Giant magnetoresistance of magnetic semiconductor heterojunctions

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The giant magnetoresistance characteristics of magnetic III–V semiconductor *p-n* heterojunctions are described. The origin of the extremely large positive magnetoresistance (2680%) observed at room temperature and at a field of 18 T is attributed to efficient spin-polarized carrier transport. The magnetocurrent ratio of the junction saturates with magnetic field. The field dependence of the magnetoresistance points to the existence of a paramagnetic component, which determines the degree of spin polarization of the junction current. This work indicates that highly spin-polarized magnetic semiconductor heterojunction devices that operate at room temperature can be realized.

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I. INTRODUCTION

Semiconductor spintronics offer many unique capabilities that can potentially revolutionize electronics and computing.[1,2] A bipolar semiconductor spintronic junction has been proposed as a building block for various magnetoelectronic and magneto-optical device architectures via control over the spin degree of freedom of free carriers.[3] Potential advantages include large magnetoresistance (MR) effects, control of magnetic properties by charge injection, and amplification.[4] Spintronics can potentially lead to integration of both information processing and storage. Theoretical calculations of the transport properties of ferromagnetic *p-n* heterojunctions showed that the current through a device would increase in a magnetic field.[5] The predicted increase is attributed to the presence of spin-polarized carriers due to the splitting in the valence and conduction bands as result of giant Zeeman effect. The achievement of magnetic semiconductor/semiconductor junctions, however, that operate at room temperature with a high degree of spin polarization remains elusive.

While there has been extensive theoretical work on dilute magnetic semiconductor (DMS) heterojunctions much less is known about their experimental transport properties.[1,3–5] A DMS *n-n**-*n* heterojunction consisting of paramagnetic ZnBeMnSe, as the spin aligner, and the nonmagnetic semiconductor ZnBeSe was fabricated and its junction characteristics measured.[6] A large positive magnetoresistance of 25% at 1 T and 4 K was observed. The origin of this positive magnetoresistance was attributed to the suppression of conduction in one of the spin channels in the nonmagnetic semiconductor. Spin-polarized electrons are injected from the DMS material and the resistance offered by the nonmagnetic material increases because only one spin channel is active instead of two. In addition, (Ga,Mn)As/GaAs Zener *p-n* diodes have been fabricated that have a large magnetoresistance with a relative change in current up to 8% (Ref. 7) and also have shown to emit circularly polarized light.[8,9] These devices, however, are operated only at temperatures up to 40 K.

Our group has previously reported on the transport properties of InMnAs/InAs *p-n* heterojunctions in fields as high as 9 T where InMnAs is the magnetic semiconductor.[10] InMnAs when grown by metalorganic vapor phase epitaxy has been shown to be ferromagnetic up to 330 K.[11,12] The high Curie temperature was attributed to Mn acceptor complexes.[13,14] A giant positive magnetoresistance up to 1300% at room temperature was observed in these devices at a magnetic field of 9 T. The magnetoresistance of these devices could be attributed to scattering of free carriers due to an inhomogeneous distribution of magnetic Mn ions at or near the depletion region.[15] A small, negative magnetoresistance of less than 1% is observed in the InMnAs thin films at low temperature and low magnetic fields related to reduced spin scattering. However, increasing the temperature leads to a small positive magnetoresistance presumably related to a decrease in mobility.[16] This suggests that spin scattering may be also be the origin of the positive junction magnetoresistance.[16]

Furthermore, magnetocapacitance measurements on these InMnAs/InAs junctions have recently been reported and indicate that spin transport is important.[17] Magnetocapacitance as high as 7% was observed at 300 K that increased with magnetic field. It was attributed to a giant Zeeman effect and to the presence of spin-polarized carriers. These spin-polarized carriers were due to splitting of the valence and conduction band in the magnetic semiconductor layer.[17] These measurements also indicated the presence of two magnetic components, one ferromagnetic and another paramagnetic in the InMnAs layer. Previous superconducting quantum interference device (SQUID) measurements on InMnAs films also support the presence of two different magnetic components.[11] Here we describe the magnetotransport properties of the InMnAs/InAs heterojunctions in magnetic fields of up to 18 T over the temperature range of 80–300 K and present a physical model for the origin of the giant junction magnetoresistance. Taking into account the splitting of the bands due to the giant Zeeman effect we model the junction electrical characteristics and the effect of magnetic field.

II. EXPERIMENT

The InMnAs/InAs heterojunctions were fabricated by depositing 100 nm of InMnAs on (001) *n*-type InAs substrates

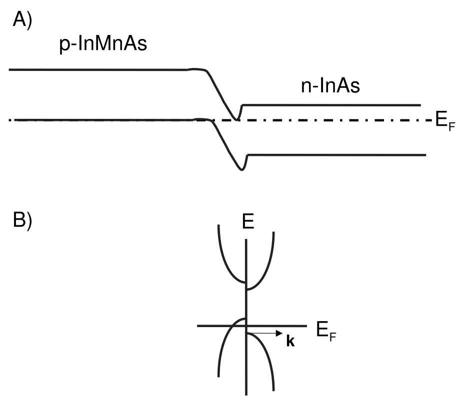

FIG. 1. (a) Band diagram for InMnAs/InAs *p*-*n* heterojunction. (b) Schematic of band structure for InMnAs which shows spin splitting of the bands and the position of the Fermi level.

as previously described in Ref. 10. The carrier concentration in the *n*-type substrate was $2.6\times10^{16}\ \mathrm{cm}^{-3}$ while the *p*-side carrier concentration was of the order of $10^{18}\ \mathrm{cm}^{-3}$. Photolithography was used to define circular Ti/Au contacts with a 300 μm diameter.

Current-voltage characteristics were measured with the magnetic field applied parallel to the direction of current flow through the mesa. Currents from −2 to 25 mA were sourced while the voltage was measured. These characteristics were measured at the MilliKelvin laboratory at the National High Magnetic Field Laboratory. A magnetic field from zero to 18 T was applied using a superconducting magnet and the *I*-*V* characteristics were measured at each field and at different temperatures.

III. MODEL

A modified diode equation [Eq. (1)] was previously shown to describe the behavior of InMnAs/InAs heterodiodes in a magnetic field.[10] The current *I* is given by

$$I = I_0 \exp\left(\frac{qV_A}{\eta k_B T}\right)\exp\left(\frac{-qIR_0}{\eta k_B T}\right)\exp\left(\frac{-qIR(H)}{\eta k_B T}\right). \quad (1)$$

In Eq. (1), q is the charge of an electron, R_0 is the junction zero-field series resistance, $R(H)$ is the magnetic-field-dependent series resistance, η is the junction ideality factor, T is the temperature, k_B is Boltzmann's constant, and V_A is the applied voltage. For the InMnAs/InAs heterojunctions, a highly conductive accumulation layer can potentially form at the *n*-type InAs interface [Fig. 1(a)], and can influence transport.[18]

The junction magnetoresistance is defined by[10]

$$\mathrm{MR}(\%) = \left(\frac{dV(H)}{dI} - \frac{dV(0)}{dI}\right) \times 100 \Bigg/ \frac{dV(0)}{dI}, \quad (2)$$

where the derivative $dV(H)/dI$ is calculated at a constant current for different applied magnetic fields.

To explain the magnetic-field dependence of the magnetoresistance of a magnetic semiconductor/nonmagnetic semiconductor junction a two channel conduction model is proposed. In this model the valence and conduction bands in the magnetic semiconductor layer are split due to the giant Zeeman effect, each forming two bands consisting of spin-up and spin-down carriers.[5] As a result the holes in the valence band and electrons in the conduction band are spin polarized. The band structure of the *p*-type injection layer is shown in Fig. 1(b). For the present study, the Fermi level in the *p*-type layer is assumed to be at the top of zero-field valence band. As the applied magnetic field increases the magnetization of the spin injector layer increases. This leads to an increase in the density of states of the spin-down hole band at the Fermi level and as a consequence their number increases. As the magnetic field increases, the spin-down hole concentration increases while that of spin-up holes decreases leading to an increase in spin polarization. Theory using Boltzmann statistics predicts that the spin-polarized current density for such a device is proportional to $\exp(\xi/k_BT)$ where ξ depends on the amount of splitting in the band.[4] The parameter ξ in turn depends on the magnetic field and the g factor of the magnetic semiconductor and is equal to $g\mu_B H$. The value of g is assumed to be constant. This assumption leads to the calculation of an effective g over this range of magnetic fields. For the present study we also assume that in the junction there are two spin channels that are in parallel that determine the total conductance.[6] The conductance G at a constant current for the heterojunction is thus described by the following equation:

$$G = \frac{1}{2\cosh(\xi/k_BT)}\{G_1 \exp(-\xi/k_BT) + G_2 \exp(\xi/k_BT)\}. \quad (3)$$

In Eq. (3), $G_1 \exp(-\xi/k_BT)$ and $G_2 \exp(-\xi/k_BT)$ are the conductances for holes with aligned and antialigned spins, respectively, the term $2\cosh(\xi/k_BT)$ is a normalization factor where at zero field $G=(G_1+G_2)/2$. The terms $\exp(-\xi/k_BT)$ and $\exp(\xi/k_BT)$ take into account the change in the population of the spin split bands with field. As the magnetic field is increased, the number of carriers in the minority spin band increases while the number of carriers in the majority spin band decreases. For this model we assume *a priori* that $G_1 > G_2$. This assumption is consistent with recent theoretical studies on magnetoresistance of dilute magnetic semiconductors at high magnetic fields.[19] In that study it was shown that a positive magnetoresistance results from scattering due to spatial disorder of magnetic ions and locally enhanced spin splitting of the band. The mobility of carriers depends on their polarization. For $G_1 > G_2$, a decrease in the total conductance with field (positive magnetoresistance) is predicted and is attributed to the exponential decrease in the conductance of the majority spin channel with a concurrent increase in the conductance of the minority spin channel.

Since bipolar devices exhibit highly nonlinear *I*-*V* characteristics, the magnetoresistance will depend on whether it is measured at a constant current or constant voltage. By analyzing the various measures of magnetoresistance, we can differentiate between the physical processes that lead to the giant magnetoresistance effects. The relative change in the current (magnetocurrent ratio) with magnetic field has also

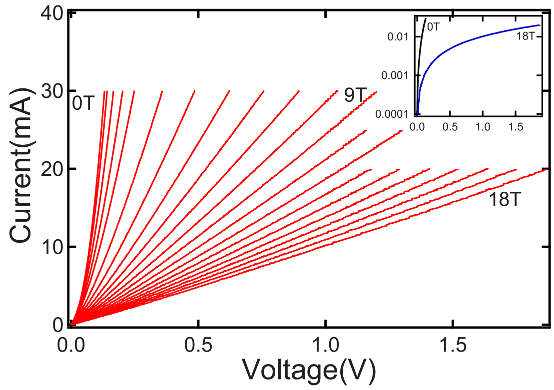

FIG. 2. (Color online) Current-voltage curves at magnetic fields from 0 to 18 T at 300 K. The inset (a semilog plot) is shown to point to the large variation in the *I*-*V* characteristics with field.

been previously used as a measure of magnetoresistance.[7,20] The ratio $[\mathrm{MR}_I(\%)]$ at a constant voltage is defined as follows:

$$\mathrm{MR}_I(\%) = [I(0) - I(H)] \times 100/I(0), \tag{4}$$

where $I(H)$ is the current measured at a field H.

IV. RESULTS AND DISCUSSION

The *I*-*V* characteristics of the *p*-*n* InMnAs/InAs heterojunctions are shown in Fig. 2 for different magnetic fields and at a temperature of 300 K. The inset shows the *I*-*V* curves at zero and 18 T, respectively, with the currents plotted on the log scale to show the differences of the currents at high fields. The forward bias junction *I*-*V* characteristics are clearly exponential when there is no magnetic field applied, consistent with Eq. (1).[10] An increase in the magnetic field, however, leads to flattening of the characteristics and an apparent loss of its exponential character. Indeed at high fields the *I*-*V* behavior appears to be nearly Ohmic. The junction *I*-*V* characteristics and its magnetic-field dependence are described by Eq. (1) up to and including fields of 18 T.

The conductance of the junction as a function of magnetic field is shown in Fig. 3. The conductance for different currents is calculated by determining tangents to the current-voltage curves at a constant current. We see that the conductance initially sharply decreases with field, but at fields higher than 9 T the conductance approaches a constant value. The dependence of the conductance on current at a low magnetic field results from the internal resistance of the diode, which is a function of bias. As the magnetic field is increased, the current-voltage behavior is nearly linear and this leads to the convergence of the measured conductance for different values of the currents.

To explain the observed magnetoresistance a two channel spin transport model was applied. We fit the conductance data at 300 K to the expression given by Eq. (3). Shown in the inset of Fig. 3 is the conductance data for a junction current of 5 mA and the theoretical fit where G_1, G_2, and g are the free parameters. We can see that there is good agreement between theory and experimental data. Values extracted from the fit are 0.335 and 0.013 S for G_1 and G_2, respectively, assuming an effective g factor of 95. The large g factor is consistent with the presence of a giant Zeeman effect. High g factors have been reported previously in II–VI DMS materials. For comparison, the g value for CdMnSe is greater than 500. A large g factor is expected to result in giant magnetoresistance effects in magnetic/nonmagnetic semiconductor heterojunctions.[21]

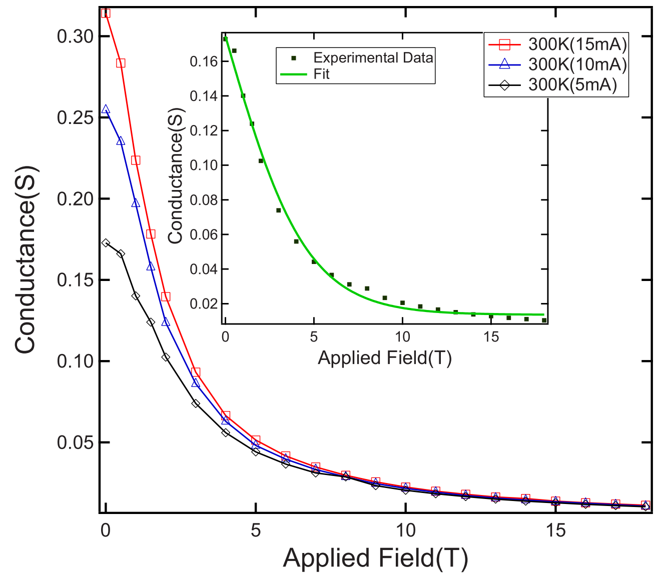

FIG. 3. (Color online) Conductance of the junction vs magnetic field calculated for currents of 5, 10, and 15 mA. (Inset: fit to conductance of junction vs applied field at 300 K. The current is 5 mA.)

The low conductance at high fields is attributed to the conduction mostly via the low mobility spin channel. The difference in the conductance for the two spin channels is presumably a result of the spin polarity dependant mobility of DMS materials.[19] It is also noted that at low fields, the junction conductance model deviates from the experimental results for junction currents of 10 and 15 mA. This deviation is due to the current dependence of the junction resistance at zero magnetic field. The zero-field junction conductivity increases with current. The deviation may also result from the presence of other competing conduction channels such as tunneling.[22]

The magnetoresistance of the device at a constant current of 15 mA at temperatures of 80, 190, and 300 K is shown in Fig. 4. At 300 K, the low bias region of the magnetoresistance has a nonlinear dependence on field, while at magnetic fields greater than 1.5 T, a linear magnetoresistance is observed. At an applied field of 18 T, the magnetoresistance defined by Eq. (2) has a value of 2680% while at lower temperatures of 190 and 80 K, the value of magnetoresistance decreases to 710% and 405%, respectively. At lower temperatures, both the turn-on voltage for the junction and its internal resistance are much larger at zero field. As the parameter MR (%) is taken relative to the zero-field value, consequently the change is smaller at lower temperatures.

The field dependence of the magnetocurrent ratio at a constant voltage given by Eq. (4) is shown in Fig. 5. At a

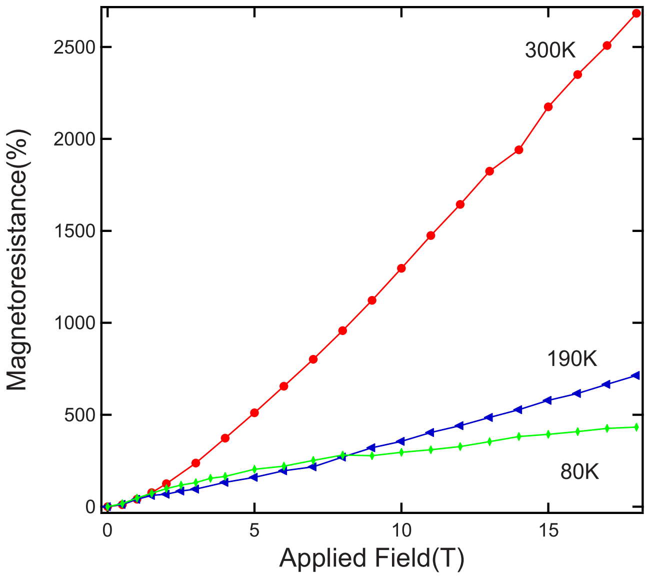

FIG. 4. (Color online) Magnetoresistance vs magnetic field at $I=15$ mA. The data are reported at $T=300$, 190, and 80 K.

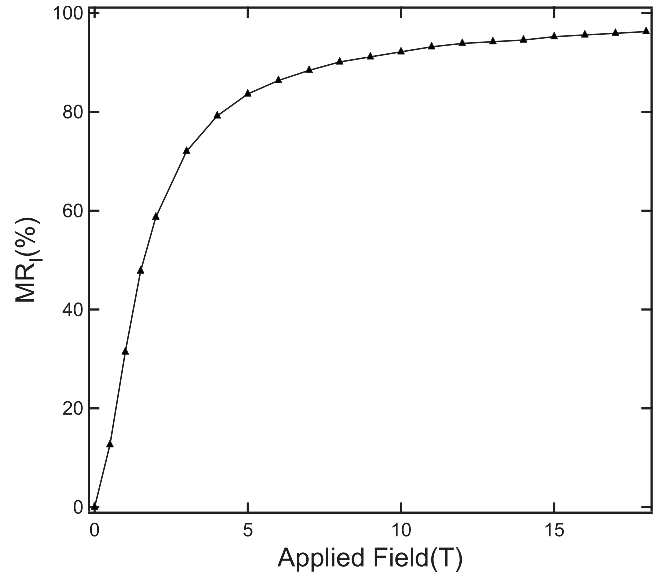

FIG. 5. Magnetocurrent ratio $[MR_I(\%)]$ vs magnetic field at 300 K and at a voltage of 0.13 V calculated using Eq. (4) (the line is a guide to the eyes).

bias of 0.13 V where this quantity is calculated, the current though the device is high at low magnetic fields and drops rapidly as the magnetic field is increased. A similar trend is seen at other bias voltages. We observe that at magnetic fields greater than 9 T, the magnetocurrent ratio starts to saturate.

To understand the origin of the magnetoresistance the relative change in the current with magnetic field given by Eq. (4) has also been measured and analyzed. Saturation of the magnetocurrent ratio with field (Fig. 5) is observed. Similar behavior was previously observed in a magnetic semiconductor heterojunction and was attributed to the saturation of the magnetization in the magnetic semiconductor layer.[20] The saturation is attributed to a spin polarization approaching 100%.

As can be seen a very high magnetic field is required (at least 9 T in the present case) to saturate the magnetocurrent ratio. The high magnetic field required for complete saturation indicates the InMnAs has a large paramagnetic component in its magnetization. The coexistence of both ferromagnetism and paramagnetism has been previously observed in these materials.[11,17] Furthermore if the ferromagnetism in the layer is carrier mediated, a reduction in this component would be expected in the junction space charge region due to lack of carriers.

While the magnetocurrent ratio shown in Fig. 5 was measured at 0.13 V, increasing the bias also shows a similar dependence of the magnetocurrent with magnetic field. This is expected due to the exponential behavior of the *I-V* characteristics observed with and without magnetic field. As to saturation of the magnetocurrent ratio it should be noted that it would be expected to saturate just above the coercive field if only a ferromagnetic component is present in the InMnAs layer.[20] Saturation of paramagnetism, on the other hand requires very high magnetic fields. The magnetocurrent and its field dependence indicate that the spin polarization continues to increase up until very high magnetic fields.

V. CONCLUSION

In summary, the magnetoresistance of InMnAs/InAs *p-n* heterojunctions was measured for magnetic fields of up to 18 T. Giant magnetoresistance effects (2680% at 18 T) are observed at 300 K. The positive giant magnetoresistance is attributed to conduction of spin-polarized carriers due to the presence of spin-split bands. High magnetic fields are required to saturate the junction magnetoresistance measured at a constant voltage. These results indicate that paramagnetism of the magnetic semiconductor layer is responsible for the spin-polarized carriers at high magnetic fields. This work indicates that highly spin-polarized, all-semiconductor junction devices that operate at room temperature can be realized, potentially leading to a new class of spintronic devices for information storage and processing.

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