Designing Silicon Tracking Detectors for High Radiation Environments

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FORWARD PHYSICS AND QCD AT THE LHC AND EIC

PHYSIKZENTRUM BAD HONNEF

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Silicon Tracking Detectors

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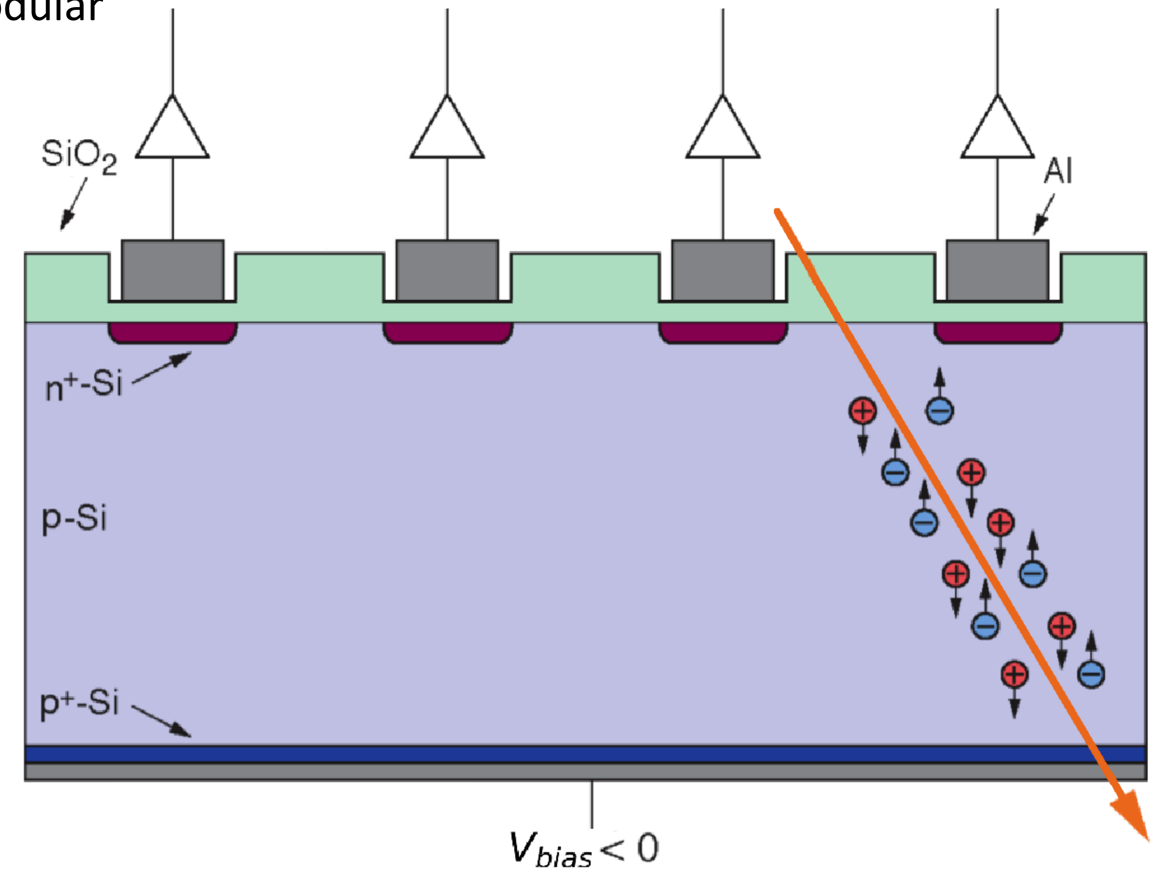
  - High precision
  - Extremely modular
  - Fast response



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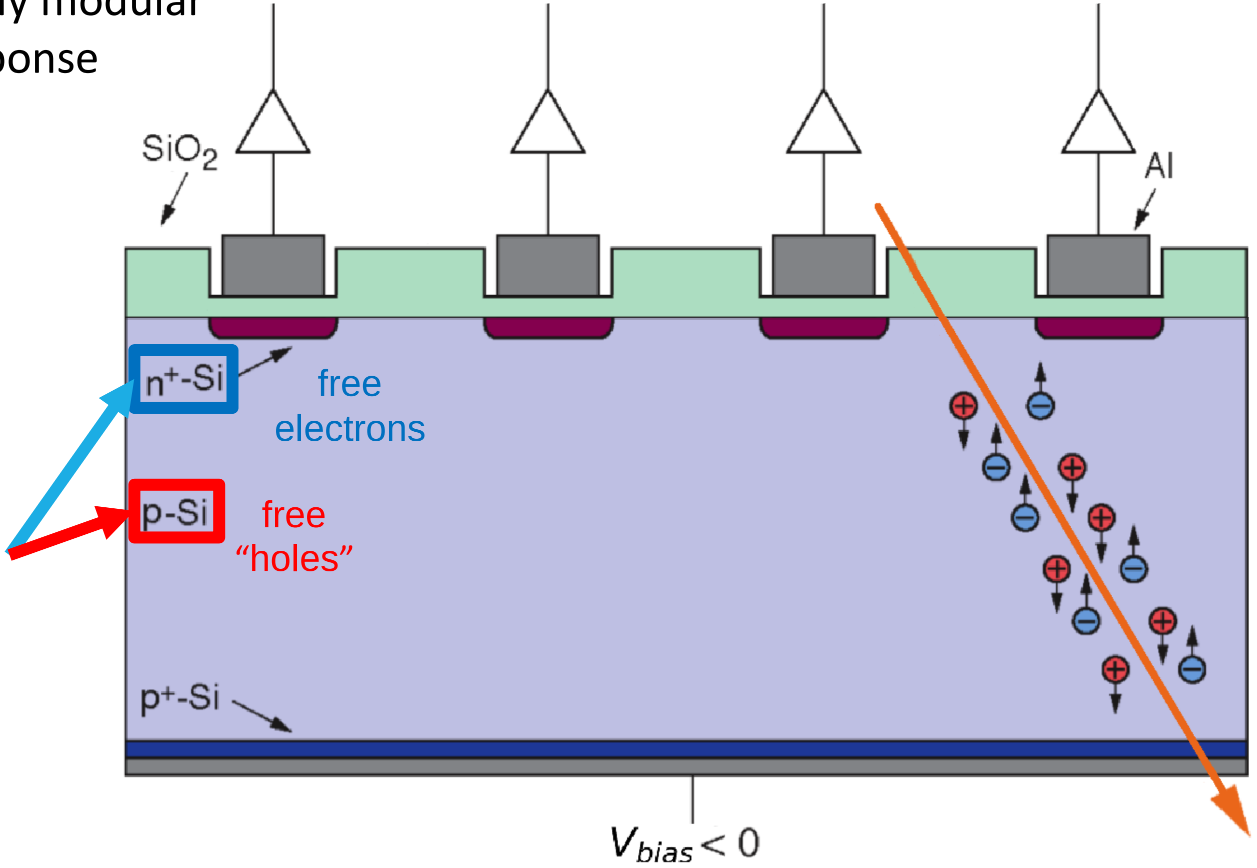

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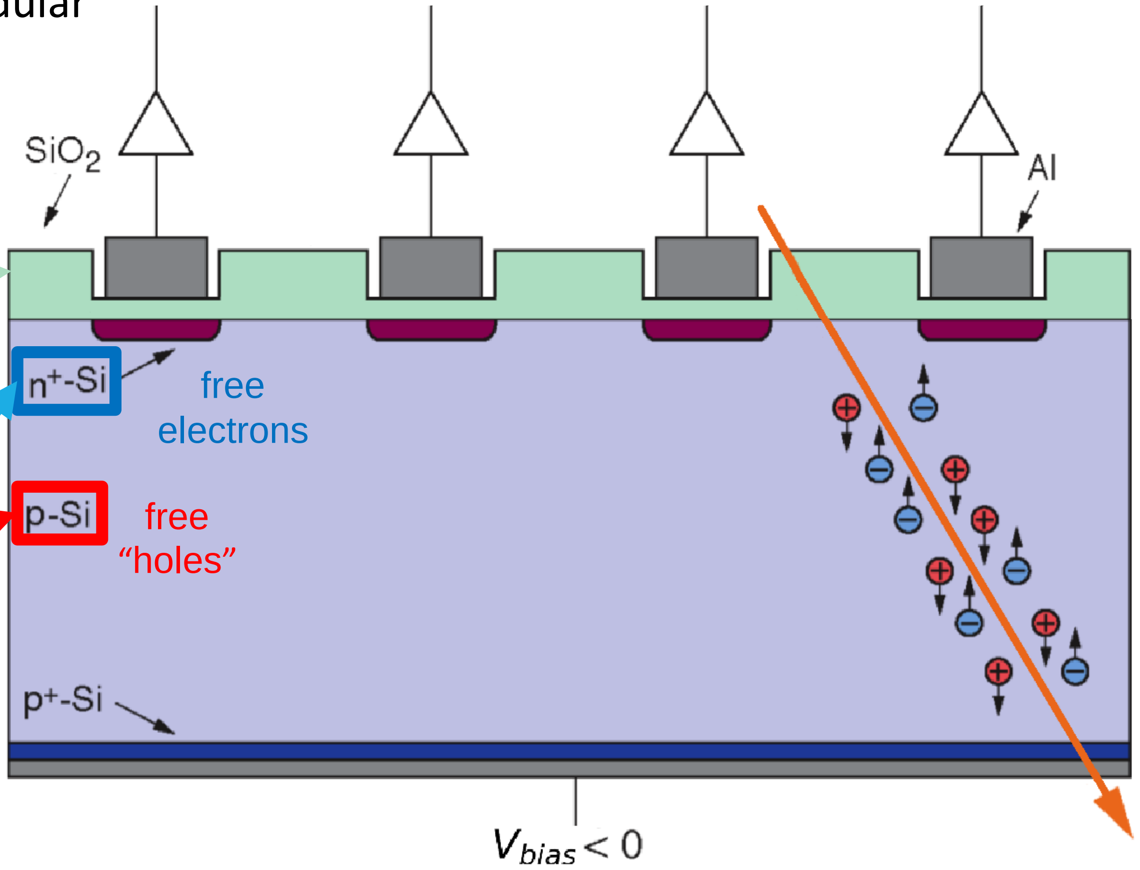

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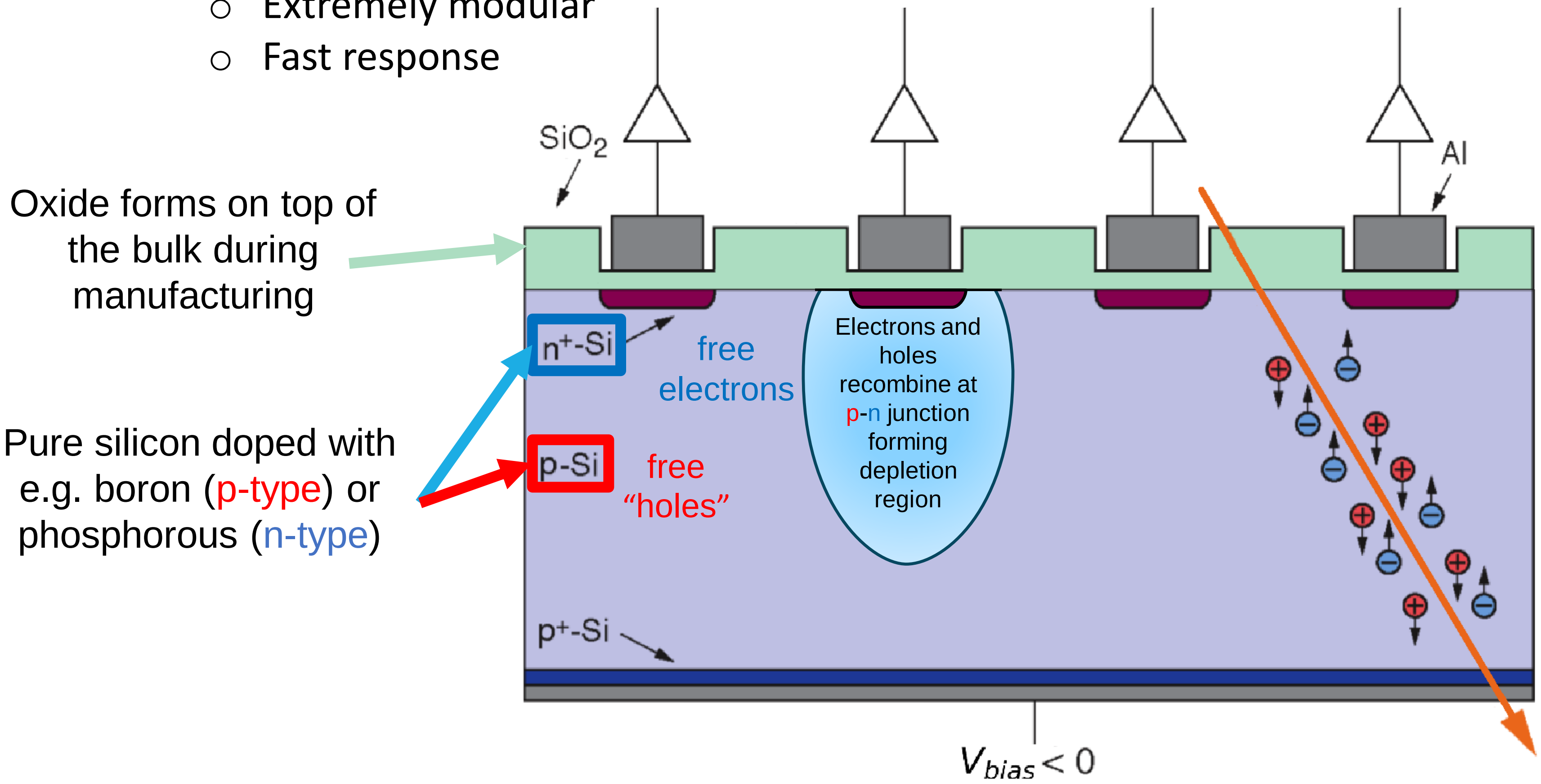

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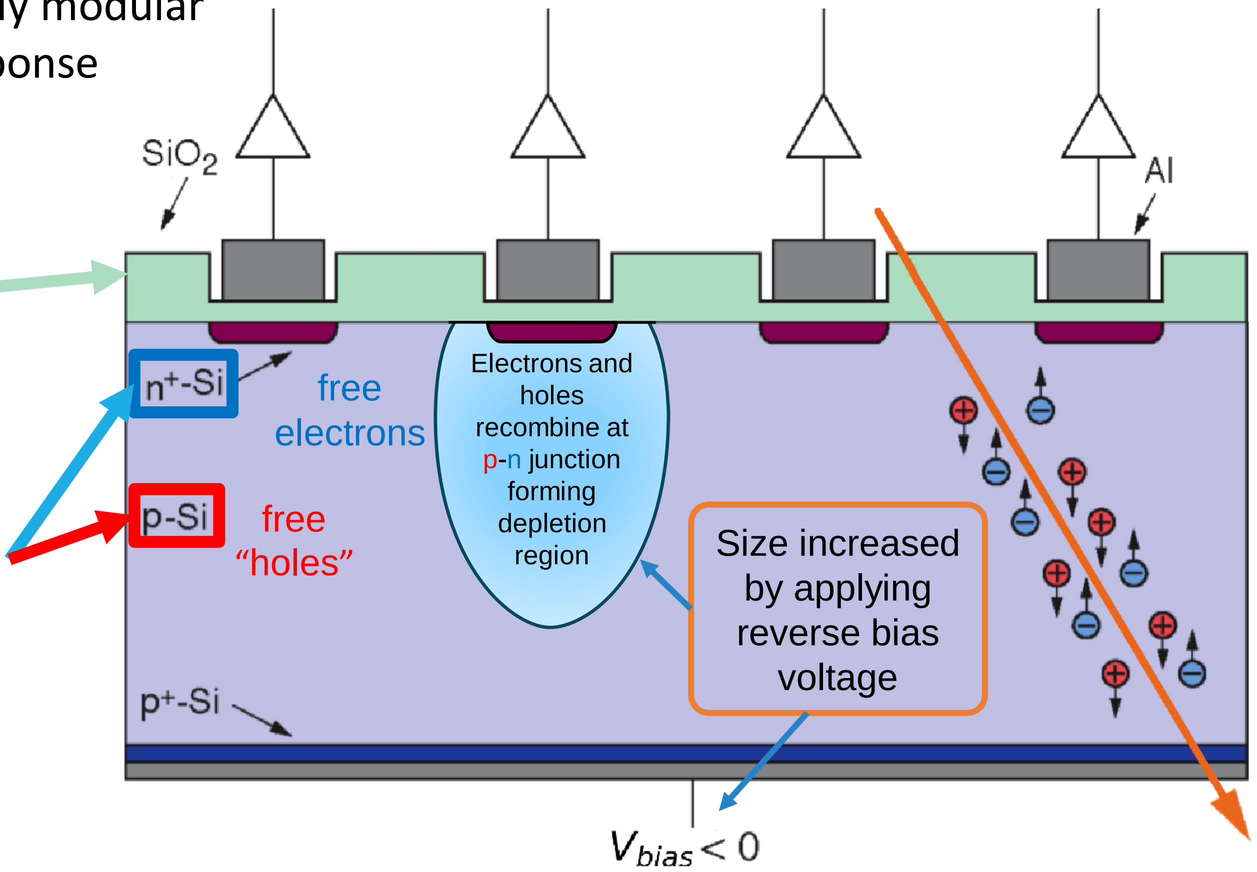

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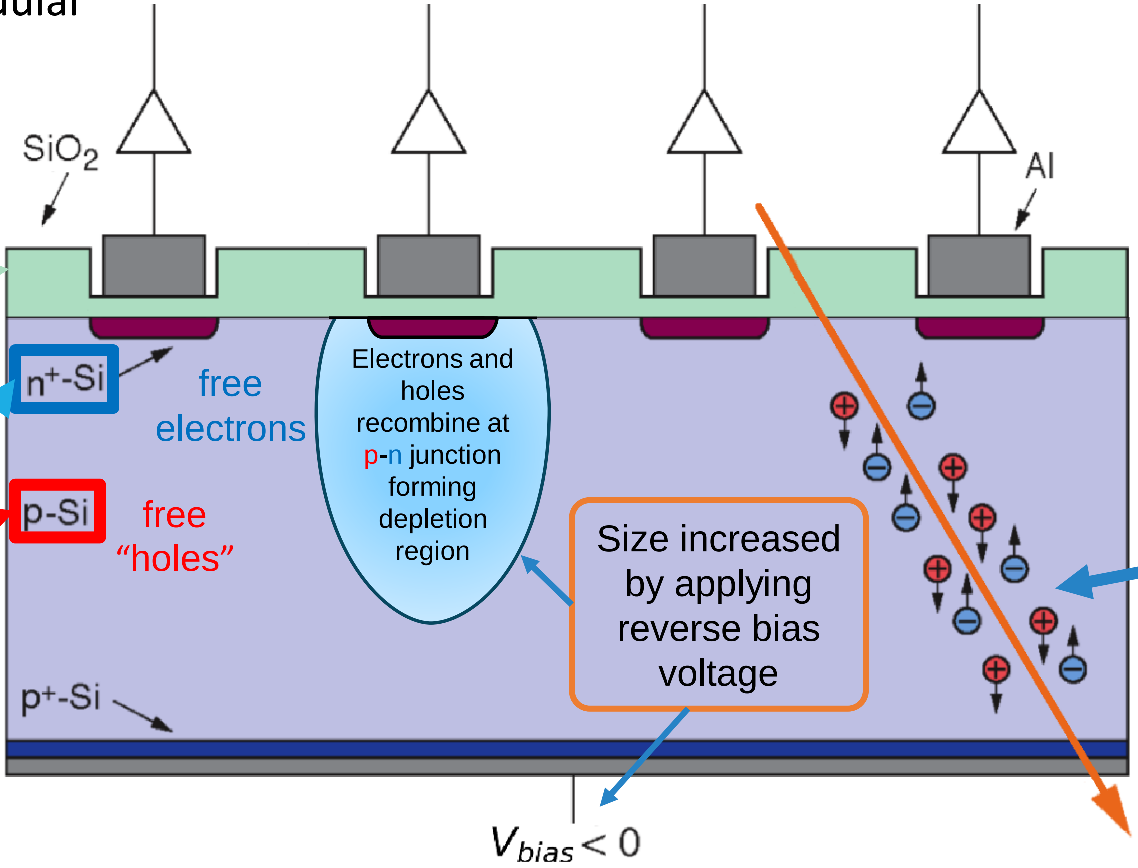

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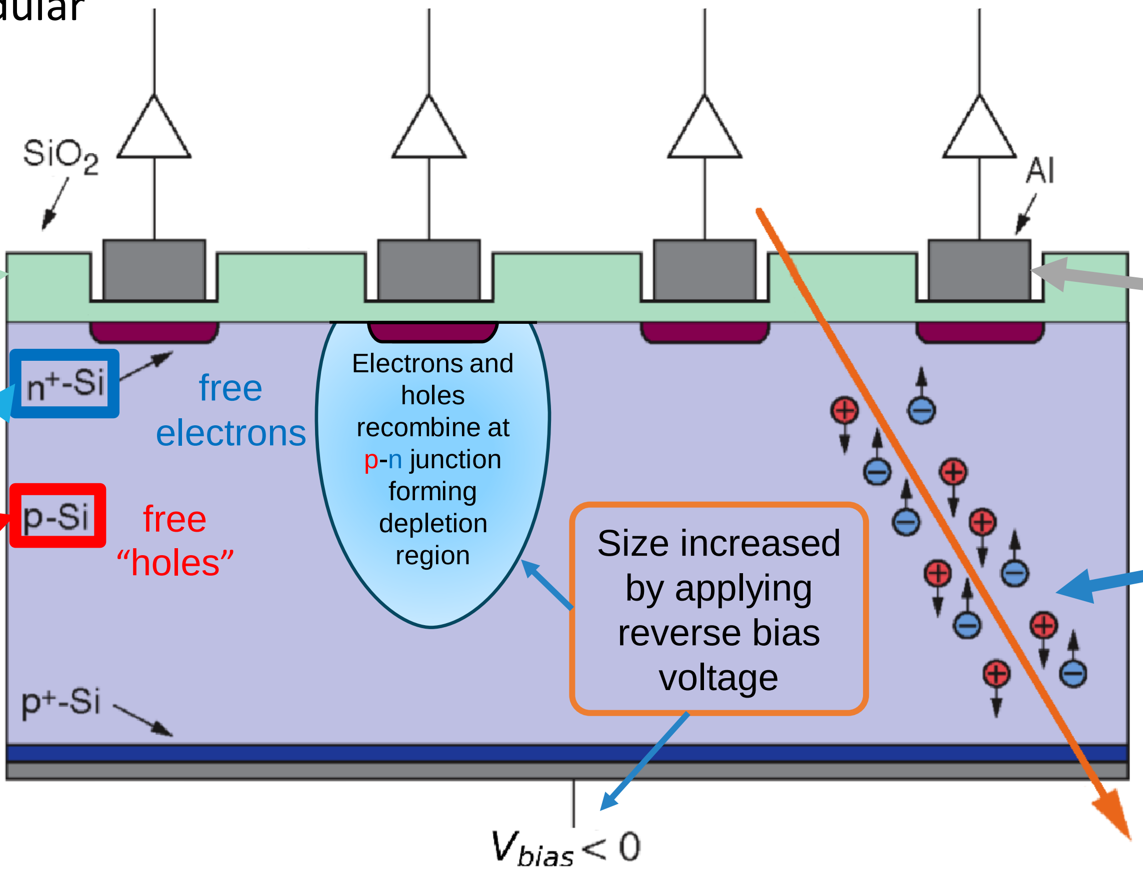
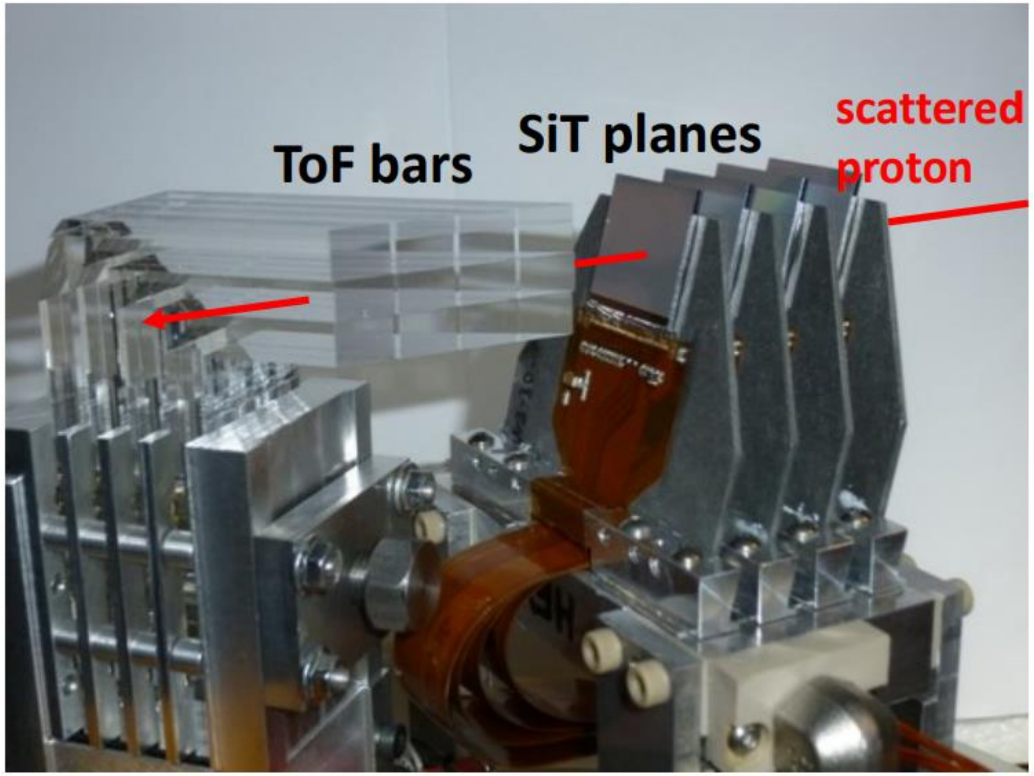


Charge carriers drift along electric field and induce a current in metal electrodes (Al)

Charged particles cause ionisation in depletion region producing electron-hole pairs

Silicon in AFP

- The **AFP spectrometer** in ATLAS uses Silicon Tracking detectors (**SiT**) to determine the p_T of deflected protons in the forward region
- Each station contains four **3D pixel** sensor planes:
    - Each plane has **336 × 80 pixels, 50 × 250 μm²** in size and is 230 μm thick
    - Total active area of 1.68 × 2.00 cm^2
    - Per pixel resolution: $\boldsymbol{\sigma_x \approx 6}$ **μm**, $\boldsymbol{\sigma_y \approx 30}$ **μm**
    - **Slim edge** to approach beam as close as possible



- Close proximity to the beam results in **intense and non-uniform irradiation** (up to 3×10^{15} n_{eq}/cm^2 in 3 years)
    - The sensors must be able to maintain sufficient performance after exposure to high levels of radiation

Radiation Damage

- When exposed to high levels of **radiation**, silicon detectors can become damaged via two main processes:
  - **Bulk Damage:** displacement of atoms from silicon lattice
  - **Surface Damage:** ionisation in oxide layers and formation of interface defects

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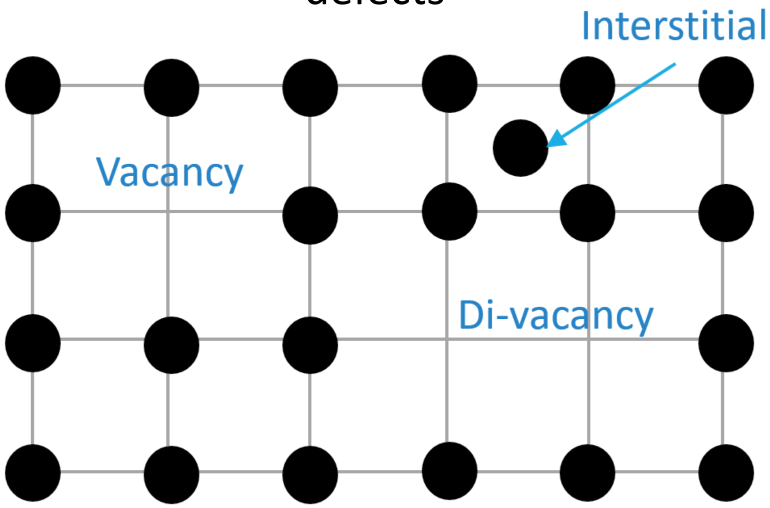
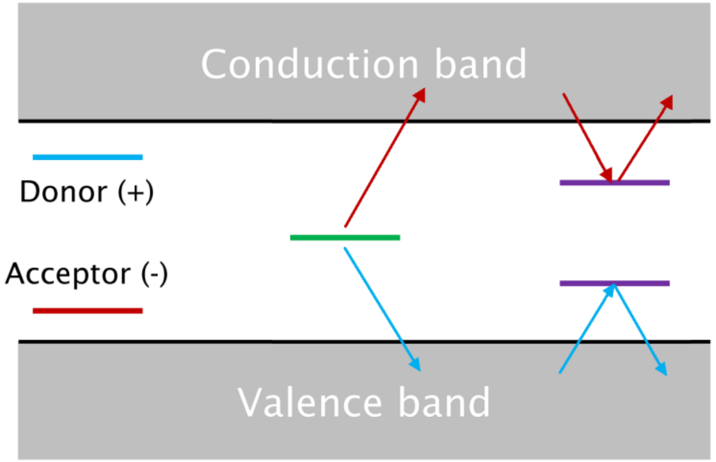


Creates new energy levels in the silicon band gap



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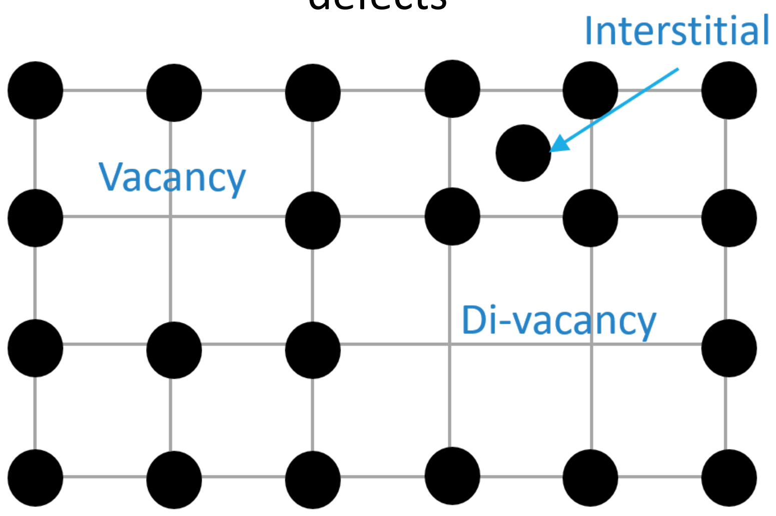

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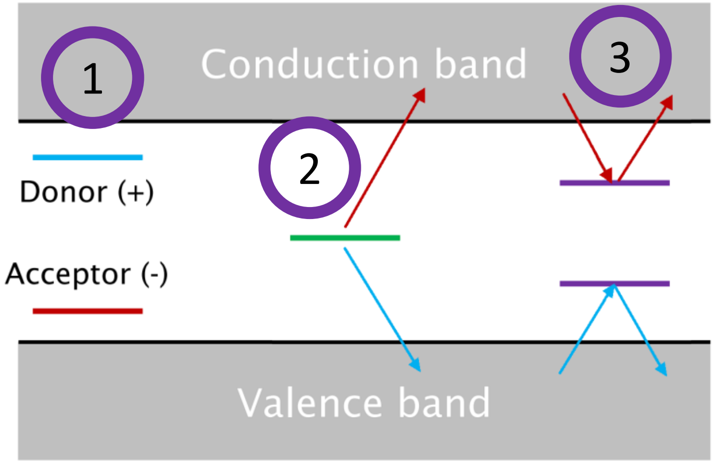

1. Reduce effective space charge
   - Increased full depletion voltage
2. Increased leakage current
   - Increased noise and power consumption
3. Charge trapping
   - Decreases charge collection efficiency

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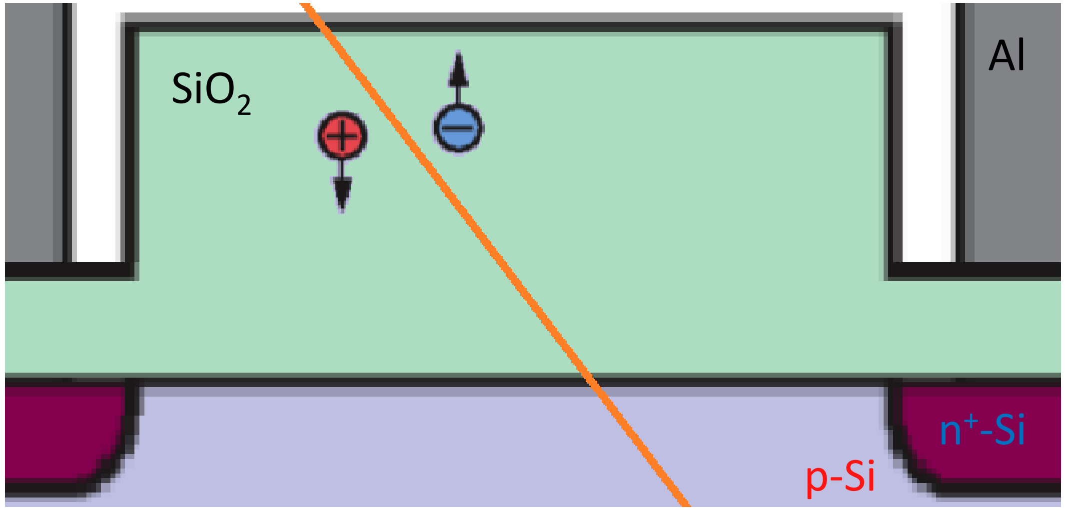
Ionisation occurs in the oxide forming electron-hole pairs



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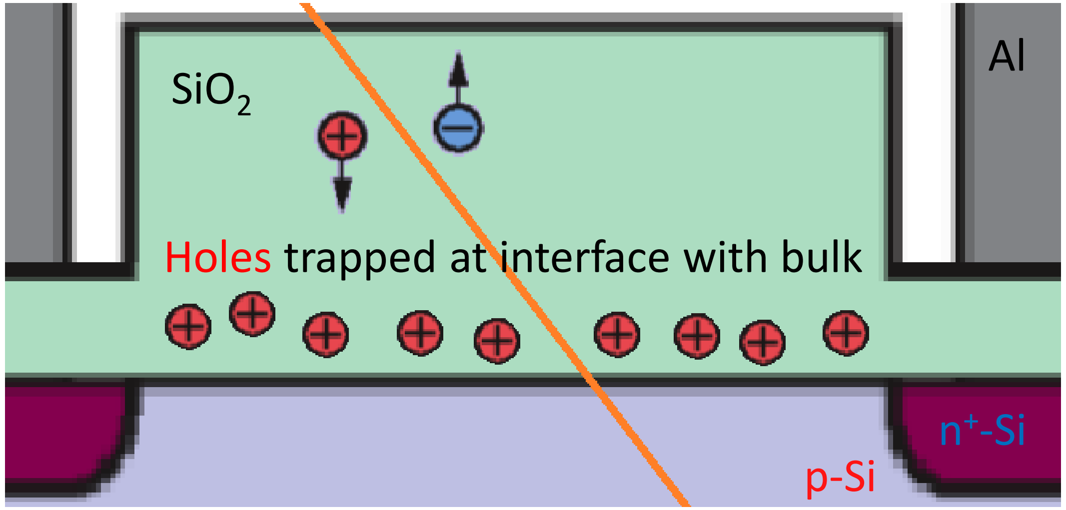

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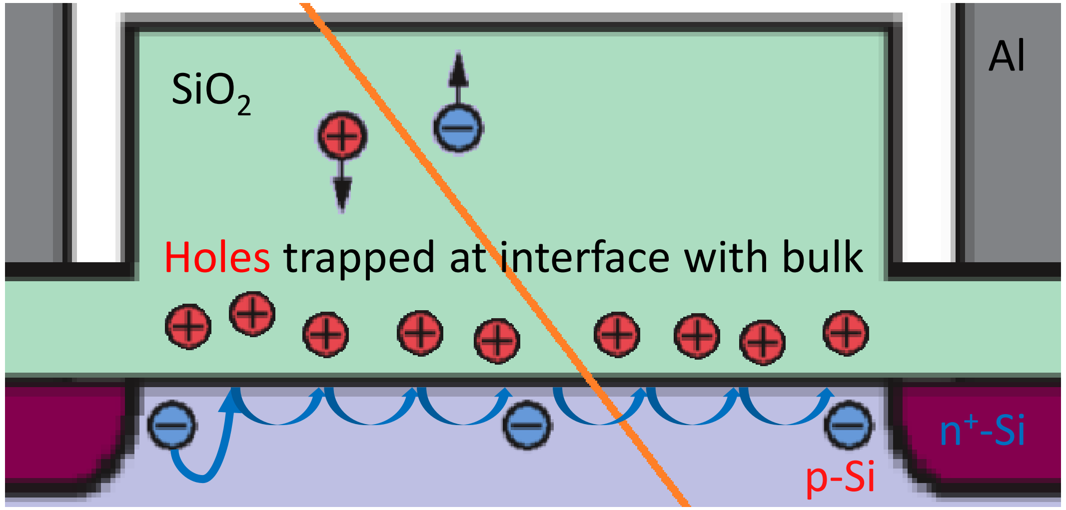


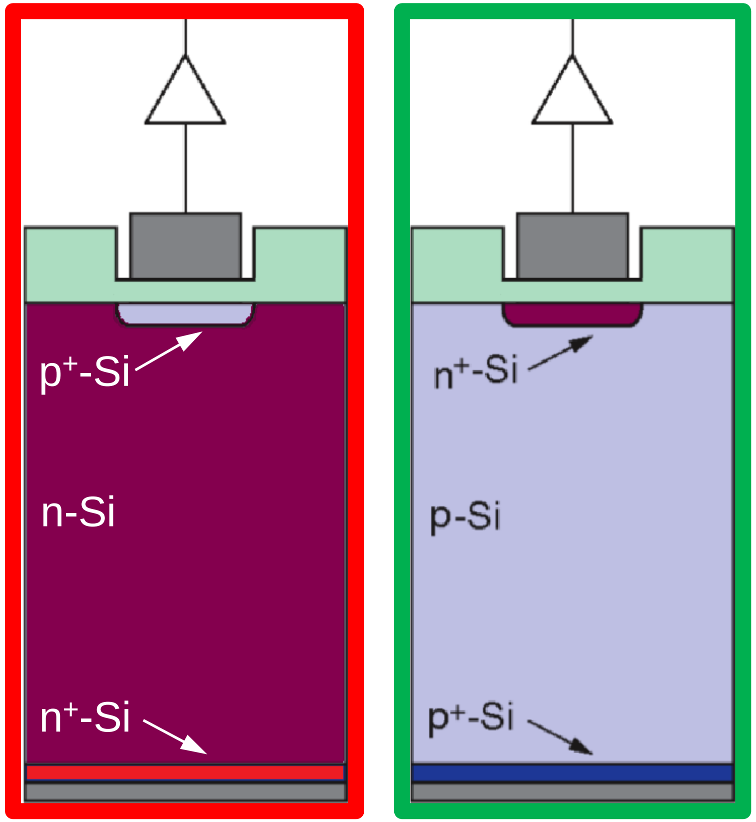
Electrons able to cross between strips

- Decreased inter-strip resistance
  - Decreased precision
  - Increased charge sharing
  - Reduced sensitivity
- Increased inter-strip capacitance
  - Increased noise

Radiation Damage - Mitigation

- There are several **design measures** which can be taken to mitigate radiation effects:

- Use n-type implants in a p-type silicon bulk (n-in-p) instead of p-in-n
    - Leads to **larger signals** in electrodes after irradiation



p-in-n n-in-p

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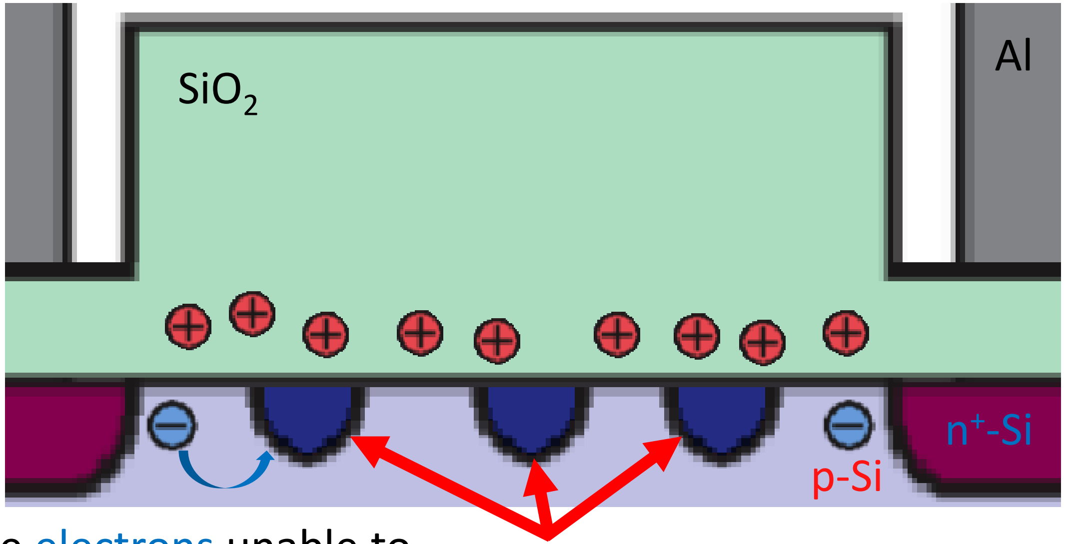
- p-type silicon can be deposited between n-type implants (**p-spray/stop**)
  - Prevents charge sharing after irradiation



Free electrons unable to cross between strips

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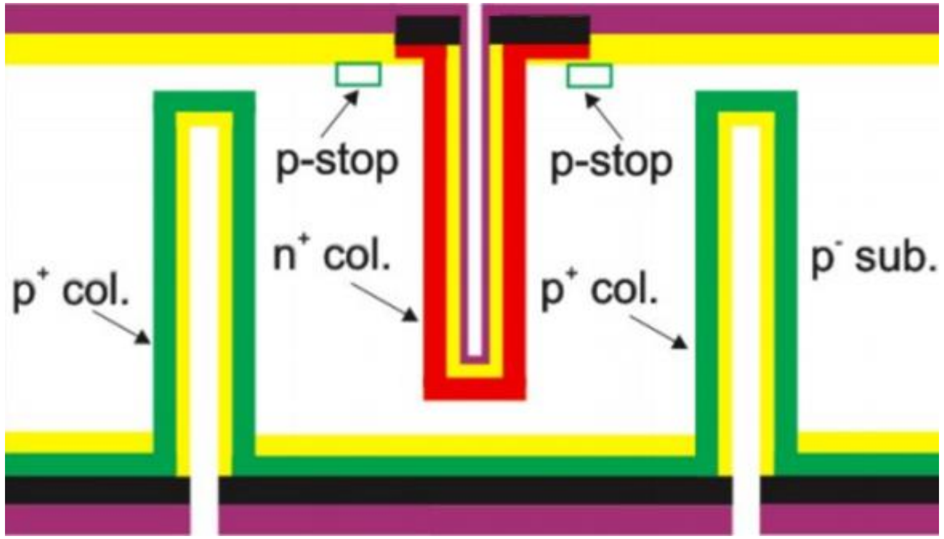
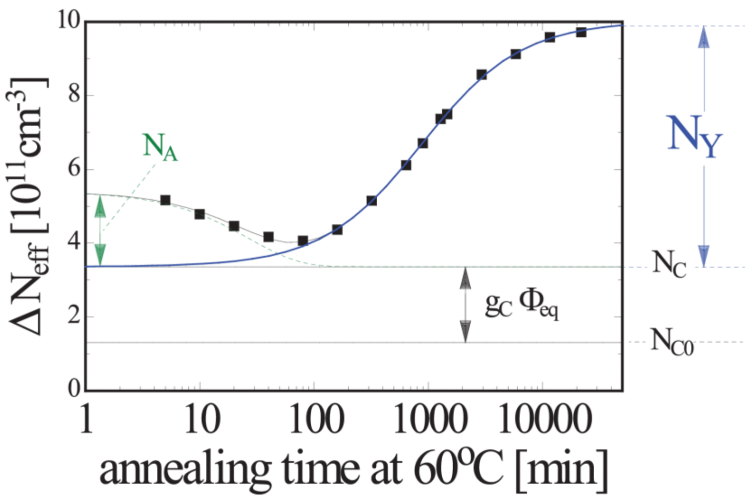
- **3D pixel detectors** use column-like n and p-type electrodes which penetrate the substrate
  - Gives smaller drift path, reducing bulk damage
  - Lower bias voltage required
  - Used in the **ATLAS IBL, AFP** and **ITk** detectors



Radiation Damage - Recovery

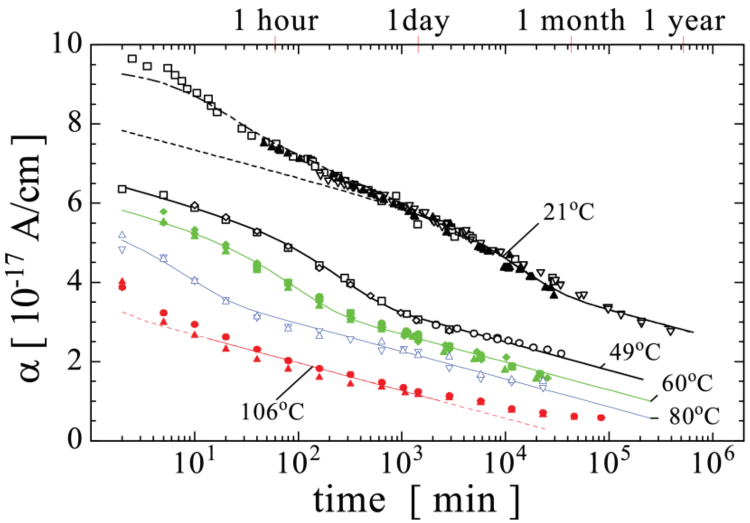
- When irradiated silicon is heated it can recover some of the damage done by radiation in a process called **annealing**
- However, too much annealing can be detrimental

DOI:10.1109/TNS.2018.2819506

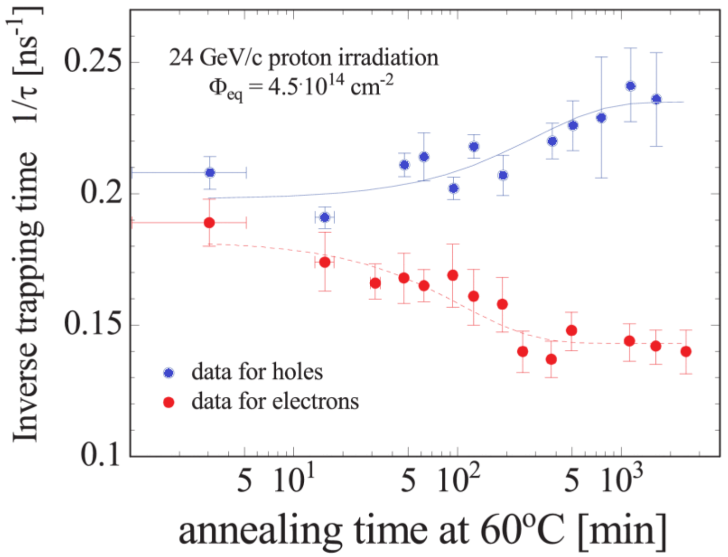


Reduction in effective space charge

❗ Will increase again after too much annealing



Continuously decreased leakage current



Decreased trapping for electrons

❗ Increases trapping for holes

Summary

- Significant use of silicon tracking detectors in forward physics
- Particularly high radiation intensities experienced in forward physics detectors
- Continued development towards reducing the effects of radiation damage

- **Long term:** silicon timing detectors currently being developed for next generation detectors (e.g. LGADs [DOI 10.1088/1748-0221/13/03/C03014]) allowing sub-ns timing