^{10}B and All That Jazz

The Impact of Thermal Neutrons on Integrated Circuit Reliability

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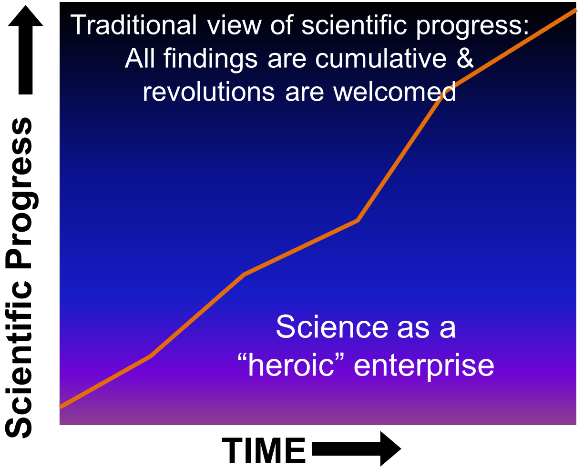
Outline

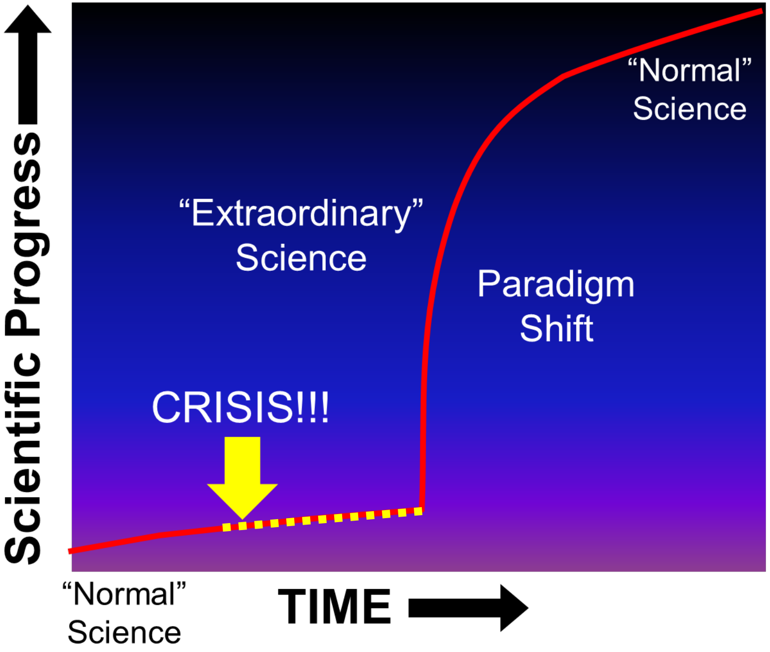
- Short history of discovery of ^{10}B problem in ICs – Example of “paradigm”
- Quick Overview: The terrestrial radiation environment
- Why is ^{10}B so bad for electronics?
- How ^{10}B sneaks it way into semiconductor processes
- Mitigation – can we can reduce the effect of thermal neutrons?
- Need for thermal/high energy neutron facilities & standards

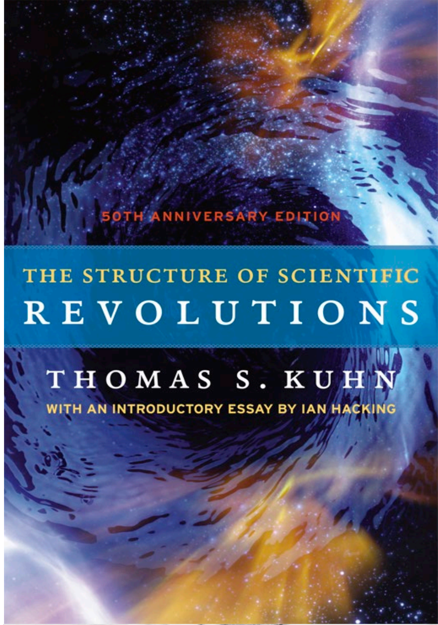
Scientific Progress in Non-linear

Popular View of Scientific Progress



Actual or “Real” Scientific Progress





Fighting the “It’s All Alphas” Paradigm

PARADIGM: “Every soft error is caused by alpha particles from contamination in VLSI process & materials.” (1979-1995)

Deconstructed DRAM IC and package process and materials looking for “smoking gun”…aka unknown or “hidden” source of alpha particles (NAA and alpha counting).

Tweaked DRAM process/design to be less sensitive alpha particles (10x-100x reduction) as confirmed by accelerate alpha testing BUT unaccelerated test returned same result as before!

Proposed high energy neutrons & thermals as cause of SER in DRAM in 1990-92 but was not allowed to publish until 1995-2000 (Trade Secret).

PARADIGM SHIFT: “Soft error are caused by alpha particles, high-energy neutrons AND thermal neutrons + ^{10}B” (1996-2005)

I. Arimura and C. Rosenberg, "ANOMALOUS DAMAGE MECHANISM IN PNP TRANSISTORS DUE TO THERMAL NEUTRONS", IEEE Trans. Nucl. Sci. NS-20, 1973.

Empirical demonstration of ^{10}B thermals causing gain reductions in BJTs.

Robert L. Fleischer, “COSMIC RAY INTERACTIONS WITH BORON: A POSSIBLE SOURCE OF SOFT ERRORS”, IEEE Trans. Nucl. Sci., NS-30(5), Oct. 1983.

First theoretical calculation showing ^{10}B + thermals could dominate soft errors.

Key Terrestrial Radiation Sources

Cosmic Background Radiation (external)

HIGH-ENERGY NEUTRONS

(E_n > 10MeV*)

Nuclear Reactions with Si, O, etc.

THERMAL NEUTRONS

(E_n ~ 0.025 eV)

Nuclear Reactions with ^{10}B (and others)

Radioactive decay (internal)

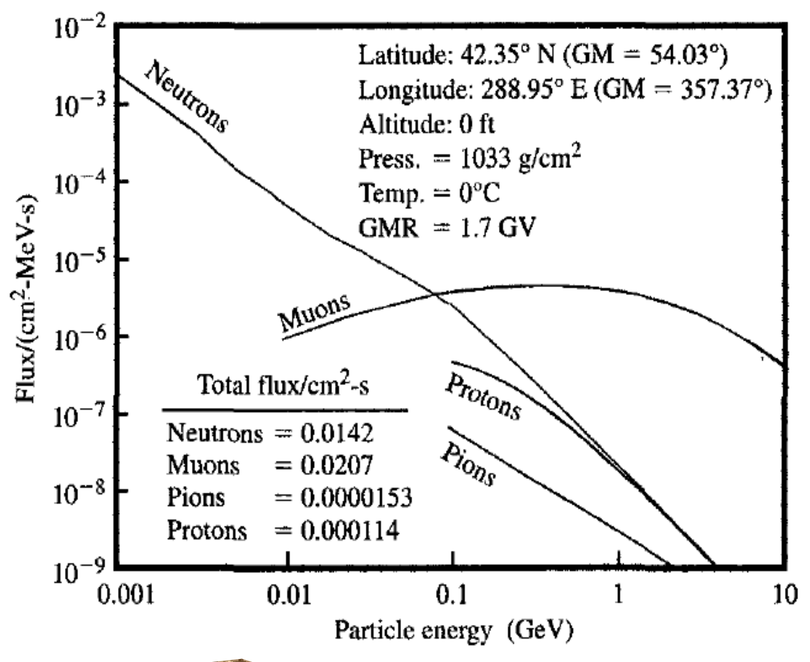
ALPHA PARTICLES

(E_a=0 – 9 MeV)

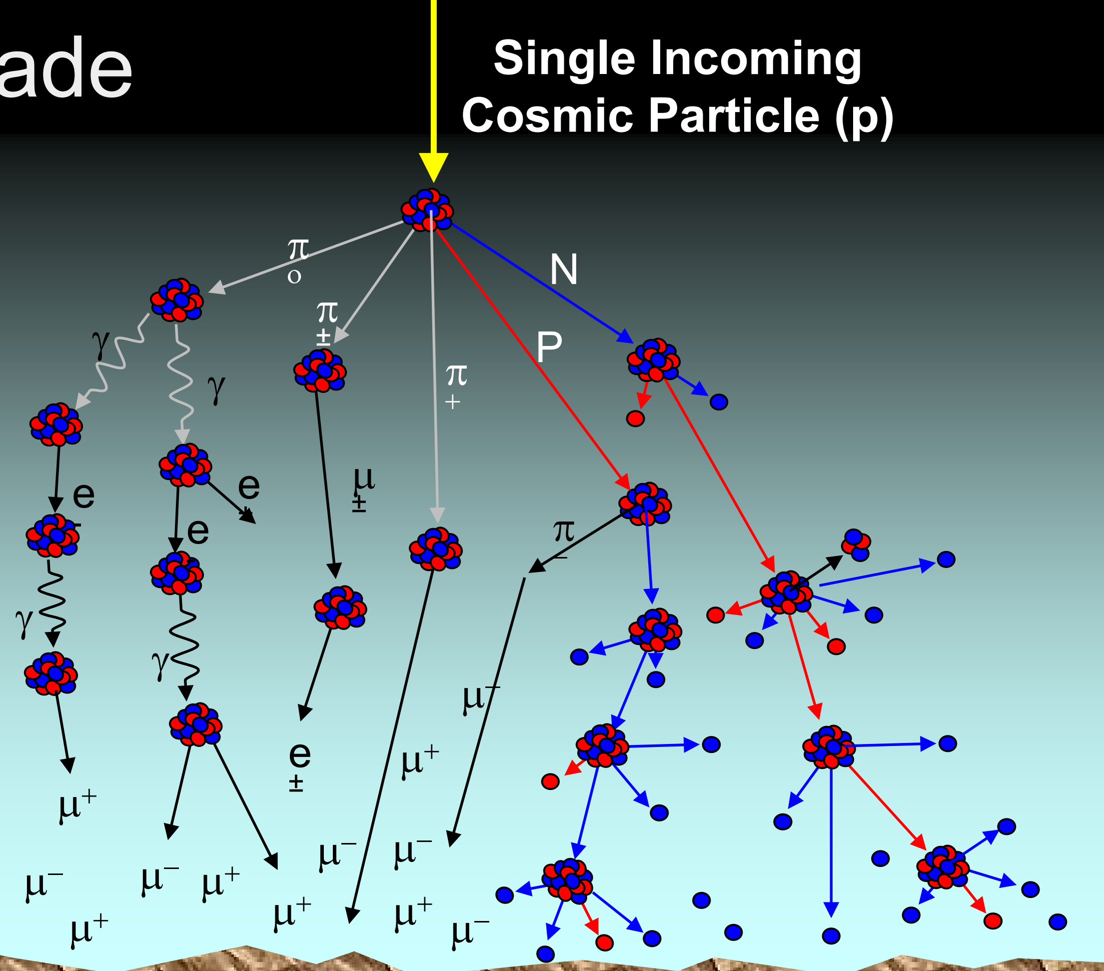
Direct Ionization

Cosmic Cascade

J. F. Ziegler, "Terrestrial Cosmic Ray Intensities," IBM J. Res. Develop., Vol. 42(1), p. 125, Jan. 1998.



Single Incoming Cosmic Particle (p)



"Tri-Peaks" Neutron Spectrum

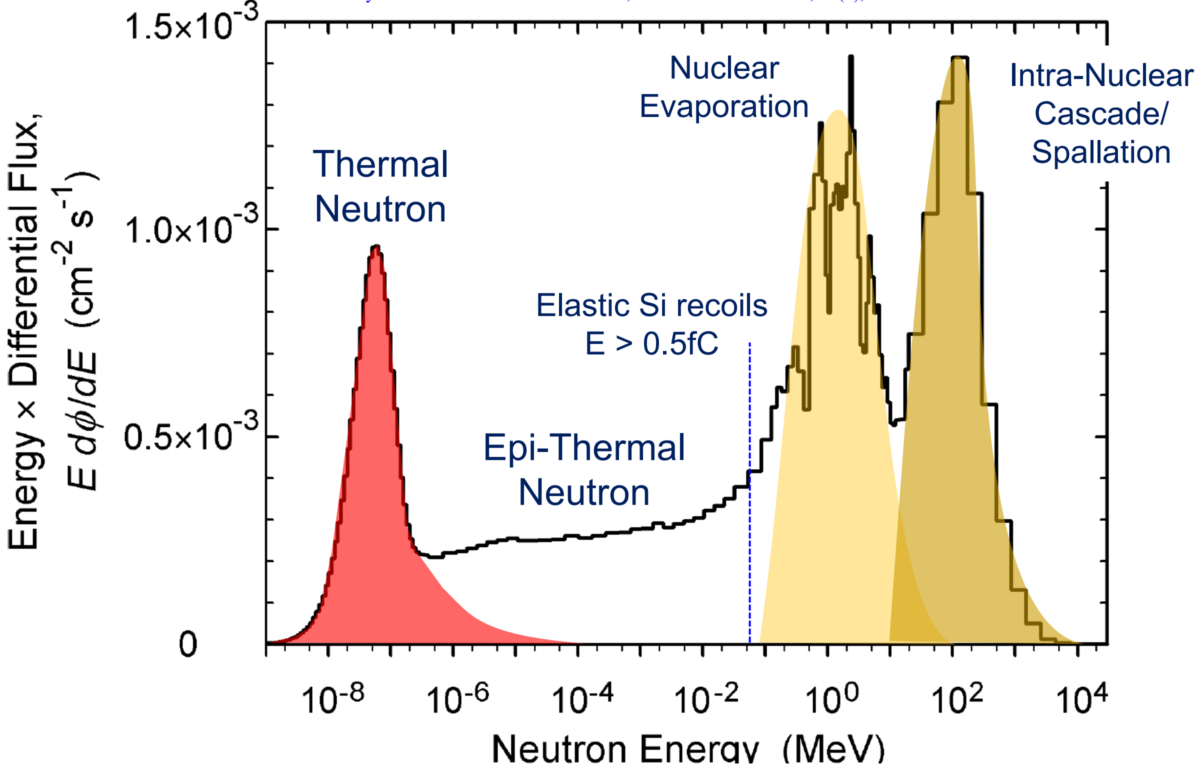
No recoils from elastic collisions
$E_{K.E.Si} < E_{binding}$

Most inelastic reactions produce compound nuclei*
(that emit gamma rays to reduce excited state)

- ~ 4 n_{th}/cm^2-hr
- ~ 13 n_{10MeV}/cm^2-hr
- ~ 20 n_{1MeV}/cm^2-hr

Flux @ NYC sea-level (per JESD89)

S. Gordon, P. Goldhagen et al, "Measurement of the Flux and Energy Spectrum of Cosmic-Ray Induced Neutrons on the Ground," IEEE Trans. Nuc. Sci., 51(6), Dec. 2004.



^{10}B & Thermal Neutrons

Natural abundance of ^{10}B is ~20%

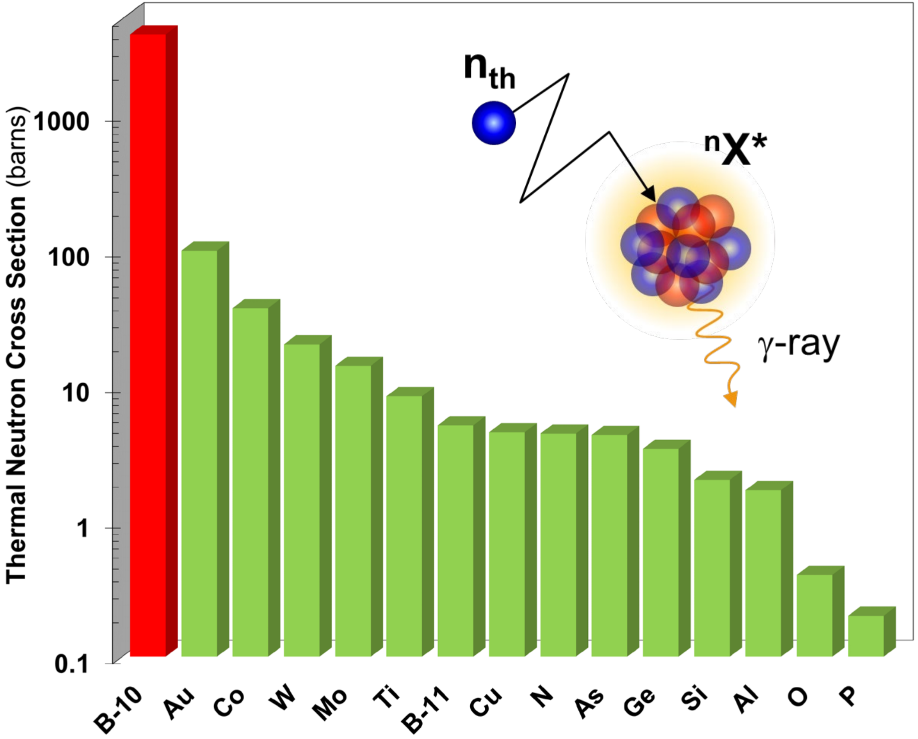
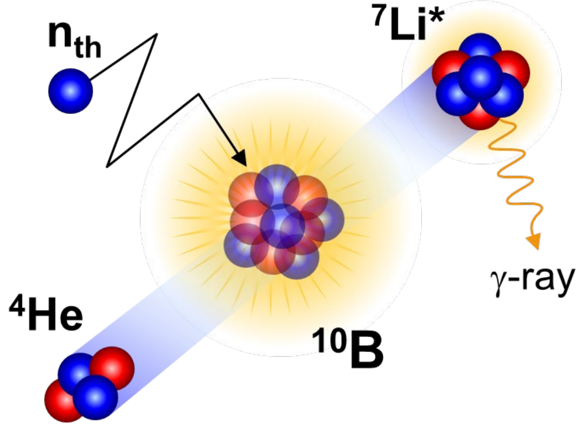


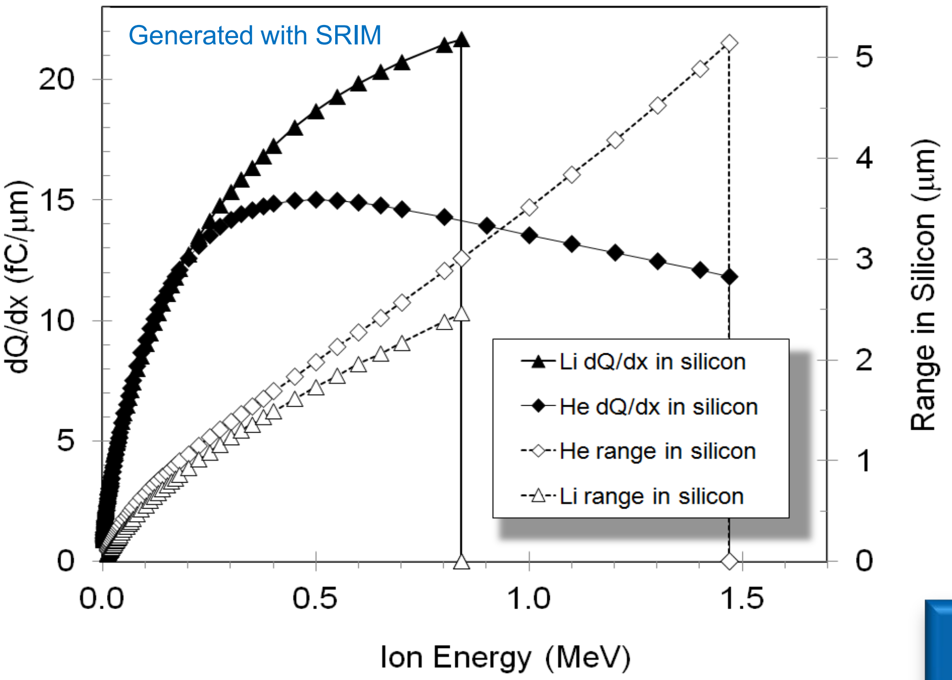
Table of Thermal Neutron Cross Sections of the Isotopes -https://link.springer.com/content/pdf/bbm:978-3-642-87614-1/1.pdf



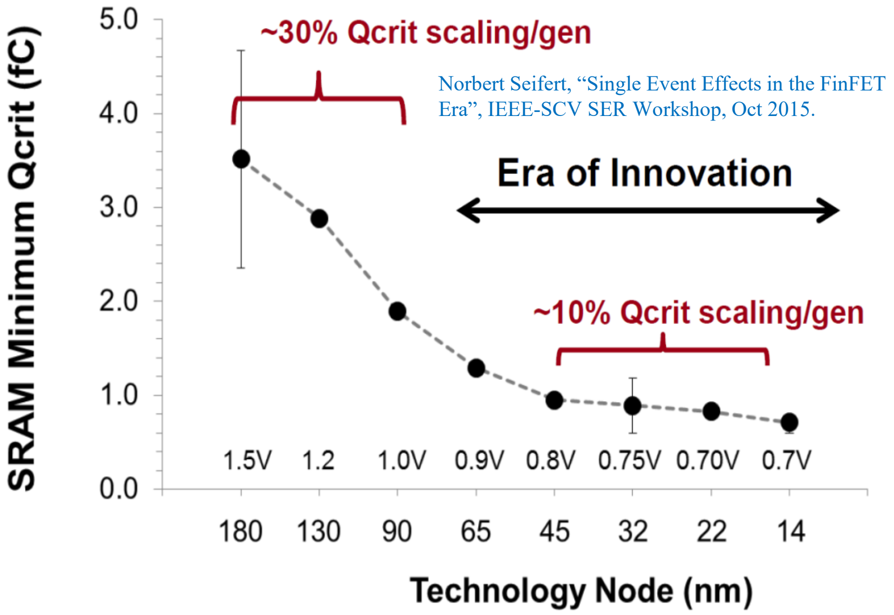
Neutron reaction	Byproduct	Stopping distance		Total charge deposited in silicon
$^{10}B(n,\alpha)^{7}Li^{*}$	1.473 MeV α	5.2 μm	~ 94%	65.2 fC
$^{10}B(n,\alpha)^{7}Li^{*}$	0.841 MeV $^{7}Li^{*}$	2.4 μm		35.5 fC
$^{10}B(n,\alpha)^{7}Li$	1.778 MeV α	6.4 μm	~ 6%	78.7 fC
$^{10}B(n,\alpha)^{7}Li$	1.015 MeV ^{7}Li	2.8 μm		44.5 fC

E. C. Auden, et al, "Thermal Neutron-Induced Single-Event Upsets in Microcontrollers Containing Boron-10", IEEE Trans Nucl. Sci, 67(1), Jan. 2020

Injected charge & Technology Sensitivity



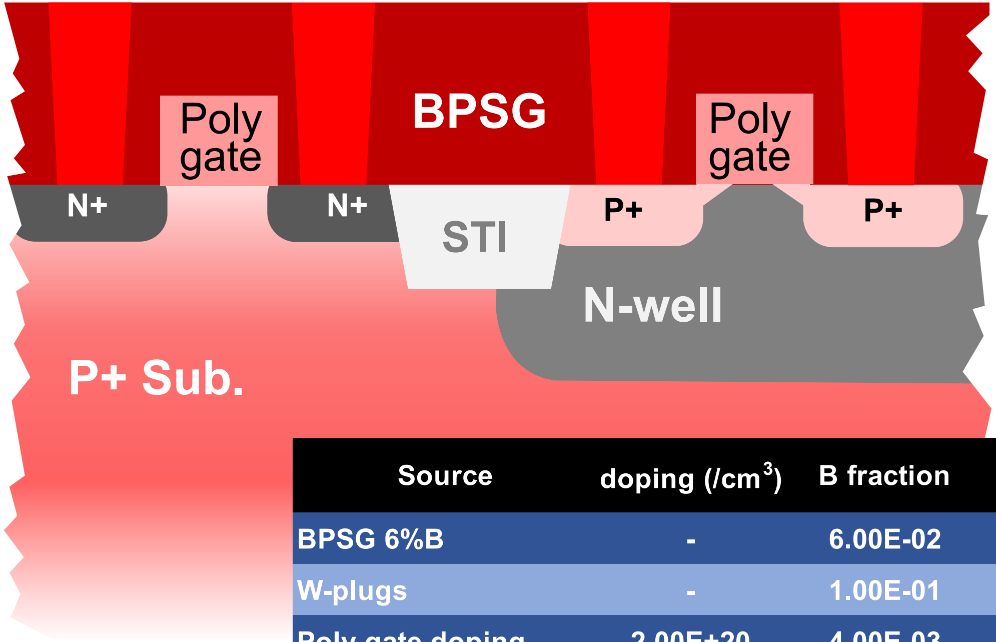
R. Baumann, T. Hossain, E. Smith, S. Murata, H. Kitagawa, "Boron as a primary source of radiation in high density DRAMs", IEEE Symp. VLSI Tech., June 1995, pp. 81 – 82.



Norbert Seifert, "Single Event Effects in the FinFET Era", IEEE-SCV SER Workshop, Oct 2015.

In "modern" technologies, ALL products of the ^{10}B reaction WILL potentially cause upsets

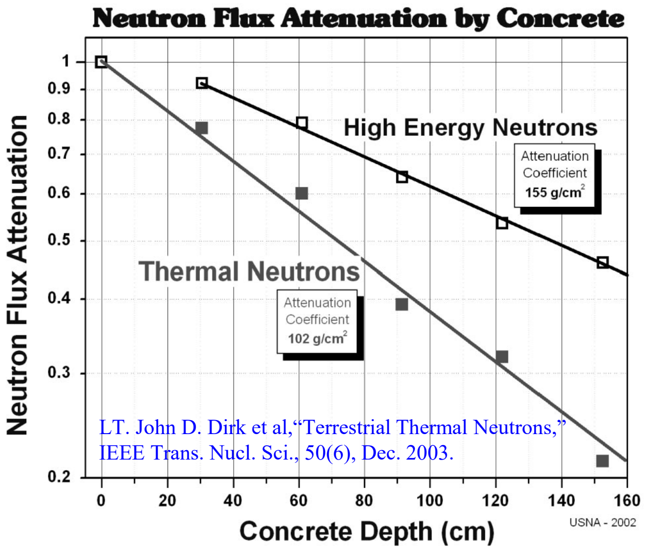
What are the sources of ^{10}B in the process?



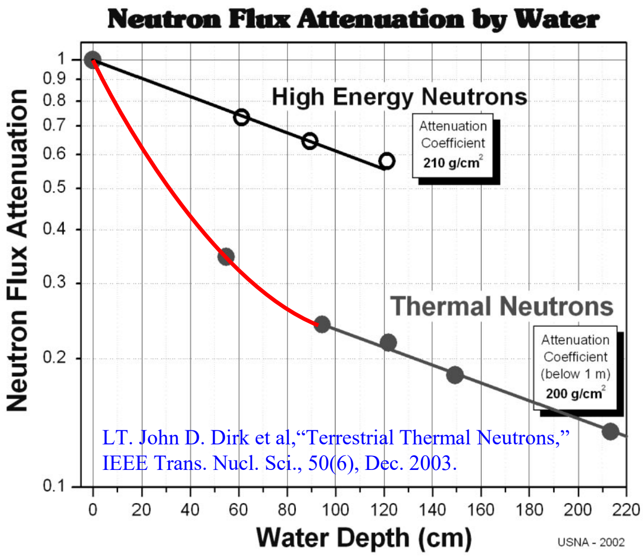
BPSG (boron doped glass) and W-plug process are ~ 100x bigger than all other ^{10}B sources combined.

Source	doping (/cm^3)	B fraction	Area Fraction	Layer Thick. (nm)	Relative Contribution
BPSG 6%B	-	6.00E-02	0.8	1000	1
W-plugs	-	1.00E-01	0.2	1000	0.42
Poly gate doping	2.00E+20	4.00E-03	0.1	500	0.004
p Substrate (0.1Ω-cm)	5.00E+17	1.00E-05	0.8	7000	0.001
S/D implants	2.50E+20	5.00E-03	0.1	100	0.001
Channel implants	1.00E+19	2.00E-04	0.05	50	0.00001

Shielding Neutrons is NOT easy!



70 cm of Concrete reduces n_{th} flux by 50%



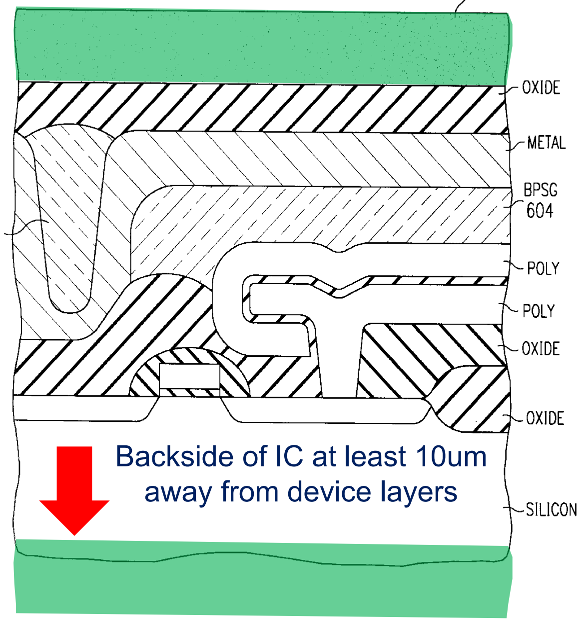
31 cm of Water reduces n_{th} flux by 50%

Fun Fact: Hitachi got SSER that was 50x lower than TI on SAME devices => Hitachi test area was in basement with water reservoir & pipes above test area!!!

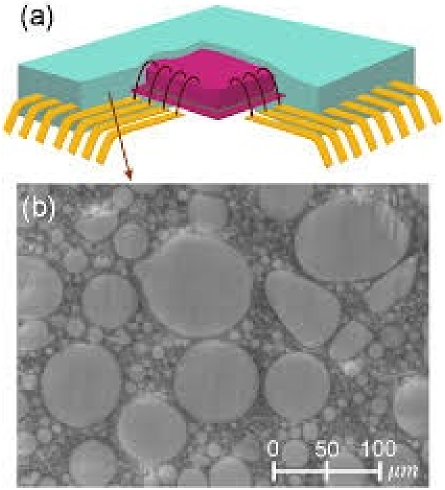
Mitigation by Using High σ_{nth} Materials?

^{10}B or Gd enriched layer

Topside on IC
on or in PO

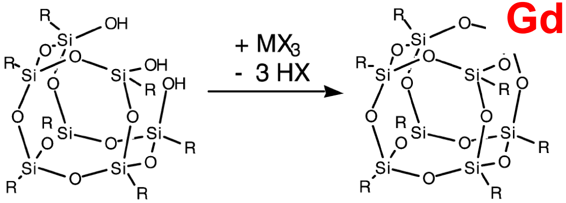


Cadmium	σ_{nth} ~ 20,000 barns
Gadolinium	σ_{nth} = 48,890 barns
Gd-155	σ_{nth} ~ 60,000 barns
Gd-157	σ_{nth} ~ 255,000 barns

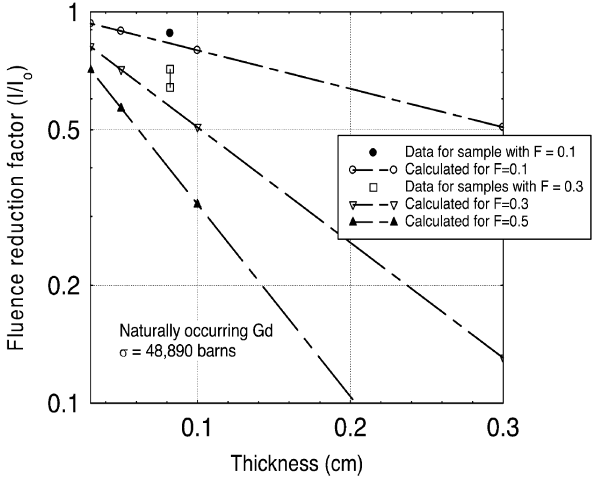


70-80% silica or alumina – doped with ≤ 20% high σ_{nth} material

M. Hwang, W. R. McKee, R. C. Baumann, "Thermal neutron shielded integrated circuits." U.S. Patent 6,239,479, issued May 29, 1996.



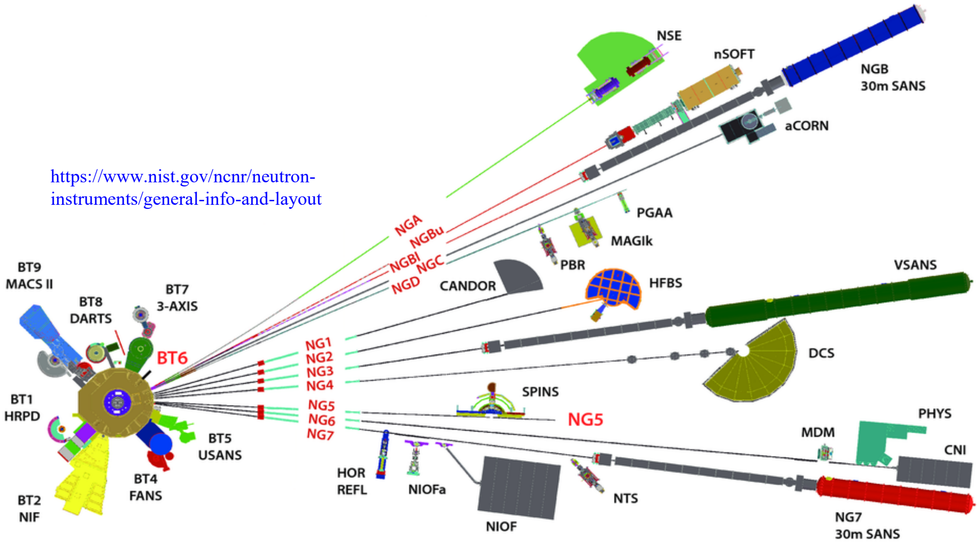
Polyhedral Oligomeric SilSesquioxanes (POSS) nanomaterial to which Gd or other high σ_{nth} atom is added



J. P. Spratt et al, "A Conformal Coating for Shielding Against Naturally Occurring Thermal Neutrons," IEEE Trans. Nuc. Sci., 52(6), Dec. 2005

Facilities and Standards

https://www.nist.gov/ncnr/neutron-instruments/general-info-and-layout



Good high-energy neutron source

- Low Gamma contamination
- Most of spectrum > 1MeV (1 – 20MeV)
- Ideally no thermal neutrons
- Good dosimetry

Good thermal neutron source

- No high energy neutrons
- No gammas
- Good dosimetry
- Minimized scattering

PRE- JEDEC JESD89

Most of industry was testing ONLY with accelerated ALPHA PARTICLE studies and reporting < 1 FIT DRAM. But SSER was ~ 2000 FIT!

JEDEC JESD89 (2001)

Most of industry was oblivious or unbelieving. Most of the industry had just accepted high energy neutron effects but thermals was still not appreciated by most.

JEDEC JESD89A (2006)

Added dedicated chapter on thermal neutron testing

E. Normand et al., "Quantifying the double-sided neutron SEU threat, from low energy (thermal) and high energy (>10 MeV) neutrons," IEEE Trans. Nucl. Sci., 53(6), Dec. 2006.

Snap-Shot – Sources and Sensitivities

- Most manufacturers have removed BPSG (especially with use of CMP)
- HOWEVER: Diborane and other boron compounds are ubiquitous in the IC processes (e.g. plug and barrier layer formation). Significant ^{10}B can be left in the process. Impact can be similar in magnitude to BPSG.
- ^{10}B from B, BX implants and diffusions generally represents < 1% of total events - for existing process flows these do NOT present significant risk.
- Use of isotopically separated (^{11}B enriched) process materials and conformal thermal neutron shielding can help mitigate the effects.
- DRAM with its 3D cell capacitance should be robust against ^{10}B events - However, SRAM/sequential/combo logic has high sensitivity ($LET_{th} < 2$).

J. L. Autran et al, "Soft-Error Rate Induced by Thermal and Low Energy Neutrons in 40 nm SRAMs," IEEE Trans. Nucl. Sci., 59(6), Dec. 2012

Final Words

^{10}B reaction with thermal neutrons produces charge injection in excess of most IC device critical charge making upsets likely in advanced technologies (SRAM, logic).

When alpha contamination has been mitigated, the contribution of thermal neutron SEE rate can be similar or greater in magnitude than that produced by higher energy neutron reactions (evaporation/spallation reactions).

While a large amount of ^{10}B has been removed from modern IC processes, plug and barrier metal formation process still introduce non-zero ^{10}B content, so the thermal neutron sensitivity of new technology should be verified before using in high reliability applications.

Facilities with the ability to produce high-energy and thermal neutron fluxes for the determination IC response will allow for rapid determination of the "level of concern" for a new device and would enable mitigation efforts (if needed) to start earlier in the process (removal of ^{10}B from process and/or package shielding).

RADIOSITY SOLUTIONS

The right answer. Faster

RAD NEXT