Real-time direct observation of temperature-dependent domain reversal behavior in epitaxial MnAs film on GaAs(001)

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We have investigated temperature-dependent domain reversal behavior in the MnAs film epitaxially grown on GaAs(001) using a magneto-optical microscope capable of real-time direct observation of domain evolution. Interestingly enough, the domain reversal in the temperature range of 20 °C ~ 35 °C shows the domain wall-motion process with the sawtooth type and, then, it changes to the nucleation-dominant process above 37.5 °C. This change could be understood by the decrease of the dipolar interaction energy and the disconnection of the ferromagnetic α-MnAs stripes, induced by the decrease of the α-MnAs volume ratio with increasing temperature. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2189016]

Ferromagnetic (FM) films on semiconductor are of considerable interest due to their spintronic device applications for spin injection.[1] Among these systems, MnAs film grown on GaAs substrate is a promising system because of the high FM transition temperature ($T_C \sim 45$ °C), relatively small coercivity (<1 kOe), and compatibility with molecular-beam epitaxy (MBE).[2–4] Recently, this system has been reported that two structurally distinct phases (hexagonal α-MnAs and orthorhombic β-MnAs) coexist with the form of self-organized periodic stripes of two phases in the temperature range of 20 °C ~ 45 °C, via strain stabilization.[5–8] Due to this unusual microstructure, the magnetic property of the film was known to be more complex as compared to that of the bulk.[8–12] So, a study on the magnetic property of the MnAs film becomes an important issue in exploring the fundamental understanding of the interplay between the structural and magnetic properties as well as in developing its application as a spin injection device.

In particular, many experimental investigations to understand the magnetic domain structure of MnAs film have performed. For example, the x-ray magnetic circular dichroism photoemission electron microscopy (XMCDPEEM) study showed the variation of the magnetic domain structure during the structural phase transition.[8] Recently, the temperature-dependent magnetic force microscopic (MFM) study provided more detailed magnetic domain structures, together with analytic simulations, in a wide coexistence temperature range of 10 °C–40 °C.[12] However, the time-resolved domain reversal study on this system is not reported yet. In this letter, we report the real-time direct observation of temperature-dependent domain reversal behavior in an epitaxially grown MnAs film on GaAs(001) by means of a magneto-optical microscope magnetometer (MOMM).

In the present study, the epitaxial MnAs film with the thickness of 50 nm was grown on a GaAs (001) substrate at 270 °C by a molecular-beam epitaxy (MBE). The epitaxial orientations of the MnAs film with respect to the GaAs(001) substrate were MnAs($\bar{1}$100)||GaAs(001), MnAs[0001]||GaAs[$\bar{1}$10], and MnAs[11$\bar{2}$0]||GaAs[110]. The torque and vibrating sample magnetometric (VSM) measurements showed that the sample has an in-plane magnetic anisotropy with an easy axis along the MnAs[11$\bar{2}$0] and a hard axis along MnAs[0001] in the film plane. The out-of-plane direction MnAs[$\bar{1}$100] is an intermediate axis. The strain-stabilized coexistence of two MnAs phases (α-MnAs and β-MnAs) existed in the film was confirmed from the temperature-dependent x-ray diffraction (XRD) experiment. It was observed that two phases coexisted with the monotonically increasing volume ratio of β phase with increasing temperature in the temperature range of 20 °C ~ 45 °C, where a complete transition to the β phase occurred at 45 °C. An atomic force microscopic (AFM) study of the MnAs film revealed that the α-MnAs and β-MnAs stripes were aligned along MnAs[0001], perpendicular to a magnetic easy axis MnAs[11$\bar{2}$0].

A homemade magneto-optical microscope magnetometer (MOMM), capable of capturing domain images with an image-grabbing rate of 30 frames/s in real time and a spatial resolution of 400 nm via the longitudinal magneto-optical Kerr effect,[13] was used to directly observe the time-resolved magnetic domain patterns during the domain reversal on the sample area of 80×64 μm^2 with ×500 magnification. The MOMM was also utilized to measure the Kerr hysteresis-loops with the field sweeping rate of 30 Oe/s. A heater capable of heating the sample maximum up to 80 °C was placed at the sample stage for temperature-dependent domain observation and Kerr hysteresis-loop measurement. The magnetic fields in both measurements were applied along the easy axis MnAs[11$\bar{2}$0] of the film.

Figure 1(a) shows the Kerr hysteresis loops of the MnAs film measured at several temperatures in the temperature range of 20 °C–45 °C. For direct comparison, the Kerr angle in each Kerr hysteresis loop is normalized by the saturation Kerr angle of the hysteresis loop measured at 20 °C. It can be seen that the squareness of the hysteresis loop is maintained, irrespective of temperature, until the hysteresis

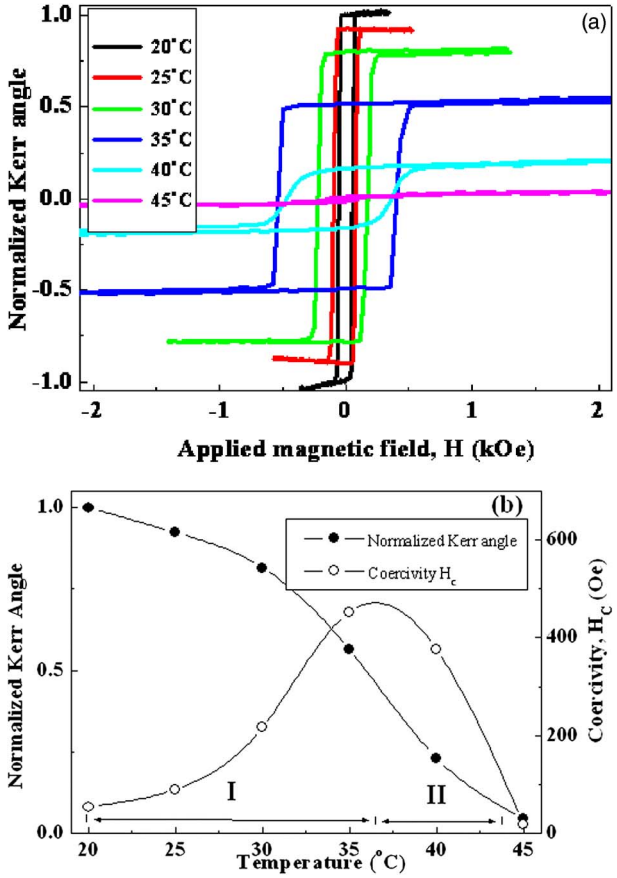

FIG. 1. (Color online) (a) Kerr hysteresis loops of the MnAs film measured at several temperatures in the temperature range of 20 °C–45 °C. (b) The normalized Kerr angle and the coercivity as a function of temperature.

loop disappeared at 45 °C, which implies that the easy axis of the film is unchanged with increasing temperature. Note that no hysteresis loop is developed at 45 °C, which is consistent with the XRD result that the ferromagnetic α phase does not existed anymore at this temperature. In Fig. 1(b), we plot the normalized Kerr angle and the coercivity as a function of temperature, obtained from Fig. 1(a). It is clearly seen that the Kerr angle monotonically decreases with increasing temperature. This is naturally expected because the FM α-MnAs volume ratio decreases with increasing temperature, as confirmed from the XRD experiment. In contrast, the dependence of coercivity on temperature shows a nonmonotonous behavior, as seen in Fig. 1(b): H_C initially increases with temperature and, then, it decreases with temperature, where we designate two regions by "I" and "II." Strikingly, we find that the different domain reversal processes govern the regions "I" and "II."

The detailed domain reversal behaviors in the regions "I" and "II" were investigated from the direct observation of the time-resolved domain patterns using the MOMM. Figure 2 shows typical domain reversal patterns with temperature in the temperature range of 20 °C–40 °C, observed on the *exactly same* area of the MnAs film. The gray level from black to white indicates the elapsed time during 4 s according to the gray palette at the right bottom of the figure. In Fig. 2, one can vividly see that the domain wall (DW) motion having the sawtooth pattern governs the magnetization reversal process in the region "I," whereas the domain nucleation-dominant process governs magnetization reversal in the region "II." We interpret this contrasting change ascribed to

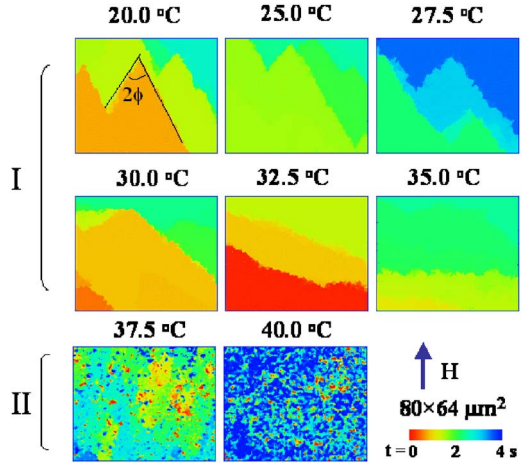

FIG. 2. (Color online) The variation of the typical domain reversal patterns with temperature in the temperature range of 20 °C–40 °C, observed on *exactly* the *same* area of the MnAs film.

two causes: the decrease of the dipolar interaction with increasing temperature and the disconnection of the FM α-MnAs stripes at high temperature near the FM transition temperature ($T_C \sim 45$ °C). The dipolar interaction between two neighboring FM α-MnAs stripes causes the magnetic moments near their boundary to be aligned in the same direction along the easy axis due to the higher energy cost in the other case,[8] which appears as the straight DW lines in a saw-tooth pattern observed at 20 °C. However, as temperature increases, the dipolar interaction decreases due to the decrease of the magnetization. This decrease of the dipolar interaction reduces the correlation between two neighboring FM α-MnAs stripes, which makes the irregular and jagged domain patterns, and causes the nucleation of new domains, as vividly witnessed from the variation of the domain reversal patterns at 35 °C and 37.5 °C. And the FM α-MnAs stripes of the film would be disconnected as the temperature approaches T_C(~45 °C),[8] which causes the nucleation-dominant process with many domain nucleation sites, as clearly witnessed from the domain reversal patterns at 40 °C.

Interestingly enough, the sawtooth angle 2ϕ during the domain reversal in the region "I" is found to increase with increasing temperature, as seen in Fig. 2. Generally, the sawtooth DW shape is developed to reduce the magnetic charge density when the magnetization directions of two domains meet head on.[14,15] The detailed shape is determined by a minimization of the total energy consisted of the magnetostatic energy, the anisotropy energy, and the DW energy. When an angle between the magnetization direction and the easy axis is small due to the strong in-plane anisotropy of the film as revealed in our film, the sawtooth angle 2ϕ is approximately expressed as $2\phi = \pi(AK_\perp)^{1/2}/8M_S^2D$,[10] where A is the exchange stiffness, $K_\perp$ is an anisotropy constant in the normal-to-film plane, M_S is the saturation magnetization, and $2D$ is the sample thickness. Hence, the sawtooth angle 2ϕ is basically determined by the competition between the DW energy of $\pi(AK_\perp)^{1/2}$ and the dipolar interaction energy of $8M_S^2D$.

To figure out a dominant origin for an increasing sawtooth angle with temperature, we have measured the saturation magnetization M_S using a superconductor quantum interference device (SQUID) magnetometer. In Fig. 3, we plot

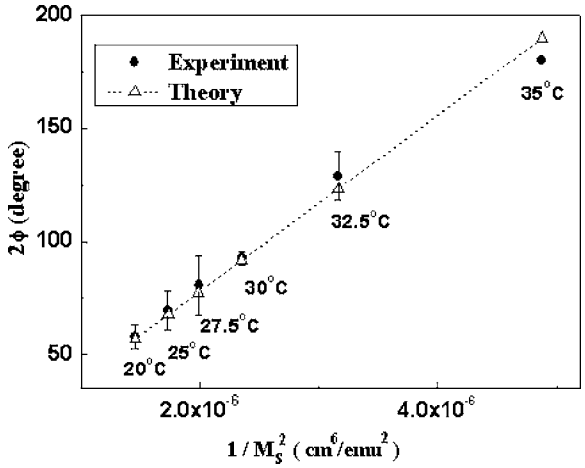

FIG. 3. The experimental and theoretical values of the sawtooth angle 2ϕ as a function of $1/M_S^2$ in the temperature range of 20 °C–40 °C.

the sawtooth angle 2ϕ vs $1/M_S^2$. Interestingly, the sawtooth angle is linearly proportional to $1/M_S^2$, which implies that a dipolar interaction plays a dominant role for the temperature dependence of the sawtooth angle. The sawtooth angle was theoretically estimated from the relation $2\phi = \pi(AK_\perp)^{1/2}/8M_S^2D$, where we have used the measure values of $K_\perp = 1.7\times10^6$ erg/cm^3, $D = 2.5\times10^{-6}$ cm, and temperature-dependent M_S and a reported value of the DW thickness of $\delta \approx 8.0\times10^{-6}$ cm. In Fig. 3, one can notice that the theoretical values are well matched to the experimental ones within the errors, which confirms our conjecture that the temperature-dependent magnetization is a major origin for an increasing sawtooth angle with temperature.

In summary, using a time-resolved MOMM system we have directly observed the systematic variation of domain reversal behavior with temperature in the epitaxial MnAs film on GaAs(001). Domain reversal in the temperature range of 20 ~ 35 °C is governed by the sawtooth typed domain-wall motion with increasing the sawtooth angle with temperature and, then, it changes to the nucleation-dominant process above 37.5 °C. This change is ascribed from the decrease of the dipolar interaction with increasing temperature and the disconnection of the FM α-MnAs stripes at higher temperature near T_C. The increasing sawtooth angle in the domain-wall motion with temperature is found to mainly ascribe to the decrease of the dipolar interaction with temperature.

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