Observation of magnetoresistance polarity reversal in 3D to 2D tunneling in an asymmetric GaMnAs resonant tunneling diode

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We investigate the magnetoresistance (MR) characteristics of a GaMnAs-based asymmetric resonant tunneling structure with a 3D GaMnAs top layer and a 2D GaMnAs quantum well (QW). The incorporation of a 2D layer distinguishes our device from the many conventional devices reported in the literature [1] in that the MR characteristics of our device result from 3D to 2D tunneling, whereas MR in a conventional device results from 3D to 3D tunneling. By observing a shift of negative differential resistance (NDR) features as an in-plane magnetic field is varied, we infer that the 3D to 2D tunneling magnetoresistance (TMR) in our device has the opposite sign from conventional TMR in GaMnAs. We relate this difference to the effect of quantum confinement on the 2D density of states in the GaMnAs QW.

Two-terminal current-voltage measurements were taken at 4 K and strong NDR associated with resonant tunneling was observed for a number of devices, which we interpret as evidence of holes tunneling from the top GaMnAs layer through bound states in the GaMnAs QW. When the relative alignment of GaMnAs layer magnetizations is switched from parallel to anti-parallel, all resonance features shift equally to higher biases. According to the sequential tunneling model [2], the bias at which NDR features are observed depends on the relative alignment of band minima across the tunnel barrier, thus we expect a change in tunnel barrier conductivity to cause a shift in NDR features. Our device behavior indicates that the tunnel barrier is more conductive for anti-parallel layer magnetizations. This is in contrast to the behavior of conventional GaMnAs TMR devices, which become more resistive for anti-parallel layer magnetizations.

The sign of the MR depends on whether the same spin species has the larger density of states at the Fermi energy on both sides of the tunnel barrier. For a conventional 3D to 3D device with in-plane magnetic field, the resistance is maximal when the magnetic layer magnetizations are anti-parallel. In our device, however, the resistance of the tunnel barrier is maximal when the layer magnetizations are parallel. This implies that opposite spin-species has the largest density of states on either side of the barrier in our device. The most obvious explanation for this polarity reversal is the 2D nature of the GaMnAs QW. Because quantum confinement energy is drastically different for heavy and light holes, the relative alignment of the hole density of states in the 2D QW and the 3D top layer can be significantly altered from the conventional 3D/3D case.

To summarize, we observed NDR in a GaMnAs 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 anti-parallel layer magnetizations. We attribute this shift to a change in tunnel barrier conductivity and propose that its inverted sign is the result of 2D confinement in the ferromagnetic QW. Our results suggest that MR can be varied and even inverted by modifying the density of states in the GaMnAs layers.

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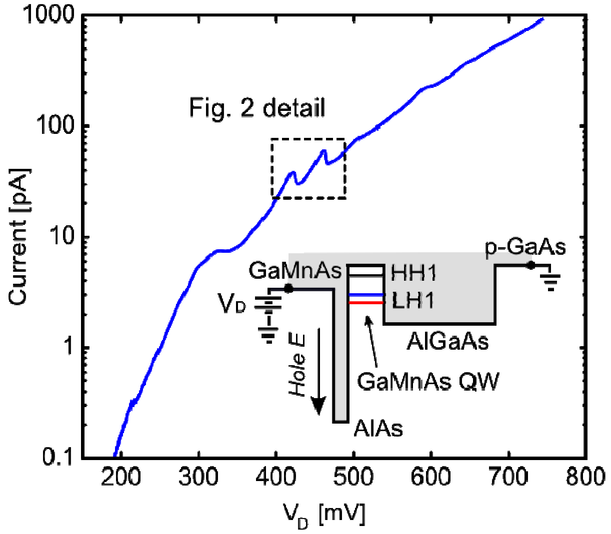

Figure 1. Current-voltage trace showing negative differential resistance features characteristic of resonant tunneling at 4K for parallel GaMnAs layer magnetization. Several resonance features are observed for positive bias (blue trace). No resonances are observed for negative bias (not shown). Inset: A possible 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. For clarity, higher bound states are not shown. The bias voltage is applied to the top GaMnAs layer and the p-GaAs substrate is grounded.

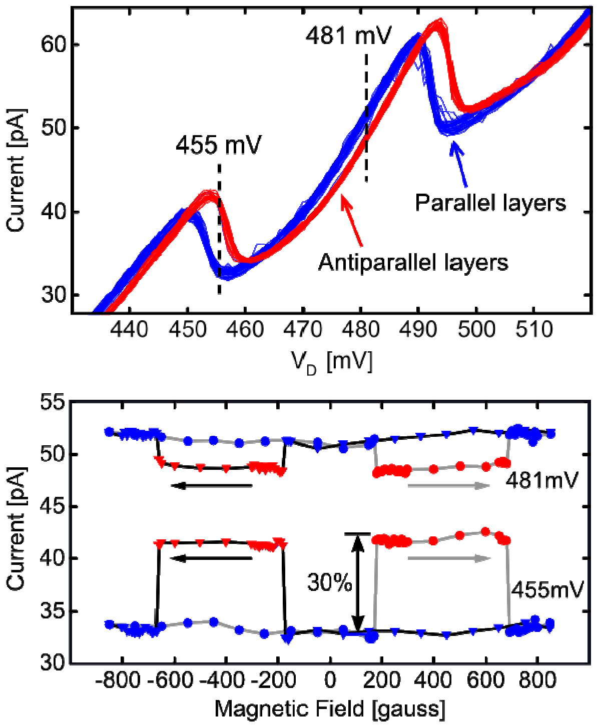

Figure 2. (Top) Detail of Figure 1 as a composite of 89 I-V traces showing NDR resonances. Blue (red) traces represent parallel (anti-parallel) GaMnAs layer magnetization. Resonances shift to higher bias for anti-parallel layer magnetization due to a more conductive AlAs barrier. (Bottom) Device current versus in-plane magnetic field showing positive and negative MR. The black (gray) trace indicates the magnetic field downsweep (upsweep). The origin and sign of MR are a result of the I-V shift shown above. The mechanism is explained by a density of states argument in Figure 3.

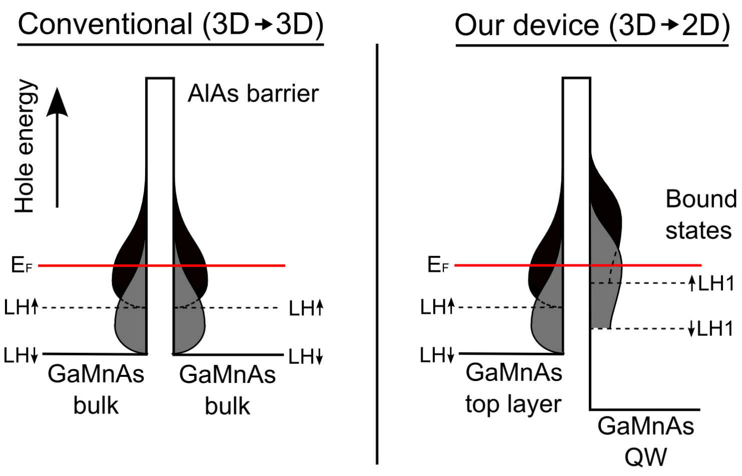

Figure 3. (Left) Hole density of states schematic for a conventional magnetic tunnel junction with two 3D GaMnAs layers under parallel layer magnetization. The barrier becomes less conductive for anti-parallel magnetization because the density of states available for holes tunneling at the Fermi energy is reduced. This can be visualized by swapping the spin-up and spin-down light hole states in one of the GaMnAs layers. (Right) Hypothetical density of states for our 3D/2D system illustrating how quantum confinement of the 2D layer alters the relative energy of the light holes such that the density of states available at the Fermi energy is now increased for anti-parallel magnetization, possibly resulting in polarity reversal of tunneling MR across the AlAs barrier.