Testing Fast Neutron-Induced Soft Errors in Semiconductor Memories

K. Ünlü,[1,2] N. Vijaykrishnan,[3] M. J. Irwin,[3] B. Heidrich,[1] C. Celik,[1,2] K. Ramakrishnan,[3]

Service Provided: Fast Neutron Irradiator

Sponsors: National Science Foundation, U. S. Department of Energy, Pennsylvania State University Radiation Science and Engineering Center, Pennsylvania State University Department of Computer Science and Engineering

Introduction

Soft errors are transient circuit errors caused due to excess charge carriers induced primarily by external radiation. Radiation directly or indirectly induces localized ionization that can flip the internal values of the memory cells. Our current work tries to characterize the soft error susceptibility for different memory chips working at different technology nodes and operating voltages.

Background and Related Work

Advances in very-large-scale integration technology have ensured the availability of high performance electronics for a variety of applications. The applications include consumer electronics like cellular phones and HDTVs, automotive electronics like those used in drive-by-wire vehicles, and million dollar servers used for storing and processing sensitive and critical data. These varied applications require not only higher throughput but also dependability. Even if a microprocessor is shipped without any design errors or manufacturing defects, unstable environmental conditions can generate temporary hardware failures. These failures, called *transient faults*, cause the processor to malfunction during operation time. The major sources of transient faults are electromagnetic interference, power jitter, alpha particles, and cosmic rays. Studies [1,2] have shown that a vast majority of detected errors originate from transient faults. Even a single-bit error may eventually lead to a computation failure. Therefore, managing the soft errors is a critical problem to solve in fully realizing dependable computing.

Soft error rate (SER) testing of devices has been performed for both neutron and alpha particles. Target 4 Flight Path 30L at the Los Alamos National Laboratory Neutron Science Center is a JEDEC prescribed test beam for soft errors, and is the only one of its kind. This beam is highly stable and it closely replicates the energy spectrum of terrestrial neutrons in the 2-800 MeV range while providing a very high neutron flux [3]. SER testing reported in the literature has been performed at this facility [4,5]. However, the beam availability is limited, necessitating the identification and testing of alternate research facilities. Alternatively in the past, experiments were carried out with alpha particles originating from ^{238}Th foils on 0.25 μm-generation SRAMs [6]. Recently, elimination of borophosphosilicate glass and ^{10}B from the process flow in the 180-nm generation of SRAMs has made the low-energy (<1 eV) neutron SER negligible [7]. High-energy (1-1000 MeV) neutrons often dominate SERs in advanced CMOS logic and memories. As seen from the Table 1, for high-energy neutrons all selected reactions have the same order of magnitude cross-sections. Hence, the need for accessible neutron testing facilities for these high-energy neutron interactions is critical for the design of next generation semiconductor devices.

This study intends to observe the effect of ^{10}B and high-energy neutrons on soft error rates. In order to investigate the effect of ^{10}B on SER, a fast neutron irradiator (FNI) is used (Figure 1). The fast neutrons are available near the Penn State Breazeale Reactor (PSBR) core by inserting a test circuit into a stand-up pipe adjacent to the PSBR core face.

Experimental Setup and Results

The PSBR was used as the neutron source in the experiments. The maximum rated power of the reactor is 1 MW in the continuous mode, and 2000 MW in the pulse mode. The high neutron flux allows for accelerated testing of the phenomenon.

The experimental setup consists of a custom board interfaced with a computer through a GPIB card (from National Instruments). The board itself has off-the-shelf SRAM memory chips. The board is controlled through a LabVIEW interface. The controlling application consists of simple routines to read and write a user specified value across the whole memory. During the readout, it compares the written value to the value in each address. The circuit board is secured in the beam cave, and connected to a PC outside using a 25-ft cable. This configuration allowed for continuous read-write, and for changing the operating conditions without interrupting the experiment.

[1] **Radiation Science and Engineering Center, The Pennsylvania State University, University Park, PA 16802**
[2] **Department of Mechanical and Nuclear Engineering, The Pennsylvania State University, University Park, PA 16802**
[3] **Department of Computer Science and Engineering, The Pennsylvania State University, University Park, PA 16802**

TABLE 1: Important reaction cross-sections, σ, for neutron interactions with semiconductor materials

Reaction	Products	Q-Value, MeV	$\sigma_{0.0017\ eV}$	$\sigma_{0.0253\ eV}$	$\sigma_{14\ MeV}$
$^{10}B + n$	$^{7}Li + \alpha$	2.79	~17000 b	~3837 b	~49 mb
$^{11}B + n$	$^{8}Li + \alpha$	-6.63	~20 mb	~50 mb	~32 mb
	$^{7}Li + \alpha + n$	-8.66			
$^{28}Si + n$	$^{25}Mg + \alpha$	-2.65	~0	~2 mb	~222 mb
$^{30}Si + n$	$^{27}Mg + \alpha$	-4.20	~0	~60 mb	~68 mb

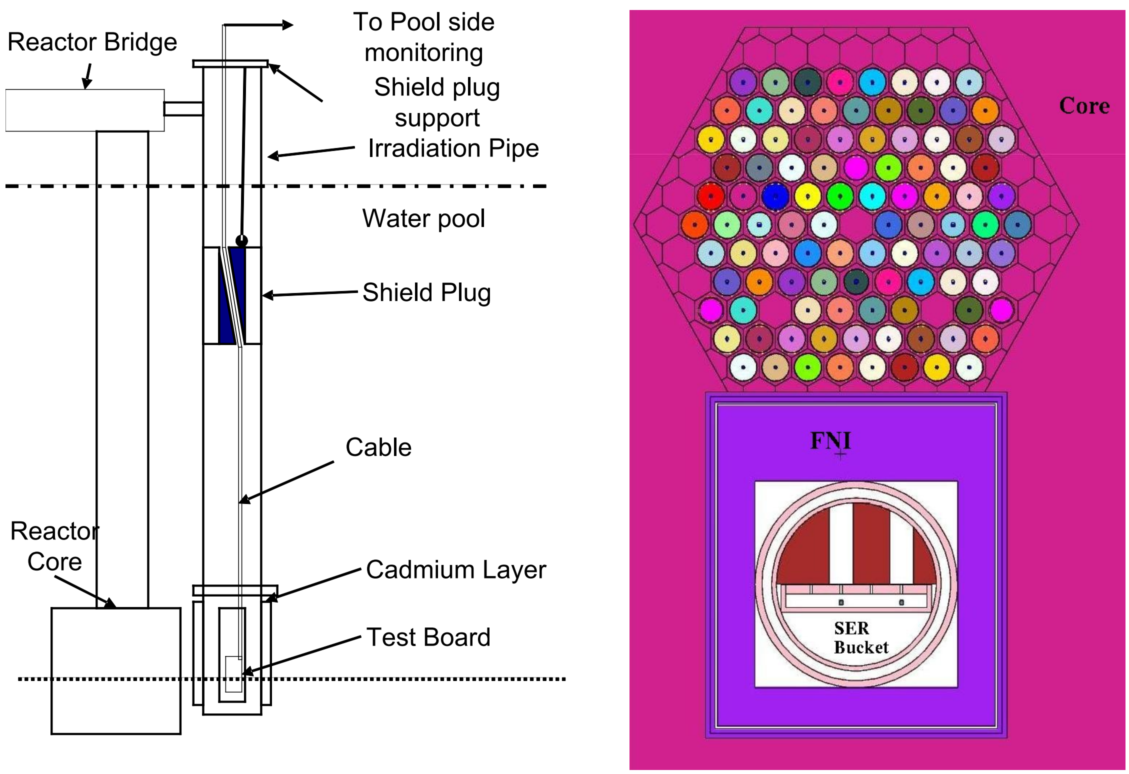

FIGURE 1: Fast neutron test setup near the reactor core (left) and MCNP model of the PSBR core and FNI (left)

The neutron flux around the reactor core is much higher than that at the neutron beam ports, where previous circuit board irradiations have been performed. Therefore, the circuit boards will be placed by the periphery of the reactor core via a vertical standpipe in order to observe the effect of fast neutrons on soft error rate. The fast neutron flux at the core boundary is 5×10^{12} neutrons/cm^{2}sec, and thermal flux is 1.3×10^{13} neutrons/cm^{2}sec at 1MW steady state reactor operation. The reactor can be pulsed for a very short duration of time, around 10 milli-sec at its full-width half-maximum, at which it generates a fast flux of about 1×10^{16} neutrons/cm^{2}sec at the core periphery. This amounts to about a four order of magnitude increase in the fast flux. The time duration is very limited, yet the amount of fast flux is immense. The test circuits will be left inside the standpipe and the reading will be taken. In addition, the walls of the pipe will be covered with boron. Boron will absorb the thermal component of the flux so that the board is affected only by fast neutrons.

Results and Discussion

The setup described here allows for accelerated testing of semiconductor memory devices fast neutrons. The experiments and analyses have been performed only on soft errors due to fast neutrons. Neutron flux at the sample box of the SER bucket in the FNI has been measured. Currently, Monte Carlo simulations using MCNP-5 [8] for the neutron flux measurements and

TABLE 2: Neutron energy groups used in MCNP-5 simulations

Group	Energy Range (MeV)
Thermal	1.000×10^{-11} to 0.625×10^{-6}
Epi-Thermal	0.625×10^{-6} to 1.000×10^{-3}
Fast	1.000×10^{-3} to 2.000×10^{1}

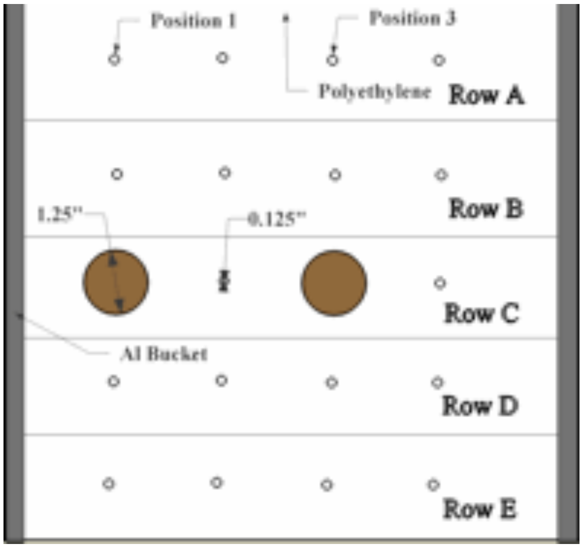

FIGURE 2: Polyethylene configuration for SER irradiations in the RSEC FNI

possible improvement methods for fast neutron flux irradiations are in progress. Neutron flux measurements were carried out with aluminum, sulfur, and gold samples in order to measure three neutron energy groups: fast, epithermal, and thermal, respectively. The front view of the SER bucket is shown in Figure 2 with two big irradiation holes in the polyethylene in row C, and the neutron energy groups are defined in the MCNP model as given in Table 2.

Experimental neutron flux results have relative errors of 25 %. MCNP-5 simulation results, with an assumption on the total number of fission neutrons in the core of 8.4×10^{16}n/sec, and experimental results for neutron flux at the irradiation point in the sample box are given in Table 3. A detailed neutron flux spectrum for the MCNP-5 calculation is also shown in Figure 3 for better understanding of pre-defined energy group neutron flux values.

Both measurement and simulation results showed higher thermal neutron flux values than the expected value. Therefore, new materials, dimensions, or designs for SER bucket are in progress.

Future Work

This report briefly summarizes a study focused on fast neutron absorption effects on soft error rates. The fast neutron flux at the core boundary is 5×10^{12} neutrons/cm^{2}sec, and thermal flux is 1.3×10^{13} neutrons/cm^{2}sec at 1 MW steady state reactor power.

TABLE 3: Neutron flux measurement and simulation results

Position	$\phi_{thermal}$	$\phi_{epi\text{-}thermal}$	ϕ_{fast}
A1	7.939E+11	2.114E+11	3.170E+11
A3	6.310E+11	3.485E+11	4.703E+11
B1	9.282E+11	1.100E+11	2.109E+11
B3	5.448E+11	2.122E+11	1.598E+11
C1	**1.061E+12**	**2.226E+10**	**3.506E+11**
C1^{exp}	**7.990E+10**	**7.890E+10**	**2.700E+10**
C3	**6.503E+11**	**5.550E+10**	**2.526E+11**
C3^{exp}	**7.000E+10**	**7.460E+10**	**2.400E+10**
D1	7.450E+11	2.262E+11	7.166E+10
D3	7.543E+11	1.814E+11	1.749E+11
E1	9.912E+11	1.117E+11	1.338E+11
E3	6.412E+11	2.079E+11	1.851E+11

Also, apart from memory chips, other processing circuits will also be put to test in similar fashion and the results observed.

The reactor can be pulsed for a very short duration of time, around 10 ms at FWHM, during which it generates a fast neutron flux of about 1×10^{16} neutrons/cm^{2}sec at the core periphery. This amounts to about a four order of magnitude increase in the fast neutron flux. The time duration is very limited, yet the amount of fast flux is immense. That might also reduce the experiment times significantly and help perform more tests with various technologies and designs.

The thermal neutron flux in the SER bucket will be decreased in order to study the fast neutron absorption on soft errors in the future by investigating the MSNP-5 simulations and experiments on materials and design of the SER bucket.

References

1. J. Sosnowski, “Transient fault tolerance in digital systems,” IEEE Micro **14**, 24-35 (1994).

2. D. P. Siewiorek, R. S. Swartz, *Reliable Computer Systems: Design and Evaluation* (Digital Press, 1992).

3. Los Alamos National Laboratory, “Neutron and Nuclear Science Flight Paths,” http://wnr.lanl.gov/_assets/flight_paths/4FP30L_about.php, accessed 4/6/15.

4. P. Hazucha, T. Karnik, J. Maiz, S. Walstra, B. Bloechel, J. Tschanz, G. Dermer, S. Hareland, P. Armstrong, S. Borkar, “Neutron soft error rate measurements in a 90-nm CMOS process and scaling trends in SRAM from 0.25-/spl mu/m to 90-

nm generation*,"* in *IEDM '03 Technical Digest* (IEEE International 2003), pp. 21.5.1-21.5.4.

5. J. Maiz, S. Hareland, K. Zhang, P. Armstrong, "Characterization of multi-bit soft error events in advanced SRAMs," in *IEDM '03 Technical Digest* (IEEE International 2003), pp. 21.4.1-21.4.4.

6. P. Hazucha and C. Svensson, "Impact of CMOS Technology Scaling on the Atmospheric Neutron Soft Error Rate," IEEE T Nucl Sci **47** 2586-2594 (2000).

7. R. Baumann, "The impact of technology scaling on soft error rate performance and limits to the efficacy of error correction," in *IEDM '02 Technical Digest* (IEEE International 2002), pp. 329-332.

8. X-5 MONTE CARLO TEAM, *MCNP- A General Monte Calro N-Particle Transport Code, Version 5,* Manual, Los Alamos National Laboratory, 2003.