Magnetotransport properties in $(1\bar{1}00)$- and (0001)-oriented MnAs films on GaAs substrates

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Magnetic-field dependence of the resistivities in MnAs$(1\bar{1}00)$ films on GaAs(001) and MnAs(0001) films on GaAs(111)B is investigated at low temperatures. Correspondence of the features in the longitudinal and transverse resistivities under reorientations of the magnetization enables us to distinguish the anisotropic magnetoresistance effect from the effects originating from the band structure of MnAs. Simultaneous contributions of holes and electrons are evidenced for the $(1\bar{1}00)$-oriented films, whereas the transport is almost completely dominated by holes for the (0001)-oriented films. The magnetization flip by an in-plane magnetic field applied along the magnetic easy axis generates jumps in the longitudinal resistivity owing to the magnetoresistance originating from the band-structure effect. © *2007 American Institute of Physics*.
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I. INTRODUCTION

Manganese arsenide is a room-temperature ferromagnetic material that can be grown epitaxially on GaAs substrates.[1,2] By choosing appropriate substrate orientations and growth conditions, a number of epitaxial orientations can be realized. Given the strong magnetocrystalline anisotropy of MnAs, the consequent control on the alignment of the magnetic easy and hard axes with respect to the surface provides a potential for unconventional magnetic devices. For instance, the uniaxial magnetocrystalline anisotropy in MnAs$(1\bar{1}00)$ films on GaAs(001) can overcome the constraints imposed by microstructuring such as the shape anisotropy:[3] The magnetic moments in narrow wires can remain fixed in the direction orthogonal to the wires.[4] The dynamics of magnetic domains, i.e., the formation and propagation of domain walls in the highly anisotropic media is hence intriguing.[5] For such investigations, not only a direct observation of the magnetic domain structures using magnetic microscopies but also their electrical characterization is possible by utilizing the dependence of the resistivity on the angle φ between the magnetization and current. The anisotropic magnetoresistance (AMR) effect is given by[6]

$$\rho_{xx} = \rho_{\perp} + (\rho_{\parallel} - \rho_{\perp})\cos^2 \varphi, \tag{1}$$

$$\rho_{xy} = \alpha(\rho_{\parallel} - \rho_{\perp})\sin \varphi \cos \varphi, \tag{2}$$

where $\rho_{\parallel}$ and $\rho_{\perp}$ are the resistivities for current oriented parallel and perpendicular to the magnetization, respectively. The numerical factor $\alpha(\leq 1)$ depends on the crystalline symmetry of the system.[7] The coupling of the electronics and the magnetics, in turn, promises implementation of electrical devices based on the magnetic-domain and/or domain-wall phenomena.

In this paper, the transport properties in the Hall bars fabricated from MnAs thin films on GaAs substrates are examined. We infer the rotation of the magnetization of MnAs driven by an external magnetic field from the coincident features in the longitudinal and transverse resistivities under certain field directions. The analysis also enables us to identify the galvanomagnetic effects originating from the band structure of MnAs. We find two-band transport for MnAs$(1\bar{1}00)$ films on GaAs(001) while the transport is almost exclusively dominated by holes in MnAs(001) films on GaAs(111)B.

II. EXPERIMENT

Epitaxial MnAs films were prepared on GaAs substrates by molecular-beam epitaxy at growth temperatures of 220 −250 °C.[2] The thickness of the films was 50 nm. Hall-bar structures were patterned from the MnAs films using electron-beam lithography and Ar ion milling.[8] The width of MnAs channels was between 10 and 30 μm. The distance between the voltage leads was 350−600 μm. The resistivities of the MnAs channels were measured using the four-probe lock-in technique at a temperature of $T=0.3$ K. The excitation current was about $I=1$ μA.

Systematic magnetotransport measurements were carried out on a $(1\bar{1}00)$-oriented MnAs film grown on a GaAs(001) substrate. For this crystal orientation, the [0001] and $[11\bar{2}0]$ directions of MnAs are parallel to the $[1\bar{1}0]$ and [110] directions of GaAs, respectively. The film possesses a strong uniaxial magnetocrystalline anisotropy.[9] The in-plane magnetic easy axis is along the $[11\bar{2}0]$ direction, whereas the hard axis lies along the [0001] direction (see Fig. 1). We investigated the transport properties by applying an external magnetic field along the easy or hard axis or normal to the film. For comparison, magnetoresistances were examined also when a magnetic field was applied normal to a (0001)-oriented film grown on a GaAs(111)B substrate. The (0001) plane is the magnetic easy plane in the latter system. Thus, the in-plane transport properties are isotropic, apart from the weak magnetocrystalline anisotropy imposed by the substrate.[10]

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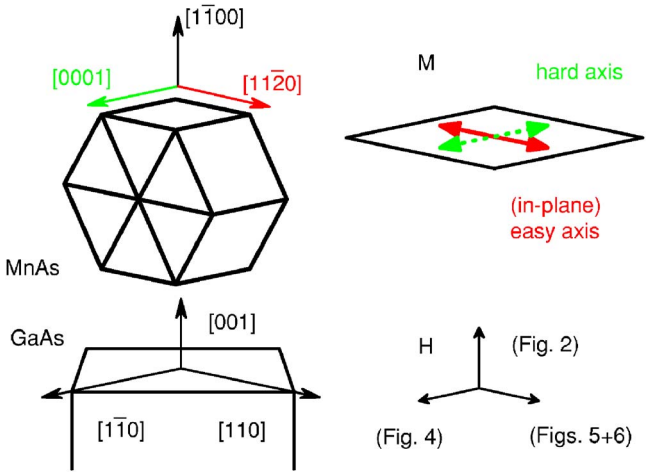

FIG. 1. Epitaxial relationship of a MnAs(1$\bar{1}$00) film on a GaAs(001) substrate. The in-plane magnetic easy axis of the magnetization M is parallel to the [11$\bar{2}$0] direction of MnAs. The magnetic hard axis is along the [0001] direction of MnAs. The direction of the external magnetic field H in Figs. 2 and 4–6 is indicated.

III. BAND-STRUCTURE EFFECTS

In Figs. 2(a) and 2(b), we show the magnetic-field dependence of the transverse resistivity ρ_{xy} and the longitudinal resistivity ρ_{xx}, respectively. An external magnetic field H was applied normal to the surface of the MnAs(1$\bar{1}$00) film on GaAs(001). The field dependencies of both ρ_{xy} and ρ_{xx} are qualitatively independent of the direction of the current, which is being along either the [0001] or [11$\bar{2}$0] direction in Fig. 2. (We, therefore, find $\rho_{\parallel} < \rho_{\perp}$.) The slope of $\rho_{xy}(H)$ is positive (hole-like) for $|H| < 20$ kOe but turns to be negative (electron-like) for $|H| > 30$ kOe, in agreement with the report by Berry *et al.*[11] Electrons and holes are thus indicated to be simultaneously involved in the transport. Note that the variation of ρ_{xy} with H becomes almost linear in high fields.

The magnetoresistance is positive for the entire magnetic-field range. The kink at $H \approx \pm 15$ kOe manifests the alignment of the magnetization to the out-of-the-plane direction. We emphasize that the kink was not detected in ρ_{xx} in the report by Berry *et al.*,[11] attesting to the superior quality of the materials employed in the present paper. The increase of ρ_{xx}, $\Delta\rho = \rho_{xx}(H) - \rho_{xx}(0)$, at low fields follows $\Delta\rho \propto |H|^{1.72}$ and $|H|^{1.67}$ when the current is along, respectively, the [0001] and [11$\bar{2}$0] directions [see the inset of Fig. 2(b)]. Beyond the field of the out-of-the-plane reorientation of the magnetization, a trend of saturation is observed. The field dependence in this regime is again proportional to $|H|^s$ with the exponent $s = 0.58$ and 0.63 (not shown) when the current is along the [0001] and [11$\bar{2}$0] directions, respectively. The two-band transport is responsible for the deviations from the common quadratic magnetic-field dependence as well as the nonmonotonic dependence of ρ_{xy}. [Note that the power-law exponent in the low-field regime is influenced also by the AMR effect, Eq. (1).] In fact, two-band model predicts that ρ_{xx} tends toward saturation in high fields when the densities of electrons and holes are not equal.[12]

For comparison, identical transport measurements were carried out for the MnAs(0001) film on GaAs(111)B. The original data of ρ_{xy} shown by the upper curve in Fig. 3 indicates a mixture of ρ_{xx} due, presumably, to a slight misalignment of the voltage leads. As $\rho_{xy} \ll \rho_{xx}$, the magnetic-field effects in ρ_{xx} could mask those in ρ_{xy}. We have, therefore, nullified ρ_{xy} at $H = 0$ by subtracting the contribution of ρ_{xx} for the lower curve in Fig. 3. Regardless of the correction, the magnetic-field dependence of ρ_{xy} in the (0001)-oriented film is found to be almost linear, in contrast to the unambiguous two-band transport in the (1$\bar{1}$00)-oriented film. The polarity of ρ_{xy} indicates that the transport is dominated almost exclusively by holes. The trend of the saturation of ρ_{xx} in high fields is much weaker for the (0001)-oriented film than that for the (1$\bar{1}$00)-oriented film, which is consistent with the practical one-band transport deduced from ρ_{xy} for the former.

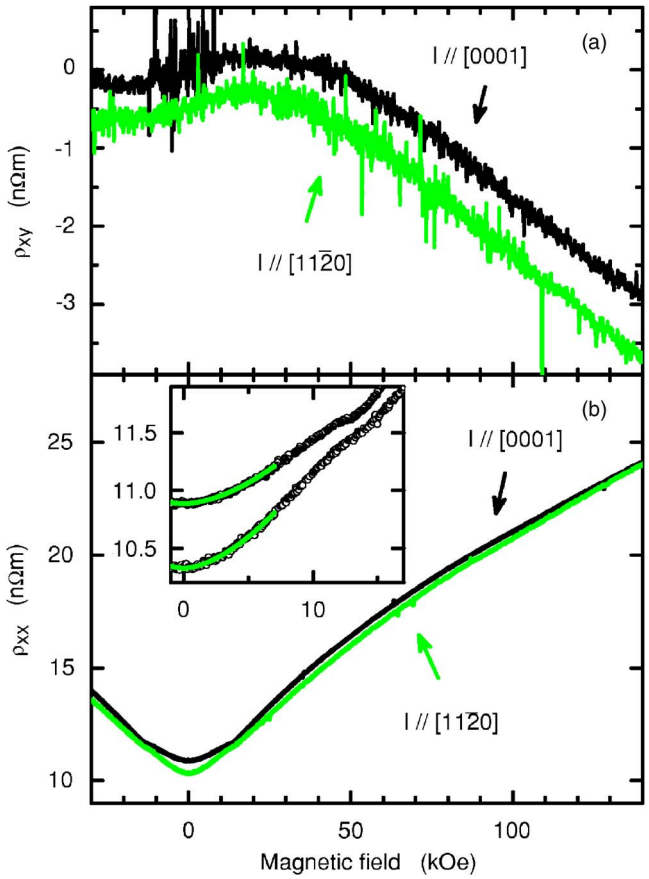

FIG. 2. (a) Transverse resistivity ρ_{xy} and (b) longitudinal resistivity ρ_{xx} in a MnAs(1$\bar{1}$00) film on GaAs(001) at a temperature of 0.3 K. The external magnetic field is applied normal to the surface. The direction of current I is along the [0001] and [11$\bar{2}$0] directions of MnAs. The inset in (b) shows ρ_{xx} (circles) at low fields with expanded scales. The solid curves are a fit to a power-law dependence.

The change of the slope of $\rho_{xy}(H)$ in Fig. 2(a) takes place roughly when the magnetization rotates to be normal to the surface. Therefore, one has to consider a possibility that the hole-like slope of ρ_{xy} around zero magnetic field is merely a consequence of the AMR effect and/or the anomalous Hall effect. The kinks in ρ_{xx} in Fig. 3 indicate that the reorientation of the magnetization to be normal to the surface occurs at $|H| \sim 40$ kOe in the MnAs(0001)/GaAs(111)B system.[14] The linear variation of $\rho_{xy}(H)$ in Fig. 3, in fact, involves a small offset of about ±5 kOe in the vicinity of zero magnetic field. However, no structure corresponding to the magnetization reorientation is found in ρ_{xy} at H

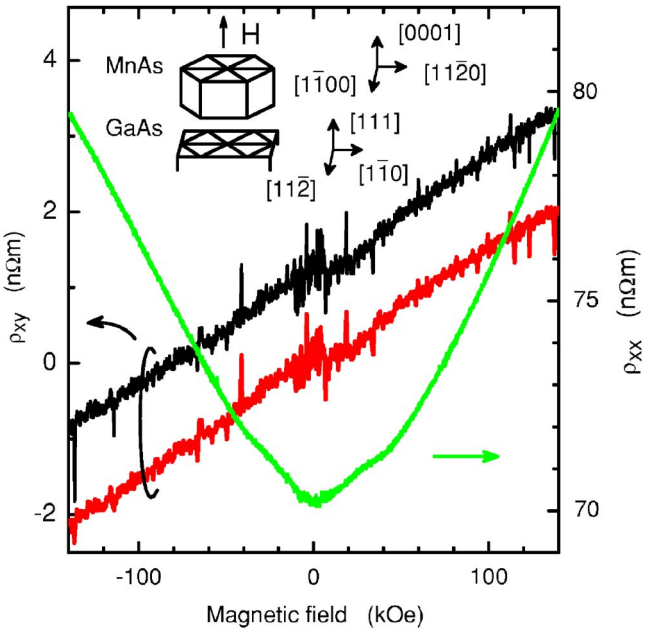

FIG. 3. Transverse resistivity ρ_{xy} and longitudinal resistivity ρ_{xx} in a MnAs(0001) film on GaAs(111)B at a temperature of 0.3 K when an external magnetic field H is applied normal to the surface. The direction of current is along a cleavage direction of the GaAs substrate. The upper curve of ρ_{xy} is the original data. For the lower curve of ρ_{xy}, the mixture of ρ_{xx} has been corrected by adjusting ρ_{xy} to be zero in the absence of magnetic field. The inset shows the epitaxial relationship of the MnAs(0001) film on a GaAs(111)B substrate.

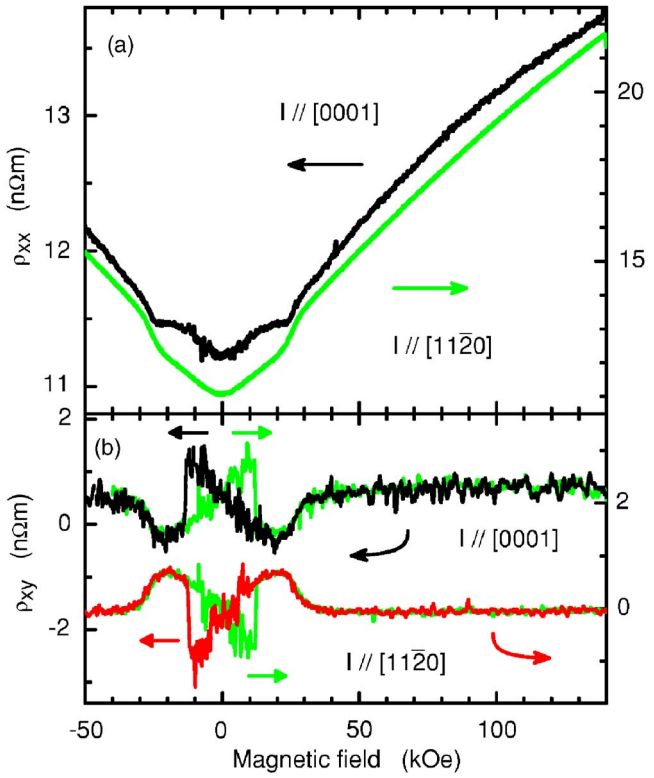

FIG. 4. (a) Transverse resistivity ρ_{xy} and (b) longitudinal resistivity ρ_{xx} in a MnAs(1$\bar{1}$00) film on GaAs(001) at a temperature of 0.3 K. An in-plane external magnetic field is applied along the magnetic hard axis, MnAs[0001]. The direction of current I is along the [0001] and [11$\bar{2}$0] directions of MnAs. The two curves for each direction of current show ρ_{xy} when the magnetic-field sweep is up and down.

$\approx \pm 40$ kOe. Moreover, we have confirmed that misalignments of the magnetic field with respect to the high symmetry directions of the MnAs crystal do not influence ρ_{xy}. A flip of the magnetization component along the easy axis resulting from a misalignment can reverse the sign of the AMR effect. (Such an example will be demonstrated in Fig. 4.) Therefore, the AMR effect and the anomalous Hall effect are concluded to play a insignificant role in the conventional Hall resistance at low temperatures.

As the c-axis orientation of MnAs switches between being parallel and perpendicular to the surface for the two substrate orientations, the contribution of the electrons to the transport properties could be dependent on the crystal orientation if the electrons possess highly anisotropic velocities. However, according to the density functional calculations by Panguluri *et al.*,[13] the velocity anisotropy is expected to be less than a factor of 2. It ought to be pointed out, however, that the carriers in the MnAs films on GaAs(111)B experience considerably stronger disorder scattering than those in the MnAs films on GaAs(001) due, primarily, to an extensive array of misfit dislocations characteristic of the former heterojunction.[2] Nevertheless, as the difference in the resistivities is about a factor of 4 in our devices, the different degrees of the disorder combined with the velocity anisotropy do not seem to be sufficient to almost completely suppress the contribution of the electrons when the substrate is GaAs(111)B.

We attribute the remarkable dependence of the electron contribution on the substrate orientation to the difference in the stress fields imposed by the two types of the substrates. The thermal expansion of MnAs is unusually large, and so the thermal strain may be large enough to dramatically alter the band occupation. The change in the lattice constant along the c axis between the growth temperature and 0 K is about 2%.[15] In addition, the first-order simultaneous magnetic and structural phase transition at the Curie temperature $T_C \approx 313$ K involves an abrupt change in the lattice constant along the a axis with a magnitude of 1.2%. While a hydrostatic pressure of about 0.2 GPa is known to induce even a phase transition in MnAs at low temperatures,[16] the discontinuous change of the stress at T_C was evaluated to be about 0.6 GPa in a 60-nm-thick MnAs film on GaAs(001) (Ref. 17).

The stress in the MnAs layers on GaAs(001) substrates is highly anisotropic. During the growth of MnAs layers, the mismatch in the lattice constants of MnAs and GaAs is almost completely compensated by introducing misfit dislocations.[2] The epitaxial layers are hence free of stress during the growth. Upon cooling from the growth temperature, the MnAs layers are tensile strained as the thermal expansion of MnAs is about an order of magnitude larger than that of GaAs. At the phase transition to the ferromagnetic phase at T_C, the lattice expands abruptly in the directions normal to the c axis, resulting in a change of the stress in the [11$\bar{2}$0] direction to be compressive for the MnAs(1$\bar{1}$00)/GaAs(001) system. In cooling further down to 0.3 K, the tensile stress in the [0001] direction and the compressive stress in the [11$\bar{2}$0] direction both grow stronger.[15] In contrast, the layers experience isotropic compressive

stress at low temperatures for the GaAs(111)B substrates as the MnAs layers are *C*-plane oriented. (The discontinuous change in the lattice constant at T_C due to magnetostriction is larger than the thermal expansion along the *a* axis.) In epitaxial films, one also needs to take into account that the lattice constant in the direction normal to the surface changes in the opposite manner in comparison to the change in the in-plane directions in order to reduce the stress energy. We speculate that these differences in terms of the anisotropy and strength in the stress fields are responsible for the dependence of the band occupation on the substrate orientation.

In a MnAs$(1\bar{1}00)$/GaAs(001) system, the two-band transport was found to be replaced by a hole-dominated transport with increasing temperature.[11] In addition to a possible thermal occupation of hole states, the reduction of the stress at high temperatures may give rise to the change in the conduction type. It was also observed that a large positive magnetoresistance changed to a weak negative magnetoresistance when the transport was dominated solely by holes at high temperatures.[11] Although the resistance change in Fig. 3 is considerably smaller than that in Fig. 2, the magnetoresistance is nevertheless positive. It is thus suggested that the negative magnetoresistance is not necessarily related to the hole domination of the transport. We note also that the small variation amplitude in Fig. 3 could be a consequence of the large carrier scattering in the MnAs(0001)/GaAs(111)B system. The negative magnetoresistance was ascribed to the suppression of the spin-disorder scattering when the magnetic moments are aligned along the external magnetic field. We point out that the positive magnetoresistance in our hole-dominated MnAs(0001)/GaAs(111)B system is not inconsistent with this interpretation as the spin-disorder scattering is insignificant at low temperatures.

The temperature dependence of ρ_{xx} was investigated in Ref. 18, in a temperature range between 258 and 415 K, using the devices employed in the present paper. This temperature range includes the second-order structural phase transition at a temperature of about 390 K as well as the first-order phase transition at T_C. Although the temperature dependence was qualitatively the same between the $(1\bar{1}00)$- and (0001)-oriented films, magnetic-field dependencies would have to be compared in detail to clarify if the difference in the conduction type influences the transport properties. Such an investigation is important as the large magnetocaloric effect around T_C, which originates from the spin scattering of the carriers, is useful for a magnetic refrigeration.[19]

IV. ANISOTROPIC MAGNETORESISTANCE EFFECT

Figures 4–6 show the magnetotransport properties when the magnetic field is oriented in in-plane directions. Throughout this section, we deal with only the MnAs$(1\bar{1}00)$/GaAs(001) system to focus our attention on its strong uniaxial magnetocrystalline anisotropy. In Fig. 4, the in-plane magnetic field was applied along the hard axis, i.e., the MnAs[0001] direction. The current is along either the [0001] or the $[11\bar{2}0]$ direction of MnAs. As the role of the magnetic field is to tilt the magnetization away from the easy axis, the magnetic-field dependence of ρ_{xx} is similar to that in Fig. 2. The magnetic field necessary to forcefully align the magnetization along the hard axis is about 25 kOe (Ref. 14), which is stronger than that to align the magnetization along the "easy axis" in the out-of-the-plane direction (Fig. 2). This is in agreement with the observations in Refs. 3 and 4, that the magnetocrystalline anisotropy was stronger than the shape anisotropy.

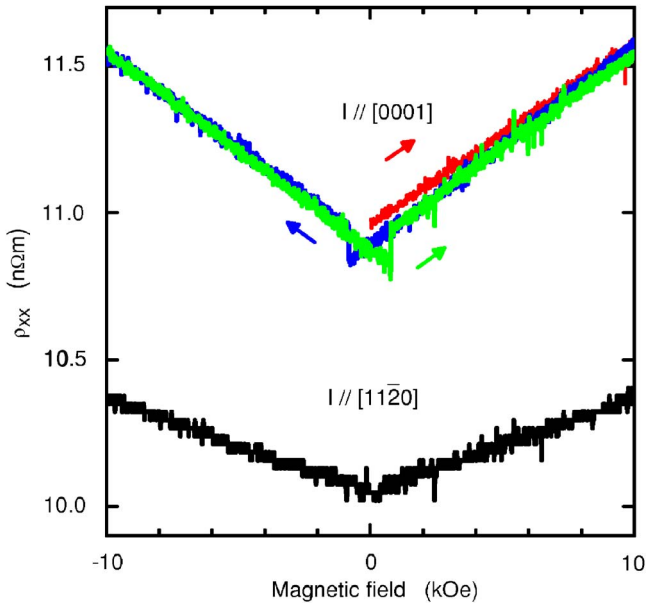

FIG. 5. Longitudinal resistivity ρ_{xx} in a MnAs$(1\bar{1}00)$ film on GaAs(001) at a temperature of 0.3 K when an external magnetic field *H* is applied along the magnetic easy axis, MnAs$[11\bar{2}0]$. The direction of current *I* is along the [0001] and $[11\bar{2}0]$ directions of MnAs. The arrows indicate the direction of the magnetic field sweep. The top-most curve (thin solid curve) is the initial magnetoresistance after cooling from room temperature.

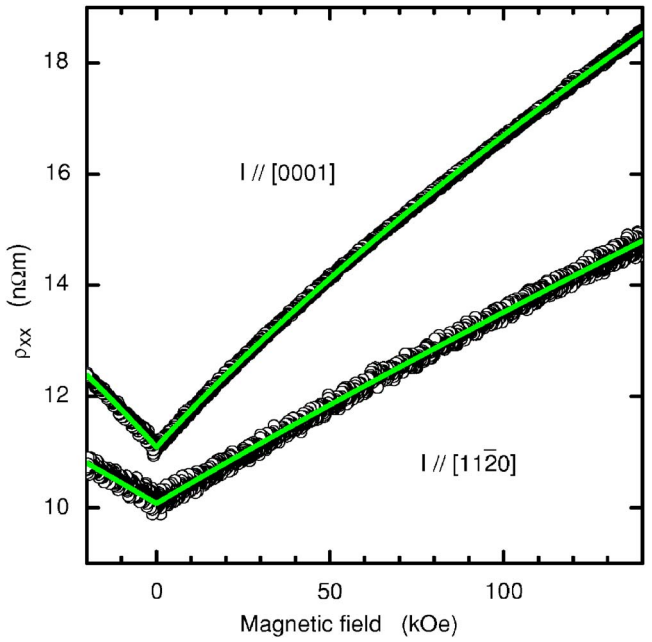

FIG. 6. Longitudinal resistivity ρ_{xx} (circles) in a MnAs$(1\bar{1}00)$ film on GaAs(001) at a temperature of 0.3 K when an external magnetic field *H* is applied along the magnetic easy axis, MnAs$[11\bar{2}0]$. The direction of current *I* is along the [0001] and $[11\bar{2}0]$ directions of MnAs. The solid curves show a fit to $c_0+c_1H+c_2H^{3/2}$.

In contrast to the ordinary Hall effect in Fig. 2(a), ρ_{xy} plotted in Fig. 4 is dominated by the planar Hall effect, Eq. (2). Abrupt jumps are found in ρ_{xy} at $H=\pm 13$ kOe, enabling us to identify a flip of the magnetization. According to Eq. (2), the planar Hall effect is absent when $\varphi=0$ and 90°. We indeed find in Fig. 4 that $\rho_{xy}=0$ at $H=0$ ($\varphi=0$ for $I\|[11\bar{2}0]$ and $\varphi=90°$ for $I\|[0001]$) and in high magnetic fields ($\varphi=90°$ for $I\|[11\bar{2}0]$ and $\varphi=0$ for $I\|[0001]$). The nonzero values of ρ_{xy} at the intermediate magnetic fields are hence associated with the gradual tilting of the magnetization between $\varphi=0$ and 90°. By taking into account an inevitable misalignment of the external magnetic field with respect to the magnetic hard axis, the magnetic-field dependence can be understood as we describe below.[20,21]

Increasing the magnetic field from $H=0$ tilts the magnetization away from the easy axis. Consequently, $|\rho_{xy}|$ increases and reaches the maximum when $\varphi=45°$. Further increase of the magnetic field reduces $|\rho_{xy}|$ to zero in the course of guiding the magnetization to be along the hard axis. When the direction of the magnetic-field sweep is reversed after reaching the highest field, the magnetization rotates from the direction of the hard axis back to that of the easy axis. It is important to recognize here that, due to an inevitable misalignment between the magnetic field and the hard axis, the restoration of the magnetization toward the easy axis is exactly in the reversed manner in comparison to that during the magnetic-field sweep up, as the rotation always progresses in the direction favored by the configuration of the misalignment. The misalignment is the origin of the abrupt jump in ρ_{xy} that occurs when the magnetic-field component in the easy-axis direction exceeds the coercive field at the opposite polarity and hence the magnetization flips from an angle φ to the angle $180°-\varphi$.

In Fig. 2, ρ_{xx} is almost isotropic in high magnetic fields. In contrast, the magnetoresistance is significantly anisotropic in Fig. 4. The magnetization is normal to the current in high magnetic fields irrespective of the direction of the current in Fig. 2, and so the contribution of the AMR effect is identical for both of the current directions. The hexagonal crystal structure of MnAs itself is hence indicated to give rise to only a small in-plane anisotropy. It is noteworthy that the relative magnitudes of ρ_{xx} for the current being along the easy and hard axes reverse with magnetic field. As the magnetization is directed to be parallel to the hard axis by the high magnetic field in Fig. 4, ρ_{xx}, when the current is along the easy axis, becomes larger than that when the current is along the hard axis, i.e., the relationship $\rho_{\|}<\rho_{\perp}$ is maintained irrespective of the direction of the magnetization.

Let us finally turn our attention to the magnetotransport properties when the in-plane magnetic field is applied along the easy axis. The current is parallel to the easy axis (and the magnetic field) for the curve in the bottom half of the panel in Fig. 5. For the set of curves in the top half of the panel, the direction of the current is 90° rotated to be perpendicular to the easy axis. The changes of ρ_{xy} with magnetic field were below the detection limit as φ remains to be almost 0 or 90°. We hence do not show ρ_{xy} for this magnetic-field direction.

The magnetic-field dependence is linear around zero magnetic field. The abrupt jumps in the resistivity at $H\approx\pm 0.8$ kOe are associated with the flip of the magnetization. As the magnetic field is along the magnetic easy axis, the magnetization flips abruptly at the coercive field for both of the measurement configurations in Fig. 5. However, for the device employed in Fig. 5, the flip gives rise to a change in ρ_{xx}, when the current is perpendicular to the magnetization, but is irrelevant for ρ_{xx} when the current is parallel to the magnetization. In several devices we have examined, the jumps always took place in ρ_{xx} when the current was perpendicular to the magnetization, whereas the absence of the jumps when the current was parallel to the magnetization was dependent on the device, i.e., jumps similar to those when the current is perpendicular to the magnetization were observed in some devices. The AMR effect, Eq. (1), is absent when $\varphi=90°$. In addition, it should result in a symmetric contribution in ρ_{xx}. Therefore, the "antisymmetric" contribution that makes the flip of the magnetization observable as a discontinuity in ρ_{xx} originates from the ordinary magnetoresistance effect.

Similar hysteretic behavior observed in a (Ga,Mn)As layer was shown by Goennenwein *et al.*[22] to be a consequence of $\rho_{\perp}$ and $\rho_{\|}$ being linear functions of the effective magnetic field $\mathbf{H}_{\mathrm{eff}}=\mathbf{H}+\beta\mathbf{M}$, where β is a constant.[23] When the magnetic field is varied across $H=0$, $\mathbf{H}$ and $\mathbf{M}$ remain antiparallel to each other until $\mathbf{M}$ is reversed at the coercive field to become parallel to $\mathbf{H}$. If the dependence of $\rho_{\perp}$ and $\rho_{\|}$ on $|\mathbf{H}_{\mathrm{eff}}|$ is linear, the X-shaped magnetic-field hysteresis occurs in ρ_{xx}. According to this interpretation, the separation in magnetic field between the two abrupt jumps corresponds to $2\beta M$, and so we find $\mu_0\beta M=80$ mT. The factor β is estimated to be ~0.1 from the saturation magnetization of MnAs (Ref. 24).

Goennenwein *et al.*[22] have shown that the (negative) magnetic-field dependence of $\rho_{\perp}$ and $\rho_{\|}$ in the (Ga,Mn)As layer[25,26] is given by $\rho(H)=\rho(0)-c_1H+c_2H^{3/2}$, which results in a linear magnetoresistance around $H=0$. This magnetic-field dependence was regarded as evidence for the magnetoimpurity scattering[27] in (Ga,Mn)As. As we show in Fig. 6, the magnetoresistance in the MnAs layer is also well described by the same functional form. However, the positive magnetic-field dependence suggests that the magnetoresistance originates from the convoluted nature of the Fermi surface rather than the magnetoimpurity scattering. For the (Ga,Mn)As layer, $\rho_{\|}-\rho_{\perp}$ was found to be independent of the magnetic field. In the MnAs layer, however, the magnetic-field dependencies of $\rho_{\|}$ and $\rho_{\perp}$ are different due to the fact that the c axis of MnAs lies in the surface. Considering the nearly isotropic transport properties found in Fig. 2, the different field dependence between $\rho_{\|}$ and $\rho_{\perp}$ suggests the importance of the asymmetric crystal structure on the spin scattering.

As we stated earlier, the abrupt jumps in ρ_{xx} when the current is along the easy axis were sample dependent. This might suggest that the origin of the jumps is not a general property, such as the magnetoresistance being given by the effective magnetic field, but a characteristic that can be sample dependent. We would like to point out a possible different explanation. That is, the spin-dependent scattering at antiphase boundaries[28] gives rise to a hysteretic resistance

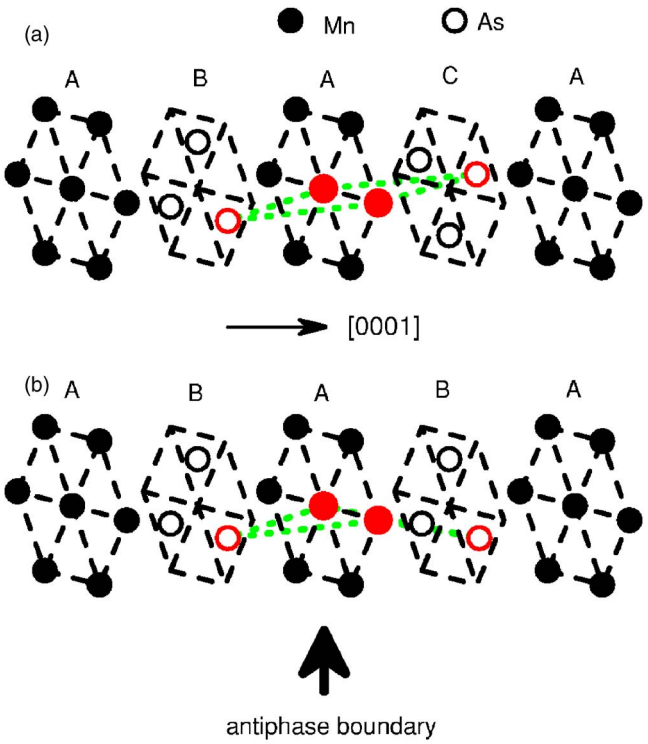

FIG. 7. (a) Crystal structure of hexagonal MnAs and (b) diagram of an antiphase boundary. The stacking sequence of the MnAs crystal along the [0001] direction is represented by alternately repeating the As layers "B" and "C" between the Mn planes "A." The magnetic coupling between two Mn atoms in a hexagonal plane takes place through the adjacent As atoms, as illustrated by the dotted lines.

peak at a magnetic field corresponding to the flip of the magnetization. If the magnetic order at the boundary between neighboring domains is altered to be antiferromagnetic or paramagnetic, the adjacent ferromagnetic domains can be exchange decoupled. A magnetoresistance arises from the spin-dependent carrier transfer in the resultant magnetic junctions consisting of domains having misaligned orientations of their spontaneous magnetization.[29] The antiphase boundaries are a crucial mechanism for the colossal magnetoresistance effect. Critically, the negative magnetoresistance due to the antiphase boundary also obeys the form $\rho(H) = \rho(0) - c_1 H + c_2 H^{3/2}$ (Ref. 30).

Antiphase boundaries are a common feature in epitaxial layers when the rotational symmetry of the layer is less than that of the substrate, or when the unit cell of the layer is an integer multiple of that of the substrate. When nucleated islands grow on the substrate surface, neighboring terraces may coalesce with unmatched sublattices. The atomic arrangement of the hexagonal MnAs along the c axis is described by the stacking sequence "$\cdots$ABACA$\cdots$," as we show in Fig. 7(a). The As sublattice can, therefore, form an antiphase boundary [see Fig. 7(b)]. For this example of the antiphase boundary, the Mn sublattice remains unchanged. The magnetic interaction between Mn atoms is hence not directly altered, for instance, to be antiferromagnetic. However, the change in the atomic configuration of the As atoms in the vicinity of two neighboring Mn atoms can be crucial in MnAs [compare the dotted lines in Figs. 7(a) and 7(b)], as the ferromagnetic order in the Mn hexagonal plane is mediated by the Mn-As-Mn bonds.[31] Consistent with our observation of the sample-dependent nature of the jumps in ρ_{xx}, carriers are always scattered by the antiphase boundary when the current is along the [0001] direction, whereas the current is parallel to the antiphase boundary in the cases in which the jumps were absent.

In the top half of Fig. 5, we have included an initial magnetoresistance curve taken after the sample cooling from room temperature, i.e., the demagnetization procedure. One finds an overall decrease in the resistivity caused by the initial magnetic-field sweep. The resistance change corresponds to the resistance associated with domain walls. A nonmagnetized MnAs channel contains a large number of domain walls. As the shape anisotropy is practically irrelevant in the MnAs channels, all the magnetic moments in the magnetic domains are oriented to be perpendicular to the direction of current when the channels are stretched along the magnetic hard axis, thereby maximizing the influence of the domain walls. As the resistance decreases when the channel is magnetized and the domain walls consequently vanish, the nominal domain-wall resistance in our samples is indicated to be positive.[5]

V. SUMMARY

The magnetotransport properties have been investigated in MnAs films on GaAs substrates having two types of crystal orientation relationships. The transverse resistivity in the $(1\bar{1}00)$-oriented film changes its polarity as being dominated by holes and electrons in the low- and high-magnetic-field regimes, respectively. In the (0001)-oriented film, in contrast, the transport is almost completely dominated by holes. In correspondence to these, the longitudinal resistivity in the $(1\bar{1}00)$-oriented film exhibits a tendency of saturation in high magnetic fields due to the two-band transport, whereas the trend is markedly weak in the (0001)-oriented film. We have identified the strength of a magnetic field that is necessary to disorient the magnetization away from the easy axis. Aligning the magnetization along the in-plane hard axis requires a magnetic field stronger than that to align the magnetization to be normal to the surface. The magnetocrystalline anisotropy is hence confirmed to be stronger than the shape anisotropy. We have observed a jump in ρ_{xx} associated with a flip of the magnetization when an in-plane magnetic field is parallel to the easy axis. While the hysteretic switching behavior can be understood if $\rho_{\perp}$ and $\rho_{\parallel}$ are determined by the effective magnetic field that includes the spontaneous field due to the magnetization, the contribution of the spontaneous field is estimated to be reduced by an order of magnitude in MnAs.

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