Subatomic Particles, Radiation Effects

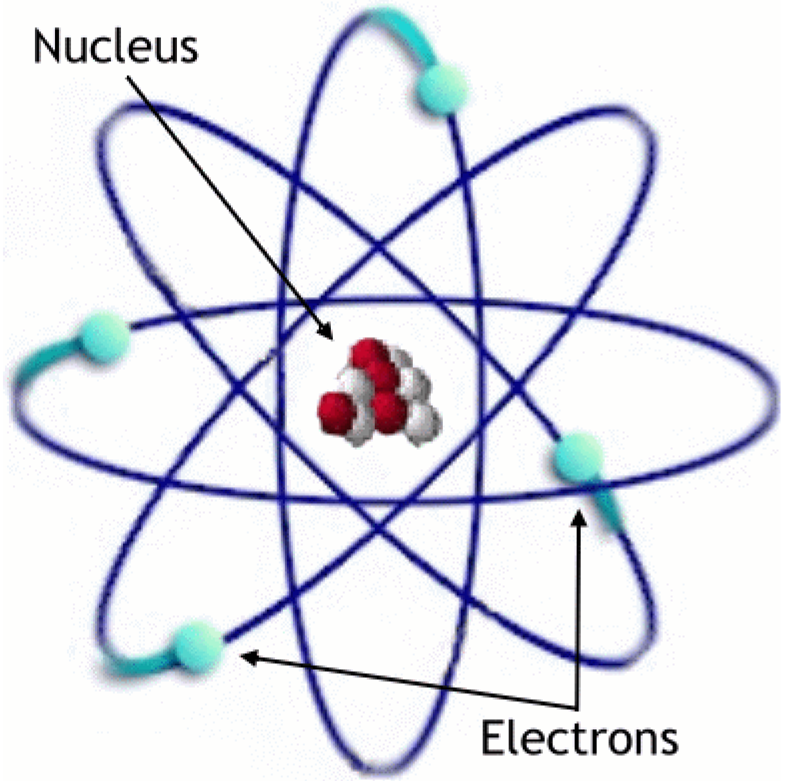
Overview

- Single-event effects: types
- Indirect ionization
- Cross-section
- Range
- Angular effects
- Poisson

Background on Radiation

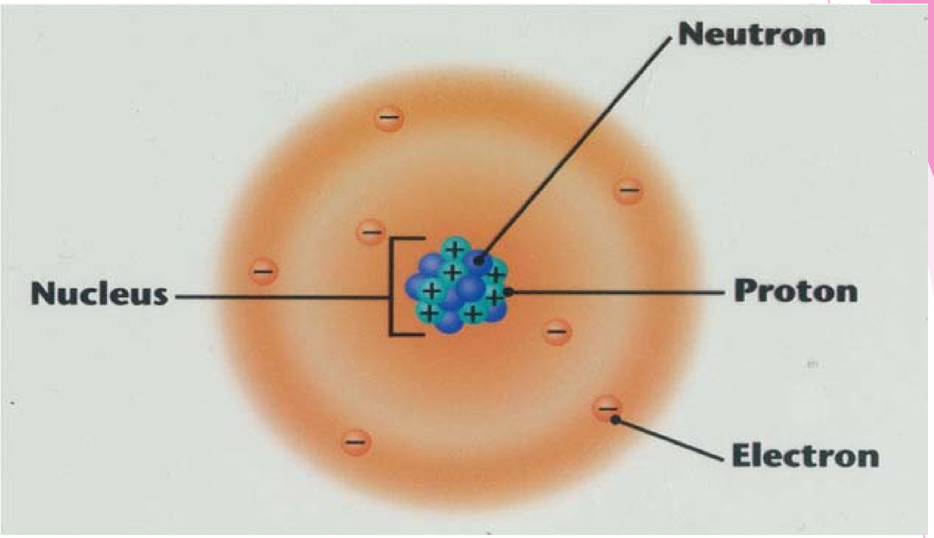
Atomic Models

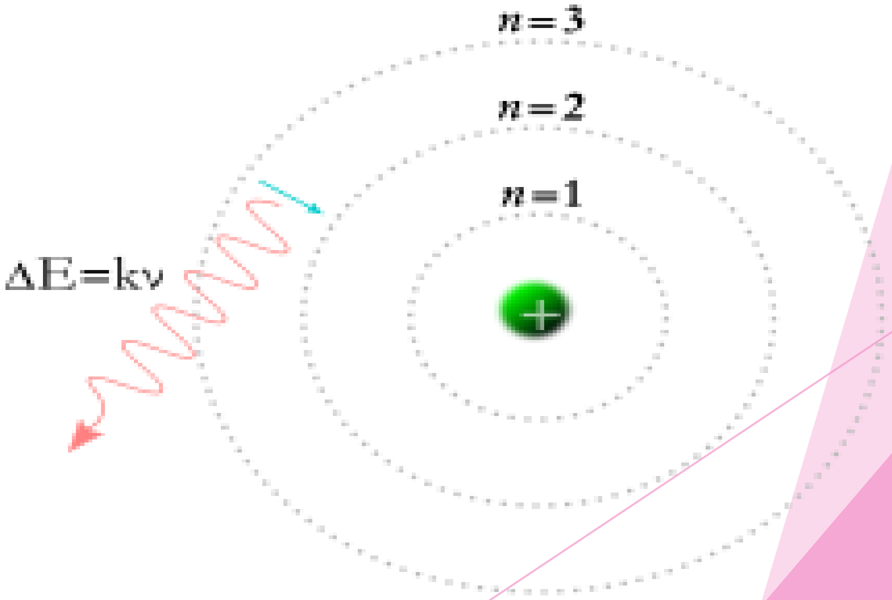
- Our earliest ideas:
  - Solid masses with no sub-components
  - “Plum pudding” model
- Rutherford Model
  - Most of the mass is in the nucleus
  - Still thinks electrons are like planets orbiting the sun



Atomic Models

- Soddy and Todd: isotopes
- Bohr: electrons have quantum levels, photons are used to go up or down levels
- Electrons are in clouds and not tracks





Atoms

- Exert a lot of energy to remain “stable” and “complete”
  - Think Jerry Maguire
- React poorly to outside stimulation which causes them to be “unstable” or “incomplete”
  - Think West Side Story/Romeo and Juliet

What does stability and completeness to atoms?

- Electrically neutral: protons and electrons are matched
- Energetically minimized: electrons are in their lowest energy states
    - The electrons can exist in a number of quantum states (shells)
    - Each shell has a maximum number of electrons that can

Many atoms are unstable by their very nature

- Isotopes are missing neutrons
- Ions have either missing electrons or two many electrons
- Many atoms have incomplete valence bands (outer shell of electrons)
  - Incomplete shells, though, are what allow atoms to join with other atoms to make molecules
  - The “Noble” gases do not bind, because they don't need any more electrons to be complete
  - The valence electrons in some substances can be removed for electrical purposes

Example: Hydrogen

- Generally, electrically stable: 1 proton and 1 neutron, although is stable without its neutron or an extra neutron
- Is not complete on its own – with only one electron, the valence band is only half full
  - Most commonly found in nature in a diatomic formation
  - The two atoms can share electrons to stabilize each other – “You complete me”

Under normal conditions

- Atoms and molecules are stable – they will form bonds to stabilize themselves
- Semiconductor devices are not normal in many ways
  - Forced into a regular lattice structure that makes them fragile
  - Electrons and holes moving around

Radiation in Semiconductors

- Introduces instability into a barely stable scenario
- The atoms and molecules will react to the situation to try to return to stability, even if it means giving up an electron or absorbing a neutron
- Action/reaction – even a nuclear level for all actions, there is a reaction
  - Absorb a neutron, release a beta
  - Scatter a proton, release an alpha and a magnesium

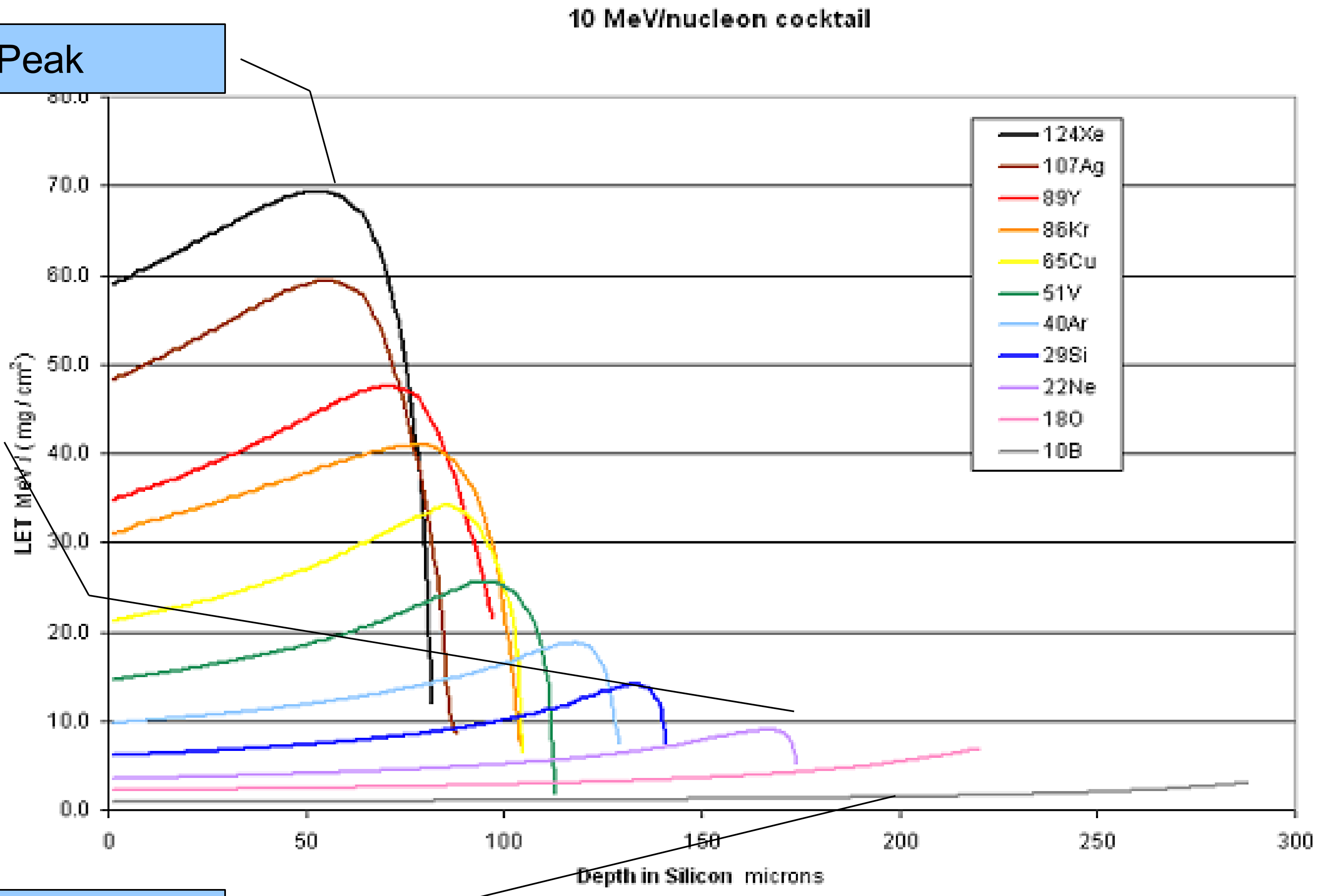
Ionization

- Many particles cause ionization as they move matter:
  - Photons
  - Electrons
  - Protons
  - Heavy ions

Energy Loss in Matter

- Ionizing particles lose energy in matter through either nuclear or electronic energy loss
  - Because electrons are easy to shed, electronic energy loss is more common
  - Only at the end of their “range” do ionizing particles have nuclear energy loss
- Total energy loss can be estimated as electronic energy loss
  - Called “linear energy transfer” (LET), which are usually in the units of MeV-cm2/mg
  - LET is “mostly” normalized

Energy Loss vs. Bragg's Peak

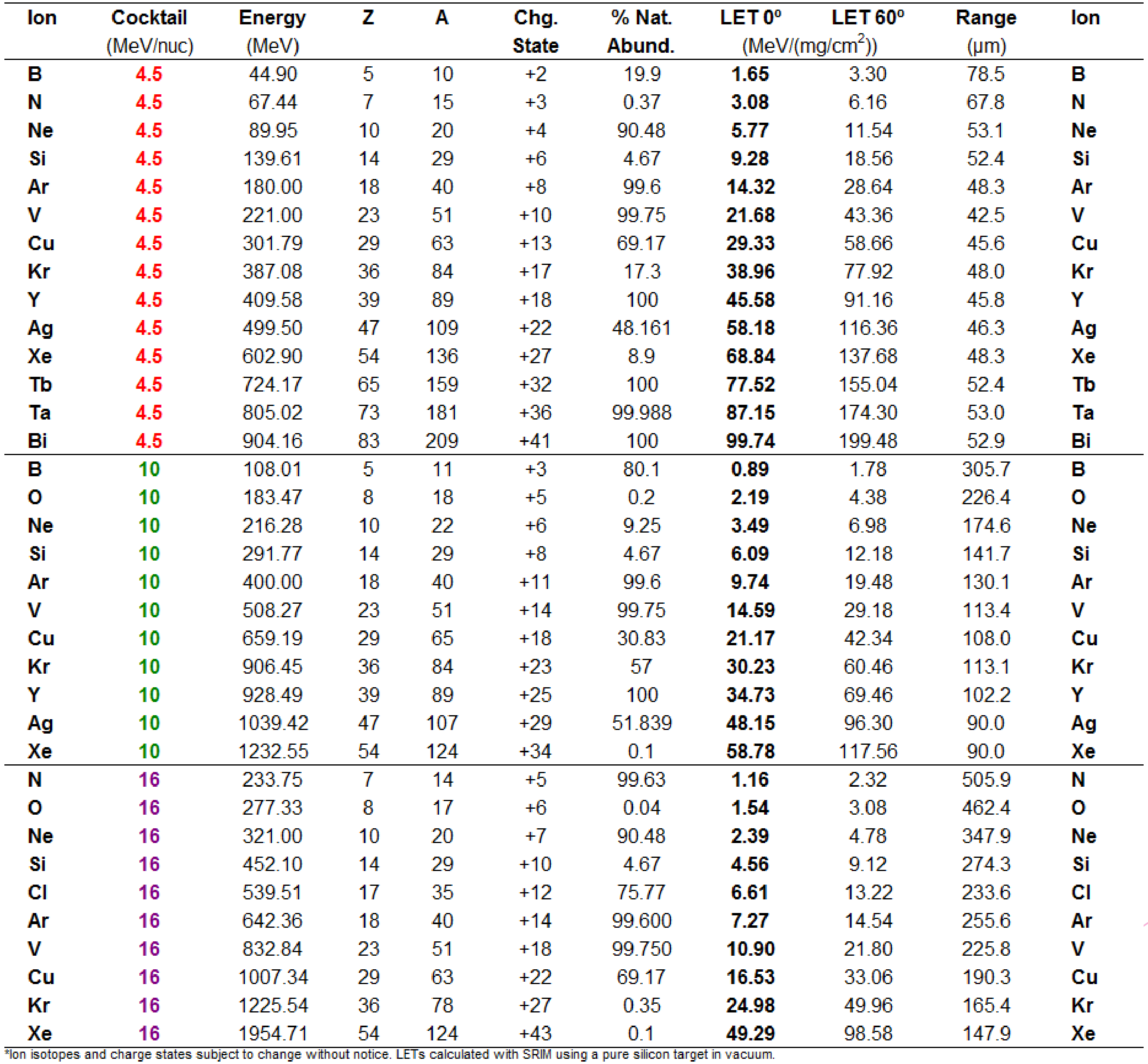


Bragg's Peak

Lower Z-> More increase in LET

Lower Z->longer range

KE vs. LET vs. Range



Ion	Cocktail	Energy	Z	A	Chg.	% Nat.	LET 0°	LET 60°	Range	Ion
	(MeV/nuc)	(MeV)			State	Abund.	(MeV/(mg/cm^2))		(µm)	
B	**4.5**	44.90	5	10	+2	19.9	**1.65**	3.30	78.5	**B**
N	**4.5**	67.44	7	15	+3	0.37	**3.08**	6.16	67.8	**N**
Ne	**4.5**	89.95	10	20	+4	90.48	**5.77**	11.54	53.1	**Ne**
Si	**4.5**	139.61	14	29	+6	4.67	**9.28**	18.56	52.4	**Si**
Ar	**4.5**	180.00	18	40	+8	99.6	**14.32**	28.64	48.3	**Ar**
V	**4.5**	221.00	23	51	+10	99.75	**21.68**	43.36	42.5	**V**
Cu	**4.5**	301.79	29	63	+13	69.17	**29.33**	58.66	45.6	**Cu**
Kr	**4.5**	387.08	36	84	+17	17.3	**38.96**	77.92	48.0	**Kr**
Y	**4.5**	409.58	39	89	+18	100	**45.58**	91.16	45.8	**Y**
Ag	**4.5**	499.50	47	109	+22	48.161	**58.18**	116.36	46.3	**Ag**
Xe	**4.5**	602.90	54	136	+27	8.9	**68.84**	137.68	48.3	**Xe**
Tb	**4.5**	724.17	65	159	+32	100	**77.52**	155.04	52.4	**Tb**
Ta	**4.5**	805.02	73	181	+36	99.988	**87.15**	174.30	53.0	**Ta**
Bi	**4.5**	904.16	83	209	+41	100	**99.74**	199.48	52.9	**Bi**
B	**10**	108.01	5	11	+3	80.1	**0.89**	1.78	305.7	**B**
O	**10**	183.47	8	18	+5	0.2	**2.19**	4.38	226.4	**O**
Ne	**10**	216.28	10	22	+6	9.25	**3.49**	6.98	174.6	**Ne**
Si	**10**	291.77	14	29	+8	4.67	**6.09**	12.18	141.7	**Si**
Ar	**10**	400.00	18	40	+11	99.6	**9.74**	19.48	130.1	**Ar**
V	**10**	508.27	23	51	+14	99.75	**14.59**	29.18	113.4	**V**
Cu	**10**	659.19	29	65	+18	30.83	**21.17**	42.34	108.0	**Cu**
Kr	**10**	906.45	36	84	+23	57	**30.23**	60.46	113.1	**Kr**
Y	**10**	928.49	39	89	+25	100	**34.73**	69.46	102.2	**Y**
Ag	**10**	1039.42	47	107	+29	51.839	**48.15**	96.30	90.0	**Ag**
Xe	**10**	1232.55	54	124	+34	0.1	**58.78**	117.56	90.0	**Xe**
N	**16**	233.75	7	14	+5	99.63	**1.16**	2.32	505.9	**N**
O	**16**	277.33	8	17	+6	0.04	**1.54**	3.08	462.4	**O**
Ne	**16**	321.00	10	20	+7	90.48	**2.39**	4.78	347.9	**Ne**
Si	**16**	452.10	14	29	+10	4.67	**4.56**	9.12	274.3	**Si**
Cl	**16**	539.51	17	35	+12	75.77	**6.61**	13.22	233.6	**Cl**
Ar	**16**	642.36	18	40	+14	99.600	**7.27**	14.54	255.6	**Ar**
V	**16**	832.84	23	51	+18	99.750	**10.90**	21.80	225.8	**V**
Cu	**16**	1007.34	29	63	+22	69.17	**16.53**	33.06	190.3	**Cu**
Kr	**16**	1225.54	36	78	+27	0.35	**24.98**	49.96	165.4	**Kr**
Xe	**16**	1954.71	54	124	+43	0.1	**49.29**	98.58	147.9	**Xe**

*Ion isotopes and charge states subject to change without notice. LETs calculated with SRIM using a pure silicon target in vacuum.

Kinetic Energy vs. LET vs. Range

- Neon is in all three cocktails
  - 4.5 MeV/nucleon Ne: LET 5.77, Range 53.1
  - 10 MeV/nucleon Ne: LET 3.49, Range 174.6
  - 16 MeV/nucleon Ne: LET 2.39, Range 347.9
- Increasing KE, decreases LET and increases in range
- Range is important for some radiation effects, because the particle needs to get to an “sensitive volume” which is buried in the device – easy in space, difficult at the accelerator

Electron-Hole Pairs

- Some of the electronic energy loss causes the creation of electron-hole (e-h) pairs
    - The e-h pairs are caused by delta rays, which are caused by the initial energy deposition
    - Sometimes these e-h pairs can be recombined, but it depends on many circumstances
        - How created
        - How many created
        - Temperature
        - Material
- The presence of e-h pairs are the basis of all ionization-based radiation effects
    - Columnar
    - Geminate

SEE Mechanisms

Single-event effects

- Unlike accumulated dose effects, single-event effects could cause transient failures with only one particle
  - Cross-section, which is an areal measurement to the sensitivity of a particular SEE, often determines how many particles to cause the SEE
  - Since the sensitive area doesn't exist continuously across the part, there are areas where particles can hit and not cause the effect
  - "time-space Poisson effects"

SEE: the transient

- Measurable effects in an “off” transistor
- Particle strike liberates e-h pairs
- E-h pairs cause charge generation
- Charge generation causes the transistor to turn “on” temporarily
- Ion->charge->e-h pairs->current->signal

- These are columnar EHPS

SEE: the transient

- Even though the particle is much smaller than the transistor, the charge generation cloud can be much larger than one or many transistors
  - Based on feature size
  - The LET of the particle

Indirect Ionization

- SEEs can be caused by both direct ionization and indirect ionization
- Indirect ionization occurs when a particle hits the lattice and creates a nuclear fragment or a nucleus to be liberated from the lattice – nuclear recoil
  - In this case the the ionization is caused by the nuclear fragment and not the incident particle
  - Because the particle has to hit an atom head on to cause the nuclear recoil, devices are less sensitive to particles that cause indirect ionization

Indirect vs. Direct Ionization

- Because indirect ionization includes a direct strike to a Si atom, it is a much lower probability event than direct ionization
- The cross-sections for indirect ionization on the same part will be 5-7 orders of magnitude
- Particles or energy ranges of particles that cause direct ionization effects are a concern

Direct vs. Indirect Ionization: Particles

Particle	Direct	Indirect
Heavy ion	X	
Proton	< 3 MeV*	> 3 MeV

*Only 45nm and smaller devices

Low vs. High energy effects

Particle	Low	High
Heavy ion	direct	direct
Proton	direct*	indirect
Neutron	indirect	indirect

*Only 45nm and smaller devices

Low-energy proton effects

- Direct ionization from low-energy protons can be problematic, because low-energy protons are very abundant in both space and terrestrial environments
- Direct ionization effects from low-energy protons would greatly increase error rates

Protons vs neutrons

- Protons and neutrons have a lot of the same effect as each other, in terms of SEE
- In general, as a rule of thumb, the effect of a proton or a neutron above 50 MeV is equivalent
- Neutrons will never have a direct ionization effect because neutrons lack charge

Low-energy neutrons

- Leaving this mostly here, because of historical content.

- There are thermal neutron effects in some parts, though
- In those cases, the problem is not the neutron (per se) but the manufacturing of the part
  - Boron is very commonly in parts to reduce neutron effects
  - B10 has a sensitivity to thermal (low-energy) neutrons – B10 + n → Li7 + alpha – both the Li7 and the alpha can cause a SEE because the reaction is occurring in the sensitive volume

B10-contamination

- A “known” problem...that isn't disappearing
- Some parts in recent years have shown a wide range of B10 contamination from really bad to none
  - B10 is a price point in manufacturing but can be hard to get rid of

Cross-section

- Like TID, devices are tested to measure the cross-section
  - On-set: lowest LET/energy to cause the reaction
  - Saturation cross-section: the maximum sensitivity to the effect
- Most devices have one or some SEEs
  - Measurements of previous parts are not a good predictor of current parts – manufacturing, feature shrink, transistor design affects the sensitivity
  - There might be different on-sets and saturation cross-sections for different effects on the same device

Cross-section example (RTAX SET)

Typically SETs
Have a freq
relation

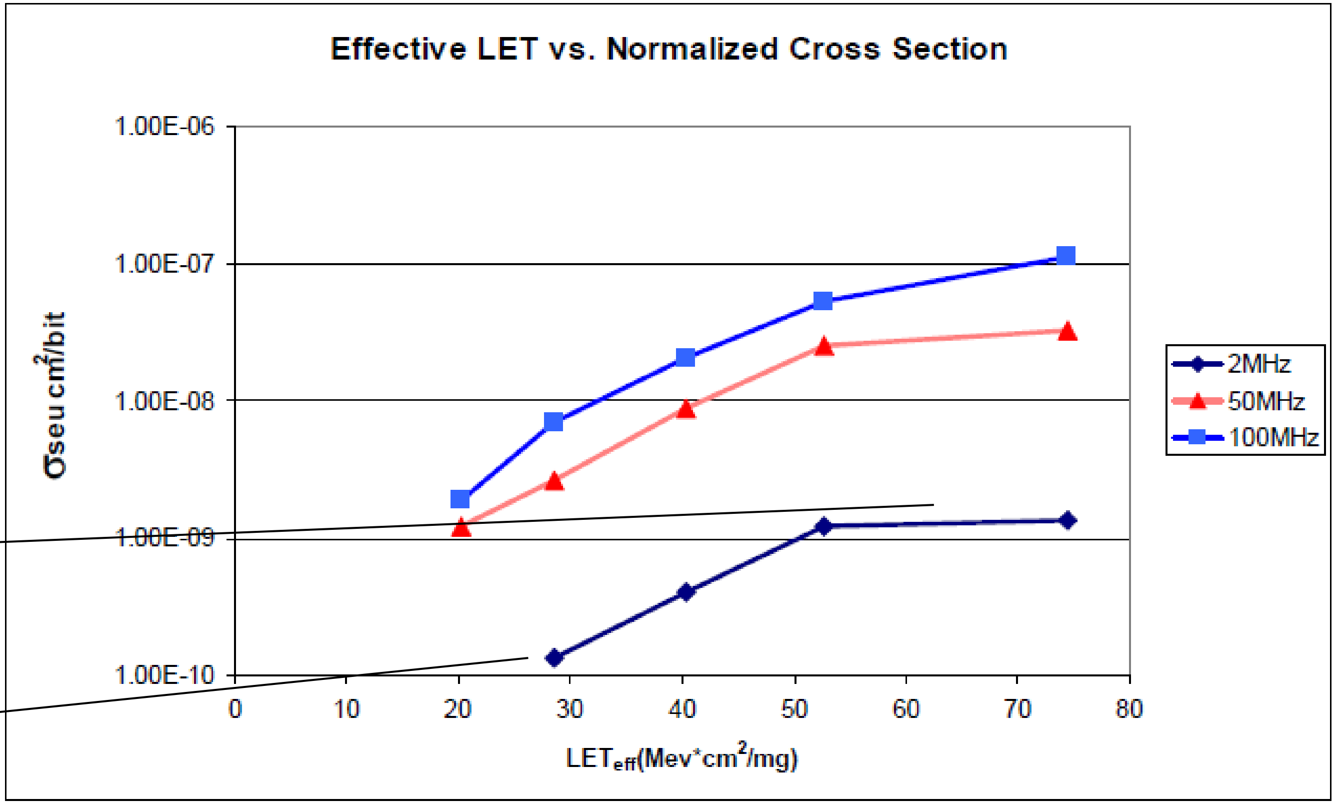


Figure 7: Comparison Cross Sections with respect to a spectrum on LET Values for Several Frequencies

Saturation

Onset

Cross-section and error rates

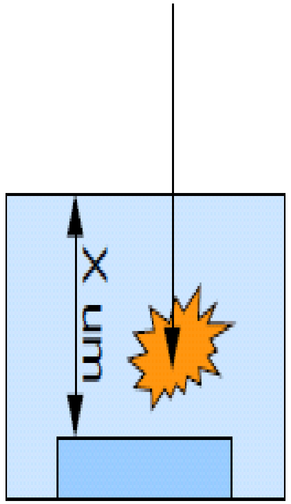
- The cross-section is combined with the environment in tools like CREME-MC to determine an error rate for the device in the environment
  - The error rate will help you determine whether mitigation is needed or not
- How does on-set affect error rates?
- How does the saturation cross-section effect error rates?

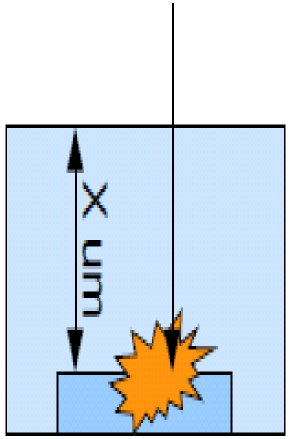
Cross-section vs. Range

- Range is an important part of testing for cross-section
- Remember that the sensitive volume is buried in the device
  - In space it doesn't matter that the sensitive volume is buried, because the particles have more kinetic energy than we can create in an accelerator
  - In testing to get an accurate measurement of cross-section, you must ensure that the radiation makes it to the sensitive volume otherwise the test is not accurate
    - This is a huge problem for SEB and SEGR. The vertical transistor is below the mesa transistor that is really deep. Low kinetic energy heavy ion beams might not have enough range to get to the sensitive volume

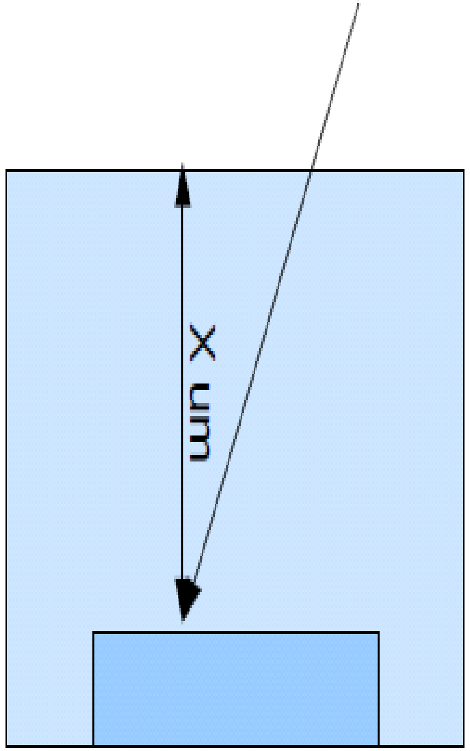
Sensitive Volume vs. Range

- In the top drawing, the radiation stops before it gets to the sensitive volume
- In the bottom drawing, the radiation gets to the sensitive volume, causing the charge generation to penetrate the sensitive volume
- It doesn't matter where it hits the sensitive volume – it just needs to get there





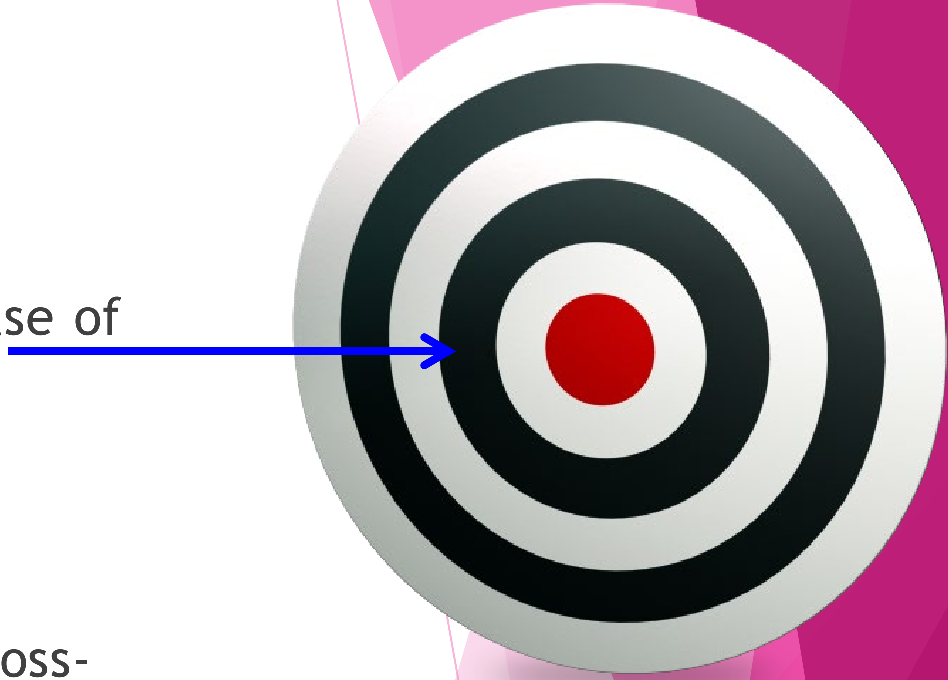
Angular Effects

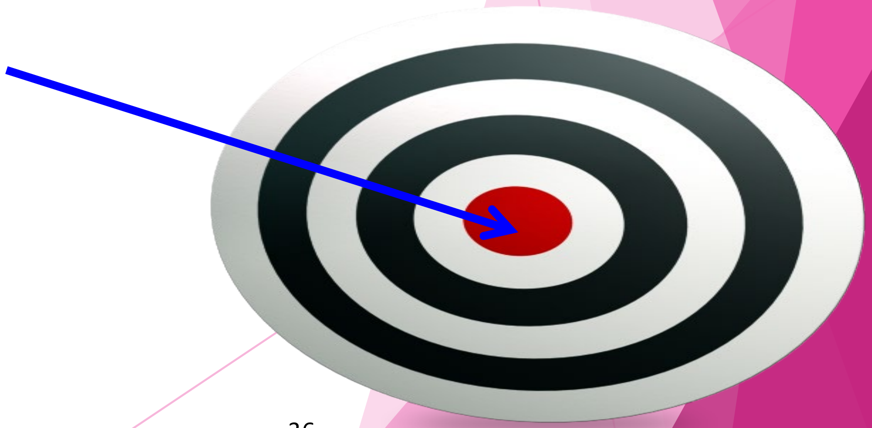


- In testing, some people will rotate the device in the beam to strike it at an angle
- What three things happen or could happen when you rotate the device?

Cross-section vs. Angle

- As long as you do not exceed the range of the ion, you get an increase of angle
- At the same time, the target shape changes
- It is now harder to hit the target
- The angle is taken into account in both the LET tested at and the cross-section – you don't want to mix the data





Angle Data on FPGAs

- Turns out that angle matters when testing FPGAs
- Many devices, especially SRAM, are very regular in their layout
- Not true for FPGAs – angular test results tends to highlight the heterogeneous layout
  - It's like mixing apples and oranges

Poisson Statistics

Poisson Statistics

- “The probability of a number of events occurring in a fixed period of time if these events occur with a known average rate and independently of the time since the last event”
- One of the thing is predicts is the probability of a certain amount of radiation within a given time
  - Since Poisson statistics affects how much radiation emits at any given time, it affects the error rates
  - For TID the Poisson statistics mostly normalizes
  - For SEE the Poisson statistics causes constant variation in the error rates

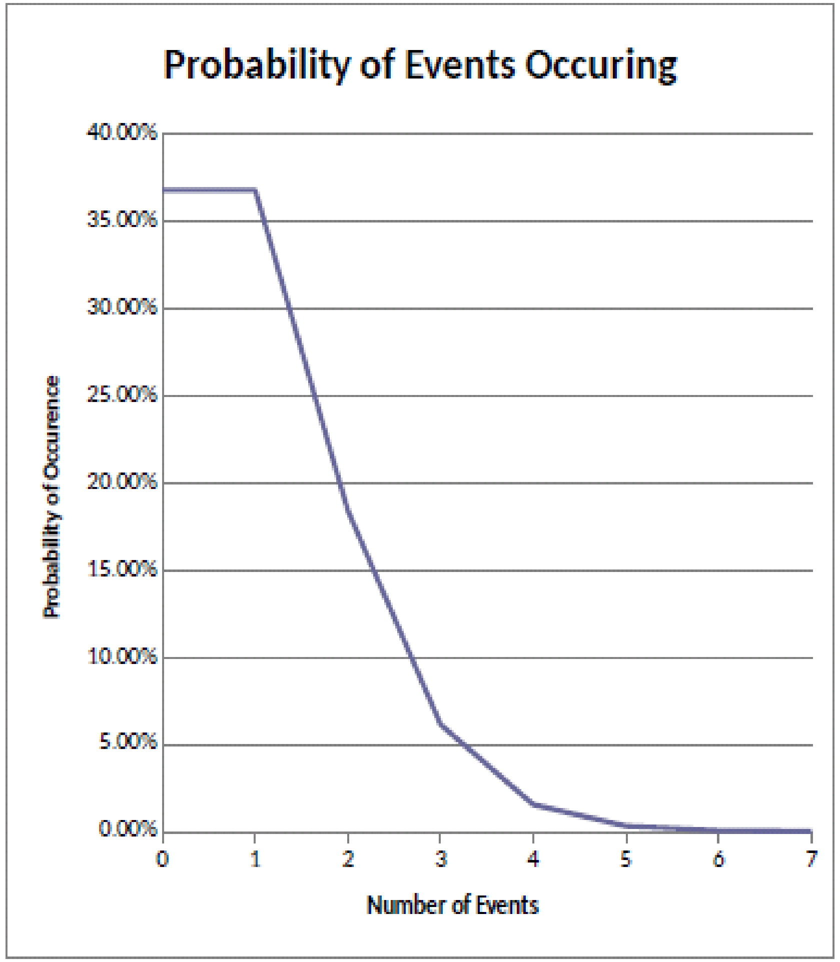
Poisson Probability Law

- The Poisson probability law tells us the probability that given
  - The average number of events per unit time, λ
  - The time τ, and
  - The number of events, k
- The probability of k events during time τ is

$$P(k; t, t+\tau) = \mathrm{e}^{-\lambda t}\frac{(\lambda\tau)^{k}}{k}$$

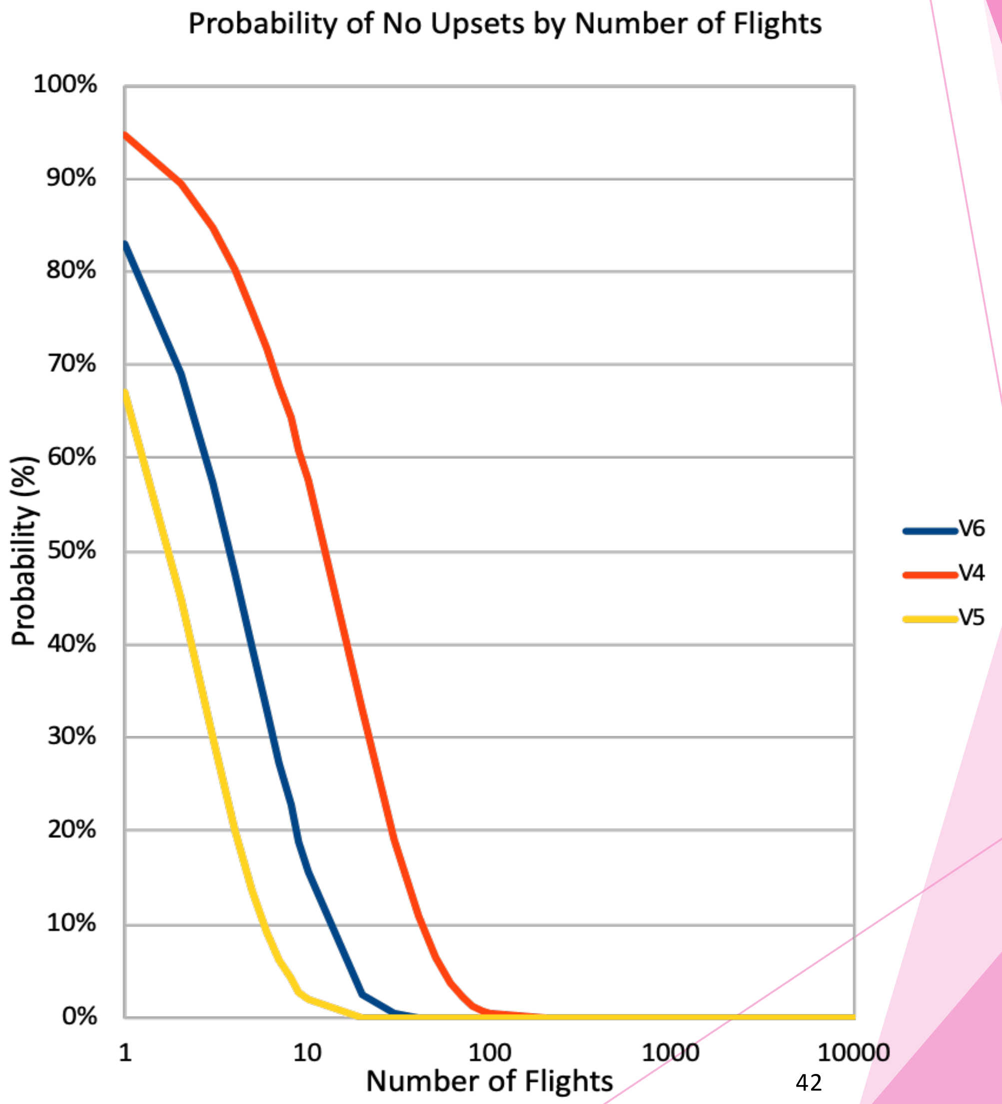
Inter-arrival time of SEEs

- Average rate only provides the "mean-average arrival rate" that upsets will occur at
- Errors will arrive based on the Poisson random process
  - MTTU gives the likely interval that errors will arrive at
  - Poisson determines when the errors will manifest
- There is an equal chance that no events and one event occur in one time period
- There is a 26% chance that 2 or more events occur



Inter-arrival time of SEEs

- Just because the sortie length < MTTU does not mean there will not be in-flight upsets
- At 20,000 feet, there is a 5% chance of having an upset in the first flight
- Each subsequent flight, it becomes increasingly less likely to <u>not</u> have an upset



Poisson Examples

- CREME-MC and QARM will provide you an estimate of what the error rate.
- You can convert that error rate into mean time to upset (MTTU) by inverting it:
  - MTTU = 1/SER
- Once you get to MTTU, then you can start asking questions like
  - Given time T, what is the probability that the system is still working?
  - Given time T, what is the probability that X upsets have happened?

What is the probability the system is still working?

- Assume that the system will fail if there are any errors. The error rate is 1 error per hour and we are interested in the first hour of operation. What is the chance that the system is still working in one hour?
- First off, our variables lambda and tau are:

$$\lambda = 1 errorperhour \qquad \tau = 1 hour$$

$$P(0 errors; 0{,}1 hour) = \mathrm{e}^{-1*1}\frac{(1*1)^0}{0!} = e^{-1} = .36$$

What is the probability the system is still working after two hours?

- Same setup, except tau is different
- First off, our variables lambda and tau are:

$\lambda = 1 errorperhour$ $\tau = 2hour$

$$P(0errors; 0{,}2hour) = \mathrm{e}^{-1*2}\frac{(1*2)^0}{0!} = e^{-2} = .14$$

What is the probability there are two errors in 1 hour?

- Same setup, except k is different
- First off, our variables lambda and tau are:

$\lambda = 1 error per hour$ $\tau = 1 hour$

$$P(0 errors; 0,1 hour) = \mathrm{e}^{-1*1}\frac{(1*1)^2}{2!} = \frac{e^{-1}}{2!} = .18$$

SEE Types

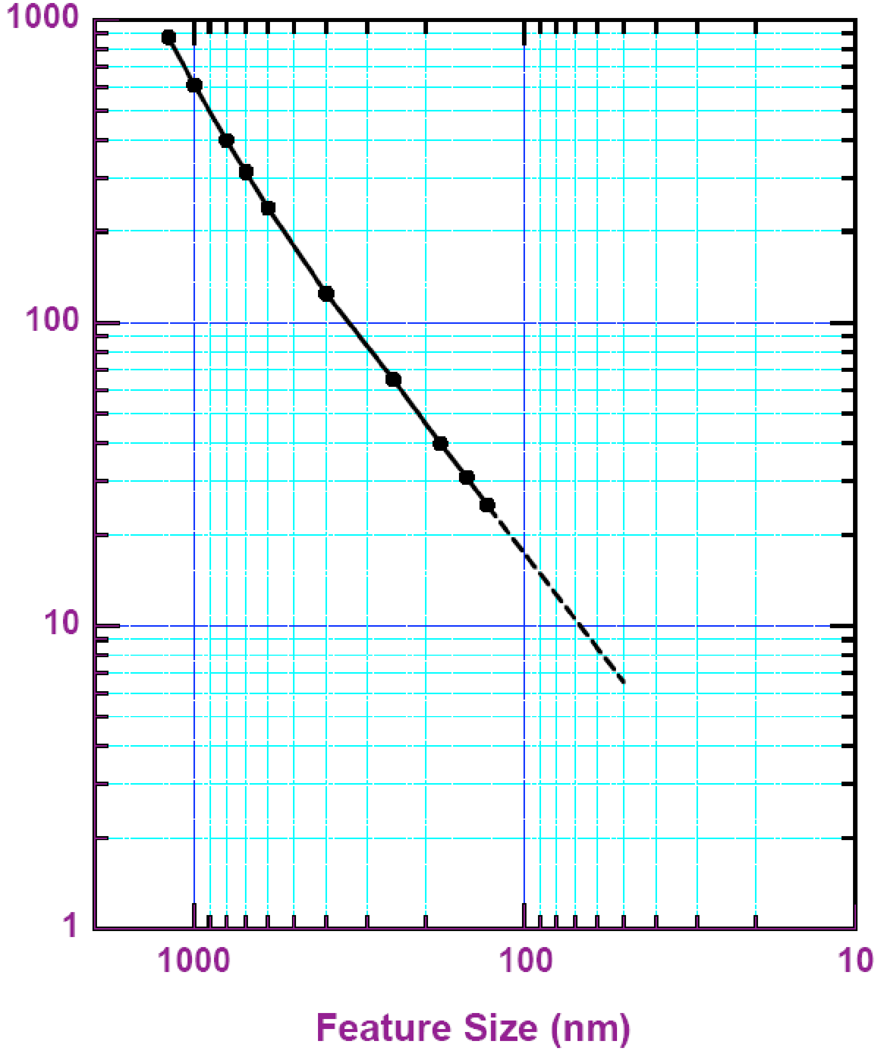
Types of SEEs

- Transient:
  - Single-event transient
  - Single-event upset
  - Single-event functional interrupt
- Destructive:
  - Single-event gate rupture
  - Single-event dielectric rupture
  - Single-event latchup
  - Single-event burnout

Single-event transients (Transients or SET)

- Radiation-induced charge temporarily changes the value of gate
  - No way to tell the difference from a real signal and a transient-affected signal
  - Transients in logic gates are a problem if latched, causes data corruption
  - Transients in the clock or reset trees can cause much more global issues
- Decreasing clock frequencies make it easier to latch a transient: transient pulse and clock signal are roughly the same

Critical Pulse Width for Unattenuated Propagation



Mavis, “Single-Event Transient Phenomena: Challenges and Solutions.” MRQW, 2002.

Single-Event Upsets (upsets or SEUs)

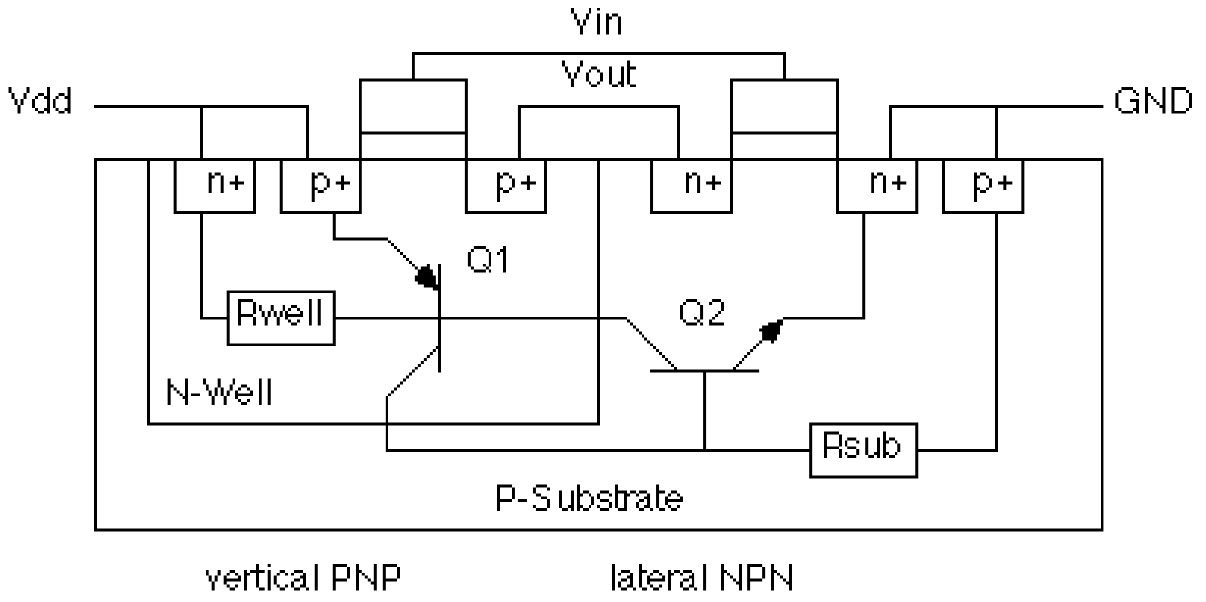
- Cause bit flips in memory-based
    - Data changes from 1→0 or 0→1
    - In some parts single-bit upsets (SBUs) are as common as multiple-cell upsets (MCUs)
        - Handy guide for MCUs:
            - All multiple SEUs are MCUs
            - Multiple-bit upsets are MCUs within a single word (memory) or frame (FPGA)
        - Paul Dodds' simulation of MCUs
- Strongly affected by feature size:
    - Smaller feature size means smaller targets, smaller Qcrit, more MCUs
    - Even with a decrease in per-bit cross-section, often see an increase in per-device cross-section increase

Single-Event Functional Interrupts (SEFIs)

- Device will not operate functionally until reset
- Often caused by an SET or SEU in control logic for the device
- Causes availability issues as part will need to be reset to return to functionality

Single-event latch-up (SEL)

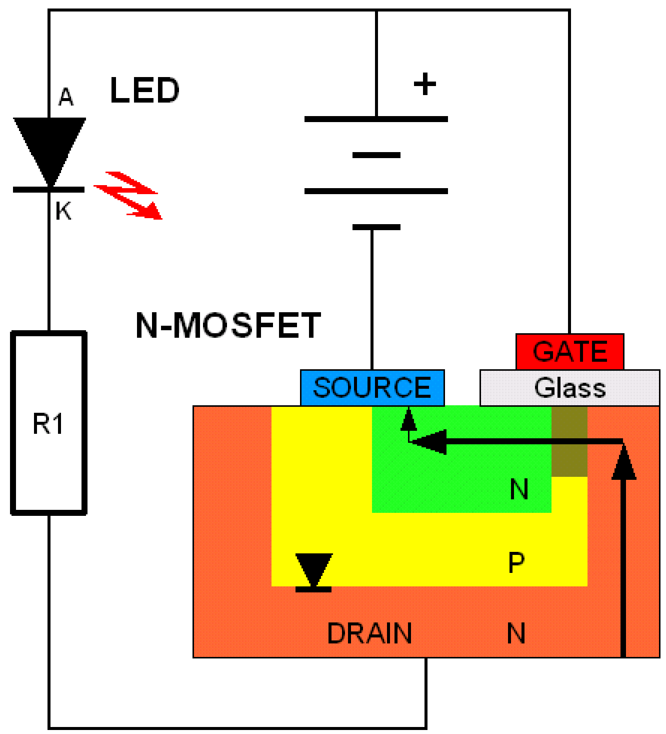
- Traditional reliability issue with CMOS due to parasitic transistors caused by well/substrate contact
  - Once turned on, current increases rapidly and destroys the part
  - Radiation is another avenue for turning on the parasitic transistor
- Military/aerospace parts often have an epitaxial layer to prevent SEL, by localizing charge collection



http://www.ece.drexel.edu/courses/ECE-E431/latch-up/latch-up.html

Single-Event Gate Rupture (SEGR)

- Common only in power MOSFETs
  - Occasionally seen in parts that have on-chip power, such as flash
- Ion-induced rupture of the gate oxide
- Destructive event – dielectric and gate electrode material “melt and mix”
- Ohmic short or a rectifying contact through the dielectric



Homework for Summer Students

Start Working on Your Related Work Sections

- Start finding references for your test, reading the references, and writing up a short summary indicating:
  - What are the results (cross sections, dose, etc),
  - How will these results help your test
    - Indicates that mitigation is needed
    - Provides a way to estimate fault or error rate
    - Provides an alternative method for doing what you are doing
      - If that is the case, list its strengths and weaknesses
- For example, previous tests on FPGAs would give you an idea of:
  - What the fault cross section is
  - Potential fault rate during the test, leading to an estimate of how long the test will last
  - Existing mitigation methods, including the amount of area the mitigation takes, effects on performance, ability to correct faults, types of errors that occur

Resources

- IEEE Transactions on Nuclear Science
- IEEE Transactions on Device and Material Reliability
- IEEE Transactions on Computers
- IEEE Radiation Effects Data Workshop (Conference not journal)

Notes on Torring on Lab Networks

- Please, please, please do not tor on lab networks
- There is likely no need to tor on lab networks – we have digital libraries to almost everything from social science to business to STEM
- Another thought: if you are torring at your home institution, this summer is your opportunity to read and download everything for free. You might want to work on the related work for your dissertation as well.