Observation of magnetic domain structure in a ferromagnetic semiconductor (Ga, Mn)As with a scanning Hall probe microscope

T. Shono and T. Hasegawa
Materials and Structures Laboratory, Tokyo Institute of Technology, Nagatsuta 4259, Midori-ku, Yokohama 226-8503, Japan and CREST, Japan Science and Technology Corporation, Japan

T. Fukumura[a]
Department of Innovative Engineered Materials, Tokyo Institute of Technology, Nagatsuta 4259, Midori-ku, Yokohama 226-8502, Japan

F. Matsukura and H. Ohno
Laboratory for Electronic Intelligent Systems, Research Institute of Electrical Communication, Tohoku University, 2-1-1 Katahira, Aoba-ku, Sendai 980-8577, Japan

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We have performed low-temperature scanning Hall probe microscopy on a ferromagnetic semiconductor ($Ga_{0.957}Mn_{0.043}$)As. The observed magnetic domain structure is a stripe-shaped pattern as has been observed in conventional nonsemiconductor ferromagnetic materials, and the measured magnetic field from the sample surface was small, reflecting the weak magnetization of (Ga, Mn)As. The domain width increased and the measured magnetic field decreased with raising temperature, which are consistent with calculated results, in which the exchange interaction between Mn spins deduced from the Curie temperature is assumed. © *2000 American Institute of Physics.* [S0003-6951(00)04935-4]

Success in growth of ferromagnetic III–V-based diluted magnetic semiconductors has opened up the possibility of semiconducting devices which combine the functionality of semiconductors with that of ferromagnetic materials.[1–4] In magnetic materials, both the size and the shape of the magnetic domains are among the most fundamental quantities, because they reflect the magnitude and anisotropy of the microscopic exchange interaction. In addition, the domain structure is associated with the carrier conduction and the possible minimum size of magnetic bits in magnetic recording media, which are of technological importance for both electronic and magnetic devices. However, there have been no experiments in order to observe the magnetic domain structures of III–V ferromagnetic semiconductors.

Recently, several scanning probe microscopic techniques for studying local magnetic properties, which detect the magnetic field from the sample surface, have been developed, such as the magnetic-force microscope,[5] the scanning superconducting quantum interference device microscope,[6] and the scanning Hall probe microscope (SHPM).[7] The SHPM has advantages of less magnetic invasiveness for the specimen and a wider operating temperature range, the latter being suitable for studying the temperature variation of the domain structure.

Here, we report SHPM measurements of the magnetic domain structure in a ferromagnetic semiconductor (Ga, Mn)As film. The results clearly showed stripe-shaped domains with their widths depending on temperature below the Curie temperature T_C. The domain width and the magnitude of the magnetic field from the domain structures are discussed on the basis of a classical magnetic domain model in which magnetostatic energy and domain-wall energy are taken into account.

A 0.2-μm-thick ($Ga_{0.957}Mn_{0.043}$)As film was grown epitaxially on a semi-insulating GaAs(001) substrate at 250 °C by the use of the molecular-beam epitaxy technique. The perpendicular magnetization at zero field was realized by the introduction of tensile strain into the (Ga, Mn)As layer using 1-μm-thick ($In_{0.16}Ga_{0.84}$)As buffer layer.[8,9] T_C is 80 K determined from a magnetization measurement. A homemade SHPM was utilized for the variable temperature measurements.[10] The Hall probe with the junction of 1 μm $\times 1$ μm was scanned $h \sim 0.5$ μm above the sample surface in order to detect the local magnetic field perpendicular to the sample surface.

Figure 1 shows the observed magnetic images of the (Ga, Mn)As film at 9–77 K. The horizontal axes of the images are along $\langle 100 \rangle$. The color denotes the magnetic field perpendicular to the sample surface B_Z. Note that each figure of Fig. 1 has a different scale of B_Z, and that the scanning area for the upper and lower panels are 4.75×4.75 and $7.3 \times 7.3\ \mu m^2$, respectively. The red and blue areas correspond to positive and negative B_Z, respectively, hence, white boundaries with $B_Z \sim 0$ correspond to the magnetic domain walls. The stripe direction is nearly parallel to the $\langle 110 \rangle$, reflecting the magnetocrystalline anisotropy, which is consistent with the theoretical prediction by the use of $k \cdot p$ perturbation method.[11] The stripe-shaped domain is preserved in a wide temperature range up to T_C, as can be seen from Fig. 1. The width of the domain d becomes wider, and B_Z decreases with raising temperature. Figure 2 (square symbols) shows the temperature dependence of d. At 9 K, d is 1.5 μm, then gradually increases with raising temperature for $T < 60$ K, and steeply increases for $T > 60$ K up to ~ 6 μm around T_C.

[a]Electronic mail: fukumura@oxide.rlem.titech.ac.jp

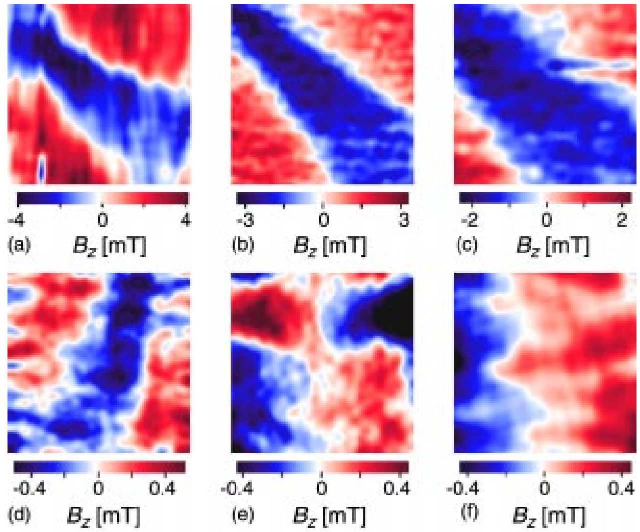

FIG. 1. (Color) Magnetic images of (Ga, Mn)As obtained by scanning Hall probe microscope. Measurement temperatures are (a) 9 K, (b) 20 K, (c) 30 K, (d) 65 K, (e) 70 K, and (f) 77 K. The image areas are 4.8×4.8 μm^2 for 9–30 K and 7.3×7.3 μm^2 for 63–77 K. The horizontal axes are $\langle 100\rangle$. The red and blue regions denote positive and negative B_Z, respectively.

Figure 3 (square symbols) shows the temperature dependence of the maximum value of B_Z above the center of the domain, B_Z^{max}. At 9 K, B_Z^{max} is ~4 mT, and decreases almost linearly with temperature up to about 60 K, then decreases slowly above 60 K. In order to calculate the magnitude of B_Z^{max}, a stripe-shaped domain model is employed as described below. The magnetic field perpendicular to the surface above a perpendicularly magnetized thin film with stripe domain array as functions of d, the thickness of the domain L, and a location (x,h), as illustrated in the inset of Fig. 3, is given by Eq. (6) in Ref. 12. In our case, the size of the Hall junction is nonzero so that the measured magnetic field should be averaged over the area of the Hall junction excluding the depletion layer, about 0.8×0.8 μm^2. Figure 3 (circle symbols) shows the calculated B_Z^{max}, $B_{Z,cal}^{max}$, by using d at each temperature, $h=0.5$ μm, $L=0.2$ μm, and the spontaneous magnetization M_S obtained from an Arrott plot as a function of temperature.[13] M_S decreases largely with increasing temperature near T_C according to the temperature dependence of a Brillouin function. However, the decrease in $B_{Z,cal}^{max}$, depending on both M_S and d, is not large but approximately linear in temperature, since d increases largely with increasing temperature near T_C. $B_{Z,cal}^{max}$ is in quantitative

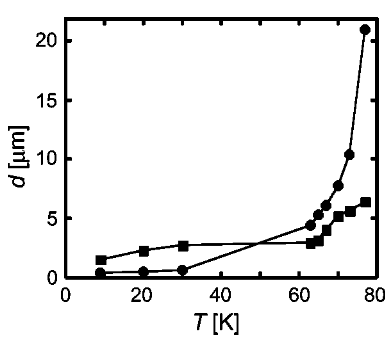

FIG. 2. Temperature dependence of the observed and the calculated domain widths, d (square symbol) and d_{cal} (circle symbol), respectively. Full lines are guides for the eyes.

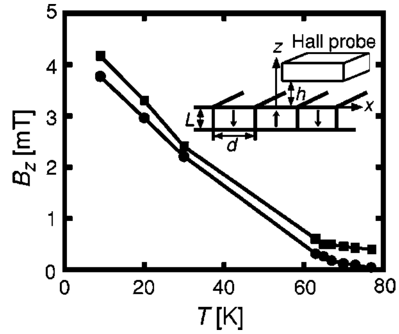

FIG. 3. Temperature dependence of the measured and calculated maximum magnetic field, B_Z^{max} (square symbol) and $B_{Z,cal}^{max}$ (circle symbol), respectively. The inset shows configurations of the magnetic domains and Hall sensor. d is the domain width, L the domain thickness, and h the sample–probe distance. Arrows denote magnetization. Full lines are guides for the eyes.

agreement with B_Z^{max} (square symbols), therefore, there is no magnetic domain smaller than the spatial resolution of the present SHPM. If a smaller domain exists, magnetic fields from the adjacent domains cancel out each other, resulting in considerable reduction of B_Z^{max}. The agreement between B_Z^{max} and $B_{Z,cal}^{max}$ also confirms that the domain structure in this compound is composed of a single magnetic domain in the direction perpendicular to the surface since L is assumed to be the whole film thickness in the present calculation.

It is well known that the most stable domain structure in ferromagnetic materials with perpendicular magnetization under no external magnetic field is the stripe domain array.[14] d is determined so as to minimize the sum of the magnetostatic energy and domain-wall energy, and expected to be expressed as $d=3.04\times10^{-3}$ $(\gamma L)^{1/2}/M_S$ in Kenneley's SI unit.[15] γ is the domain-wall energy per unit area given by $\gamma=4$ $(nJS^2xK/a)^{1/2}$, where n is the number of cation sites in the unit cell, J the exchange between Mn spins, S the magnitude of the Mn spin, x the molar concentration of Mn, K the magnetocrystalline anisotropic constant, and a the lattice constant. We assumed J between Mn spins substituted for Ga sites taking the nearest-neighbor cations into consideration in mean-field theory as $J=3k_BT_C/2zS(S+1)x$, where k_B is the Boltzmann constant, and z is the number of nearest-neighbor cation sites.[13,16] Using the relation between the magnetic anisotropic energy E_a and K, $E_a\approx K\sin^2\theta$, $K=1.0\times10^4$ J/m^3 is obtained from the hysteresis loss in the magnetic-field dependence of the Hall resistivity at various angles between the magnetic field and the easy-magnetization axis θ at 10 K.[9] Taking $T_C=80$ K, $n=4$, $z=12$, $S=5/2$, and $a=0.567$ nm, γ is calculated to be 3.4×10^{-4} J/m^2. The calculated temperature dependence of domain width d_{cal} by the use of the obtained γ and M_S determined from the Arrott plot as a function of temperature and $L=0.2$ μm of the thickness of the (Ga, Mn)As layer, well reproduces d, as shown in Fig. 2 (circle symbols). d_{cal} is weakly temperature dependent below 60 K and abruptly increases near T_C mainly due to the reduction of M_S, where the disagreement between d and d_{cal} due to the neglect of the temperature dependence of K is observed.

In summary, we have observed the magnetic domain structure of (Ga, Mn)As by using a scanning Hall probe microscope. It is shown that (Ga, Mn)As has stripe-shaped domains with widths of 1.5–6.4 μm increasing with raising temperature for 9–77 K. The measured magnetic field can be quantitatively accounted for in the perpendicularly magnetized thin-film model. Hence the domain width is not smaller than 1 μm parallel to the sample surface and the structure is composed of a single domain perpendicular to the surface. The observed domain widths are reproduced by a model considering the magnetostatic and domain-wall energies, assuming exchange interaction deduced from T_C.

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