Anisotropic magnetoresistance in $Ga_{1-x}Mn_xAs$

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We have measured the magnetoresistance in a series of $Ga_{1-x}Mn_xAs$ samples with $0.033 \leqslant x \leqslant 0.053$ for three mutually orthogonal orientations of the applied magnetic field. The spontaneous resistivity anisotropy (SRA) in these materials is negative (i.e., the sample resistance is higher when its magnetization is perpendicular to the measuring current than when the two are parallel) and has a magnitude on the order of 5% at temperatures near 10 K and below. This stands in contrast to the results for most conventional magnetic materials where the SRA is considerably smaller in magnitude for those few cases in which a negative sign is observed. The magnitude of the SRA drops from its maximum at low temperatures to zero at T_C in a manner that is consistent with mean-field theory. These results should provide a significant test for emerging theories of transport in this new class of materials.

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The recent discovery of ferromagnetism at temperatures as high as 110 K in $Ga_{1-x}Mn_xAs$ has greatly broadened interest in diluted magnetic semiconductors over the past few years.[1–3] A large number of groups are now investigating these materials which could form the basis for a wide variety of new magnetoelectronic devices that may be grown pseudomorphically on GaAs. The utility of similar devices has already been established using nanocomposite structures based on metallic magnetic materials (the so-called giant magnetoresistance and tunnel junction magnetoresistance[4,5]). The semiconducting materials open up new opportunities as they also introduce the prospects of optical or electronic control of the magnetic properties.[6,7]

These new materials present many interesting challenges as we embark on efforts to make use of their properties in real devices. These challenges come from both the fundamental point of view (trying to understand their properties and what factors control them) and from the desire to manufacture high-quality materials in the face of the severe constraints imposed by the possibility of nucleating unwanted phases during growth.[2] These two challenges are intimately connected since the density of carriers is expected to influence such material properties as the Curie temperature and magnetic anisotropy,[8,9] but this density is strongly influenced by defects included in the structure as a result of the constraints on the growth conditions.

In view of our limited understanding of these materials it is prudent to spend some effort exploring the transport properties of individual material layers in preparation for constructing multilayered structures to form devices. Toward that end, in this article we report on magnetotransport measurements in a series of $Ga_{1-x}Mn_xAs$ films ($x=0.033$ to 0.053). We concentrate on the dependence of the film resistivity on the orientation of an applied magnetic field in the hope that this dependence might be less sensitive to the details of the disorder in the films than is the resistivity itself.

The Mn-alloyed films were grown at temperatures in the range of 275–285 °C. The substrates were cleaved from GaAs wafers and prior to growth of the alloy two GaAs buffer layers were deposited (the first one 100 nm thick and grown at 550 °C and the second one 300 nm thick and grown at the alloy growth temperature). The important physical properties of the films are listed in Table I. The nominal concentrations were determined by comparing the film lattice constant (determined from the 004 reflection) to the values given by Ohno *et al.*[1] (but note that this can lead to systematic errors as the lattice constant can also depend on the growth conditions as pointed out by Schott *et al.*[10]). The paramagnetic Curie point for each film was determined by assuming that the Hall resistance is dominated by the extraordinary Hall effect for small fields and temperatures not too far above T_C. We then linearly extrapolate the inverse low-field Hall resistance above T_C to zero in order to establish T_C. The films were patterned into standard Hall-bar geometry (sample dimensions were 3.4 mm long with 1.8 mm between the longitudinal voltage leads and 350 μm wide) using conventional photolithography and etching in a solution of (H_2SO_4:H_2O_2:H_2O) in the ratio (1:8:10). The resistance was measured using Ohmic In contacts to connect the sample to a Quantum Design 1802 bridge. Fields up to 6 T were applied over a temperature range extending from 1.4 K to above T_C. The slight compressive strain imposed on the films by the substrate results in an intrinsic magnetic anisotropy with an in-plane easy axis.[2,9]

In describing this orientational dependence of the magnetotransport we will use a coordinate system in which the z axis defines the film growth direction and the x axis lies along the direction of the measuring current. Figure 1 shows the magnetoresistance for three $Ga_{1-x}Mn_xAs$ films ($x=0.033$, 0.048, and 0.053) for situations where the magnetic field is oriented along each of the three axes at a temperature

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TABLE I. Physical properties of $Ga_{1-x}Mn_xAs$ films.

x (nom) ± 0.005	t (nm) ± 30 nm	T_G (°C) ± 5 °C	ρ_{300} ($\mu\Omega$ m) $\pm 5\%$	$\rho_{4.2}$ ($\mu\Omega$ m) $\pm 5\%$	T_C (K) ± 3 K	p (nm^{-3}) $\pm 20\%$	$SRA_\perp$ (at 4.2 K) $\pm 10\%$
0.033	300	285	54	67	43	0.37	−0.070
0.048	300	275	57	71	57	0.30	−0.045
0.053	300	275	61	79	52	0.23	−0.051

of 15 K (here and in the following we use the notation H_x, H_y, and H_z to refer to an applied field directed along the indicated axis). Similar data are seen for other temperatures below the Curie temperature. Two features are immediately apparent from the data in this figure. First, there is the overall negative magnetoresistance seen for large fields, and second, the resistance obtained by extrapolating the high-field behavior to zero field differs for the three field orientations. The first has been noted before, and it has been attributed to a field-induced reduction in the spin disorder responsible for much of the resistance near T_C.[11] The second feature is the spontaneous resistivity anisotropy (SRA), which has not yet been systematically studied in the new ferromagnetic semiconductors but is a familiar magnetotransport property in conventional magnetic materials.[12]

Figure 2 exhibits the anisotropic magnetoresistance (AMR) as differences between the magnetoresistance (MR) seen for fields applied perpendicular to the current (i.e., H_z or H_y) and that seen for a field applied along the current (H_x). In this figure these differences have been normalized to the zero-field value of the resistance. The rapid drop in the AMR seen at low fields in this figure represents the SRA and we note that, contrary to the behavior seen in most conventional ferromagnets, the resistivity of these new materials is greater when the magnetization is oriented perpendicular to the current than when it lies parallel to the current. This no doubt contributes to the familiar low-field peaks seen in typical MR data on $Ga_{1-x}Mn_xAs$ for fields oriented perpendicular to the sample plane.[11] When the applied field is sufficient to overcome the intrinsic anisotropy of the material, the resistivity increases as some domains that were originally aligned with the current are reoriented out of the plane (thereby increasing the resistivity of that portion of the sample). To confirm this interpretation we note that the peaks are also present when the field is applied in the plane as long as it is perpendicular to the current, but are absent when the field is applied along the current.

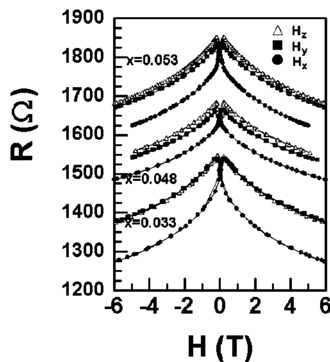

FIG. 1. Resistance as a function of magnetic field at $T=15$ K for $Ga_{1-x}Mn_xAs$ films with three different values of x and three different orientations of the magnetic field.

Looking at Fig. 2, it is apparent that the AMR for the two more concentrated samples is not restricted to low fields. The out-of-plane AMR ($AMR_\perp$) shows a distinct field dependence above 0.5 T for $x=0.048$ and 0.053, which indicates that for these samples the high-field MR also depends on the field orientation. As-grown samples of GaMnAs exhibit a

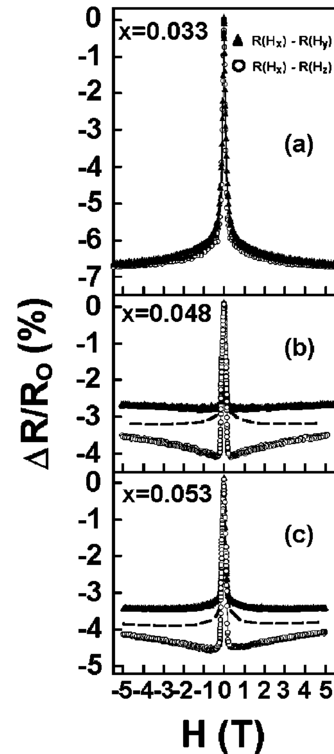

FIG. 2. Anisotropic magnetoresistance obtained from the data in Fig. 1 by subtracting from the data obtained with fields applied along the direction of the current (the x direction) those data taken with the field oriented along the y or z axes (giving $AMR_\parallel$ and $AMR_\perp$, respectively). Ignoring small effects from demagnetization, the extrapolation of the high-field value of this difference to zero field defines the spontaneous resistivity anisotropy for both the in-plane and out-of-plane conditions. The dashed line shown in (b) and (c) demonstrates that the upward trend seen in $AMR_\perp$ for these two samples may be attributed to an extra ordering field that suppresses in-plane spin disorder when the magnetization lies in the plane of the sample (see text).

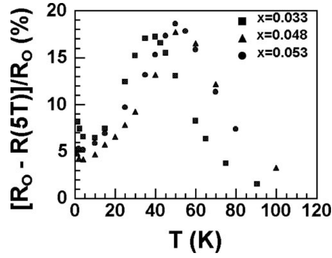

FIG. 3. Temperature dependence of the magnitude of the longitudinal magnetoresistance at relatively high fields. We define the MR as the resistivity in a field of 5 T applied parallel to the current minus the resistivity in zero field normalized to the latter value. Note the peak near T_C and the nonzero value reached for low temperatures.

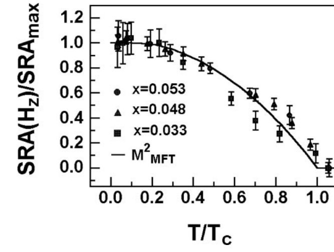

FIG. 4. The normalized temperature dependence of the $SRA_\perp$ for the three samples compared to the variation expected for the square of the magnetization in a mean-field Heisenberg ferromagnet with $S=5/2$.

distinct peak in the temperature dependence of their resistivity and this peak has been demonstrated to arise from spin fluctuations by comparing the temperature variation of the resistivity above T_C to the magnetic susceptibility (as expected from the fluctuation-dissipation theorem).[13,14] If we assume that high-field MR is due to the suppression of similar spin disorder by the applied field, then the behavior exhibited in Fig. 2 indicates an anisotropy in that spin disorder below T_C. To gain some insight into the origin of this anisotropy we consider the dashed lines shown in Figs. 2(b) and 2(c), which represent the quantity $[R(H_z+H_o)-R(H_x)]$, as a function of the applied field strength. Here, the field strength is given by $|H_z|=|H_x|$, and H_o represents a small offset field (0.4 T for $x=0.048$ and 0.3 T for $x=0.053$). These "shifted-field" $AMR_\perp$ data for these two compositions look remarkably like the in-plane AMR data in character. We therefore attribute the upward trend seen in the raw $AMR_\perp$ data (open circles in Fig. 2) to an extra in-plane ordering field. We note, however, that this extra field is not sufficient to account entirely for the observed difference between the in-plane and out-of-plane SRA ($SRA_\parallel$ and $SRA_\perp$, respectively, below) in our two more concentrated samples. This suggests that the SRA is not dependent solely on the relative orientation of the current and the magnetization in these two samples; there is also a contribution that depends on the orientation of these two vectors with respect to the sample's crystal structure which has a slight tetragonal distortion due to the substrate.

Some additional insight into the disorder present in these films may be obtained by looking at the temperature dependence of the high-field MR. In Fig. 3 we plot the MR (defined as the difference between the zero-field value of the resistance and the resistance at 5 T, normalized to the zero-field value) as a function of temperature. This MR reaches a maximum magnitude near T_C. This helps to confirm magnetic disorder as the origin of the well-known peak in the resistivity itself near T_C which has been attributed to critical spin fluctuations.[13] Interestingly, the MR does not approach zero as the temperature is lowered but rather saturates at a value near -5%. This suggests that a substantial portion of the spin disorder in these samples is not critical, or even thermal, in origin but rather reflects the presence of frustration in the spin system. The data shown in this figure are taken with the field aligned parallel to the measuring current, but similar data (though they differ slightly in magnitude) are seen for the other two orientations of the magnetic field.

Spin-orbit coupling lies at the heart of any description of the SRA (since the phenomenon itself intimately links the carrier spin with its orbital motion) but quantitative descriptions also depend upon the details of the Fermi surface and a model of transport for the materials in question. Theoretical descriptions of the SRA in conventional magnetic materials are typically described within a parallel conduction model for the transport (one channel for spin-up electrons, another for spin-down electrons) and spin-orbit coupling is treated as a perturbation.[12,15] However, in $Ga_{1-x}Mn_xAs$ the spin-orbit coupling strength is comparable to the Fermi energy,[9] so such a parallel conduction model for transport is not appropriate for these materials. In order to assist those trying to develop more appropriate theories for these materials, we provide some additional information on our samples along with some qualitative analysis below.

We have determined the carrier concentration in our samples by measuring the Hall resistance in very large magnetic fields (up to 55 T) at low temperatures (down to 600 mK) using the pulsed-field facility at Los Alamos National Lab.[16] For such extreme conditions, the extraordinary effect should saturate and therefore the slope of Hall resistance versus applied field for fields above 20 T can be used to determine the carrier concentration (p).[3] The carrier concentrations so derived are displayed in Table I. We also note, as displayed in Fig. 4, that the temperature dependence of $SRA_\perp$ is consistent with the behavior expected for a mean-field Heisenberg model. This indicates that a mean-field approach might be adequate to describe the SRA even though its validity for predicting the Curie temperature and the temperature dependence of the magnetization has been called into question.[8,17,18] The adequacy of the mean-field approach in this case may reflect our extrapolation from field greater than 0.3 T back to zero in determining the SRA. Fields this large may be sufficient to suppress any fluctuations in these samples beyond those expected from mean-field behavior.

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