# ENHANCED TMR SIGNAL IN A SPIN-VALVE TRANSISTOR

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The hot electron effect is studied for a $Co/Al_2O_3/Fe$ magnetic tunnel junction grown on an n-type GaAs substrate using a three-terminal device: a Co emitter, an Fe base and a GaAs collector. The Fe layer thickness is designed to be thin enough to enable ballistic transport of electrons in the base. So a fraction of the hot electrons injected through the $Al_2O_3$ barrier into the Fe base can reach the GaAs collector before relaxing inside the base. The Schottky barrier at the n-GaAs/Fe interface works as an energy filter for the hot electrons incident on the collector. These collector electrons are only a small fraction of the total electrons injected from the emitter to the base. The magnetocurrent properties are examined for the emitter and collector current as a function of the emitter voltages up to 2 V at 1.5 K. Both the emitter and collector signal show a dip near 5 mT. The depth of the dip in the emitter decreases gradually with the emitter voltage up to 2 V. The depth of the dip in the collector signal also decreases gradually with the emitter voltage up to 1.2 V, however, above this voltage, it increases dramatically reflecting the effect of hot electrons subjected to the highly asymmetric spin density of states in Fe.

## 1 Introduction

Controlling electron spins is essential for developing spintronic devices, which leads to applications in magnetic field sensors, read-write heads, non-volatile memories, etc. Among those spin manipulation devices a spin-valve transistor [1] that utilizes hot electron transport in a magnetic multilayer configuration has received much attention because of its outstandingly large magnetocurrent change (>300%). [2] The electron energies involved in the spin-transistor performance range typically from 0.2 to 3 eV above the Fermi level, where the asymmetry in the density of states (DOS) for the 3d transition metals such as Fe, Co, and Ni is most pronounced. Because of this large energy range involved, the device may also offer a unique opportunity for investigating the energy dependent nature of spin-dependent electron tunneling across the magnetic layers and across the ferromag./semiconductor interfaces.

## 2 Device Structure and Measurement

We investigated the spin-valve transistor made from a Co emitter, an $Al_2O_3$ tunnel junction, an epitaxially grown Fe base and a GaAs collector. We used a structure with $Co(20nm)/Al_2O_3/Fe(20nm)$ layer grown on an n-GaAs substrate ($n=1\times10^{18}$ $cm^{-3}$) to fabricate a three terminal device. Figs. 1 and 2 show the schematic energy diagram of the device, and the cross section transmission electron microscope (TEM) image of the $Co/Al_2O_3/Fe/GaAs$ structure, respectively. Hot electrons were injected via tunneling from the emitter to the base through the $Al_2O_3$ barrier and the electron energy was varied as a function of the emitter voltage, $V_E$.

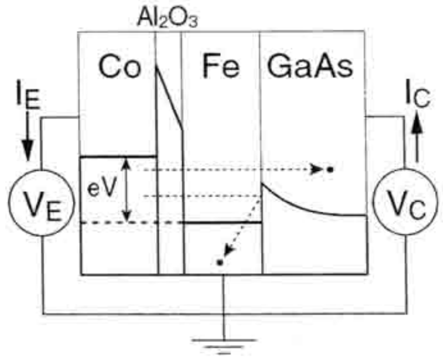


Fig.1. Schematic energy diagram of the three terminal device.

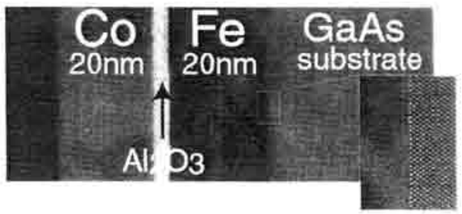


Fig.2. Cross section TEM image of $Co/AL_2O_3/Fe/GaAs$ structure

A Schottky barrier is formed at the Fe/GaAs interface, and the Schottky characteristics measured for the actual device are shown in Fig.3. We evaluate the Schottky barrier height to be ~ 0.6 eV. The Schottky barrier works as an energy filter for the hot electrons since those electrons having a sufficiently large energy compared to the barrier height can only contribute to the collector current. Fig.4 shows the ratio of the collector current, $I_C$, to the emitter current, $I_E$, versus emitter voltage, $V_E$. The ratio of $I_C/I_E$ was less than $10^{-5}$ in the voltage range below 2 V, showing that only a small fraction of the hot electrons reaches the collector without relaxing in the base.

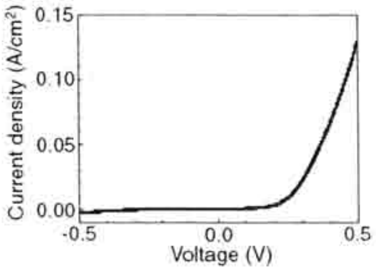


Fig.3. I-V characteristic of the Fe/GaAs Schottky junction. T=300K.

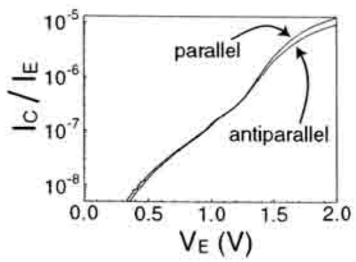


Fig.4. Characteristic of normalized collector current $I_C/I_E$ versus emitter voltage $V_E$ for parallel and antiparallel alignment of emitter and base magnetization. $V_C$=0, T=1.5K.

Fig.5 shows the emitter and collector current as a function of the applied magnetic field. Both the emitter and collector current exhibited minima at around ±5 mT reflecting the hysteresis of magnetization of the Co and Fe layers: here, the minimum values of $I_E$ and $I_C$ correspond to the antiparallel orientations of Co and Fe magnetization where as the asymptotic values of $I_E$ and $I_C$ at higher magnetic fields (~ 50 mT) correspond to the parallel orientations. The relative changes of $I_E$ and $I_C$ with respect to the antiparallel value (= minimum current) are shown on the right axis of Fig.5 in percent.

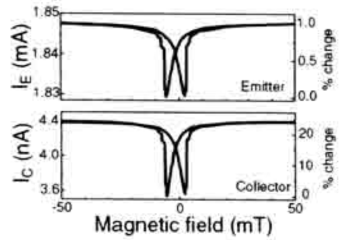


Fig.5. Hysteresis curve of emitter and collector current. $V_E$=1.5V, $V_C$=0, T=1.5K.

The ratio of the current change, called magnetocurrent (MC), is defined as $(I_P - I_{AP})/I_{AP}$, where P and AP refer to the parallel and antiparallel magnetic configuration of the two ferromagnetic electrodes, respectively. Fig.6 shows the $V_E$ dependence of MC for the emitter and the collector signals. The emitter MC decreases monotonously with increasing emitter voltage $V_E$. The collector MC shows a similar dependence up to 1.2 V, however, it increases dramatically for the higher emitter voltage up to 2 V. We have observed more or less the same results for most of the devices while the same structure.

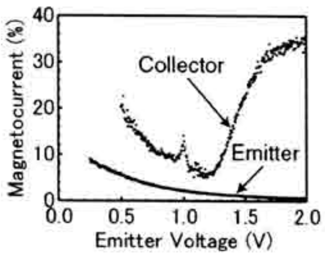


Fig.6. Dependence of the magnetocurrent (MC) on emitter voltage ($V_E$). $V_C$=0, T=1.5K.

## 3 Discussion

Although our device configuration is different from the conventional tunnel magnetoresistance (TMR) device due to the presence of GaAs collector layer, we are simply observing the TMR signal across the $Co/Al_2O_3/Fe$ junction; note that the device does not have any spin-valve effect within the base, i.e., the Fe layer, unlike the devices reported in refs 1 – 3, and also note that no significant spin effect is expected for the junction across the Fe/GaAs Schottky barrier interface, either. If we apply the Julliere's model[4] to our observatoin, which simply interpret the origin of the TMR as due to the asymmetry in the DOS of tunneling electrons, we can possibly attribute the enhanced MC in the higher energy range to the pronounced asymmetry in the density of states of Fe well above the Fermi level.

It is usually the case for the conventional TMR devices that the MC gradually decreases with increasing bias voltage; this also applies to emitter MC - $V_E$ characteristics of our devices. The enhanced TMR effect is observed only for the collector current, not for the emitter current. In our device, the electrons of the entire energy range can flow into the base from the emitter, while only the higher energy electrons selected by the energy filter at the Fe/GaAs interface (Schottky barrier) can contribute to the collector current. Since these high-energy electrons are only a small fraction of the total injected electrons (= emitter current), although they are also present in the emitter current, they may not be visible in the emitter MC-$V_E$ characteristics of the emitter current (Note that the collector current level is less than $10^{-5}$ of the emitter current as is shown in Fig.4).

We also observed a minor peak in the collector MC-$V_E$ characteristic at around 1 V. From no anomaly in dI/dV of $Co/Al_2O_3/Fe$ and Fe/GaAs junctions, this peak is considered to reflect some electronic states above the Fermi level in Fe. But the peak has not yet been fully investigated.

In conclusion, we used a $Co/Al_2O_3/Fe$ tunnel junction grown on an *n*-GaAs substrate to fabricate a three terminal device. We observed an enhancement of collector current MC for a high emitter voltage due to the effects of hot electrons subjected to the strong asymmetry of the spin DOS in the Fe layer base.

## References


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