CPC(HEP & NP), 2009, **33**(5): 369—373 **Chinese Physics C** Vol. 33, No. 5, May, 2009

Equivalent properties of single event burnout induced by different sources

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Abstract The experimental results of single event burnout induced by heavy ions and ^{252}Cf fission fragments in power MOSFET devices have been investigated. It is concluded that the characteristics of single event burnout induced by ^{252}Cf fission fragments is consistent to that in heavy ions. The power MOSFET in the "turn-off" state is more susceptible to single event burnout than it is in the "turn-on" state. The thresholds of the drain-source voltage for single event burnout induced by 173 MeV bromine ions and ^{252}Cf fission fragments are close to each other, and the burnout cross section is sensitive to variation of the drain-source voltage above the threshold of single event burnout. In addition, the current waveforms of single event burnouts induced by different sources are similar. Different power MOSFET devices may have different probabilities for the occurrence of single event burnout.

Key words single event effect, single event burnout, power MOSFET, radiation sources

PACS 25.60.Dz, 25.70.Kk, 25.60.Lg

1 Introduction

Since early 1980, the domain of space radiation effects has been the concern of research on single event effects. In the past twenty years, many studies have been performed to harden the design of spacecraft electronic systems, and in the early 21st century, increasing interest in single event effects is expected. In the investigation of the single event effect, basic simulation techniques for single event effects in integrated circuits have been exploited using different radiation sources. In these experimental studies, besides heavy ions produced in accelerators, some other radiation simulations have been developed in the laboratory, such as the use of ^{252}Cf fission fragments to simulate single event phenomena in electronic circuits. In 1986, Single Event Burnout (SEB) in power MOSFET induced by a ^{252}Cf fission fragment was first reported by A.E. Waskiewicz et al. from the Aerospace Corp[1]. Power MOSFET devices have been widely used in spacecraft electronic systems, especially in the power supply subsystems, and SEB has been observed in the electronic instruments on board[2]. The experimental techniques and evaluation methods of SEB in power MOSFET devices used in spacecraft electronic systems have also been explored in our laboratory[3]. Discrepancies in the characteristic parameters used to evaluate the SEB sensitivity of power MOSFET were observed when the experimental results for different radiation sources were compared and analyzed. For the design of spacecraft electronic circuits, it is, however, important to investigate the consistency of SEB of power MOSFET induced by different radiation sources. In this paper the equivalent properties of SEB in power MOSFET induced by heavy ions and ^{252}Cf fission fragments are discussed in combination with experimental results.

2 Comparison of radiation sources

The radiation sources used to simulate energetic heavy ions in the space radiation environment are ^{252}Cf isotope fission fragments and energetic heavy ions produced by an HI-13 accelerator. As we know, highly ionizing particles encountered in the space radiation environment can be typified by 100 MeV Fe^{+} ions which have a LET (Linear Energy Transfer) of 27 MeV/mg/cm^2. As the energy and LET of a ^{252}Cf

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Received 12 June 2008

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isotope fission fragments overlap those of 100 MeV Fe^+, it was proposed as a cosmic ray simulator. ^{252}Cf isotope sources are available for experimental work. Because the fission fragments have a shorter range in silicon, it is mainly used in experimental research on integrated circuits where the sensitive volume is superficial. In our experiment, the ^{252}Cf radiation source facility consists of a test chamber, a vacuum system, a ^{252}Cf isotope source, with a radiation activity about 5×10^3 fissions per second. Stephen showed that 95% of the fission fragments have a LET between 41 and 45 MeV/mg/cm^2, while 59.4% have a LET between 43 and 44 MeV/mg/ cm^2[3]. In general, it is considered that the fission fragments have an average LET of 42 MeV/mg/cm^2, and the fission fragments have ranges in silicon between 6 μm and 16.5 μm. In our experiments for single event burnout of power MOSFET, the HI-13 accelerator was used to produce energetic heavy ions (oxygen, chlorine, bromine and iodine) with various energies. The energies, LETs, and ranges in silicon for different ions are shown in Table 1.

Table 1. Ion energy, LET, and range in silicon.

ion	energy/ MeV	LET/ (MeV/mg/cm^2)	range in Si/ μm
^{252}Cf fission fragment	108.00	42.00	6.00—16.50
O^+	79.91	4.89	49.90
Cl^+	119.47	20.45	23.00
Br^+	172.99	41.00	23.67
I^+	203.50	58.30	23.30

3 Comparison and analysis of experimental results

In our experiments with ^{252}Cf the devices under test are IRF250, 2N6798 and ATP60M75TVR, which are manufactured with different N channel industry technologies. On the basis of the operation properties of IRF250 and 2N6798 power MOSFET in a DC-DC converter, we have characterized the test conditions mainly by the alteration of the drain-source voltage (V_{ds}), the fission fragment flux and the gate-source voltage (V_{gs}). The devices exposed to the energetic heavy ions produced by the HI-13 accelerator are IRF250, 2N6798, 2N6766 and 2N6770. From the experimental result, it could be deduced that the emergence of SEB is intimately related to the level of the drain-source voltage, the linear energy transfer of the exposure to heavy ions, and the operation condition of the power MOSFET.

Analyzing the experiment from the perspective that a non-destructive test method[4, 5] was used and taking into account all possible factors that might affect the occurrence of SEB in power MOSFET, one can conclude that the results for the ^{252}Cf fission fragments are consistent with those for the heavy ions produced by the HI-13 accelerator. Accordingly, among the correlations between the burnout cross section and the drain-source voltage, the ion energy or LET in silicon, and the operating condition of the power MOSFET, there is also a good deal of consistency between exposure to a ^{252}Cf fission fragment source and exposure to heavy ions produced by the HI-13 accelerator.

3.1 Cross section changes with drain-source voltage

Under conditions of a constant flux of fission fragments and the power MOSFET being in the off-state, we present the calculated results in Table 2. The results have been obtained for different drain-source voltages and counting the current pulses in the same interval. The burnout cross section is defined as the number of destructive current pulses divided by the ion flux[6, 7]. Fig. 1 shows the burnout cross section as a function of the drain-source voltage for IRF250 using ^{252}Cf fission fragments as an irradiation source. It can be concluded that the burnout cross section caused by ^{252}Cf fission fragments increases with V_{ds}, the increase becoming steeper at higher voltages.

Table 2. SEB cross section changes with drain-source voltage (^{252}Cf fission fragments irradiation).

time record T/min	V_{gs}/ V	V_{ds}/ V	pulse count N	cross section σ/cm^2
30	0	155	3	0.12×10^{-4}
30	0	165	4	0.15×10^{-4}
30	0	170	19	0.75×10^{-4}
30	0	175	208	8.25×10^{-4}

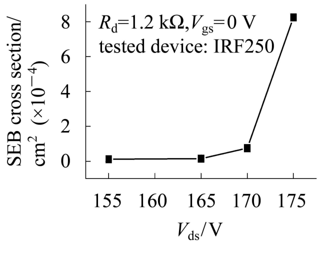

Fig. 1. Burnout cross section versus drain-source voltage for IRF250.

In the case of the devices exposed to different ions produced by the HI-13 accelerator, the power MOSFET operated in the off-state and the gate-source voltage remained constant in the irradiation procedure. As the drain-source voltage increases up to the threshold, SEB phenomena are observed and monitored by the oscilloscope. The test system is controlled by a remote PC. If a current pulse waveform appears on the oscilloscope, the test system gets a pulse count at the same time. By the varying drain-source voltage of the power MOSFET gradually, the burnout cross section was obtained in the same way as described in the section on the burnout section calculation method. If the drain-source voltage exceeds the threshold voltage, the burnout cross section rises quickly with increasing voltage. Fig. 2 and Fig. 3 show the behavior of the burnout cross section with varying drain-source voltage for the tested samples. From the experimental data presented in Table 3, which refers to test sample 2N6766 irradiated with 173 MeV Br^+ ions, one observes a steep rise of the cross section from 1.578×10^{-6} cm^2 to 4.3×10^{-3} cm^2, as the drain-source voltage changes from 180 V to 195 V.

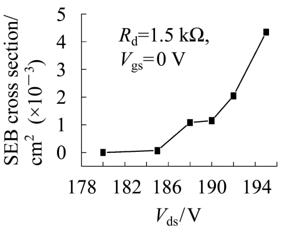

Fig. 2. Burnout cross section versus drain-source voltage for 2N6766.

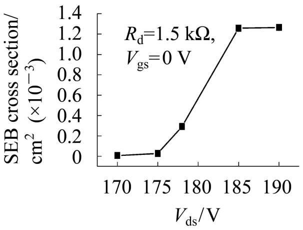

Fig. 3. Burnout cross section versus drain-source voltage for 2N6798.

Comparing the experimental results it can be concluded that the burnout cross section varies with the drain-source voltage in the same way for both accelerated heavy ion and ^{252}Cf fission fragment exposure, respectively. That is to say, the burnout cross section is sensitive to variation of the drain-source voltage over the power MOSFET SEB threshold. Fig. 1, Fig. 2 and Fig. 3 show the same properties of burnout cross sections versus drain-source voltage.

The experimental results show that the threshold V_{ds} markedly decreases with higher energy and LET of the heavy ions. In our tests samples 2N6766 and 2N6798 were exposed to 203 MeV iodine ions, and the thresholds V_{ds} were at 155 V and 170 V, respectively. But for the 120 MeV chlorine ions, the threshold V_{ds} was 190 V for both samples. However, the LET of the ^{252}Cf fission fragments is close to that of 173 MeV bromine ion, Therefore the V_{ds} threshold should be almost the same. For the test sample 2N6798 under exposure to the 173 MeV bromine ion, the threshold V_{ds} was 170 V and under exposure to ^{252}Cf fission fragments the threshold V_{ds} was 175 V. The lower threshold V_{ds} under irradiation with bromine ions is thought to be due to their longer range in silicon and the higher energy which induces a larger electron-hole plasma filament. On the other hand, one should also take into account the energy loss of the ions in the sensitive volume of the devices. Although in principle the LET of the ^{252}Cf fission fragments is close to that of the bromine ions on the surface of the devices, the LET of the ^{252}Cf fission fragments is actually less than that of the bromine ions when the ions reach the sensitive section in the power MOSFET. This is related to the fact that the average ^{252}Cf fission fragment is heavier than the bromine ion. These two reasons may be responsible for the different V_{ds} thresholds for the ^{252}Cf fission fragments and the bromine ions.

Table 3. SEB cross section change with drain-source voltage (test sample 2N6766, 173 MeV Br^+ irradiation).

V_{ds}/ V	V_{gs}/ V	time record/ min	pulse counts	cross section/ cm^2
180	0	20	2	1.578×10^{-6}
185	0	7	30	69.947×10^{-6}
188	0	16	927	1078.75×10^{-6}
190	0	20	1585	1150×10^{-6}
192	0	10	1358	2049×10^{-6}
195	0	10	2357	4345.86×10^{-6}

3.2 Cross section change with heavy ion LET

The experimental results show that there is a discrepancy between the thresholds V_{ds} and the burnout cross sections, with respect to a variation of the energy and LET of incident ions. From the experimental data given in Table 4, it can be seen that the V_{ds} threshold decreases, and the burnout cross section increases markedly with increasing LET of the incident ions. It should also be noted that the burnout cross section increases with higher energy of those incident ions that have similar LET values in silicon.

Under the same conditions we measured the burnout cross section of sample 2N6798, using various types of heavy ions, such as O^+, Cl^+, Br^+, I^+. The cross section increases from less than 7.4×10^{-11} cm^2 up to 7.22×10^{-2} cm^2 while keeping the drain-source voltage constant at a value of 185 V, i.e. there is a pronounced increase of the burnout cross section with increasing LET and energy of the incident ions. A similar increase of the burnout cross section (from less than 8.30×10^{-11} cm^2 to 1.15×10^{-3} cm^2) is observed for a drain-source voltage of 190 V. Fig. 4 illustrates this situation. As Fig. 4 shows, there is an obvious discrepancy between the burnout cross sections for different V_{ds}'s, the burnout cross section of 2N6798 for 195 V being larger by two orders of magnitude compared with that for the 180 V.

Table 4. SEB cross section changes with LET (test sample 2N6798).

ions	ion energy/ MeV	LET/ (MeV/mg/cm^2)	V_{ds}/ V	cross section/ cm^2
O	79.92	4.89	185	$<7.40\times10^{-11}$
Cl	119.47	20.45	185	1.412×10^{-6}
Br	172.99	41.00	185	1.32×10^{-5}
I	203.50	58.30	185	7.22×10^{-2}
O	79.92	4.89	190	$<8.30\times10^{-11}$
Cl	119.47	20.45	190	2.95×10^{-6}
Br	172.99	41.00	190	1150×10^{-6}

Concerning the burnout cross section, there may well be a similarity between the ^{252}Cf fission fragments and the heavy ions having comparable LET values. For example, the 173 MeV Br$^+$ and ^{252}Cf fission fragments have very similar LET values in silicon. The burnout cross section of the power MOSFET 2N6798 (7#) exposed to 173 MeV Br$^+$ is 1.23×10^{-3} cm^2 for a drain-source voltage of 190 V, and that of the power MOSFET IRF250 (similar to 2N6798) exposed to fission fragments is 5.0×10^{-3} cm^2 for a drain-source voltage of 180 V.

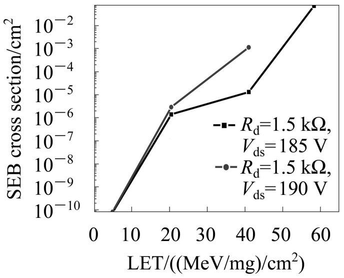

Fig. 4. SEB cross section versus LET of incident ion for 2N6798.

3.3 Cross section dependence on the operating state

The SEB phenomena is intimately related to the operation condition of the power MOSFET. In this case all the other conditions imposed on the power MOSFET remained constant and the burnout cross section was measured in the state of "turn-off" and "turn-on". The burnout cross section for IRF250 exposed to ^{252}Cf fission fragment is presented in Table 5. Analyzing the experimental data obtained in the ^{252}Cf fission fragment test, one can conclude that the power MOSFET under the test condition "turn-off" is more susceptible to single event burnout than it is in the "turn-on"state. Similarly, in the case of the tested power MOSFET 2N6798 exposed to 173 MeV bromine ions, the burnout cross section increases quickly with the device being in the "turn-off" state. The details are shown in Table 6. From Table 5 and Table 6, it can be deduced that the sensitivity of SEB on the operating conditions of the power MOSFET can be described consistently.

Table 5. Cross section versus gate-source voltage (^{252}Cf fission fragment irradiation).

test sample	V_{ds}/V	V_{gs}/V	cross section/cm^2
IRF250	175	0 (off)	8.25×10^{-4}
	175	2.5 (off)	1.27×10^{-4}
	175	3.5 (on)	0.35×10^{-4}

Table 6. Cross section versus gate-source voltage (173 MeV Br$^+$ irradiation).

test sample	I_{ds}/mA	V_{ds}/V	V_{gs}/V	cross section/cm^2
2N6798	0	185	0 (off)	1.26×10^{-3}
	0	180	0 (off)	2.92×10^{-4}
	145	180	3 (on)	1.04×10^{-4}

Our experiments showed an abrupt increase of the drain-source current (I_{ds}) after irradiating the test device for 14 hours. This variation of I_{ds} with V_{ds} is shown in Fig. 5. This failure of the test sample after a long exposure to ^{252}Cf fission fragments was observed whenever the drain-source voltage exceeded the V_{ds} threshold. The current waveform of the single event burnout was at the same time recorded by a digital oscilloscope.

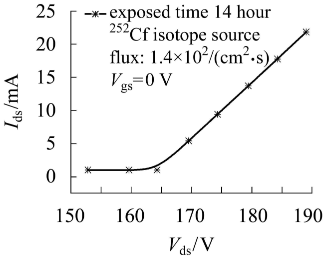

Fig. 5. Drain source current I_{ds} versus V_{ds} (test sample is 2N6798).

The same failure of the test sample 2N6798(3#) was observed when irradiating it with heavy ions, such as O$^+$, Cl$^+$, Br$^+$.

3.4 SEB current pulse waveform observation

In the test of SEB, a whole pulse current waveform of such events was detected with a digital oscilloscope, as shown in Fig. 6. There is a similarity between the current pulse waveform induced by energetic heavy ions and those induced by the ^{252}Cf fission fragments. The various single event burnout waveforms are similar in shape, a larger pulse width, followed by several anomalous peaks with increasing time. The maximum voltage of the pulse peaks is about 3—5 times the normal sampling voltage. Heavy ions induce current pulses with higher amplitudes. Without a protection resistor connected to the drain, the device would be destroyed after the pulse.

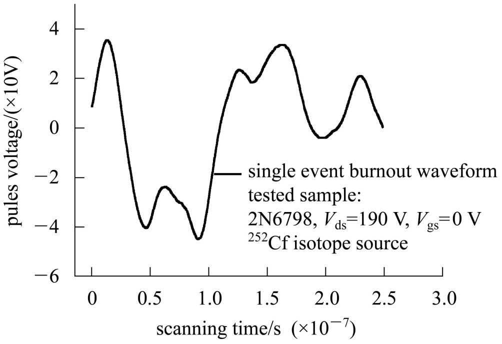

Fig. 6. Single event burnout pulse waveform.

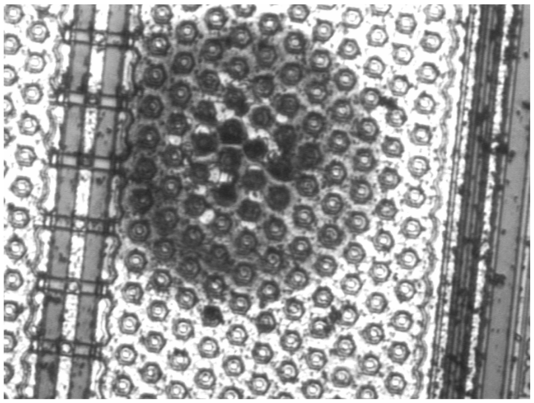

Fig. 7. Single event burnout in 2N6798.

An optical image of the burnout in the 2N6798 device is shown in Fig. 7, where the burnout occurred over a region of tens of cells on the surface.

4 Summary

The experiment on SEB for several N channel power MOSFET devices, such as IRF250, 2N6798, and 2N6766, has been carried out with different simulation sources. SEB phenomena in the power MOSFET were observed keeping the drain-source voltage above the threshold. The experimental results of SEB for samples IRF250 and 2N6798 induced by heavy ions and ^{252}Cf fission fragments have been compared. It is concluded that the characteristics of single event burnout induced by ^{252}Cf fission fragments is similar to that of heavy ions delivered by the HI-13 accelerator. The power MOSFET under the condition of “turn-off” is more susceptible to single event burnout than it is for “turn-on”. The $V_{\rm ds}$ thresholds for the SEB induced by 173 MeV bromine ions and the ^{252}Cf fission fragments are close to each other. The burnout cross section is sensitive to variation of the drain-source voltage at or above its SEB threshold. In addition, the current waveforms in the process of SEB are similar to each other, whether the irradiation occurs by heavy ions or by ^{252}Cf fission fragments. For some power MOSFET devices, different cross-sections for the single event burnout have been observed. The equivalent properties of the two irradiation methods have been characterized by the alteration of the cross section with $V_{\rm ds}$ and the linear energy transfer of the heavy ions.

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