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Experimental study on radiation effects in floating gate read-only-memories and static random access memories*

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Radiation effects of the floating gate read-only-memory (FG ROM) and the static random access memory (SRAM) have been evaluated using the 14 MeV neutron and 31.9MeV proton beams and Co-60 γ-rays. The neutron fluence, when the first error occurs in the FG ROMs, is at least 5 orders of magnitude higher than that in the SRAMs, and the proton fluence, 4 orders of magnitude higher. The total dose threshold for Co-60 γ-ray irradiation is about 10^4 rad (Si) for both memories. The difference and similarity are attributed to the structure of the memory cells and the mechanism of radiation effects. It is concluded that the FG ROMs are more reliable as semiconductor memories for storing data than the SRAMs, when they are used in the satellites or space crafts exposed to high energy particle radiation.

Keywords: single event effect, total ionizing dose effect, FG ROM, SRAM
PACC: 6180, 7340Q

1. Introduction

Static random access memory (SRAM) and erasable programmable read-only-memory (EPROM) are the two most important memories in electronic systems for space applications nowadays. Compared with SRAM, floating gate read-only-memories (FG ROMs), such as flash read-only-memory (Flash ROM) and electrically erasable and programmable read-only-memory (EEPROM), have their advantages that data in them are nonvolatile and cannot be lost even if power supply is removed. Compared with the EPROM, the data in the FG ROM can be read, erased and written just under 5V voltage, without requiring more than 20V voltage or ultraviolet light. Accordingly the FG ROMs begin to be used in electronic system for space applications, and thus their radiation effects have become a matter of the utmost concern.[1−23]

Single event effects (SEEs) and total ionizing dose (TID) effects (TDEs) are two of the most concerned radiation effects in semiconductor devices in space, which can seriously deteriorate the reliability and cause great loss, even catastrophes.

The SEEs in SRAMs have been studied widely. Heavy ion SEEs in Flash ROMs were tested in Refs.[5–7], and total dose and dose rate effects in FG ROMs were investigated in Refs.[8–10]. Protons in space and neutrons in the atmosphere, however, are two important causes of SEEs in semiconductor devices, especially memories. How about proton and neutron radiation effects in FG ROMs? Our experiments show that the radiation effects of 31.9 MeV protons and 14 MeV neutrons in SRAMs are typical SEEs; however, the radiation effects of 31.9 MeV protons and 14 MeV neutrons in the Flash ROMs and EEPROMs are TID effects rather than SEEs, which are confirmed by Co-60 γ-ray irradiation experiments. In this paper, the radiation effects in FG ROMs are compared with those in SRAMs and the reasons for their differences are analysed.

2. Radiation effects in FG ROMs and SRAMs[12−14]

2.1. Experiment

Neutron experiments are carried out in a 14 MeV neutron generator. The neutron flux is between 2.12×10^8 cm$^{-2}\cdot$s^{-1} and 6.36×10^8 cm$^{-2}\cdot$s^{-1}. Proton experiments are performed on a proton accelerator. Proton flux is 9.5×10^6 cm$^{-2}\cdot$s^{-1} on average. Co-60 γ-ray experiments are done and γ-ray dose rate

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is 1.8 rad(Si)/s.

The devices under test are SRAMs (62256, 628128 and 628512), Flash ROM 29C256 and EEPROM 28C256. The data '55H' is written in each byte before irradiation and then read out continuously during irradiation. If upset is induced by irradiation, the data in each byte is not 55H. The error cells are recorded and the errors are counted.

2.2. Neutron radiation effects

For SRAMs, data errors occur instantly when they are irradiated by 14 MeV neutrons at a flux of about 10^8 cm$^{-2}\cdot$s^{-1}. There is no fluence threshold when errors occur. Errors in all SRAMs (62256, 628128 and 628512) go up linearly with the neutron fluence, no matter how many errors there are (see Fig.1(a)). Logic 1 in the memory cell changes to logic 0 and also the change from '0' to '1' occurs simultaneously. The upset rates of both types are almost equal within the deviation of statistics. The phenomena in different capacity SRAMs are the same, except for different upset numbers. In addition, the upsets can be corrected by rewriting. The 14 MeV neutron radiation effects in SRAMs are definitely SEEs.

For FG ROMs, however, the phenomena are quite different from those for SRAMs. There is a neutron fluence threshold. Data errors occur when the neutron fluence is above the threshold; no error occurs when below the threshold. Figure 1(b) shows the increase of data errors in 28-107# 28C256 and 29-105 #29C256. The number of data errors does not rise up linearly with the neutron fluence. The error of '0'-to-'1' occurs in 28-107# 28C256 when the neutron fluence reaches 5.501×10^{13} cm^{-2}; while the error of '1'-to-'0' appears when the neutron fluence is at 5.747×10^{13} cm^{-2}. For 29-105# 29C256, the fluence threshold is 5.832×10^{13} cm^{-2}. Above a certain fluence, the errors increase rapidly. Furthermore, the errors cannot be corrected by rewriting.

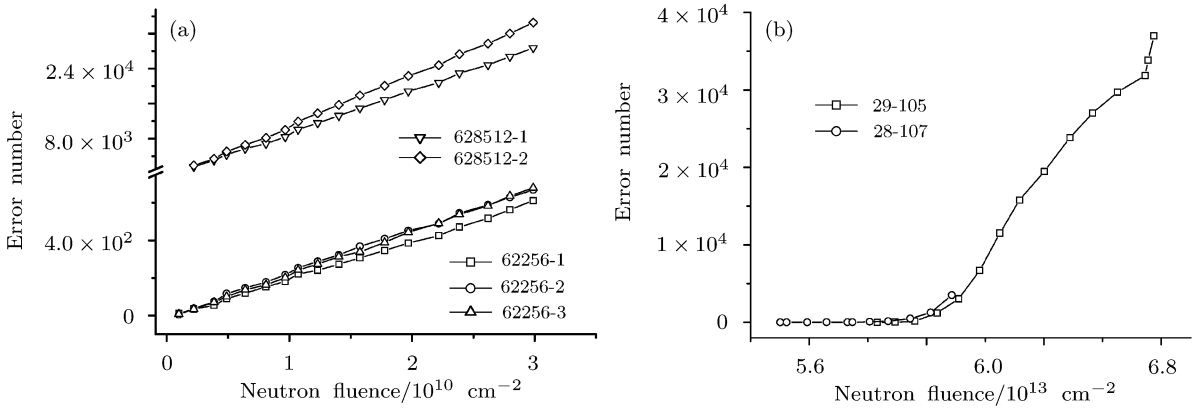


Fig.1. The increase of data errors in (a) SRAM and (b) 29C256 and 28C256 under neutron irradiation. The curves are labelled as number–number, in which the first number represents the device model and the second one only represents the serial number in experiments to distinguish single devices (the same as below). In (a), errors go up linearly with the neutron fluence; however, errors do not rise up linearly with the neutron fluence in (b). They are due to different mechanisms.

2.3. Proton radiation effects

For all SRAMs, data errors occur instantly when they are irradiated by 31.9 MeV protons at a flux of 9.5×10^6 cm$^{-2}\cdot$s^{-1}. There is no fluence threshold as the case of 14 MeV neutron (see Fig.2(a)). The upsets can be corrected by rewriting. The radiation effects of SRAMs irradiated by the 31.9 MeV protons are mostly SEEs.

For all FG ROMs, however, the radiation effects are not SEEs and have a fluence threshold similar to that in the case of the irradiation by 14 MeV neutron (see Fig.2(b)). Data errors do not increase linearly with the proton fluence. '1'-to-'0' error occurs in 29-1# 29C256 at a proton fluence of 9.275×10^{10} cm^{-2}, and '0'-to-'1' at 9.513×10^{10} cm^{-2}. Above a certain fluence, the errors increase steeply. Furthermore, the errors cannot be corrected by rewriting.

2.4. γ-ray radiation effects

For all SRAMs and FG ROMs, the phenomena are shown in Fig.3 when they are irradiated by Co-60 γ-rays at a dose rate of 1.8 rad(Si)/s. Although

there are some differences, the trends of the curves are almost the same, which is consistent with what happen to FG ROMs under neutron and proton irradiations. There is a dose threshold. Data errors occur when dose is above the threshold; no error occurs when below the threshold. Above a certain dose, the number of error increases in an avalanching manner. Furthermore, the errors cannot be corrected by rewriting. The dose thresholds are (0.6777, 0.9473, 1.0335)$\times 10^4$ rad(Si) for 3 SRAMs, respectively; the dose thresholds are almost the same for 6 pieces of Flash ROM 29C256, i.e. 1.0122×10^4 rad(Si) on the average; 1.0212×10^4 rad(Si) on the average for 5 pieces of EEPROM 28C256. The dose thresholds are almost the same for all SRAMs and FG ROMs. The reason why the difference changes from device to device is that devices under test are obtained from commercial market and their functions are only checked before irradiation without being singled out in advance.

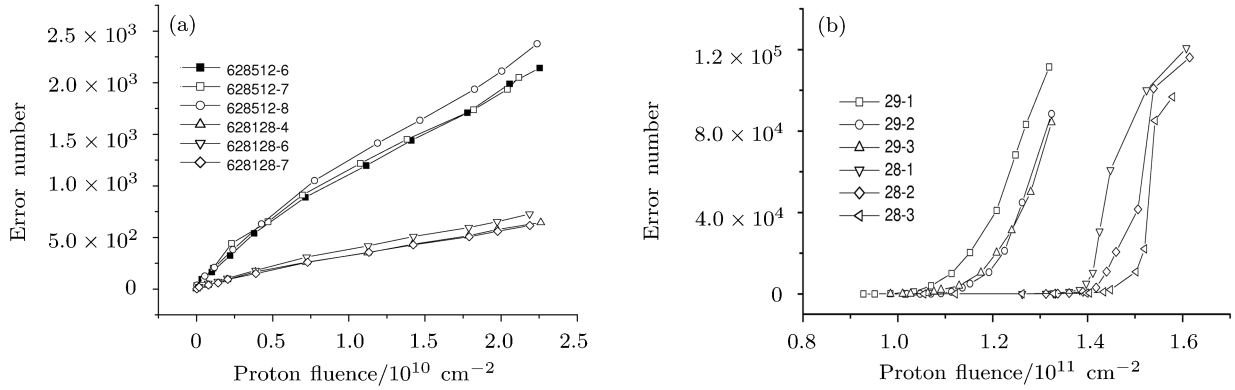


Fig.2. The increase of data errors in (a) SRAM and (b) 29C256 and 28C256 under proton irradiation. In (a), errors go up linearly with the proton fluence; however, errors does not rise up linearly with the proton fluence in (b). They are due to different mechanisms.

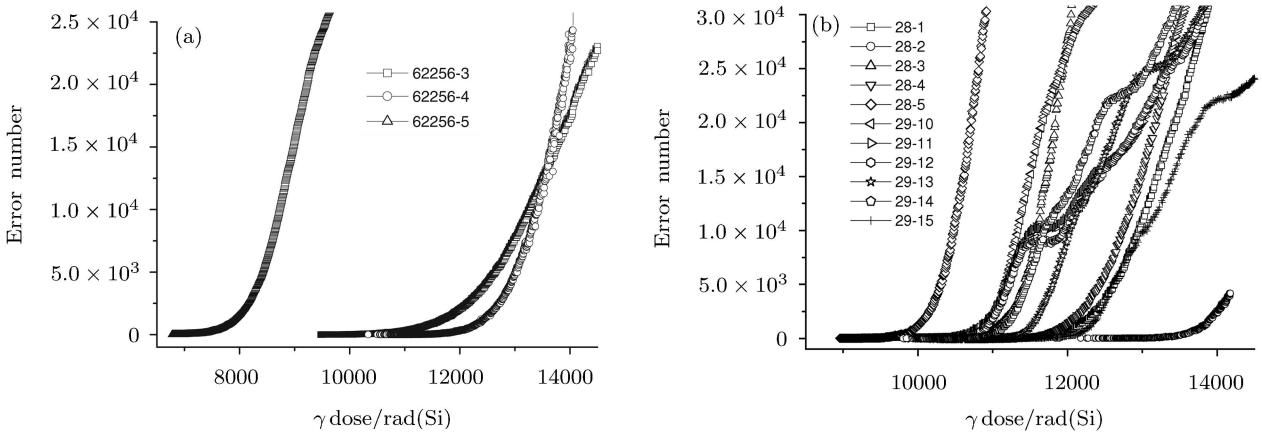


Fig.3. The increase of data errors in (a) SRAM (b) 29C256 and 28C256 under γ-ray irradiation. In both (a) and (b) errors do not rise up linearly with the neutron fluence. They are due to the same mechanism.

3. Analysis of radiation effects[15]

Irradiated by Co-60 γ-ray, both SRAMs and FG ROMs behave consistently and γ-ray radiation effect is typical TID. When they are irradiated by 31.9 MeV protons and 14 MeV neutrons, FG ROMs behave quite differently from SRAMs. The radiation effects in SRAMs are typical SEEs; however, those in FG ROMs are TID effects rather than SEEs as some people usually think.

3.1. Mechanisms for SRAM

An SRAM cell is a bistable circuit that consists of two inverters. Figure 4 shows a complementary metal oxide semiconductor static random access memory (CMOS SRAM) cell. The state of the cell is determined by the transistors T_1, T_2, T_3 and T_4. When

T_1 and T_4 are 'on' and T_2 and T_3 are 'off', $Q = 0$, representing logic 0 in the cell. On the contrary, when T_1 and T_4 are 'off' and T_2 and T_3 are 'on', $Q = 1$, representing logic 1 in the cell. T_5 and T_6 are the transistors respectively for write and read, controlled by word line W.

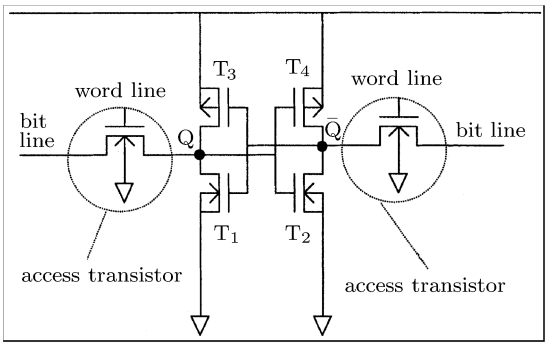


Fig.4. CMOS SRAM memory cell.

For a CMOS SRAM, there are two sensitive regions in a cell, which are the reverse biased PN junction in the drain of 'off' transistors. If protons or the secondary ions generated by protons or neutrons enter into the sensitive regions, high density charge tracks are created and charges are collected by sensitive nodes. When the charge collected exceeds the critical charge in quantity, the bistable circuit upsets and a data error occurs. Because the errors are due to the transfer between the two states and the parameters of the transistors do not change, the errors can be corrected by rewriting. This phenomenon is SEE.

Certainly, γ-ray can produce electron-hole pairs in the sensitive regions, too, but the density of electron-hole pairs created by γ-rays is very lower than that created by heavy ions. The charges induced by one photon are not enough to change the logic state of the cell immediately; and thus the SEE is not observed in this case. However, the holes may be trapped in an oxide layer, forming oxide trapped charges, or at the border between the oxides and semiconductor, forming interface trapped charges. As a result, the threshold voltage of transistors shifts gradually. If the threshold voltage shift is greater than a threshold voltage, the "off" transistor turns on, or in reverse. Then the logic state of memory cell changes, and the data error occurs. Oxide and interface trapped charges build up through a gradual process which depends on the dose, so that the data errors occur above a threshold dose in this case. The more ionizing dose is absorbed, the larger the number of error in the memory cells will be. Because the threshold voltages of transistors have shifted, the errors cannot be corrected by rewriting. This phenomenon is TID effect.

Therefore the radiation effects from the 31.9 MeV protons and 14 MeV neutrons are mostly SEEs for the SRAM; but in the case of the Co-60 γ-ray irradiation the TID effect becomes a leading effect.

3.2. Mechanisms for FG ROM

A schematic drawing of the FG memory cell is shown in Fig.5. It is different from that of the SRAM. FG ROM has two gates. One is the control gate and the other is the floating gate between the channel and the control gate. The oxide between the channel and the floating gate is very thin and allows electrons to be transferred to and from the floating gate by either of two mechanisms: Fowler–Nordheim (F–N) tunnelling from the source or channel, or hot-electron injection from the channel region. According to the charge state of the floating gate, the memory cell becomes a depleted or enhanced transistor. When a voltage is applied to the control gate, the transistor is on or off, representing logic '0' or '1'. There are no electrons in the floating gate generally before writing, and the transistor is on, representing logic '1'. The process of writing is to inject electrons into the floating gate and then the transistor is off, representing logic '0'.

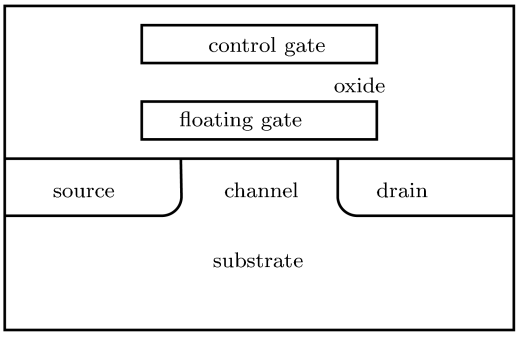


Fig.5. Schematic diagram of the FG memory cell.

The logic state of the cell in the FG memory depends on whether there are electrons in the floating gate. The floating gate is very thin and its area is about $0.1\mu m^2$; however, the area of sensitive region in SRAM, such as HM62256, is about 10 μm^2 and thus the sensitive region in FG ROM is smaller. Few charges are produced in the floating gate by protons and the secondary ions generated by protons or neutrons, so that the logic state is unchanged and the

SEE is not observed in this case. However, electron–hole pairs are produced in the insulator layers around the floating gate by protons or the secondary ions generated by protons or neutrons, and γ-rays. The electron–hole pairs are drifted by an electric field. The electrons drift towards the channel or the control gate, and the holes may be drifted to the floating gate, which can reduce the number of the electrons in it, or may form oxide trapped charges and interface trapped charges. Consequently, the threshold voltage of transistors gradually shifts. The result is just as the case of SRAM irradiated by Co-60 γ-rays. Therefore, the radiation effects are TID effects in FG ROMs for 31.9 MeV protons, 14 MeV neutrons and Co-60 γ-rays.

3.3. Comparison between SRAM and FG ROM

Besides the different phenomena and mechanisms, there are other differences between SRAM and FG ROM.

As the radiation effects in FG ROMs are the TID effects for 31.9 MeV protons and 14 MeV neutrons, we convert proton and neutron fluences into doses (see Table 1). For 14 MeV neutrons, the conversion factor is called Kerma factor, and its value is 1.25×10^{-9}rad$\cdot$ cm^2 in silicon. For 31.9 MeV protons, the conversion factor is 2.4×10^{-7} rad$\cdot$ cm^2 in silicon. The conversion factor for 31.9 MeV protons is two orders of magnitude higher than that for 14 MeV neutrons. So we can predict that the fluence, when the first error occurs in FG ROMs irradiated by 31.9 MeV protons, is two orders of magnitude smaller than that by 14 MeV neutrons. The experimental results confirm this prediction. In other words, 31.9 MeV proton is much easier to induce errors in FG ROMs than 14 MeV neutrons.

The fluences and the doses causing the first error in the FG ROMs and SRAMs are compared in Table 1 for 31.9 MeV protons, 14 MeV neutrons and Co-60 γ-rays. We can see that the neutron fluences, when the first error occurs in the FG ROMs, are at least 5 orders of magnitude higher than those in the SRAMs, and the proton fluences, 4 orders of magnitude higher (see Table 1). Therefore, FG ROMs are more resistant than SRAMs against 14 MeV neutron and 31.9 MeV proton irradiations. The dose thresholds by Co-60 γ-ray irradiation are about 10^4rad (Si) for both FG ROMs and SRAMs because the mechanisms causing the errors are the same.

Table 1. Fluences/doses for FG ROMs and SRAMs when the first error occurs.

device type	(neutron fluence/cm^{-2})/(dose/rad(Si))	(proton fluence/cm^{-2})/(dose/rad(Si))	γ dose/rad(Si)
EEPROM 28C256	$5.501\times10^{13}/6.876\times10^4$	$(1.055\sim1.312)\times10^{11}/(2.532\sim3.149)\times10^4$	$(0.8953\sim1.1422)\times10^4$
flash ROM 29C256	$5.832\times10^{13}/7.29\times10^4$	$(0.928\sim1.013)\times10^{11}/(2.227\sim2.431)\times10^4$	$(0.9806\sim1.0816)\times10^4$
SRAM 62256	$< 2.1\times10^{8\dagger}/ < 0.263$	$< 9.5\times10^{6\dagger}/ < 2.375$	$(0.6777\sim1.0335)\times10^4$

†For SRAMs, data errors occur instantly when they are irradiated by 14 MeV neutrons at a flux of 2.1×10^8 cm$^{-2}\cdot$s^{-1} and by 31.9 MeV protons at a flux of 9.5×10^6 cm$^{-2}\cdot$s^{-1}. $2.1\times10^8$and 9.5×10^6 represent their flux, not threshold. At lower fluxes, data errors may occur.

Now we devote attention to the dose converted from fluence in Table 1. First, all the doses, when the first error occurs in FG ROMs, have the same order of magnitude, i.e. 4, which implies that their damage mechanisms are the same, although they have some differences among the cases of neutrons, protons and Co-60 γ-rays. As the Kerma factor refers to the charges due to secondary ions generated by the neutrons, part of charges will not make contribution to the radiation effect because the sensitive region of FG ROMs is not larger than the volume where charges are generated. Therefore the dose derived from the Kerma factor is greater than that of Co-60 γ-rays, and about 1/7 of charges generated from neutrons can make contribution to the radiation effect. Due to the direct ionization of protons and different reactions between proton with silicon and neutron with silicon, the space distribution of doses generated by protons is different from that by neutrons and the probability of proton ionization in the sensitive region of device is greater than that of neutron. Therefore the ratio is bigger than that of neutron, in other words, about 1/2 of charges generated from protons can make contribution to the radiation effect. This is why there are some differences in dose thresholds for neutrons, protons and Co-60 γ-rays in Table 1. Second, the doses, when the first error occurs in SRAMs irradiated by neutrons and protons, are quite smaller than those irradiated by Co-60 γ-rays (last line in Table 1). For an SRAM irradiated by neutrons and protons, dose is not a key factor because the mechanism is the SEE; however, it becomes a key factor when the SRAM is

irradiated by Co-60 γ-rays because the mechanism is the TID effect. Third, for the neutron and proton irradiations, the doses, when the first error occurs in SRAMs, are quite smaller than those in FG ROMs, too. This is because that the SEE mechanism plays a major role in SRAM while the TID effect mechanism plays a major role in FG ROMs. Therefore, the neutron and proton radiation effects in FG ROMs are the TID effects rather than the SEEs as some people usually think.

In addition, both SRAMs and FG ROMs are irradiated under the same condition. If errors in FG ROMs result from the TID effects due to package activation, it should be the same for SRAMs; however, SRAMs behave quite differently from FG ROMs. So the neutron and proton radiation effects in FG ROMs do not come from the package activation.

For application in satellites or spacecrafts, the reliability is the matter of utmost concern. According to the said discussion, it is concluded that the FG ROMs are more reliable than the SRAMs when they are used as the semiconductor memories for storing data in the satellites or spacecrafts which are exposed to the high energy particle irradiation.

4. Conclusions

The neutron and proton radiation effects in FG ROMs are the TID effects rather than SEEs as some people usually think. The neutron fluences, when the first error occurs in the FG ROMs, are at least 5 orders of magnitude higher than that in the SRAMs, and the proton fluence, 4 orders of magnitude higher. Therefore, FG ROMs are more resistant than SRAMs against 14 MeV neutron and 31.9 MeV proton irradiations. The dose threshold by Co-60 γ-rays irradiation is about 10^4 rad(Si) for both FG ROMs and SRAMs. Thus, it is concluded that the FG ROMs are more reliable than the SRAMs when they are used as the semiconductor memories for storing data in the satellites or spacecrafts which are exposed to the high energy particle irradiation.

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