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 varies with fluence. The SEU cross section decreases with increasing fluence. We attribute the trend to the shrinking of the sensitive area of the memory cells. The test standard test procedures assume that SEU behavior will be consistent with that of flash memory, and we do not take into account the variability in the error rate with fluence. Therefore, heavy ion irradiation with variable fluence 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 it is essential to find their in-flight space systems technologies thanks to the technology's high density and low cost. Without NAND flash memory, most businesses would be unprofitable. NAND flash memory is becoming the primary storage technology in various commercial vendors, including the Micron and Samsung NAND flash memory. A recent study of device manufactures found that over the continued shrinking of the memory cell area have introduced new challenges for readout and testing. Existing single-event effect (SEE) test standards include the JESD57, JESD51B, and JESDR5013. These test standards provide results that do not accurately represent the actual radiation environment. We published a more detailed test guideline specifically targeted at current radiation environments (J). However, the current test methodologies need to be continuously updated with new findings. For example, the irradiation test procedures are independent on the assumption that the SEE cross section remains constant with fluence. So the desired upset rate in space is constant over time. Typically, logical errors are not allowed to persist over the lifetime of the device, yet they are a serious problem in the device sensitive regime. In this investigation, we observed the cross section varies inversely with the fluence, which attributes to the range of upset sensitivities of the memory cells.

DEVICE DETAILS
The MT2F921208CG8B388 is a 128 Gb NAND flash memory built on Micron's 16 nm technology. The 16 nm NAND flash memory is a plastic encapsulated flash memory (IGA) package. Figure 1 shows a photograph of a single chip of NAND flash device.

EXPERIMENTAL
We irradiated four parts in vacuum at the Lawrence Berkeley National Laboratory (LBNL). Berkeley Accelerator Space Effects (BASE) Facility with a cocktail of 16 different ion species. Table 1 shows the heavy ion beam information, including the ion species, energy, LET, and ion penetration ratio in silicon. Cocktails:

<table>
<thead>
<tr>
<th>Ion Species</th>
<th>Linear Energy Transfer (LET)</th>
<th>Range in Si (µm)</th>
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<tr>
<td>He</td>
<td>0.5 MeV·cm²/µm</td>
<td>5 ± 1</td>
</tr>
<tr>
<td>Fe</td>
<td>10 MeV·cm²/µm</td>
<td>5 ± 10</td>
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RESULTS
Figure 3 shows the single-event upset cross section as a function of effective LET for devices subjected to different irradiation conditions. Each data point represents the average cross section of all the tested devices, ranging from approximately 10⁻⁶ to 10⁻⁴ ions/cm². The dashed line shows the SEU cross section curves for Micron's previous generation 25 nm NAND flash.

SEE characteristics:
- Micron 4G NAND flash devices: 25 nm technology
- Multiple ion species: He, Fe, He, Fe, ... |
- Linear energy transfer (LET) during irradiation on dynamic read and dynamic read/masked write tests.
- The 2 curves of functional failure isolated to the least level only during dynamic read/masked write tests.
- Functional failure observed at LET of 21 and 58 MeV·cm²/µm

The threshold voltage distributions of the exposed cells at different fluence levels are shown in Figure 7. The threshold voltage distribution changes from a Gaussian distribution to a flat distribution as the fluence increases.

<table>
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<th>The threshold voltage is</th>
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<td>At fluence increases, heavy ion irradiation exposes a larger sample of the total population including the cells with lower threshold voltage.</td>
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<td>At higher fluence, upset cells make up a smaller percentage of the population.</td>
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<td>Upset sensitivity decreases over time similar to the initial read effects.</td>
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<td>Lower LET rates are unable to upset population with higher fluence, as the cross section decreases more significantly with increasing fluence.</td>
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CONCLUSION
The phenomenon raises questions regarding current test standards and typical test methodologies with implications for the future. The reverse fluence dependence of the cross section implies that a space system carrying such a NAND device can potentially experience a higher upset rate earlier in the mission than later in the mission. The traditional test methodology of irradiating to a fluence of 10¹⁰ to 10¹¹ cm⁻² may lead to underestimating the upset cross section and on-orbit upset 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 continue other flash memory technologies, because of the known variable distribution of cell upset sensitivities in flash. For example, it may be that we can reduce this the fluence, the intrinsic errors will begin to overwhelm the upset rate. With that said, the enhancement to the upset rate from a fluence of 10¹⁰ to 10¹¹ cm⁻² is not significant for this device. It is expected that a basic error correction scheme such as a read/verify will be sufficient to mitigate the effects. However, a critical question/concern is how will technology accommodate this effect.

REFERENCE