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Magnetoresistance in an asymmetric $Ga_{1-x}Mn_xAs$ resonant tunneling diode

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In a GaMnAs/AlGaAs resonant tunneling diode (RTD) structure, we observe that both the magnitude and polarity of magnetoresistance are bias dependent when tunneling from a three-dimensional GaMnAs layer through a two-dimensional GaMnAs quantum well. This magnetoresistance behavior results from a shift of negative differential resistance features to higher bias as the relative alignment of the GaMnAs layer magnetizations is changed from parallel to antiparallel. Our observations agree with recent predictions from a theoretical analysis of a similar *n*-type structure by Ertler and Fabian, and our results suggest that further investigation into ferromagnetic RTD structures may result in significantly enhanced magnetoresistance.

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GaMnAs has emerged as a model ferromagnetic semiconductor[1–3] for developing proof-of-concept spintronic devices because it exhibits hole-induced ferromagnetism with Curie temperatures as high as ~185 K.[4,5] A number of magnetoresistance device configurations have been demonstrated, including magnetic tunnel junctions,[6,7] spin valves,[8] and spin-based hot carrier transistors.[9]

In this Rapid Communication we investigate the magnetoresistance characteristics of a GaMnAs-based resonant tunneling diode (RTD). In our device, two ferromagnetic GaMnAs layers, one of which is a quantum well (QW), are separated by a single tunnel barrier. In this regard, our device is similar to a conventional single-barrier tunneling magnetoresistance (TMR) device,[6] with the important difference that magnetoresistance in our device results from tunneling from a three-dimensional (3D) contact through a two-dimensional (2D) QW, whereas magnetoresistance in a conventional device results from 3D to 3D tunneling. In our device, we find that switching the relative orientation of the GaMnAs layer magnetizations from parallel to antiparallel results in a uniform shift of the negative differential resistance (NDR) features to higher bias. This leads to a bias dependence of both the magnitude and polarity of the magnetoresistance.

The layer structure of the material used in this experiment, in order from surface to substrate, is 50 nm $Ga_{0.96}Mn_{0.04}As$, 1 nm GaAs, 1.5 nm AlAs, 1 nm GaAs, 7 nm $Ga_{0.92}Mn_{0.08}As$ QW, 1 nm GaAs, and 100 nm $Al_{0.4}Ga_{0.6}As$, all grown by molecular-beam epitaxy on a *p*-GaAs substrate (*p*-type doped 2×10^{18} cm^{-3}). Layers starting from the GaMnAs QW layer were grown at a reduced temperature of 250 °C. Secondary ion mass spectroscopy profiling shows the layer structure as expected. Superconducting quantum interference device (SQUID) measurements presented in Fig. 1 show two distinct T_C, providing confirmation that the two GaMnAs layers are ferromagnetic below 15 K.[10] Devices were fabricated by etching circular mesas of 50 μm diameter. A schematic band diagram of the device is shown as the inset of Fig. 2.

The devices were cooled to 4 K and connected in a two-terminal configuration with contacts (40 nm Cr/40 nm Au) to the GaMnAs top layer and to the *p*-GaAs substrate. Current-voltage traces were taken for a number of devices. For positive bias, holes tunnel from the top GaMnAs layer, through the QW, and into the substrate. Under this bias condition, we observed several NDR features associated with transmission resonances through bound states in the QW, which were seen with varying degrees of sharpness in a number of tested devices. A current-voltage trace taken from the device with the most prominent NDR is shown in Fig. 2. Our analysis focuses on the two features with strongest NDR, which are enclosed in a dashed box in Fig. 2 and are shown in greater detail in Fig. 3(a).

An applied magnetic field in the [110] direction was swept through ±800 G at various device biases. For high magnetic fields (≳700 G), the GaMnAs layer magnetizations adopt a parallel orientation. As the magnetic field is reversed, the magnetizations of the GaMnAs layers switch

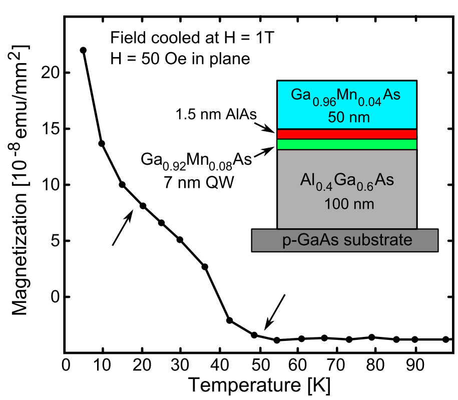

FIG. 1. (Color online) Magnetic properties of the sample. The temperature dependence of the in-plane magnetization resolves two distinct T_C of about 15 and 50 K (denoted by arrows), indicating the presence of two distinct GaMnAs layers. (Inset) Layer diagram of the sample.

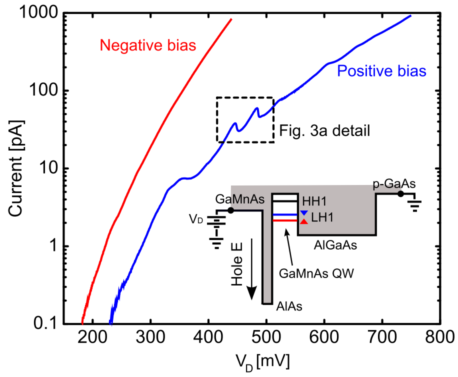

FIG. 2. (Color online) Current-voltage trace showing resonant tunneling behavior at 4 K for parallel GaMnAs layer magnetizations. Several NDR features are observed for positive bias (blue trace), while negative bias (red trace) shows no resonances. (Inset) An approximate schematic band diagram based on a GaAs RTD that includes the first heavy-hole bound state as well as the first spin-split light hole bound state (see Ref. 11). The bias voltage is applied to the top GaMnAs layer and the *p*-GaAs substrate is grounded.

independently because their different thicknesses and Mn contents result in different coercive fields.[12] This leads to sequential regions of parallel, antiparallel, and then parallel layer magnetizations for each magnetic field upsweep or downsweep. Example sweeps of current versus magnetic field are plotted in Fig. 3(b) for two different device biases.

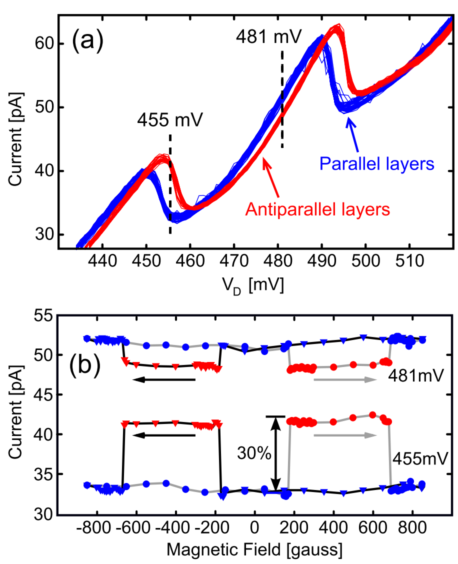

FIG. 3. (Color online) (a) Detail of Fig. 2 as a composite of 89 *I-V* traces showing NDR features. Blue (red) traces were taken with parallel (antiparallel) GaMnAs layer magnetizations. Resonances shift to higher bias for antiparallel layer magnetizations. Peak-to-valley ratio is approximately 1.15 and 1.13 for parallel and antiparallel layer magnetizations, respectively. (b) Device current versus in-plane magnetic field applied in the [110] direction for device biases of 455 and 481 mV. The black (gray) trace indicates the magnetic field downsweep (upsweep). The origin and sign of magnetoresistance result from the *I-V* shift shown in (a).

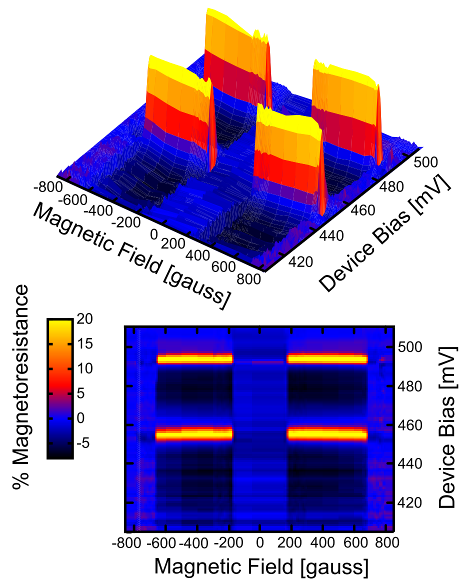

FIG. 4. (Color online) Colormap plot showing the magnetoresistance properties of the device as a function of device bias and applied magnetic field. The distinct regions of positive and negative magnetoresistance result from the shift of NDR features to higher bias, as shown in Fig. 3(a). The upper range of the color map was limited to 20% magnetocurrent to enhance the contrast at low negative values.

A maximum magnetocurrent of 30% was observed at a bias of 455 mV. Measurements taken for both the [110] and [$\bar{1}$10] in-plane magnetic field directions show no dependence on orientation that would indicate the presence of anisotropic magnetoresistance.[13]

When the relative alignment of GaMnAs layer magnetizations switches from parallel to antiparallel, all NDR features shift equally to higher biases, as shown in Fig. 3(a). This *I-V* shift of NDR features results in regions of positive and negative magnetoresistance depending on device bias, as can be seen in the colormap shown in Fig. 4. A device with similar behavior was reported in the literature; however, in that device the resonances appear only in derivative spectra and the authors do not comment on the NDR shift.[14]

One goal of using ferromagnetic semiconductors, such as GaMnAs, is to realize devices with high magnetoresistance. Single-barrier GaMnAs-based devices have demonstrated 75% magnetoresistance (MR).[6] It has been theoretically predicted that the MR could be increased drastically (to greater than 800%) by separating the ferromagnetic electrodes with a QW, thereby restricting transport to the transmission resonances of the RTD structure.[15] Experimentally, however, such structures have only shown MR of a few percent.[9,16] A similar RTD structure comprised of a ferromagnetic QW and one ferromagnetic 3D electrode has recently demonstrated up to 18% MR, although this device did not actually show NDR (the differential resistance only became negative in second derivative spectra), and, perhaps as a result, the bias regime of maximal MR was near 0V rather than near the resonance features.[14] Using the device presented here, which utilizes a ferromagnetic emitter and QW, we obtain 30% MR due to the shift in NDR features. Given the unoptimized nature of our structure, we expect that further enhancement of MR could be obtained by tailoring the transmission resonances of the RTD structure.

The MR in our device arises from the shift in NDR features reported in Fig. 3(a). A theoretical investigation by Ertler and Fabian of a similar system (an RTD structure with a ferromagnetic QW and top layer) predicts a shift in NDR features similar to what we report.[17] In order for us to apply their theoretical analysis, however, the tunneling holes must be highly spin polarized. This is not immediately apparent for GaMnAs under an in-plane magnetic field, as some reports indicate that only light holes exhibit significant spin polarization and that heavy holes are not spin split.[18] However, there are reports that demonstrate a high percentage of spin-polarized carriers when tunneling from GaMnAs into *n*-type GaAs.[19] Additionally, experiments on *p*-type GaAs RTDs have shown significant hole mixing during tunneling, with light holes dominating the transport because their lower effective-mass results in an exponentially greater tunneling probability.[20] It therefore is likely that transport in our device is dominated by spin-polarized light holes, and thus the theory of Ertler and Fabian should apply.

A simple understanding of the operation of our device consists of spin-polarized light holes tunneling from the 3D GaMnAs top layer through spin-split light hole bound states in the GaMnAs QW. In this picture, as described by Ertler and Fabian, we would expect to see the NDR features appear at lower device bias for parallel layer magnetizations because the lower energy spin species in the top layer matches that the lower energy spin species in the QW. When the layer magnetizations are antiparallel, we expect the NDR features to shift to higher bias because the lower energy spin species in the top layer is now the higher energy spin species in the QW. Additionally, Ertler and Fabian predict a reduction in NDR peak-to-valley ratio for antiparallel layer magnetizations because the spin-polarized transport channels open sequentially, in which case the NDR would be degraded by spin scattering. As can be seen in Fig. 3(a), we report a ~2% reduction in NDR peak-to-valley ratio (from 1.15 to 1.13) when the magnetic orientation was switched from parallel to antiparallel.

We observed that the shift in NDR features was very sensitive to the device structure. When we increased the QW thickness to 10 nm, we were unable to observe any significant NDR features. This is similar to the report in Ref. 14 which only observed weak resonances in derivative spectra for a 12 nm QW. This may be the result of the bound-state energies in a wide QW being too closely spaced to be resolved. Upon increasing the thickness of the AlAs barrier to 5 nm (while keeping a 7 nm QW), we did observe similar NDR features; however, in this case the NDR features appeared only for negative bias (likely due to the difficulty in consistently controlling the Fermi level in GaMnAs) and we observed a negligible shift in the NDR features with magnetic field. This reduced magnetoresistance of a thick AlAs tunnel barrier may not be surprising in light of reports of a similarly strong reduction in single-barrier tunneling magnetoresistance as the barrier thickness is increased beyond ~2 nm.[6]

To summarize, we observed NDR in a GaMnAs/AlGaAs asymmetric resonant tunneling diode which displays either positive or negative magnetoresistance depending on applied bias. This magnetoresistance is associated with a shift in NDR features to higher bias for antiparallel layer magnetizations. We note that this shift conforms well to the theoretical investigation of Ertler and Fabian for spin-polarized resonant tunneling through a quantum well. Further investigation into ferromagnetic RTD structures is warranted and may result in significantly enhanced magnetoresistance.

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