Magnetoization Dependent Current Rectification in (Ga,Mn)As Magnetic Tunnel Junctions

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We have found that the current rectification effect in triple-layer (double-barrier) (Ga,Mn)As magnetic tunnel junctions strongly depends on the magnetization alignment. The direction as well as the amplitude of the rectification changes with the alignment, which can be switched by bi-directional spin-injection with very small threshold currents. A possible origin of the rectification is the energy dependence of the density of states around the Fermi level. The tunneling density of states in (Ga,Mn)As shows a characteristic dip around zero bias indicating the formation of a correlation gap, the asymmetry of which would be a potential source of the energy-dependent density of states.

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Figure 1 shows a typical TMR for a major magnetic field loop. The lineshape resembles to those reported so far, suggesting similarity in magnetization alignments, of which a possible set are illustrated for typical values of magnetic field. Actually, there should be several variations in the alignment around those simplified ones as can be seen in the small step structures. This is probably due to the reduction in the in-plane crystallographic anisotropy through the relaxation of biaxial strain with micro-fabrication.

Note that the smallest coercive force is assumed in the top layer in the illustrated alignments for natural interpretation of the response to current injection. This clearly appears in the response to the spin injection by current pulses. A sequence consists of a minor field loop 0 T → 0.06 T → 0 T and a current injection at zero field is adopted in Fig. 2(a). As shown in Fig. 2(a), the junction resistance jumps up to the branch of the highest resistance when the electric current of 500 µA flows from the substrate to the upper electrode (we define this direction as “negative” current). The pulse width can be as short as 3 ms, which is limited by wiring in the cryostat. A resistance leap with a smaller increment is also observed for a positive current pulse. To assign these states of resistance to the alignments of magnetization, we need to assume that the [010] direction is the second easy axis of the magnetization in the middle layer.

Concentration of device characteristics through spin-degree of freedom is one of the expected novel functionalities in semiconductor spintronics. In metallic magnetic tunnel junctions (MTJs), rectification of microwaves driven by ferromagnetic resonance (FMR) has been reported. This arouses interest in the effect of ferromagnetism on the rectification properties in diluted magnetic semiconductor (DMS) devices. In strongly asymmetric structures such as Schottky or p–n junctions, the rectification is naturally realized through steep electrostatic band bending, which cannot be expected in unipolar MTJs ordinarily obtained in DMSs. For example, in the case of (Ga,Mn)As the material should be p-type for the appearance of ferromagnetism, which is mediated by charge carrying holes. Instead, spin-polarization may thus be utilized to commutate alternative currents.

In this letter, we report such a rectification effect in (Ga,Mn)As tri-layer MTJs, which have a very small threshold current for spin-injection magnetization reversal. The rectification is sensitive to the alignment of the magnetizations and hence can be controlled through bi-directional current injection.

The inset of Fig. 1 schematically shows the cross section of the layered structure grown by low-temperature molecular beam epitaxy (LTMBE) onto a (001) p+-doped GaAs substrate with the growth temperature of 320 °C. The middle “free” layer is designed to be thinner than the other two, to have a smaller coercive force, which turned out to be, in reality, comparable to that of the top layer as we will see later. The ferromagnetic transition temperature estimated from the appearance of hysteretic tunneling magnetoresistance (TMR) is about 40 K. With the use of electron beam lithography, the film was wet-etched into mesas with 1.6 × 0.9 µm² rectangles along [100], which is one of the easy axes of the in-plane magnetization, although the anisotropy should be weakened through the stress relaxation. Each device was attached to a coplanar waveguide (CPW) with [100] parallel to the external magnetic field. Here, the doped substrate is electrically bonded to the center strip and separately ordinal wires for DC are connected. The AC and DC lines were cut by bias tees. Due to the high impedance, the devices were in the voltage-driven mode by the AC sources. The rectified currents were measured through a current–voltage amplifier or calculated from the DC voltages along the device and the current–voltage (I–V) characteristics. An external magnetic field of 0.7 T was applied along [100] during cooling from room temperature to 4.2 K.
amplitude. We here eliminated the possibility of heating under the AC voltages by measuring the TMR and hence the magnetic coercive force, which is found to be sensitive to the temperature. A type of conductance, \( G_r = (\text{rectified DC current})/(\text{AC drive voltage amplitude}) \), can therefore serve as a measure of the rectification.

In spite of the almost symmetric \( I-V \) characteristics, a clear rectification voltage appears with the application of AC voltages. Figure 3(b) shows \( G_r \) as a function of external magnetic field at the AC frequency \( f \) of 1.4GHz and the amplitude of 1.7mV. \( G_r \) has a small positive value for parallel alignments and large negative outputs appear for alignments with anti-parallel or perpendicular junctions. Clear correspondence between \( G_r \) and the TMR is observed, although it is not monotonic. Because \( G_r \) is sensitive to the magnetization alignment, it can also be controlled with spin-injection. Figure 3(c) displays flip-flop switching of the rectification conductance. The conditions can also be tuned so that the direction of the rectification can be switched with spin-injection. Figure 3(d) demonstrates such reversal of rectification direction by current (spin) injection at zero field in another device.

Henceforth, we discuss the possible origin of the rectification. The fact that the sign of output changes with the configuration of magnetization eliminates the possibility that the source is zero-point shift in the \( I-V \) characteristics due to some imbalance in the circuit including thermoelectric voltages in cryogenic wires, which only modifies the amplitude. We have measured the frequency dependence of \( G_r \) from 1 to 8GHz (the limit of our microwave source) and found it very weak. The spin torque diode effect is ruled out because it is based on FMR and thus should have strong frequency dependence.

We look for a possible explanation in the simplest model of magnetic tunnel junctions (MTJs) by Julliere,\(^7\) in which the conductance of an MTJ is a function of the majority and minority subbands density of states in the electrodes. Here for simplicity, we consider a magnetic bilayer structure and the result is applicable to the present tri-layer structure within a simple series resistance model, which, we believe, is a good approximation for materials with very short mean free paths such as (Ga,Mn)As. A slight modification to the Julliere model is energy \( \epsilon \) and electrode \( j = 1,2 \) dependent density of states \( f_j(\epsilon) \) and \( g_j(\epsilon) \) for the majority and the minority spin subbands, respectively. We take the Fermi energy \( \epsilon_F \) as zero and the current differences \( \Delta J_{ap} \) for voltages \( \pm V \) are proportional to sum of convolutions as
\[
\Delta J_p(V) \equiv J_p(V) + J_p(-V)
\]
\[
\alpha \int_0^{\epsilon_f} d\epsilon [f_1(\epsilon - eV)g_2(\epsilon) + g_1(\epsilon - eV)f_2(\epsilon)] \\
- f_2(\epsilon - eV)g_1(\epsilon) - g_2(\epsilon - eV)f_1(\epsilon),
\]
(1)
\[
\Delta J_p \propto \int_0^{\epsilon_f} d\epsilon [f_1(\epsilon - eV)f_2(\epsilon) + g_1(\epsilon - eV)g_2(\epsilon)] \\
- f_2(\epsilon - eV)f_1(\epsilon) - g_2(\epsilon - eV)g_1(\epsilon),
\]
(2)
for anti-parallel and parallel configurations, respectively.

In eqs. (1) and (2), one can easily confirm that \( \Delta J_p = \Delta J_n = 0 \) when \( f_j, g_j \) are even functions or when the magnetic layers are symmetric \( (f_1 = f_2, g_1 = g_2) \). Hence the rectification stems from the above mechanism only when the density

The switching between these two is reversible, i.e., as shown in Fig. 2(b), the state flip-flops between them with alternating current injections, which can be explained with assuming conditions such as 90° rotation of the free layer with injected spin torques.

The \( I-V \) characteristics were strongly nonlinear, that is, the differential resistance is reduced with the source–drain voltage, as shown in Fig. 3(a). When the junction is driven by an AC voltage, the time-averaged resistance is hence reduced, and this can be utilized for estimation of the AC
of states are asymmetric to $\epsilon_F$ (zero in the above) and also between the electrodes. In MTJs with metal ferromagnets, constant density of states approximation usually holds around $\epsilon_F$ and the rectification does not appear.

To check whether the density of states in (Ga,Mn)As has such energy dependence, we prepared a tunnel junction, which connects (Ga,Mn)As and p+$\text{GaAs}$ layers with a single AlGaAs barrier layer [the inset of Fig. 4(a)]. The film was cut into a $10 \times 10 \mu m^2$ mesa and two metal electrodes were placed both on the top and the bottom layers for four-wire measurement.

Figure 4(b) shows the differential conductance of the junction as a function of bias voltage in four-wire measurement. At the origin, we observe a dip structure, which can be expressed as $\sim e^2$. This is probably due to a so called Efros–Shklovskii (ES) gap, which originates from electron–electron configuration interaction in disordered insulators. The ES gap manifests that the hole states in (Ga,Mn)As are close to those in disordered insulators rather than those in degenerate semiconductors. Though the leading term of the gap is symmetric to $\epsilon_F$ and cannot be the origin of the rectification, the measured gap structure in the inset of Fig. 4(b) actually has a significant asymmetry probably due to configuration interaction asymmetric to $\epsilon_F$. The observed asymmetry can cause the rectification in combination with the difference between layers due to that in the thicknesses, etc. For example, at the bias of $\pm 2 mV$, the difference in the tunnel conductance is $3 \times 10^{-7} S$, which is about 10% of the conductance itself, in accordance with the observed rectification amplitude in Fig. 3.

Attention must be paid also to characteristic peaks and shoulders in negative bias. These can be interpreted as the result of quantum confinement in the (Ga,Mn)As layer, which is put between the internal (Al,Ga)As layer and the surface Schottky barrier. The voltage derivative of differential conductance is shown with a possible quantized level assignment in Fig. 4(b). For the assignment, we assume the effective thickness of the (Ga,Mn)As as 8 nm, namely, the Schottky depletion width is 12 nm. The triangular potential with 12 nm width and 0.5 eV height gives $300 \Omega/\mu m^2$ for the contact resistance, which is in reasonable agreement with that estimated from the difference between the two-wire and the four-wire resistances ($300$–$800 \Omega/\mu m^2$). The result indicates that while the impurity band states are nearly localized, the valence band of matrix GaAs is kept comparatively ordered and coherent. Also, the result suggests the possibility of designing the rectifying characteristics because these anomalies can be controlled through the thicknesses of the constituent layers.

In summary, we have found a current rectification effect in tri-layer (Ga,Mn)As MTJs for AC voltages up to 8 GHz. The rectification is strongly dependent on the alignment of the magnetizations and can be reproducibly switched by using current injection with a very low threshold at zero field. We have shown that the asymmetry of the density of states at the Fermi energy is a possible origin of the rectification.

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