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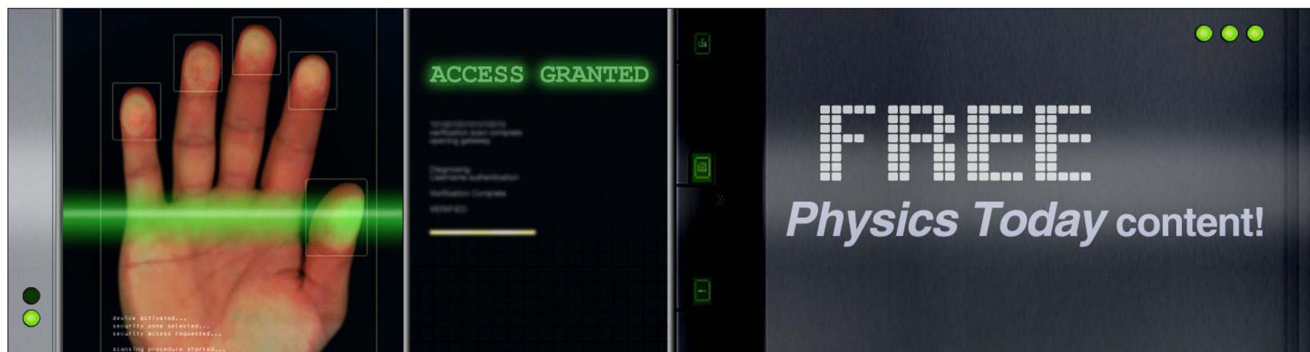

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APPLIED PHYSICS LETTERS **99**, 152503 (2011)

Gate control and amplification of magnetoresistance in a three-terminal device

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Gate control and amplification of magnetoresistance are demonstrated at room temperature in a fully epitaxial three-terminal GaAs-based device. In addition to the two ferromagnetic spin injector and detector electrodes of a MnAs/AlAs/GaAs:Mn/AlAs/MnAs vertical spin valve, a third non-magnetic gate electrode (Ti/Au) is placed directly on top of the heavily p-doped GaAs channel layer. The magnetoresistance of the device can be amplified to reach values as high as 500% at room temperature with the application of a bias to the gate terminal, which modulates the spin selectivity of the tunnel barriers. The experimental results are modeled by solving spin drift-diffusion and tunneling equations self consistently. © *2011 American Institute of Physics*. [doi:10.1063/1.3652765]

The magnetoresistance (MR) effect measured in GaAs-based spin valves at room temperature is ≤1%.[1] It is therefore essential to be able to amplify the magnetoresistive effect by controlling the flow of spin polarized carriers in a conventional spin valve. Such control, generally using a third (or gate) terminal, has been proposed[2] by several authors by invoking different physical principles. Some of these include magnetic bipolar junction transistors,[3,4] spin Hall effect transistors,[5] and the electrical modulation of spin-orbit coupling in the channel of a spin valve.[6–8] Higher values of magnetoresistance have been measured at or near room temperature in semiconductor-based tunneling magnetoresistance (TMR) devices[9] and vertical spin valves.[1] This is due to the short tunneling or transport distance in these devices controlled by epitaxial growth. In this work, we developed a GaAs/MnAs vertical spin valve with a third gate terminal, and produced ∼500% modulation of the magnetoresistance at room temperature. The gate terminal effectively shifts the band energy in the GaAs channel and thereby changes spin injection, transport, and detection. The modulation of magnetoresistance has been analyzed by a model based on one-dimensional (1D) spin drift-diffusion and the voltage dependence of tunneling resistance at the tunnel injector contacts.

The three-terminal device is schematically shown in Fig. 1(a), together with the biasing scheme for the measurements. A description of the molecular beam epitaxial growth of the heterostructure and subsequent device processing is provided as supplementary information.[10] A micrograph of the fabricated device and its dimensions are shown as an inset to Fig. 1(a). To verify spin injection and precession in our channel, three-terminal Hanle measurements[11] were carried out on a lateral device (since such measurements cannot be done in the vertical configuration) with identical doping level and thickness of the p^+-GaAs channel region, tunnel barrier, and spin contacts as the vertical spin-valve structure. The results are shown in Fig. 1(b). A fit to our Hanle data using the standard equation $\Delta\mu(B) = \Delta\mu(0)/(1+(\omega_L\tau)^2)$ gives a spin lifetime and diffusion length of 400 ps and ∼14 nm, respectively. The relatively high spin lifetime can be attributed to two effects: (1) enhancement of spin accumulation at the FM/SC interface[12] and (2) suppression of spin relaxation due to Mn dopants in the GaAs channel.[13] A more rigorous study needs to be done to quantify the contributions from each and is beyond the scope of this paper. However, from our low $\Delta\mu(0)$ value, spin accumulation at the interface states dominating the Hanle signal can be ruled out.

MR measurements were made with the devices in a closed-loop He cryostat placed between the poles of an electromagnet. The magnetic field is applied in-plane along the easy axis of MnAs $[\bar{1}\bar{1}20]$. Measurements were first made with no bias (gate floating) applied to the gate (third) terminal, the device thereby behaving as a vertical spin valve. The characteristics of such a device[1] and similar two-terminal vertical devices[14] have been reported but are described here for completeness. As will be evident later, analysis of the magnetoresistance behavior of such a device helps us to explain the observed characteristics of the three-terminal device. A constant dc bias current (I_{ds}) is applied between the two MnAs contact layers (source and drain), and the voltage V_{ds} is measured between the same terminals while varying the applied magnetic field. The magnetoresistance response at a bias current of 20 nA measured at room temperature is shown in Fig. 2(a). The magnetoresistance is calculated as $MR = (V_{AP} - V_P)/V_P$, where V_P and V_{AP} are the measured terminal voltage V_{ds} for parallel and anti-parallel alignment of the two MnAs contacts. We are able to achieve a value of MR ≅ 25%, which is the largest reported in any semiconductor spin valve at room temperature. The measured variation of MR with bias current is shown in Fig. 2(b), where a decrease of MR with increasing bias is observed. No magnetoresistance was observed in control devices with (a) channel thickness much greater than the spin diffusion length and (b) the top MnAs contact replaced by a non-ferromagnetic Ti/Au contact.

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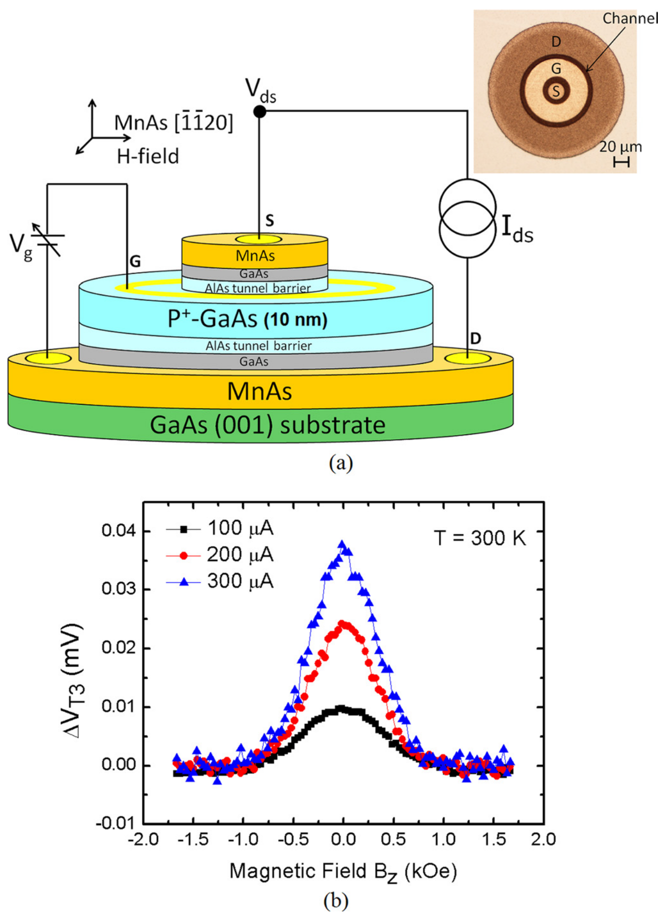

FIG. 1. (Color online) (a) Schematic diagram of the device heterostructure and measurement scheme. Inset shows a micrograph of a fabricated device before passivation and metallization. The top MnAs electrode is 15 μm in diameter, the channel region is 75 μm in diameter, and the bottom MnAs is 200 μm in diameter. (b) Three-terminal Hanle data on a Mn doped GaAs channel at room temperature for a bias current of 100, 200, and 300 μA.

The results of three-terminal measurements, with the application of a gate bias, are described next. With reference to Fig. 1(a), a constant current bias I_{ds} is applied between the two MnAs contacts and a voltage V_g is applied to the gate terminal. The two MnAs contacts are successively set in parallel and anti-parallel magnetization with the application of appropriate magnetic fields (depending on the individual coercivities of the contacts) and in each case $V_{ds} = V_P$ or V_{AP} is measured as the gate bias is varied. Figures 3(a) and 3(b) depict the measured variation of MR with V_g at room temperature for two values of I_{ds}. The control of magnetoresistance with the gate terminal is evident. Very large values of magnetoresistance are measured in our experiment. The source to drain current is biased high to achieve a higher MR amplification ratio $(MR(V_g = V_{critical})/MR(V_g = 0))$. However, the device can be biased either high or low; the amplification magnitude and characteristics will not be affected.

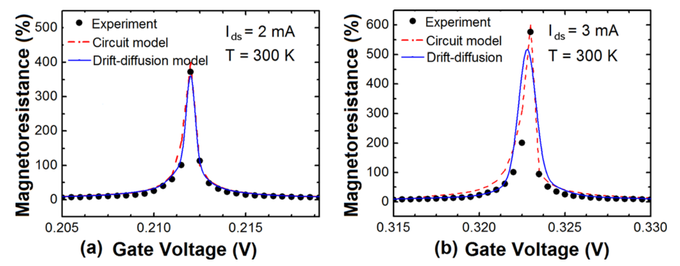

FIG. 3. (Color online) Measured and calculated magnetoresistance as a function of gate voltage at T = 300 K at a current bias of (a) 2 mA and (b) 3 mA.

In order to understand the variation of MR with current bias in the two-terminal spin valve and the control of MR with the gate electrode, it is first important to note that the GaAs channel is heavily doped p-type ($p \sim 9 \times 10^{19}\,cm^{-3}$) with Mn acceptors. The Mn concentration at this doping level is ~0.9%, for which there is no ferromagnetism at room temperature[15] and the Curie temperature is ~20 K.[16] The incorporation of Mn in the GaAs channel serves two purposes: first, high quality single-crystal p^+-GaAs can be grown at $T \sim 250\,°C$, which is essential here, and second, the Mn atoms provide valence band states in the channel for spin polarized carrier transport. The band diagram of the two-terminal heterostructure spin valve with the Schottky tunnel injector contacts, together with the doping profile and the Fermi levels, is obtained by a self-consistent solution of the Schrödinger and Poisson equations and is shown in Fig. 4(a) for zero applied bias. With an applied current bias, spin polarized electrons injected by the source MnAs/AlAs/GaAs tunnel barrier are transported across empty valence band states at the Fermi energy in the GaAs channel and are collected at the drain ferromagnet-semiconductor Schottky tunnel contact.[1] At the same time, the band bending in the semiconductor changes, mostly at the drain end, accompanied by a change in width and height of the drain Schottky tunnel barrier (see supplementary document). In effect, the interface resistance and spin selectivity of the tunnel contacts are modulated. Additionally, at high values of applied bias, unpolarized electrons

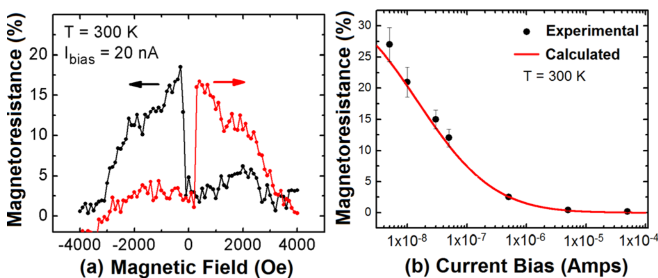

FIG. 2. (Color online) (a) Magnetoresistance response at a current bias (I_{ds}) of 20 nA at T = 300 K. The arrows indicate magnetic field sweep direction. (b) Measured and calculated magnetoresistance as a function of current bias at T = 300 K.

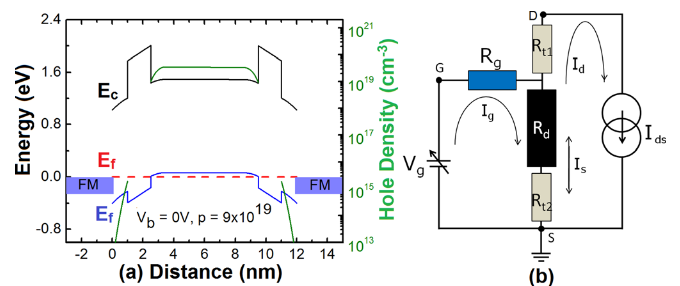

FIG. 4. (Color online) (a) Calculated energy band diagram of the vertical spin valve heterostructure. The channel is degenerately p-doped, and the Fermi-level lies within the valence band of the p^+-GaAs channel. (b) Circuit model of the three-terminal device.

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from filled valence band states below the Fermi level in GaAs can tunnel into the MnAs contact layer and result in a component of unpolarized current. The bias dependence of magnetoresistance due to the changes in the bands and contacts is analyzed by describing spin transport with the drift-diffusion model of Valet and Fert[17] and Yu and Flatte.[18] Tunneling across the source and drain Schottky barriers is analyzed with the Tsu-Esaki model[19] using the WKB approximation, assuming no spin scattering at the ferromagnet-semiconductor interfaces. The spin diffusion length at room temperature in the p-doped GaAs is obtained from our temperature-dependent measurements reported earlier.[1] Thus, the bias dependence of the tunneling resistance and the MR of the device are obtained. A two-channel model for spin-up and spin-down carriers across the device is described in the supplementary document, together with the relevant equations. Spin injection into a semiconductor material causes the electrochemical potential of spin-up and spin-down electrons to split in the channel. Although the transport direction is vertical in this device, the physics is similar to a lateral spin device, allowing us to model spin transport in this structure using the widely known two-channel spin transport model.[20] The calculated variation of MR with bias in the two-terminal spin valve is shown alongside the measured data in Fig. 2(b), and the agreement is very good.

To understand the increase, peaking, and near-symmetrical decrease of the magnetoresistance with gate bias, reference is made to the resistive model of the device shown in Fig. 4(b). R_{t1} and R_{t2} are the magnetization and bias dependent interface resistance of the drain and source Schottky tunnel contacts, respectively, R_d is the series resistance of the p-doped GaAs channel, and R_g is the resistance of the gate contact. With no applied gate bias (gate terminal floating), the voltage measured across the device is $V_{ds} = |I_{ds}|\ (R_{t1} + R_{t2} + R_d)$, where $|I_{ds}|$ is the magnitude of the constant current bias applied across the device. When a gate bias is applied, the bands in GaAs and the tunnel barrier thickness are changed, mostly at the drain contact. A current I_g will flow across R_g and a reduced current $(|I_{ds}| - I_g)$ will flow across R_d and R_{t2} to obey Kirchoff's current law; consequently $V_{ds} = (|I_{ds}| - I_g)(R_{t2} + R_d) + |I_{ds}|R_{t1}$. The current flowing through R_{t1} is always equal to I_{bias} since I_{bias} is an externally applied constant current bias. Similarly, when $I_g = |I_{ds}|$, no current flows across R_{t2} and R_d and $V_{ds} = |I_{ds}|R_{t1}$. With increasing V_g, I_g becomes larger than $|I_{ds}|$, and at a critical value of V_g, the net voltage drop across the source and drain terminal is made zero (voltage drop across R_{t1} is equal to the voltage drop across R_d and R_{t2}, but opposite in sign). At this critical gate voltage, in the parallel magnetization configuration of the two MnAs contacts, $V_{ds} = V_p \approx 0$ and MR becomes very large. At this point, there is no net tunneling between the source and drain contacts. For larger values of V_g, the polarity of V_{ds} is reversed and finite in value (voltage drop across R_{t1} is smaller compared to the voltage drop across R_d and R_{t2}), leading to a sharp decrease of MR. The rise and fall of MR is near symmetric with V_g, as observed experimentally, since the change of V_{ds} with V_g is also near-symmetric around $V_{ds} \cong 0$ (see supplementary information). As I_{bias} is increased, the critical value of V_g, for which MR is a maximum, should also increase since a larger current I_g would be required to offset I_{bias}. This is observed experimentally as seen in Figs. 3(a) and 3(b). The calculated variation of MR with V_g, with respect to the equivalent circuit of Fig. 4(b), is shown by the dashed curves in Figs. 3(a) and 3(b) and is in reasonable agreement with measured data. Also shown by the solid curves in Figs. 3(a) and 3(b) are the calculated MR in accordance with the self-consistent drift-diffusion and tunneling model. The observed variation of MR with V_g is a result of the change in the effective bias applied between the two MnAs Schottky tunnel contacts, which change the band bending in GaAs, the tunnel barrier thickness, and the interface resistance and spin selectivity of the tunnel contacts. In effect, the gate terminal modulates the spin current collected at the drain terminal.

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