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Shape anisotropy in patterned ferromagnetic GaMnAsP films with perpendicular anisotropy

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ABSTRACT

We investigate the effects of physical dimensions on the behavior of magnetic anisotropy in lithographically-fabricated nanoscale squares of the ferromagnetic semiconductor GaMnAsP using SQUID magnetometry and ferromagnetic resonance (FMR). Both measurements show that perpendicular magnetic anisotropy is strongly affected by the size of the ferromagnetic nano-scale elements, while their Curie temperature and their in-plane anisotropy remain unchanged in the range studied. In addition to uniform-mode FMR, we observe a series of spin-wave resonances, whose analysis suggests that surface anisotropy plays an important role in determining the properties of nanoscale magnets.

It is well established that thin films of ferromagnetic semiconductor $Ga_{1-x}Mn_xAs_{1-y}P_y$ grown epitaxially on GaAs (001) substrates are subject to tensile strain in the film plane, which causes the easy axis of magnetization to lie along the growth direction due to strain-induced perpendicular anisotropy. [1] In this work we present a study of the effects of dimensions on magnetic properties of this quaternary alloy when it is reduced to nanometer scale, [2–4] with special attention on the behavior of magnetic anisotropy as determined by SQUID magnetometer and ferromagnetic resonance.

$Ga_{1-x}Mn_xAs_{1-y}P_y$ films used in this study were grown by molecular beam epitaxy (MBE) to a nominal thickness of 25 nm, with Mn concentration of $x \sim 6\%$ and P concentration of $y \sim 9\%$, as determined by lattice constant obtained by X-ray diffraction (XRD) measurements. As expected, the XRD results also show that the films are under tensile strain, with no noticeable relaxation. After growth, the GaMnAsP film was then annealed at 260 °C in N_2 flux, and patterned by electron-beam lithography into arrays of nanoscale squares with different dimensions: 1000 nm, 700 nm, 400 nm and 200 nm, with square sides oriented along the {110} directions. The total size of each nanofabricated array was 3mm × 3mm, which was sufficiently large for magnetization and ferromagnetic resonance measurements. Additionally, a piece of the film without nanofabrication was used as a control sample. Fig. 1 shows scanning electron micrographs (SEM) of the fabricated arrays. Note that the etching process has penetrated the entire thickness of the GaMnAsP layer, so that all the nano-squares are separated from each other, with no connecting GaMnAsP material.

Ferromagnetic resonance (FMR) measurements were carried out at 9.48 GHz using a Bruker electron paramagnetic resonance spectrometer. [5] In FMR experiments the applied magnetic field **H** was in the horizontal plane, and the microwave magnetic field was vertical. The sample was placed in a suprasil tube inserted in a liquid helium continuous flow cryostat, which could achieve temperatures down to 4.0 K. A detailed description of the apparatus, along with the coordinate system used in discussing our results, can be found in [5]. Magnetization measurements on the GaMnAsP nano-square arrays were carried out as a function of magnetic field and temperature using a Quantum Design SQUID magnetometer.

Hysteresis loops at $T = 5$ K for the control sample and 700 nm and 200 nm nano-square arrays measured with the magnetic field applied normal to the sample plane (i.e., along the [001] crystallographic direction) are shown in the Fig. 2. The hysteresis loops for the 1000 nm and 400 nm nano-square arrays (not shown) are similar to that for the 700 nm sample. The nearly square loop observed on the control sample indicates that the magnetic easy axis is oriented along the [001] direction, as expected for the built-in tensile strain in the GaMnAsP film. However, as the size of the nano-squares decreases, the hysteresis loop evolves into an elongated shape, suggesting that the easy axis direction is modified by the effects of reduced dimension. The temperature dependence of magnetization measured in an 8 Oe field applied along the [001] direction is shown in the inset in Fig. 2. Note that all specimens have the same Curie temperature of ~ 110 K, indicating that the overall quality of ferromagnetic order is not affected by the nanofabrication. However, the remnant magnetization seen in Fig. 2 is clearly reduced as the size of nano-square decreases, indicating that the size-induced anisotropy plays an important role in determining magnetic properties of the nano-sized squares.

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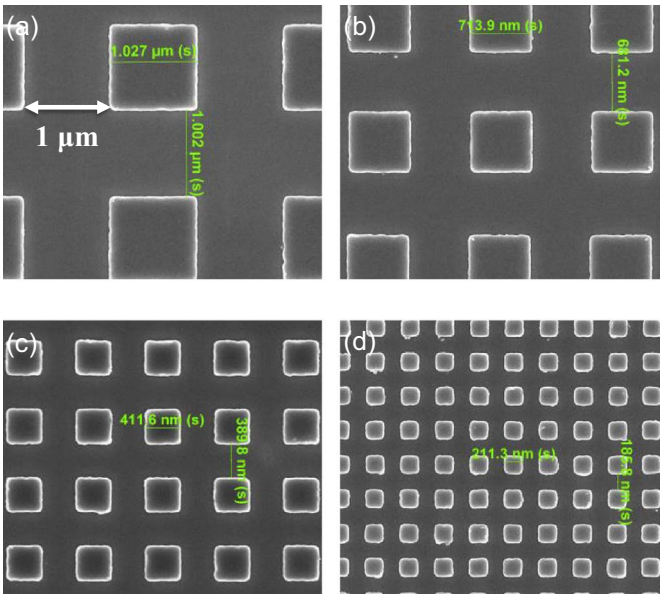

Fig. 1. (color online) SEM image of arrays of nano-scale GaMnAsP squares viewed from top. The edges of squares are (a) 1000 nm, (b) 700 nm, (c) 400 nm, and (d) 200 nm, respectively.

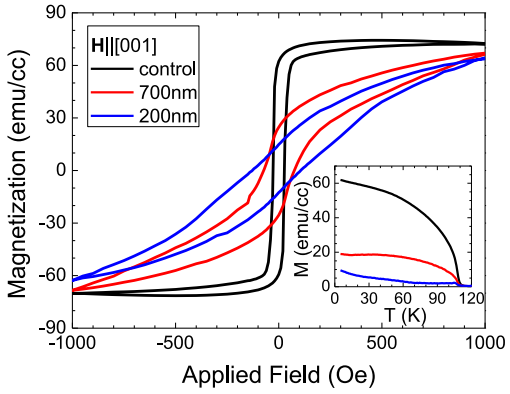

Fig. 2. (color online) Hysteresis loops measured at 5 K with magnetic field applied along the [001] direction. Black: control sample; red: 700 nm squares; blue: 200 nm squares. Inset: corresponding magnetization as a function of temperature measured in 8 Oe magnetic field applied along [001] for all samples. M(H) and M(T) measured on 1000 nm and 400 nm squares are similar to those obtained on700 nm squares.

In order to investigate anisotropy changes as a function of nano-square size, FMR measurements were carried out using two setups, which we will refer to as “vertical” and “horizontal” . [5] In the “vertical” setup, the [110] edge of the specimen was oriented vertically. This configuration allows measurements with the dc field in any arbitrary direction in the (1–10), from the [1–10] direction to [001]. In the “horizontal” setup, the sample was mounted with the layer plane horizontal (i.e., the [001] direction pointing up). In this configuration we could measure the angular dependence of FMR when the field was confined to the layer plane, including the high-symmetry orientations **H**||[110], **H**||[1–10], and **H**||[100], as well as intermediate in-plane orientations.

In Fig. 3 we show FMR spectra at 4.0 K for the control sample and all four nano-sized square arrays in two basic configurations: **H**||[001] and **H**||[100]. Clear Lorentzian-shape FMR lines are observed for all samples (and persist up to the Curie temperature T_C), indicating homogeneous strong long-range ferromagnetic order of Mn^{2+} spins in these nanoscale squares. We find this to be remarkable, since each of 3mm × 3mm GaMnAsP nano-square arrays contains between 25 and 625 million nano-squares. Observation of sharp and uniform FMR

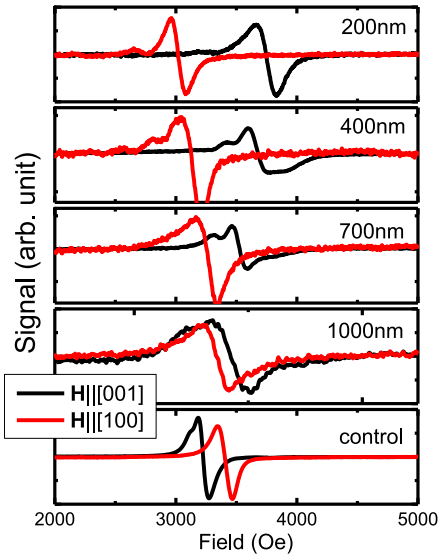

Fig. 3. (color online) FMR spectra observed at $T = 4$ K for control and all four nano-square arrays in high symmetry configurations of **H**||[001] and **H**||[100].

spectra in such arrays also suggests that the magnetization is nearly homogenous throughout the nano-square, and can thus be treated as a single magnetic moment precessing coherently around the dc magnetic field.

Through their dependence on the field orientation relative to the crystal lattice, the FMR spectra in Fig. 3 establish that magnetic anisotropy plays a major role in determining the field at which FMR occurs. Interestingly, the FMR positions at **H**||[001] and **H**||[100] cross as the nano-square size decreases. To determine magnetic anisotropy parameters of the nano-squares from the FMR data, we employ the Stoner-Wohlfarth model, where the ferromagnetic nano-square is assumed to consist of a single homogeneous magnetic domain with four magnetic anisotropy fields: $H_{2\perp}$ and $H_{4\perp}$, representing the perpendicular uniaxial and perpendicular cubic anisotropy; and $H_{2||}$ and $H_{4||}$, representing in-plane uniaxial and in-plane cubic fields, respectively. Note than the sign of $H_{2\perp}$ will be different for compressive and for tensile strains. [6]

In Fig. 4 we plot FMR fields H_R as a function of applied field orientation for all samples, top panels corresponding to results obtained in the “vertical” setup, and bottom panels to results from the “horizontal” setup. Strikingly, two-fold symmetry dominates the angular dependence of H_R fields observed in the vertical setup (top panels), and the in-plane angular dependence (bottom panels) is characterized by a four-fold symmetry. From the evolution of the angular dependence of H_R with size, we note that, as the size of nano-squares decreases, field orientations corresponding to the lowest resonance field (which indicates the orientation of the easy axis) shift from [001] direction seen in the top left panels to the [100] direction seen in the bottom panels. This indicates that the easy axis of the GaMnAsP sample, which lies along [001] for the control sample, gradually changes to the [100] direction as the square size decreases toward 200 nm. The behavior of the bottom panels in Fig. 4, which show the angular dependence of H_R for **H** confined to the (001) plane, is particularly interesting for two reasons. First, it reveals that the magnetic in-plane anisotropy (which we attribute to the cubic anisotropy term $H_{4||}$) is quite strong. And second, it is evident that this symmetry of FMR positions does not change as the nano-square size decreases, although the entire curve shifts downward with decreasing size due to reduction of the dominance of perpendicular anisotropy.

To obtain the values of anisotropy fields quantitatively, we analyze the FMR results in Fig. 4 using the formalism described earlier. [5] Specifically, the analysis yields five parameters: $H_{4||}$, $H_{2||}$, $4\pi M$ - $H_{2\perp}$,