



Rensselaer
IEEE Student Branch



Radiation Hardening Semiconductors

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GBM Attendance



Assumptions We Take For Granted as Engineers

Air resistance is negligible

$$g = 10$$

$$\pi = 3$$

Everything is not constantly being bombarded by ionizing radiation, alpha particles, and neutrons traveling near the speed of light



the sun



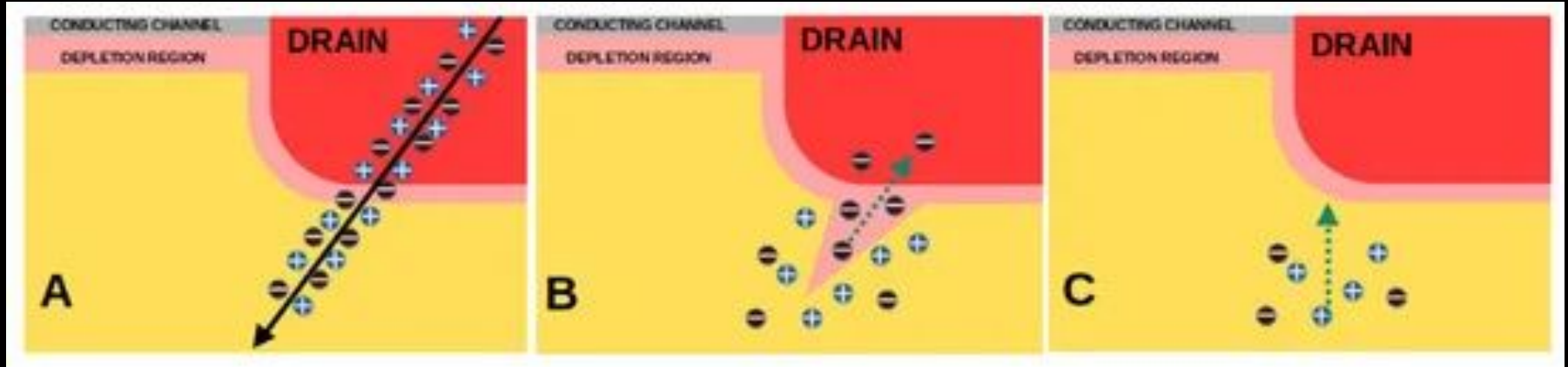
Types of errors

There are two primary types of errors associated with the two types of radiation

Ionic radiation causes Single Event Effects

Non-ionic radiation causes Crystalline Lattice Defects

Single Event Effects



A: Ionic interference creates electron hole pairs

B: Funnel effect pulls in the majority of either holes or electrons, creating phantom signal

C: Residual charge takes a much longer time to dissipate, possibly collecting

SEE Soft Error, Bit Flip

In digital terms, this can cause a bit flip

Instruction register

0001000100000110: 4,385

Single Event Effect

1001000100000110: 37,126

32,000 ish instructions skipped

YOU'VE SEEN

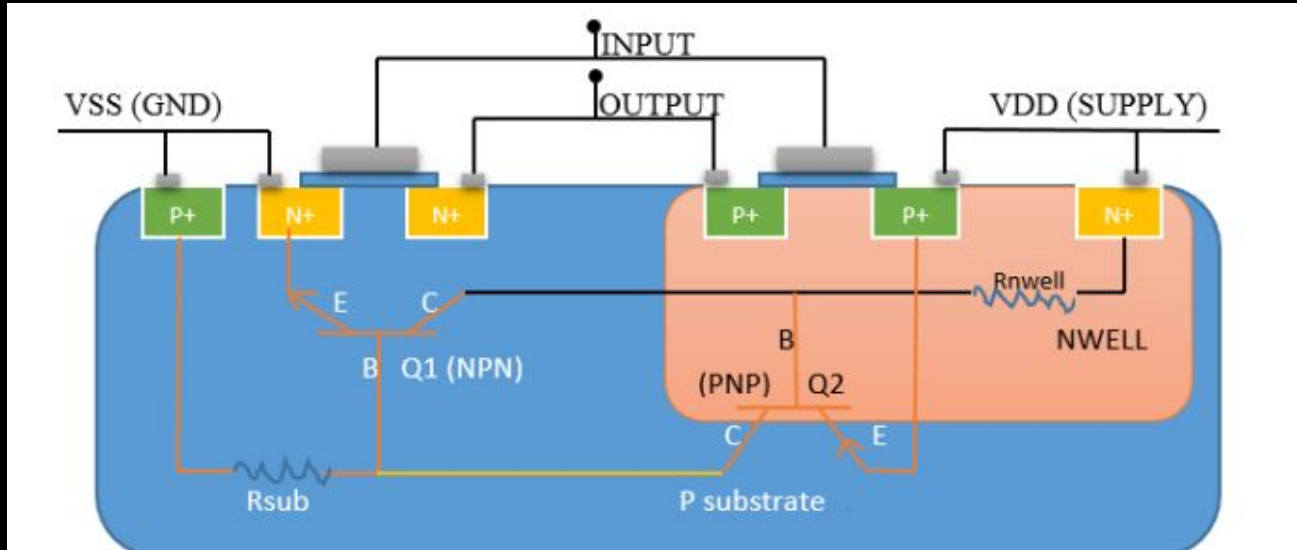
ROM, EPROM, DRAM, SRAM

NOW GET READY FOR

ARIM:
Arbitrarily Rewriting Itself Memory

SEE Hard Error, Latch Up

If the charge accumulation is sufficient, the transistor can enter a Latch Up state, turning your inverter into a space heater, pun intended



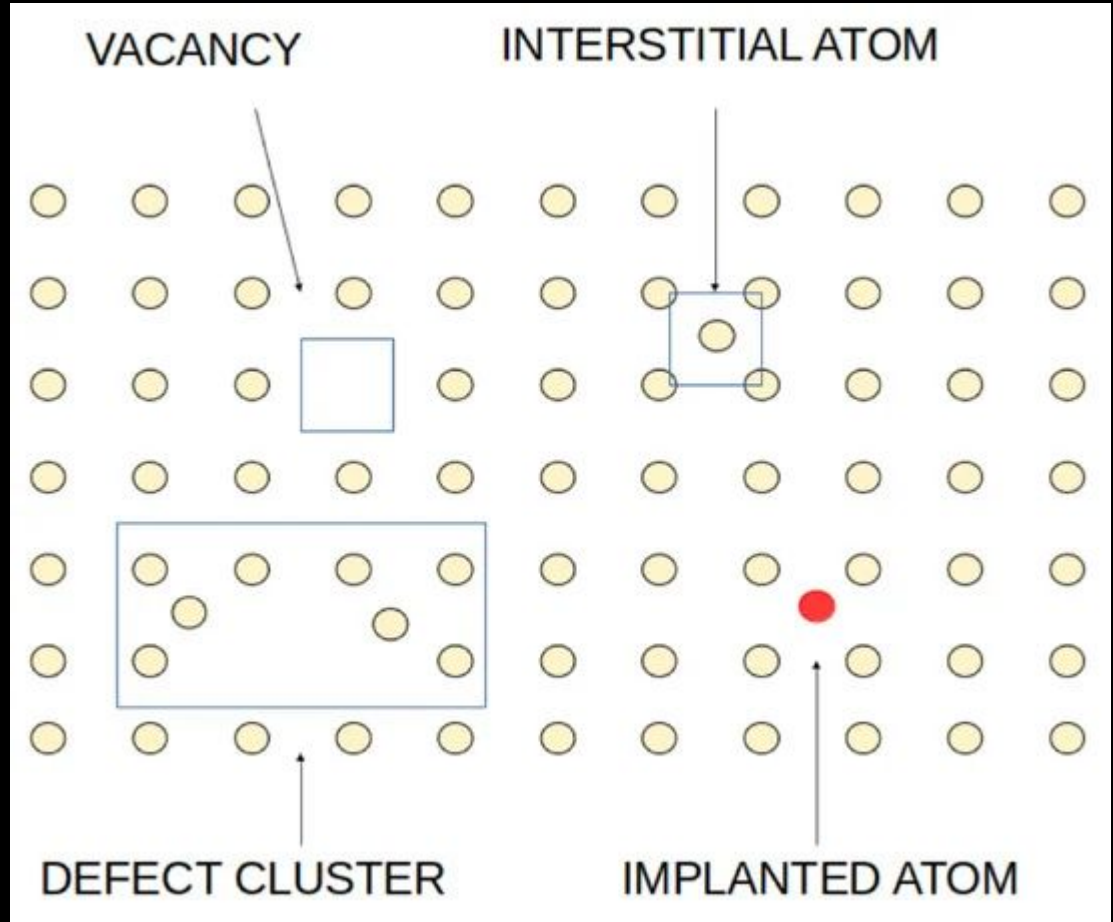
Crystal Defects

Results of near light speed non ionized particles

Occur when a neutron or non ionized particle like a gamma ray hits silicon

Results in defects in the silicon

Affect all materials, not just silicon, including polysilicon, ceramics, metals, and thermal conductors



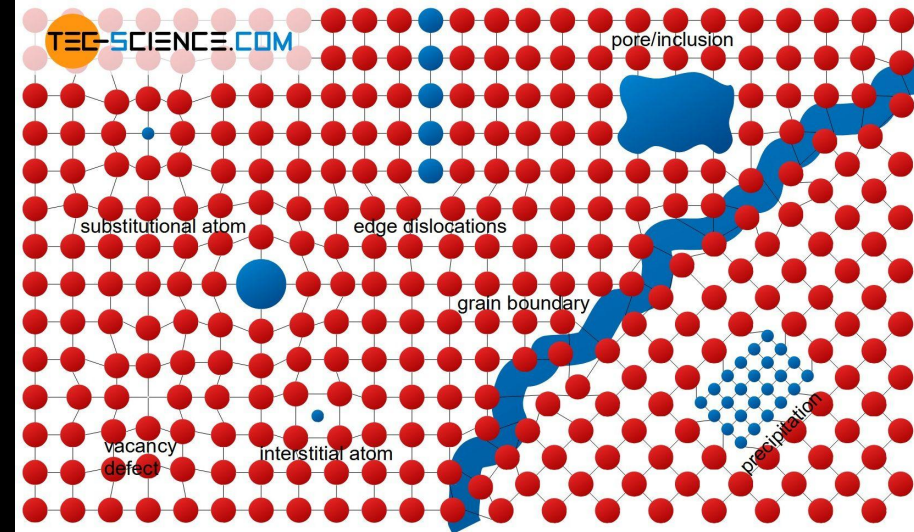
Crystal Defects

Trapping: create a trap where charge carriers can get stuck,

Recombination: serve as a point where electrons and holes recombine,

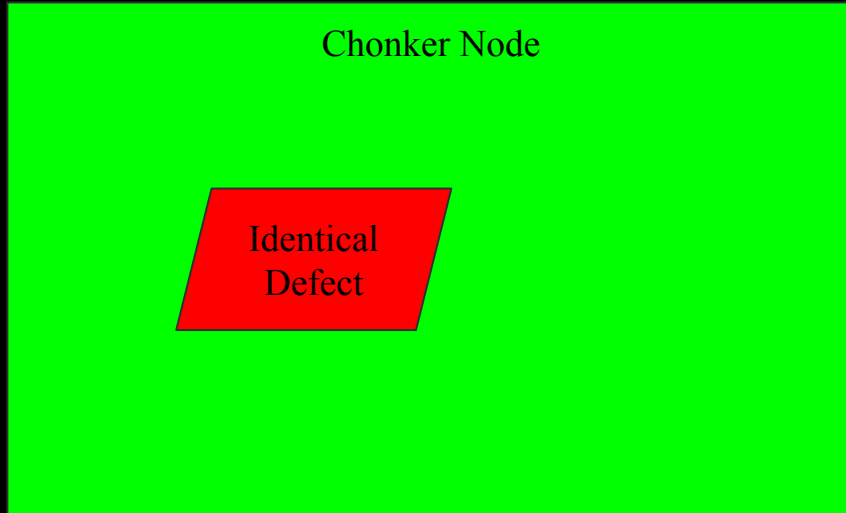
Pathways: serve as high or low impedance pathways for charge carriers

Resistance Changes

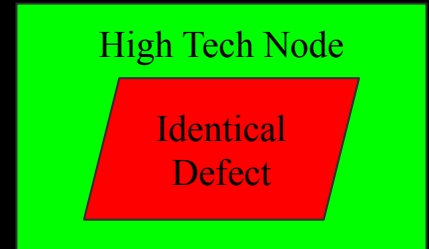


Factors of Lattice Defects

Size: larger nodes are more likely to get hit by cosmic radiation and suffer defects, but the relative impact of these defects will be smaller, on net meaning larger nodes maintain functionality better in space



Defects of the same size have very different proportional effects on the device



Factors of Bit Flips

Q_{crit} , or critical charge, is defined as the magnitude of charge required to flip a bit,

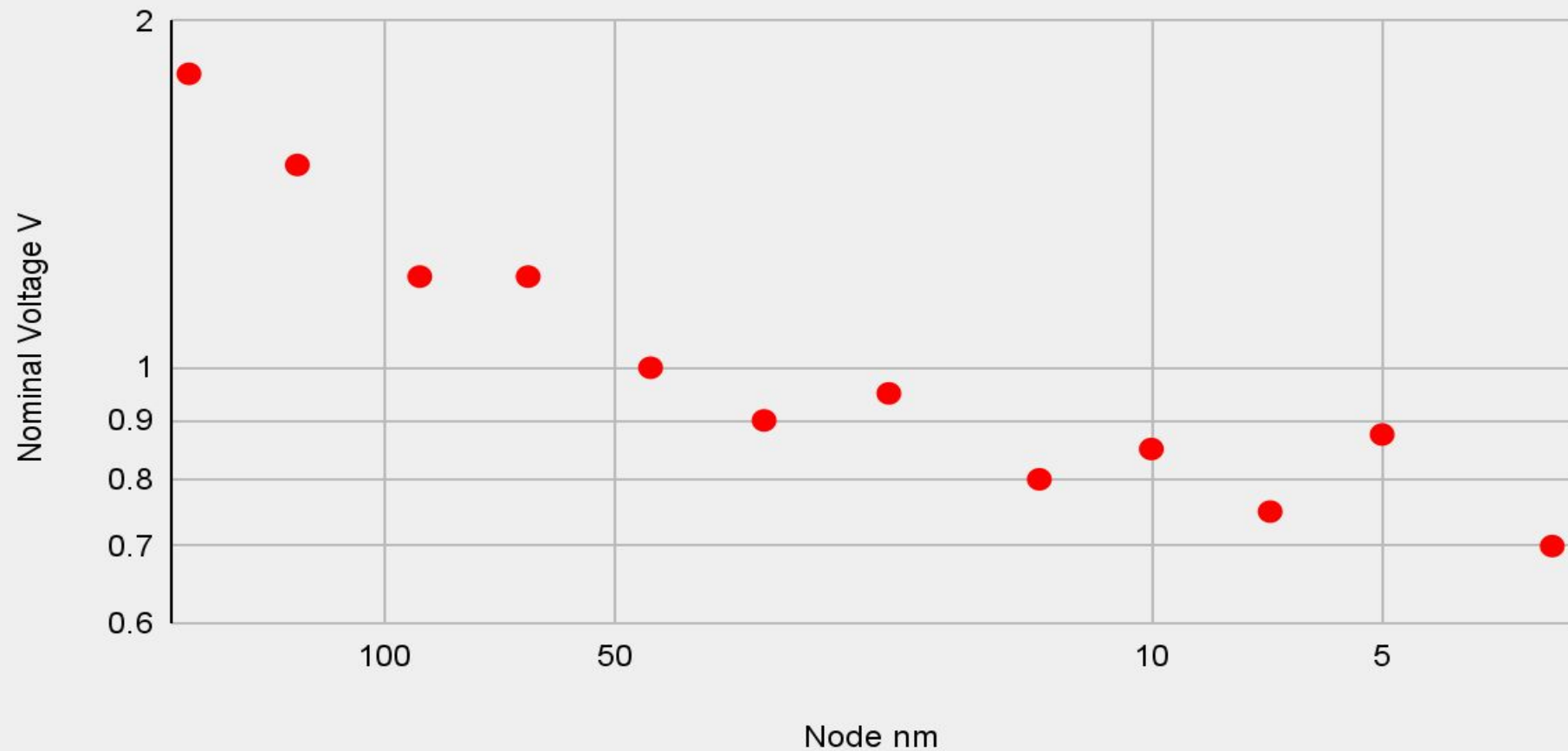
From $C = Q/V$, and $C \propto A/d$, we can surmise that $Q_{crit} \propto AV/d$

Q_{crit} is directly related to nominal voltage: $Q_{crit} \propto V$

Q_{crit} is also directly related to transistor size: $Q_{crit} \propto A/d$

If we assume all dimensions scale equally, then $Q_{crit} \propto \text{Scale}$

Nominal Voltage V vs. Node nm



Bigger is Better

That graph shows how more advanced nodes have lower nominal voltages

So as we get into more advanced nodes, the charge required for a bit flip decreases exponentially as a function of regular performance

At the extreme, SSEs can start impacting arrays of cells if the node is small enough

Additionally, lattice defects have a diminished relative effect over larger components

One easy solution is to just use big old technology nodes that can effectively “tank” the radiation



Shielding

Astronauts are also susceptible to radiation based damage, yet we are able to send them into space kinda-sorta-mostly-safely-ish

We protect astronauts with passive shielding made of low z atoms and molecules like water, food, fecal matter, custom hydrogen dense polymers, and aluminum

This passively protects electronics just as well as it protects astronauts, which is to say pretty decently



Lockheed Martin's AstroRAD Vest tested on Artemis I, decreased exposure by 60%

Imperfect Solution

These are imperfect solutions for three reasons

One: Older nodes and shielding limit technical capabilities and location

Two: These solutions add weight, a precious commodity in space

Three: Neither of these solutions are expensive or complex enough to allow the semiconductor industry to adequately shakedown space firms, and our bonuses aren't paying for themselves

Radiation Hardening By Design or Process

RHBD vs RHBP

RHBD is faster and cheaper to implement

RHBD involves anything in the design process of the semiconductor

RHBP involves the materials and manufacturing processes of the semiconductor

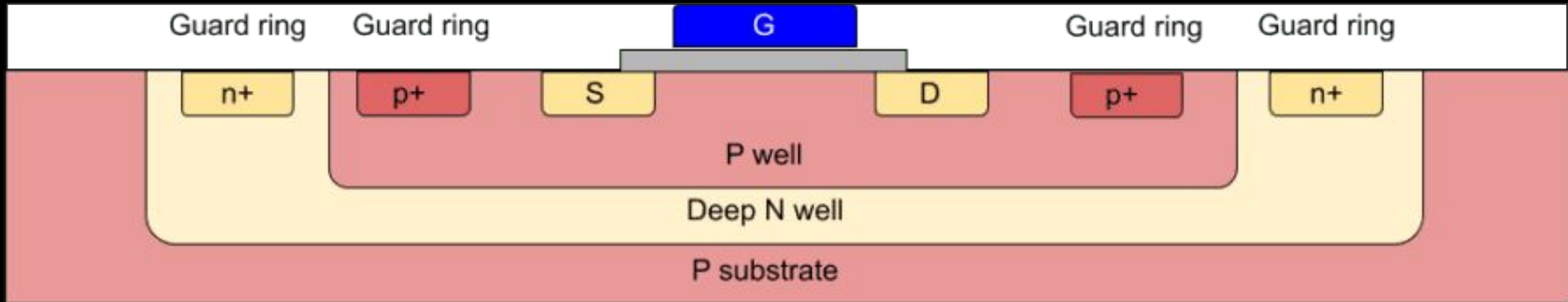
Both play a crucial role in rad hardening electronics

Guard Rings and Wells

Guard Rings are connected by conductors to Vcc or gnd to provide a path for charges

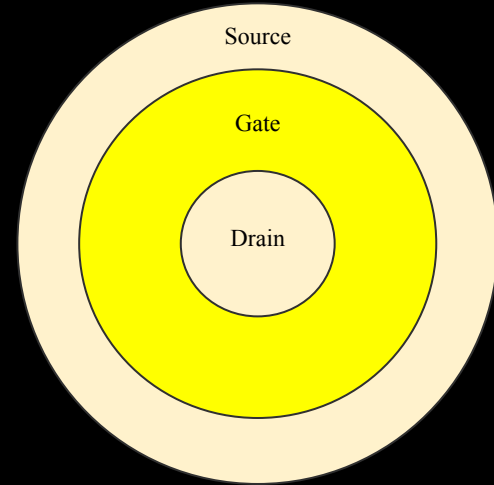
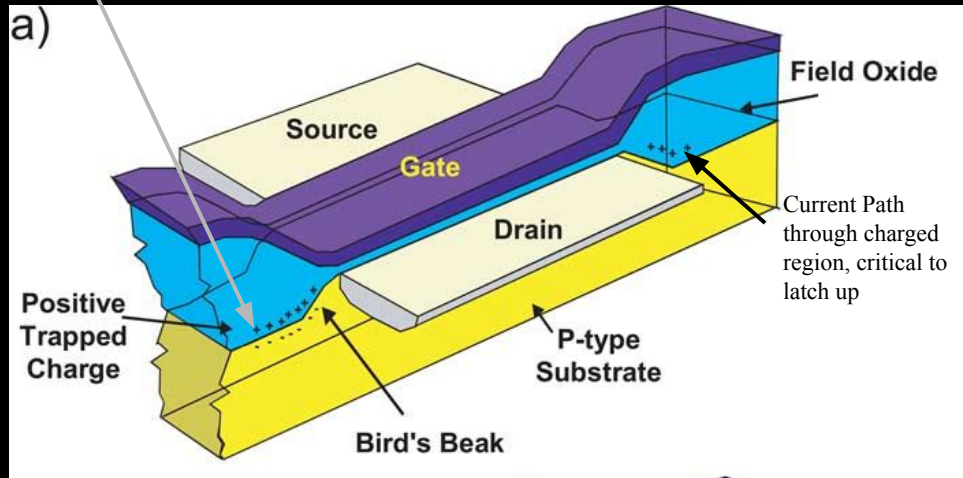
Normally used on earth for protecting analog circuits from digital noise

Protects the transistor from stray charge ending up in substrate for bit flips or latch up



Annular Transistors

This is the charge that causes latch up



Metal Shielding

- While they can scatter secondary radiation, high Z atoms do a great job at stopping lower energy radiation, and decreasing the energy of high energy radiation
- We could just put all our electronics in a trash can, but we get better weight and protection when the shielding is closer

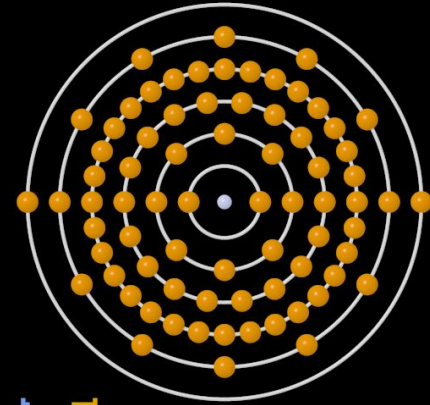


Why Tungsten

Tungsten has double the electron density of copper, which means for each distance traveled in tungsten, a given gamma ray (photon) will have twice as large a chance of hitting an electron and slowing down.

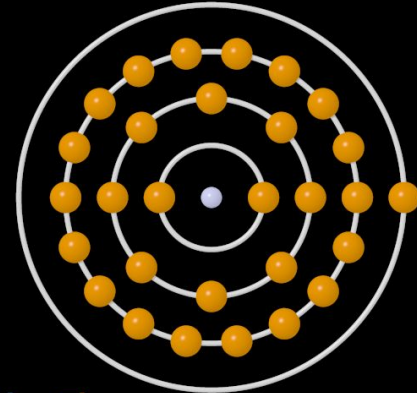
Tungsten also has a higher charge, keeping its inner electrons in more strongly, decreasing the risk that a random electron the gamma ray hits will be ejected causing further problems

Tungsten




www.webelements.com

Copper

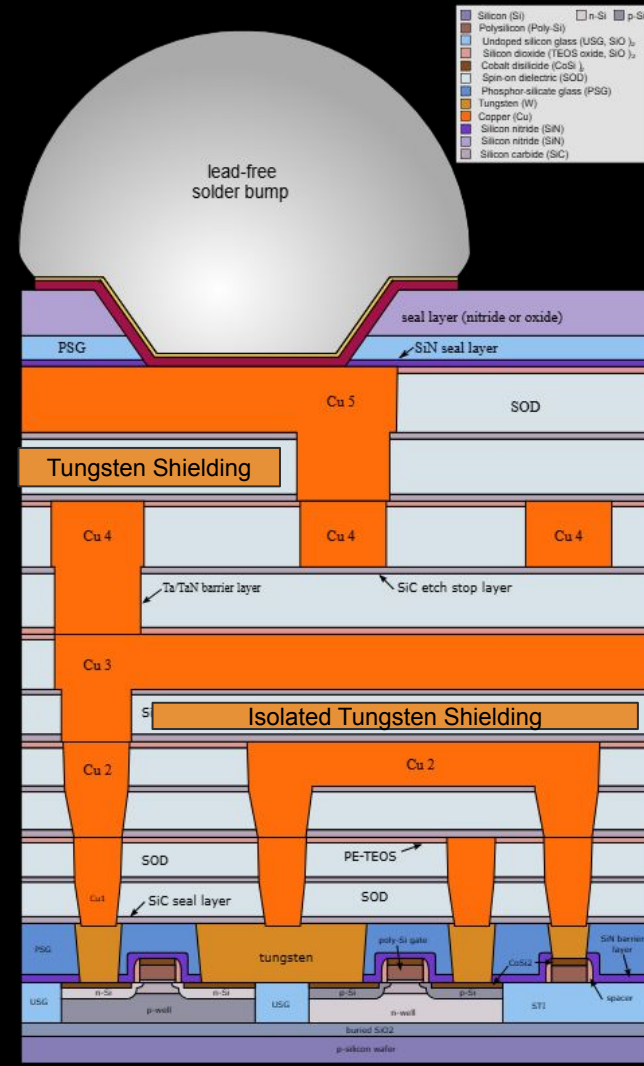



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Tungsten Shielding

Tungsten is Z-74, making it good for shielding, especially since it is a normal material in semiconductor fabrication processes

We can throw a sheet of it in one of the metal layers to get better shielding with less total mass than shielding the entire chip



Dual-Interlocked-Storage-Cell

The acronym for this is DICE, not DISC, no joke

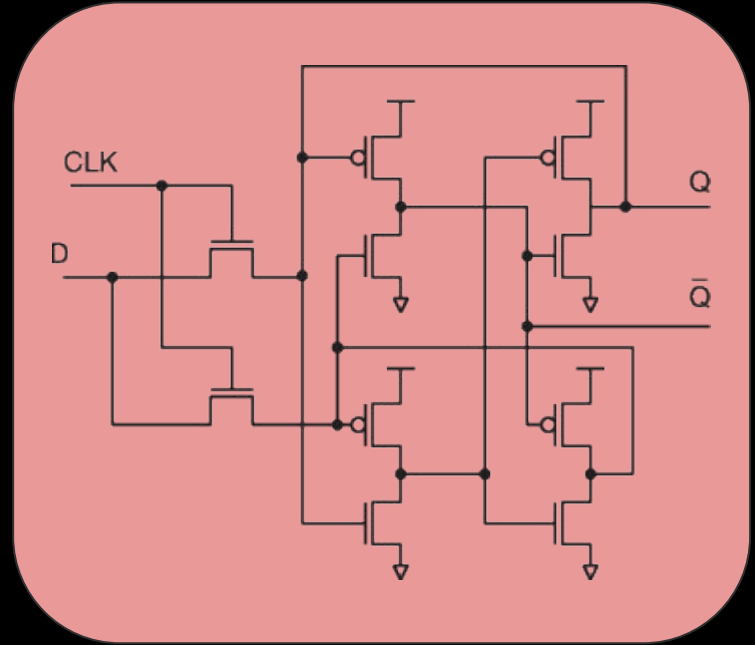
SLOW

POWER INEFFICIENT

UNREASONABLY LARGE

But all signals are always driven, so any random charge appearing at any point will be absorbed by the system and corrected for quickly

PROOF



Design to Process

The previously mentioned methods were all considered RHBD

The following methods fall under RHBP

RHBP lags behind by a decade or two because unlike RHBD which can be made in existing fab processes sometimes altering standard cells, RHBP definitionally requires process changes

Implemented well, RHBP can provide much more benefit than RHBD, it just takes forever

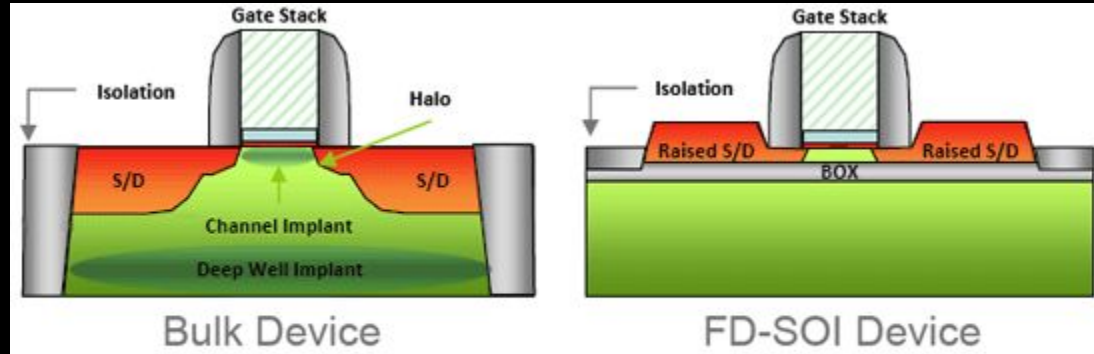
Node Analogy

By Design relies on making better use of processes we already have, like finfets, they can provide performance optimizations within the limits of our manufacturing capabilities

By Process techniques require custom fabs, designed and built from the ground up to optimize for radiation hardening. Like how EUV came in over budget and late, but can reach performance levels no gate reshaping ever could, RHBP is a brutally expensive endeavor that can make devices with up to 8 times the total ionizing dose tolerance compared to RHBD

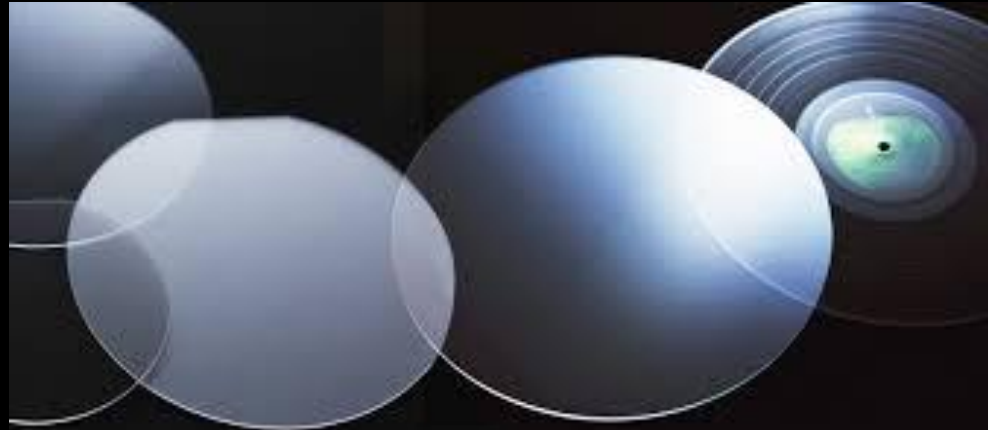
Silicon on Insulator

- Isolates transistors from substrate with Buried Oxide layer (BOX)
- Greatly decreases volume for charge accumulation
- Eliminates the parasitic pnpn structure in traditional transistors since all transistors are isolated from the substrate
- Requires electron traps in the BOX to avoid charge accumulation



Silicon on Sapphire

- Similar in concept to SOI
- No silicon substrate at all, use a sapphire wafer instead, quintupling cost
- The lack of a substrate means there is no risk of stuff happening in the substrate causing interference
- Better thermal properties (heats up less)
- Better insulating properties
- Very pretty wafers



Metal Shielding's Mechanical Flaw - Tungsten

- Metal shielding in semiconductors is typically done by tungsten as a high Z atom that is already used in semiconductor processes as a conductor
- Metal shielding layers are thicker and larger than interconnects, introducing risks of bending the die or not being uniformly leveled
- Large planes of tungsten are prone to delamination (peeling) and require special layers below them to adhere them to the die
- Large tungsten components are brittle and can suffer microfractures at processing temperatures

RHBP Improvements

- Molybdenum is beginning to be researched as an alternative to tungsten with superior physical properties, including thermal expansion coefficient
- Backside Compensation Layers are layers added to the back of the wafer to counteract the bowing effect of the tungsten shields
- The interfaces between the tungsten and rest of the wafer are undergoing continuous development to not only improve adhesive properties, but to isolate mechanical stresses the tungsten introduces

MOLYBDENUM

VERSUS

TUNGSTEN

Visit www.PEDIAA.com

MOLYBDENUM	TUNGSTEN
Molybdenum is a silvery grey transition metal that has the atomic number 42	Tungsten is a silvery white metal that has the the atomic number 74
Has a much lower melting point	Has a much higher melting point
Less dense	Denser
Has a higher thermal conductivity	Has a lower thermal conductivity
Considered more machinable	Less machinable
Typically less expensive	More expensive

Boron-10 Depletion

Boron is a the standard P type dopant with good electrical and manufacturing properties

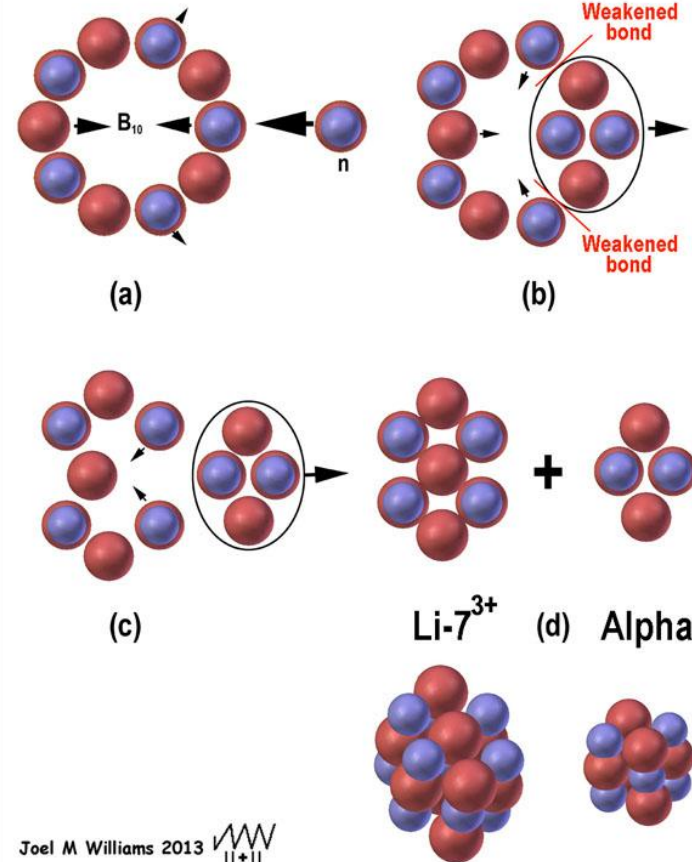
Natural Boron is 20% Boron-10, which is stable but can react with neutrons to decay, wreaking havoc on a nm scale system

Pure B-11 can be sourced from nuclear reactors (the B-10 absorbs neutrons and decays) or through industrial isotopic distillation

Rad Hardened electronics can use Pure B-11 to mitigate this problem, adding another cross contamination consideration for fabs

Neutron Capture by Boron-10

(modeled with Dumbbell Baryons)



VERY FUNNY...

Heresy - Replace Silicon

- While when we think of electronics we think silicon, all we really need is a semiconductor
- The most extreme, expensive, and potentially effective method of rad hardening is to replace all the silicon with a different semiconductor



**NOW,
FACE THE WALL**

Diamond Transistors?

- Theoretically, Diamond would be the perfect material
- Monster bandgap, 5.5 eV
- Diamond is near impossible to break the lattice of because of how strong it's bonds are
- Diamond devices are also not yet developed enough to provide sufficient performance to be worth consideration



Alternatives to Silicon (Bandgap 1.1 eV)

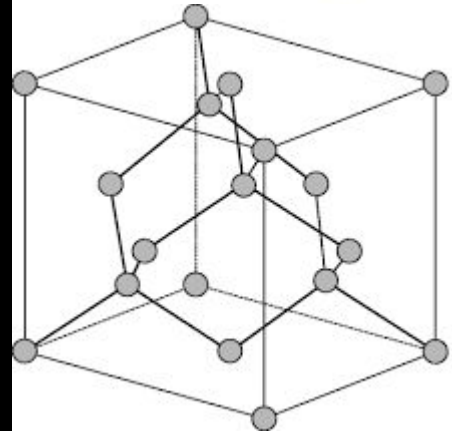
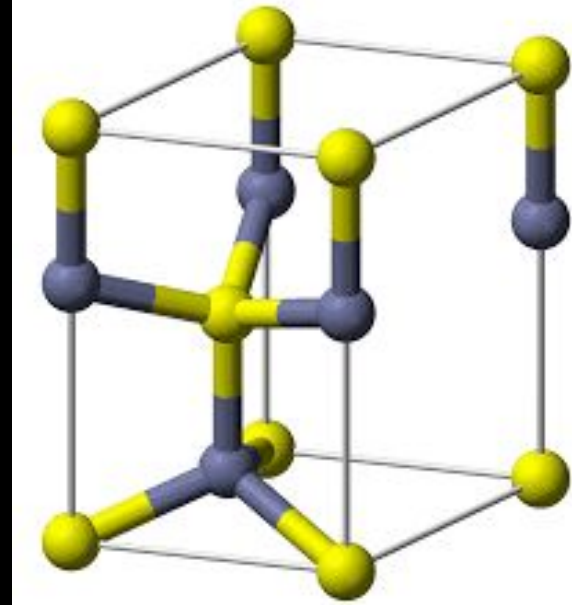
Material	Bandgap (eV)	Primary Strength	Functionality
Gallium Arsenide (GaAs)	1.4	High Speed	• No oxide layer, gates are metal semiconductor junctions, so there is no oxide layer for charge to become trapped in • Great analog properties and linearity • Less parasitics • Lower voltage • Faster electron travel/less switching time
Gallium Nitride (GaN)	3.4	Annealing	• Massive bandgap means it takes a ton more energy to excite an electron • Also exhibits self healing properties for 90% of defects from radiation • No oxide layer, gates are metal semiconductor junctions, so there is no oxide layer for charge to become trapped in • Massive breakdown voltage (48 vs 12 V)

GaN Self Healing

GaN possesses a strong wurtzite crystal structure (mean bond strength of 9 eV, vs ~ 1.1 eV for Si) vastly increasing resistance to crystalline defects

In the event of damage, GaN re-crystallizes, especially under high radiation, where the radiation itself serves as the source of energy to fix the crystalline structure

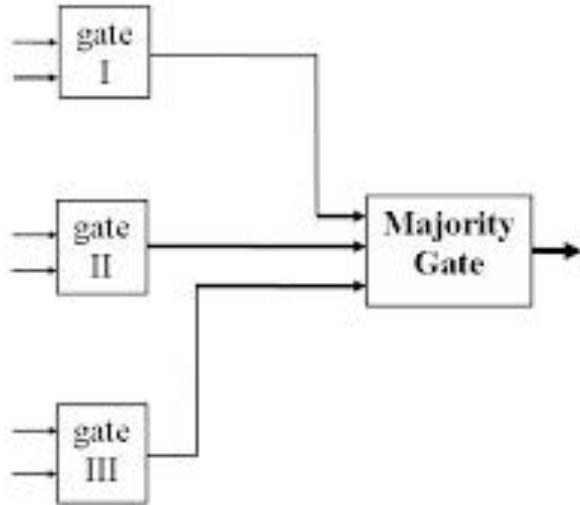
The Nitrogen sublattice specifically has a threshold energy of 0 to return to its original position, so it just fixes itself ambiently



Data Science Side

- Even with all these physical protections, we can only minimize risk of radiation damage not eliminate it altogether, so every extra protection helps
- This can take the form of copies, or more complex methods like check codes
- We will take a very limited dive into the Data Science side, as that falls outside the EPS/EDS scope
- It follows the same principles of data, transmission, and calculation redundancy for on Earth systems

Triple Modular Redundancy



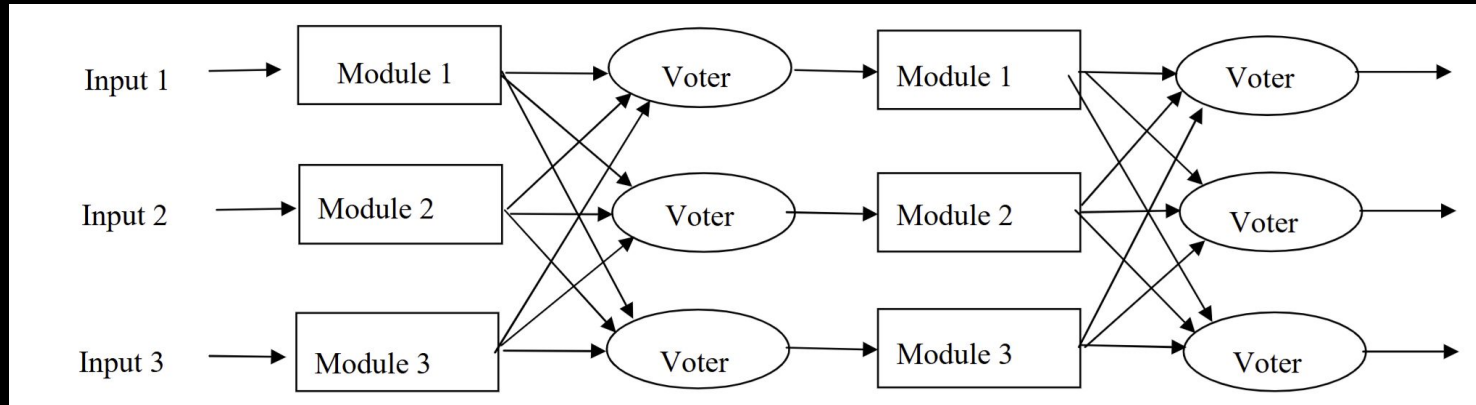
TMR involves having three copies of something, and everytime you want it's result, use a voter circuit to do majority rules so if any of the three fail, the system maintains full integrity

This is mainly used for memory but can also be used for computational resources

Considerations

SSE's can hit multiple adjacent bits, or even entire arrays of bytes in a memory location, so we can't store redundant memory cells together.

Also, the voter itself is liable to damage, so do we need triplicate voters? How do they vote?

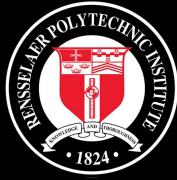


Conclusion

- Rad hardening is not achieved by any one solution, it is fundamentally unsolvable as all semiconductors, even those on earth, wear out over time
- Through the combination of as many methods as we can, we try to delay the inevitable as long as possible
- The Rad Hardening industry is projected to grow to 2.3 Billion dollars domestically by 2030, partly spurred on by the burgeoning space based data center industry, which is itself expected to reach 1.9 billion dollars in the same time period
- Rad Hardening electronics is a highly specialized field that combines material science, chemistry, nuclear physics, quantum mechanics, and electrical engineering, representing an often ignored but very lucrative industry where top engineers (not counting managers) can make upwards of \$200,000

TIME IS MARCHING TOWARDS OUR INEVITABLE Wear Based Failure





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Thank You For Your Time

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