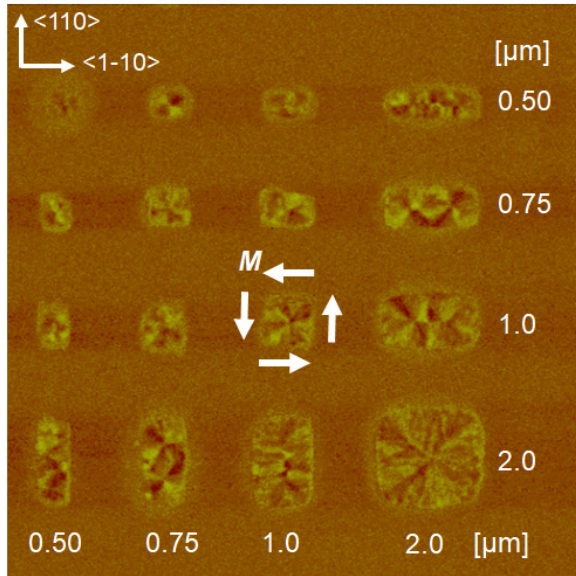


Figure 1 MFM image of patterned CoFe nanolayers deposited on GaAs (001) substrate with the thickness of 35 nm. Crystallographic orientations of the GaAs substrates are shown in the image.

CoFe nanolayers with a thickness of 35 nm, the contribution of a fourfold magnetic anisotropy becomes dominant, which was a good agreement with the results that we observed multiple magnetic domains for the nanolayer thickness of 35 nm under as-deposited conditions.

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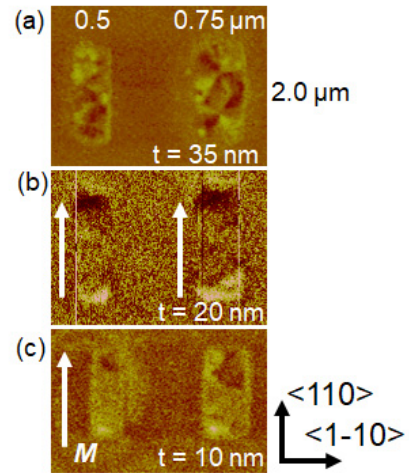


Figure 2 MFM images of patterned CoFe nanolayers, in which the elongated direction parallel to the $\langle 110 \rangle$ orientation of the GaAs substrates.

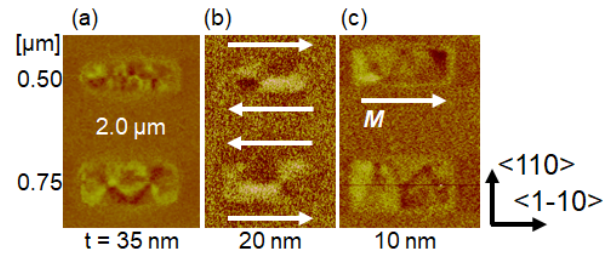


Figure 3 MFM images of patterned CoFe nanolayers, in which the elongated direction parallel to the $\langle 1-10 \rangle$ orientation of the GaAs substrates.