SEE induced by neutrons in electronic components: an introduction

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Outline

SEEs are caused by unwanted charge injection

Ionising radiation generates electron hole pairs in semiconductor materials.

Charged particles (especially heavy ions) are highly ionising and can cause SEE by generating charge in or near sensitive circuit nodes.

Neutrons generate electron-hole pairs *indirectly*, through nuclear interactions.

- High energy neutrons (MeV–GeV) can interact with nuclei of silicon or other materials emitting energetic ionising reaction products.
- Low energy neutrons (meV) react exothermically with ^{10}B dopants in semiconductor material or in overlayers.

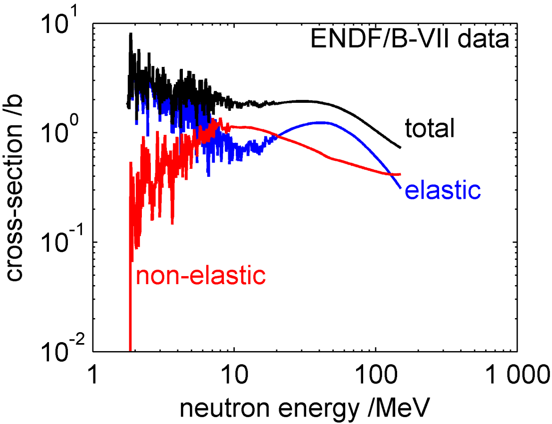
On average 3.6 eV is required to generate one electron-hole pair in silicon.

1 MeV of ionising energy liberates 44 fC of charge *inside the device structure*.

Circuit nodes in many modern devices care sensitive to charge disturbances in the fC range.

Fast neutron interaction cross-sections

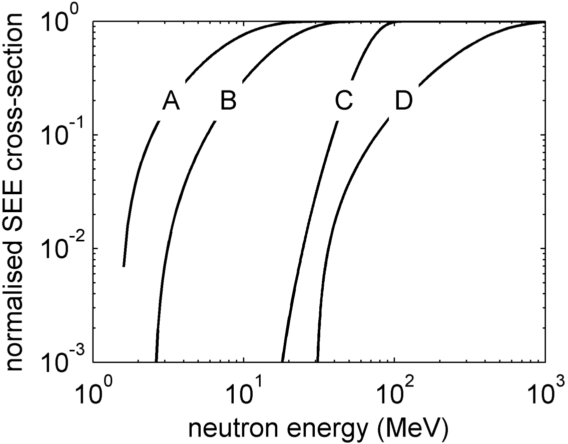
example for ^{28}Si



[ENDF/B-VII]

Example neutron SEU cross-section curves

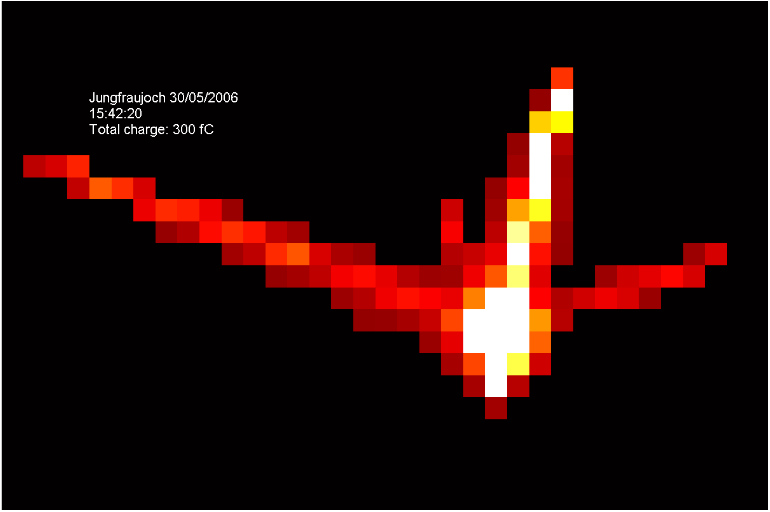
Weibull fit approximation to measured data



[Dyer et al. (2004), Yahagi et al. (2004), Hands et al. (2009), Platt et al. (2010)]

Example cosmic ray neutron interaction with silicon

observed in a CC at high altitude



Silicon is not the only target

Interactions with overlayer materials are a source of SEE

- Dielectric materials. Oxygen and similar materials interact with neutrons in a similar way to silicon, generating ionising particles close to semiconductor regions. [Lambert et al. (2005)]
- Metallisation. High-energy neutron interactions with heavy metals (e.g. W plugs for conductor interconnections) can result in extremely highly-ionising reaction products entering sensitive regions. [Schwank et al. (2005), Lesea et al. (2005)]
- Dopants. Boron dopants in dielectric overlayers (BPSG – borophosphosilicate glass) are a significant source of SEE from *low-energy* neutrons [Fleischer (1983), Baumann et al. (1995), Normand et al. (2006)].

SEEs can also occur in other semiconductor technologies (III-V/SiGe).

SEE-inducing thermal neutron interactions with boron

Boron is widely used in semiconductor device manufacture

- in small quantities as an electron acceptor (p-type dopant)
- in much larger quantities as a dopant in dielectric layers (BPSG)

^{10}B (c. 20% abundance in natural boron) has an exothermic reaction with neutrons, with a high cross-section especially at low energies. [Fleischer (1983), ENDF/B-VII]

$$^{10}\mathrm{B}(\mathrm{n},\alpha)^{7}\mathrm{Li}$$

$$Q = 2.8\,\mathrm{MeV}$$

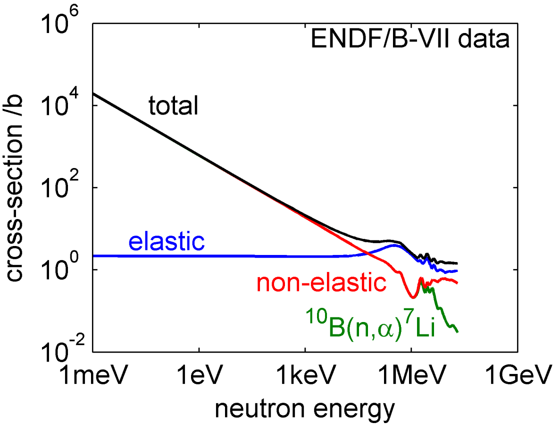
	94%	6%
α	1.47 MeV	1.79 MeV
^{7}Li	0.84 MeV	1.01 MeV
γ	0.48 MeV	

Thermal and epithermal neutrons can be a major cause of SEE in commercial electronic devices.

[Baumann et al. (1995), Baumann (2005), Normand et al. (2006)]

Neutron interaction cross-sections

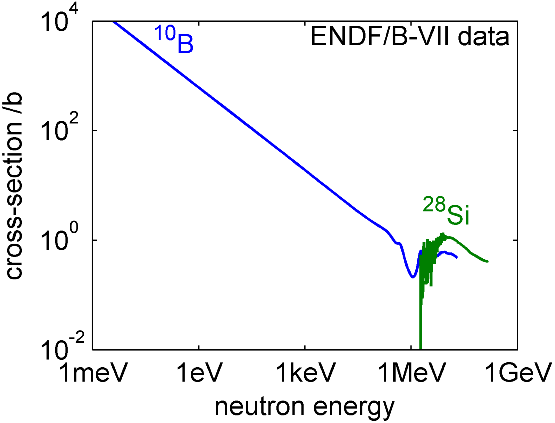
in ^{10}B



[ENDF/B-VII]

Non-elastic neutron interaction cross-sections

in ^{10}B and ^{28}Si



[ENDF/B-VII]

The neutron SEE threat is “double sided”

High-energy

Neutrons in the MeV range (and higher) react with Si, O, W etc., producing energetic ions with mass numbers from 1 to that of the parent ion (i.e. elastic scattering).

Low-energy

Neutrons in the meV range react exothermically with any ^{10}B present liberating ionising α particles and ^{7}Li ions.

[Normand et al. (2006)]

Neutron environments

Cosmic rays

Other SEE sources

Cosmic rays

Primary cosmic ray flux

- Energetic charged particles
- Predominately hydrogen, fewer helium, occasional heavier ions
- Galactic / solar origin

Secondary cosmic rays

- Derive from interaction between primary particles and atmospheric ions
    - neutrons
    - protons
    - heavy ions
    - pions
    - muons
    - gamma

Neutrons are the most significant for terrestrial SEE

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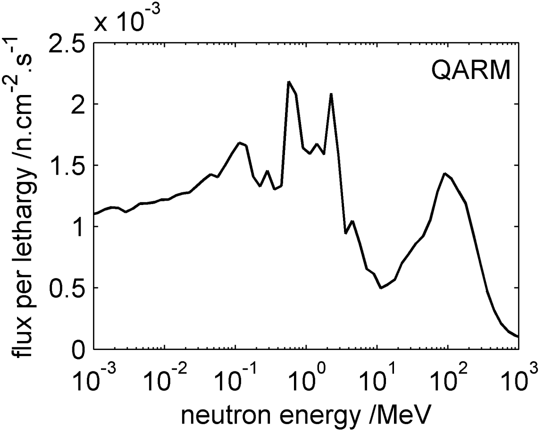
Neutrons are the most significant for terrestrial SEE

Cosmic-ray neutron flux at Legnaro

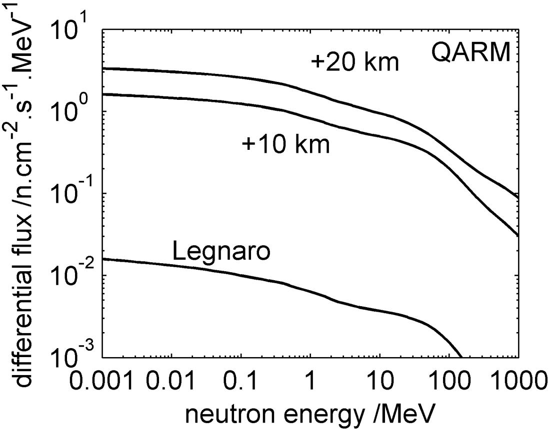
calculated using the QinetiQ Atmospheric Radiation Model



[QARM]

Altitude variation of cosmic-ray neutron flux

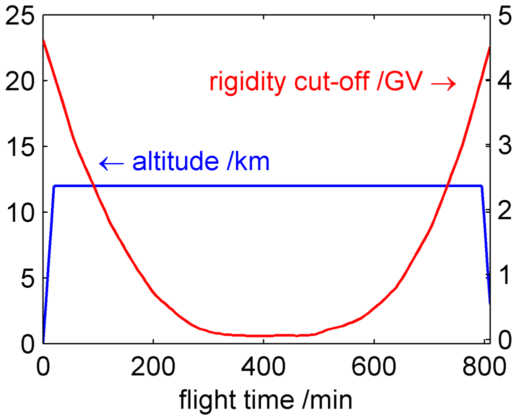
calculated using the QinetiQ Atmospheric Radiation Model



[QARM]

Example SEU calculation

Device B, VCE–LAX great circle

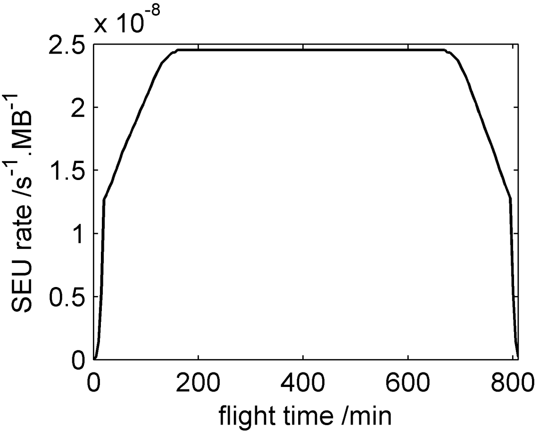


Magnetic field protection decreases close to the poles.

[QARM]

Example SEU calculation

Device B, VCE–LAX great circle



Neutron flux increases as rigidity cut-off decreases (at high latitudes).
Expect c. 1 event per gigabit per transatlantic flight.

[QARM]

Measurements and analytical models of the atmospheric neutron environment

Measurements of the neutron spectrum at New York City and associated analytic fits [Gordon et al. (2004), Gordon et al. (2005)] were adopted by JEDEC as a reference neutron spectrum for use in evaluation of terrestrial SEE [JESD89A (2006)].

Scaling factors are provided to adjust for altitude and rigidity cut-off.

Online tools are provided to assist calculations [seutest.com]

Neutron environments

Cosmic rays

Other SEE sources

Other neutron fields causing SEE

Other sources of SEE-inducing neutrons

- Particle accelerators
- Nuclear reactors
- Nuclear weapons

Neutrons are not the only threat

Radioactive impurities are becoming significant again at low altitude.

Effects of neutron SEE

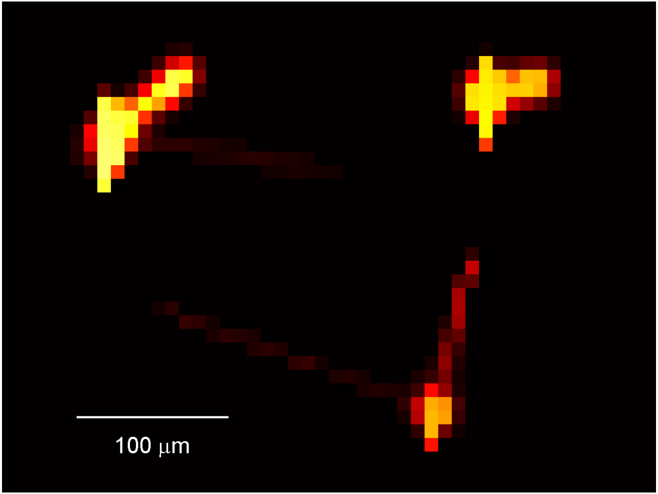
Examples of neutron SEE

Neutron SEE examples

- Parity errors in Los Alamos Cray-1 supercomputer in 1976 lead to development of error-correction coding and are now attributed to cosmic neutrons. [Normand et al. (2010)]
- Medical devices have been shown to be susceptible to cosmic rays [Bradley & Normand (1998)] and have also been shown to generate neutron fields capable of causing SEE [Wilkinson (2005)]
- Sun Enterprise servers lacked cache ECC and were unreliable. Parallel redundancy was retrofitted.
- Line cards in Cisco routers failed. Soft errors are "a daily event" for Cisco (Allan Silburt, Cisco Systems, IRPS 2010)
- IBGTs in power modules for use at SNS failed due to cosmic ray interactions. The problem was solved by screening and derating. [Borivina et al. (2003)]
- Australian Transport Safety Bureau investigation AO-2008-070 is considering SEE as a possible cause of an accident on flight QF72 on 7 Oct 2008. [Australian Transport Safety Bureau (2009)]

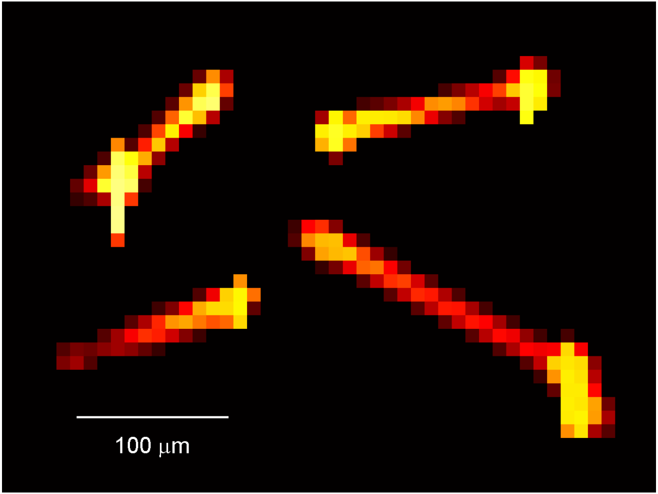
Examples of neutron interactions in silicon

Montage of events from a natural field (Hochalpine Forschungsstation Jungfraujoch)



Examples of neutron interactions in silicon

Montage of events from a synthetic field (ISIS VESUVIO)



Neutron SEE testing

Test standards

Accelerated test facilities

Neutron SEE test standards

JEDEC

- Measurement and Reporting of Alpha Particle and Terrestrial Cosmic Ray-Induced Soft Errors in Semiconductor Devices [JESD89A (2006)]
- Test Method for Beam Accelerated Soft Error Rate [JESD89-3A (2007)]

JEITA

- JEITA SER Testing Guideline [EIAJ EDR-4705 (2005)]

IEC

- Process management for avionics – Atmospheric radiation effects [IECTS 62396]

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Neutron SEE testing

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Accelerated test facilities

Preferred testing method is in atmospheric-like neutron beams ("white", "spallation", "broad spectrum" beams).

- SEE rate in service extrapolated simply from SEE rate during accelerated testing if the test spectrum is faithful to the natural neutron field.

Several test facilities are in common use:

- Los Alamos Neutron Science Center ICE House [ICE House, ICE House spectrum]
  - Capacity being doubled this year
- TRIUMF, Vancouver [TRIUMF PIF & NIF, Blackmore et al. (2003), Blackmore (2009)]
  - Three different neutron fields available
- The Svedberg Laboratory, Uppsala [The Svedberg Laboratory, Prokofiev et al. (2007), Prokofiev et al. (2009)]
  - ANITA
  - Quasi monoenergetic neutrons and protons collocated
- Research Center for Nuclear Physics, Osaka

A British/Italian collaboration

UK Government funding has just been confirmed for a new facility, ChipIr, at Rutherford Appleton Laboratory ISIS Target Station 2

Summary

Neutrons can cause SEE *indirectly*

- High energy neutrons interact with Si and other device materials generating energetic ionising particles
- If ^{10}B is present low-energy (thermal) neutrons react exothermically

In avionic and many ground applications cosmic ray neutrons are the main cause of SEE

- At typical aircraft cruising altitudes neutron flux is about 2 orders of magnitude greater that at sea level.
- High-latitude flights are particularly vulnerable because of the loss of magnetic shielding.

Neutron SEE is a significant issue in many high reliability applications, even on the ground. Many electronic device manufacturers and system integrators have active neutron SEE mitigation programmes, including accelerated test campaigns

- Test standards have been developed by organisations including JEDEC, JEITA and IEC.

Appendix

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