Ion Induced Stuck Bits in 1T/1C SDRAM Cells

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Abstract--**Radiation exposure of certain types of devices tends to stick bits, causing them to not be read out correctly after programming. Evidence of a linear trend in stuck bits in SDRAM memory cells is presented. This trend makes a cross section, as traditionally defined for single event effects (SEE), unambiguous. However, there is considerable part-to-part variations in the cross section.**

I. Introduction

Stuck bits created by heavy-ion irradiation in the memory elements of some devices, such as DRAMs and some SRAMs, are believed to occur from either of two types of mechanisms. One mechanism is single event gate rupture, while another is micro-dose [1]. The issue of stuck bits has been examined to some extent for SRAMs [2-7] and the TID radiation response of SDRAMs have similarly been studied [8-9]. The present paper is concerned with those stuck bits that are believed to be caused by micro-dose, as evidenced by a certain degree of annealing. Micro-dose is a hybrid between total ionizing dose (TID) and a single event effect (SEE). Like SEE (but unlike TID), the disturbances created by heavy-ion hits are spatially non-uniform. Like TID (but unlike SEE), damage created by different hits at the same location is expected to be cumulative. This distinction between micro-dose and SEE raises a question regarding the meaning of a cross section for stuck bits. The experimental definition of a cross section, associated with a given ion, is taken here to be an increment of counts divided by an increment of fluence. For conventional SEE, this experimental definition gives an unambiguous result, in the sense that the cross section does not depend on previous irradiation history (assuming that TID does not significantly alter the characteristics of a device). However, it is not obvious whether this does or does not also apply to stuck bits, so there is a question as to whether traditional SEE rate calculation methods can be used to estimate stuck bit rates in a space environment. The objective of this paper is to experimentally answer this question for a particular device, which is the Hyundai 16Mx4 SDRAM.

The experimental data shown later in this paper support the assertion that cross sections can be measured, and rates in space can be estimated, using the same methods used for SEE; at least for the tested device. However, additional tests and/or modeling efforts are needed to determine whether this conclusion is universal, or limited to special families of devices. Also, the phrase "same methods used for SEE" should be qualified, because the directional dependence of device susceptibility may or may not be typical of other types of SEE (e.g., single event upset). We did not investigate directional effects (all measurements were at normal incidence), so this is a subject for future work. Our concern was merely to answer the question of whether cross section is or is not a function of irradiation history.

II. Several Postulated Models

The experimental measurements discussed in this paper are believed to be important because it is not obvious whether stuck bit rates in space should be calculated in a similar fashion as the procedure pertaining to typical SEE phenomenon, or as something more complicated (e.g., prior damage from light and abundant ions increases device susceptibility to subsequent hits). Each of the conflicting possible answers is supported by a credible argument, derived from one of the several imagined cases (or postulated models) below. Prior to obtaining experimental data, one model would seem as credible as another, so an objective was to determine whether the data tend to support one model more than another. We consider three imagined cases, with the first leading to a different conclusion than the other two. In all three examples we assume that the number of stuck bits (accumulated during laboratory tests and in space environments) is small enough so that the number of bits that are still candidates for sticking (i.e., not already stuck) is approximately constant even as stuck bits accumulate.

For the first case, all bits in a device can be regarded as identical in terms of construction. Furthermore, susceptibility within a bit is uniform, in the sense that each bit has some (but not yet physically identified) geometric area such that an ion hit at any location in this area has the same effect as a hit at any other location within this area (hits outside this area have no effect). A "hit to a bit" is interpreted to mean a hit to one of these areas. For ions having a sufficiently large linear energy transfer (LET), call it 30 MeV-cm^2/mg for illustration, a single hit to a bit will stick it, while some lower LET, call it 20 for illustration, requires two hits to the same bit. For this example, the experimentally defined device cross section will equal the size of the geometric area multiplied by the number of bits in the device for ions having LET=30. However, this is not true at LET=20. Instead, the cross section is proportional to the fluence accumulated from these test ions up to the time of the cross section measurement. This is because the number of bits that are susceptible to a hit is the number of bits that have already been hit once, and this number is proportional to the fluence. The cross section at LET=20 is ambiguous unless a complete irradiation history has been specified. Calculating rates in space (which contains a mixture of different particle types) is a non-trivial task if this model is correct.

For a second example, suppose all bits can be regarded as identical in construction, but susceptibility within a bit is not uniform. Instead, susceptibility depends on the location of the hit in some vicinity of a bit. For a given LET, we can now define two areas (which have not yet been physically identified), where each area may depend on the selected LET. One area (which could be zero, but assume it isn't) is defined by the condition that one hit, by the selected LET, will stick the bit, while the other area requires two or more hits. We also assume, for this example, that the two areas compare in such a way that a single hit to the first area is much more probable (for the fluence used in a test) than two or more hits to the second area. Then nearly all contribution to the measured cross section is from the first area. The fact that damage is cumulative is irrelevant to the cross section. Cross sections can be measured, and rates in space can be estimated, using the same methods used for SEE.

For a third example, suppose susceptibility for each bit is uniform within some (but not yet physically identified) sensitive area, but the bits are not identical. Instead, there are statistical variations between bits. For a given LET, we can define two subsets of bits (the two subsets may depend on the selected LET). A bit in one subset will stick from a single hit, while a bit in the other subset requires two or more hits. We also assume, for this example, that the numbers of bits in the two subsets compare in such a way that a single hit to a bit in the first subset is much more probable than two or more hits to a common bit in the second subset. The conclusion is the same as with the second example. Cross sections can be measured, and rates in space can be estimated, using the same methods used for SEE. It will be argued in Section IV that this third model may be the best candidate of the three.

III. Experimental Method and Data

Excluding an exception noted below, the experimental method starts with one device and exposes it to only one type of heavy ion (one LET value). The fluence is applied in increments, and the number of stuck bits is recorded after each fluence increment. The data are used to plot the cumulative number of stuck bits as a function of the cumulative fluence. The test is then repeated, using a fresh device and a different LET. This produces the curves in Fig.1. The exception to the experimental method is the fluorine test of Device 3. This device was pre-exposed to carbon, producing an initial (prior to the fluorine test) number of stuck bits (which is slightly smaller than the number at the end of the carbon test because some annealing occurred). However, all plots demonstrate a strong linear relationship, indicating an unambiguous (i.e., not a function of irradiation history, at least for fluences up to those used in the test) cross section at each LET. A similar test method, but using 200 MeV protons instead of heavy ions, produced Fig.2, which also shows this linear behavior. The slopes of the curves in the figures were used to calculate cross sections. The 200 MeV proton cross section was found to be 1.4×10^{-9} cm^2/device. The heavy-ion cross sections are shown in Fig. 3.

IV. Observations from the Data

One observation from the data is the linearity discussed in the previous section. This is not consistent with the first model in Section II, but is consistent with the second and third models. Another observation is considerable part-to-part variations, as seen by comparing different points (which are from different devices) at the same LET in Fig. 3. The fact that each device shows a strong self-consistency (i.e., linearity with minimal scatter in Fig. 1) indicates that variations between devices are true part-to-part variations, rather than an artifact of experimental scatter. This is not consistent with the second model in Section II, but it may be consistent with the third. Because the devices contain about 67 million bits, a cross section that reflects an average bit would not be expected to show much part-to-part variation (assuming different devices are manufactured under the same conditions). A large variation suggests that the cross section does not reflect an average bit, it reflects the most extreme (in terms of susceptibility) bits. This is consistent with the third model, because this model implies that the cross section reflects the weakest bits.

Another observation, from Fig. 3, is that the cross section increases much more slowly with increasing LET than is typical of SEE. If the cross sections for different devices at the same LET are averaged together, the data can be fit fairly well by a straight line in a linear-linear plot, which is the smooth curve in the log-linear plot in Fig. 3. This is not typical of other types of SEE, but may be consistent with ionization in an oxide. Ionization in an oxide is followed by a prompt recombination of carriers, which occurs before electrons are driven out of the oxide by any electric field (built-in and/or applied) that is present. The relevant quantity is surviving charge (i.e., survives the prompt recombination) rather than liberated charge. The surviving charge is measured in terms of a charge yield. However, this yield is a function of particle LET (in addition to the electric field strength in the oxide), and decreases with increasing LET [10]. Therefore, when yield and LET are taken together, different ions become more nearly equivalent than a comparison of LETs would indicate. This is consistent with the cross section being insensitive to LET, and suggests that the sensitive areas may be oxide regions. A quantity that may be more relevant than LET is a "reduced LET", which is the yield times the ordinary LET, and relates to surviving charge in the same way that ordinary LET relates to liberated charge.

V. Conclusions

From the point of view of calculating rates in space for the tested device, there are two important observations. One is linearity (counts are proportional to fluence). This is important because it justifies the use of traditional SEE rate calculation methods. Another is part-to-part variation, which is important because it implies that lot testing is needed. However, it is not yet known whether these observations are universal, or limited to special devices, so it may be important to obtain a physical understanding. This is a subject for future work, but the present work may be of some guidance. Of the three models postulated in Section II, the third is the only one consistent with both linearity and part-to-part variations. Furthermore, the very slow variation of cross section with increasing LET is not typical of SEE, and suggests that some other parameter may be more relevant than ion LET. This is consistent with dose deposition in an oxide, in which a yield function (describing prompt recombination) must be included. When yield and LET are taken together, different ions become more nearly equivalent than a comparison of LETs would indicate. A credible model is that the sensitive area of a bit is a gate oxide, but only a small fraction of the bits contribute to the measured cross section because the cross section reflects the weakest bits in a statistical distribution.

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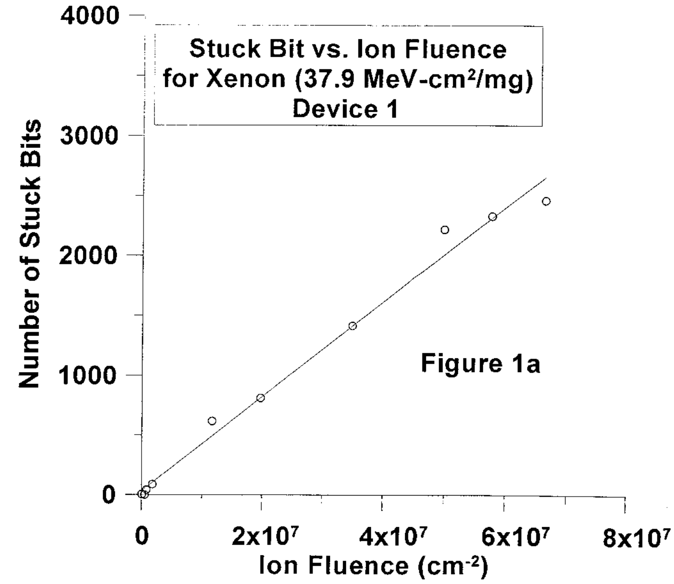


Figure 1a

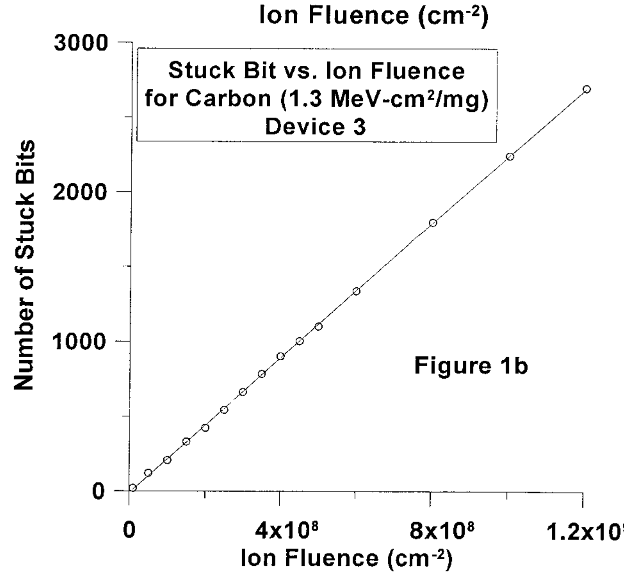
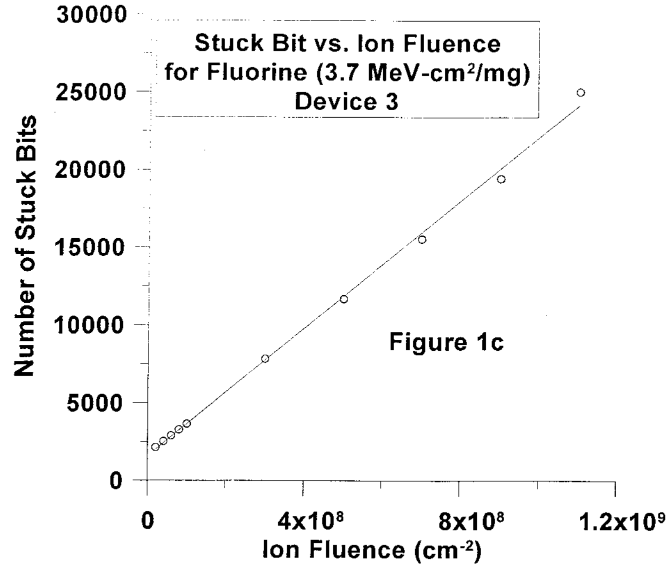
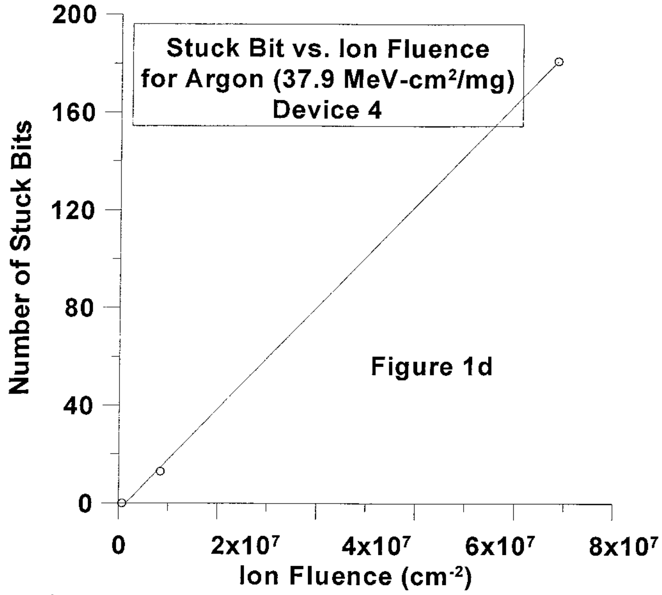
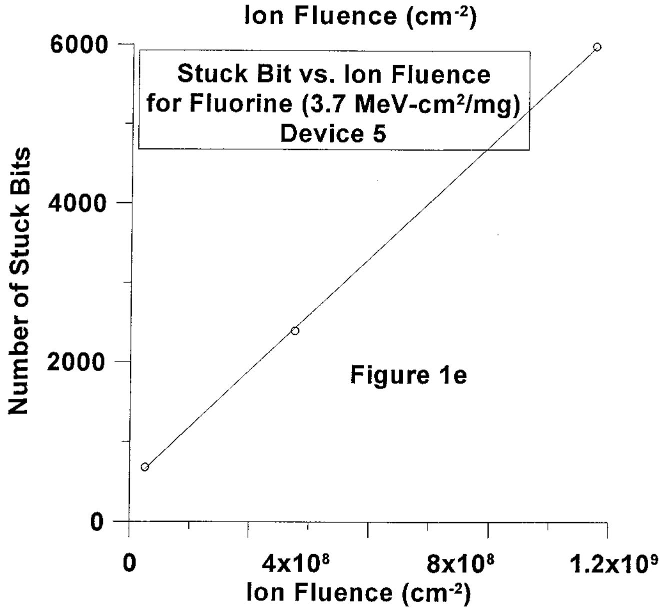
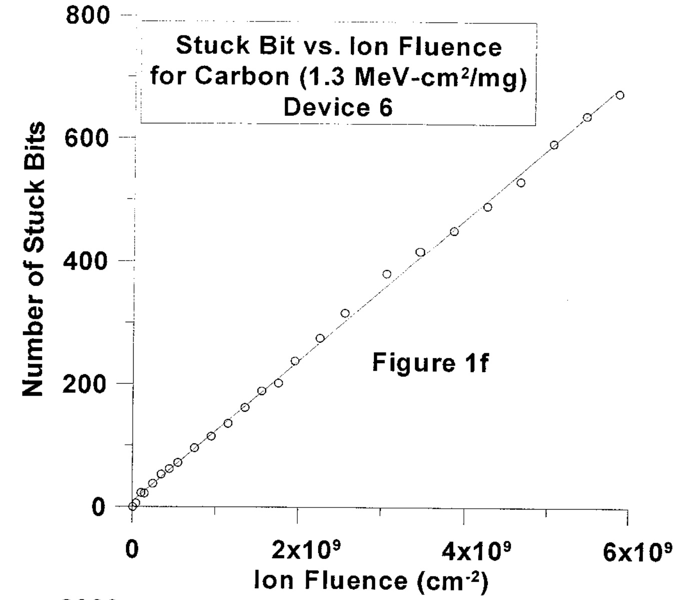


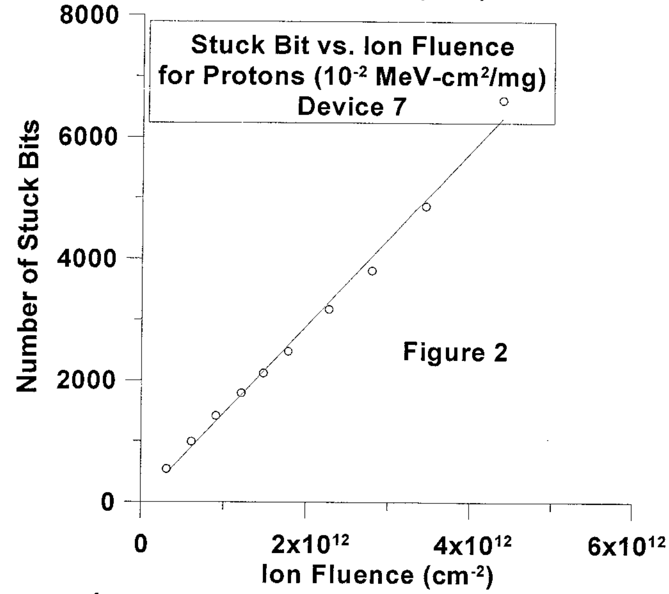
Figure 1b

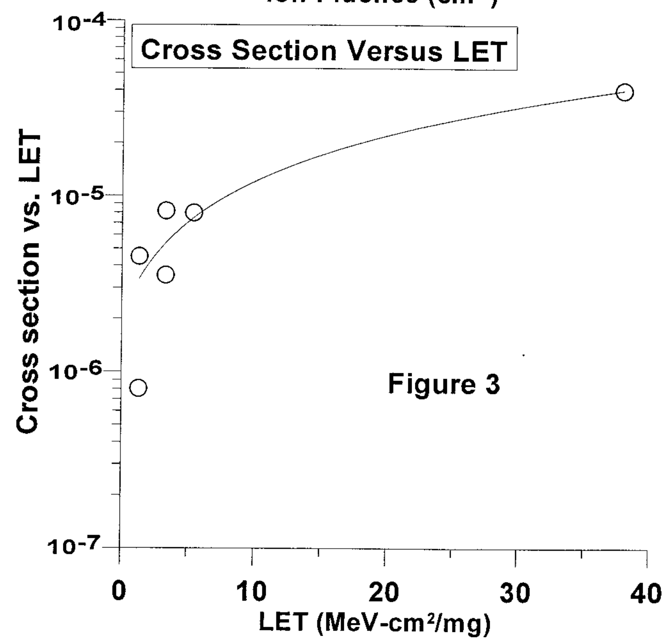

Stuck Bit vs. Ion Fluence
for Fluorine (3.7 MeV-cm²/mg)
Device 3
Number of Stuck Bits
Ion Fluence (cm⁻²)
30000
25000
20000
15000
10000
5000
0
4x10⁸
8x10⁸
1.2x10⁹
Figure 1c


Stuck Bit vs. Ion Fluence
for Argon (37.9 MeV-cm²/mg)
Device 4
Number of Stuck Bits
Ion Fluence (cm⁻²)
200
160
120
80
40
0
2x10⁷
4x10⁷
6x10⁷
8x10⁷
Figure 1d


Stuck Bit vs. Ion Fluence
for Fluorine (3.7 MeV-cm²/mg)
Device 5
Number of Stuck Bits
Ion Fluence (cm⁻²)
6000
4000
2000
0
4x10⁸
8x10⁸
1.2x10⁹
Figure 1e


Stuck Bit vs. Ion Fluence
for Carbon (1.3 MeV-cm²/mg)
Device 6
Number of Stuck Bits
Ion Fluence (cm⁻²)
800
600
400
200
0
2x10⁹
4x10⁹
6x10⁹
Figure 1f


Stuck Bit vs. Ion Fluence
for Protons (10⁻² MeV-cm²/mg)
Device 7
Number of Stuck Bits
Ion Fluence (cm⁻²)
8000
6000
4000
2000
0
2x10¹²
4x10¹²
6x10¹²
Figure 2


Cross Section Versus LET
Cross section vs. LET
LET (MeV-cm²/mg)
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
0
10
20
30
40
Figure 3