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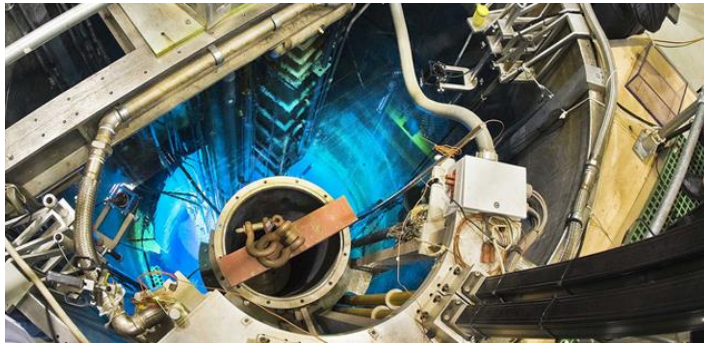

Radiation Effects in Electronics

Elizabeth Auden, SEERI talk, 29 July 2015

U.S. DEPARTMENT OF ENERGY | NNSA National Nuclear Security Administration

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Overview

Sandia National Laboratories

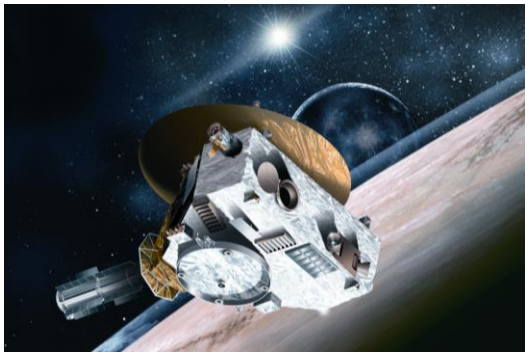
1. Applications and environments
2. Electronics
3. Radiation effects
4. Mitigation and exploitation

Applications

- Aerospace and military
- Satellites and space missions
- Nuclear power applications
- Terrestrial computing
- Medical physics

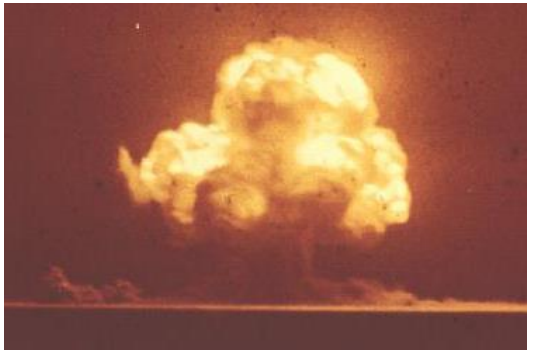
F-15 Eagle Jet Fighter


LANL Cielo supercomputer


NASA New Horizons probe


MRI and PET brain scans

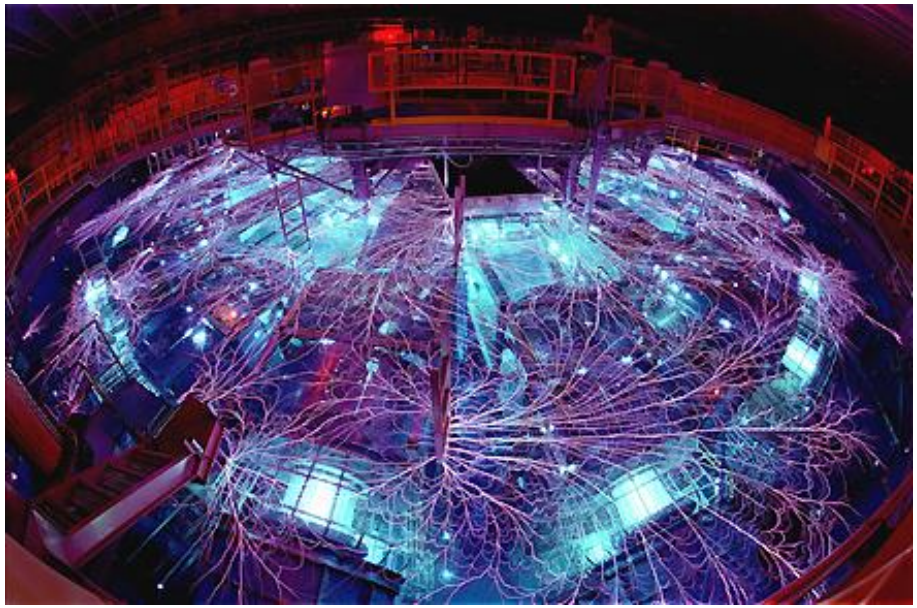

Palo Verde nuclear plant


Trinity atomic bomb test

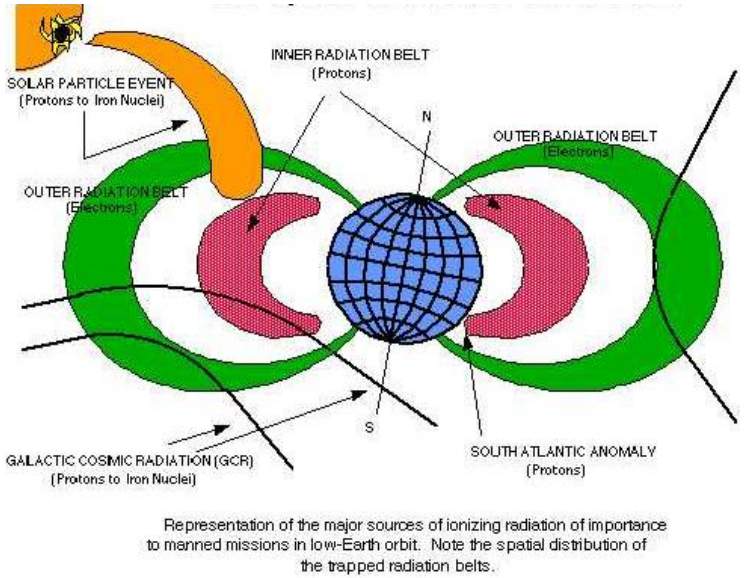
Radiation environments

- Terrestrial
- Space
- Man-made radiation environments

Sandia Mountains



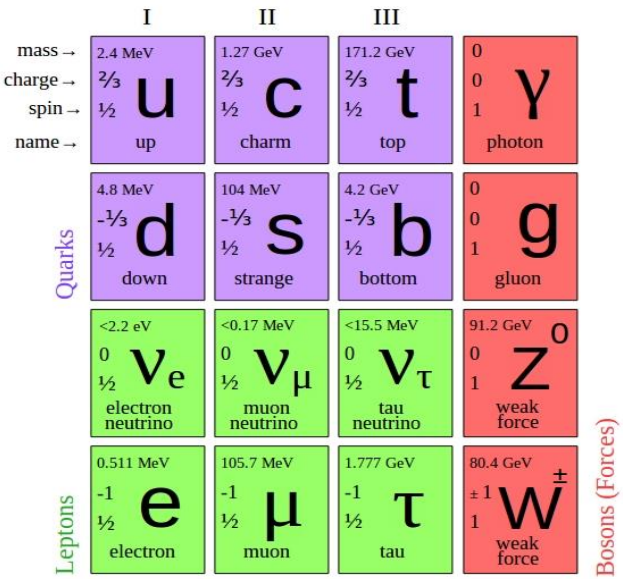
Z Pulsed Power Facility



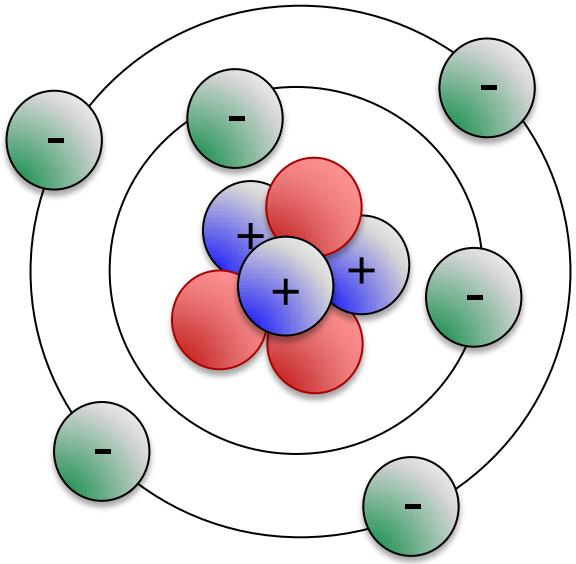
Representation of the major sources of ionizing radiation of importance to manned missions in low-Earth orbit. Note the spatial distribution of the trapped radiation belts.

Space radiation environment
[After Smith, NASA Quest, 1997]

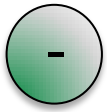
Radiation particles

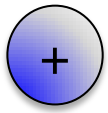


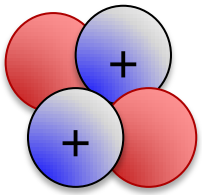
Periodic table of particles



n_0



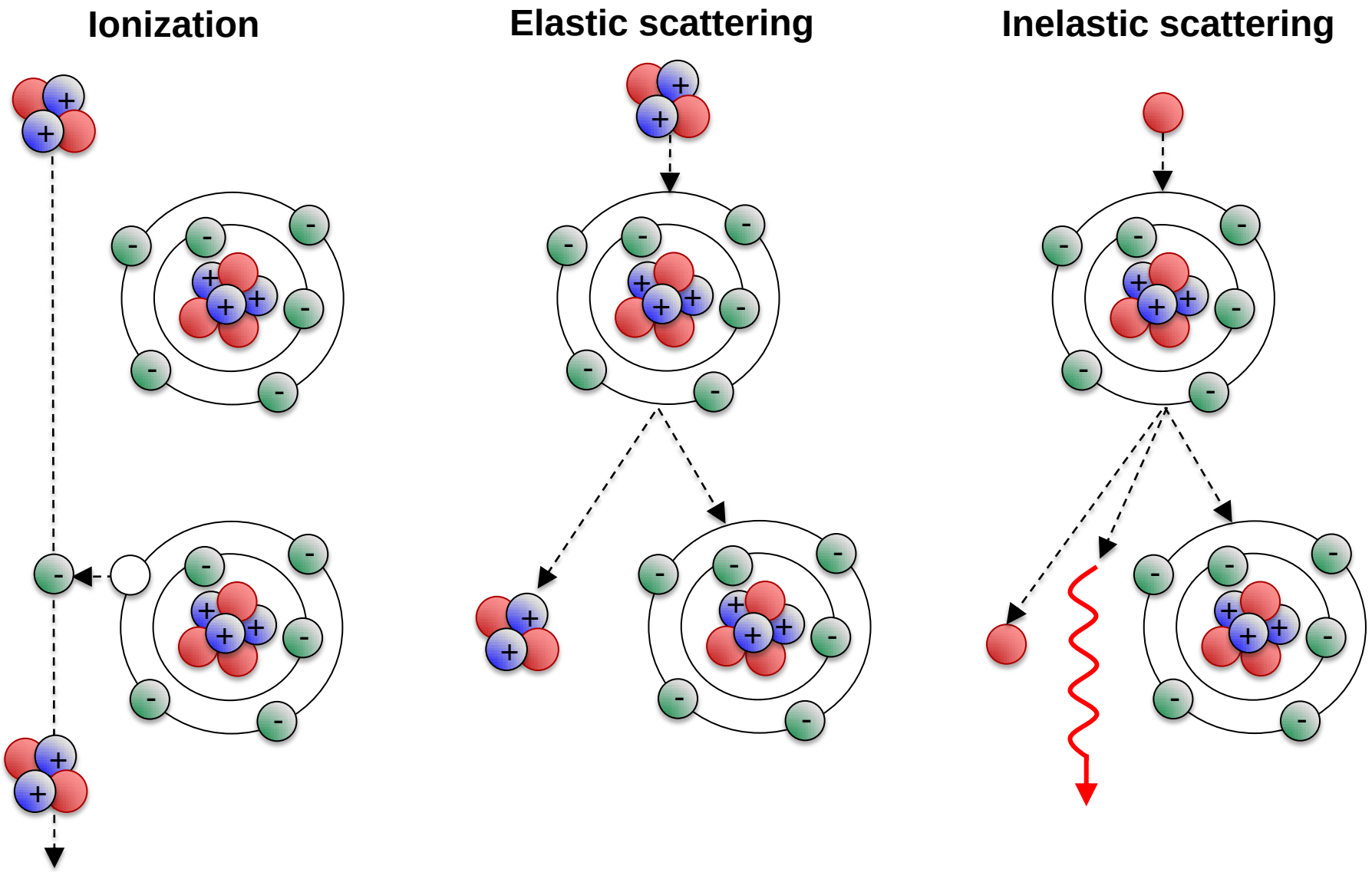




γ e^- p^+ α heavy ion ($Z > 2$)

Mass

Radiative interactions



Overview

1. Applications and environments
2. Electronics
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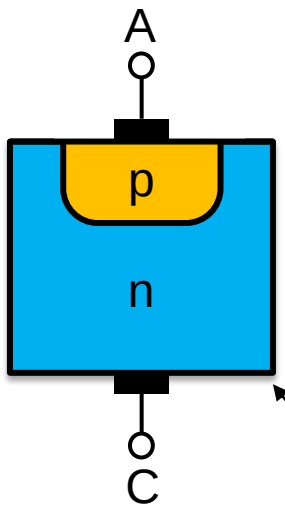
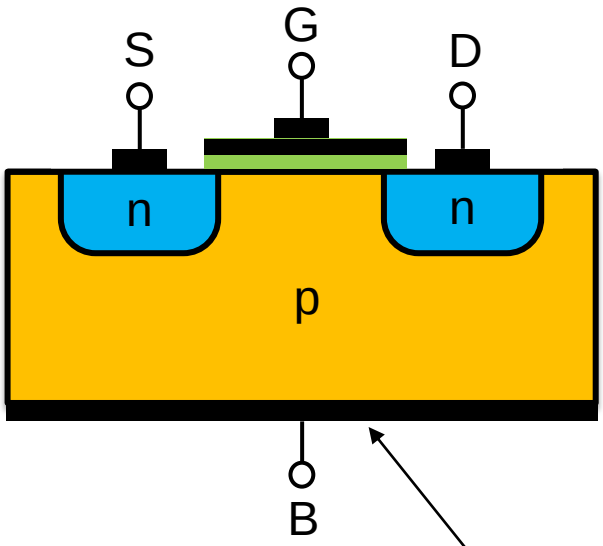
Electronics timeline





Cretaceous Period
65 million years ago

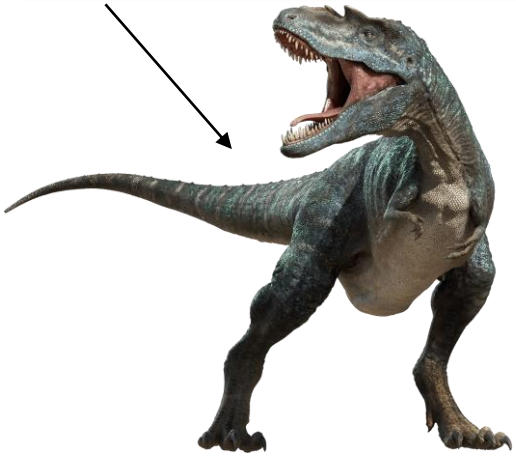
PN-junction
1940

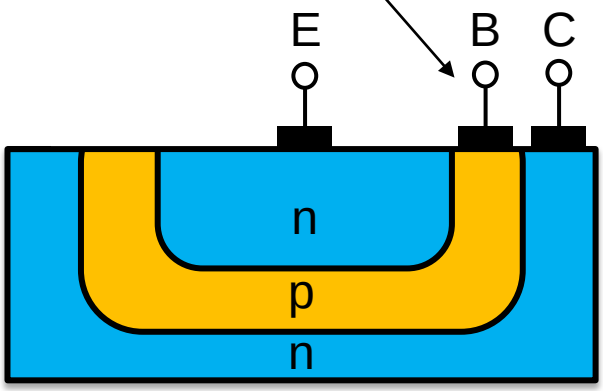
BJT
1947

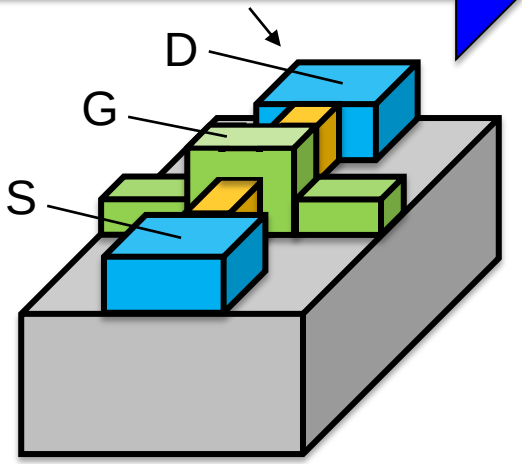
MOSFET
1959

FinFET
1999

Today
2015



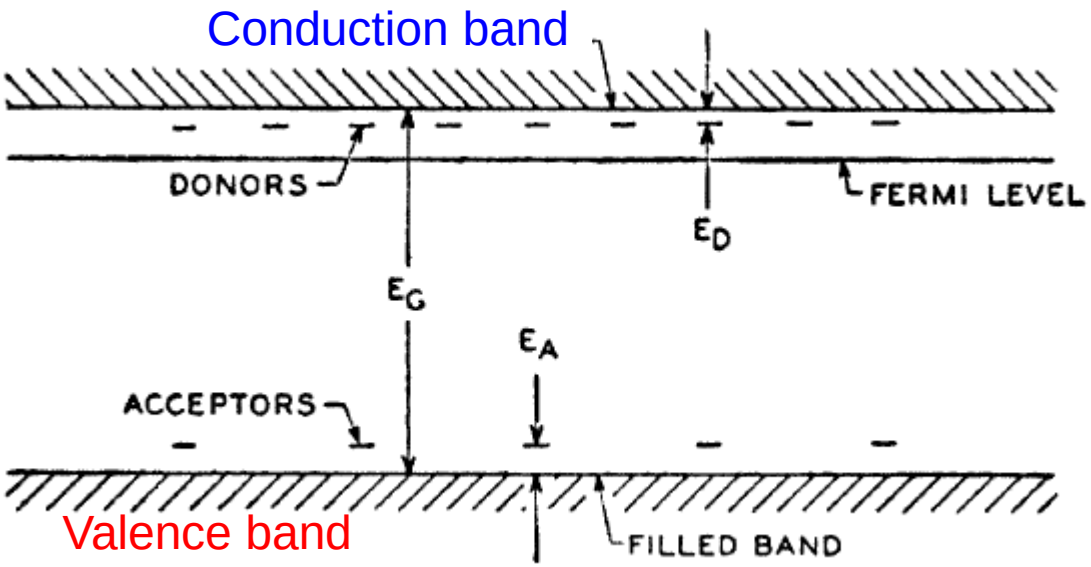




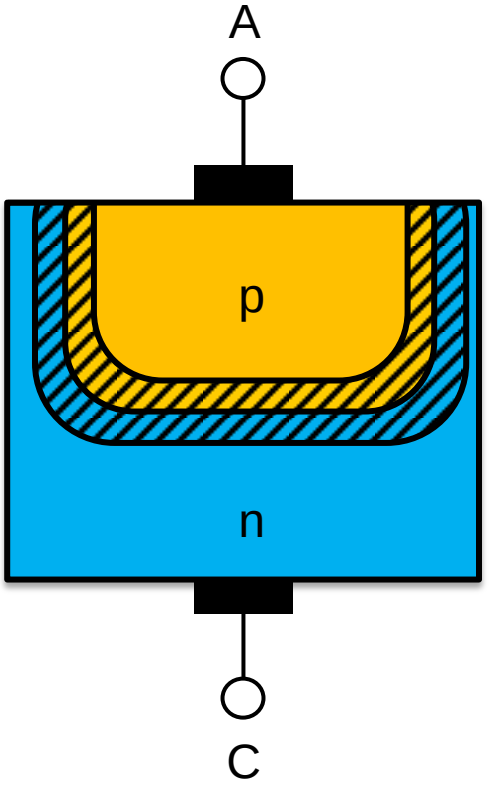
Electrons and holes

In semiconductors, current can flow in the presence of an electrical field.

- "Forbidden gap" separates valence and conduction bands
- Electron excited to conduction band leaves hole in valence band



Energy band diagram for silicon
[After Pearson, *Phys. Rev,* 1949]



Depletion region surrounding pn-junction

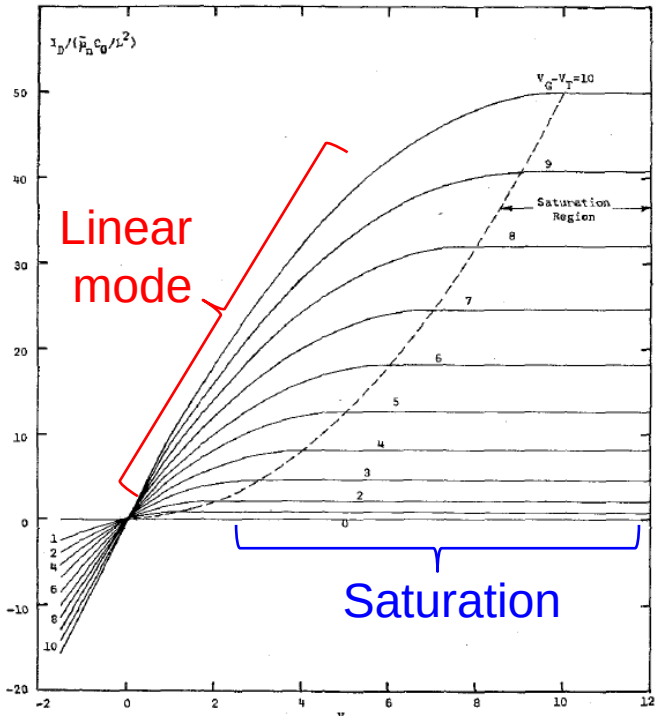
Majority carrier devices

Current flow depends on

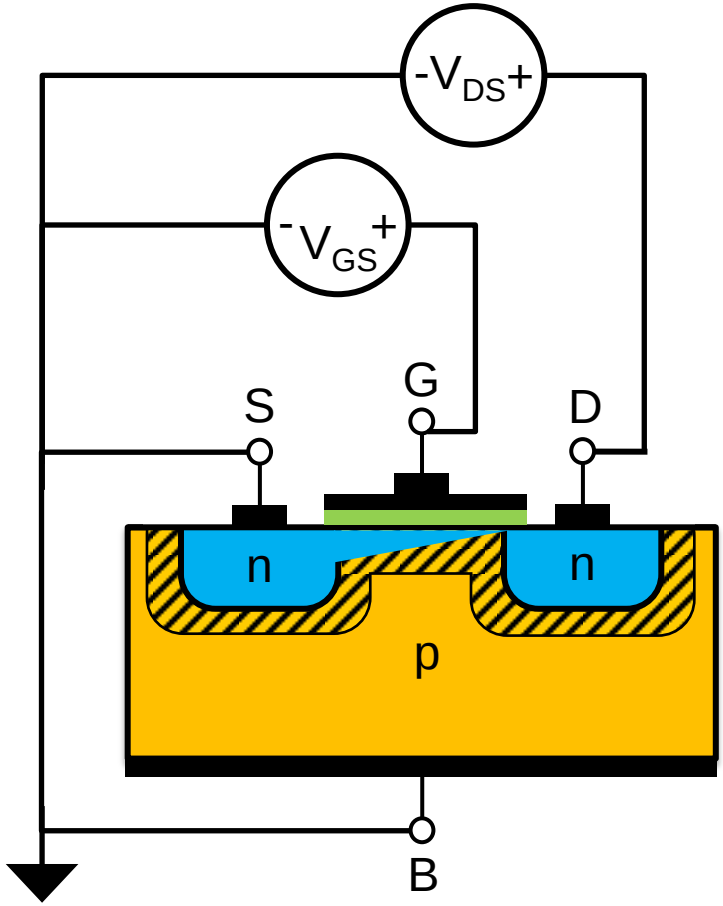
- electrons in n-doped regions
- holes in p-doped regions

Examples:

- MOSFETs
- Schottky diodes



MOSFET IV curve [After Sah, *TED,* 1964]



n-channel MOSFET in saturation mode: current is carried by electrons in channel

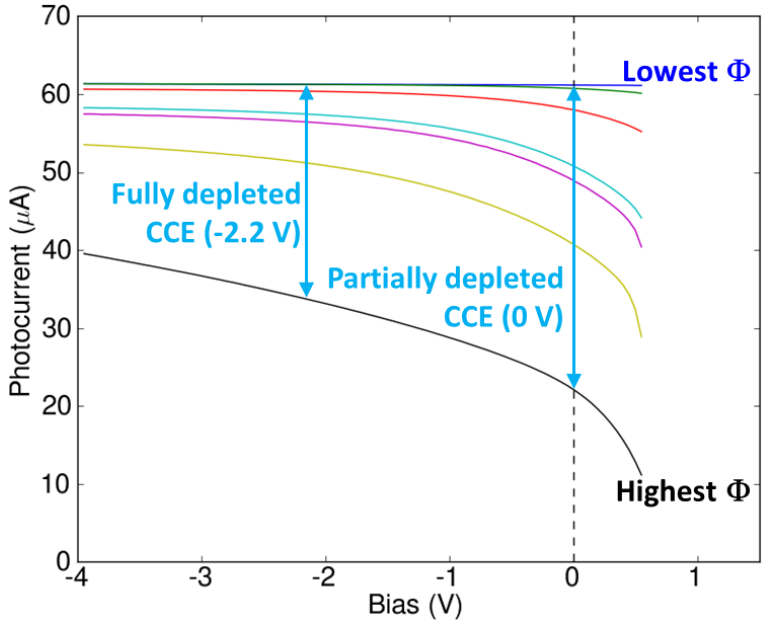
Minority carrier devices

Current flow depends on

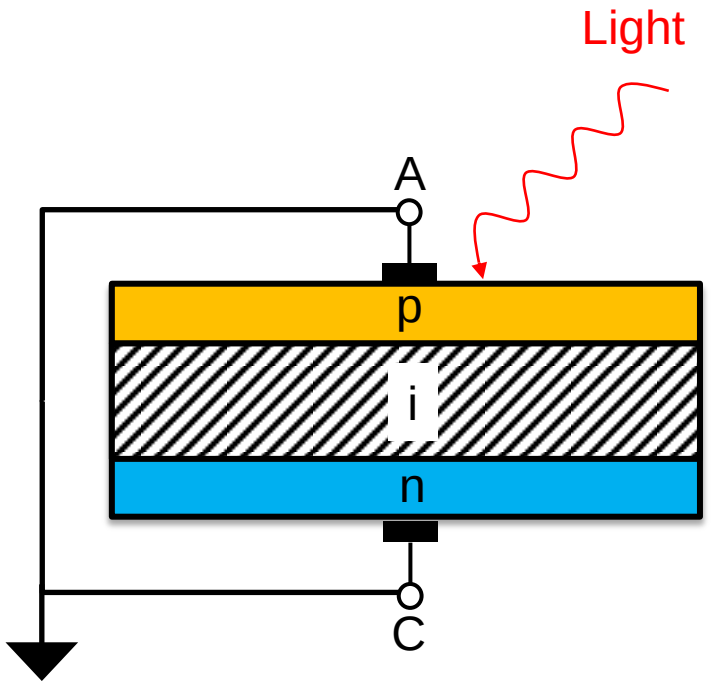
- holes in n-doped regions
- electrons in p-doped regions
- holes and electrons in depletion regions

Examples:

- Bipolar junction transistors (BJTs)
- P-i-N diodes



Photocurrent in irradiated GaAs P-i-N diode (org. 1111)



P-i-N photodiode: current is carried by holes and electrons

Overview

Sandia National Laboratories

1. Applications and environments
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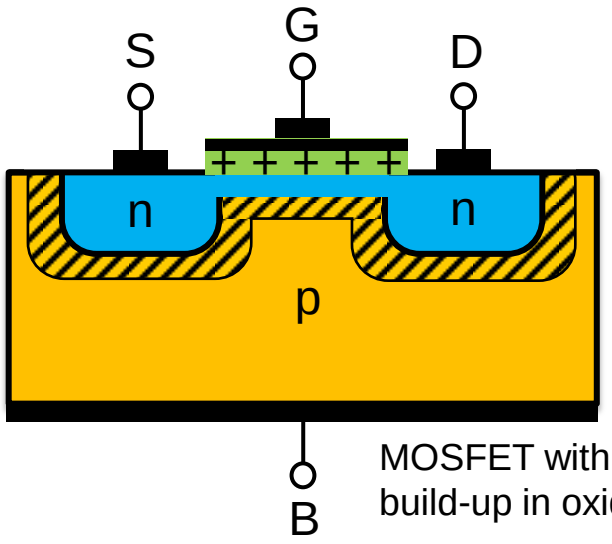
Radiation effects

- Total ionizing dose
  - Long term degradation from trapped charge
- Displacement damage
  - Long term degradation from lattice damage
- Single event effects
  - Soft errors
  - Hard errors

Total ionizing dose

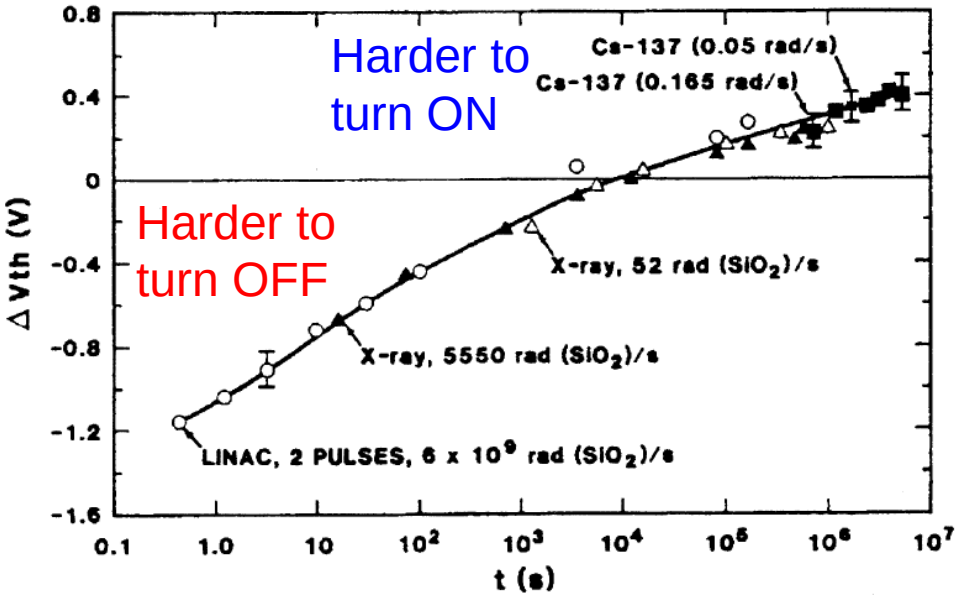
Long term ionization creates build-up of charge

- Oxide layer most vulnerable
- Threshold voltage (V_{th}) shift



MOSFET with hole build-up in oxide

Telstar satellite, Bell Labs

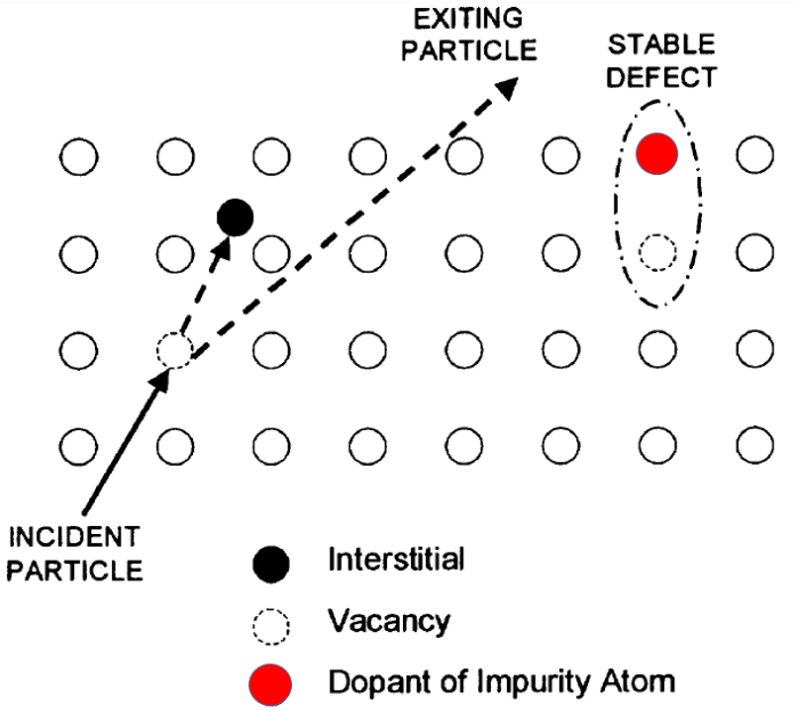


MOSFET V_{th} shifts [After Fleetwood, *TNS*, 1991]

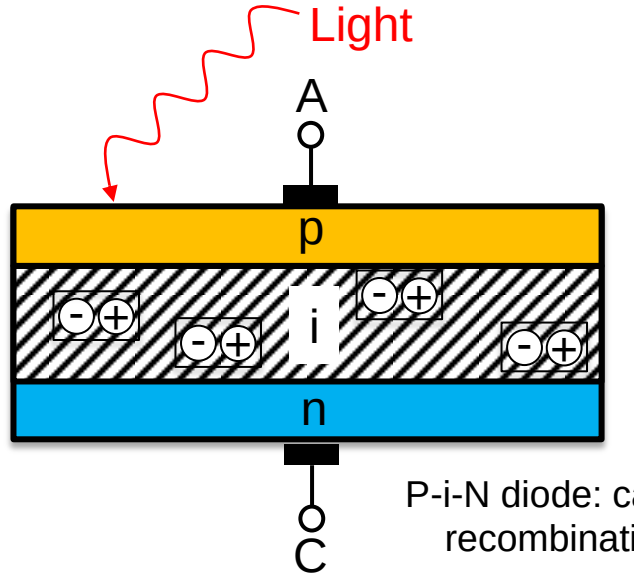
Displacement damage

Atoms are displaced in the semiconductor lattice

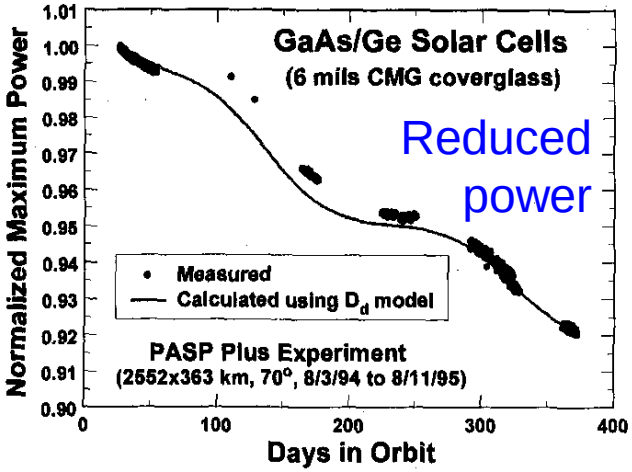
- Carriers recombine at midgap defects
- Minority carrier devices more vulnerable.



Defect clusters produced by single ions
[After Marshall, NSREC short course, 1999]



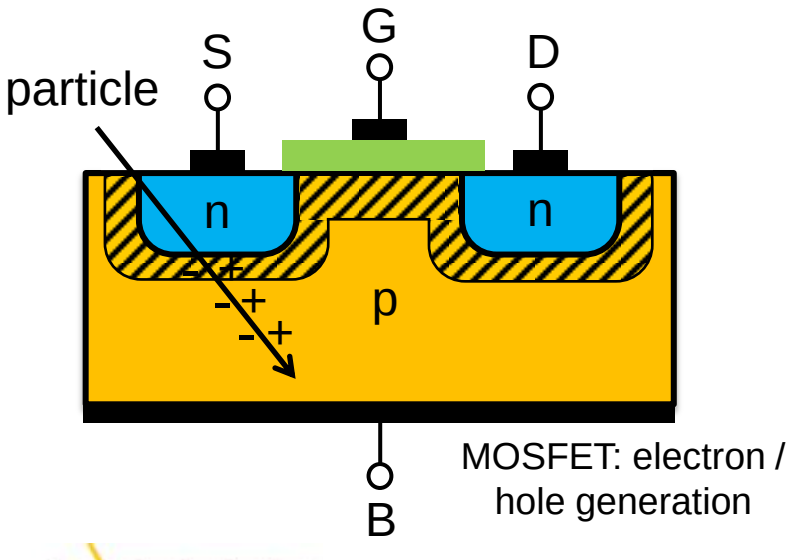
P-i-N diode: carrier recombination



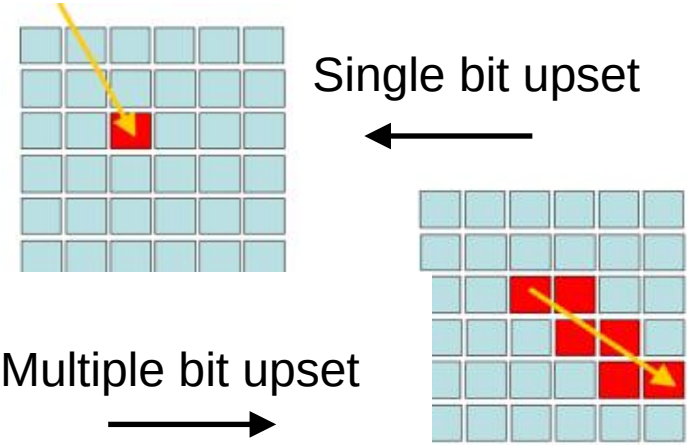
Measured and calculated maximum power degradation in GaAs / Ge solar cells [After Messenger, *TNS,* 1999]

Single event upsets

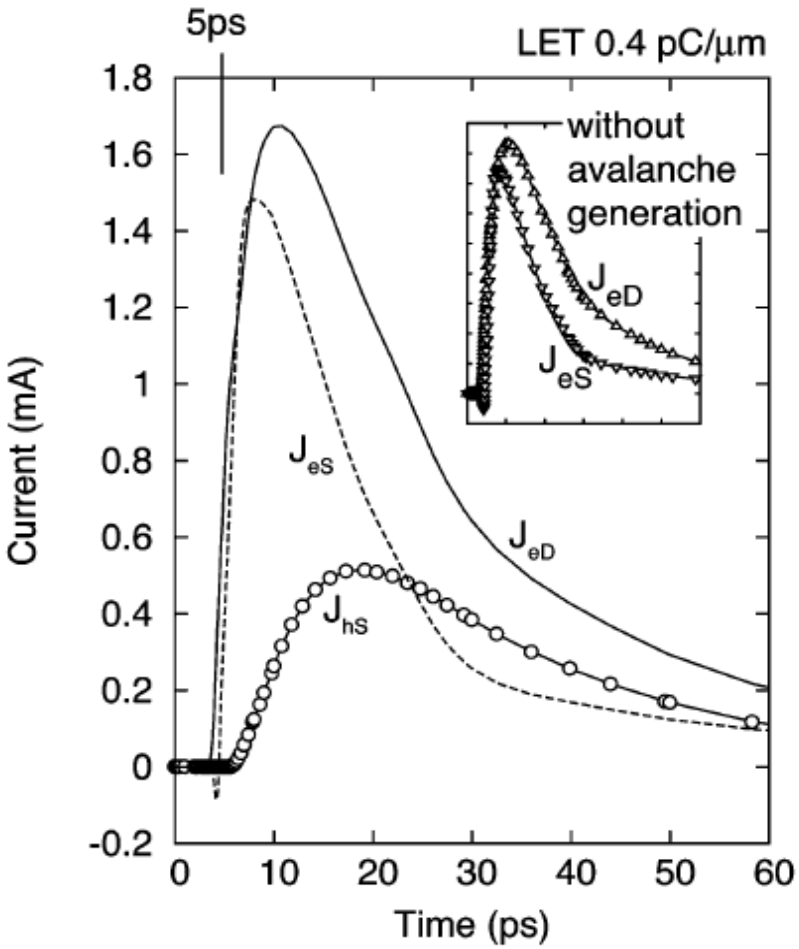
Electron / hole pairs are generated through ionization



MOSFET: electron / hole generation



Single bit upset and multiple bit upset in device array [After LaBel & Cohn, NASA / DTRA, 2005]



Normalized current transient in MOSFET [After Kobayashi, *TNS*, 2006]

Overview

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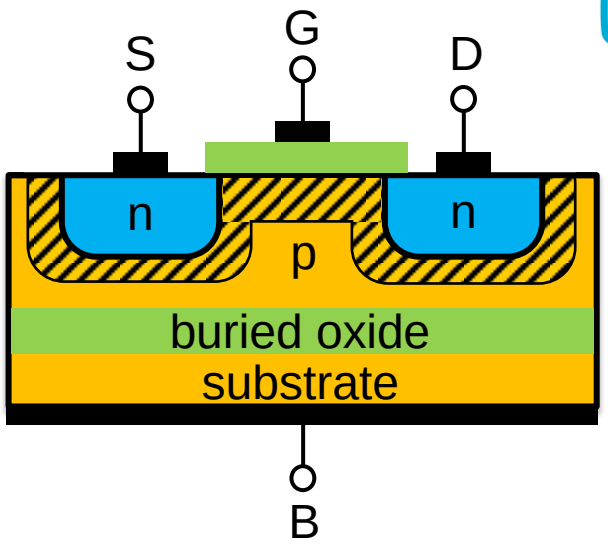
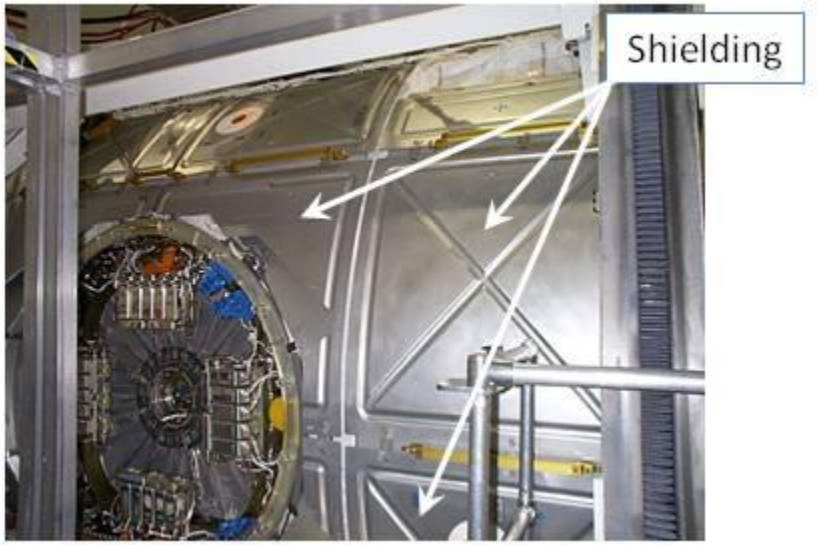
Mitigation

Radiation effects can be reduced:

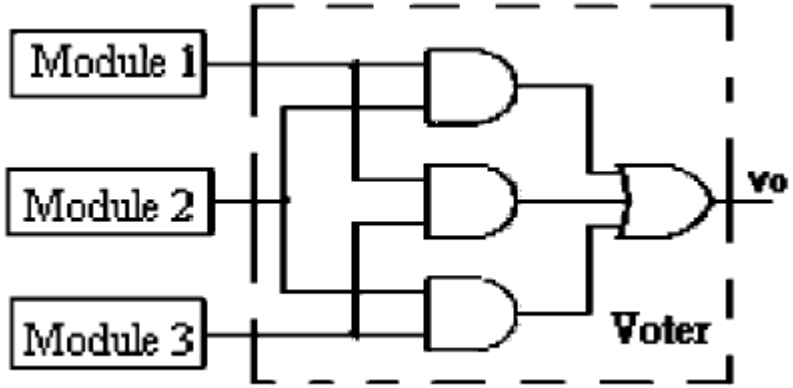
- Fabrication techniques
- Redundancy
- Shielding



MOSFET with buried oxide (silicon-on-insulator)



Satellite shielding, Johnson Space Flight Center NASA

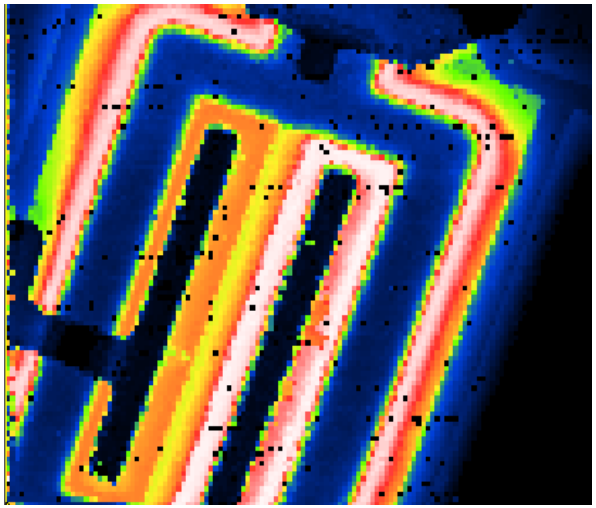


Triple modular redundancy circuit [After She, *TNS*, 2009]

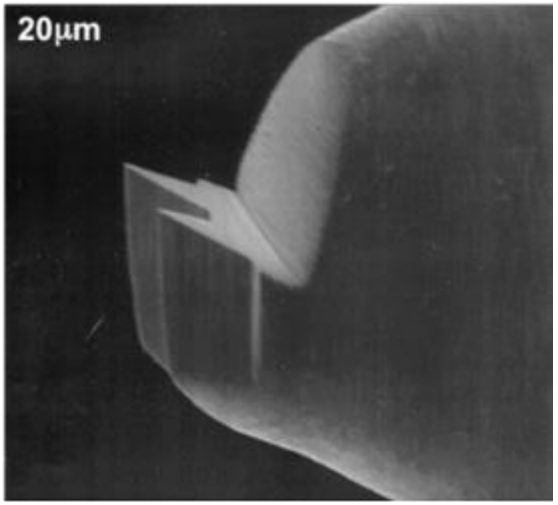
Exploitation

Radiation effects can be used for analysis and fabrication

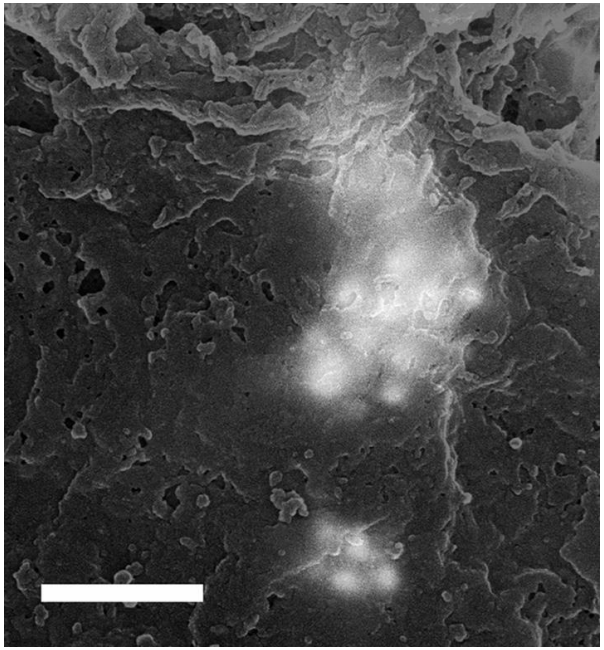
- IBIC, TEM, XRD...
- Focused ion beam



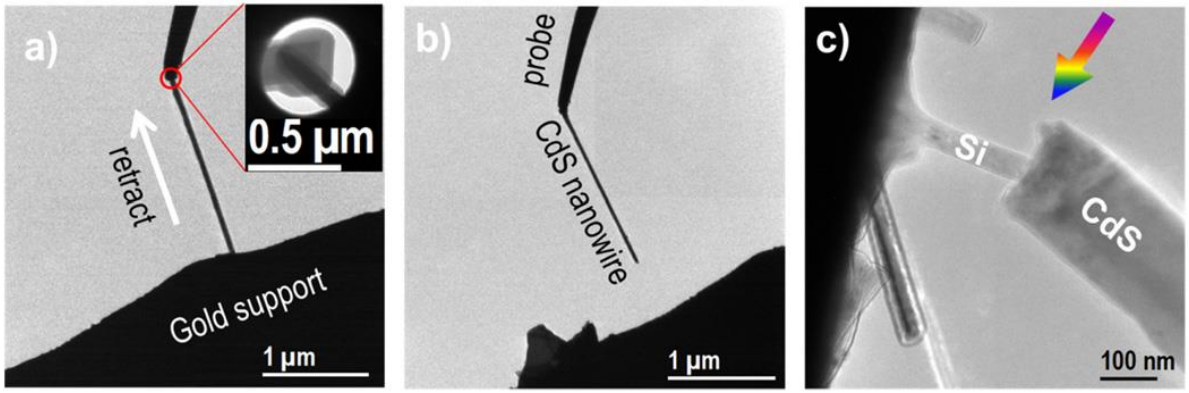
IBIC scan of JFET diode (org. 1111)



FIB-shaped micro-tools (org. 1832)



Nanoparticles detected in brain tissue. composite image of scanning electron microscopy backscattered electrons. [After Kempen, *Micron*, 2015]



Transmission electron microscope (TEM) images of CdS nanowire [After Zhang, *Nanotechnology*, 2015]

Summary

- Radiation is present in space and terrestrial environments
- Radiation affects majority and minority carrier electronics
- Fabrication, circuit design, and shielding can mitigate radiation effects
- Radiation effects can also be exploited for analysis and fabrication

References

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2. C.-T. Sah and H. C. Pao, *IEEE Trans. Electron Devices* 13, 1964
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4. C. Marshall and P. Marshall, NSREC short course, 1999
5. S. R. Messenger *et al*., *IEEE Trans. Nucl. Sci.* 46, 1999
6. K. LaBel and L. Cohn, "Radiation testing and evaluation issues for modern integrated circuits," NASA / DTRA, 2005
7. D. Kobayashi *et al*., *IEEE Trans. Nucl. Sci.* 53, 2006
8. X. She and K. S. McElvain, *IEEE Trans. Nucl. Sci. 56, 2009*
9. P. Kempen *et al., Micron* 68, 2015
10. C. Zhang *et al.*, *Nanotechnology* 26, 2015

Questions? Thank you.