Magnetoamplification in a Bipolar Magnetic Junction Transistor

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(Received 11 May 2010; published 9 September 2010)

We have demonstrated the first bipolar magnetic junction transistor using a dilute magnetic semiconductor. For an InMnAs *p-n-p* transistor magnetoamplification is observed at room temperature. The observed magnetoamplification is attributed to the magnetoresistance of the magnetic semiconductor InMnAs heterojunction. The magnetic field dependence of the transistor characteristics confirm that the magnetoamplification results from the junction magnetoresistance. To describe the experimentally observed transistor characteristics, we propose a modified Ebers-Moll model that includes a series magnetoresistance attributed to spin-selective conduction. The capability of magnetic field control of the amplification in an all-semiconductor transistor at room temperature potentially enables the creation of new computer logic architecture where the spin of the carriers is utilized.

DOI: 10.1103/PhysRevLett.105.117202 PACS numbers: 85.75.−d, 73.40.Kp, 75.47.−m, 75.50.Pp

Spintronic devices are being developed as an alternative to conventional semiconductor devices for many applications, including information storage, communications, and information processing [1–3]. Hybrid unipolar devices comprising ferromagnetic metals and semiconductors have been employed to demonstrate spin injection and detection in Si [4,5]. However, for integration and fabrication of all-semiconductor magnetoelectronic devices, dilute magnetic semiconductors are the likely candidates, and many possible unipolar and bipolar devices have been already proposed using these materials [6]. Furthermore, a semiconductor transistor where one or more of the active layers is replaced with a ferromagnetic semiconductor has been proposed to exhibit additional functionalities [7–9]. In particular the bipolar magnetic junction transistor (MJT) has been predicted to have unique properties like magnetoamplification (MA), which is the change of amplification upon application of an external magnetic field [10].

The basic building blocks of a bipolar magnetic junction transistor are magnetic diodes. Recently, we have shown that *p-n* junctions using the *p*-type magnetic semiconductor InMnAs show a giant positive magnetoresistance [11]. The magnetotransport properties of InMnAs/InAs *p-n* junctions were previously simulated using a modified Shockley equation that includes magnetoresistive effects. The giant positive magnetoresistance is attributed to spin-selective conduction through spin-split bands [12]. InMnAs, when grown by metal organic vapor phase epitaxy, is a ferromagnetic semiconductor with a Curie temperature of 330 K [13]. Magnetic circular dichroism experiments on InMnAs indicate a strong *s*, *p-d* exchange at room temperature, leading to formation of spin-split bands that result in a positive magnetoresistance [14]. The giant magnetoresistive properties of the InMnAs junction make this material an ideal candidate for use in an MJT. Here we report on the room temperature operation of an InMnAs-based bipolar magnetic junction transistor. Magnetoamplification is observed for the first time in a bipolar magnetic junction transistor. To describe the experimentally observed transistor characteristics, we propose a modified Ebers-Moll model that includes a series magnetoresistance.

Figure 1 shows a schematic of the structure of the InMnAs bipolar MJT used in this study. *P*-type InAs ($p_E = 5\times10^{18}$ cm^{-3}) substrate is the emitter and the InMnAs ($p_C = 1\times10^{18}$ cm^{-3}) epitaxial layer is the collector. A 150 nm thick layer of undoped epitaxial InAs serves as the base. The InMnAs/InAs/*p*-InAs heterojunctions were fabricated by depositing 150 nm of InAs ($n_B = 1\times10^{16}$ cm^{-3}) by metalorganic vapor phase epitaxy followed by 75 nm of InMnAs on a *p*-type (001) InAs substrate. Photolithography was used to define circular

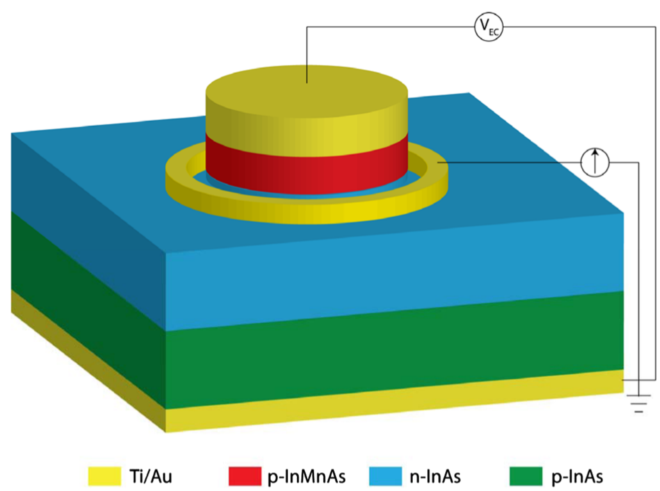

FIG. 1 (color online). A schematic of the InMnAs bipolar magnetic junction transistor. The base and collector were deposited by metalorganic vapor phase epitaxy.

Ti/Au collector contacts with a 250 μm diameter. The base and emitter contacts were defined in subsequent photolithography and contact deposition steps. The transistor properties were measured using a Keithley 4200 semiconductor parameter analyzer. All reported measurements are in the common emitter mode where the InAs p-type substrate serves as the emitter. The I-V characteristics were measured at 298 K. The emitter-collector voltage is varied between 0 to 0.4 V, and the base current ranges from 0 to 5 μA, in steps of 1 μA. The transistor characteristics were measured in a magnetic field that is perpendicular to the plane of the junction, using fields from 0 to 8 T.

To explain the behavior of a bipolar magnetic junction transistor in the presence of a magnetic field, its characteristics have been previously modeled for the case of a magnetic emitter and base [7,10,15]. An Ebers-Moll transistor model was used and these calculations showed that in the presence of an equilibrium spin polarization, injection and transport of spin polarized carriers leads to a change of amplification for the transistor with magnetic field strength [16]. In this model, the equilibrium spin (due to spin splitting of the conduction or valence band of the semiconductor) is accounted for in the prefactor to the forward and reverse biased coupled diode current expressions. The model predicts a positive magnetoamplification effect where increasing the magnetic field leads to an increase in amplification.

In contrast, in this study, a negative magnetoamplification was observed where increasing the magnetic field leads to a decrease in amplification. To describe the experimentally observed transistor characteristics, we propose a modified Ebers-Moll equivalent circuit that includes a series magnetoresistance. In the absence of nonequilibrium spin, the reverse current term used in the Ebers-Moll model for a bipolar magnetic junction transistor is replaced with a modified Shockley diode equation. Figure 1S (in the supplementary information [19]) shows the equivalent circuit for the device consisting of two coupled diodes and a magnetic-field-dependent resistance $R(B)$ in series with the collector-base (reverse) diode. This resistance accounts for the magnetoresistance in the collector-base magnetic junction. The modified reverse diode current (I_R) is given by

$$I_R = I_{R0} \exp\left[\frac{V_{\mathrm{CB}} - I_R R(B)}{\eta_{\mathrm{CB}} Vt}\right] \qquad (1)$$

where I_{R0} is the current prefactor, $R(B)$ is the magnetic-field-dependent resistance, η_{CB} is the junction ideality factor, Vt is the thermal voltage, and η_{CB} is the applied bias. The details of the model are given in the supplemental information [19].

The modified Ebers-Moll model is used to relate the magnetoamplification of the transistor to the magnetoresistance of the collector-base junction. The magnetoamplification results from the magnetoresistance of the collector-base (p-InMnAs/undoped-InAs) junction. We attribute this magnetoresistance to spin-dependent transport through two spin channels [12]. When a magnetic field is applied, spin-selective transport in the reverse biased p-n junction leads to an increase in $R(B)$, as has been previously shown [12]. This, in turn, leads to a decrease in the collector current for both zero base and finite base currents [17]. Since the decrease in the collector current for a finite base current is larger than the decrease in the collector current at zero base current, a negative magnetoamplification will be observed [18]. For a given emitter-collector bias (V_{EC}) and a given base current I_B, a change in the resistance in InMnAs/InAs junction results in changes in both the forward and reverse diode currents as these diodes are coupled. Our calculations show that the magnetoamplification depends on the functional form of the magnetoresistance for the InMnAs collector junction and its magnetic-field dependence [19]. Furthermore, our calculations show that for a given base current the magnetoamplification decreases for increasing V_{EC}.

Figure 2 shows the measured characteristics of the bipolar MJT where the magnetic InMnAs layer is the collector. The device shows a tendency toward saturation for voltages less than 0.05 V. For voltages higher than 0.05 V, the slope of the collector current curve decreases as expected for the active region of a transistor [20]. With an increase in base current, an increase in the collector current is observed as shown in the inset of Fig. 2. As V_{EC} is increased, there is a corresponding increase in the collector current. This presumably results from base-width modulation (Early effect) and leads to a nonzero slope. A reverse bias applied to the n-InAs/p-InMnAs junction results in a very high hole current that leads to the high collector currents observed in the transistor. The high hole concentration of 5×10^{18} cm^{-3} in the p-InAs emitter improves

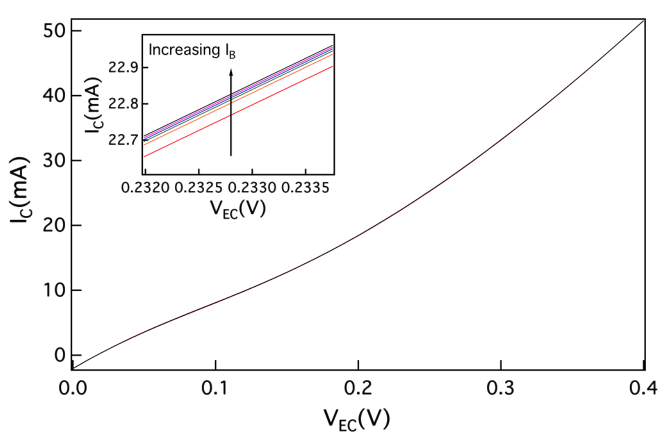

FIG. 2 (color online). Transistor characteristics measured in the common emitter mode at 298 K and zero magnetic field. The slope of the characteristic curve is high for very small voltages and decreases for voltages higher than 0.05 V. Inset: The change in collector current is shown as a function of base current. The base current increases in steps of 1 μA.

the transistor performance. At higher V_{EC}, an increase in slope occurs in the collector current curve.

Small changes in the base current result in significant changes in the collector current and correspond to a positive amplification. The amplification (β_{dc}) of the transistor was measured where β_{dc} is defined as follows:

$$\beta_{dc} = \frac{I_C(I_B) - I_C(0)}{I_B} \tag{2}$$

where $I_C(I_B)$ is the collector current for a constant base current of (I_B) and $I_C(0)$ is the collector current for zero base current.

In Fig. 3 the amplification is plotted as a function of the collector current on a log-log plot for different base current values. The highest amplification observed for our heterojunction device is 20. In the MJT, for a very low collector current the amplification is very small due to generation-recombination in the emitter-base depletion region. As the collector current increases the relative contribution of generation-recombination current to the total collector current decreases, thereby leading to an increase in the amplification [21]. For a low collector current, the amplification is a function of the collector current given by $\beta_{dc} \propto I_C^{[1-(1/\eta_{EB})]}$, where η_{EB} is the ideality factor for the emitter-base junction. Thus, on a log-log plot, the relationship between the log of amplification and log of collector current is linear, as is evident in Fig. 4 for a base current of 2 μA.

At intermediate collector currents, there is a narrow region where the transistor characteristics approach ideal behavior, and a plateau is reached in the amplification-collector current curve. However, at higher collector currents, the amplification drops rapidly. Note that the slope of the amplification curve is large (and negative) in the high collector current region. In this case, an increase in the base or emitter resistance leads to a decrease in the collector current and amplification. A high injection level caused by current crowding also adds to a decreasing amplification at higher voltages. This is a result of deviation of the emitter-base junction from ideal diode behavior [20,21].

A change in the transistor amplification is observed in the presence of an external magnetic field. The change in amplification upon application of an external magnetic field, the MA, is calculated as follows:

$$\text{MA} = \frac{\beta_{dc}(B) - \beta_{dc}(0)}{\beta_{dc}(0)} \times 100 \tag{3}$$

where the term $\beta_{dc}(B)$ is the amplification at a magnetic field of B and a bias V_{EC}, and $\beta_{dc}(0)$ is the zero magnetic field amplification at the same bias. The magnetoamplification is calculated for a constant emitter-collector bias for a given base current. For the case of $\beta_{dc}(B) < \beta_{dc}(0)$, a negative magnetoamplification results.

Figure 4 shows the magnetoamplification as a function of magnetic-field and emitter-collector bias. A negative magneto-amplification is observed for magnetic fields between zero and 8 T and voltages between 0.18 and 0.30 V. For magnetic fields of less than 2 T, the absolute magnetoamplification rises rapidly with the field, whereas for fields higher than 2 T, the decrease in amplification with the field is smaller. As V_{EC} is further increased, the absolute magnitude of magnetoamplification subsequently decreases. For voltages higher than 0.03 V but less than 0.18 V, the absolute magnetoamplification is much higher since the device is not in saturation. This bias dependence of magnetoamplification indicates that the region for active operation decreases with increasing magnetic field.

The observed negative magnetoamplification qualitatively agrees with calculations using the modified Ebers-Moll equations as shown in Fig. 2 S (in the supplementary information [19]). For a given magnetic field, the calculated magnetoamplification decreases with increasing emitter-collector bias. The nonidealities in the junction that lead to the very high currents are neglected in the

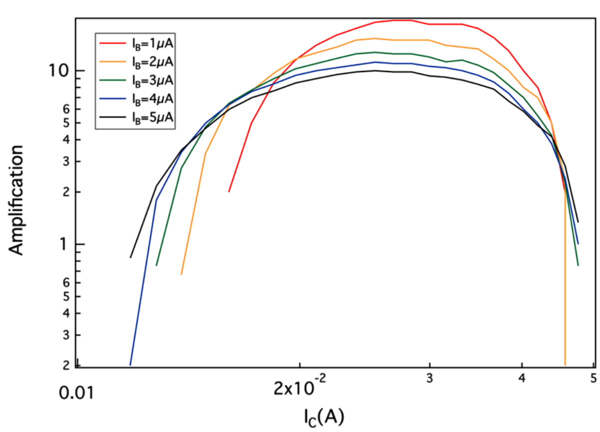

FIG. 3 (color online). Log amplification vs. log collector current as a function base current. We see that the device amplification is linear at low collector currents.

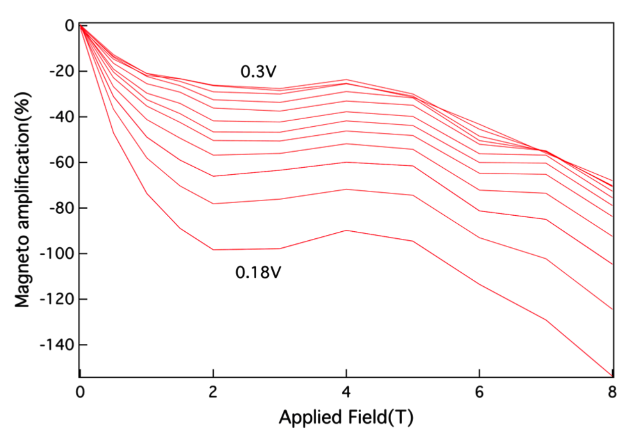

FIG. 4 (color online). Magnetoamplification as a function of magnetic field for various emitter-collector biases and a base current of 3 μA at 298 K. For very high magnetic fields, the device stops amplifying.

model. This results in the quantitative differences between the experimental data and the calculated magneto-amplification.

It is of interest to note that the transistor magnetoamplification curve is similar to the magneto-current dependence of magnetic field for a InMnAs/InAs diode [12]. The sudden increase in magnetoamplification for the transistor at lower magnetic fields, and the gradual saturation, is similar in functional form to the previously experimentally observed magneto-current ratio for magnetic semiconductor heterojunction diodes [12]. The current through the device at zero and finite base currents determines the amplification of the device and the magnitude of the base current depends on the magnetoresistance of the p-InMnAs/n-InAs junction. The positive junction magnetoresistance was previously attributed to conduction of spin polarized holes via spin-split valence band [12].

For a zero magnetic field and a finite base current, the transistor is amplifying and it is in a partly "on" state. One could, in principle, turn the transistor from an amplifying to a nonamplifying (less than 1) state by changing the magnitude of the magnetic field, as can be seen in Fig. 4. In a conventional bipolar junction transistor, the base current traditionally controls the amplification. At zero base current where the device is not amplifying, it is in the off state. In the present device, an amplification of less than one would be the equivalent of the off state. Application of a magnetic field would result in the magnetic transistor going from an amplifying to a nonamplifying state. This presumably could be achieved while the device is in operation and could potentially lead to reconfigurable logic. This magnetic field control over the amplification could potentially result in applications in new paradigms of computer architecture.

In summary, we have demonstrated the first bipolar MJT using a dilute magnetic semiconductor. For an InMnAs p-n-p transistor, room temperature magnetoamplification is observed that depends on the base current and the emitter-collector bias. The observed magnetoamplification is attributed to the magnetoresistance of the magnetic semiconductor InMnAs/InAs heterojunction. The magnetic-field dependence of the transistor characteristics confirms that the magnetoamplification results from the magnetoresistance of the collector junction. The capability of magnetic field control of the amplification in an all-semiconductor transistor at room temperature potentially enables the creation of new computer logic architecture where the spin of the carriers is utilized.

We thank Hooman Mohseni for helpful discussions. Extensive use of MRSEC facilities at Northwestern University (under Contract No. DMR-0520513) is acknowledged. The field dependent junction characteristics measurements were carried out at Argonne National Laboratory in the Center for Nanoscale Materials (CNM). This work was supported by AFOSR under Contract No. FA9550-07-1-0381.

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[17] The coupled nature of the Ebers-Moll equations lead to changes in both the forward and reverse bias currents for a given base current. Also, our calculations and experiments show that the collector current for zero and finite base current changes leading to the observed behavior.
[18] We observe a positive magnetoresistance in our collector-base junction, and this positive magnetoresistance indicates that there is an increase in the transistor resistance as the magnetic field is increased. The increased resistance of the device leads to a negative magnetoamplification.
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