Universität Bielefeld
Technische Fakultät

RVS
Rechnernetze und Verteilte Systeme

Technische Informatik I

Vorlesung 11: Single Event Effects

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Single Event Effects (SEE)

- Single Event Upset
  - A bit gets flipped
    - $0 \rightarrow 1$ or $1 \rightarrow 0$ or ....
- Single Event Latchup
  - A bit gets permanently set
- Single Event Burnout
  - A spark burns a track through the memory element
  - "Spark" means an occurrence of the **Avalanche effect:** electrons have sufficient energy that they cause release of other electrons when they interact with nearby atoms

SEE

- Do SEEs exist?
  - Yes. SEU first observed in 1978 with the fabrication of the first SRAMs. These contained traces of U238 (uranium isotope) and Th 230 (thorium isotope) in the silicon substrate. Both these isotopes decay to form α**-particles** (a particle consisting of two **protons** and two **neutrons** - the nucleus of helium) with an energy/mass of 5-10 MeV.
  - The track of an α-particle generates about **3 million** electron/hole pairs

SEEs

- Apparently, in 1978, miniaturised transistors became sensitive to the effects of 3 million electron/hole pairs
- In 1979, memory based on charge-coupled devices (CCDs) used "typical" charges of 50,000 electrons per bit
- This was about a factor of ten lower than the minimum charge in a transistor circuit (thus 500,000 electrons per bit)
- One can see these are comparable

Other SEEs

- What about SEL and SEB?
  - **SEL found when a high-energy particle (say, in a cosmic ray) activates a parasitic transistor** in, say, a CMOS gate. This can turn a circuit fully on, until the device burns up (SEB) or the power is recycled
  - SEB first reported in 1994 by European and Japanese manufacturers of **high-voltage semiconductors** (in particular, **power MOSFET**s) used in, for example, rail locomotive engines. SEB can be the result of SEL for high-voltage devices, since a short circuit is likely to cause a burnout. High-voltage devices are typically rated at 4500V and typically operate at 55-60% of rated voltage

Where to expect SEEs

- Small dense devices sensitive to current spikes of the order of 3 million electron/hole pairs (SRAMs, DRAMs)
- Electronics in high-energy particle streams
  - Near-earth space contains significant flux of protons from the sun
  - These and other primary "cosmic rays" interact with the atmosphere to produce secondary cosmic rays, which contain about equal amounts of protons and neutrons, also other particles such as electrons, pions, kaons, muons.
- In high-intensity e**lectromagnetic** fields

Spacecraft SEEs

- It's a big and known problem in the design of spacecraft electronics
- Mainly thought to be due to protons, which stream earthwards from the sun
  - Proton-induced latchup: Adams et al., A Verified Proton Induced Latchup in Space, IEEE Trans. Nucl. Sci. 39 (1992) p1804. Nichols et al., An Observation of Proton-Induced Latchup, IEEE TNS 39 (1991) p1654.
  - A. C. Tribble, The Space Environment: Implications for Spacecraft Design, Princeton U.P., 1995

Where do Cosmic Rays Come From?

- The sun produces streams of particles
- Neutrons are massive (2,000 times the mass of an electron), with no charge
- But the mean life of a neutron is only 14.8 minutes
  - It decays into a proton (positively charged, similar mass to that of a neutron) and an electron
- The sun is 9 minutes away, so there aren't many neutrons left when they get here
- The mean life of an electron is essentially infinity

Where Do Cosmic Rays Come From?

- There are also electron showers, the result of cosmic ray bursts from astronomical events
- There are interactions between these "primary" cosmic rays and the atmosphere
  - The interactions produce neutrons, more protons, pions, electrons, positrons, muons and other stuff
  - These are the "secondary" cosmic rays
  - They are most intense at 55,000ft or so

Secondary Cosmic Rays

- They are mostly protons and neutrons
  - About 2,000 per sq. m per steradian per second at 50,000ft/15km
  - Half that at 33,000ft/10km (1,000 per ...)
  - One-tenth of that at 16,000ft/5km (100 per...)
- Electrons and positrons
  - 400 per ...at 15km, falls off similarly
- Pions
  - 10 per.. at 15km, falls off similarly

Secondary Cosmic Rays

- Muons
  - 200 per ... at 15km, stays constant to 5km and falls off to 100 per ... at ground level
- And other things

Secondary Cosmic Rays: Summary

- Most intense at about 55,000-65,000ft
- Vertical flux varies roughly log-linearly to ground (protons, neutrons, electrons, positrons, pions) or is constant (muons, some others)
- But the rays are in principle isotropic (come not just from the vertical direction)
- European Physical Journal C, 15(1-4), 2000: Review of Particle Physics, Part 20: Cosmic Rays

Atmospheric SEEs in computer memory

- Often claimed to be mainly due to neutrons (see especially papers by E. Normand, Boeing Radiation Effects Lab)
- Data not convincing (to me):
  - Significant gaps; very indirect inference
  - Anomalies in results of direct attempts to verify
- Data and explanations not convincing (to particle physicist colleagues)

Atmospheric SEEs

- Neutrons do not interact electrically with other particles. It has no charge; its magnetic moment is about 2,000 times less than that of an electron. It interacts mainly through elastic collisions, mainly with atoms with nuclei of similar size (hydrogen nuclei, so water!)
  - Its mean free path through water is just over 80 cm
- Charged particles are thought to be easily stopped by small amounts of material, say, the skin of an aircraft
  - Mean free path of protons in aluminium is of the order of millimeters or less

Atmospheric SEEs

- But that seems to be the extent of the reasoning
  - CREAM claims to see effects due to charged particles -electrons, protons, alphas - in its detectors
  - CREAM has about 14 gm per sq. cm shielding from overlying material
  - Atmospheric shielding is 72 gm per sq. cm at 60,000ft and 120 gm per sq. cm at 50,000ft

Atmospheric SEEs

- CREAM data from Concorde flights
  - Lower-energy channels: many incidents detected, supposed due to secondary protons, α-particles, neutrons and possibly electrons
    - Chennels 1 and 2: "most likely" contribution from slow protons of energy less than 60 MeV at flux of 0.4 per sq.cm per second
    - Estimate that a relativistic electron flux of 4 per sq. cm per second "could contribute around 20% via oblique incidence events"
    - Channels 3-5 "could be due to neutron reactions" and show a flux of around 10 per sq. cm per second
    - Also incorporated 60C31 microprocesor and HM6167 memory and saw nothing in 51 hours of flying above 50,000ft

Measuring Atmostpheric SEEs

- Measured by flying 64KB SRAMs on commercial and military aircraft
- IBM/DoD tests on an AWACS/E-3 at 29,000ft and NASA ER-2 at 65,000ft
  - ER-2 recorded rates between $4.6 \times 10^{(-9)}$ bits per flight hour and $2.3 \times 10^{(-8)}$ bits per flight hour
  - **E3 recorded a rate of $1.6 \times 10^{(-9)}$** bits per flight hour
  - **Two similar flights in Europe recorded similar rates**

Measuring Atmospheric SEEs

- "Commercial jet" on transatlantic flight reported 1 x $10^{(-9)}$ bits per flight hour (MIL-HDBK-781)
- **"Fleet of commercial jets" reported 3.3-4.1 x $10^{(-10)}$** bits per flight hour (conference paper and word of mouth)
- **30 Concorde flights (Nov 1988-Feb 1989) of the CREAM detector. Flights at 60,000ft, between 12°N and 52°N, yielded 51 hours of flight above 50,000ft**

Measuring Atmospheric SEEs

- Absolute numbers
  - IBM experiments on E-3 and ER-2 yielded about 75 upsets in 300 flight hours. SRAMs were loaded, flown, and read out at end of each flight phase
  - A CC-2E flight computer aboard military aircraft yielded 136 upsets in 783 flight hours
- Comments
  - The E-3 and ER-2 data were not constant altitude data, they were mostly-constant-altitude data (the SRAMs were also exposed during climb and descent)

Measuring Atmospheric SEEs

- CREAM counted at rates of about
  - Channel 1: 570 events per five minutes
  - Channel 2: 58 events per five minutes
  - Channel 3: 17 events per five minutes
  - Channel 4: 1 event per minute
  - Channel 5: 1 event per five minutes
  - Channel 6: 3 events per 50 minutes
  - Channel 7: 1 event every 40 hours
  - Other channels did not see any event
- Channels range from low energy to high

Measuring Atmospheric SEEs

- What do you measure SEEs with?
  - SRAMs and other electronic devices, obviously
- What do you measure cosmic rays with in general?
  - Different detectors for different particle types
    - extremely light, uncharged particles - neutrinos
    - Light, charged particles - electrons, positrons
    - Moderately massive particles - kaons, muons
    - Heavy charged particles - protons, α-particles
    - Heavy uncharged particles - neutrons

Measuring Atmospheric SEEs

- What's the best for protons, α-particles, neutrons?
- Silicon!
  - Neutrons collide with silicon nuclei and knock off α-particles
  - α-particles are easily detected by semiconductor electronics of a certain size - this is exactly our problem!
- For example, CREAM is an array of "ten pin diodes operated at 172 μm depletion under 15 V reverse bias and connected in parallel to afford 10 cm^2 of sensitive area"

Atmospheric Cosmic Rays

- Intensity varies with latitude
  - Strength and direction of the geomagnetic field, and pure cosmic ray penetration capability
  - Orientation to the sun's radiation
  - Thickness and density of the atmosphere (affects the expected number of interactions generated the secondary particles)
- London-Barbados CREAM flights collected significantly different data from London-USA flights

Is This a Problem?

- Suppose your chip has 1MB of on-board memory
- Each bit suffers SEE at a rate of $O(10^{(-9)})$ per flight hour at altitude
- Assume these upsets are not corrected
- An individual 64-bit word suffers failures at a rate of $O(10^{(-7})$) per flight hour at altitude
- What's the failure rate of the memory?

The Problem

- The acceptable failure rate for flight-critical components is $10^{(-9)}$ per flight hour
- The memory fails due to SEEs at a rate much higher than this
- So there is need for error detection and correction
- A one-bit correction/two-bit detection will cost 12.5% more bits (along with their associated failures!) and rather more in the way of embedded algorithms in the electronics
- Error detection and correction is big!