Magnetization dependent rectification in (Ga,Mn)As tri-layer tunnel junctions

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Abstract. Current rectification in (Ga,Mn)As tri-layer magnetic tunnel junctions (MTJs) is found to be controllable through the alignment of magnetizations, which can be changed with small current injections. The tunneling magnetoresistance (TMR) at 4.2K is 120% in amplitude, showing three step structure, which corresponds to the alignment of magnetizations. With a minor field loop, the alignment of magnetization can be anti-parallel for the top and the bottom layers and then current injections with alternative direction can reverse the direction of the magnetization in the middle layer. The threshold current is as low as $2 \times 10^{-4}$ A/cm$^2$. We have found the junctions have small rectification effect up to 8GHz, which is strongly dependent on the alignment of the magnetization. Hence the direction of the rectification as well as the amplitude can be switched by the bi-directional current injections. The rectification can be explained within the Julliere model with energy dependence of the density of states. To check this we performed tunneling measurements and obtained positive results.

Nanoscale devices of diluted magnetic semiconductors form a crossover of semiconductor physics, magnetism and technology of spins (spintronics). Current rectification is one of the basic functionalities in semiconductor devices, which is realized with the strong imbalance in the concentrations of majority and minority carriers. In a representative diluted magnetic semiconductor (DMS) (Ga,Mn)As and related compounds, only $p$-type materials show the carrier-mediated ferromagnetism and unipolar devices made of such DMSs have been believed to have no rectification effect.

In this paper we report rectification effect in (Ga,Mn)As tri-layer magnetic tunnel junctions (MTJs), which is strongly dependent on the alignment of magnetizations. The effect apparently originates from the spin-polarization, which might be the counter part of the rectification with charge polarization through the effect is still small reflecting the fact that the spin-polarization is based on the magnetic dipoles. Even within the constraint, the effect would be maximized with knowing the underlying mechanism. The phenomena can be understood in the simplest Julliere model and the result of tunneling density of state measurement for the support of the model is presented.

Our devices consist of three (Ga,Mn)As layers (30nm, 5nm, 15nm) with the critical temperature of 40K and GaAs barrier layers (5nm) inbetween them. 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. With the use of electron beam lithography, the film was wet-etched into mesas with $1.6 \times 0.9 \mu m^2$ rectangles along [100], which is on of the easy axes of the in-plane magnetization. Each device was attached to a coplanar waveguide (CPW) with [100] parallel to the external magnetic field. The AC and DC lines were cut by bias tees. the AC sources drove the device voltages and the rectified currents were measured through a current-voltage amplifier.

Figure 1 shows a typical tunneling magnetoresistance (TMR) for a major magnetic field loop. The
Figure 1. Typical TMR of a tri-layer (Ga,Mn)As MTJ. The arrows along the curve show directions of resistance variations with a field cycling. Stacked blocks with arrows schematically show rough hypothetical configurations of magnetization at some points of the field.

The lineshape resembles to those reported so far [1], 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 small step structures. The smallest coercive force is assumed in the top layer in the illustrated alignments in order 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 $0T \rightarrow 0.06T \rightarrow 0T$ 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 $500 \mu A$ flows from the substrate to the upper electrode. The pulse width can be as short as 3ms, the limit is coming from the stray capacitance in the cryostat. Resistance jumps with smaller increment are observed also for positive current pulse. To assign these states of resistance to the alignments of magnetization, we need to assume that [010] direction is the second easy axis of the magnetization in the middle layer. The switching between these two states is reversible, i.e., as shown in Fig.2(b), the state flip-flops between them with alternating current directions, which can be explained with assuming conditions as 90 degree rotation of the free layer with injected spin torques.

The DC output under the application of microwave 1.4GHz is shown in Fig.3(a), where the output is represented as a kind of conductance defined as $G_i = (\text{rectified DC current})/(\text{AC drive voltage amplitude})$. $G_i$ is hysteretic for the magnetic field apparently corresponding to the alignment of magnetization. It is apparent that $G_i$ comes from the spin polarization though it is not ferromagnetic resonance origin because $G_i$ depends only on the microwave amplitude, not on the frequency.

Instead, the phenomena can be interpreted within the simplest Julliere model. [2] 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. 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 $\Delta J_{a,b}$ for voltages $\pm V$ are proportional to sum of convolutions as

$$\Delta J_a(V) \propto \int_0^{\epsilon_F} d\epsilon (f_1(\epsilon - eV)g_2(\epsilon) + g_1(\epsilon - eV)f_2(\epsilon) - f_2(\epsilon - eV)g_1(\epsilon) - g_2(\epsilon - eV)f_1(\epsilon)),$$

$$\Delta J_b \propto \int_0^{\epsilon_F} d\epsilon (f_1(\epsilon - eV)f_2(\epsilon) + g_1(\epsilon - eV)g_2(\epsilon) - f_2(\epsilon - eV)f_1(\epsilon) - g_2(\epsilon - eV)g_1(\epsilon))?$$
for anti-parallel and parallel configurations respectively.

We can immediately know from the above expressions that the rectification only appears when there is some asymmetry as well as energy dependence in the density of states above and below the Fermi level $\epsilon_F$. In ordinary metals the density of states is almost constant around $\epsilon_F$ and no rectification is expected. In dirty metals, however, such as (Ga,Mn)As the strong correlation effect often results in some anomaly around $\epsilon_F$, which may be detected in, e.g., tunneling conductance.

In order to confirm the above expectation, we have grown a simple tunneling junction structure, in which a (Ga,Mn)As (Mn content 4%) layer (thickness 20nm) and a heavily Be doped $p$-type GaAs are separated by a 5nm (Al,Ga)As barrier. The film was cut into a 10×10 (µm)$^2$ mesa and two metal electrodes were placed both on the top and the bottom layers for four wire measurement.

Figure 3(c) 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 probably due to so called Efros-Shklovskii (ES) gap, which originates from electron-electron configuration interaction in disordered insulators[3]. The ES gap manifests that the hole states in (Ga,Mn)As is 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.3(c) actually has a significant asymmetry to zero-bias probably due to configuration interaction asymmetric to $\epsilon_F$[4]. 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 ±2mV, the difference in the tunnel conductance is $3\times10^{-7}$S, which is about 10% of the conductance itself, in accordance with the observed rectification amplitude in Fig.3(a).

The characteristic peaks and shoulders in negative bias are also notable. 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[5]. The voltage derivative of differential conductance is shown with a possible quantized level assignment is shown in Fig.3(c). For the assignment, we assume the effective thickness of the (Ga,Mn)As as 8nm, namely the Schottky depletion width as 12nm. The triangular potential with 12nm width and 0.5eV height gives 300 Ω(µm)$^2$ 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 Ω/(µm)^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.

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