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Nanoscale Magneto-Resistance Sensors with improved sensitivity using Resonant Tunneling Magnetic Tunnel Junctions

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Abstract

We propose the use of resonant tunneling as means to enhance the sensitivity of magneto-resistance (MR) sensors. Using the non-equilibrium Green's function formalism on a resonant tunneling magnetic tunnel junction structure, we predict higher sensor currents (up to 261%) and a higher magneto-resistance (up to 80%) as compared with traditional trilayer MTJ MR sensors.

1. Introduction

Magneto-resistance (MR) sensors have a wide variety of applications as magnetic field sensors, position and rotation sensors. A method to use magnetic tunnel junctions (MTJ) as linear magneto-resistance sensors is to initially align the fixed and free magnets perpendicular to each other. In the presence of a magnetic field the magnetization of the free layer settles at a new equilibrium angle leading to a change in the current as the resistance of a MTJ varies with the angle between the fixed and free layers.

In a recent work [1], we predicted that a resonant tunneling magnetic tunnel junction (RTMTJ), a device with a hetero-structure quantum well sandwiched between the fixed and free layer has extremely high tunnel magneto-resistance (>1000%). Owing to this, we explore the potential advantages of using RTMTJs over traditional trilayer MTJs as MR sensors.

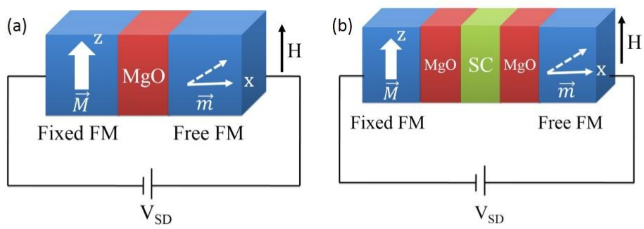

Fig. 1 (a) Traditional trilayer device with an insulating MgO layer between the fixed and free layers. (b) Resonant tunneling magnetic tunnel junction with a MgO-Semiconductor-MgO heterostructure between the fixed and free layers. The magnetization of fixed and free layers are initially perpendicular. An external magnetic field (H) is applied along the intermediate axis of the free layer.

2. Simulation Details

Device Details

The schematics of both the trilayer MTJ and RTMTJ are shown in Fig. 1. In both the devices, the magnetization of the fixed layer is along the z axis and the free layer is along the x axis when no magnetic field is applied. The hard axis for both the magnets is the y axis (into the plane). The applied magnetic field that is measured is along the intermediate axis of the free layer i.e. the z axis. The trilayer MTJ has a layer of MgO between the magnets while the RTMTJ has a heterostructure of MgO-Semiconductor-MgO sandwiched between the fixed and the free magnets leading to resonant peaks in the transmission spectrum. The devices are held at a fixed voltage during measurement of the magnetic field.

Simulation Framework

We employ the non-equilibrium Green's function formalism within the effective mass framework to calculate the charge current in the devices [1,2]. To account for the finite cross-section we assume the transverse modes to be uncoupled and sum over the currents in the transverse modes. We use the Landau-Lifshitz-Gilbert equation to calculate the equilibrium magnetization of the free layer in the presence of a magnetic field.

Our simulations use CoFeB as the ferromagnetic material with Fermi energy, $E_f = 2.25$eV and exchange splitting $\Delta = 2.15$eV. The effective mass in CoFeB is $m_{FM} = 0.36\ m_e$, in MgO is $m_{OX} = 0.18\ m_e$ and in the semiconductor, $m_{SC} = 0.36\ m_e$ (m_e is the mass of an electron). The barrier height of the CoFeB-MgO interface is $U_B = 0.76$ eV above the Fermi energy [3]. The anisotropy field is $H_k = 44$ Oe and the thickness of the free layer is 2 nm.

2. Results

Current Sensitivity

We first examine the change in the current in the MR sensors on application of a magnetic field. For small fields we see the change in the current in both devices is linear, at higher fields $H > H_k$, the magnetization of the free layer aligns along the magnetic field (intermediate axis of the free layer) and the current saturates. Therefore, these devices are viable linear MR sensors for fields $H < H_k$. Both these devices are kept at the same DC voltage during the measurement.

As seen in Fig. 2 the change in the current in the RTMTJ is much higher than the change in the current in the trilayer MTJ. The slope of the change in the current of the RTMTJ is $1.15 X 10^{-5}$ A/Oe compared to $3.18\ X 10^{-6}$ A/Oe in the trilayer MTJ. Thus the current sensitivity of the RTMTJ is 261% higher.

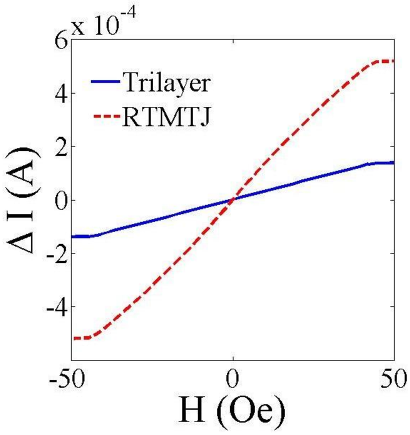

Fig. 2 Change in the current in a trilayer MTJ (blue) and a RTMTJ (red) on application of a magnetic field (H). The current saturates at $H = H_k$. The current in a RTMTJ is 261 % more than the current in a trilayer MTJ at a given magnetic field and voltage.

Mageneto-Resistance Sensitivity

As seen in Fig. 3, resistance in the trilayer MTJ changes from 49 Ω at H = -50 Oe to 21 Ω at H = 50 Oe, with R = 29 Ω at H = 0 Oe. For the RTMTJ the resistance goes from 28 Ω at H = -50 Oe to 7.2 Ω at H = 50 Oe with R = 11 Ω at H = 0 Oe. Thus the resistance of the trilayer MTJ varies over a larger range.

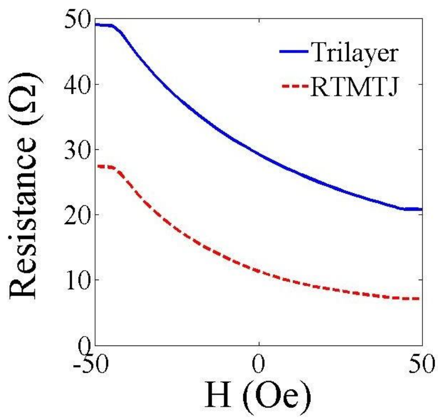

Fig. 3 Resistance of the trilayer MTJ (blue) and the RTMTJ (red) as a function of applied magnetic field along the intermediate axis. The trilayer MTJ resistance varies from 49 Ω to 21 Ω. The RTMTJ resistance varies from 28 Ω to 7.2 Ω.

However, if we compare the percentage change in the resistance in the two devices in Fig. 4, it becomes clear that the RTMTJ is much more sensitive than the trilayer MTJ. The percentage change in the resistance at H = -50 Oe is 148% in the RTMTJ as opposed to 68% in the trilayer device. At H = 50 Oe the percentage change in resistance in the RTMTJ is -37% compared to -29% in the trilayer MTJ. The percentage change in the resistance is also higher in the RTMTJ for all intermediate magnetic fields as well indicating that the RTMTJ sensor is more sensitive.

The field sensitivity is defined as $S = (dR/dH)/R(0)$ [4]. S can be shown to be proportional to the tunnel magneto-resistance (TMR) of the device. In the trilayer MTJ for small magnetic fields, $S = 0.023$ Oe^{-1}. While in the RTMTJ owing to the improved TMR, field sensitivity for small magnetic fields is nearly double at $S = 0.045$ Oe^{-1}.

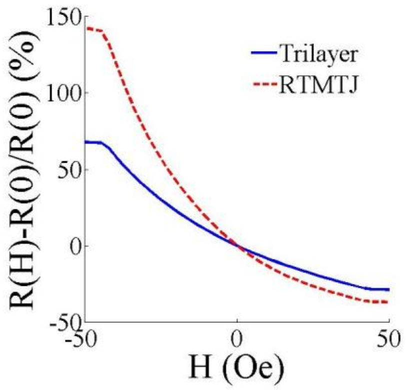

Fig. 4 Percentage change of the resistance versus applied magnetic field (H). The RTMTJ shows a higher percentage change in resistance for all values of magnetic field.

4. Conclusions

We have demonstrated that MR sensors designed using the RTMTJ structure lead to improved current and MR sensitivities due to the enhanced TMR characteristics of the RTMTJ. The current sensitivity of the RTMTJ was shown to be 261% better than that of the trilayer MTJ. While the percentage change in resistance in an RTMTJ was 80% more than that in the trilayer MTJ.

Acknowledgements

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