Total ionizing radiation-induced read bit-errors in toggle magnetoresistive random-access memory devices*

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The 1-Mb and 4-Mb commercial toggle magnetoresistive random-access memories (MRAMs) with 0.13 μm and 0.18-μm complementary metal–oxide–semiconductor (CMOS) process respectively and different magnetic tunneling junctions (MTJs) are irradiated with a Cobalt-60 gamma source. The electrical functions of devices during the irradiation and the room temperature annealing behavior are measured. Electrical failures are observed until the dose accumulates to 120-krad (Si) in 4-Mb MRAM while the 1-Mb MRAM keeps normal. Thus, the 0.13-μm process circuit exhibits better radiation tolerance than the 0.18-μm process circuit. However, a small quantity of read bit-errors randomly occurs only in 1-Mb MRAM during the irradiation while their electrical function is normal. It indicates that the store states of MTJ may be influenced by gamma radiation, although the electrical transport and magnetic properties are inherently immune to the radiation. We propose that the magnetic Compton scattering in the interaction of gamma ray with magnetic free layer may be the origin of the read bit-errors. Our results are useful for MRAM toward space application.

Keywords: magnetoresistive random-access memories, total ionizing dose effect, magnetic tunneling junction, magnetic Compton scattering effect

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1. Introduction

Nowadays, magnetoresistive random-access memory (MRAM) as one of the non-volatile memory devices has long been of interest for its potential applicability in space exploration.[1–10] Embedding the magnetic memory cell in the complementary metal–oxide–semiconductor (CMOS) circuit back-end process is the way to achieve MRAM devices.[11] The magnetic tunneling junction (MTJ) in the device is the core component used for data storage.[12–14] Each MTJ is comprised of two ferromagnetic layers separated by a thin insulating layer. The layer whose magnetization is fixed in one direction is called a pinned layer while the other can be changed by external stimuli, such as the magnetic field and spin-polarized current, is called a free layer. The resistance of MTJ depends on the relative directions of the magnetization of the free layer and the pinned layer. The parallel state gives a low resistance that is datum "0" while the anti-parallel state gives a high resistance that is datum "1". Thus, the magnetic properties of the free layer play a role in determining the characteristics of the MRAM.[15,16]

It is often claimed that the MTJ is inherently immune to the total ionizing dose (TID) radiation.[17–19] However, a few experimental results show that there are read bit-errors appearing during irradiation[20,21] when the electrical functions of the device are normal. The reason for that has not been made clear yet. In this paper, we perform the TID radiation experiments on commercial 1-Mb and 4-Mb MRAMs with different CMOS processes and different MTJ stacked structures. The read bit-errors are observed in the 1-Mb MRAM while the electronic function is normal at a certain dose. According to the analysis of MTJ stacked structure and the interaction of gamma ray with magnetic materials, we propose a possible explanation to this issue. That will be helpful to the radiation-hardened MRAM devices design.

2. Device description

The devices under tests (DUTs) are MR2A08A and MR0A08B from the Everspin Corporation. The storage capacity of MR2A08A is 4-Mb (512 k×8-bit) with 1T–1MTJ[8,22] (1 access transistor and 1 MTJ) bit cell built on 0.18-μm commercial CMOS process, while the MR0A08B is 1 Mb (128 k×8-bit) with 1T–1MTJ bit cell built on 0.13-μm commercial CMOS process. Both of the devices feature 3.3-V V_{DD}, 8-bit word width, and 35-ns access time with infinite endurance. They are toggle MRAM where the write operation uses a magnetic field induced by pulse current. The toggle structure of the MRAM is shown in Fig. 1. During the write operation, two orthogonal pulse currents pass through the bit line and the digit line, respectively. Neither of the two pulse currents can reverse the magnetization of the free layer, thus only the MTJs at the intersections of bit line and digit line are selected while others are half-selected. The datum "0" or "1"

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can be written by controlling the direction of the current.

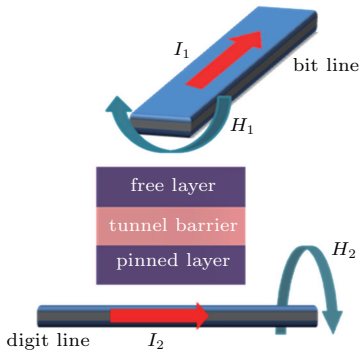


Fig. 1. (color online) Toggle MRAM structure. The magnetic moment of the pinned layer is fixed by an antiferromagnetic layer, which is not shown. The magnetization direction of the free layer can be changed by a magnetic field generated by bit line and digit line.

3. Experimental set-up

3.1. Test facility

The TID experiments are performed on the Cobalt-60 facility at room temperature at a dose rate of 50 rad (Si)/s with a series dose of 30 krad (Si), 60 krad (Si), 90 krad (Si), and 120 krad (Si). The electrical functions of DUTs are tested on a Verigy 93000 SOC test system. In order to compare the influences of different bias conditions during the irradiation, each of the 1-Mb and 4-Mb DUTs is divided into two groups. In the first group, MRAMs operate in static state, which means that the able pins are all pulled up and half of the address and data pins are connected to 3.6 V, the other half are connected to the ground as shown in Fig. 2. In the second group, MRAMs are in the off state, that is to say, all of the pins are electrically floating. Figure 3 shows the photo of DUTs.

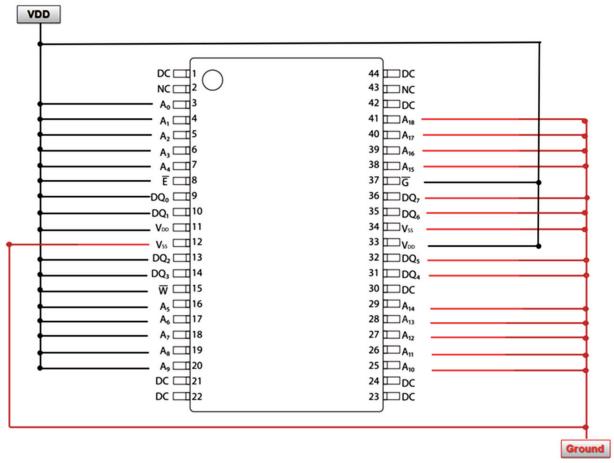


Fig. 2. (color online) Simplified circuit diagram of MRAMs operating in static state during irradiation. The worst-case state V_{dd} is biased to 3.6 V.

3.2. Test procedure

The 1-Mb and 4-Mb MRAMs with serial numbers 010801 and 010802, 040801 and 040802, are tested with static state while the others with serials numbers 010803 and 010804, 040803 and 040804 are tested with off state. Before each irradiation step, all the DUTs are programmed with checkboard pattern. When a certain dose as mentioned above is reached, the store data are first read and checked. If there are errors, they will be logged. Then the electrical functions of the DUTs are measured, including AC standby current (I_{sb}), read and write operation supply currents (I_{ddr} and I_{ddw}), read/write access time (t_{AVAV}), and address access time (t_{AVQV}). Finally, the patterns of all-0, all-1, March C and checkboard are programmed by turns. This test procedure is repeated during the irradiation. After the final irradiation step, all the DUTs are annealed at room temperature for 144 h in off state.

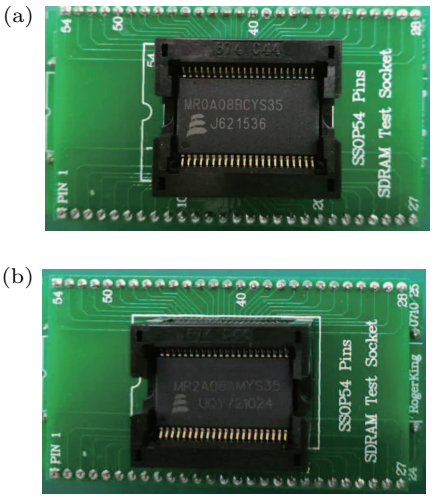


Fig. 3. (color online) Photos of MRAM devices: (a) 44 pins 1-Mb MRAM and (b) 44 pins 4-Mb MRAM, under test.

3.3. Experimental results and discussion

Figures 4 and 5 exhibit the changes of the electrical parameter of 1-Mb MRAM during the irradiation under different bias conditions, respectively. It is seen that the electrical parameters change a little and the function always keeps normal even the dose accumulates to 120 krad (Si) whether the devices are under static state or off state. That is to say, the electrical function of 1-Mb MRAM is immune to TID radiation till 120 krad (Si). However, the results for 4-Mb MRAM are different. Figures 6 and 7 show the electrical parameters versus gamma ray dose of 4-Mb MRAM under different bias conditions, respectively. It is seen that the electrical parameters of the devices under the static state shift out of the normal range and the function turns into failure at the dose of 120 krad (Si) while the devices under off state keep normal. According to the results of *in-situ* test during the irradiation, the electrical parameters of devices under static state start to increase steadily from 91 krad (Si). Thus, we can make a conclusion that the irradiation tolerance of the device under off state is better than under static state. Moreover, the 1-Mb MRAM with 0.13-μm CMOS process exhibits better irradiation tolerance than the 4-Mb MRAM with 0.18-μm CMOS process.

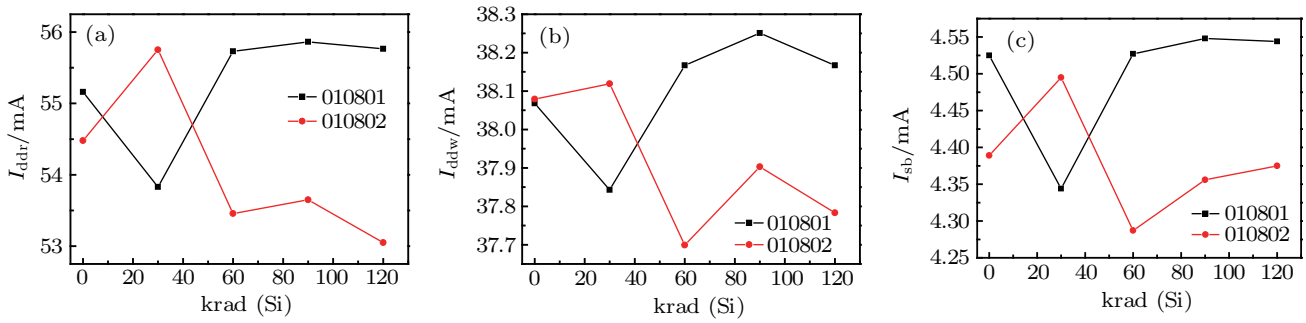


Fig. 4. (color online) Variations of (a) current in read operation, (b) current in write operation, and (c) AC standby current with gamma ray dose of 1-Mb MRAM under the static state.

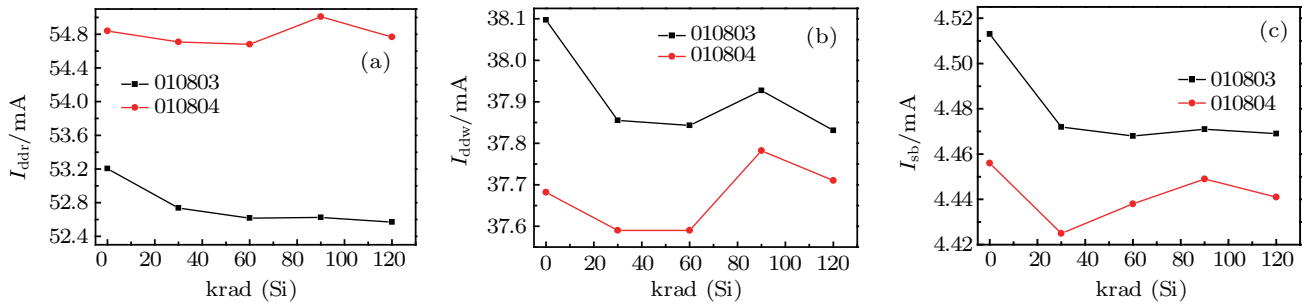


Fig. 5. (color online) Variations of (a) current in read operation, (b) current in write operation, and (c) AC standby current with gamma ray dose of 1-Mb MRAM under the off state.

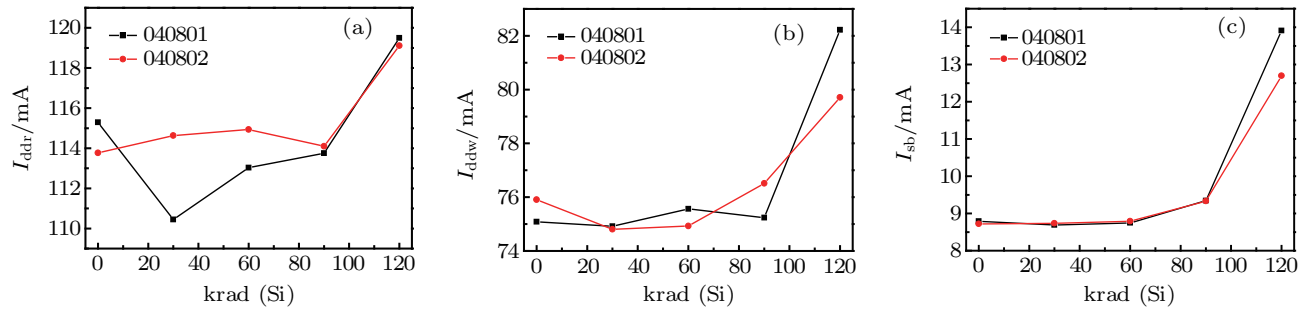


Fig. 6. (color online) Variations of (a) current in read operation, (b) current in write operation, and (c) AC standby current with gamma ray dose of 4-Mb MRAM under the static state.

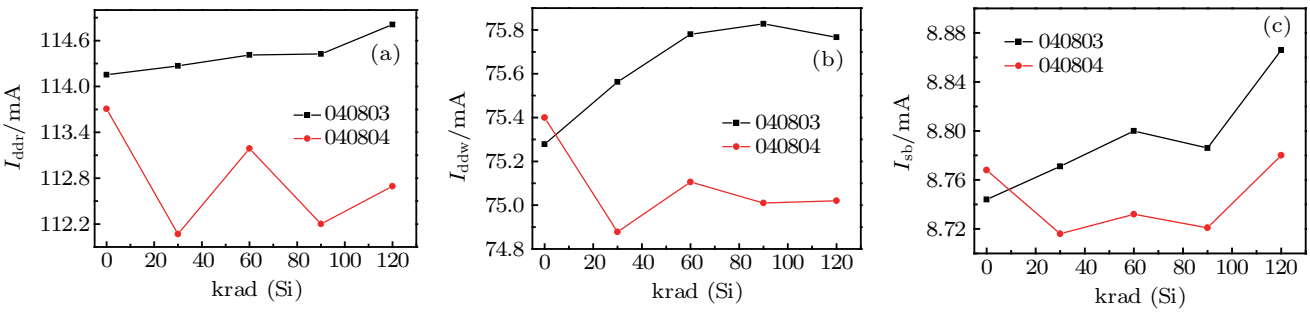


Fig. 7. (color online) Variations of (a) current in read operation, (b) current in write operation, and (c) AC standby current with gamma ray dose of 4-Mb MRAM under the off state.

Figure 8 shows the electrical parameters of the failed 4-Mb MRAM as a function of the annealing time. With annealing time increasing, the operation currents of DUTs steadily decline. The electrical functions recover to normal state after 96-h annealing and the electrical parameters return to normal value after 144-h annealing. Besides, the AC electrical parameters (such as t_{AVAV} and t_{AVQV}) show no obvious change during the irradiation. For 1-Mb MRAM, as the electrical parameters and functions almost keep normal during the irradiation as shown in Fig. 5, they do not show obvious changes during annealing treatment.

Additionally, as mentioned above, we first check the read bit-errors after each irradiation step. There are 2-bit errors, 5-bit errors, and 6-bit errors (bits initially write "1" and then

flip to "0" or initially write "0" and then flip to "1") appearing randomly only in the 1-Mb MRAMs under static state after irradiation doses have accumulated to 30 krad(Si), 60 krad (Si), and 120 krad (Si), respectively, and the read bit-errors always exist so long as the device is not reprogrammed, which is independant of annealing treatment. It should be noted that the electrical functions of 1-Mb MRAM always keep normal during the whole irradiation process. When we reprogram with new data to the MRAM again and then check the data, the read bit-errors disappear. It indicates that the read bit-errors may come from the influence of irradiation on the magnetic memory cell. On the other hand, the 4-Mb MRAMs under static state show no read bit-errors before their electrical functions are failed at the dose of 120 krad (Si). Therefore, we suppose that the MTJ stacked structure of the device plays a role in this issue. This phenomenon has also been observed by other researchers,[20,21] but the reason for it has not been clear yet. Here we propose a possible explanation as discussed below.

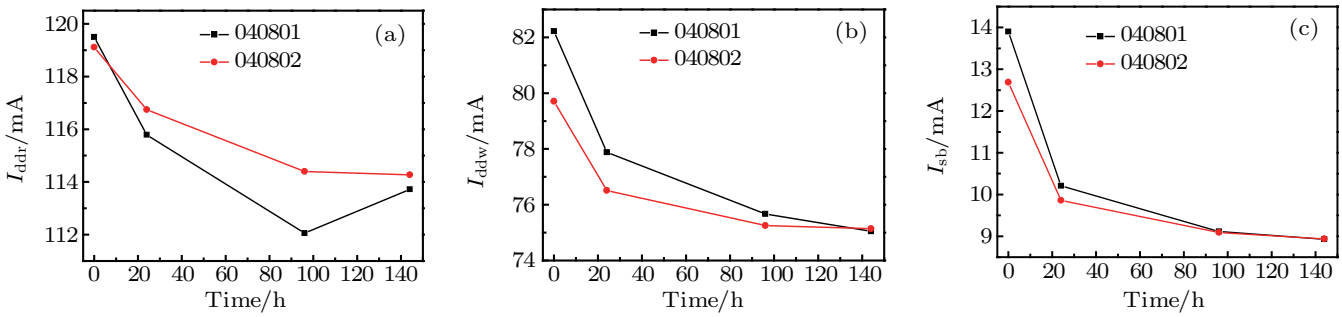


Fig. 8. (color online) Variations of (a) current in read operation, (b) current in write operation, and (c) AC standby current with annealing time of the failed 4-Mb MRAM. The DUTs are annealed at room temperature with pins electrically floating.

In order to understand the mechanism of the read bit-errors, the magnetic memory cell structures of 1-Mb and 4-Mb MRAMs are analyzed by a transmission electron microscope equipped with energy dispersive x-ray spectroscopy (TEM-EDX). Figure 9 shows the MTJ stacked structures of 1-Mb and 4-Mb MRAMs. To obtain more information, we perform the EDX analysis on it as shown in Fig. 10. It is clear that the MTJ structures of 1-Mb and 4-Mb MRAMs are quite different. For 1-Mb MRAM, the stacked structure of MTJ from bottom to top consists of Ta/MnPt/CoFeNi/AlO/$(Co/Ni)_n$/MnNi. The CoFeNi film is the reference layer whose magnetic moment is fixed by the bottom antiferromagnetic MnPt layer, the $(Co/Ni)_n$ multilayer films form the free layer of the MTJ whose magnetic moment is oriented by the top pinned antiferromagnetic MnNi layer. For 4-Mb MRAM, the stacked structure of MTJ is as follows: Ta/MnPt/CoFe/Ru/CoFe/AlO/CoFe/NiFe. The pinned layer is the CoFe/Ru/CoFe which uses the synthetic antiferromagnet (SAF) sandwich structure and the upper CoFe film is the free layer of the MTJ whose magnetic moment is oriented by the top pinned antiferromagnetic NiFe layer. Thus, the free layer which stores the data of 1-Mb and 4-Mb MRAMs is different. From the point of view of the data storage mechanism, MTJ with CoFe film utilizes the spin valve effect while the MTJ with the $(Co/Ni)_n$ multilayer films utilizes the domain wall motion effect.[23,24] Since the accurate thickness of the $(Co/Ni)_n$ is not obtained nor of the $(Co/Ni)_n$, we could not know more about the magnetic properties of these two kinds of free layers. However, we are back to the results of TEM–EDX spectra shown in Figs. 9 and 10, where it is seen that the Mn diffusion from the antiferromagnetic layer to the free layer of the MTJ stacked structure of 1-Mb MRAM is more serious than 4-Mb MRAM diffusion. It will destroy the lattice and interface structure of the $(Co/Ni)_n$ multilayer film[25,26] and reduce the magnetocrystalline anisotropy as well as the interface anisotropy, which leads to the degeneration of the effective magnetic anisotropy barrier to stabilize the magnetization along one direction.[27]

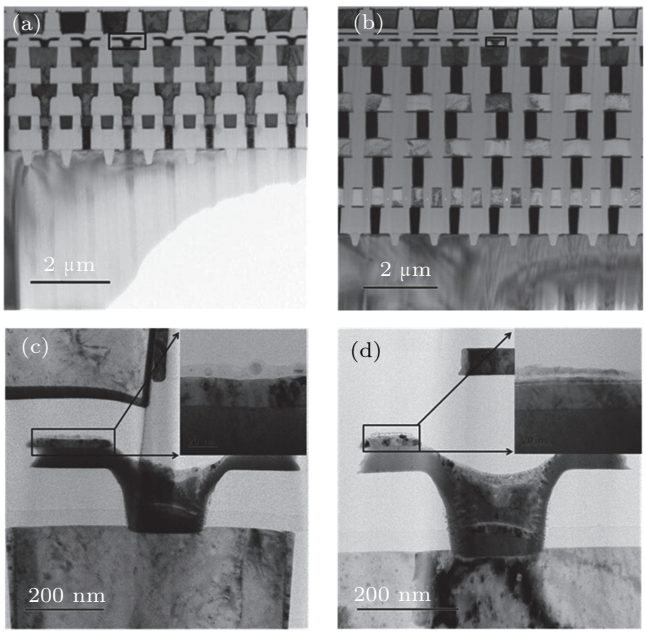


Fig. 9. (a) TEM cross-section images of 1T–1MTJ memory cell of (a) 1-Mb MRAM and (b) 4-Mb MRAM, where MTJs are marked by the black boxes. Enlarged MTJ images of (c) 1-Mb MRAM and (d) 4-Mb MRAM, where insets show enlarged images of the MTJ stacked structures.

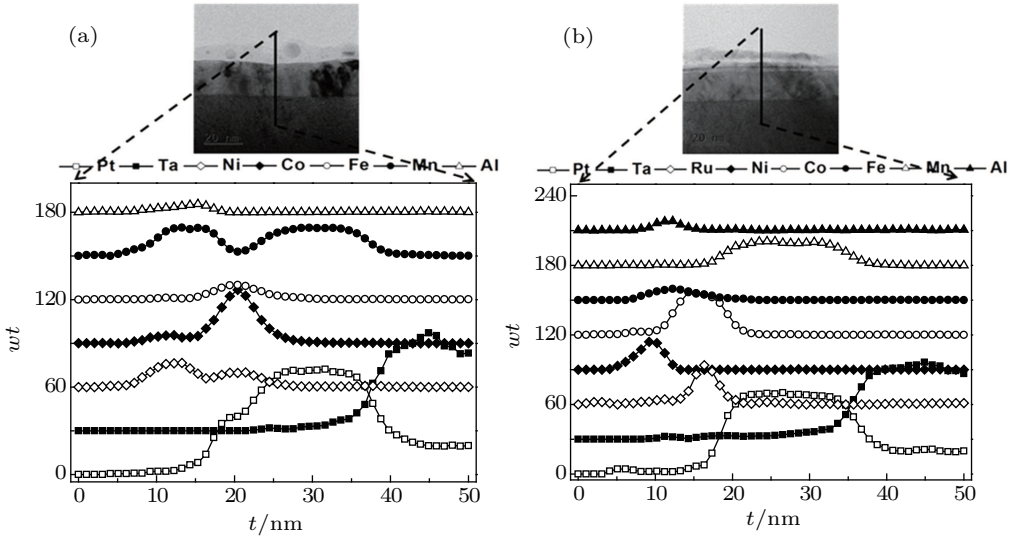


Fig. 10. Metal element EDX spectra of 1-Mb and 4-Mb MTJ stacked structures. The t is the depth from the top layer to the bottom layer of the MTJ. The test depth is 50 nm which is shown in the MTJ image labeled by the black stick. (a) The EDX spectra of 1-Mb MTJ stacked structure. For clarity, all curves are shifted along the y axis in the order of Pt, Ta, Ni, Co, Fe, Mn, and Al from bottom to top. (b) The EDX spectra of 4-Mb MTJ stacked structure. For clarity, all curves are shifted along the y axis in the order of Pt, Ta, Ru, Ni, Co, Fe, Mn, and Al from bottom to top.

On the other hand, the photoelectric effect, Compton scattering, and pair production will occur in the process of the interaction between gamma photons and matter.[28] It should be noted that the particle energy of the Cobalt-60 source used in our TID experiment is 1.17 MeV or 1.33 MeV and the values of atomic number Z of the irradiated materials Co and Ni respectively are $Z_{\mathrm{Co}} = 27$ and $Z_{\mathrm{Ni}} = 28$ which are relatively small. Thus, the Compton scattering is dominant among the three kinds of effects.[28]

According to these results, we propose a possible explanation to the read bit-errors of 1-Mb MRAM during the irradiation. Since the $(\mathrm{Co/Ni})_n$ multilayer film is ferromagnetic and there are a small number of circularly polarized photons in the gamma ray, the magnetic Compton scattering[29,30] will occur when the gamma ray passes through the film. That is to say, the circularly polarized gamma photons would be scattered by spin-unpaired electrons in the ferromagnetic film. Part of the energy of photons is transferred to electrons, which results in the decrease of the energy of photons and the excitation of electrons. Generally, the motion of the magnetic moment depends on the status of spin-unpaired electrons and it can be reflected by the magnetic Compton profiles ($J_{\mathrm{mag}}(p_z)$) of spin-up and spin-down electrons,[29,30] and $J_{\mathrm{mag}}(p_z)$ is written as

$$J_{\mathrm{mag}}(p_z) = \frac{1}{\mu}\iint_{-\infty}^{\infty} n_{\mathrm{spin}}(p)\,\mathrm{d}p_x\,\mathrm{d}p_y,$$

where μ is the number of the spin-unpaired electrons in the ferromagnet, $n_{\mathrm{spin}}(p)$ is the three-dimensional electron momentum distributions for the spin-up and spin-down electrons. As $n_{\uparrow}(p)$ and $n_{\downarrow}(p)$ are different in the ferromagnet, the magnetic moment of $(\mathrm{Co/Ni})_n$ multilayer film will be reversed by gamma photons. Besides, the high-energy free electrons excited by gamma photons in the process may collide with lattice atoms, which will result in the lattice displacement damage, hence lowering the anisotropy of the free layer. Furthermore, gamma ray irradiation will induce the lattice heating, and generally does not make the material temperature rise by more than 2 °C compared with room ambient temperature. Although temperature changes a little, which could also lower the effective magnetic anisotropy barrier of the free layer by a level of $k_{\mathrm{B}}T$, thus increasing the thermal-assisted spin-flip probability. These mechanisms will contribute to the magnetic moment reversal of the free layer during the irradiation exposure.

Combined with the results mentioned above, the effective magnetic anisotropy energy barrier of $(\mathrm{Co/Ni})_n$ multilayer films is degenerated due to the diffusion of the Mn ions and the effective thermal effect produced by the interaction between gamma ray and materials. Thus, the magnetization in the domain wall of $(\mathrm{Co/Ni})_n$ multilayer film is easier to transit from one direction to the opposite direction during the irradiation through the magnetic Compton scattering effect, which will change the magnetoresistance of MTJ, and induce the read bit-errors. Since the number of circularly polarized photons is very small, the number of read bit-errors is few. What is more, the flip of magnetic moment only changes the data storage status, which does not affect the electromagnetic properties/functions of the MTJ/device.[18,19] Hence, the read bit-errors disappear when we write data to the device again.

4. Conclusions and perspectives

In this work, we perform a TID radiation experiment on the commercial 1-Mb and 4-Mb MRAMs with 0.13-μm and 0.18-μm CMOS processes under static state and off state. The results demonstrate that the electrical functions of 1-Mb

MRAM, no matter whether it is under static bias or off state, always keep normal even though the dose accumulates to 120 krad (Si). While the electrical functions of 4-Mb MRAM under static state fail when the dose reaches 91 krad (Si) and the DUTs under off state are normal; additionally, the performance of failed 4-Mb MRAM is recovered after 144-h annealing at room temperature. It indicates that the device with 0.13-μm CMOS process exhibits better resistance to the gamma irradiation than the device with 0.18-μm CMOS process, and the device under off state shows better radiation tolerance.

On the other hand, we observe the read bit-errors in 1-Mb MRAM during the irradiation procedure. Since the electrical functions of 1-Mb MRAM are always normal, we infer that the read bit-errors originate from the magnetic memory cell although the electromagnetic properties of MTJ have been proven to be immune to irradiation. Through analyzing the MTJ stacked structure and the mechanism of the interaction between gamma photons and magnetic materials, we propose that the magnetic Compton scattering may be responsible for the read bit-errors during the irradiation. It should be noted that the gamma source used in our experiment is non-polarized so that the effect is relatively weak. If the gamma source is circularly polarized there should be more read bit-errors. A future study is needed in this regard.

Summarizing, we propose that the data store in MTJ has the probability to be flipped during the TID radiation, which depends on properties of effective magnetic anisotropy energy barrier of the free layer. Our results are useful for the radiation-hardened MRAM design.

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