Very Large Tunneling Anisotropic Magnetoresistance of a (Ga, Mn)As/GaAs/(Ga, Mn)As Stack

C. Rüster,[1] C. Gould,[1] T. Jungwirth,[2,3] J. Sinova,[4] G. M. Schott,[1] R. Giraud,[1] K. Brunner,[1] G. Schmidt,[1] and L. W. Molenkamp[1]

[1]*Physikalisches Institut (EP3), Universität Würzburg, Am Hubland, D-97074 Würzburg, Germany*
[2]*Institute of Physics ASCR, Cukrovarnická 10, 162 53 Praha 6, Czech Republic*
[3]*School of Physics and Astronomy, University of Nottingham, Nottingham NG7 2RD, United Kingdom*
[4]*Department of Physics, Texas A&M University, College Station, Texas 77843-4242, USA*
(Received 20 August 2004; published 18 January 2005)

We report the discovery of a very large tunneling anisotropic magnetoresistance in an epitaxially grown (Ga, Mn)As/GaAs/(Ga, Mn)As structure. The key novel spintronics features of this effect are as follows: (i) *both* normal and inverted spin-valve-like signals; (ii) a large nonhysteretic magnetoresistance for magnetic fields perpendicular to the interfaces; (iii) magnetization orientations for extremal resistance are, in general, not aligned with the magnetic easy and hard axis; (iv) enormous amplification of the effect at low bias and temperatures.

DOI: 10.1103/PhysRevLett.94.027203 PACS numbers: 75.50.Pp, 85.75.Mm

The emerging field of semiconductor based spintronics, which explores the spin and charge degrees of freedom on an equal footing, is expected to lead to novel information technologies that will overcome current key obstacles in the microelectronics road map [1]. A main component needed to realize the full potential of this technology is a device with similar behavior as current metal-based spin valves [2], *and* with novel spintronics features unattainable in their metal counterparts. Previous attempts in this direction have yielded promising spin-valve results [3] apparently mimicking the functionality of the metal devices. However, our recent discovery of tunneling anisotropic magnetoresitance (TAMR) in a single (Ga,Mn)As layer structure [4] suggests that the moderate magnetoresistance (MR) effects observed so far in structures such as the one in Ref. [3] may originate from TAMR rather than the traditional metal tunneling MR (TMR). If this is the case, the device behavior should be much richer than for TMR, and could offer many new functionalities not possible in metal-based devices. To investigate this hypothesis, we have fashioned a tunnel structure based on the ferromagnetic semiconductor (Ga,Mn)As. We report the existence of a huge TAMR effect exceeding 150 000% in these structures at low temperature.

The full layer structure of our device, shown in Fig. 1(a), consists of a $Ga_{0.94}Mn_{0.06}As$(10 nm)/GaAs(2 nm)/$Ga_{0.94}Mn_{0.06}As$(100 nm) trilayer grown by low temperature molecular beam epitaxy (LT-MBE) on a semi-insulating GaAs substrate and an undoped GaAs buffer layer. The (Ga,Mn)As layers are intrinsically highly *p* type due to the Mn and have metallic transport character. The undoped LT-GaAs layer on the other hand is insulating and forms an epitaxial tunnel barrier.

A schematic of the patterned device is shown in Fig. 1(b). The heterostructure was patterned into a square mesa with sides of 100 μm and a surrounding electrical back contact. Contact to the square mesa is established by an *in situ* Ti/Au deposition, whereas the back contact is made after patterning by depositing W/Au onto the lower (Ga,Mn)As layer. Two-probe MR measurements are then performed for current flowing vertically through the layer stack. Since the bulk resistivity of the (Ga,Mn)As is only $\sim 10^{-3}$ Ω cm, the device resistance is dominated by the

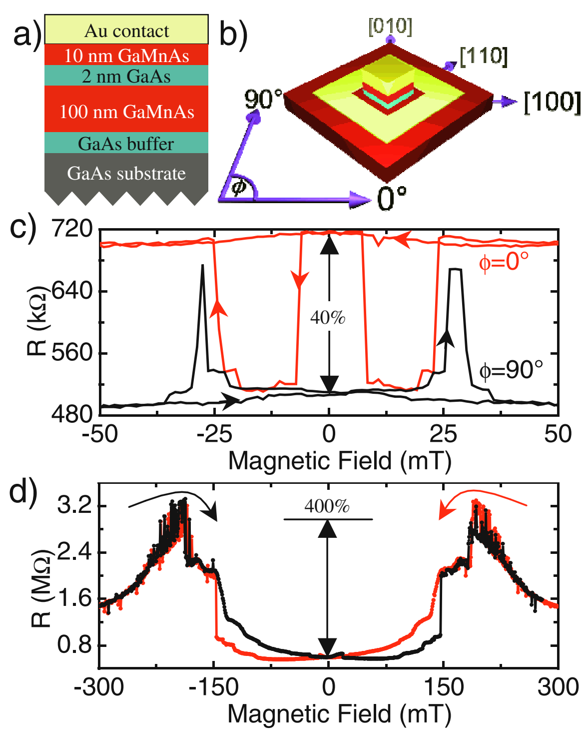

FIG. 1 (color online). (a) Layer stack and (b) sample layout. (c) 4 K magnetoresistance near each in-plane easy axis showing both positive and negative 40% effects. (d) 4 K magnetoresistance in perpendicular field showing a 400% signal.

tunnel barrier. Identically patterned control samples without a tunnel barrier have a resistance of 10 Ω, proving that any bulk (Ga,Mn)As MR is fully negligible.

Transport measurements were carried out in a magnetocryostat fitted with three orthogonal sets of Helmholtz coils allowing the application of magnetic fields **H** of up to 300 mT in any direction. Fields applied in the plane of the layers are denoted by their angle ϕ with respect to the [100] crystallographic direction. Two types of **H** scans are presented: MR scans, which consist of saturating the sample magnetization in a negative magnetic field along a given direction and then measuring the resistance of the device as $|\mathbf{H}|$ is swept to positive saturation and back again; and ϕ scans, where the resistance is measured for constant $|\mathbf{H}|$ while sweeping ϕ.

Figure 1(c) shows MR scans taken with a bias voltage $V_B = 10$ mV at a temperature $T = 4.2$ K along $\phi = 0°$ and 90° near the two cubic magnetic easy axes in the (Ga,Mn)As. At low $|\mathbf{H}|$ after crossing zero in either sweep direction, **M** abruptly reverses its direction, yielding a 40% spin-valve signal. The measurement along 90° appears similar to previous observations [3], and could easily be mistaken for traditional TMR. However, the remarkable sign change observed at $\phi = 0°$ points to a different origin of the effect, and strongly suggests an interpretation in line with our previous observations of TAMR in single-ferromagnet devices [4].

As we apply $|\mathbf{H}|$ at other angles in the plane, the amplitude of the effect remains constant, whereas the position and sign of the sharp switching events display a strong angular dependence, with an underlying symmetry consistent with that reported for a single magnetic layer device [4]. Neglecting some fine structure in the peak shape, the relatively straightforward picture of two step magnetization reversal reported in [4] accounts for this low $|\mathbf{H}|$ symmetry. It comes from a combination of the magnetic anisotropy of the (Ga,Mn)As, which is principally cubic with a small in-plane uniaxial contribution, and the fact that magnetic reversal takes place via 90° domain wall nucleation and propagation. At low fields, the dominating reversal mechanism consists of the magnetization switching abruptly whenever the energy gain by doing so is greater than the energy needed to nucleate/propagate a domain wall. This model is consistent with previous studies in epitaxial Fe layers [5].

Another observation distinguishing our effect from TMR is a strong MR signal observed when **H** is applied perpendicular to the plane of the sample, i.e., along the magnetic hard axis. Figure 1(d) shows such a MR scan at $T = 4.2$ K and $V_B = 5$ mV. The TAMR in Fig. 1(d) is ~400%, much larger than for **H** in plane under similar conditions. We attribute this to a significant growth direction strain in our (Ga,Mn)As layers that induces a large anisotropy between the [001] and [100] (or [010]) directions, compared to the relatively weak in-plane uniaxial anisotropy mentioned above, and leading to stronger TAMR in the perpendicular to plane geometry. Note also that the perpendicular TAMR is not hysteretic, but occurs on both sides of $\mathbf{H} = 0$, indicating that it must be related to the absolute rather than the relative orientations of the ferromagnetic layers.

TAMR is further evidenced through ϕ scans at higher magnetic fields. As can already be seen in Fig. 1(c), the resistance at saturation is dependent on the direction of magnetization, varying from 480 to 700 kΩ as **M** changes from along [010] to [100]. This is in contrast to regular TMR, which depends only on the relative orientation of **M** in the two layers. Our sample is thus a sensor of the absolute direction of **H**. This is demonstrated in the 5 mV, $|\mathbf{H}| = 300$ mT ϕ scan of Fig. 2(a). The measurement is identical for clockwise or counter clockwise ϕ sweeps as $|\mathbf{H}|$ is sufficiently large to saturate **M** such that $\mathbf{M} \parallel \mathbf{H}$. The resistance changes by more than 250% between its minimum at 90° and its maximum at 165°.

We now turn to Fig. 2(b), which shows that the ϕ scan changes dramatically with $|\mathbf{H}|$. Here $|\mathbf{H}| = 25$ mT was chosen to be slightly above the biggest coercive field in the sample. The sample was prepared in a known state by saturating **M** along the uniaxial easy axis (90°) and $|\mathbf{H}|$ was then lowered to 25 mT, and ϕ swept in the clockwise or counter clockwise direction.

The main features of the data are ~40% jumps in the resistance between the 500 and 700 kΩ levels. These can be understood rather simply by noting that at $\phi = 90°$ the sample is in a low resistance state associated with **M** along the [010] easy axis. As ϕ is swept nearer to the [100] easy axis, **M** will eventually switch to this direction, corresponding to a high resistance state due to the additional uniaxial field that breaks the in-plane cubic symmetry in the (Ga,Mn)As layers. The curves must be different for the two sweep directions as they should have approximate mirror symmetry about the easy axis. The deviations from this symmetry may be attributed to nonuniform strain distributions.

A few additional levels are seen on the edges of the large switching events, and can be explained in a straightforward way. By design, the magnetic anisotropies of the two layers are not identical as different strain conditions and thick-

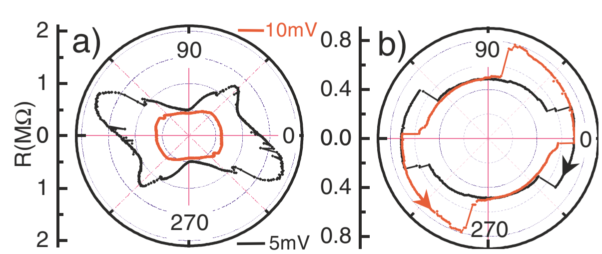

FIG. 2 (color online). ϕ scans at 4.2 K (a) in a saturation magnetic field $|\mathbf{H}| = 300$ mT, and (b) $V_B = 5$ mV at $|\mathbf{H}| = 25$ mT, just sufficient to switch M between easy axes.

nesses create different coercive fields. As **H** is rotated, the softer layer switches earlier. This creates configurations where the magnetizations of the two layers are not collinear, but perpendicular to each other. As a control experiment, a similar ϕ scan at $|\mathbf{H}| = 15$ mT was done, and since 15 mT is below the smallest coercive field in the structure, no switching or resistance change occurs. This behavior suggests design perspectives for spin valves programmable in rotating magnetic fields above a certain magnitude, but not below.

The data in Figs. 1 and 2 establish unambiguously the TAMR nature of the measured effect. Anisotropies in the (Ga,Mn)As density of states (DOS) with respect to **M**, which result from the strong spin-orbit coupling in the ferromagnetic semiconductor valence band, are large enough to explain the effect [4]. Consistently, a sizable anisotropy of the MR with respect to **M** in (Ga,Mn)As-based tunneling structures was found in an independent theoretical work employing the Landauer transport formalism [6]. The DOS anisotropy calculations in Ref. [4], based on the kinetic-exchange model coupling of valence band holes and polarized Mn local moments, have explained the change of the sign of the TAMR signal with field angle and temperature, and predicted strong enhancement of the effect in epitaxial tunnel junctions characterized by a larger degree of in-plane momentum conservation. Our present study confirms this prediction and some of the new experimental features of the (Ga, Mn)As/GaAs/(Ga, Mn)As TAMR can also be understood based on the DOS anisotropy.

The relative DOS anisotropies, $\Delta\mathrm{DOS}_{\mathrm{int}}/\mathrm{DOS}_{\mathrm{int}}$, for the DOS at the Fermi energy E_F, integrated over an assumed range of momenta k_z along the tunneling direction and summed over the occupied spin-split valence bands, are plotted in Fig. 3 for several in-plane magnetization orientations. Note that states at E_F with the largest k_z are expected to have the largest tunneling probability when in-plane momentum is conserved and, therefore, increasing the range of k_z contributing to the tunneling DOS corresponds to relaxing the in-plane momentum conservation condition, or increasing the tunnel barrier transparency. Although the bulk hole densities in our (Ga,Mn)As layers are of order 10^{20} cm^{-3}, a significant depletion is expected in the region near the (Ga, Mn)As/GaAs interface with hole concentration closer to those in panels 3(b) or 3(a). The substitutional $\mathrm{Mn_{Ga}}$ concentration of 4% considered in the calculations is consistent with the nominal total Mn doping in our (Ga,Mn)As layers. A uniaxial strain along [010] was introduced to model the broken in-plane cubic symmetry.

Figure 3 demonstrates that the magnitude of the $\mathrm{DOS_{int}}$ anisotropy as well as the magnetization orientations corresponding to extremal tunneling DOS have a complex dependence on the magnetic tunnel junction parameters. Data in panel 3(a), e.g., show $\mathrm{DOS_{int}}$ anisotropies exceeding 100% for $\mathrm{DOS_{int}}/\mathrm{DOS_{total}} \sim 10\%$. ($\mathrm{DOS_{total}}$ denotes the total DOS at E_F.) Here the minimum $\mathrm{DOS_{int}}$ is for **M** at $\phi = 270°$ while the maximum $\mathrm{DOS_{int}}$ is at $\phi = 330°$, i.e., off the main crystal and magnetic anisotropy axis. The result provides an explanation for the distorted cubic symmetry observed in Fig. 2(a). The enhanced DOS anisotropy shown by the dashed line in the main panel, which was obtained for larger strain value (larger magnetic anisotropy), is consistent with the experimentally observed enhancement of the TAMR when magnetization is switched between the easy and the hard axis (see Fig. 1). We emphasize, however, that Fig. 3 is only illustrative; a more quantitative comparison between the experiment and theory requires a detailed characterization of the experimental tunnel junction and a systematic theoretical analysis of the TAMR and TMR contributions to the hole transmission coefficients, which is beyond the scope of this Letter and will be published elsewhere.

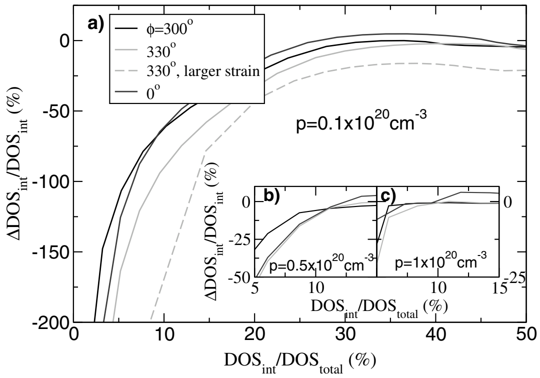

FIG. 3. Theoretical diagrams obtained for hole densities 0.1 (a), 0.5 (b), and 1×10^{20} cm^{-3} (c) showing the relative difference between the integrated DOS at the Fermi energy for M along $\phi = 270°$) and three different angles ϕ. The x axis represents the integrated DOS at the Fermi energy that is assumed to contribute to tunneling, relative to the total DOS at the Fermi energy. Solid (dashed) lines were obtained for a uniaxial strain along the [010] direction of 0.2% (0.4%).

Another prominent characteristic of our device is the very strong V_B dependence of the signal displayed in Fig. 4(a). The various curves show the MR along $\phi = 65°$ at $T = 4.2$ K with V_B ranging from 500 μV up to 10 mV. The low resistance state has a relatively small variation of $\sim$20% with decreasing bias. In contrast, the high resistance state increases by more than 250%. The amplitude of the TAMR effect is also very sensitive to T. In Fig. 4(b) we show a $V_B = 1$ mV curve at 1.7 K where the effect has grown to 150 000%. Indeed, this is merely a lower limit corresponding to the detection limit of our current amplifier. Although the amplitude of the effect increases dramatically at low V_B and T, the general symmetry remains, indicating that the origin of the effect is unchanged, but that it is amplified by an additional mechanism.

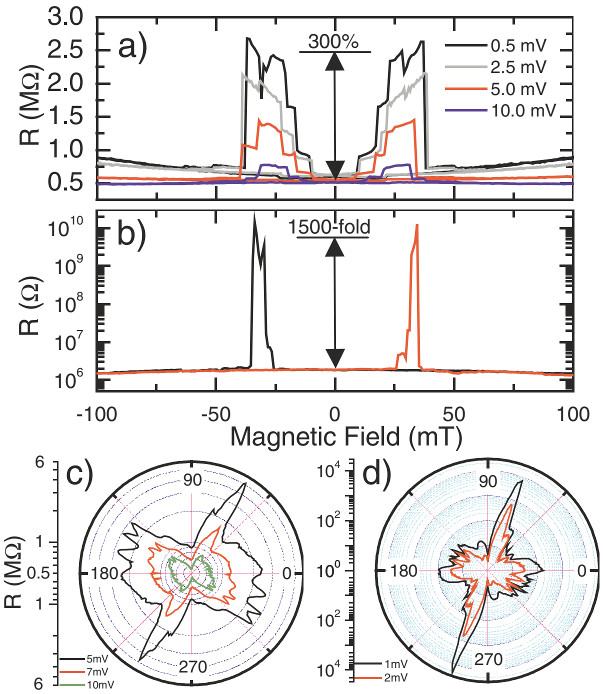

FIG. 4 (color online). Amplification of the effect at low bias voltage and temperatures. (a) TAMR along $\phi = 65°$ at 4.2 K for various bias voltages. (b) Very large TAMR along $\phi = 95°$ at 1.7 K and 1 mV bias. (c), (d) ϕ at various bias at 1.7 K.

This very large amplification of the TAMR can be understood as a manifestation of a well-known zero bias anomaly [7] in tunneling from a dirty metal which appears due to the opening of an Efros-Shklovskii gap [8] at E_F when crossing the metal-insulator transition. Indeed, such an effect should be observed in our device given the short (Ga,Mn)As mean free path of a few Å which limits the injector region to a very thin layer near the barrier. Depletion near the barrier must therefore cause a lower carrier density in the injector region than in the bulk of the (Ga,Mn)As slab. The injector will thus be much closer to the metal-insulator transition than a typical (Ga,Mn)As layer. Moreover, we know that the DOS changes with **M**. Therefore, when we perform experiments at low V_B and T, the effective DOS participating in the tunneling can be brought through the metal-insulator transition with reorientation of **M**, leading to a large amplification of the TAMR effect. A further indication that the Efros-Shklovskii gap is the dominant enhancing mechanism is that the amplification of the effect as T changes from 4.2 to 1.7 K is strong for low bias voltage (1 mV), but disappears at higher voltages (10 mV), consistent with tunneling experiments near the metal-insulator transition of Si:B [7]. Other possible mechanisms for the enhancement of the TAMR, such as disorder and impurity mediated tunneling, may also play a role and should not be summarily dismissed. Further study is needed before the amplification mechanism can be claimed to be fully understood.

Finally, in Fig. 4(c) and 4(d) we present ϕ scans at 1.7 K for various V_B, which demonstrate another important characteristic of our device which is that it acts as a detector for the anisotropies in the DOS of the (Ga,Mn)As layer. Figure 4(c) already shows some fine structure, which becomes much more pronounced at lower bias. This is to be expected since we start detecting fine structure in the anisotropy of the DOS, which should be complex given that the opening of the gap should develop differently for the various bands which have different effective masses.

In summary, we have observed a very large TAMR effect in a (Ga, Mn)As/GaAs/(Ga, Mn)As tunnel structure which can be of order of a few hundred percent at 4 K, and can be amplified to 150 000% at lower temperatures. The behavior of the structure not only mimics normal TMR when the field is applied along the [010] direction, suggesting the need for a reinterpretation of previous TMR results in similar structures, but also exhibits new functionalities such as a sensitivity to not only the amplitude, but also to the direction of an applied magnetic field. While many of the experimental features of this novel effect can be understood through the one-particle tunneling DOS anisotropies with respect to the magnetization orientation, the dramatic amplification at low biases and temperatures poses new challenging questions for the theory of tunneling transport in disordered interacting electronic systems with strong spin-orbit interaction.

The authors thank A. H. MacDonald and M. Flatté for useful discussions and V. Hock for sample preparation, and acknowledge financial support from the EU (SPINOSA), the German BMBF (13N8284) and DFG (BR1960/2-2), the Czech Republic GACR (202/02/0912), and the DARPA SpinS program. R. G. thanks the Humboldt Foundation for financial support.

[1] Semiconductor Industry Association, "International Technology Roadmap for Semiconductors," 2003 ed., http://public.itrs.net/Files/2003ITRS/Home2003.htm.
[2] J. S. Moodera, L. R. Kinder, T. M. Wong, and R. Meservey, Phys. Rev. Lett. **74**, 3273 (1995).
[3] Y. Higo, H. Shimizu, and M. Tanaka, J. Appl. Phys. **89**, 6745 (2001); D. Chiba, F. Matsukura, and H. Ohno, Physica E (Amsterdam) **21**, 966 (2004).
[4] C. Gould *et al.*, Phys. Rev. Lett. **93**, 117203 (2004).
[5] R. P. Cowburn *et al.*, J. Appl. Phys. **78**, 7210 (1995).
[6] L. Brey, C. Tejedor, and J. Fernández-Rossier, Appl. Phys. Lett. **85**, 1996 (2004).
[7] M. Lee, J. G. Massey, V. L. Nguyen, and B. I. Shklovskii, Phys. Rev. B **60**, 1582 (1999).
[8] A. L. Efros and B. I. Shklovskii, J. Phys. C **8**, L49 (1975).