Heavy Ion Irradiation Fluence Dependence for Single-Event Upsets of NAND Flash Memory

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Abstract: *We investigated the single-event effect (SEE) susceptibility of the Micron 16 nm NAND flash, and found the single-event upset (SEU) cross section varied inversely with fluence. The SEU cross section decreased with increasing fluence. We attribute the effect to the variable upset sensitivities of the memory cells. The current test standards and procedures assume that SEU follow a Poisson process and do not take into account the variability in the error rate with fluence. Therefore, heavy ion irradiation of devices with variable upset sensitivity distribution using typical fluence levels may underestimate the cross section and on-orbit event rate.*

INTRODUCTION

NAND Flash memories are currently the dominant mass storage technology in the commercial market, and they are finding their way into space systems thanks to the technology's high density and low cost [1]. NASA and other government agencies as well as academia have actively investigated the radiation susceptibility of each generation of NAND flash from various commercial vendors, including the Micron and Samsung [2]−[4]. The growing complexity of the device's control circuits as well as the continued shrinking of the memory cell area have introduced new challenges for radiation testing.

Existing single-event effect (SEE) test standards include the JESD57, ASTM F1192, and ESCC No. 25100 [5]−[7]. These test standards provide top level guidance for single-event testing in general. NASA has recently published a more detailed test guideline targeted specifically at current nonvolatile memories [8]. However, the current test methodologies need to be continuously updated with test findings.

For example, the traditional test protocols are predicated on the assumption that the SEE cross section remains constant with fluence. So the device upset rate in space is constant over time. Therefore, typical heavy ion tests demand a fluence high enough to cover a representative portion of the device sensitive regions. In this investigation, we observed the cross section varies inversely with the test fluence, which we attribute to the range of upset sensitivities of the memory cells.

DEVICE DETAILS

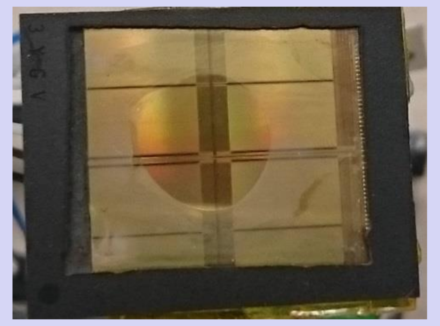

Figure 1. Die map of a third generation device, showing sensitive locations during pulsed-laser testing. The upset areas are indicated by circles and the respective run number.

The MT29F128G08CBECBH6 is a multi-level cell NAND flash memory built on Micron's 16 nm CMOS process. The single-die 128 Gb device is available in a plastic encapsulated ball grid array (BGA) package.

Figure 1 shows a photograph of an etched device.

Array performance:
– Read page: 115μs (MAX)
– Program page: 1600μs (TYP)
– Erase block: 3ms (TYP)
Reliability:
– Data retention: JESD47 compliant
– Endurance: 3000 PROGRAM/ERASE cycles

EXPERIMENTAL

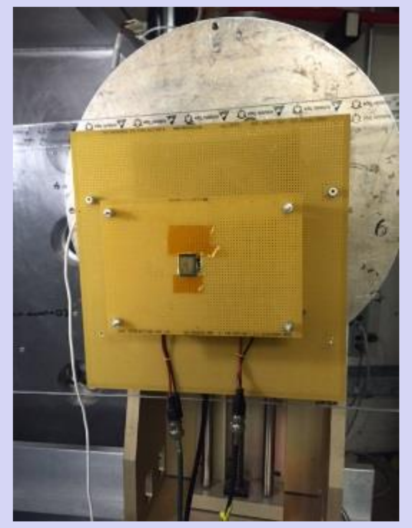

Figure 2. Photograph of the test setup inside the LBNL irradiation chamber.

Tester: ARM Cortex-M4-based 32-bit microcontroller operating at 120 MHz. The microcontroller is directly connected to the I/O pins of the Flash memory under test. Figure 2 shows a photograph of the test setup inside the irradiation chamber at LBNL. The microcontroller tester is located underneath the device-under-test (DUT). The majority of the heavy ion spectrum will be stopped prior to reaching the microcontroller. So only the flash memory will be exposed to the heavy ions.

Data pattern:

- 00, FF, AA, 55, Counter

Test mode:

- Unpowered
- Static (standby)
- Dynamic read
- Dynamic read/erase/write

IRRADIATION DETAILS

We irradiated four parts in vacuum at the Lawrence Berkeley National Laboratory (LBNL) Berkeley Accelerator Space Effects (BASE) Facility with a cocktail of 16 MeV/amu heavy ions. Table I shows the heavy ion beam information, including the ion specie, energy, linear energy transfer (LET), and ion penetration range in silicon.

Cocktail: 10 MeV/amu
Flux: 5×10^3 to 1×10^5 $cm^{-2} \cdot s^{-1}$
Fluence: 1×10^5 to 1×10^7 cm^{-2}

Table I
Heavy-ion specie, linear energy transfer (LET) value, range, and energy.

Ion	Initial LET in air (MeV·cm²/mg)	Range in Si (μm)	Energy (MeV)
B	0.9	306	**108**
Ne	3.5	175	**216**
Si	6.1	142	**292**
Ar	9.7	130	**400**
Cu	21.2	108	**659**
Xe	**49.3**	**148**	**1232**

RESULTS

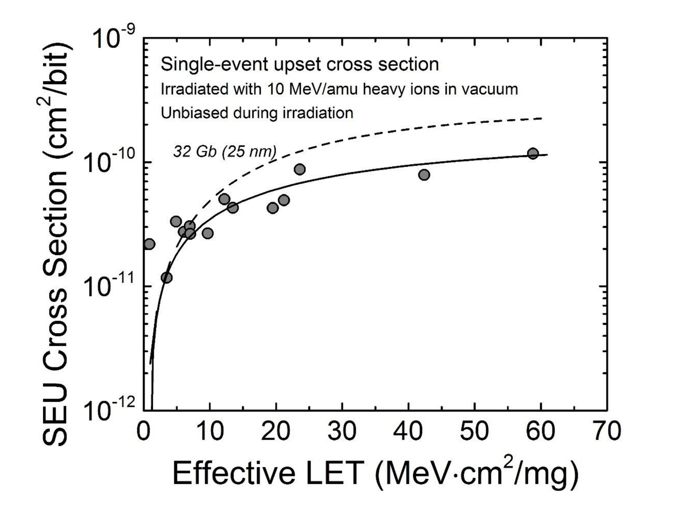

Figure 3. Single-event upset cross section vs. effective LET for the Micron 128 Gb NAND flash. The error bars due to Poisson errors are smaller than the symbols. Weibull fitting parameters: LET_0 = 0.89 MeV·cm²/mg, Sigma = 1.5×10^{-10} cm², S = 0.9, W = 40.

Figure 3 shows the single-event upset cross section as a function of effective LET for devices that were irradiated in the unpowered (static off) condition. Each data point represents the average cross section for ion fluence ranging from approximately 10^5 to 10^7 ions/cm². The dashed line shows the SEU cross section curve for Micron's previous generation 25 nm NAND flash.

SEE characteristics:

- SEU LET_{th} < 0.9 MeV·cm²/mg
- Observed only single-bit errors; Multiple-bit upsets most likely masked due to address interleaving
- Observed SEFI during static on, dynamic read, and dynamic read/erase/write tests
- Observed 2 cases of functional failure isolated to the block level only during dynamic read/erase/write testing
- Functional failure observed at LET of 21 and 58 MeV·cm²/mg

FLUENCE DEPENDENCE

Figure 4 shows the cross section decreasing with increasing fluence for various LETs. The curve fits show that the cross section is proportional to the power of the fluence. Figure 5 shows the cross section data at two fluences for each logic level. Figure 6 shows the normalized cross section as a function of fluence for Ne, Ar, and Cu.

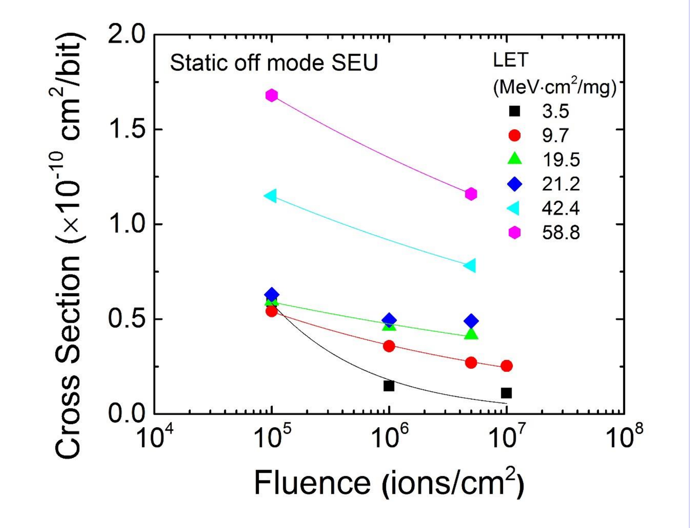

Figure 4. Single-event upset cross section vs. effective fluence at various LETs. Parts were irradiated unbiased with 10 MeV/amu heavy ions in vacuum. The curve fits are power law.

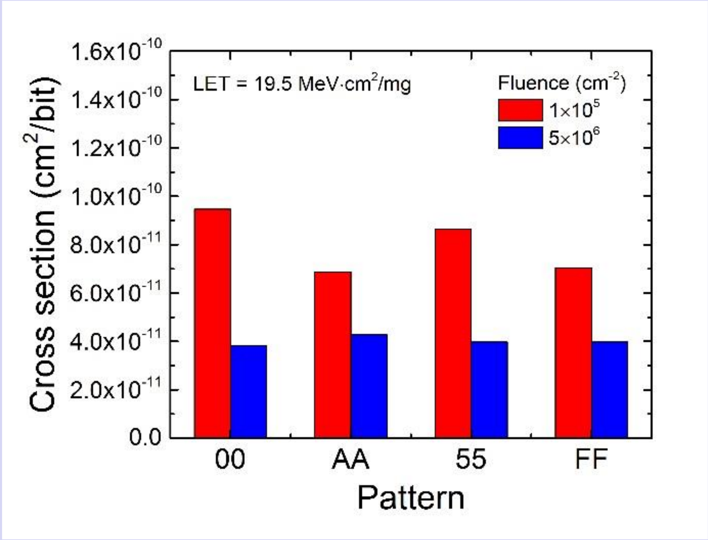

Figure 5. Single-event upset cross section vs. data pattern for fluence of 1×10^5 cm^{-2} and 5×10^{-6} cm^{-2}, at LET of 19.5 MeV·cm²/mg.

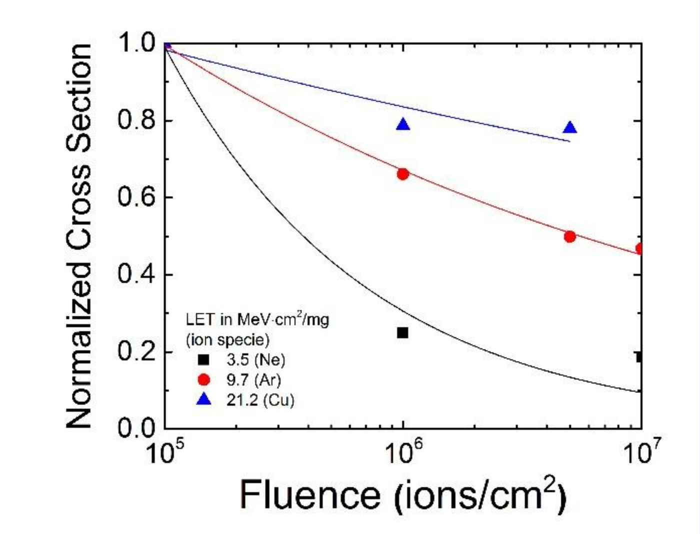

Figure 6. Normalized single-event upset cross section vs. fluence for different ions and LET. The curve fits are power law.

SEU characteristics:

- Cross section inversely proportional to fluence, increasing for decreasing fluence
- Cross section shows similar sensitivity for each logic state, similar to previous generation Micron flash [9]
- Fluence dependence consistent across all logic states
- Magnitude of fluence dependence is more significant for lower LET ions
- Cross section reduction of 80% for Ne and 20% for Cu from fluence of 10^5 cm^{-2} to 5×10^6 cm^{-2}

Figure 7 schematically illustrates the threshold voltage distributions of the exposed cells at different fluence levels. The black curve represents the entire distribution for all of the memory cells. The blue and red curves represent the number of exposed cells for irradiation with fluences of 10^7 and 10^5 ions/cm², respectively. Figure 7 also shows the putative shifts in the distributions after irradiation, based on studies of older generation NAND flash devices [10]. Heavy ion irradiation causes 1) a secondary peak in the distribution, and 2) spreading out in the tail of the distribution.

- The tail end of the distribution is most vulnerable
- As fluence increases, heavy ion irradiation exposes a larger sample of the total population, including the cells with higher V_{th}
- At higher fluence, upset cells make up a smaller percentage of the population than at lower fluence
- Consequently the cross section decreases for increasing fluence
- Upset sensitivity decreases over time similar to the infant mortal effectCross section reduction of 80% for Ne and 20% for Cu from fluence of 10^5 cm^{-2} to 5×10^6 cm^{-2}
- Lower LET ions are unable to upset population with higher V_{th}, so that the cross section decreases more significantly with increasing fluence

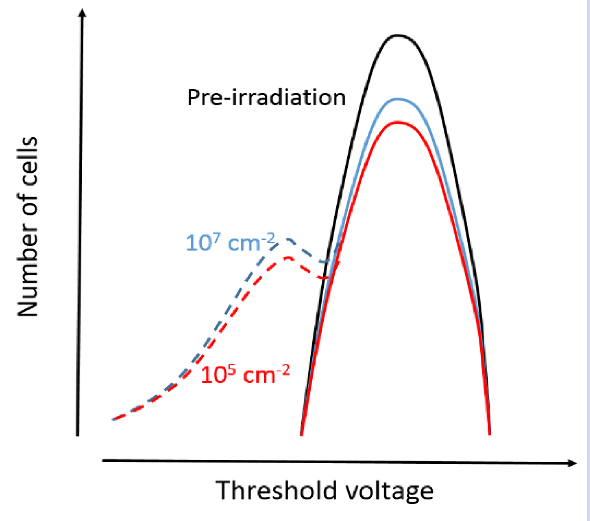

Figure 7. Schematic illustration of the cell distribution vs. threshold voltage. Black solid curve represent the total number of cells before irradiation. The blue and red curves represent the number of exposed cells for irradiation with fluences of 10^5 and 10^7 ions/cm². Dashed lines represent the shifts in the tails of the distributions after irradiation.

CONCLUSION

The phenomenon raises questions regarding current test standards and typical test methodologies with implications for hardness assurance. The inverse fluence dependence of the cross section implies that a space system carrying such a device can potentially experience a higher upset rate earlier in the mission than later in the mission. Traditional test methodology of irradiating to a fluence of 10^6 to 10^7 cm^{-2} may lead to underestimating the upset cross section and on-orbit event rate. Therefore, we may need to systematically test at various fluence levels and correlate with the mission environment. This would apply for any device with variable upset sensitivity of its sensitive volumes. It is worthwhile to evaluate other flash memory technologies, because of the known variable distribution of cell upset sensitivities in flash. One constraint may be that as we continue to reduce the fluence, the intrinsic errors will begin to overwhelm the radiation-induced errors. With that said, the enhancement in the upset rate from a fluence of 10^7 to 10^5 cm^{-2} is not significant for this device. It is expected that a basic error correction scheme such as reed-solomon will be sufficient to correct most if not all of the SEU in most missions. However, a critical question/concern is how will technology scaling impact this effect.

The results shown here introduce a novel problem in radiation testing of a high density memory device with a non-constant upset rate. If the error rate is high enough that they cannot be corrected via error correction code, then this phenomenon will force us to reconsider the traditional approach for single-event effect testing of flash devices.

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