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Temperature dependence of inverted tunneling magnetoresistance in MgO-based magnetic tunnel junctions

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Abstract

MgO-based magnetic tunnel junctions (MTJs) of the following main structure: Ir₂₂Mn₇₈ (10 nm) /Co₉₀Fe₁₀ (2 nm) /Ru (0.85 nm) /CoFeB (0.5 ≤ *t* < 2 nm) /MgO (2.5 nm) /CoFeB (3 nm) have been fabricated, with a thin CoFeB layer in the pinned synthetic antiferromagnetic CoFe/Ru/CoFeB stack. These MgO-based MTJs are of good barrier quality. Inverted tunneling magnetoresistance (TMR) has been observed for these MTJs, and the temperature (*T*) dependence of the inverted TMR are discussed in this work. The inverted TMR ratios are -33% at room temperature and extrapolated to -84% at 0 K for MTJs with *t* = 1.0 nm, after annealing at 300 °C. In this case, the TMR ratio at low temperature is more than double that of room temperature. Furthermore, the TMR ratio at low *T* is 3.8 times larger than that of 300 K for MTJs with *t* = 0.5 nm, after annealing at 250 °C. These results may be useful for spin electronic devices.

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1. Introduction

Spin polarized tunneling magnetoresistance (TMR) research has been much promoted since the TMR effect was discovered 30 years ago [1]. Subsequently slow progress was made with amorphous AlO_x-based magnetic tunnel junctions (MTJs) at room temperature [2]–[4]. In 2001, Butler and Mathon *et al.* predicted the large TMR effect in single-crystal MgO-based MTJs [5], [6]. Soon after that, very large TMR ratios were achieved in such MTJs [7], [8]. Nowadays well-oriented (001) MgO-based MTJs have given a TMR ratio of more than 1000% at low temperature and 500% at room temperature [9]. The high TMR effect in MgO-based MTJs devices is due to the spin filter effect of the crystalline MgO barrier, which is relatively transparent for the majority spin electrons injected from an oriented bcc Fe or Fe-Co electrode but attenuates the minority spin electrons, as result of the different symmetry of the ↑ and ↓ wavefunctions. From an application point of view, MgO-based MTJs are the better choice for next-generation magnetic recording and memory

devices due to their higher sensitivity and lower noise compared to those of AlO_x-based MTJs.

In this work, we give a systematic study of the temperature dependence on the inverted TMR effect for MgO-based MTJs. A thin CoFeB layer in the pinned synthetic antiferromagnetic (SAF) CoFe/Ru/CoFeB stack is selected. A large ratio of the TMR between low temperature and room temperature (RT) has been obtained for these MTJs.

2. Experiment

Typical MTJ multilayer design is Ta (5) /Ru (50) /Ta (5) /Ni₈₁Fe₁₉ (5) /Ir₂₂Mn₇₈ (10) /Co₉₀Fe₁₀ (2) /Ru (0.85) /Co₄₀Fe₄₀B₂₀ (*t*) /MgO (2.5) /Co₄₀Fe₄₀B₂₀ (3) /Ta (5) /Ru (5), and the order is from the bottom electrode to the top, with thickness given in nanometers [10]. The thickness (*t*) of the pinned Co₄₀Fe₄₀B₂₀ (CoFeB) layer was varied from 0.5 to 1.5

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nm. All multilayers were grown under high vacuum and at room temperature in a Shamrock sputtering tool. A well-oriented (001) MgO barrier can be achieved and high TMR ratio was observed in MTJs with a thick pinned CoFeB [10], [11]. More details can be found in Ref. [10].

3. Results and Discussions

Figure 1 (a) presents the magnetization loop of MgO-based MTJs with $t = 1.0$ nm, measured by a vibrating sample method (VSM, DMS MODEL 4 HF, made in American ADE company) before patterning. Independent switching of the magnetization in the IrMn, NiFe, and free CoFeB layers is observed. The magnetization switching of the SAF stack in the loop is weak for these MgO-based MTJs, which may be due to the thin pinned CoFeB layer in the SAF stack. Free switching of the magnetization and the squareness of the hysteresis loops create well-defined parallel and antiparallel states (see the inset).

Fig. 1 Major Magnetization and minor (inset) loops (a), TMR major and minor (inset) curves (b) measured at RT for a MTJ with $t = 1.0$ nm.

Fig. 2 TMR major and minor (inset) curves measured at 77 K (a) and 24 K (b) for the same MTJ as that shown in Fig. 1 (b).

Figure 1 (b) shows the TMR curves measured at RT for a typical MTJ with $t = 1.0$ nm after annealing at 300 °C for an hour in an applied magnetic field of 800 mT. Transport measurements have been performed on micro-scale square-shaped junctions by a standard DC four-probe technique. Typical resistance-area products are around $5 \times 10^6 \Omega \mu\text{m}^2$ [10]. An inverted TMR ratio as high as -33% is observed at RT for MTJs with $t = 1.0$ nm. Here the TMR ratio is defined as $(R_{\text{low}} - R_{\text{high}})/R_{\text{low}}$. It is found that the coercivity and exchange field of the MTJ sample become higher after a micro-fabrication process, which can be seen from the major and minor loops as shown in Fig. 1 (a) and (b).

Fig. 2 shows the TMR curves at 77 K and 24 K for the same MTJ as shown in Fig. 1 (b). The TMR ratio is up to -67% and -77% at 77K and 24 K, respectively. An extrapolated TMR ratio of -84% at 0 K can be obtained, as shown in Fig. 3 (d). Minor loops show the detailed switching of magnetization of the free CoFeB layer (see the insets). The exchange bias of IrMn became large at low temperature, and we could not measure it due to the limited applied magnetic field of the measuring equipments (around 200 mT).

Figure 3 shows the current-voltage characteristics, and bias voltage dependence of the resistance (R_{high} and R_{low}) and the TMR ratio measured at 24 K for the same junction shown in Fig. 1 (b). The current-voltage characteristics are nonlinear, as expected for spin polarized tunneling across the MgO insulator layer. This MTJ provides an inverted TMR response at bias voltage as high as 2.0 V, which suggests that it is of good barrier quality. The bias dependence of the resistance measured in the low and high configurations shows the zero bias anomaly in the high resistance state, which is similar to a MTJ device with a normal TMR effect [12-14]. The zero bias anomaly at low temperature is attributed to magnon-assisted inelastic tunneling. The asymmetry in the TMR-V curve reflects the dissimilarity of the MTJ sandwich between the top and bottom oxide/ferromagnet interfaces.

A temperature dependence of the TMR ratio and resistances is plotted in Fig. 3 for two MTJs with $t = 0.5$ and 1.0 nm. The resistance is different due to the different junction size. The magnetic fields of + 10 and - 10 mT were separately applied to set the high and low states of MTJs. The TMR ratios are - 7.1% at 300 K and extrapolated to -27.1% at 0 K for MTJ with $t = 0.5$ nm, after annealing at 250 °C. In this case the TMR ratio at low temperature is 3.8 times larger than that of 300 K, see Fig. 3 (c). It can be seen that the R_{high} increases from 37.7 kΩ to 49.4 kΩ with temperature decreasing from RT to 20 K for MTJ with $t = 0.5$ nm, but R_{low} increases from 35.2 kΩ to 39.8 kΩ with temperature decreasing from RT to 32K, then decreases to 39.5 kΩ with temperature decreasing to 20 K. So a large ratio of the TMR effect between RT and 0 K can be obtained. Moreover, it is found that R_{low} starts to decrease with temperature decreasing from 200 K for MTJ with $t = 1.0$ nm.

This abnormal temperature dependence of R_{low} at low temperature has been observed for these MgO-based MTJs having the inverted TMR effect, despite of the high resistance-area products! Although a similar change of the R_{low} with the

temperature has been observed compared to the results reported by Ventura *et al.* [15], [16], pinholes in the MgO layer can be ignored for these MTJs due to the high resistance-area products. In addition, the decrease of R_{low} at low temperature can not be in terms of the magnon-assisted inelastic tunneling, which is found to be associated with R_{high} [12–14]. The abnormal temperature dependence of R_{low} implies something else happens for these MgO-based MTJs. The origin of this phenomenon is still elusive, and further considerations are needed.

Fig. 3 I - V curves (a), bias voltage dependence of the resistances (b), and the TMR ratio (c) for the same MgO-based MTJ shown in Fig. 1 (b). The resistance (R_{high} and R_{low}) and TMR values are extracted from the I - V curves.

Fig. 4 Temperature dependence of the TMR ratio and resistance (R_{high} and R_{low}) for two MgO-based MTJs with $t = 0.5$ nm (a) and (c); and 1.0 nm (b) and (d).

4. Conclusion

In conclusion, we have successfully fabricated the good quality MgO-based MTJs, with a thin pinned CoFeB layer in

the SAF stack. Their magneto-transport properties are investigated at RT and low temperature.

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