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ORIGINAL PAPER

Strain-Controlled Variation of Magnetoresistive and Magnetic Anisotropy in (Ga,Mn)As

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Abstract The influence of strain on the anisotropic magnetoresistance (AMR) and magnetic anisotropy (MA) of (Ga,Mn)As is systematically investigated in layers grown on relaxed (In,Ga)As/GaAs templates. By choosing different In contents, the vertical strain ε_{zz} in the (Ga,Mn)As layers could be varied over a wide range from tensile to compressive, including the case of (nearly) zero strain. The AMR and the MA of the as-grown and annealed samples were probed at 4.2 K by means of angle-dependent magnetotransport measurements. The respective resistivity and anisotropy parameters, determined by an appropriate fitting procedure, were found to linearly vary with ε_{zz}. The MA was additionally manipulated by preparing narrow stripes from the (Ga,Mn)As layers, resulting in an in-plane uniaxial contribution to the free energy, which is not present in unstrained samples.

Keywords (Ga,Mn)As · (In,Ga)As · Strain · Anisotropic magnetoresistance · Magnetic anisotropy

Anisotropic magnetoresistance (AMR) and magnetic anisotropy (MA) are characteristic features of the dilute ferromagnetic semiconductor (Ga,Mn)As making it potentially suitable for novel spintronic applications such as nonvolatile memories or magnetic-field-sensitive devices [1]. Although the AMR and the MA are known to be very sensitive to strain, experimental studies addressing this issue have so far been restricted to merely a limited number of representative samples with compressive or tensile strain.

In this work, we analyze the influence of strain on the AMR and the MA in a systematic way by investigating a series of differently strained (Ga,Mn)As layers grown by molecular-beam epitaxy on relaxed (In,Ga)As/GaAs templates with different In content [2]. After the deposition of a thin GaAs buffer layer on semiinsulating GaAs(001) at $T_S \approx 580\,^\circ$C, a graded (In,Ga)As layer with an In content between 0 and 12% was grown at $\sim$430 °C. A 180-nm-thick (Ga,Mn)As layer with 5% Mn was then grown on the (In,Ga)As/GaAs template at $\sim$250 °C. After the growth, the samples were cleaved into several pieces and some of them were annealed in air for 1 h at 250 °C. High-resolution X-ray diffraction reciprocal space mapping of the (224) reflex was used to determine the vertical strain $\varepsilon_{zz} = (a_\perp - a_{\mathrm{rel}})/a_{\mathrm{rel}}$ of the (Ga,Mn)As layers, where the relaxed lattice constants a_{rel} were derived from the lateral and vertical lattice constants $a_\parallel$ and $a_\perp$, respectively, applying Hooke's law. The values of ε_{zz} were found to gradually vary from +0.22% for the most compressively strained sample with 0% In to −0.46% for the most tensely strained sample with 12% In. For the magnetotransport measurements, two types of Hall bars with current directions along [100] and [110] were prepared. The hole densities p were determined by means of high-field magnetotransport measurements (up to 14.5 T) at 4.2 K, and the Curie temperatures T_C were estimated from the peak positions of the temperature-dependent sheet resistivities at 10 mT. The values were found to scatter only slightly around $p = 3.4 \times 10^{20}$ cm^{-3} and $T_C = 66$ K for the as-grown samples and $p = 5.8 \times 10^{20}$ cm^{-3} and $T_C = 91$ K for the annealed samples.

MA is referred to as the dependence of the free-energy density F on the orientation $\boldsymbol{m}$ of the magnetization

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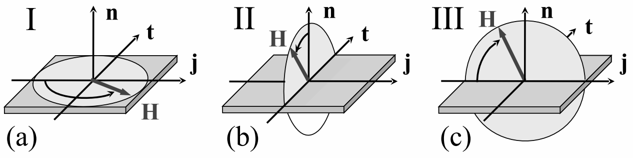

Fig. 1 The external field $\boldsymbol{H}$ was rotated within three different planes (**a**) perpendicular to $\boldsymbol{n}$, (**b**) perpendicular to $\boldsymbol{j}$, and (**c**) perpendicular to $\boldsymbol{t}$

$\boldsymbol{M} = M\boldsymbol{m}$.[1] Our theoretical considerations are based on a single-domain model assuming the magnitude M of the magnetization to be constant under the given experimental conditions. Hence, the normalized quantity $F_M = F/M$ is considered instead of F, allowing for a concise description of the MA. In the presence of an external magnetic field $\boldsymbol{H} = H\boldsymbol{h}$, the Zeeman energy $-\mu_0\boldsymbol{Hm}$ has to be added to F_M. The resulting normalized free-enthalpy density reads as

$$G_M(\boldsymbol{m}) = (B_{2\perp} + B_{\mathrm{d}})m_z^2 + B_{4\|}\left(m_x^4 + m_y^4\right) + B_{4\perp}m_z^4 + B_{\bar{1}10}(m_x - m_y)^2/2 - \mu_0 H\boldsymbol{hm} + \text{const.} \tag{1}$$

The anisotropy parameters $B_{2\perp}$, $B_{4\|}$, and $B_{4\perp}$ refer to intrinsic contributions arising from the spin–orbit coupling in the valence band. The parameters B_{d} and $B_{\bar{1}10}$ describe the demagnetization energy of an infinite plane (shape anisotropy) and a uniaxial in-plane contribution, respectively. In the case of a perfect cubic crystal, symmetry requires $B_{2\perp} = 0$ and $B_{4\|} = B_{4\perp}$. Given an arbitrary magnitude and orientation of $\boldsymbol{H}$, the direction of $\boldsymbol{m}$ is determined by the minimum of G_M with respect to the components of $\boldsymbol{m}$.

In the present work, the AMR and the MA were probed by means of angle-dependent magnetotransport at 4.2 K [3, 4]. The longitudinal and transverse resistivities ρ_{long} and ρ_{trans}, respectively, were measured as functions of the magnetic field orientation at fixed field strengths of $\mu_0 H = 0.11$, 0.26, and 0.65 T. For this purpose, the Hall bars were mounted on the rotatable sample holder of a liquid-He-bath cryostat allowing for any orientation of the Hall bars with respect to the field $\boldsymbol{H}$. The cryostat was positioned between the poles of an electromagnet system providing a maximum field strength of 0.68 T. At each field strength, $\boldsymbol{H}$ was rotated within three different crystallographic planes perpendicular to the directions $\boldsymbol{n}$, $\boldsymbol{j}$, and $\boldsymbol{t}$, respectively. The corresponding configurations, labeled I, II, and III, are shown in Fig. 1.

The vector $\boldsymbol{j}$ defines the current direction, $\boldsymbol{n}$ the surface normal, and $\boldsymbol{t}$ the transverse direction. For current directions $\boldsymbol{j} \parallel [100]$ and $\boldsymbol{j} \parallel [110]$, the resistivities can be written as [4]

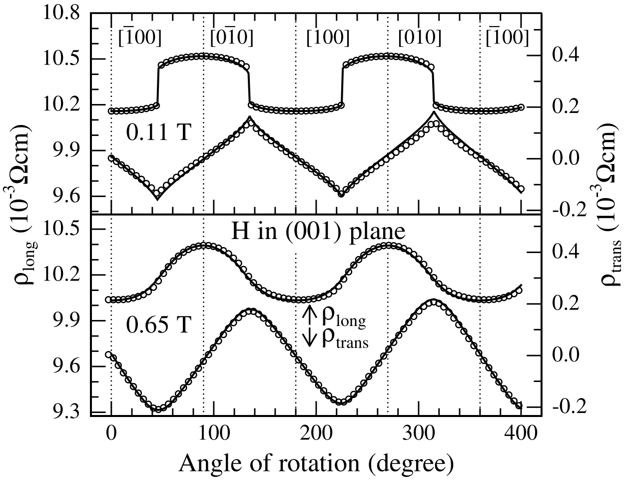

Fig. 2 Resistivities ρ_{long} and ρ_{trans} recorded from the (Ga,Mn)As layer with $\varepsilon_{zz} = -0.04\%$ at 4.2 K and $\mu_0 H = 0.11$ and 0.65 T (*open circles*). $\boldsymbol{H}$ was rotated in the (001) plane (configuration I), and the direction of $\boldsymbol{j}$ was along [100]. The *solid lines* are fits to the experimental data using (2) and one single set of resistivity and anisotropy parameters

$$\rho_{\mathrm{long}} = \rho_0 + \rho_1 m_j^2 + \rho_2 m_n^2 + \rho_3 m_j^4 + \rho_4 m_n^4 + \rho_5 m_j^2 m_n^2, \tag{2}$$
$$\rho_{\mathrm{trans}} = \rho_6 m_n + \rho_7 m_j m_t + \rho_8 m_n^3 + \rho_9 m_j m_t m_n^2,$$

where m_j, m_t, and m_n denote the components of $\boldsymbol{m}$ along $\boldsymbol{j}$, $\boldsymbol{t}$, and $\boldsymbol{n}$, respectively. At sufficiently high magnetic fields, the Zeeman energy in $G_M(\boldsymbol{m})$ dominates, and the magnetization direction $\boldsymbol{m}$ follows the orientation $\boldsymbol{h}$ of the external field. The resistivity parameters ρ_i are then obtained from a fit of (2) to the experimental data recorded at 0.65 T. With decreasing field strength, the influence of the MA increases, and $\boldsymbol{m}$ more and more deviates from $\boldsymbol{h}$. Controlled by the anisotropy parameters B_i, the shape of the measured curves changes, and the B_i are obtained from a fit to the data recorded at $\mu_0 H = 0.26$ and 0.11 T. In the fit procedure, $\boldsymbol{m}$ is calculated for any given field $\boldsymbol{H}$ by numerically minimizing G_M with respect to $\boldsymbol{m}$. Figure 2 exemplarily shows the angular dependence of ρ_{long} and ρ_{trans} for a nearly unstrained as-grown (Ga,Mn)As layer at $\mu_0 H = 0.11$ and 0.65 T with $\boldsymbol{H}$ rotated in the (001) plane (configuration I). The experimental data are depicted by open circles and the fits by solid lines.

Applying the procedure described above to the whole series of (Ga,Mn)As layers, the resistivity and anisotropy parameters were determined as a function of the vertical strain ε_{zz}. Due to length restrictions, the resistivity data are only presented for the as-grown samples.

Whereas the values obtained for ρ_0 randomly scatter in the range from 5.0×10^{-3} to 8.8×10^{-3} Ω cm, presumably due to variations in the hole concentration and mobility, a distinct linear correlation with ε_{zz} is found for the normalized quantities ρ_i/ρ_0 $(i = 1, \ldots, 8)$. Figure 3 shows the results for $\boldsymbol{j} \parallel [100]$. The parameter ρ_9/ρ_0 (not shown) turned

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[1] Throughout this work, unit vectors are denoted by bold lower-case letters.

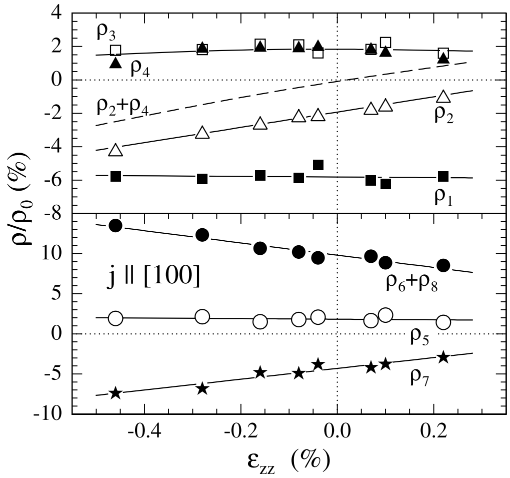

Fig. 3 Normalized resistivity parameters ρ_i/ρ_0 ($i = 1, \ldots, 8$) for $\boldsymbol{j} \parallel [100]$ plotted against the vertical strain ε_{zz}. The *solid lines* are smoothing splines and are drawn to guide the eye

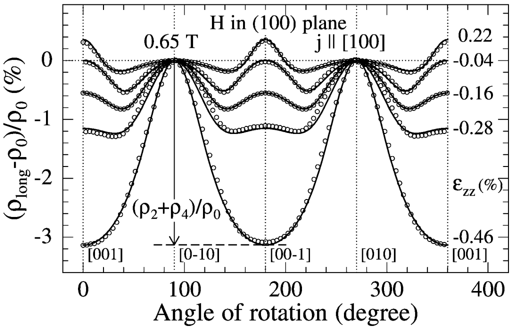

Fig. 4 Variation of the angle-dependent normalized longitudinal resistivity $(\rho_{\mathrm{long}} - \rho_0)/\rho_0$ with vertical strain ε_{zz} at $\mu_0 H = 0.65$ T and $T = 4.2$ K recorded in configuration II

out to be negligibly small. The effect of strain on the AMR is exemplarily demonstrated in Fig. 4, where the variation of the angle-dependent normalized longitudinal resistivity $(\rho_{\mathrm{long}} - \rho_0)/\rho_0$ with ε_{zz} is depicted.

The dependence of the anisotropy parameters $B_{2\perp} + B_{\mathrm{d}}$ on ε_{zz} is shown in Fig. 5(a) for the as-grown and annealed samples. For zero strain, the cubic symmetry requires $B_{2\perp} = 0$. Inferring the strain-independent parameter B_{d} from the intercept of the vertical axis, we obtain $B_{2\perp}$ as a function of ε_{zz}. Normalizing $B_{2\perp}$ to the corresponding hole concentrations p yields the same linear dependence of $B_{2\perp}/p$ on ε_{zz} for both the as-grown and the annealed samples as shown in Fig. 5(b). We thus find the experimental relationship $B_{2\perp} \propto p\,\varepsilon_{zz}$. The values for the fourth-order parameters $B_{4\parallel}$ and $B_{4\perp}$ (not shown) are nearly independent of ε_{zz} with values scattering around -30 mT. The uniaxial in-plane contribution $B_{\bar{1}10}$ turns out to be negligibly small in the samples under study.

Narrow stripes along [010] were prepared from a second series of 40-nm-thick (Ga,Mn)As layers in order to additionally manipulate the MA by in-plane strain relaxation perpendicular to the stripes. The stripes were 50 µm long, and their width was varied from 12.8 µm down to 60 nm. The anisotropy parameter B_{100} of the resulting additional contribution $B_{100} m_x^2$ to G_M in (1) was studied as a function of the stripe width for different ε_{zz} of the unpatterned layers. The result is depicted in Fig. 6. For $\varepsilon_{zz} \approx 0$, no significant variation of B_{100} is observed demonstrating that changes in the shape anisotropy only play a minor role. The drastic increase (decrease) of B_{100} with decreasing stripe width in the compressively (tensely) strained layer reveals that, due to strain relaxation, the direction [100] perpendicular to the stripe becomes magnetically harder (easier) compared to the [010] direction along the stripe.

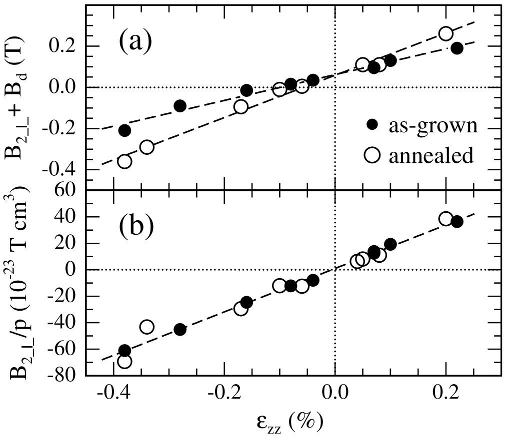

Fig. 5 Dependence of (**a**) the anisotropy parameters $B_{2\perp} + B_{\mathrm{d}}$ and (**b**) the ratio $B_{2\perp}/p$ on the strain ε_{zz}

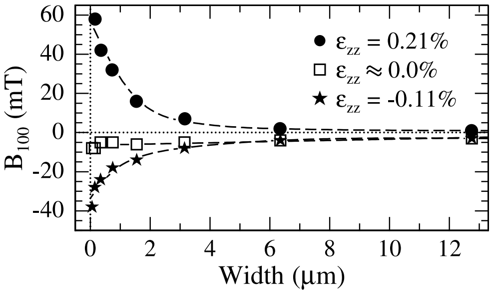

Fig. 6 Dependence of the anisotropy parameter B_{100} on the stripe width for different vertical strains ε_{zz}

In summary, the strain in a series of (Ga,Mn)As layers was gradually varied from compressive ($\varepsilon_{zz} = +0.22\%$) to tensile ($\varepsilon_{zz} = -0.46\%$) using relaxed (In,Ga)As/GaAs templates with different In content. The resistivity and anisotropy parameters derived from angle-dependent magnetotransport measurements show a linear dependence on ε_{zz}. In particular, the uniaxial out-of-plane anisotropy field $B_{2\perp}$ was found to be proportional to both ε_{zz} and p. Preparing narrow stripes from the (Ga,Mn)As layers, an additional width-dependent uniaxial in-plane magnetic anisotropy was introduced due to strain relaxation perpendicular to the stripes.

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