Spontaneous magnetization reversal caused by magnetic fluctuation in GaMnSb thin films

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Abstract. Time dependences of the magnetic moment \( m(t) \) in GaMnSb thin films with MnSb clusters are measured. The \( m(t) \) dependences are straightened in semi-logarithmic coordinates \( m(\ln t) \). The field dependences of magnetic viscosity \( S(H) \) corresponding to the slope of straight lines \( m(\ln t) \) are studied. It is demonstrated that the behaviour of dependences \( S(H) \) is governed by the magnetic moment fluctuations of MnSb clusters with lognormal distribution of the magnetic anisotropy energy.

1. Introduction

Dilute magnetic semiconductors are characterized by high degrees of spin polarization of charge carriers and may be used in the design of spintronic devices. However, the strength of indirect exchange, which helps maintain the spin-polarized state, is so low that the corresponding Curie temperatures are well below room temperature. The reasons for this are the low solubility of transition-metal impurities in the semiconductor matrix and the resulting formation of various clusters of the secondary phase [1−6]. For example, the theoretically predicted Curie temperature in GaMnSb is 40 K, while the value measured experimentally in thin films grown by molecular beam epitaxy is no higher than 25 K [7−9]. However, the anomalous Hall effect with hysteresis up to room temperatures was observed in GaMnSb thin films grown by pulsed laser deposition [10]. Since long-range ferromagnetism in the GaMnSb films is impossible at room temperature, the authors of [10] interpreted the observed phenomenon as spin polarization of holes tunneling through the MnSb-GaMnSb Schottky barrier. MnSb clusters are the ferromagnetic secondary phase embedded in GaMnSb thin films [10]. The basic magnetic characteristics of thin films (coercive force, blocking temperatures, magnetic anisotropy constants, etc.) were determined in [11, 12]. In the present study, time dependences of the magnetic moment \( m(t) \) of GaMnSb thin films with MnSb clusters were measured. The aim of the study was to reveal the effect of magnetic anisotropy distribution of MnSb clusters on spontaneous magnetization reversal of GaMnSb thin films.

2. Experiment

GaMnSb films with a thickness of 90 nm were grown by pulsed laser deposition under high vacuum at a temperature of 100 °C. The GaSb-MnSb eutectic alloy was used as the target. Single-crystal Al₂O₃ served as a substrate. Following deposition, the samples were annealed at a temperature of 350 °C for 30 min. The structure and the composition of thin films were checked with a scanning probe microscope and a scanning electron microscope. The chemical composition of the near-surface layers of films was determined by energy-dispersive spectroscopy. The image of the surface of a GaMnSb
thin film (not present) obtained using a magnetic force microscope shows that the films had magnetic nanoinclusions. The technique for sample fabrication and assessment was described in detail earlier in [13, 14]. Time dependences of the magnetic moment \( m(t) \) of samples were performed using a SQUID magnetometer MPMS 5XL Quantum Design. The sample was first magnetized in a magnetic field \( H = 2 \) kOe (exceeding the strength of the saturation field). The time of exposure of the sample to this magnetic field was 300 s. Following such treatment, the field directed opposite to the magnetic moment vector of the sample was switched on. The time of field reversal was approximately 90 s. After the reverse magnetic field was set, the time dependence of the magnetic moment was measured during 2400 s.

3. Experimental results and discussion

3.1. Time dependences of magnetic moment

Figure 1 shows the magnetic moment increment dependences \( \Delta m(t) \) at a temperature \( T = 8 \) K in different magnetic fields directed opposite to the magnetic moment vector of the sample on a logarithmic time scale.

\[
\frac{\Delta m}{m_S} \sim S \ln t,
\]

where \( m_S = 3.2 \) \( \mu_B \) is the saturation magnetic moment. Slopes of \( \Delta m(\ln t) \) curves and correspondent magnetic viscosities are non-monotonic functions of magnetic field (figure 1).

3.2. Magnetic viscosity

The shape of the \( S(H) \) function depends on volume distribution of ferromagnetic clusters [15, 16]. In case of lognormal distribution, the dependence \( S(H) \) is described by the following formula [15, 16]:

\[
\frac{S(H)}{m_S} = \frac{T}{25T_B \left( 1 - \frac{H}{H_A} \right)^2} \frac{1}{\sqrt{2\pi \ln \sigma}} \exp \left\{ -\frac{1}{2} \left[ \ln \left( \frac{T T_B^{-1} \left( 1 - \frac{H}{H_A} \right)^2 \right) \right] \right\},
\]

where \( T_B \) is the blocking temperature, \( H_A \) is the magnetic anisotropy field, \( \sigma \) is the standard deviation. The blocking temperature \( T_B = 390 \) K and the magnetic anisotropy constant \( K = H_A m_S / 2 = 7.2 \times 10^4 \) erg/cm\(^2\) at \( T = 8 \) K were extracted from the approximation of \( S(H) \) dependence by Equation

\[
\frac{\Delta m}{m_S} \sim S \ln t,
\]
(2). Field dependence $S(H)$ at $T = 8$ K shows a maximum at the coercive field $H_C = 600$ Oe (figure 2) corresponding to the extremum of Equation (2): $H_C = H_A \left(1 - \sqrt{TT_B^{-1}\sigma^{-\ln \sigma}}\right)$.

As follows from Equation (2), the slope of the $\Delta m(\ln t)$ curve (magnetic viscosity $S$) is a non-monotonic function of temperature. Function $S(T)$ has a maximum at $T = T_B \left(1 - HH_A^{-1}\right)^2$. The temperature dependence $S(T)$ was discussed in [17].

Figure 3 shows the size (diameter $D$) distribution of MnSb clusters derived from the magnetic force microscopy data and magnetic anisotropy energy distribution $\rho(E_A)$ obtained as a result of the approximation of $S(H)$ dependence according to Equation (2). Function $\rho(E_A)$ corresponds to a lognormal distribution in Equation (2), where $H = 0$ Oe, $E \sim k_BT$ and $E_A \sim 25k_BT_B$ (here $k_B$ is Boltzmann constant). It follows from figure 2 and figure 3 that the field dependence of the magnetic viscosity $S(H)$ is governed by the lognormal distribution of the magnetic anisotropy energy of MnSb clusters.

4. Summary
The correlation between the size distribution of MnSb clusters, which was derived from the magnetic force microscopy data, and the distribution of MnSb clusters over the magnetic anisotropy energy,
which was obtained as a result of analysis of time dependences of the magnetic moment $m(t)$ of GaMnSb thin films, was found. This correlation suggests that $m(t)$ dependences and magnetic viscosity are governed by the lognormal size (magnetic anisotropy energy) distribution of MnSb clusters.

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