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Tuning Magnetic Microstructures of Reference Layer in Magnetic Tunneling Junctions

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Magnetic microstructures in the reference layer in magnetic tunneling junctions (MTJs) are tuned by a reversal field under ambient conditions to investigate their effects on the magnetoresistance (MR) and the exchange coupling field ($\mathrm{H_E}$) between the reference layer and the free layer. Magnetization changes in the reference layer can be probed by measuring minor MR loops. The results show the $\mathrm{H_E}$ of the minor MR loops versus the applied reversal field changes from negative to positive and crosses zero. These results can be explained by the magnetic inhomogeneities at the interface between anti-ferromagnetic/pinned-ferromagnetic layers, which causes the partial magnetization reversal in the reference layer.

Index Terms—**Exchange coupling, magnetic microstructure, magnetic tunneling junction.**

I. Introduction

MAGNETIC TUNNELING JUNCTIONS (MTJs) have been extensively investigated because of their fundamental interest and potential applications to magnetic random access memory (MRAM), read heads, and other magnetic devices. The basic structure of the MTJ is a sandwich of two ferromagnetic (FM) layers separated by a thin insulating layer. Its tunneling resistance is related to the relative magnetization orientation between the two FM layers [1], [2]. To get higher sensitivity, we need to get a larger magnetoresistance (MR) ratio [3]–[6] and better control of the low field properties [7]–[10], such as the exchange coupling field ($\mathrm{H_E}$), coercivity field ($\mathrm{H_c}$), etc.

In this paper, the effect of the magnetic microstructures in the reference layer in MTJs is studied. We applied a magnetic reversal field to tune the magnetization states in the reference layers under ambient conditions (without changing the physical structures of the MTJ samples). The MR change in the minor loops can be used to probe the magnetic microstructures in the reference layer.

II. Experiment

Spin dependent tunneling (SDT) wafers were deposited using dc magnetron sputtering in a Sharmrock system with a base pressure lower than 1.0×10^{-7} Torr. The layer structure of the MTJ samples is 80Ru-40CoFeB-50RuTa-40CoFeB-15 Al_2O_3-50CoFeB-9Ru-54FeCo-350CrMnPt (in Å) (Fig. 1). A $Co_{60}Fe_{20}B_{20}$ (at %) target and a $Co_{40}Fe_{60}$ target were used. The Al_2O_3 barrier was formed by depositing a layer of about 12 Å thick metallic Al and then oxidizing it in a plasma of Ar/O_2. From the transmission electron microscopy (TEM) pictures, the thickness of the Al_2O_3 is estimated to be about 15 Å [6]. A magnetic field of 4 kA/m was applied during the magnetic layer deposition to induce the easy axis. Annealing was done in forming gas at a temperature of 250 °C for 1 hour with an applied field of 318 kA/m to align the pinning layer structure [11]. The antiferromagnetic (AFM) CrMnPt layer for pinning is at the top. In the 54FeCo-9Ru-50CoFeB layers structure, the Ru thickness is adjusted to make the two FM layers antiparallelly aligned to form synthetic antiferromagnetic (SAF) structure. Inside the SAF structure, the CoFeB is the reference layer. The junctions were fabricated using photolithographic techniques to pattern the pinned and free layers separately, with one layer of metal to connect the junctions and test pads [12].

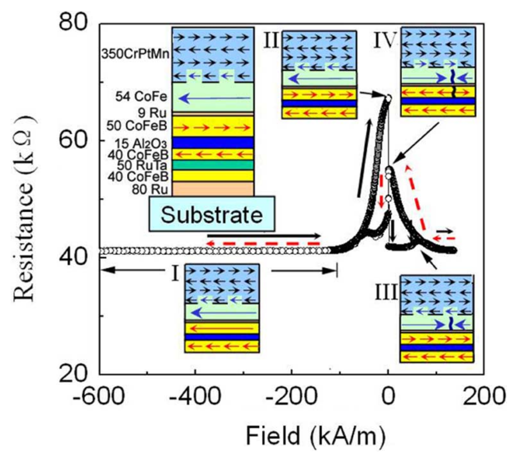

Fig. 1. The magnetoresistance (MR) loops for MTJ samples. The insets show the magnetization of each layer of the MTJ at various magnetic fields ranges.

III. Results and Discussion

As shown in Fig. 1, the MR loops are measured with applied magnetic field from −605 to 119 kA/m and back to −605 kA/m. In the field range from −605 to −119 kA/m, the resistance of the junction stays at the low resistance state. This illustrates that the magnetization of the free layer and reference layer are aligned in the same direction (as shown in inset I in Fig. 1). In this field range, the large field overcomes the exchange coupling

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and causes the reference layer to rotate to align with the applied field.

In the field range from −119 to 24 kA/m, the resistance increases to a maximum (67.4 kΩ) and then decreases sharply to 40.7 kΩ as the field increases. When the field increases, the amplitude of the external field is not large enough to overcome the coupling in the SAF structure (that prefers antiparallel alignment), but is still large enough to align the magnetization of the free layer. The magnetization of the reference layer switches to the direction opposite to the applied field, making it antiparallel to the magnetization of the free layer. This causes an increase in the resistance. When the field increases to a positive value, the magnetization of the free layer begins to switch with the applied field, while the reference layer stays same, so the free layer and the reference layer are parallelly aligned. This causes the resistance to decrease (as shown in inset II in Fig. 1).

In the field range from 24 to119 kA/m, the resistance is first at low resistance state. That indicates the magnetization of the free layer and the reference layer are parallel aligned. With the field increases, the resistance increases and forms a bump. The bump has been observed and explained by the well coupled SAF layer that rotating with the applied magnetic field [13]. However, the MR curve in the reference paper is not the same as our MR curves. So another mechanism should be involved in our sample. With the field larger than 24 kA/m, the magnetization of the free layer should be aligned with the field, so the magnetization of the reference layer is also expected to align with the field. However, we have observed the increasing resistance at the field larger than 24 kA/m. Since the magnetization of the free layer is still aligned with the field, the magnetization of the reference layer should be changed with the field. That may be explained by multidomain formation in the CoFe layer (as shown in inset III in Fig. 1). The CoFe layer couples with the AFM layer and also may align with the large applied field. The competition between these two effects may generate multidomain in it. Also in SAF structure, the reference layer strongly couples with the CoFe layer. That may cause correlated multidomains in the reference layer and cause the MR changes.

As field decreases from 119 kA/m, the resistance monotonically increases and reaches a maximum resistance. But this tunneling resistance, 55.4 kΩ, is lower than the maximum resistance obtained when field increases from −119 to 24 kA/m. That may be explained by some regions of the AFM layer at the interface of the CrMnPt/CoFe weakly coupled with the rest of the AFM layer. When the field decreases from the reversal field, the magnetization of these defect regions do not switch back (as shown in inset IV in Fig. 1). Due to the exchange coupling, the adjacent regions in the CoFe layer may align with these defect regions and form domains. Then, the exchange coupling in the SAF structure makes the reference layer form multidomains and decrease the junction resistance.

Minor loops measure the resistance change under a small magnetic field (from −8 to 8 kA/m) that only changes the magnetization of the free layer. The magnetization of the reference layer is not expected to change under such a small magnetic field. By measuring the minor loop (Fig. 2), we can probe the magnetization change in the reference layer after applying different reversal fields. The minor loops of the MTJs are measured

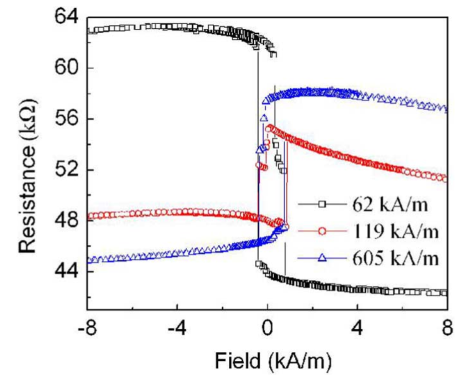

Fig. 2. Minor magnetoresistance loops for MTJs after applied reversal fields of 62, 119, and 605 kA/m.

after sweeping the field from −605 kA/m to a reversal field and back to zero field. The reversal field is defined as the large positive field applied. For example, in Fig. 1, the reversal field is 119 kA/m. As shown in Fig. 2, the R_{AP} is 63.2 kΩ and R_P is 42.0 kΩ with the reversal field as 62 kA/m. With the reversal field increases to 119 kA/m, the minor loop of the MTJs changes directions from the previous case and the center of the MR loop shifts to positive field. The R_{AP} also decreases to 55.3 kΩ and R_P increases to 47.4 kΩ. As the reversal field further increases to 605 kA/m, the R_{AP} increases to 58.3 kΩ and R_P decreases to 43.5 kΩ.

Fig. 3 shows the R_{AP}, R_P, TMR, H_E, and H_c of the minor loops as the applied reversal field ranges from 0 to 605 kA/m. It shows that $R_P(R_{AP})$ increases (decreases) with saturation field, reaches a maximum (minimum) at a reversal field of 98 kA/m, and then decreases (increases). The TMR (Fig. 3(b)) of the minor loop calculated from R_{AP} and R_P has a minimum at 98 kA/m. Fig. 3(c) shows the H_E of the minor loops changes from negative field to positive field and reaches zero after applied a reversal field of about 98 kA/m. Fig. 3(d) shows the coercivity field (H_c) of the minor loop has no obvious variation after applying different reversal fields.

$R_P(R_{AP})$ reaches a maximum (minimum) after applying a reversal field of 98 kA/m. H_E changes from negative to positive and crosses zero also at a reversal field of 98 kA/m. These results can be explained by the magnetic inhomogeneity at the interface between AFM/pinned-FM layers. As we discussed, in the field range of 24 to 119 kA/m, the two ferromagnetic layers of the SAF structure may form multidomains, which will decrease the magnetization in the reference layer. At 98 kA/m, the effect of the multidomain may cause a randomly distributed magnetization of the reference layer, which causes the TMR drop to about zero. The multidomain formation at the reference layer can also explain the changes in H_E. H_E results from the exchange coupling at the interface between FM and AFM materials and Neel coupling and/or the stray field that comes out from the reference layer. Neel coupling is also called “orange peel” coupling, which is caused by the magnetostatic interactions between the free poles at the two ferromagnetic interfaces next to the nonmagnetic barrier in a MTJ [14], [15]. The Neel coupling is related to the roughness of the interface between the two FM layers adjacent to the barrier layer. It is larger for a

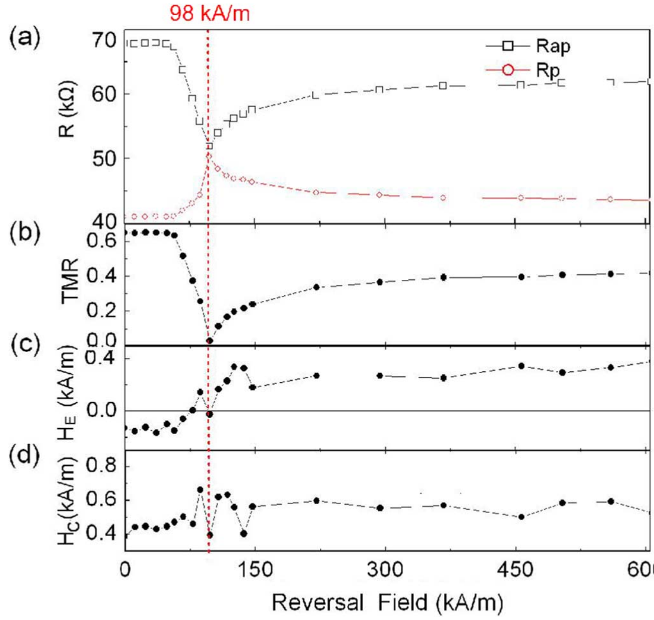

Fig. 3. (a) R_{AP} and R_P, (b) TMR, (c) H_E, and (d) H_c of the minor loops for different applied reversal fields.

rougher interface. In this study, the physical roughness of the MTJ are kept the same, only the magnetic roughness changes. This may change the Neel coupling and the stray field at the junction edges. If the two FM layers in the SAF layer structure are perfectly coupled, no stray field emerges from the SAF layer structure to affect the free layer. However, there is always some small amount of stray field comeing out of the SAF layer structures due to the imbalanced coupling between the two FM layers. The stray field at the edge will be reduced due to the correlated multidomain formation in the two FM layers of the SAF structures [16].

IV. Conclusion

The magnetization of the pinned layer structures is changed by an applied reversal field. The TMR and H_E of the minor loops versus applied reversal field have a minimum. The change in R_P, R_{AP}, TMR, and H_E of the minor loops after different applied reversal fields can be explained by the multidomain formation in the reference layer. This may originate from the magnetic inhomogeneity at the interface between AFM/FM layers. Due to the nonuniform exchange coupling (and defects), domains are formed in the FM layer adjacent to the AFM layer. The exchange coupling between the SAF structures causes domain formation in the reference layer, which affects the MR properties of the MTJs.

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