Abstract

Three types of heavy-ion upsets occurred in an advanced FPGA-configuration PROM: (1) address errors, (2) premature end-of-program signals, and (3) functional interrupt. The threshold LETs were near 5 MeV-cm²/mg. Latchup was also measured above a higher threshold LET of 55. These SEEs limit viable space applications for this device.
Single-Event Upset Test Results for the Xilinx XQ1701L PROM

S. M. Guertin, G. M. Swift and D. Nguyen
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Introduction

Programmable logic devices are frequently
used in space applications because of the ease of
reconfiguration which significantly lowers overall
cost. Earlier work has been done to investigate the
effects of radiation on some of these technologies
[1-6], most of which used antifuse technology for
programming. The technology used by Xilinx in
their SRAM-configurable gate-arrays requires an
initial programming sequence on power-up in
order to program the gate array. This paper
presents test results for an advanced, 3.3-V PROM
that is designed to interface with Xilinx FPGAs
(field programmable gate arrays) and provide the
initialization sequence. This device, the
XQ1701L, has a storage capacity of approximately
1-Mb and is fabricated on a bulk substrate. It can
be operated in a low-current standby mode as well
as in a normal mode.

The XQ1701L is a one-time programmable
read only memory with a serial output. It is
compatible with the configuration requirements of
a number of 3.3-V Xilinx XC4000 and 2.5-V
Virtex family SRAM-based FPGAs which are
attractive to spacecraft designers. However, the
configuration memory that is loaded by the PROM
is SEU susceptible [3,4]. The threshold LET was
approximately 5 MeV·cm²/mg for both 5-V and
Xilinx is marketing a number of their FPGAs
with a 7 μm epitaxial layer as high reliability,
radiation tolerant devices in ceramic packages.
The “radiation tolerant” claim is based on (1) no
observed SEL, (2) moderate TID levels, (3)
moderate SEU LET threshold, and (4) the
capability of continuously monitoring the
configuration SRAM for upsets. Since re-loading
the FPGA takes a large fraction of a second,
designs for collecting critical data or controlling
expendables require a significant risk mitigation
effort. These FPGAs do appear suited to a broad
range of other applications, such as sensor and
camera controllers.

The PROM is critical for these applications,
because any errors in the PROM will cause
erroneous configuration of the FPGAs with which
it interfaces. The present work is the first heavy
ion testing reported for these devices. Unlike the
FPGAs, the configuration PROM is not fabricated
on an epitaxial substrate; as shown later, the
PROM is susceptible to single-event latchup
(SEL). The continuous monitoring capability
proposed by Xilinx requires checking the SRAM
contents against a known good copy, presumably
from the PROM. Thus, the various PROM upset
phenomena observed will cause malfunctions of
configuration monitoring, making spacecraft usage
more problematic.

Test Device Properties

Three XQ1701LCC44 (date code 9849)
samples in 44-pin VQFP packages were tested, one
unprogrammed (s/n: 3848) and two programmed
(s/n: 3849 and 3850). Only three pins are used to
exercise the devices with a fourth for the serial
output and a fifth for output control. Additionally,
there are three power pins; the remaining 36 pins
have no connection.

The devices were programmed using a Xilinx
HW130 programmer. Device 3848 was not
recognized by the programmer, necessitating
leaving it unprogrammed. A short section of
S/N 3849 would not program to the intended pattern,
but the test software was modified to ignore the
problem. The low programming success rate (one
in three) may be indicative of device
quality/consistency problems or may be related to
the programmer itself which was not calibrated or
otherwise checked out immediately prior to this
use.

The pattern programmed into the devices was
approximately half "ones" and half "zeros"and
was designed to permit trapping of selected types
of errors. Although this does not correspond to a
typical configuration pattern, it provides visibility
of selected types of errors during dynamic testing.
Additional details will be provided in the full
paper.

Approach Used for Radiation Testing

SEU and latchup tests were done at Brookhaven
National Laboratory. Properties of the ions that
were used are listed in Table 1, below. Because
this device has a bulk substrate, ion range is an
important consideration.
Table 1. Ions Used for SEU Testing

<table>
<thead>
<tr>
<th>Ion</th>
<th>Energy (MeV)</th>
<th>LET (MeV-cm²/mg)</th>
<th>Range (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>150</td>
<td>3.2</td>
<td>&gt;100</td>
</tr>
<tr>
<td>Cl</td>
<td>210</td>
<td>11.5</td>
<td>81</td>
</tr>
<tr>
<td>Ni</td>
<td>260</td>
<td>27</td>
<td>40</td>
</tr>
<tr>
<td>Br</td>
<td>290</td>
<td>37</td>
<td>36</td>
</tr>
<tr>
<td>I</td>
<td>350</td>
<td>60</td>
<td>31</td>
</tr>
</tbody>
</table>

Dynamic testing was done on these devices during the time that they were exposed to heavy ions. A PCI interface card was used, connected to the device under test with a TTL-differential receiver that could drive fast signals over ribbon cable. Special software was used, containing a dynamic link library to handle I/O routines. The I/O routines were written in Visual C++ and the user interface routines were written in Visual Basic.

Two different algorithms were used to determine whether the PROM functioned properly. The first algorithm began by resetting the part, and then applying a sequence of clock signals. With this algorithm, no attempt was made to compare the output of the memory. Error detection was based on detection of the end-of-address space output (CEO pin), ensuring that it only provided an output at the end of the proper number of clock cycles. If the CEO output occurred prematurely, that indicated that an error had occurred in the address control logic. The advantage of the first algorithm was ease of execution. It was primarily used in initial evaluations of the device to determine what types of errors and malfunctions occurred.

The second algorithm was more complete, and executed a bit-by-bit comparison of the actual output of the PROM with the contents expected from the initial programming. The bit read position could be dynamically adjusted. The more complex algorithm could detect address failures and individual bit errors.

Functional Test Results

Changes in the internal stored data were not observed in this PROM device. However, errors were observed in the bit stream as well as overall functionality errors. The functionality errors interfered with the quantification of bit-stream upsets.

The first type of functional error occurred in the end-of-pass output signal (EOP) which indicates the end of a read cycle. That signal is of critical importance in applications of the XQ1701 device, and could be detected by both of the test algorithms. The false EOP condition causes the output of the device to "freeze" and any errors that produce an erroneous EOP result will be difficult to recover from in most applications. During SEU tests, a number of EOP errors occurred. Figure 1 shows how the cross section for EOP errors depends on LET. The threshold LET is approximately 10 MeV-cm²/mg. The cross section gradually increases by about two orders of magnitude with increasing LET. EOP errors persist until the part undergoes reset or power cycling.

Address failures were also observed during the SEU tests. The address failures were observed by comparing the actual location of data within the device with the expected location based on the number of data strobe cycles. Figure 2 shows how the cross section for address errors depends on LET. The threshold LET was approximately 5 MeV-cm²/mg. Recovery from address failures required reset or power cycling.

Figure 1. Cross section for end-of-pass errors in the Xilinx XQ1701L PROM.

Figure 2. Cross section for address errors in the Xilinx XQ1701L PROM.
Several events were also observed where part functionality was lost, and the operating current decreased to very low values, implying that the device had been triggered into the standby operating mode. However, the only way to recover from this mode was to initiate power cycling, which is not required to recover from a normal standby operating mode. As shown in Figure 3, the cross section for these functional interrupt (SEFI) errors was similar to that of the other two types of functional errors.

Latchup Test Results

Latchup test results are shown in Figure 4. The cross section is plotted as a function of effective LET, assuming that the “cosine law” applies. There is reasonable agreement between data points for ions at normal incidence with others at nearly the same LET at angle (note the similarity in cross section for LET = 84.6, iodine at 0°; and LET = 74.7, bromine at 60°), implying that the cosine law assumption is valid for this device. The effective ranges of the two ions are 18 and 30 μm, respectively without considering the thickness of passivation or metal layers.

The threshold LET for latchup is approximately 55 MeV·cm²/mg, as determined from the null results at LET = 52.8 and the general shape of the LET cross section. Latchup results for the unprogrammed device (x3848) under static bias were consistent with dynamic results obtained for the other two samples.

Table 2 summarizes the three types of functional errors that occurred, along with the required sequence to recover from the erroneous condition. The devices always recovered completely provided the proper recovery method was used. None of the errors affected the internal programmed state of the PROM.

Table 2. Functional Errors Observed During SEU Tests of the XQ1701L PROM

<table>
<thead>
<tr>
<th>Error Type</th>
<th>Circuit Effect</th>
<th>Recovery Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>EOP</td>
<td>False EOP signal; output lockout</td>
<td>Reset or power cycle</td>
</tr>
<tr>
<td>Address</td>
<td>Address error</td>
<td>Reset or power cycle</td>
</tr>
<tr>
<td>SEFI</td>
<td>Stuck output condition; low operating current</td>
<td>Power cycle only</td>
</tr>
</tbody>
</table>

During latchup testing, the higher than normal operating current was detected and measured within about 100 ms. After 500 ms, power was temporarily removed. Latchup equilibrium voltages -- that is, the voltage reached by the device during latchup with the current limited to 20 mA -- were measured for each latchup event. A histogram of these voltages is shown in Figure 5. The voltage distribution for the majority of latchups ranged from 2 to 3 V, but two latchup events were observed with significantly higher voltages. These results will be discussed in more detail in the complete paper.
Figure 5. Histogram of equilibrium voltages that occurred just after latchup in the XQ1701L PROM.

Discussion

Four different failure modes were observed during SEU tests of the XQ1701L PROM device. These included three functional operational modes: (1) end-of-program errors; (2) address failures; and (3) stuck-bit failures. The first two types of errors could be recovered from by applying a reset signal to the device, but the third type of error could only be recovered from by cycling the power.

All three types of functional errors had similar threshold LET values and cross sections. The estimated error rate from these types of upsets is about 1% per year from galactic rays in space, with a comparable rate per day for an intense solar flare. However, those error rates do not consider the possibility of upset from protons. Proton testing was not done, but other devices on bulk substrates have been sensitive to proton upset when the LET threshold was below approximately 7 MeV-cm²/mg.

The PROM was also susceptible to latchup, but only at relatively high LET (55 MeV-cm²/mg). Because of the high threshold LET, the probability of latchup is relatively low in these devices, and the risk is probably acceptable for many applications.

One way to mitigate SEU effects in these devices is to control the time period during which they operate. Since they are only used to initialize FPGA devices during start-up periods, it is relatively straightforward to minimize the time which they actually operate. An alternative approach is to cycle the power in the PROM just before configuring or reconfiguring the FPGA devices that are driven by the PROM to avoid the functionality errors that can be induced by SEU effects. However, this is less desirable because latchup, if it occurs, would continue for extensive periods until the next power cycle occurs. Either approach precludes reliable, continuous comparison of the FPGA configuration with the PROM.

SEE effects in the XQ1701L do not preclude its use in space, but system users must assure that the functional errors caused by heavy ions do not cause catastrophic system effects. Although proton testing was not done, the low threshold LET makes it likely that protons will cause all three upset phenomena in the PROM to occur. This will increase the estimated error rates, particularly in earth-orbiting systems that have to pass through the earth’s proton belts. Alternatively users may wish to wait for Xilinx to release the 7µm epi replacement PROM currently under development and expected to have better latchup performance [7].

References

7. Howard Bogrow, Xilinx Engineer, personal communication.