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ARTICLES

The effect of γ-ray irradiation on the SOT magnetic films and Hall devices

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Abstract: Magnetoresistive random access memories (MRAMs) have drawn the attention of radiation researchers due to their potential high radiation tolerance. In particular, spin-orbit torque MRAM (SOT-MRAM) has the best performance on endurance and access speed, which is considered to be one of the candidates to replace SRAM for space application. However, little attention has been given to the γ-ray irradiation effect on the SOT-MRAM device yet. Here, we report the Co-60 irradiation results for both SOT (spin-orbit torque) magnetic films and SOT-Hall devices with the same stacks. The properties of magnetic films are not affected by radiation even with an accumulated dose up to 300 krad (Si) while the magnetoelectronic properties of SOT-Hall devices exhibit a reversible change behavior during the radiation. We propose a non-equilibrium anomalous Hall effect model to understand the phenomenon. Achieved results and proposed analysis in this work can be used for the material and structure design of memory cell in radiation-hardened SOT-MRAM.

Key words: SOT-MRAM; γ-ray irradiation; TID effect; anomalous Hall effect

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1. Introduction

In the space radiation environment, there are many kinds of energic particles, such as protons, electrons, heavy ions. Energic particle strike may damage the electronic system, which leads to the system function failure. Nowadays, with wide applications of system on chips (SoCs) in spacecrafts and satellites, space-grade SoCs call for novel non-volatile memory devices featuring both high speed and high reliability. Magneto-resistive random access memory (MRAM) as one of the non-volatile memory devices[1–3] has long been of interest for its potential applicability in space exploration[4, 5] due to its various advantages such as non-volatility, high density, high reliability and wide operating temperature range. Embedding a magnetic tunneling junction (MTJ) in the complementary metal–oxide–semiconductor (CMOS) circuit back-end process is the way to achieve MRAM devices. The core structure of MTJ is composed of two ferromagnetic layers separated by a thin insulator layer. The ferromagnetic layer whose magnetization is fixed in its easy axis is called pinned layer, while the layer whose magnetization direction can be changed by external stimuli is called free layer. Due to the parallel and anti-parallel magnetizations of these two ferromagnetic layers, MTJ gives a low resistance state (data "0") and a high resistance state (data "1"), respectively. Up to now, MRAMs have experienced three generations of technological development, Toggle-MRAM, STT-MRAM and SOT-MRAM. Among them, SOT-MRAM has the best performance on endurance and access speed.

It is often claimed that the MTJ is inherently immune to the total ionizing dose (TID) radiation[6]. However, the device structure and write mode of SOT-MTJ is quite different from the conventional Toggle-MTJ and STT-MTJ[7–14]. To date, the radiation effect[15] on SOT-MTJ has rarely been revealed experimentally. Thus, there is no clear evidence that SOT-MTJ is also immune to TID radiation.

In this paper, we perform Co-60 γ-ray radiation experiments on SOT magnetic film and SOT Hall devices with the same stack structure. We observe that magnetic properties of SOT film remain unchanged and even the irradiation dose accumulates to 300 krad(Si), while the anomalous Hall resistance of SOT Hall devices exhibits a reversible changing behavior during the radiation. According to the analysis of the interaction of γ-ray with magnetic materials and the Hall device, we propose a possible explanation to understand this phenomenon. Our results pave a way for further exploration of transient TID radiation effect in SOT-MTJ and will also be helpful to the radiation-hardened SOT-MRAM device design.

2. Experimental description

The stack structure of SOT magnetic film used in our experiment is $Si/SiO_2/Ta(5)/Pt(3)/Co(1)/Ta(5)/MgO(2)$ (in nanometers). It is grown by magnetron sputtering, in which the bottom Ta layer acts as the seed layer that determines the crystal orientation of the upper layer grown. The Co layer is a magnetic free layer with perpendicular anisotropy. The top Ta

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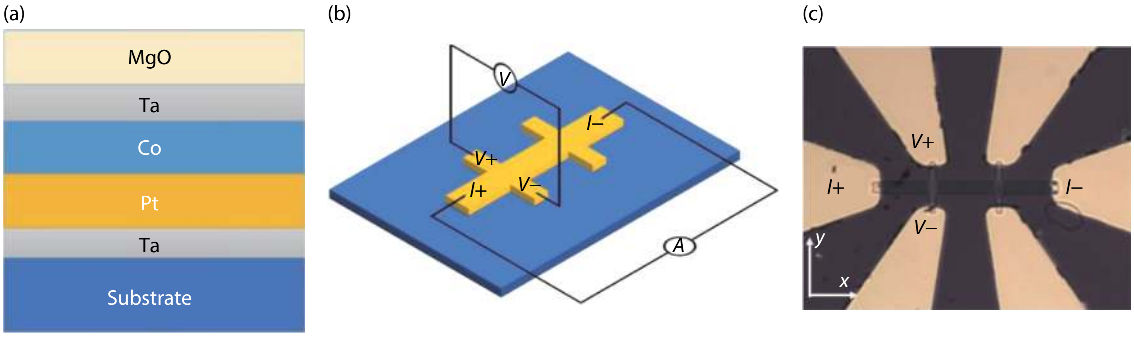

Fig. 1. (Color online) (a) The structure of SOT magnetic film. (b) The structure of SOT Hall device. (c) The image of SOT Hall device.

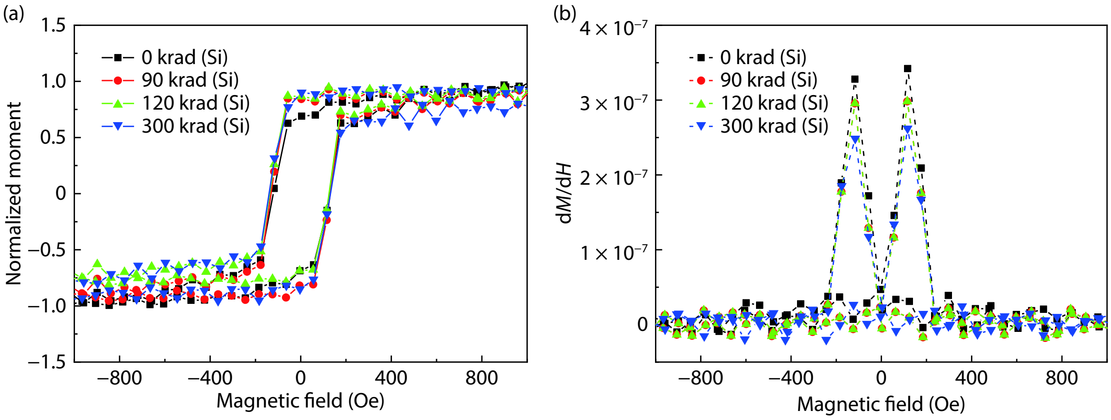

Fig. 2. (Color online) (a) The normalized hysteresis loops of SOT magnetic films under different radiation doses. (b) The differential curves of SOT magnetic films hysteresis loops under different radiation doses. The magnetic field sweep rate is 15 Oe/s. All the experiments are performed at room temperature.

and MgO layer act as the capping layer for protection. Then SOT magnetic films are separated into two parts. One part of the films is cut into a 1 × 1 mm^2 fragment as shown in Fig. 1(a), in order to study the influence of radiation on magnetic properties of the free layer. Another part of the films is patterned into a Hall device sized in 10 × 140 μm^2 by I-line lithography for the R_{AHE}–I measurement as shown in Figs. 1(b) and 1(c). When there is an electron current passing through the heavy metal Pt layer, a spin current will be produced in the direction perpendicular to the current and interacts with the magnetization of Co layer. If the spin current exceeds a critical value, the magnetization direction of the Co layer will be switched, that is the SOT effect. What is more, the state of Co magnetization can be read by anomalous Hall effect. Therefore, the SOT Hall device can be used to study the influence of radiation on magnetoelectric properties of the free layer in SOT-MTJ.

TID experiments are performed on the Co-60 facility at room temperature. The dose rate is set as 50 rad (Si)/s. The R_{AHE}–I measurements of SOT Hall devices and M–H hysteresis loop measurements of SOT magnetic films are conducted at 90, 120, and 300 krad (Si), respectively. The R_{AHE}–I measurements are performed on a probe station with three-dimensional Helmholtz coil while M–H hysteresis loop measurements are carried out using the SQUID-VSM system. All the measurements are performed at room temperature.

3. Results and discussions

Fig. 2 shows the normalized hysteresis loops (M–H) and their differential curves of as-prepared magnetic films under different irradiation dose conditions. The field scanning range is from –1000 to +1000 Oe. The shape of the hysteresis loops and the coercive field are not affected by the radiation, which means the macro magnetism of the SOT film is immune to γ-ray irradiation even the accumulated dose is up to 300 krad (Si).

However, the electrical measurement results for the SOT Hall device are quite different. Fig. 3 shows the current-induced magnetization switching of SOT Hall devices, which is probed by anomalous Hall effect under in-plane magnetic field Hx of 50 Oe. It can be seen that the shape of the loops shows a reversible change during radiation. Before radiation, the switching loop of R_{AHE}–H is normal without any disturbing. As the dose of radiation increases, the switching loops become more and more irregular. When the dose accumulates 120 krad (Si), it exhibits a parabola-like behavior, which means the anomalous Hall resistance of the SOT Hall device is affected by radiation. According to the results mentioned above, the magnetic properties of SOT film remain unchanged during radiation. Thus, we infer that there must be an altering of electronic properties in the Pt layer induced by radiation. Interestingly, the switching loop returns to normal at the dose of 300 krad (Si). This phenomenon has not been observed by any other researchers yet. Here we propose a possible explanation as discussed below.

Before we launch further analysis, we need to note the fundamental of anomalous Hall effect first. Although the origin is still confused, it is generally accepted that the magnetic con-

T Z Yang et al.: The effect of γ-ray irradiation on the SOT magnetic films and Hall devices

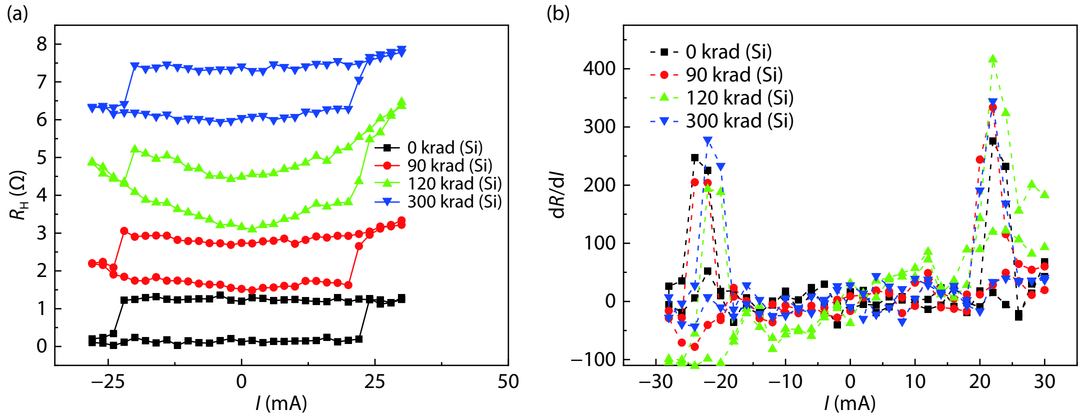

Fig. 3. (Color online) (a) The anomalous Hall curves of SOT Hall device films under different radiation doses at room temperature. (b) The differential curves of SOT Hall devices films under different radiation doses at room temperature. The in plane magnetic field is 50 Oe. The pulse time of current is 0.5 ms.

ductor exists in spontaneous perpendicular magnetization. The magnetization can be equivalent to magnetic field H. When the conductor carries a current (in x axis) and the effective magnetic field that is in perpendicular direction (in z axis), the carriers will deviate from their path and accumulate at the edge of the conductor by the Lorentz force, which gives a voltage in the y axis called Hall voltage[16–20].

Theoretically, Hall resistance includes normal Hall resistance and anomalous Hall resistance. Without external field, normal Hall resistance can be ignored. So the anomalous Hall resistance R_{AHE} has the relation with the writing current as follows:

$$R_{\mathrm{AHE}} = 4\pi R_{\mathrm{s}} M_{\mathrm{z}}\,(I)\,, \tag{1}$$

where R_{s} is the anomalous Hall coefficient, which only depends on the specific material characteristics, M_{z} is the component of magnetization perpendicular to the surface of the Hall device which can be tuned by current through SOT effect[21]. For the SOT Hall device used in our experiments, it has perpendicular magnetic anisotropy. Thus, the anomalous Hall resistance should reflect the information of macro magnetism of the free layer.

According to Eq. (1), R_{AHE} is in proportion to M_{z}. From the results of Fig. 3, it seems like that γ-ray radiation has made some influence on the magnetization of Co layer. However, as mentioned above, the macro magnetism of the Co layer remains unchanged during the radiation as shown in Fig. 2. Thus, there must be another reason for the phenomena of Hall measurements.

Theoretically, the anomalous Hall resistance comes from the anomalous Hall voltage, which depends on the charge distribution on Hall electrodes. Hereby we infer that there may be extra radiation-induced non-equilibrium carriers that alter the anomalous Hall voltage. Generally, the non-equilibrium carriers in metal will recombine in a time of nanoseconds to microseconds. However, specific to our sample, non-equilibrium carriers induced by radiation are affected by the horizontal driving electronic field and the perpendicular effective magnetic field at the same time. Therefore, the non-equilibrium carriers will accumulate at the both edge of Hall electrodes through the Lorentz force that makes the recombination time much longer. On the other hand, it should be noted that because the positive charge and negative charge have different mobility in the metal, non-equilibrium carrier distribution at the edge of Hall electrodes is asymmetric, which contributes to an irregular anomalous Hall resistance. Thus, we introduce an extra time-dependent Hall resistance term in the Eq. (1) as the following:

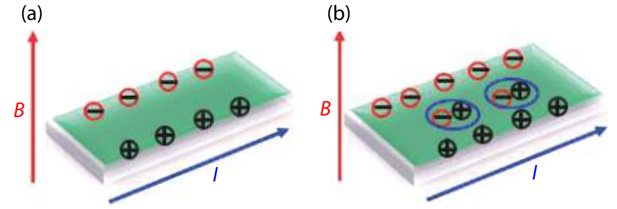

Fig. 4. (Color online) (a) The distribution of equilibrium carriers in the Hall device before radiation. (b) The distribution of nonequilibrium carriers induced by irradiation in the Hall device.

$$R_{\mathrm{AHE}} = 4\pi R_{\mathrm{s}} M_z\,(I) + R_{\mathrm{non}}(I,t), \quad R_{\mathrm{non}}(I,t) = R_1\,(I)\,\mathrm{e}^{\frac{-t}{\tau}}, \tag{2}$$

where $R_{\mathrm{non}}\,(I,t)$ is the non-equilibrium anomalous Hall resistance term induced by radiation, τ is relaxation time of the non-equilibrium carriers in metal electrodes and $R_1\,(I)$ is the non-equilibrium anomalous Hall coefficient depending on the Hall current.

On the one hand, the non-equilibrium anomalous Hall coefficient $R_1\,(I)$ increases nonlinearly with the increase of Hall current. This is because lots of charge recombination centers are formed during the TID radiation. The carrier velocity increases with the increase of Hall current, which leads to more non-equilibrium carriers are captured by charge recombination centers. So the effective carriers intensity of the Hall device is no longer a constant but has a negative correlation with Hall current at that time as shown in Fig. 4. This may be the reason for the irregular change of R_{AHE}–I loop at the dose of 120 krad (Si).

On the other hand, although the dose of radiation is increasing, the number of charge recombination centers is limited. They constantly capture the non-equilibrium carriers to recombination on time scales that makes the carriers intensity change to a new constant[22] and the recombination rate of electron–hole pairs in metal is much faster than in semiconductors. This is the reason why the R_{AHE}–I loop returns to the original shape at 300 krad (Si). This reversible phenomenon means that the non-equilibrium carriers induced by radiation relax to a new equilibrium state that may be different from the original state and give new carriers intensity. And the transport performance of the Hall device in the new equilibrium state is normal.

Therefore, according to the results mentioned above, we have reason to believe that the SOT-MTJ devices may not be as robust as STT-MTJ or Toggle-MTJ when used in the γ-ray radiation environment. Because the SOT-MTJ utilizes the SOT effect to write the data, the temporarily non-equilibrium carriers induced by radiation will lead to an inhomogeneous Hall electronic field that may have influence on the switching characteristics of the SOT-MTJ device. Fortunately, the non-equilibrium state is temporary, therefore its influence will disappear when the device relaxes to a new equilibrium state.

4. Conclusion

In summary, we make a survey on the TID effect on SOT magnetic films and Hall devices with the same stack. According to the results of our experiments, the γ-ray radiation had no effect on the magnetic properties of SOT magnetic films even though the total ionized dose reached 300 krad (Si). That means magnetic films have a robust tolerance of TID. However, we find a reversible change for the R_{AHE}–I loop of the Hall device during radiation, which means the magnetoelectronic transport properties of carriers are affected by the radiation. We introduce an extra time and current-related term $R_{\mathrm{non}}(t)$ into the anomalous Hall resistance equation to explain the phenomena. However, the physical mechanism behind is not completely clear and needs to be further studied.

On the other hand, for the SOT-MTJ device used in the γ-ray radiation environment, we infer that the inhomogeneous Hall electronic field generated by the non-equilibrium carriers during the radiation may have an unknown effect on the switching process of SOT-MTJ as it may break the time-reversal symmetry according to our experimental results and analysis. It means that SOT-MTJ may be not as anti-radiation as conventional MTJ. Therefore, our results are also helpful for the radiation-hardened SOT-MRAM design.

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