Needs: EDAC montecarlo, poisson montecarlo, scrub of flow
And simplification of material.

Testing for Rare SEEs in FT Devices

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Outline

- Background on RHBD/FT Test Challenges
- Information about UT699
- Test results for a rare event type
- Discuss test and analysis methods for event
- Apply methods to show event is a true SEE
- Conclusions
Goals

• Discuss Microprocessor/SOC testing, focusing on effects in RHBD/FT devices.

• Present a case study of a rare SEE in the Aeroflex UT699 (on the order of 1/100,000 years in GEO).

• Discuss test and analysis methods to identify true SEE rather than overwhelming of FT

• Apply test and analysis methods to verify the rare SEE is a true SEE
Background – What is a Rare SEE?

• ASTM 1192 and JEDEC 89 both indicate that when ruling out an event type, $1e7/cm^2$ is a good fluence goal for testing.

• A rare event is one where only a couple occur with this fluence... but it leads the actual space error rate in some environments.

• In RHBD/FT systems these may be hard to test due to difficulties involved in increasing flux.
SEE Testing of SOC/Processors

• Somewhat normal test procedure or flow
  – Measure the cross section for static elements
    • SRAM/Latches/FFs
    • External monitoring (i.e. JTAG) or self-interrogation
    • Minimize impact of dynamic elements and operations
  – Check SOC subsystems for sensitivity of these elements during operation
    • Operate key elements (processor, communication, memory interfaces)
    • Self-interrogation required
    • Establish event cross sections for running code in these subsystems
  – Gather minimal information for key analysis issues
    • Test with altered flux (try for 33+ times over or under – prefer low)
    • Test with altered fluence
    • Test with altered clock

• Analyze data to identify potential anomalies
Anomalies, Test Artifacts, SETs

• Analyze dynamic tests to establish estimated static elements involved
  – I.e. Processor: #total bits in: registers, caches, look up/history tables, and pipeline latches.
  – Then apply an application dependent factor for duty cycle.

• If analysis shows static elements are not the most significant source
  – (Looking for ~10x increase in rates when changing operating conditions – alternate mode, clock rate, flux etc.)
  – Try to identify the following causes:
    • Errors in the test system
    • Flux dependence
    • Fluence dependence
    • SETs – IO interfaces and/or
  – If any were missed during testing, errors were found, or no solution is found, improve test sensitivity and repeat test.
  – If you still don’t have a good answer for cause, write a paper.
Impact of RHBD on SEE Testing

• RHBD in digital devices can reduce SEE sensitivity
  – DICE Latch
  – 6-T SRAM Cells
  – SET reduction through filtering

• This impacts test planning
  – Many of the elements we know how to test will no longer upset
  – Multiple SEE sensitivities may turn on at various LETs
  – SEE’s leading space event rates may require new test methods
Impact of FT on SEE Testing

• Fault tolerance is used a lot in modern SOC/Microprocessors
  – EDAC and/or parity in on-board caches
  – EDAC on off-chip memories
  – CRC or other checks on communications packets
• Often used on elements with no RHBD
• While testing, event rates in underlying structures may be relatively high
• This impacts test planning
  – Fluence between “scrubbing” must be controlled
  – Intrinsic “scrubbing” in many devices is the L1 cache usage, or the duration of a packet transmission, indirectly affecting flux.
  – Test software must support operation of FT and verify it
Aeroflex UT699 – Leon 3FT

- Built with fault tolerance
  - Caches and external memory bus
- And RHBD elements
  - FFs with threshold LET of 54 MeV-cm²/mg
  - SRAM cells with threshold of about 10 MeV-cm²/mg

- SEE Data Reported
  - Upsets in FT protected cells reported in 2009 NSREC Data Workshop (Hafer et al.)

- Chosen for further study
  - Initial testing included some anomalous events
  - Test software not adequate to find out if FT systems overloaded.
The Register File EDAC

- FT in the UT699 registers is accomplished with 32/7 EDAC

| CB0   | D0 ^ D4 ^ D6 ^ D7 ^ D8 ^ D9 ^ D11 ^ D14 ^ D17 ^ D18 ^ D19 ^ D21 ^ D26 ^ D28 ^ D29 ^ D31 |
| CB1   | D0 ^ D1 ^ D2 ^ D4 ^ D6 ^ D8 ^ D10 ^ D12 ^ D16 ^ D17 ^ D18 ^ D20 ^ D22 ^ D24 ^ D26 ^ D28 |
| CB2#  | D0 ^ D3 ^ D4 ^ D7 ^ D9 ^ D10 ^ D13 ^ D15 ^ D16 ^ D19 ^ D20 ^ D23 ^ D25 ^ D26 ^ D29 ^ D31 |
| CB3#  | D0 ^ D1 ^ D5 ^ D6 ^ D7 ^ D11 ^ D12 ^ D13 ^ D16 ^ D17 ^ D21 ^ D22 ^ D23 ^ D27 ^ D28 ^ D29 |
| CB4   | D2 ^ D3 ^ D4 ^ D5 ^ D6 ^ D7 ^ D14 ^ D15 ^ D18 ^ D19 ^ D20 ^ D21 ^ D22 ^ D23 ^ D30 ^ D31 |
| CB5   | D8 ^ D9 ^ D10 ^ D11 ^ D12 ^ D13 ^ D14 ^ D15 ^ D24 ^ D25 ^ D26 ^ D27 ^ D28 ^ D29 ^ D30 ^ D31 |
| CB6   | D0 ^ D1 ^ D2 ^ D3 ^ D4 ^ D5 ^ D6 ^ D7 ^ D24 ^ D25 ^ D26 ^ D27 ^ D28 ^ D29 ^ D30 ^ D31 |

- Four key test patterns
  - All have same check bits
  - 0x0000_0000 and 0xffff_ffff set by code – others seen after SEE

<table>
<thead>
<tr>
<th>Value</th>
<th>Check Bits</th>
</tr>
</thead>
<tbody>
<tr>
<td>0x0000_0000</td>
<td>0b000_1100</td>
</tr>
<tr>
<td>0xffff_ffff</td>
<td>0b000_1100</td>
</tr>
<tr>
<td>0x0000_ffff</td>
<td>0b000_1100</td>
</tr>
<tr>
<td>0xffff_0000</td>
<td>0b000_1100</td>
</tr>
</tbody>
</table>

- The UT699 is also protected with parity bits on the cache lines (1 parity for 8 bits). Errors are silently corrected by re-fetch since the caches are write-through only.
Radiation Testing of UT699

- Testing Performed at TAMU Cyclotron

- Tested with Ar and Kr, $\text{LET}_{\text{eff}} = 8.7 \text{ to } 60 \text{ MeV-cm}^2/\text{mg}$

- Tested at $V_{\text{core}} = 2.3\text{V}, V_{\text{IO}} = 3.0$, and $\text{Clk} = 75 \text{ MHz}$
UT699 SEEs in SRAM and FFs

- Previous testing showed upset sensitivity in static elements... - verified during testing for this work:

Original plot is from 2009 IEEE Radiation Effects Data Workshop, by Hafer et. al.

Additional points are from this testing.

- Previous conclusions about impact of scrubbing apply to the upsets reported in this figure.
Register Testing Anomalies

- In-situ test code was improved to the point where events were identified by the code.
- A non-FT type event was seen at low LET with low cross section (important because at high LET the low cross section would hide it behind FT events).
- The event type was manifest as a “partial” 0’ing of a register.
  - Manifested as 0’ing of a 16-bit field in a register
  - Results in 16-bit “SEU”
  - Or an EDAC uncorrectable
  - (9 extra bits of check unused)

- \(2^{32}\) “good” values, \(39*2^{32}\) SBE values, means that 40/128 of the \(2^{32}\) data patterns – or 31.5% chance resulting error will cause no system detectable event...

<table>
<thead>
<tr>
<th>Check Bit Patterns for Test Data Patterns</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
</tr>
<tr>
<td>----------------</td>
</tr>
<tr>
<td>0x0000_0000</td>
</tr>
<tr>
<td>0xffff_ffff</td>
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<tr>
<td>0x0000_ffff</td>
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</tr>
</tbody>
</table>
Register Test Anomalies

- Very low cross section, but just high enough to put a thorn in the analysis...

But what if there is flux dependence? (Test code may depend on FT elements.)

How does the 1/33 flux point impact our understanding?

Should more data have been taken, or is it sufficient to draw conclusions?
Flux Effects – Analysis

• What if partial register 0’ing is coming from a flux dependency?

• High flux cannot prove true SEE if device has flux dependence.
  – Unless test methods are fully able to keep the system healthy during elevated flux, results will be inconclusive
  – Statistics of rare events are such that if there is no flux dependence, the results may still be inconclusive.
Statistical Analysis of Flux Dependence
(assuming no other dependencies)

• Given observation of \( N_1 \) & \( N_2 \)
  – \( \phi_i \) are fluxes, \( T_i \) are test periods and \( \tau \) is dead time per event
    \[
    \sigma_i = \frac{N_i}{\phi_i(T_i - N_i\tau)}
    \]
  – Assume \( N_i\tau \ll T_i \) (i.e. dead time is small and effect is not saturated)

• Examination of \( \sigma_1 \) & \( \sigma_2 \)
  – \( \sigma_1 = \sigma_2 \) if there is no flux dependence
  – \( \sigma_1 / \sigma_2 \propto \phi_1 / \phi_2 \) if flux dependent (to first order)
    • (True if dependence is due to two random SEUs in one EDAC word.)

• Two statements (for a given \( \phi_1 / \phi_2 = r > 1 \)):
  – If \( N_1 \) is very similar to \( N_2 \), how small must \( N_2 \) be for a given \( N_1 \) and \( r \) to be inconsistent when claiming no flux dependence?
  – If \( N_1 \) is bigger than \( N_2 \), how much bigger must it be to show flux dependence?
Events Required for Statistics, $\frac{\phi_2}{\phi_1} = r > 1$

Maximum $N_2$ below which flux dependence must be considered, for $r = 30$ and $N_1$ given below.

<table>
<thead>
<tr>
<th>$N_1$ (r=30)</th>
<th>$N_2$ (90%)</th>
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</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>2</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>15</td>
<td>6</td>
<td>2</td>
<td>n/a</td>
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<tr>
<td>20</td>
<td>10</td>
<td>7</td>
<td>1</td>
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<tr>
<td>25</td>
<td>14</td>
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<td>70</td>
<td>55</td>
<td>51</td>
<td>45</td>
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<tr>
<td>$N &gt; 70$</td>
<td>$N - 1.81\sqrt{N}$</td>
<td>$N - 2.16\sqrt{N}$</td>
<td>$N - 2.88\sqrt{N}$</td>
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Minimum $N_2$ above which (proportional) flux dependence must excluded, for $r = 30$ and $N_1$ given below.

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- Assumes same fluence - 30x longer test time at low flux...
- Results derived using Monte Carlo simulations
- Values are conservative for $r > 30$ on left, and $r < 30$ on right.
- 3 confidence levels given, using 2-sided tails, so 5%, 2.5%, and 0.5% tails were used
- Confidence levels indicate likelihood of error when adopting table statements.
Events Required when Fluence Reduced

Maximum $N_2$ below which flux dependence must be considered, for $r=30$ and $N_1$ given below.

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<tr>
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- Picked fluence difference of 10x for realistic test scenarios.
- Results derived using Monte Carlo simulations.
- Values are conservative for $r>30$ on left, and $r<30$ on right.
- 3 confidence levels given, using 2-sided tails, so 5%, 2.5%, and 0.5% tails were used.
- Confidence levels indicate likelihood of error when adopting table statements.
Application of Statistics on Register Clobber

- Measured at 1 LET (13.2 MeV-cm²/mg)
  - At fluence = 1.5x10⁷/cm²
    - 2 events at flux = 3.3x10³/cm²
  - At fluence = 1.5x10⁸/cm²
    - 12 events at flux = 1x10⁵/cm²

- For these numbers of events we cannot reject the possibility that there is no flux dependence. (Low flux appears to give higher cross section.)

- We can reject linear flux dependence if N₂ (2 in this case) is above 1 with 95% confidence... so we reject the linear flux dependence option.
Conclusions

• RHBD and FT devices require special test considerations
  – Devices may require in-situ operation
  – Many event types will have low cross section
  – FT structures get overwhelmed during testing
  – SET sensitivities may lead fundamental upset modes

• UT699 was found to have a low rate SEE
  – Event type was partial reset of registers
  – Difficult to find because of FT and complexity of test software
  – Likely to lead event rate (<1/100,000 years) in low GCR orbits

• Statistical analysis necessary to determine if events are true SEE or overwhelming of FT
  – Evidence of flux dependence does not prove all events are due to overwhelming FT
  – Partial O’ing of registers showed to be inconsistent with overwhelming FT
Backup: Why do MC simulation?

- We are attempting to compare two measurements, one or both of which may involve a small number of counts.
- Estimators for the mean of a Poisson distribution from a small number of observed events N are not handy functions:
  - I.e. let P be probability of accepting an incorrect value, P = 1-C.I.
    - i.e. for 95% CI, P = 0.05, then:
    - CI = (qChi-Sq(P/2,2*N)/2,qChi-Sq(P/2,2*(N+1))/2)
    - qChi-Sq is the inverse Chi-Sq cumulative distribution function (requires calculation of inverse regularized gamma function)
- Going to the impact of comparing 2 measurements and applying the full formalism is less valuable than explaining the MC techniques.

See also:
http://www.math.mcmaster.ca/peter/s743/poissonalpha.html
http://statpages.org/confint.html
Backup: Flux Effects – Testing

• Flux can impact testing, especially when testing fault-tolerant devices or test systems (FT test system refers to scrub intervals or similar software loop periods).
Backup: Fluence Effects

• Fluence build up can affect testing if hidden control bits can upset, or tests are dependent on “soaking”.

• Hidden control bit sensitivity is possible, but somewhat contrived.

• But tests are often based on soaking, even when not intended – for example, self-test code often assumes