Silicon Tracking Detectors

Sally Seidel
University of New Mexico

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The role of the tracking detector is to image with the highest possible precision the trajectories of charged particles.

Their many applications in a particle physics experiment:

1. **Reconstruct vertices**: identify cases where 2 or more tracks emerge from a common point. The primary vertex indicates the initial hard interaction. The secondary vertex signals that a particle decay occurred at that vertex – typically a heavy particle: c, b, τ.

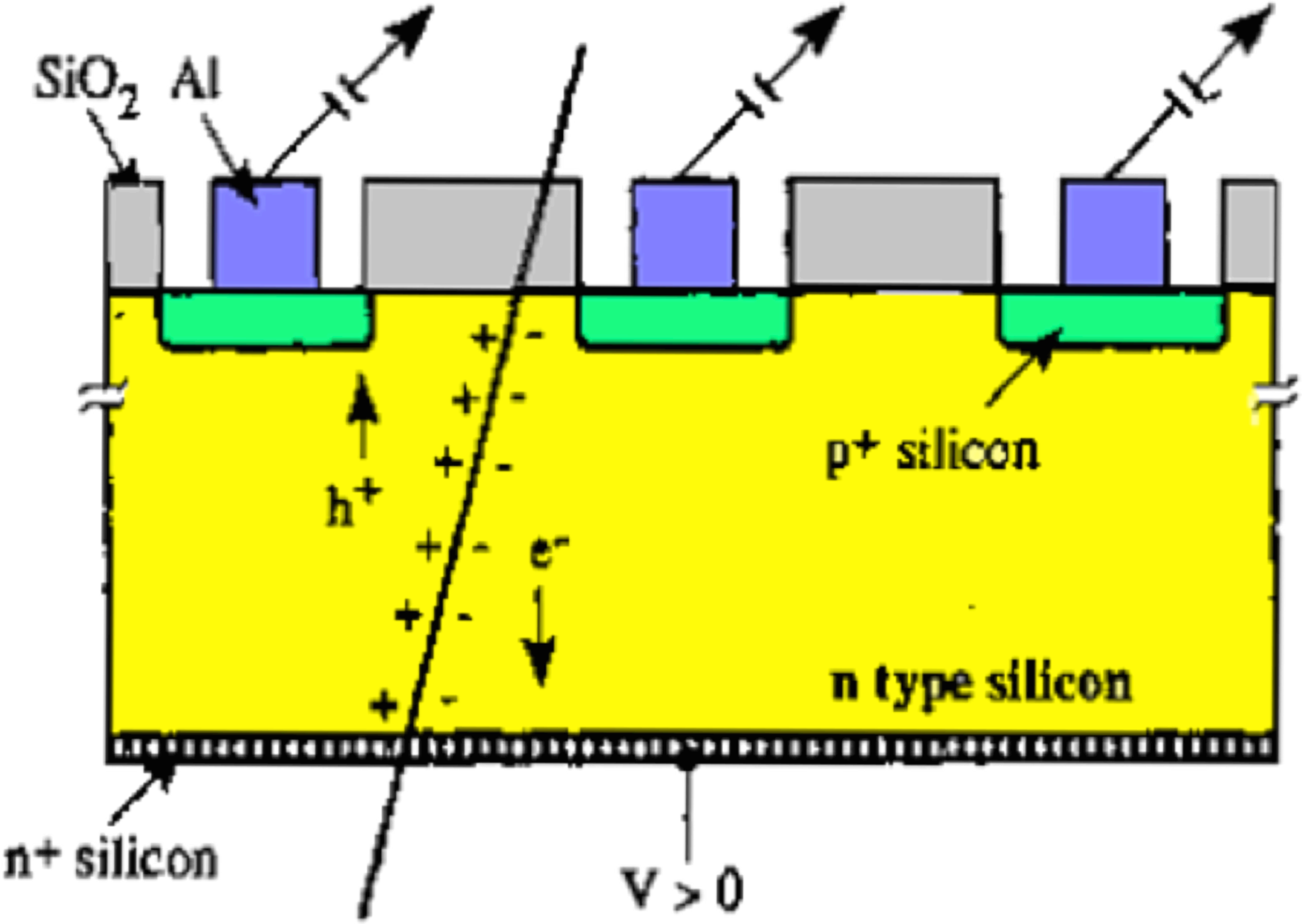
2. **Reconstruct the curvature of tracks** in a known magnetic field – to infer their momentum p. The sign of the curvature gives the particle's electric charge.

3. **Measure track impact parameter:** gaps between vertices, or events where the momentum emerging from a secondary vertex does not point to the primary vertex – these indicate intermediate particles.

4. **Measure finite particle lifetimes** – to identify production of b-hadrons or tau leptons.

5. **Provide a trigger** for events of special interest.

The concept: **ionization** produced **along the track** of a particle as it traverses the detector, **drift to electrodes** where it is **integrated, digitized, read out to provide stored timing and pulse height information**.



Challenges to position resolution

The value of the tracker is in the precision it can provide. Achieving this involves overcoming **design challenges**. The variety of solutions to those challenges have led to the variety of silicon tracking detectors in use today and envisioned for the future.

Challenge #1: Seeking signs of new physics, researchers probe **increasingly rare processes.** Generating rare processes requires production of **large amounts of data**. We work to make the **rate of collisions at a facility like LHC as high as possible**.

Rate of collisions: "instantaneous luminosity" – interactions/cm^2/sec

But the possibly interesting particles produced in each collision ***also damage the detectors*** *that are placed to characterize them.*

High luminosity : new discoveries but radiation-damaged detectors

Challenge #2: **The silicon detectors are positioned as close as possible to the point of particle production** (in colliders, the primary vertex or bunch crossing point).

The motivations:

- **precision** tracking: minimum distance = minimum extrapolation error
- input to **real-time triggering** that examines tracks where their curvature is negligible, simplifying algorithms, speeding decisions

The challenges:

- **radiation damage**: fluence $\sim 1/r^n$ $(1.5 < n < 2)$
- **jets of particles are most compact near the production point**, so individual tracks are hardest to resolve at short distances – demands high segmentation

Demand for high granularity motivates the use of solid state sensors.

Solid state sensors produce electrons and holes (compare gaseous detectors: electrons and positrons).

- **Can be patterned with thousands of independent sensing elements per cm^2**, reduced range of secondary electrons in the dense substrate leads to position resolution on the order of a few microns.

- **Energy needed to ionize is low** (3.6 eV in Si, compare gas chambers at 30 eV) – so sensitivity is high. Energy resolution is good: $\dfrac{\Delta E}{E} \propto \dfrac{1}{\sqrt{N}}$

- **Signal speed is high** (~20 ns, compare gas chambers' speed, nanosecond to microseconds).

- With very small sensing structures,

  Advantages:
  - low geometrical capacitance leads to **initially low noise**
  - high channel density leads to **low occupancy per channel, reduces event buffering needs**

  Challenges: the higher the density of the circuit, the harder it is to **read out, cool, and handle mechanically.**

Challenge #3: **minimizing multiple scattering** of the detected tracks.

- The tracker is the first detection system the particle encounters. **Anything that comes between the primary vertex and the tracker needs to be specially engineered for minimum mass**
    - this is: detector mechanical support, readout, cooling, cables and interconnects
    - and: the beampipe itself
- **It is critical to minimize the tracking detector's material itself.** Silicon has a low-Z advantage (Z = 14, compare germanium at Z = 32).

A few pages of history, and some things that were learned at each step along the way

1943 – a crystal of AgCl (4 mm thick, 4 cm diameter) **voided of free charge by cooling** in liquid air, demonstrated ionization by beta and alpha particles (P.J. Van Heerden, Utrecht)

>> the insights:

- An insulator may produce an ionization signal
- Free charge in the crystal will annihilate the signal, so suppress free charge

1950 – a germanium detector produced, **structured with a p-n junction**, depleted by reverse-bias, collected electrons and holes from alpha bombardment (K.G. McKay, Bell Labs)

>> the insights:

- Creating a p-n junction at the surface of the crystal, and applying reverse bias, can deplete the sensing volume of free charge, providing a free path for ionization produced by through-going particles.
- The applied bias across the crystal produces an electric field. The ionization particles drift along the field lines to electrodes on the crystal surface.

1955-65 – **Silicon detector development starts** (Oak Ridge, Chalk River, Harwell, CEA).
1961 – **patterned, multiple rectangular diodes** on one Si substrate.

>> **insight:** if the electrodes on the crystal surface are segmented, signals arriving at different segments at different times can be combined to reconstruct the path of the particle that produced the ionization.

1971 – Si **strip-like sensors** (few gold 3mm wide strips spaced by 0.2 mm produced by a wire mask, operated at -20° C over-depleted (Karlsruhe, similar at Argonne, Fermilab, Southampton)

>> **insight**: maximize precision of track reconstruction by maximizing the number of segments – make segments as narrow and close as possible. The segments are strips that connect to amplifiers adjacent to the sensor's edge.

1973 – unstructured Si used to make **a telescope** of 5 depleted active targets (active area 300 mm^2, thicknesses 200 micron or 1 mm). Production experiment $\pi^-+\mathrm{Si} \rightarrow \pi^+\pi^-\pi^-+\mathrm{Si}$ with a 16 GeV π^- beam (CERN)

>> **insight**: the ionization can be related to the energy of the incident particle.

1978-82 NA-11 Experiment
1982-86 NA-32 Experiment
First use of silicon microstrip detectors in particle physics, motivated by goals to measure charmed particle masses and lifetimes (0.1 ps, $c\tau$~30 microns at the CERN SPS). The 8 detectors used in NA-11 were n-doped, 2-in. diameter, 280 microns thick, strip pitch 20 microns, achieved resolution 4.5 microns, placed before and after target. (J. Kemmer, NIM A 169 (1980) 499-502; E.H.M. Heijne et al., NIM A 178 (1980) 331.)

1984: birth of the pixel concept, implemented in WA94 (OMEGA) at CERN (1990-93). This begins to shift technology challenges toward readout.

1989 - 2000's DELPHI, L3, ALEPH, OPAL, Mark-II – **silicon mini-strip and pixel detectors arranged in barrels around the interaction points** of the collider. Single-sided and eventually double-sided planar Si detectors for tracking.

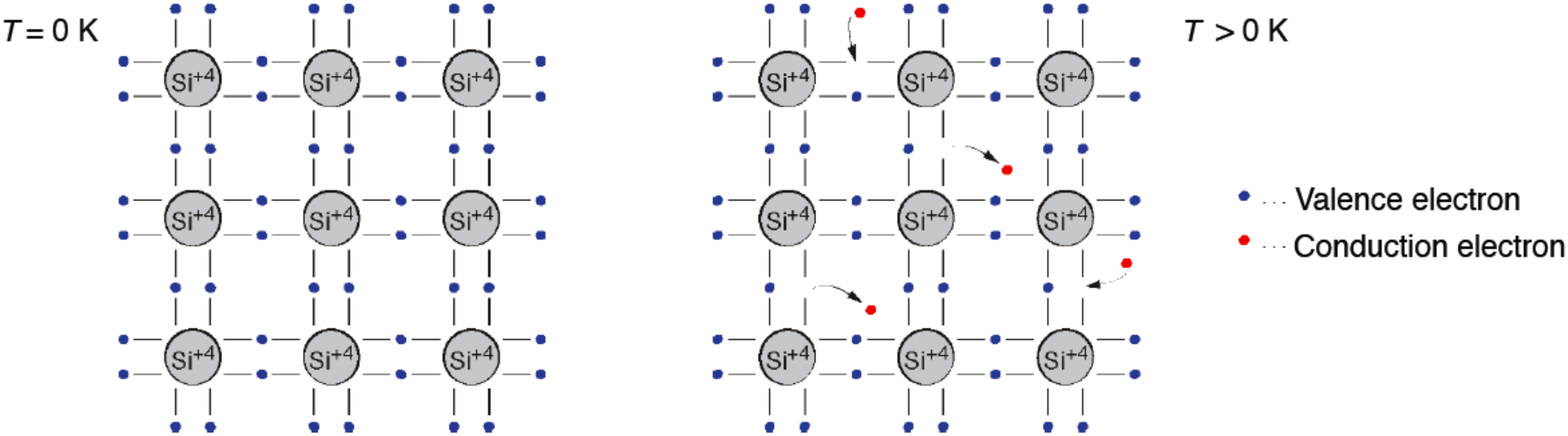
1992 – onward: CDF and D0 **Si strip detectors for vertexing, Level 2 triggering** based on impact parameters. The extended proton bunch length and short crossing time drive development of specialized readout electronics.

2005 – onward: LHC experiments implement **very large scale** pixel pattern and strip detectors

And in space: AMS, GLAST multilayer silicon strip detectors

A little bit about foundations: semiconductors and p-n junctions

Compare 2 silicon crystals at different temperatures:

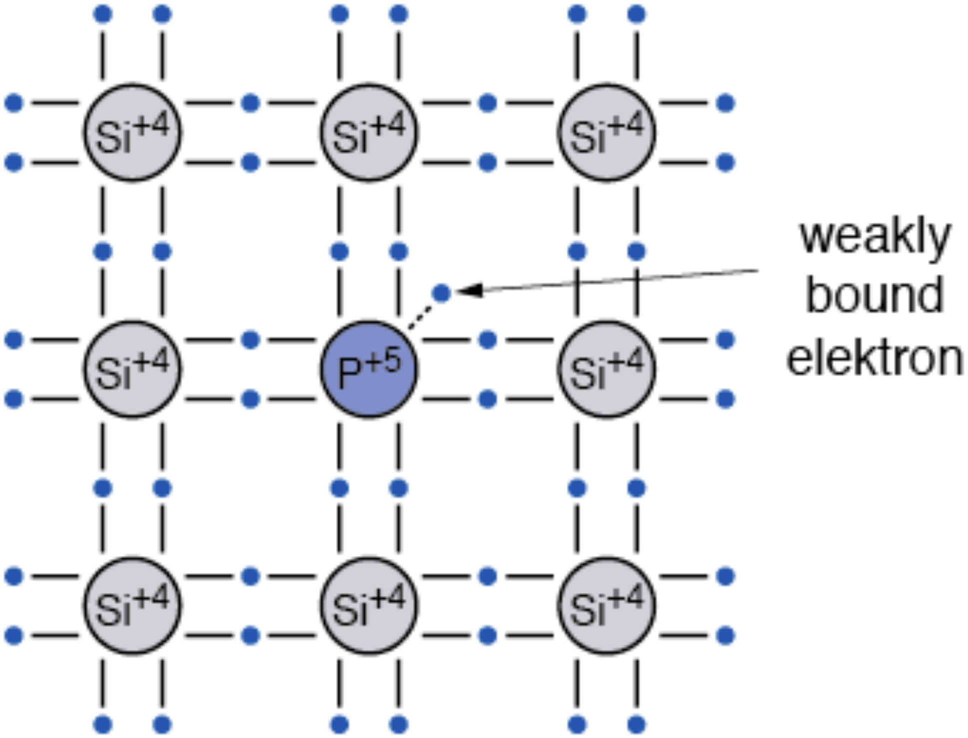


- **An electron that leaves its bond provides conduction. What remains is a "hole." When a different electron restores the bond** ("fills the hole") it leaves a new hole somewhere else ("**the hole migrates**").

- The experimenter wants free electrons to be produced only by ionization from through-going external particles. Some **ways to suppress the production of unwanted thermally-produced free electrons:**
  - lower the temperature (this strategy was used with the AgCl in 1943 and is still used for germanium)
  - choose a crystal with very high bond strength (the strategy behind diamond detectors)
  - sweep away free charge by applying a voltage across the crystal...

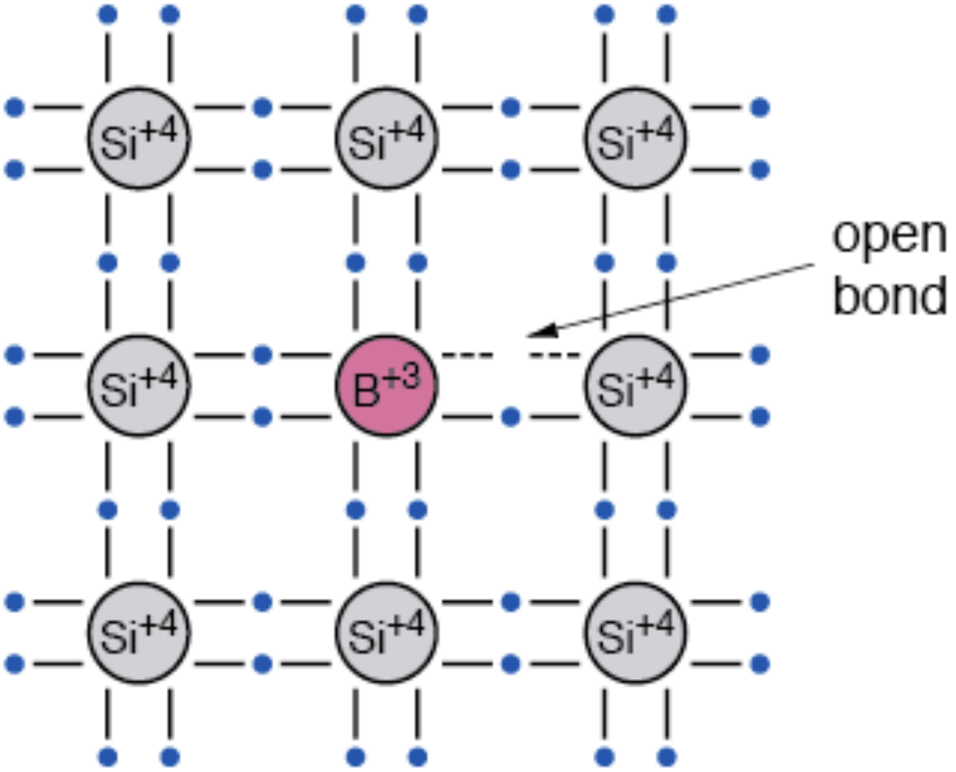
The detector starts as a pn junction. *Assembling a pn junction:*

Silicon is a Type-IV atom. Its outermost shell has 4 electrons. Replace a small percentage of the silicon atoms in a crystal with Type-V atoms (As, P), and the resulting silicon is called "n-type". *The crystal remains electrically neutral*, but one of the dopant's electrons is only weakly bound. A small perturbation frees it for conduction, leaving a hole. The dopant is called a *"donor."*



Doping is done via ion implantation + heat cure, or thermal diffusion

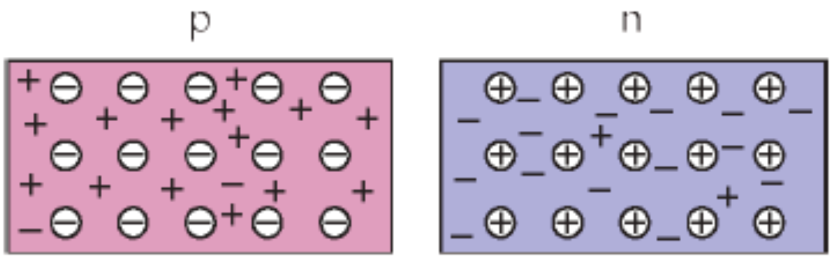
Similarly build a p-type silicon wafer by replacing a small fraction of the silicon atoms with Type-III atoms (Al, B) called "*acceptors*." Still the whole *wafer remains electrically neutral, but one bond per dopant has a hole.* It can receive an electron from another atom in the lattice. As the electron fills it, the hole migrates.

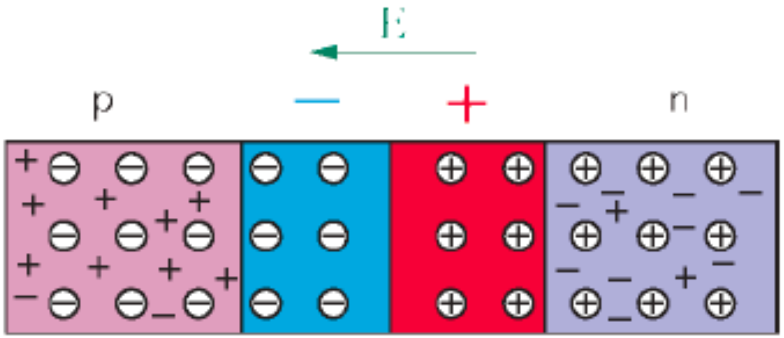


Now build the pn junction:

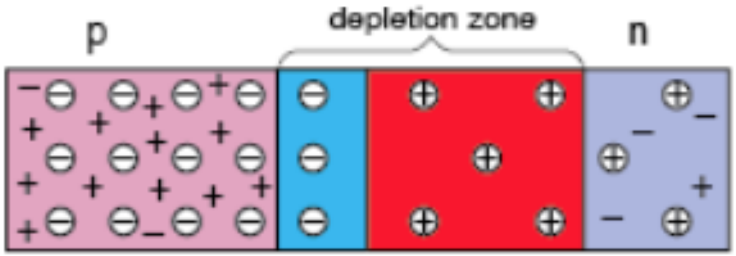
Interface the n-type ($N_{donors}=10^{12}/cm^3$) with the p-type ($n_{acceptors}=10^{15}/cm^3$) silicon. Electrons from the n-type side and holes from the p-type side diffuse across the interface until thermal equilibrium is reached. This establishes a **small electric potential across the region of the interface, called the built-in potential. It blocks further diffusion.**

Apply an external potential with – to the p-side and + to the n-side (*"reverse bias"*) **to sweep free charge out and grow the depletion zone.**
Width of the depletion zone is greatest on the n-side because of the dopant density imbalance:





Define $N_{eff} = N_{donors} - N_{acceptors}$



That depleted n-type zone is the tracking sensor.
When a charged particle crosses the depletion zone and ionizes atoms along its track, there is no free charge present to extinguish the liberated electrons and holes. They drift along the external electric field to electrodes on the opposing surfaces.

The width of the depletion zone depends on the applied voltage through the Poisson Equation:

$$\vec{\nabla} \cdot \vec{E} = \frac{\rho}{\varepsilon \varepsilon_0}$$

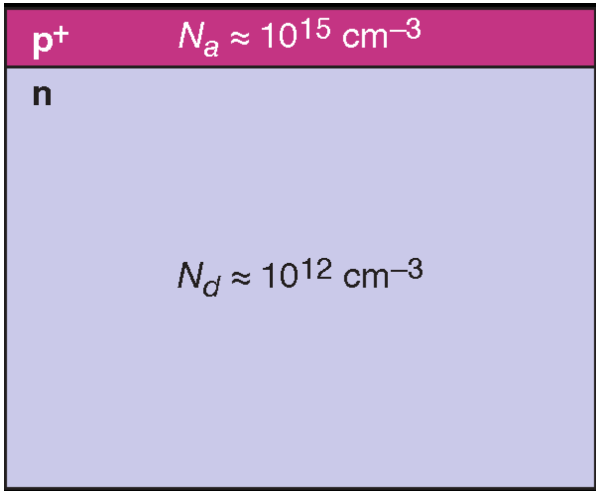
But $\vec{E} = -\vec{\nabla} V$ and $e \cdot N_{eff}$

So $$-\frac{d^2 V(x)}{dx^2} = \frac{e \cdot N_{eff}}{\varepsilon \varepsilon_0}$$

E is maximized at the junction and zero at the opposite edge "w" of the depleted region. Then,

$$V(x) = -\frac{e \cdot N_{eff}}{\varepsilon \varepsilon_0} \cdot \frac{(w-x)^2}{2}$$

$$w = \sqrt{\frac{-2 \cdot V \cdot \varepsilon \varepsilon_0}{e \cdot N_{eff}}} \Rightarrow \sqrt{\frac{2 \cdot V \cdot \varepsilon \varepsilon_0}{e \cdot |N_{eff}|}}$$



When w = the physical width of the sensor, then V = V$_{\text{dep}}$, “depletion voltage”

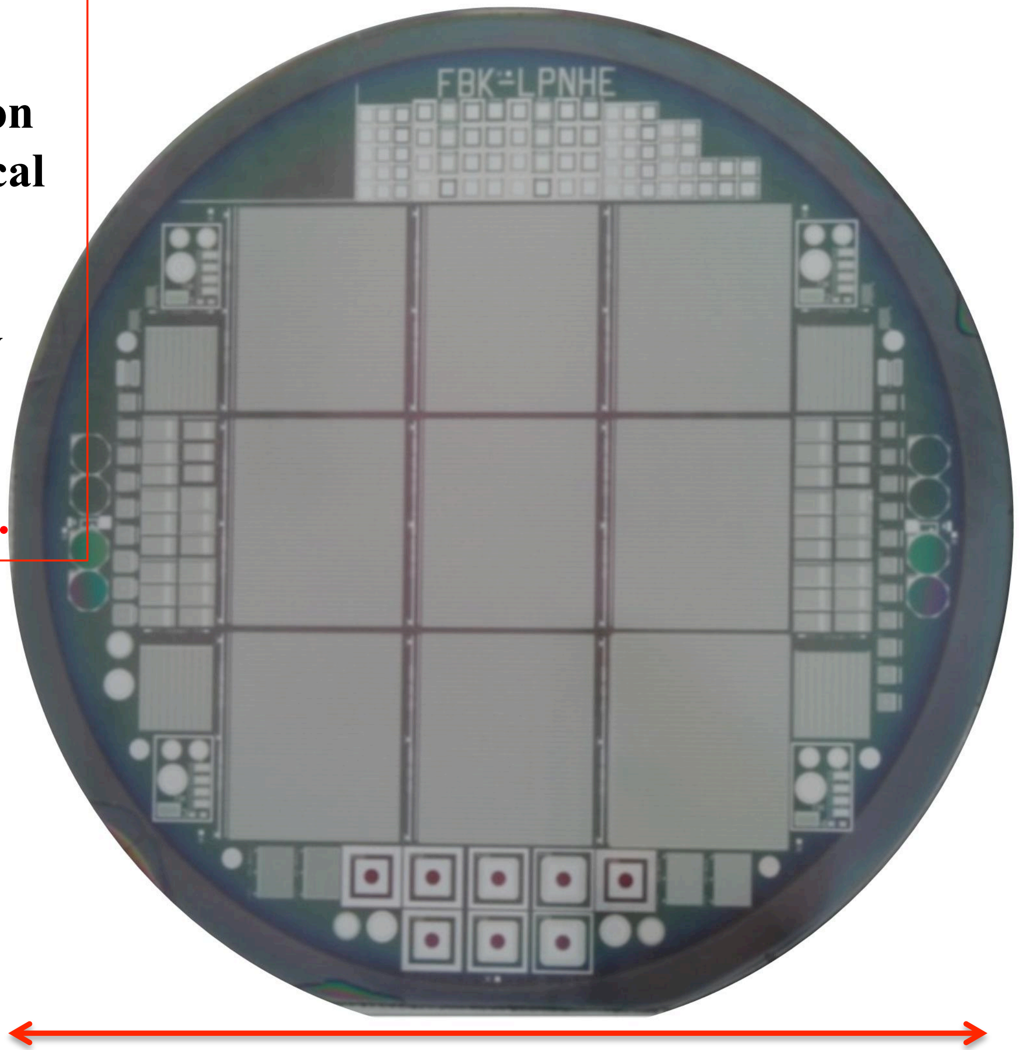
A paradigm of silicon sensor geometry, and implementation choices

The sensor is fabricated on a thin silicon wafer whose type (n or p) will define the depleted bulk.

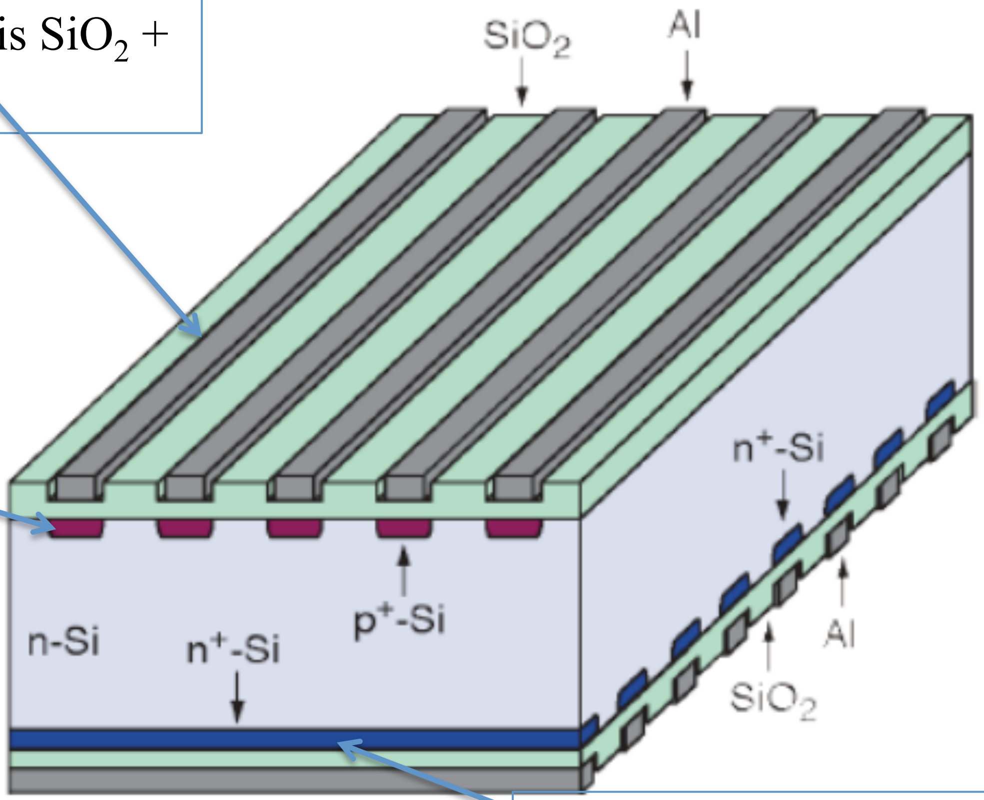
The pn junction is formed when the other type (resp. p or n) is deposited on the wafer surface, typically by chemical vapor deposition (CVD) or sputter.

Patterns and structure are defined by photolithography.

This is the basis of the planar process.



6 inches



In modern detectors, typically signal routed to read-out electronics is capacitively induced on **metal electrodes**. The capacitor dielectric is SiO_2 + Si_3N_4.

SiO_2 grows naturally on wafer surface, and electrically **isolates channels.**

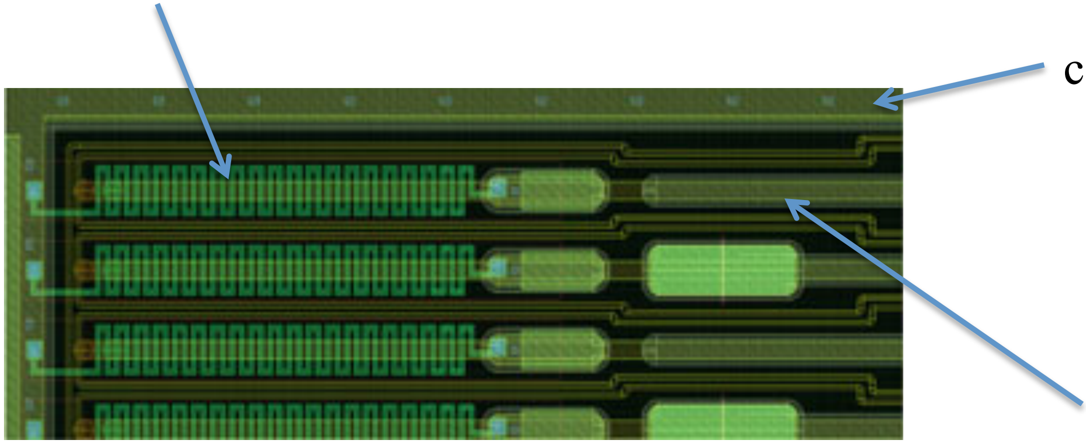
The pn junction is at the interface of the bulk with these **implanted strips** (“p^+” means $10^{18} \geq n_{dopant}/cm^3 >> 10^{13}$). Under reverse bias, the region depleted of free carriers grows from the junction toward the n^+ side (“back side”).

The **back side also takes an implant, which** can be segmented (in “double sided detectors”) or not.

Implementation issue #1:

The strips need to be isolated from each other to provide distinct charge collections
-but-
they must all be connected to a source of bias voltage.

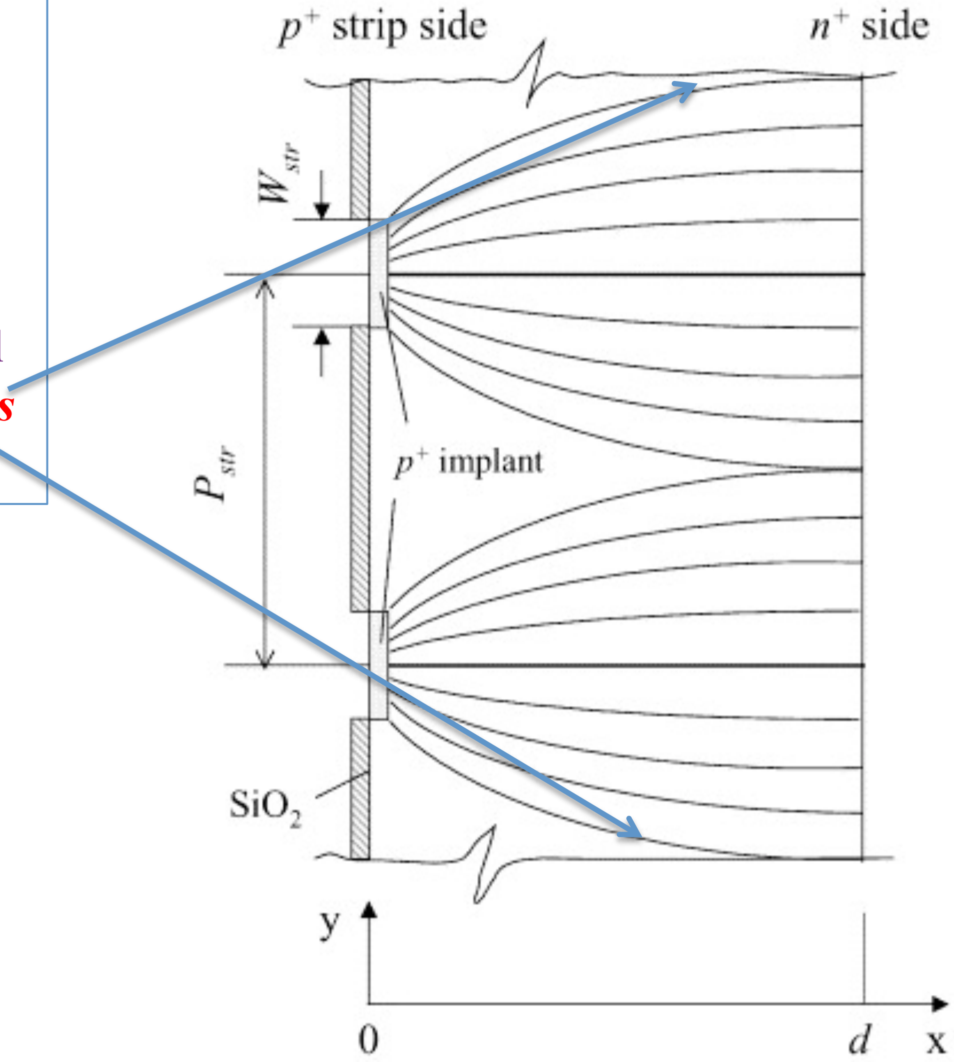
Solution: apply the bias potential to the strip through a very high resistivity (>1 MΩ) resistor ("**the polysilicon bias resistor**")



Implementation issue #2

The process of laser cutting the sensor from the wafer produces micro-cracks and dangling bonds.

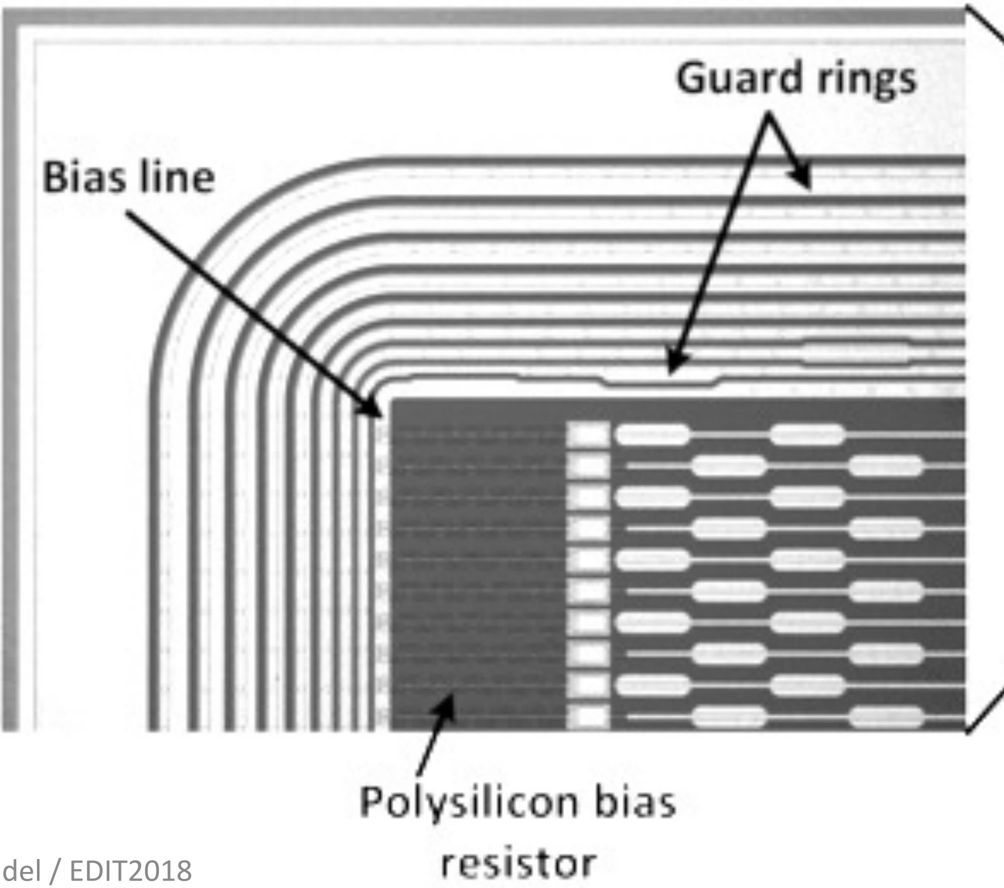
As the depletion region develops, it expands toward the cut edge, which is conductive, producing a condition unstable and sensitive to environmental changes: ***need to manage the boundaries of the electric field.***



3 solutions:

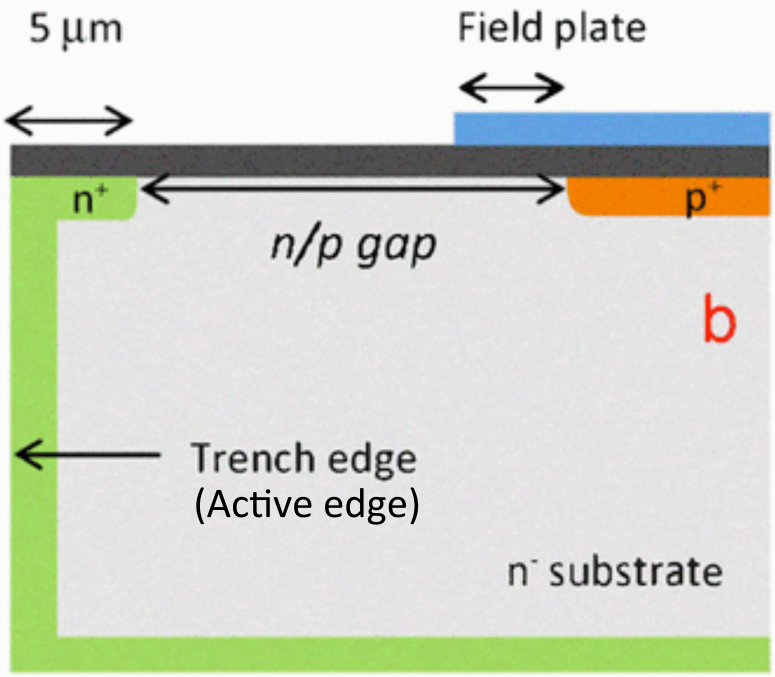
(1) On planar detectors - guard rings: **metal lines atop the oxide, and one or more ring-shaped p-n junctions that surround the sensor array but are not contacted or biased directly.**

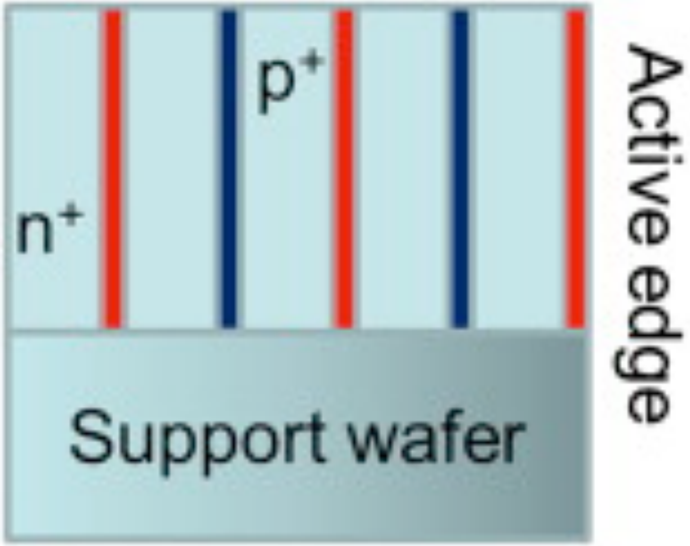
For p-implants in n-bulk: **bias the n-side, ground the active area and innermost guard.** As bias voltage rises, **depletion region expands.** When it contacts the first floating ring, that **guard charges up. Increasing V biases all the rings sequentially.** Each ring's V depends on: bulk doping concentration, inter-ring distance, and oxide charge. **The rings distribute the diode's field beyond the diode's perimeter, reducing the gradient of V at every surface point.**



(2) Active edges: a broad implant at the edge of the sensor cut face, of the same polarity as the back side doping, shapes the field and prevents it from reaching the sidewalls and providing conductive link for leakage current.

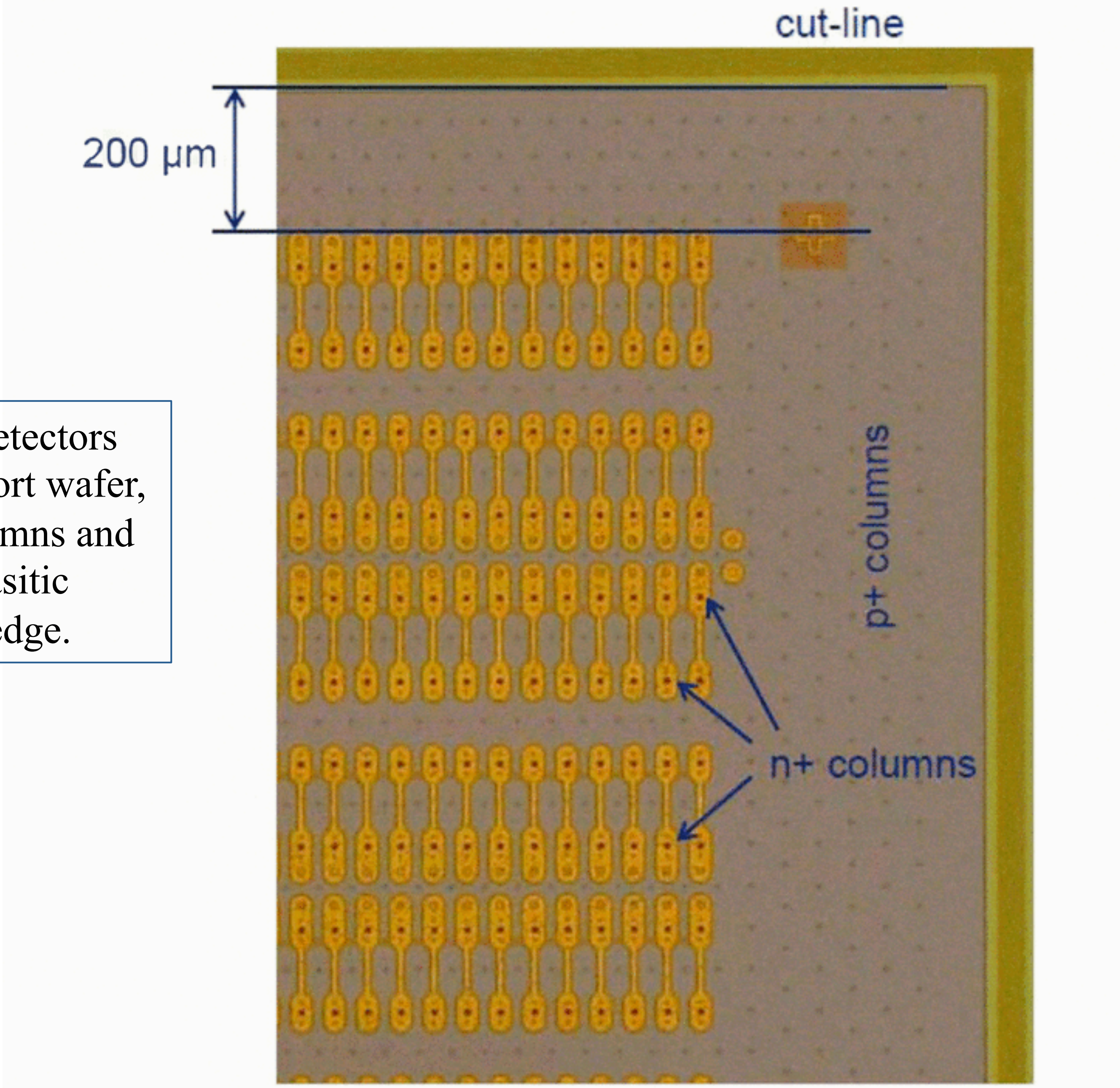
Traditional planar processing, with the electrodes parallel to wafer surfaces:





3D geometry – to be explained further – electrodes are perpendicular to wafer surfaces.

(3) Slim edges – on 3D detectors fabricated without a support wafer, a “fence” of junction columns and ohmic columns drain parasitic current coming from the edge.



Characteristics of the operating sensor

The detector records ionizations:

- A minimum ionizing particle traversing the Si loses energy at rate ***dE/dx*** **= 3.87 MeV/cm**.
- The mean ionization energy for silicon is $\boldsymbol{E_0}$ **= 3.62 eV.**

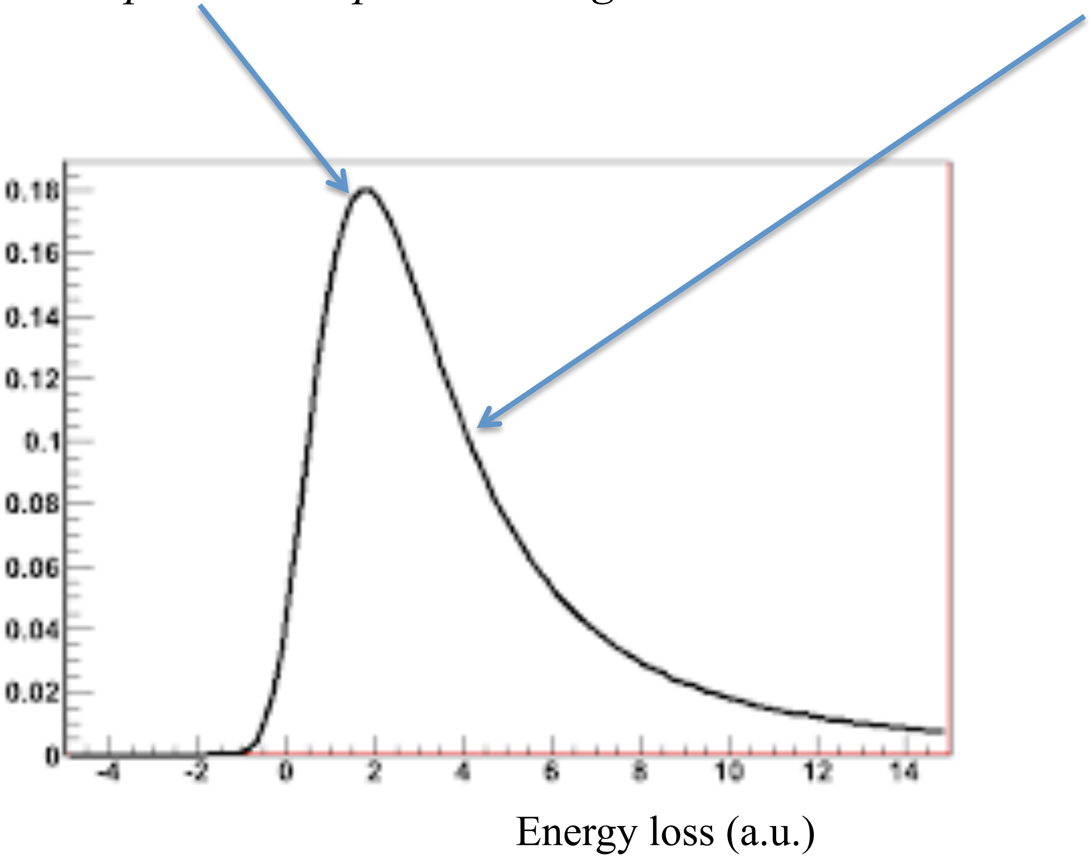
Thus: A detector of area A = 1 cm^2 and thickness *d* = 300 microns records a mean **signal**:

$$\boxed{\frac{\frac{dE}{dx}\cdot d}{E_0} = 3.2\times 10^4 \text{ electron-hole pairs signal}}$$

Notice why depleting the detector is critical for silicon:

In an undepleted, undoped ("intrinsic") semiconductor, the densities of holes and electrons are equal. In silicon at temperature 300K they are ***both*** $\boldsymbol{1.45\times 10^{10}/\text{cm}^3}$. Scale that to the thickness *d* = 300 microns to predict **4.35×10^8 thermal (noise) e-h pairs in undepleted silicon. Without depletion, they will swamp the signal**.

But the ionization is a statistical process, leading to a distribution in deposited charge: The *most probable deposited charge is not the same as the mean*.



This **Landau distribution** combines #collisions in a finite medium (Poisson distribution) with energy transfer per scatter (includes "straggling function" for high-energy delta-electron transfer).

For a MIP, most probable # pairs = 76/micron; mean # pairs = 108/micron.

The detector produces leakage current:

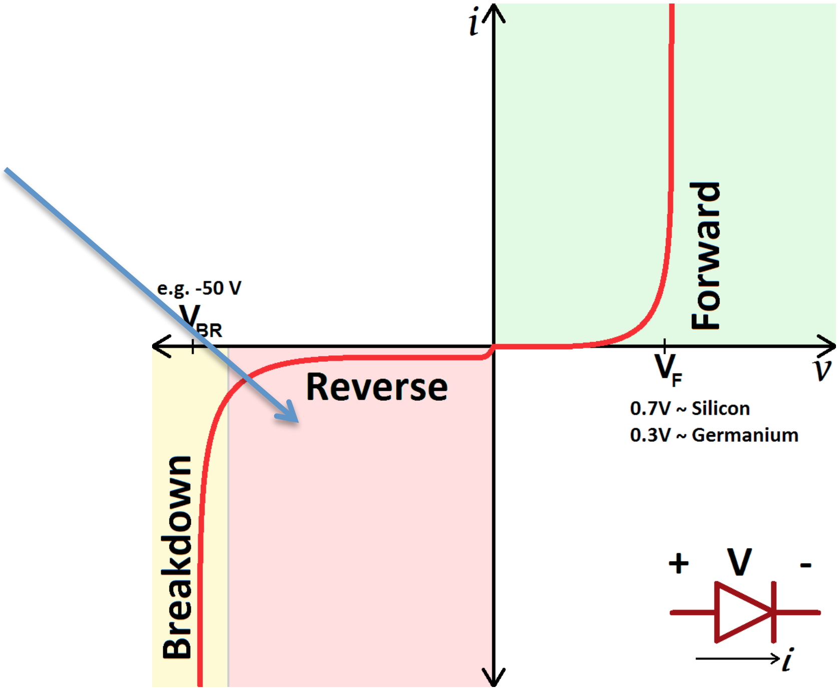
- thermal generation in the depleted region:

$$i \sim T^{3/2} \cdot \exp\left(E_{gap} / 2kT\right)$$

- and diffusion inward from the undepleted region

This current is both a diagnostic of the quality of the crystal and a source of noise.

The current versus voltage ("IV") characteristic of a detector is typically the first thing you will measure to check that it is operating properly and to find the range of safe bias voltages.



The sensor presents a capacitance to the preamplifier:

The capacitance depends on the depth *w* of the depletion region:

$$C = \frac{dQ}{dV} = \frac{dQ}{dw}\frac{dw}{dV}$$

Recall (Slide 18): $w(V) = \sqrt{\frac{2\varepsilon\varepsilon_0 V}{e|N_{eff}|}}$, so $\frac{dw}{dV} = \sqrt{\frac{\varepsilon\varepsilon_0}{2e|N_{eff}|V}}$

For a capacitor of area A and thickness w storing charge Q,

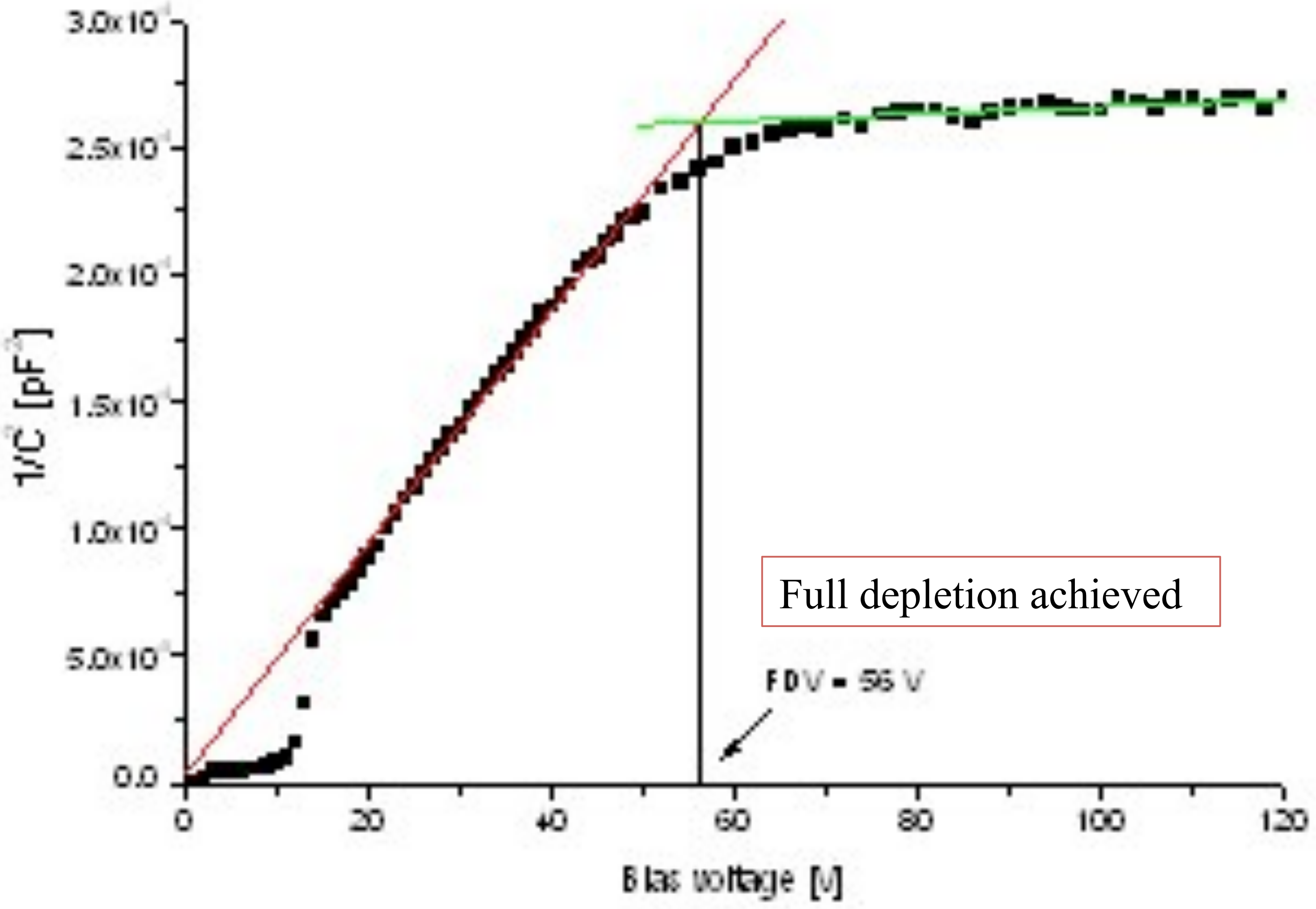
$Q = e|N_{eff}|Aw$, so $\frac{dQ}{dw} = e|N_{eff}|A$

Then $C = e|N_{eff}|A \cdot \sqrt{\frac{\varepsilon\varepsilon_0}{2e|N_{eff}|V}} = A\sqrt{\frac{\varepsilon\varepsilon_0 e|N_{eff}|}{2V}}$

Note: $\mathbf{C \sim V^{-1/2}}$

We measure the capacitance as a function of applied voltage to determine when the sensor's depletion zone has been extended to the full physical volume of the crystal ("the sensor has been fully depleted.")

$C \sim V^{-1/2}$ so, prior to full depletion, $1/C^2 \sim V$

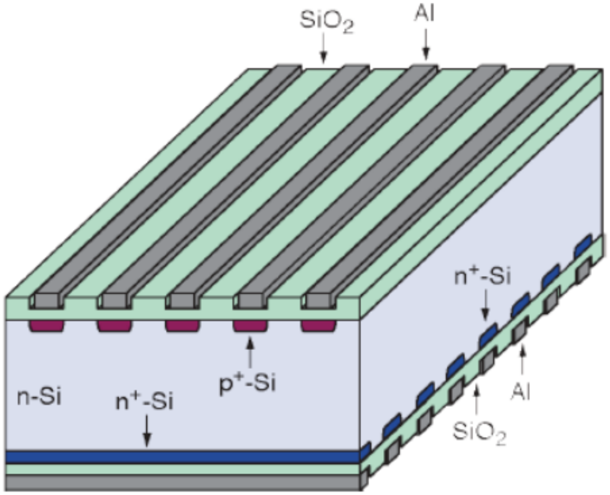


Full depletion achieved

Some useful numbers:

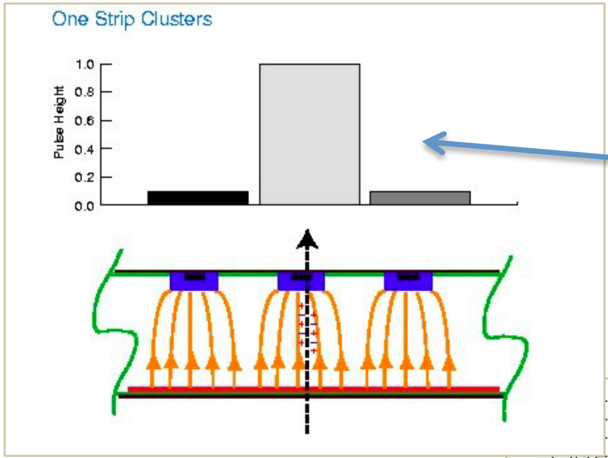
Modern typical **thickness is about 300 microns or less.**

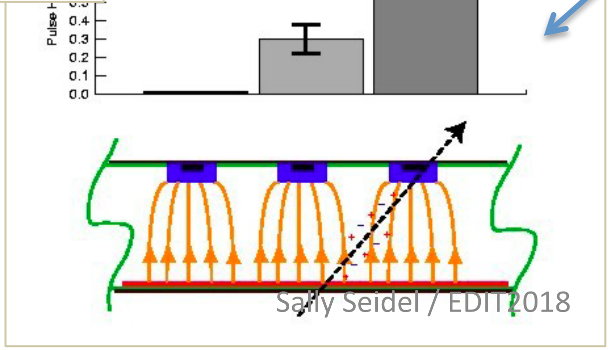
For “high resistivity” silicon ($N_{donors} \sim 2.2 \times 10^{12}/cm^3$) the pre-irradiation $V_{dep} \sim 150$ V



A typical strip **pitch is p = 50 µm**.

- For binary charge readout on a single strip, the position resolution is σ = p/√12.
- If the charge is shared over multiple strips, with analog readout, resolution improves to σ ≅ p/(signal-to-noise ratio)



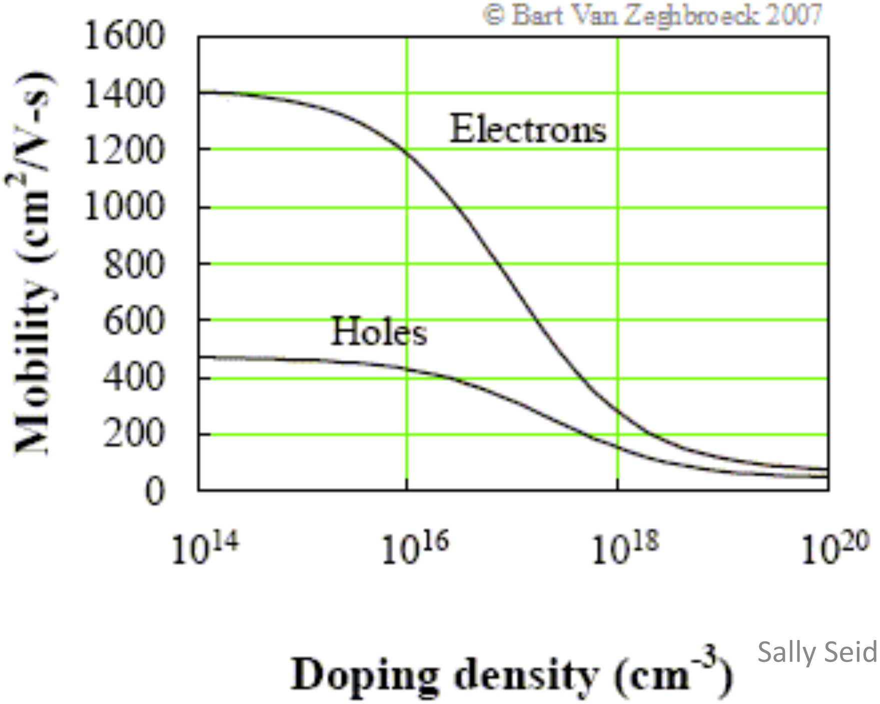


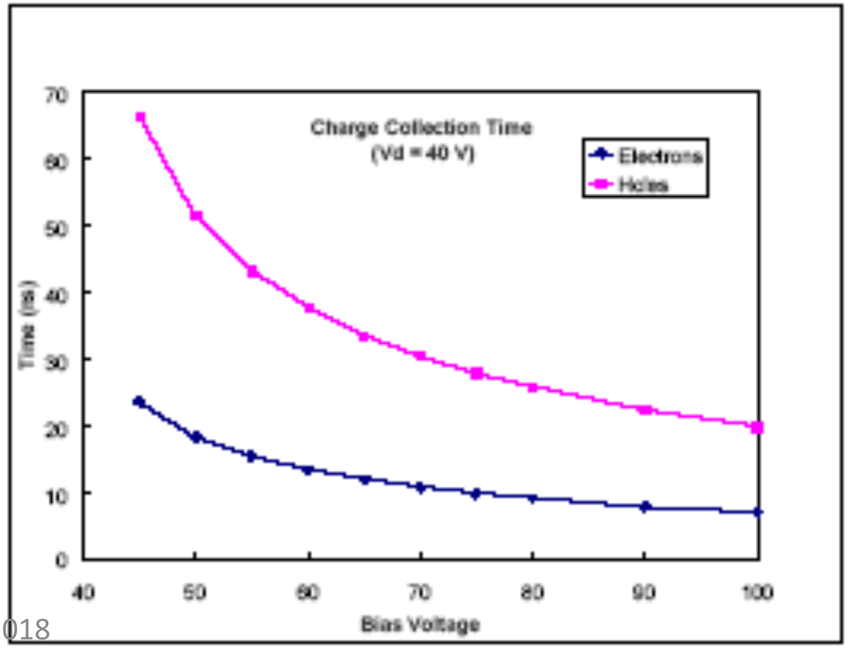
The sensor can be designed to collect the electrons, the holes, or both.

The mobility of a carrier is given by $\boxed{\mu = \frac{e\tau}{m}}$ where m = effective mass, τ = mean time between collisions, e = electron charge.

Electrons have higher mobility:
$\mu_e = 1400\ \mathrm{cm^2/Vs}$
$\mu_h = 450\ \mathrm{cm^2/Vs}$
so they are collected faster.

Their velocities depend simply on the applied field E: $\boxed{v_{e,h} = \mu_{e,h} E}$





Experimental goals and their impact on sensor optimization

The experimenter wants to maximize signal/noise.
Typical strip detector signal to noise ratio before irradiation: 15.

There are several **sources of noise in this sensor:**

- Capacitance C (interstrip, bulk, coupling...). Equivalent noise charge $ENC \sim C$
- Leakage current. $ENC \sim \sqrt{I_{leakage}}$
- Thermal noise in the bias resistor of resistance R: $ENC \sim \sqrt{\frac{kT}{R}}$
- Series resistance in the aluminum traces and connection to the amplifier: $ENC \sim \sqrt{R_{series}}$

To optimize S/N in strip detectors: ***minimize capacitance, minimize leakage current, maximize bias resistance, minimize the resistive connection to the amplifier.*** The contribution from capacitance typically goes inversely as the pre-amplifier integration time, so ***use long integration time*** (but this is restricted by the accelerator beam structure).

For pixel detectors the critical parameter is Signal/Threshold. Typical contemporary front end electronics threshold ~ 2500 e.

The experimenter also wants to optimize position resolution. Contributors to this:

- The shape of the Landau distribution indicates that the ionization deposited in the detector includes statistical variation. (E.g., a delta-ray production due to a hard collision with an electron will redirect the track.)

- The ionization electrons and holes *drift* along the electric field to the electrodes, but at the same time they *diffuse*. Diffusion broadens the cluster.

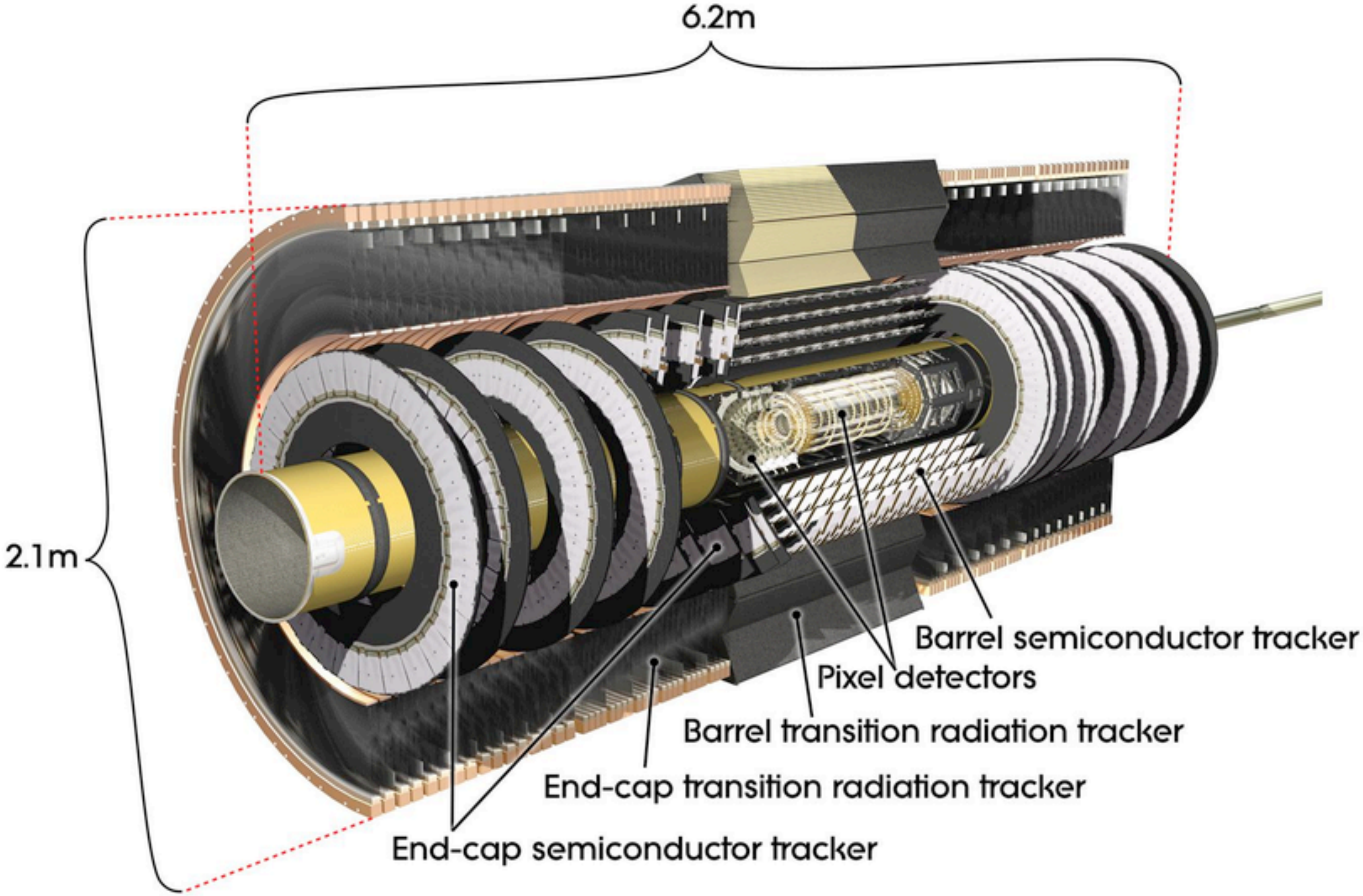
For drift time t, temperature T, mobility μ:

Diffusion coefficient $D = \dfrac{kT\mu}{e}$

Width of the ion distribution $\sigma = \sqrt{2Dt}$

If multiple channels are hit due to diffusion, and analog readout is employed, resolution is improved.

- Material in the detector: minimize thickness to reduce multiple scattering.



Radiation damage

Irradiation causes nonstop damage to the silicon, effectively producing artificial donor- and acceptor-like sites in the lattice. Developing radiation tolerant detectors (and detectors that can be dynamically modified to respond to changing conditions) is a priority research activity.

The measurable unit of radiation is ***integrated fluence***: energy deposited on a surface per unit area. Radiation damage depends on particle charge and mass – typically any damage is normalized to that of a 1 MeV neutron (“n_{eq}”). Target lifetime radiation hardness goals for LHC silicon are in the range 10^{15} - 2×10^{16} n_{eq}/cm^2, depending upon the expected distance of the detector from the interaction point.

Radiation sources in a particle collider:

- The main source of **charged radiation: collisions at the interaction point**, so their fluence $\Phi\sim1/r^2$.
- The main source of **neutrons: backsplash from the calorimeter**, so their Φ depends on shielding and design.

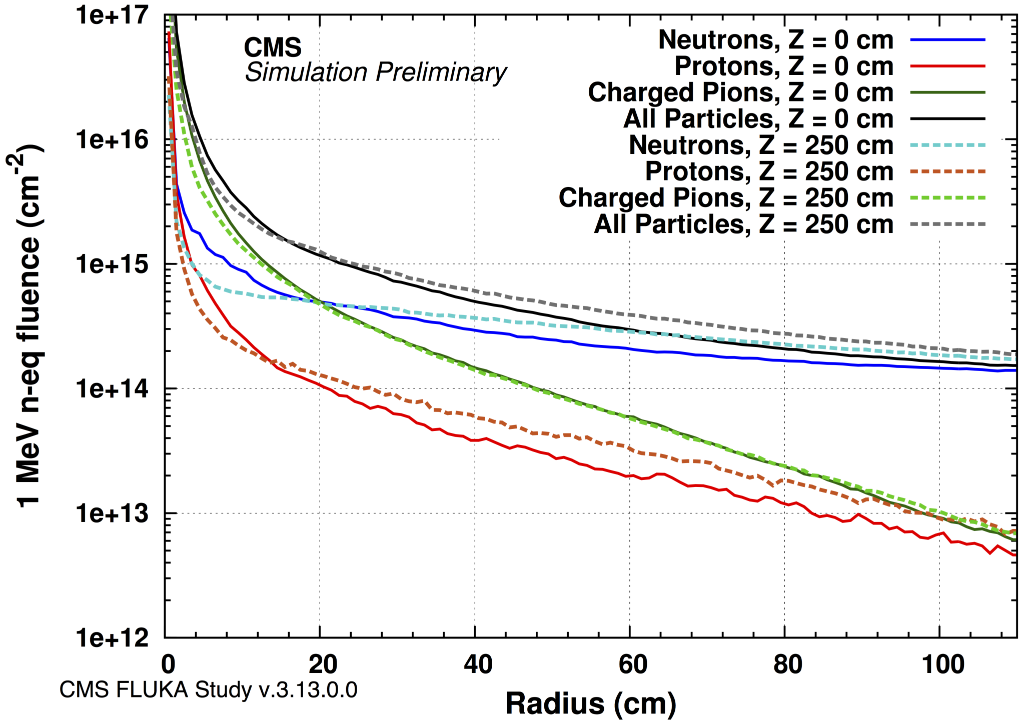
Two types of effects: bulk damage and surface damage

Bulk radiation damage

Through-going particles cause **dislocations in the crystal lattice that disrupt the band structure**.

The displaced atom (“the primary knock-on atom (PKA)”) becomes a silicon interstitial (Si_i) and leaves a vacancy. The recoiling PKA can strike neighboring atoms, so typically **damage sites occur in clusters. The clusters can remain mobile and evolve, leading to macroscopic *time-dependent* effects.**

- **Neutrons** cause cluster-like vacancy agglomerates through hard core nuclear scattering.
- Protons add isolated vacancies and interstitials: “point defects” through Coulomb interactions.
- Pions are the most common product of proton-proton collisions AND they cause the worst damage to silicon, through Δ-resonance production when they collide with a proton in a nucleus in the detector.



CMS FLUKA Study v.3.13.0.0

Surface damage

Silicon in the wafer naturally develops **a layer of SiO_2. Ionizing radiation generates bound charge in that layer and at the interface between the Si and the SiO_2.**

The interface states become filled and saturate at about 100 kRad so for the sensors this is not as severe a problem as the bulk damage. But surface damage is a major challenge for readout electronics.

No saturation of bulk damage has been observed, up to Φ = a few × $10^{15}/cm^2$.

The radiation damage changes everything about the operation of the device. Typically radiation adds donors and removes acceptors. Contemporary designs are the response to this pressure.

Leakage current increases:

$$\boxed{J(\Phi) = \alpha\Phi + J_{\text{intrinsic}}}$$

where α is the “current-related damage constant.” The $\Delta J = \alpha\Phi$ is due to **production of generation-recombination centers in the semiconductor’s bandgap.**

Leakage current causes stochastic noise in the amplifier:

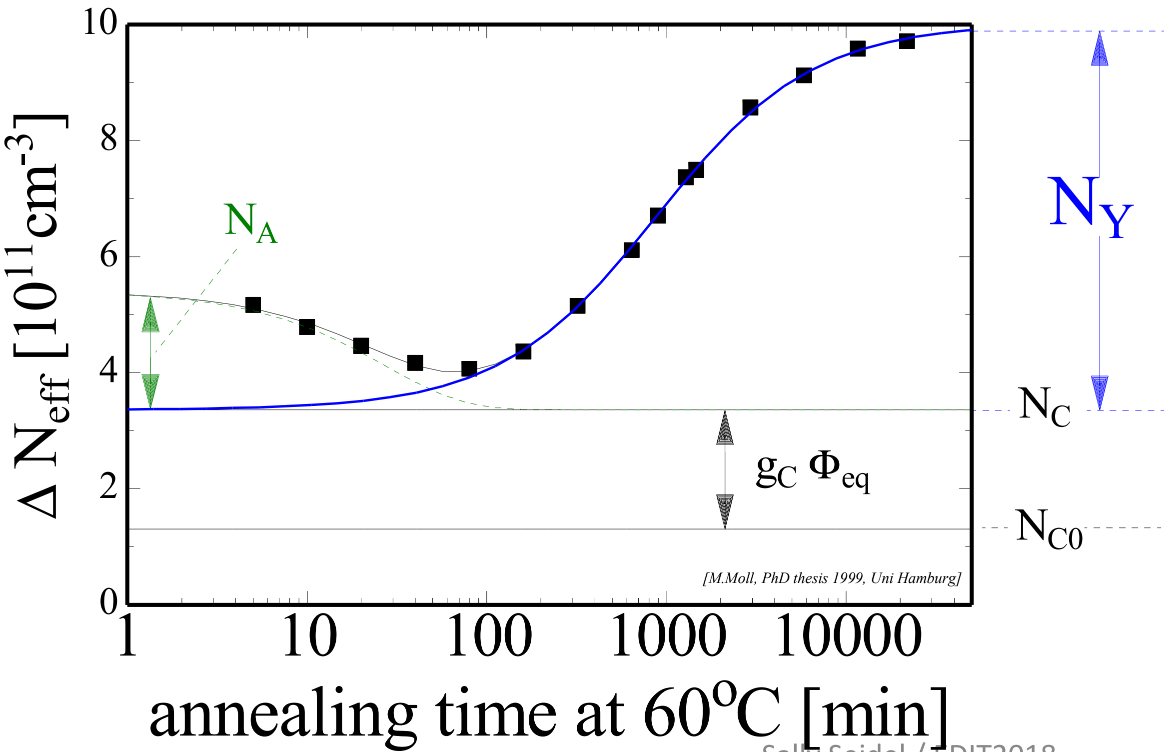
$$\boxed{ENC \sim \sqrt{I_{leakage} \cdot \tau_{shaping}}}$$

Remedy: cooling. The ATLAS pixel detectors operate at -10°C. The ATLAS strips operate at 0°C.

The *effective dopant concentration* of the substrate changes with fluence.

- $\Delta N_{eff}(\Phi) = \Delta(N_{donor} - N_{acceptor}) = N_C + N_a + N_Y$ where:

- $N_C = N_{c0}(1 - e^{-c\Phi}) + g_C\Phi$: “stable damage” coefficient, with no time constant
- $N_a = g_a\Phi e^{-t/\tau(a)}$: “short term beneficial annealing” which is insignificant after 2 days at room temperature
- $N_Y = g_Y\Phi(1 - e^{-t/\tau(Y)})$: “reverse annealing.” Its value begins at 0 for t = 0 and grows to saturate at $g_Y\Phi$ as t approaches ∞



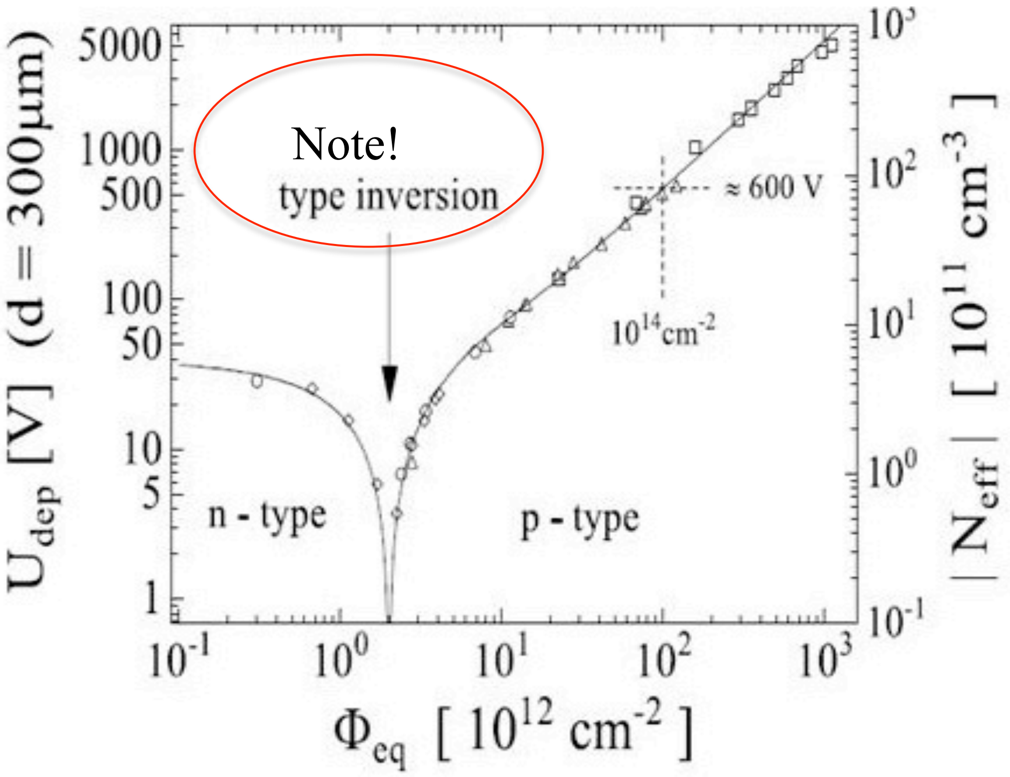
[M.Moll, PhD thesis 1999, Uni Hamburg]

The damage continues to develop after the irradiation is over and is thought to **be due to thermal mobility and aggregation or disaggregation of the defects).**

This reverse annealing rate is temperature dependent and can be effectively frozen out below about -5C.

Problem: (Recall from Slide 18) **the potential needed to deplete the sensor is directly related to $|N_{eff}|$:**

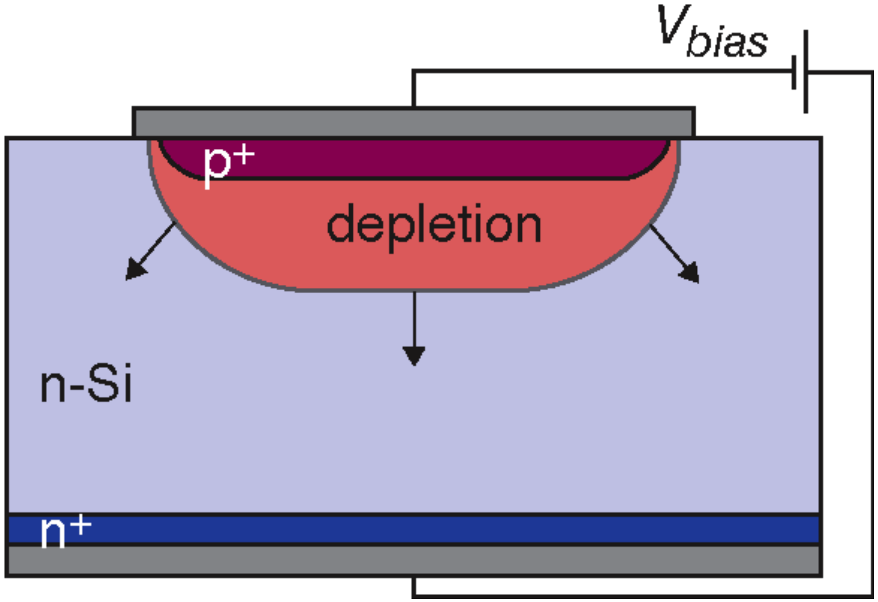
$$V_{depl}(\Phi) = \frac{w^2 q N_{eff}(\Phi)}{2\varepsilon}$$



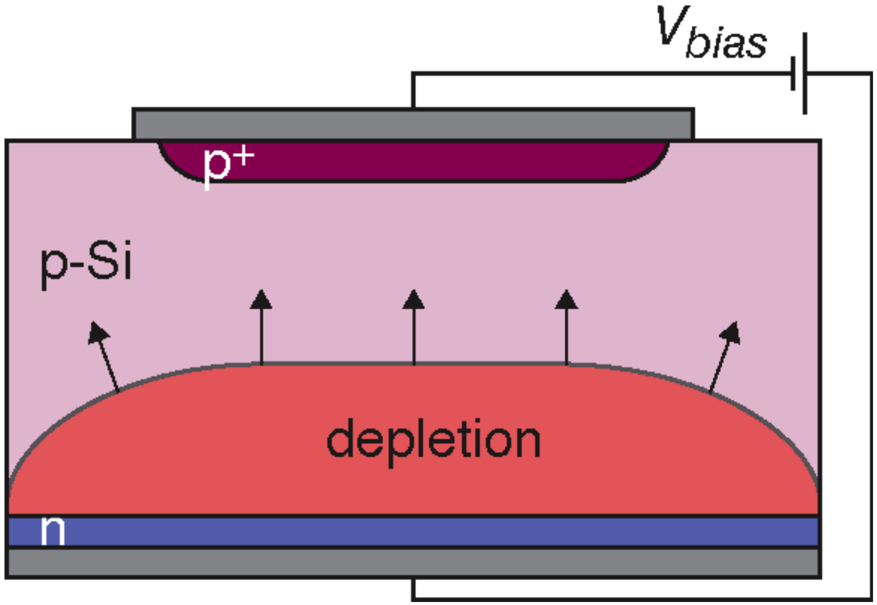
Notice: V_{depl} and $I_{leakage}$ both depend upon fluence Φ, so power consumption (heat generated) ~ fluence Φ^2. This has significant impact on cooling and power budget.

Problem: **after type inversion, the junction is on the back side.**

In "p-on-n" sensors (p implants, n bulk): depletion zone grows from the p-implants to the backplane n-implant. These detectors can be operated under-depleted if necessary as the signal-forming depletion region is always in contact with the segmented strips.



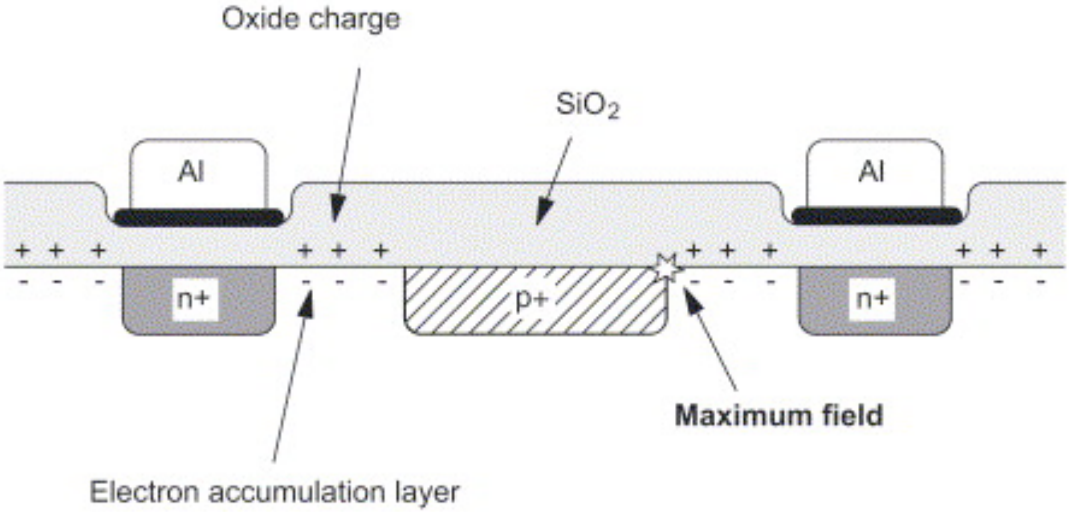
The polarity of the bias voltage remains unchanged **after inversion, but the signal doesn't reach the readout until the full depletion is achieved.**



Solutions to this problem: n^+-on-p or n^+-on-n.

Surface damage to the bonds at the silicon-SiO_2 interface grows. Implications:

- These attract electrons from the bulk to produce **an "accumulation layer" of fixed negative charge between n-type implants of a detector. The isolation of adjacent structures can be compromised, leading to "microdischarge."**
- **The capacitance** (which depends on the effective area of the implants) **grows.**

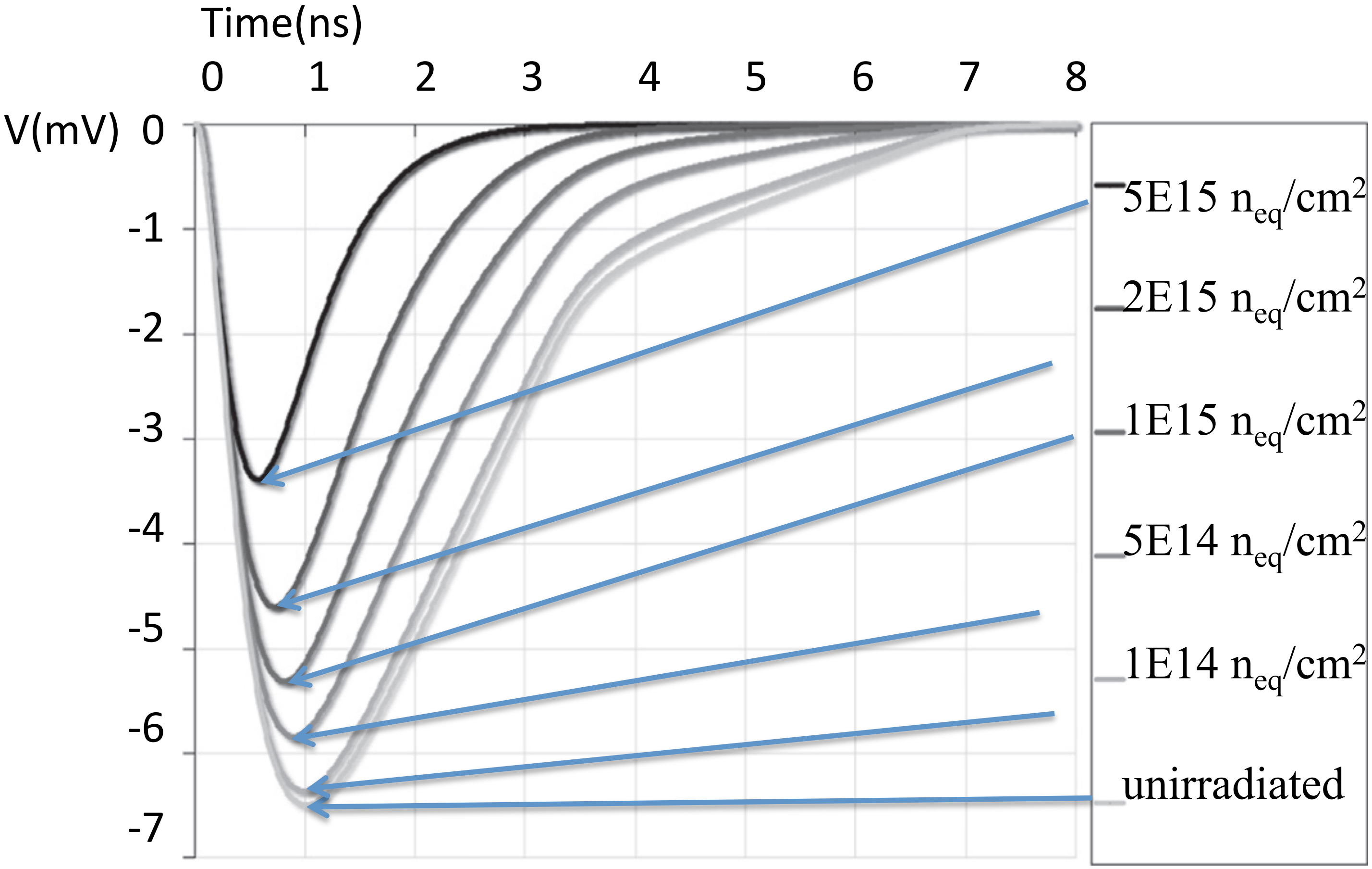


Remedies: **structures of p-type material that disrupt the accumulation layer:**

- p-stops - a p-implant structure
- p-spray - a diffuse layer of p-dopants matched to the surface charge saturation value is $3\times10^{12}/cm^2$
- or a combination of p-stops and p-spray

Problem: **Signal loss**

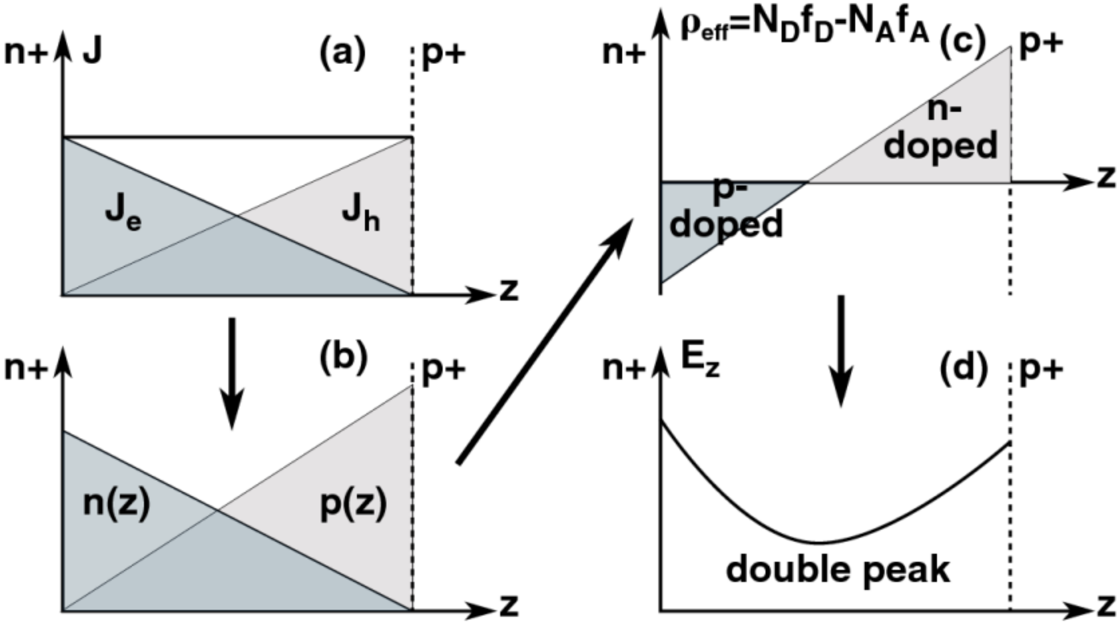
Bulk defects produce metastable states. Delayed release of charge from these states leads directly to loss of collected signal. Example for a silicon detector of thickness 300 microns, operated at 500 V and 300 K, with $V_{depl} = 50$ V:



B. Baldassarri et al., NIM A 845 (2017) 20-23

Problem: **trapping centers lead also to the development of a second junction:**

Thermally generated carriers in the bulk are trapped in the course of their drift to the electrodes. **Expected linear electric field across the bulk becomes parabolic and charge collection is reduced.**



At this fluence, measuring $1/C^2$ versus V_{bias} will no longer predict the charge collection, as it presumes a linear E field extending across the full bulk – better to measure charge collection efficiency ("CCE") directly, typically by stimulating the sensor with a penetrating (IR) laser.

These radiation effects have stimulated technological development.

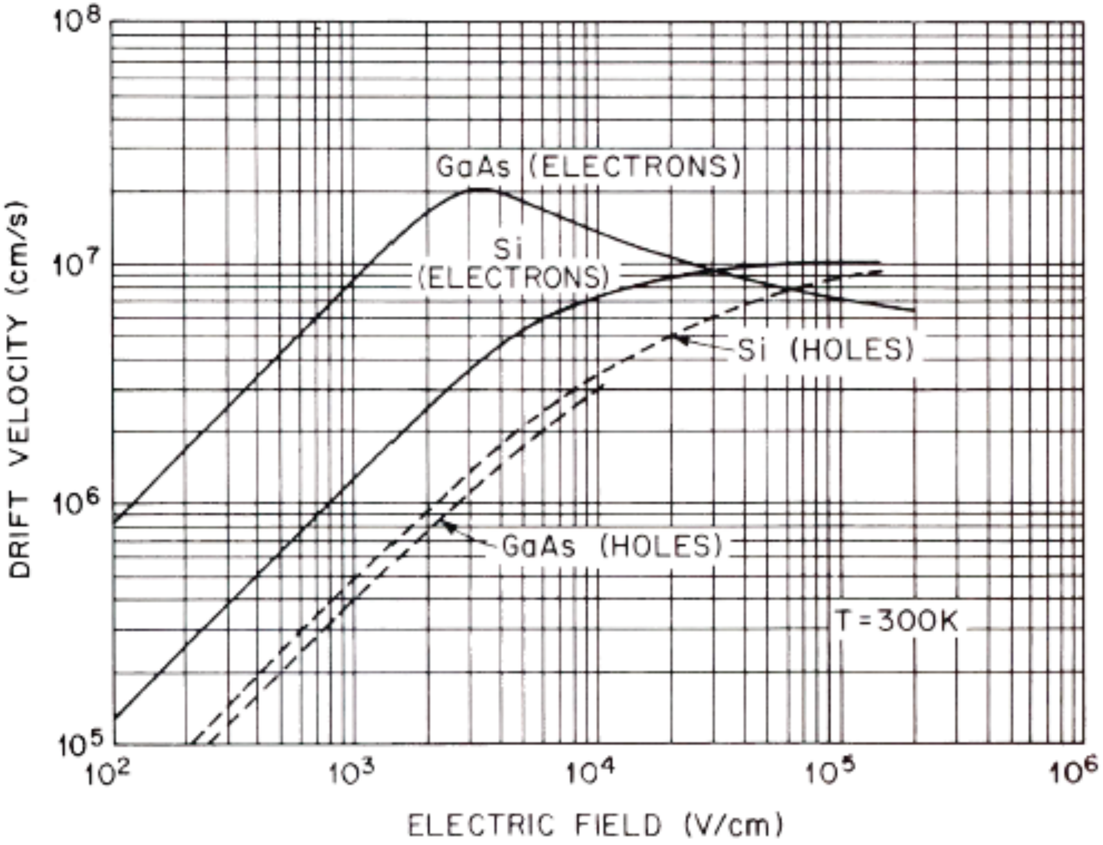
One response to the type-inversion of n-type bulk is: Build the sensors on p-type substrate to begin with. Optimize the readout for signals from n-on-p detectors. (This is the baseline for ATLAS and CMS upgrades.)

Advantages:

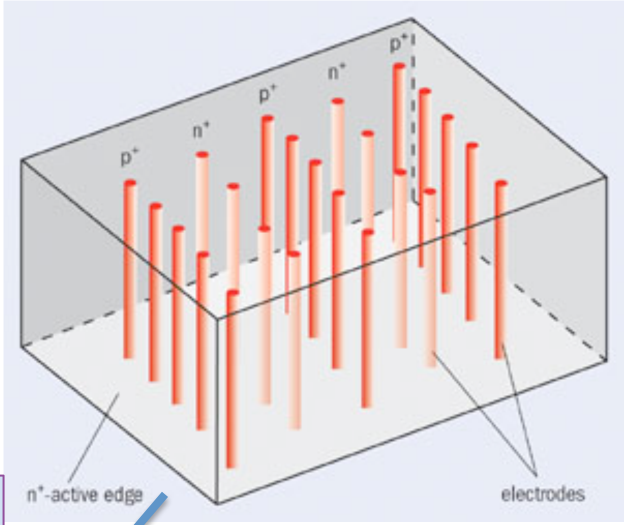
- **n-strips on p-bulk collect electrons**

Electrons' drift velocity is ~3 times faster than holes'.

- **economical advantage:** n-in-p sensors do not need structures to accommodate the type inversion, so they can be processed on 1 side only and are less sensitive to damage on the back side.

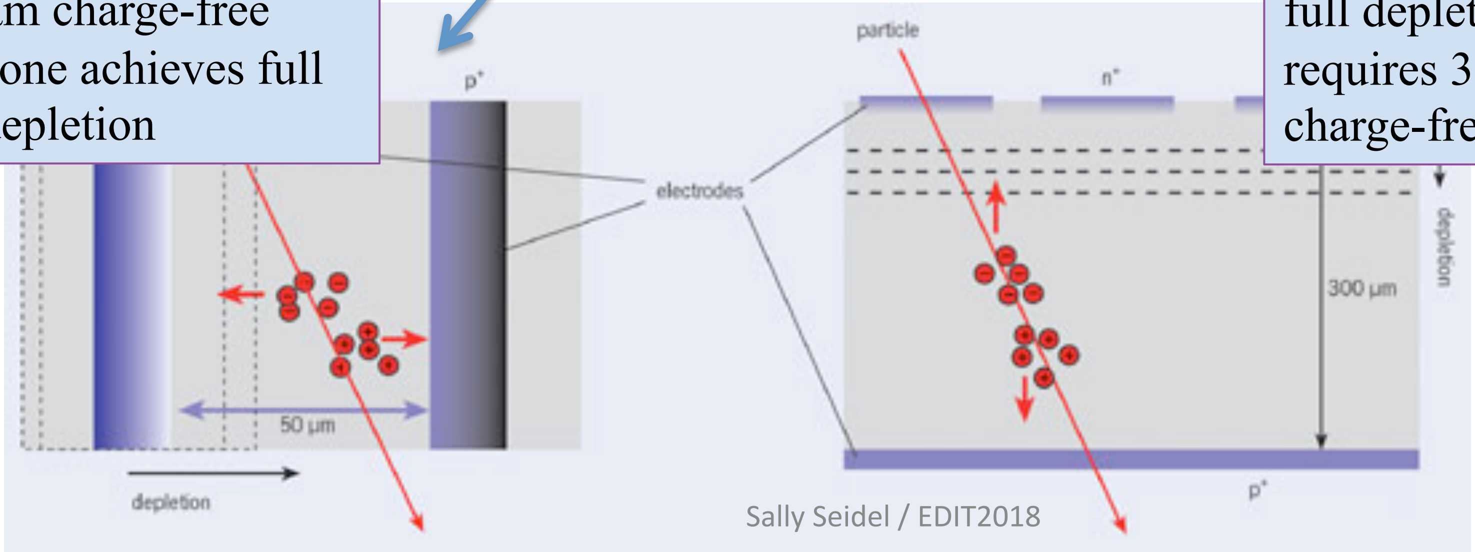


One response to the rising depletion voltage is to reorient the electrodes. Traditional planar detectors place the electrodes on the surface. **“3D” detectors orient the electrodes perpendicular to the surface using Deep Reactive Ion Etching (DRIE)**:



Prior to irradiation, these deplete at < 5V.

This is 3D: only 50 μm charge-free zone achieves full depletion



Compare planar: full depletion requires 300 μm charge-free zone

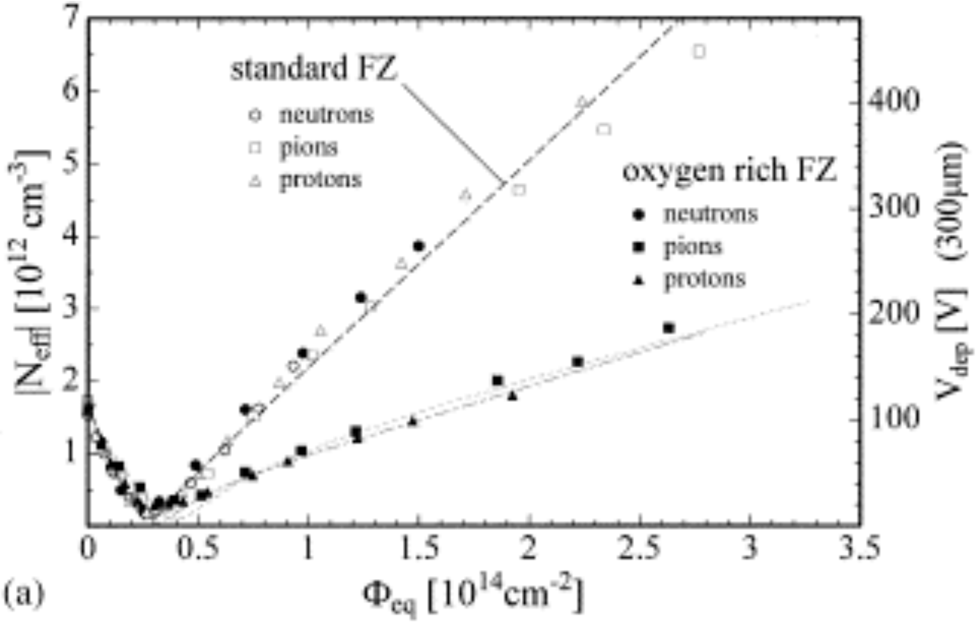
Combating the effects of radiation damage by engineering the semiconductor:

Approaches:

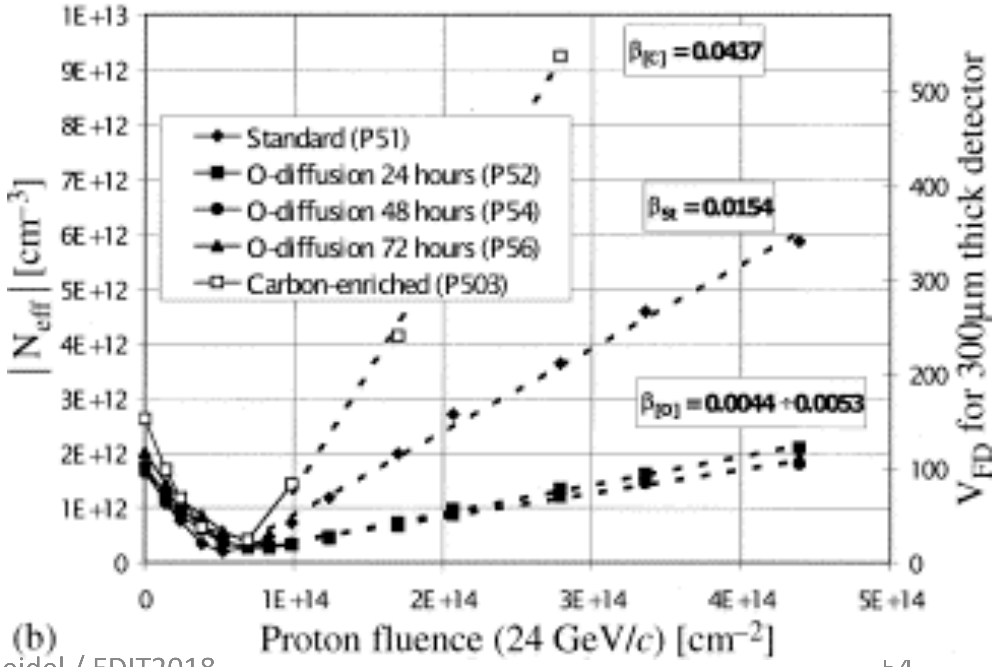
- **Defect engineering: Enrich the silicon substrate with oxygen** before irradiation: the oxygen is thought to capture vacancies in stable and electrically neutral point defects, leading to **improved hardness against *charged* hadrons.**

Observed results: reduced full depletion voltage, reverse annealing time constant increased

See: CERN RD50 Collaboration



(a)



(b)

Consider other semiconductors

Thus far silicon has outcompeted them on the basis of

- **ubiquity in industry**, leading to competition pricing, available simulation tools
- small band gap provides **low threshold for signal production**
- high specific density provides **high signal production rate**
- **rigidity** allows self-supporting structures to be very thin
- High mobility for both carriers permits **fast charge collection**

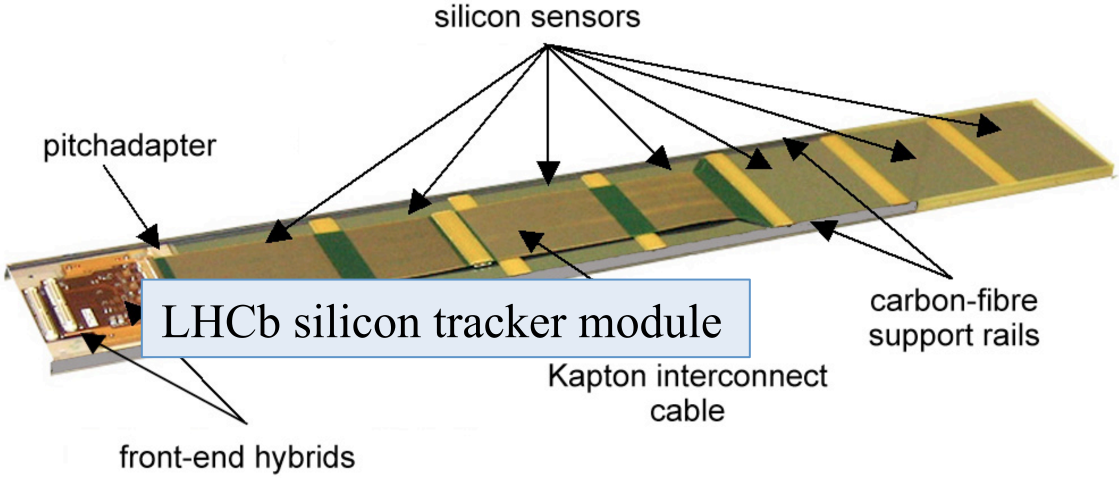
But there is a strong worldwide effort in **diamond** sensor development (see: CERN RD-42 Collaboration). Diamond is used in beam condition monitoring at LHC.

Diamond	Property	Silicon
5.5	Band gap E_g [eV]	1.12
10^7	$E_{breakdown}$ [V/cm]	3×10^5
1800	electron mobility μ_e [cm^2/Vs]	1450
1200	hole mobility μ_h [cm^2/Vs]	450
2.2×10^7	saturation velocity [cm/s]	8×10^6
13	ionization energy (produce e-h pair) [eV]	3.6
4.4	#e-h pairs per radiation length	10.1

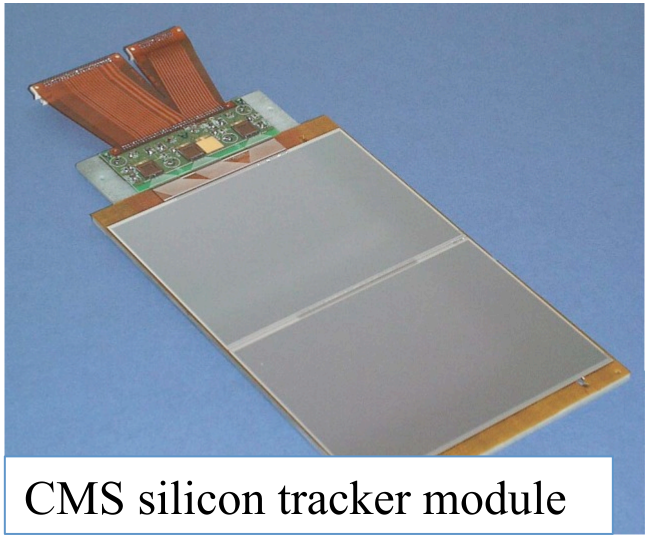
lower noise

more signal

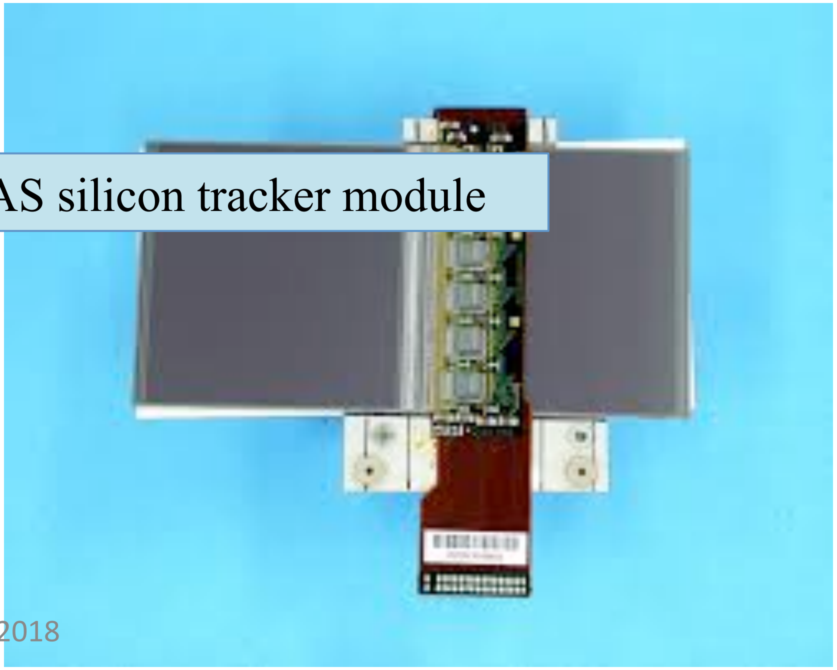
Putting the detector together: combining the sensor, front-end electronics, mechanical support, cooling, and connections into a module



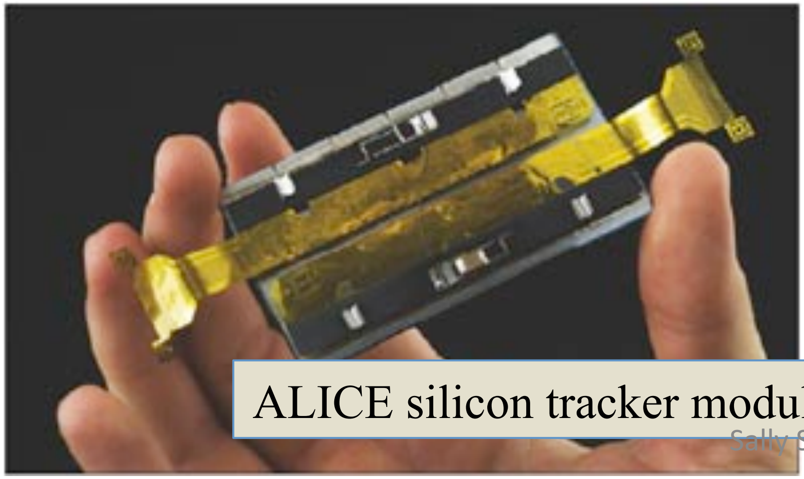
LHCb silicon tracker module



CMS silicon tracker module

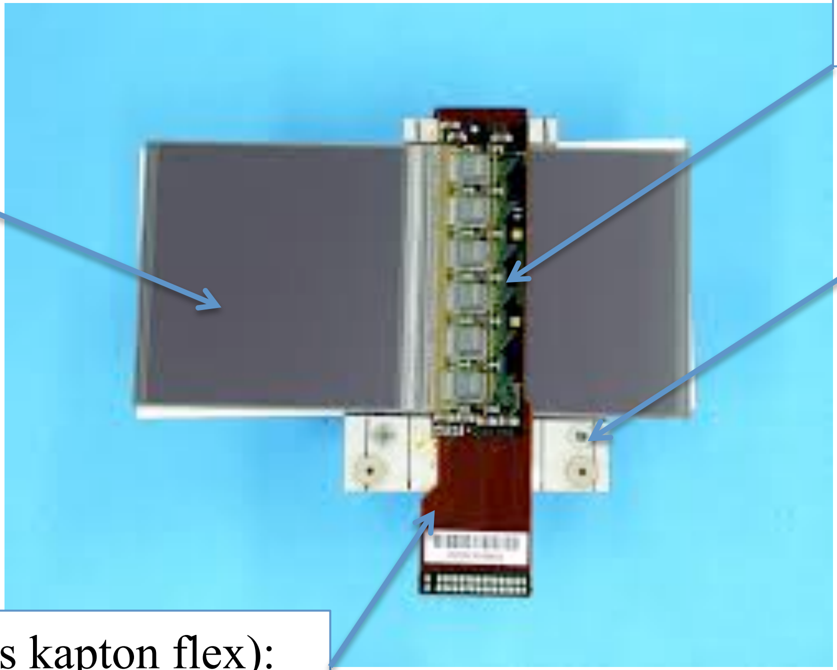


ATLAS silicon tracker module



ALICE silicon tracker module

The module typically includes:



Sensors
(here there are 4, back-to-back strip sensors with small stereo angle)

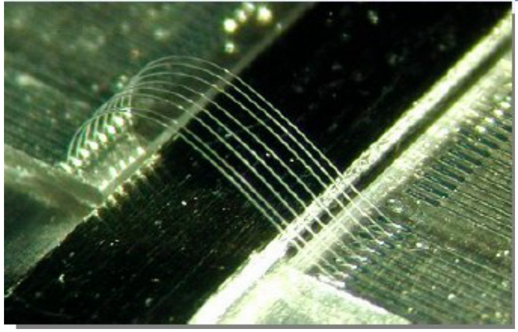
Preamplifier chips
(here there are 12).

Mechanical support

The "**hybrid**" (here it is kapton flex): wraps above and below sensors, carries

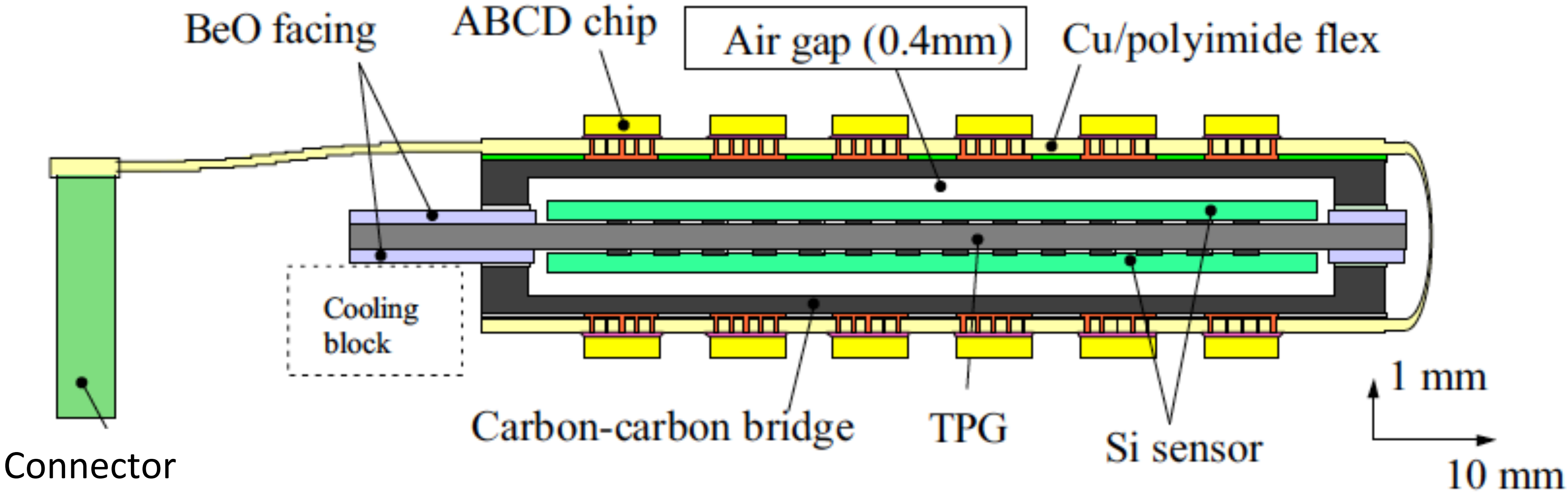
- the preamplifier chips,
- a pitch adaptor between sensors and readout chips,
- a connector to the off-detector electronics,
- copper routing for signals and power.

Aluminum wirebonds connect chips and sensors to the pitch adaptor:



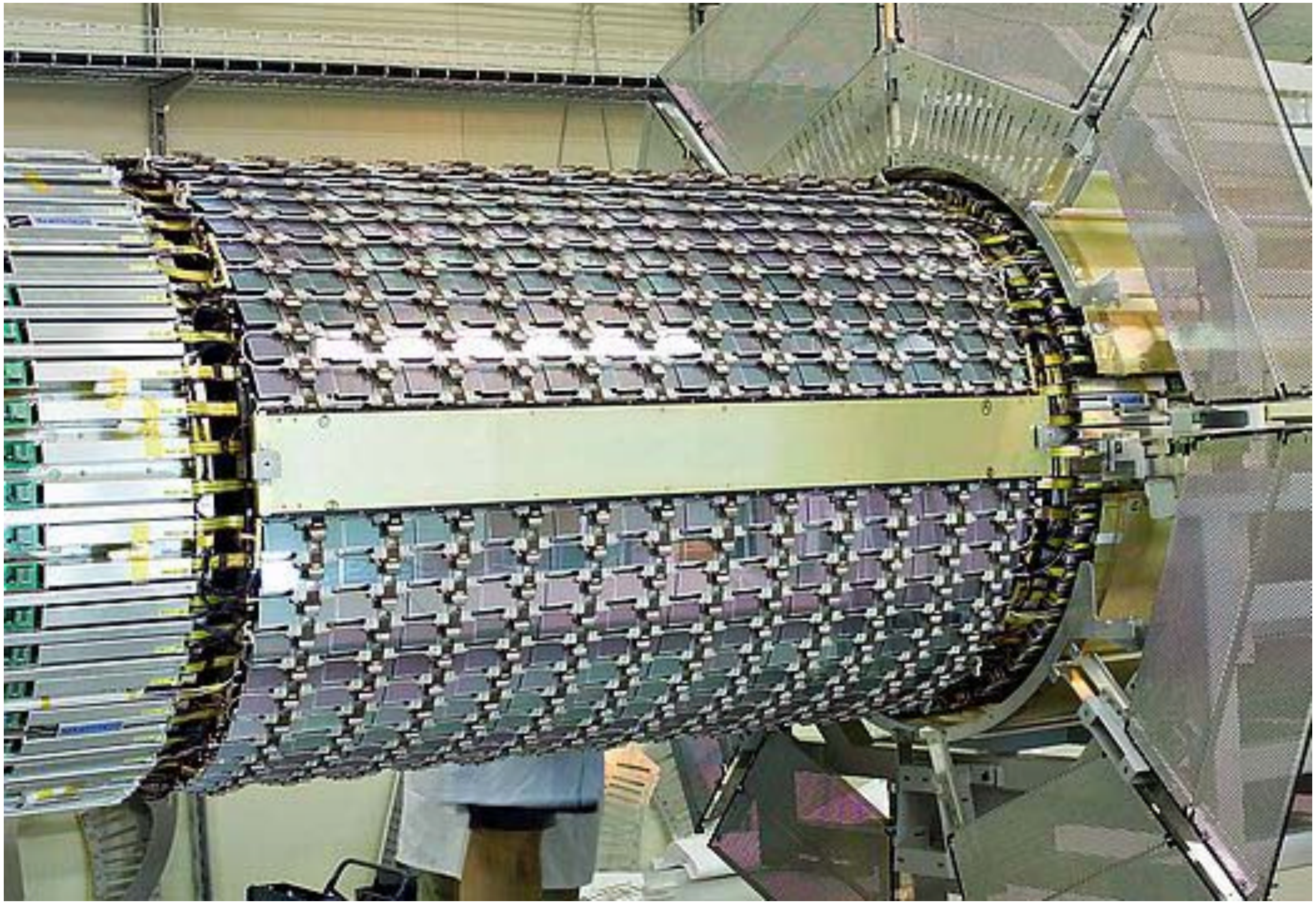
But through-silicon-vias (TSV) can replace wirebonding in the upgrade era.

A little more about strip detector modules, because modules have so many roles (using a cross section of the ATLAS SCT as an example):

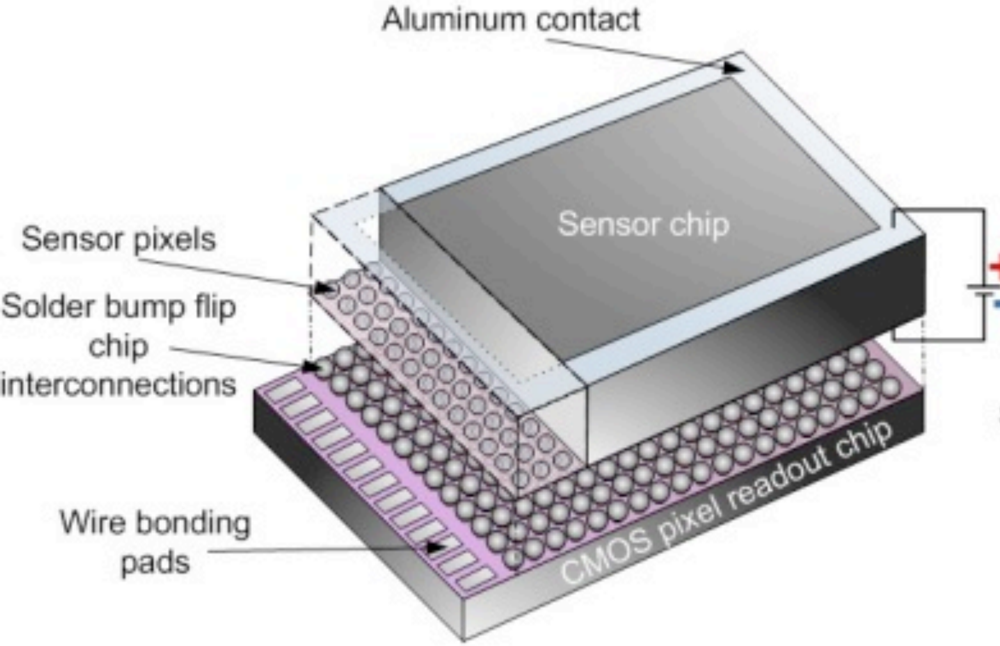


- Hybrid bridges over the sensor for reduced risk of damage
- High thermal conductivity critical
- Minimize radiation length
- High mechanical strength in carbon-carbon

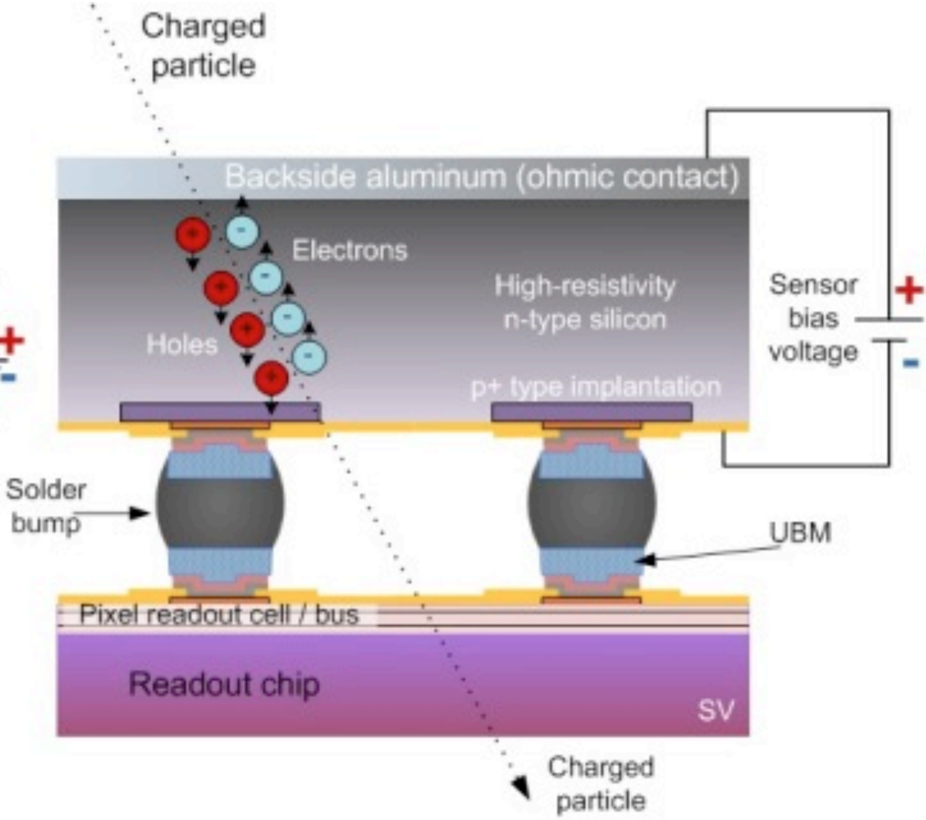
An example barrel of installed modules (in ATLAS):



The structure of a *pixel* module differs from that of a *strip* module because the preamplifier chips are placed directly below their sensors:



Generic pixel detector



Cross-sectional cut

Connections are provided with the "flip chip technique" by metal bumps typically solder or indium of diameter about 15 μm.

Pixel detectors are typically chosen over strips for innermost tracking.

Pixel advantages:

- ***Very fine space-point resolution*** without need for stereo or double-sided detectors
- small pixel area: low geometrical capacitance --- ***high signal to noise ratio***

And disadvantages:

- The ***number of connections is high, and connection rework*** is difficult

Hybrid versus monolithic pixels

Pixel detectors that combine separate sensor and electronics, fabricated with different processes, are a hybrid technology.

The *hybrid* geometry of the detector *introduces substantial material into the detection volume.*

This can be traced to the demands this design makes on the power budget through: sensor bias, analog and digital architecture, and data transmission.

This translates to copper conductors and cooling systems, and reduced positional resolution.

Initiatives to reduce power consumption in hybrid detectors:

- reduce material per detector layer
- integrate power conductors in mechanical support
- introduce special powering systems including DC-DC converters and serial powering of modules.

A different solution: *monolithic detectors*....

W. Snoeys, NIM A 731 (2013) 125-130.

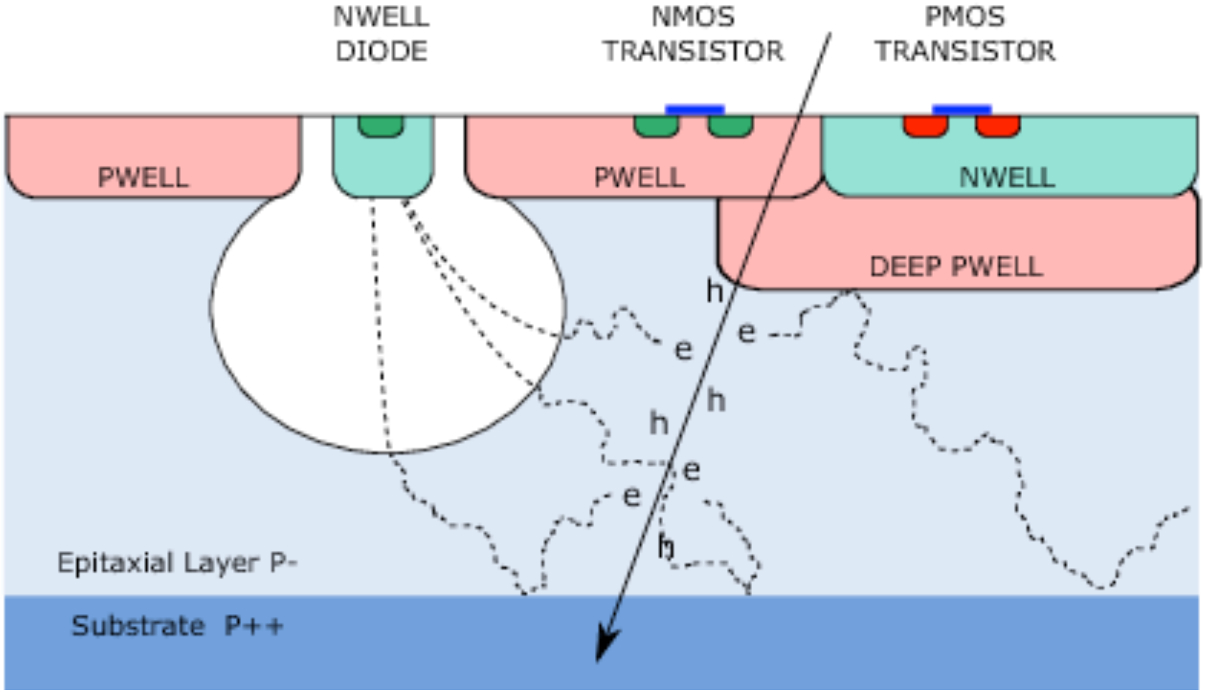
Monolithic detectors integrate the sensor with the readout.

Monolithic silicon tracking detectors have been used by

- **BELLE-II** (DEPFET technology) **and**
- **STAR** (Monolithic Active Pixel Sensor –MAPS– technology).

They are under consideration for future experiments including those at CLIC, ILC, and LHC.

On the next pages: some monolithic technologies in active development.



Monolithic Active Pixel Sensors[1,2] **(MAPS)** use an n-channel MOSFET transistor (NMOS) embedded in an *epitaxial* p-layer (thickness 15 microns) similar to standard CMOS chips. The n-well of the transistor collects the electrons generated by charged particles from a thin depletion layer through diffusion only.

[1] R.Turchetta, et al., Nucl. Instr. and Meth. in Phys. Res. A 458: 677-689, 2001.
[2] I. Peric, Nucl. Instr. and Meth. in Phys. Res. A 582: 876-885, 2007.

Image from: F. Reidt, “Upgrade of the ALICE Inner Tracking System,” POS (VERTEX2014) 007.

Related technology: **HV-CMOS and HR-CMOS**

A deeper depletion layer and hence larger signals are achieved by applying higher bias voltages or by the use of high resistivity epitaxial layers.

The electrons are collected through drift.

MAPS advantage: a mature commercial process
MAPS challenge: not yet LHC-level radiation hard.

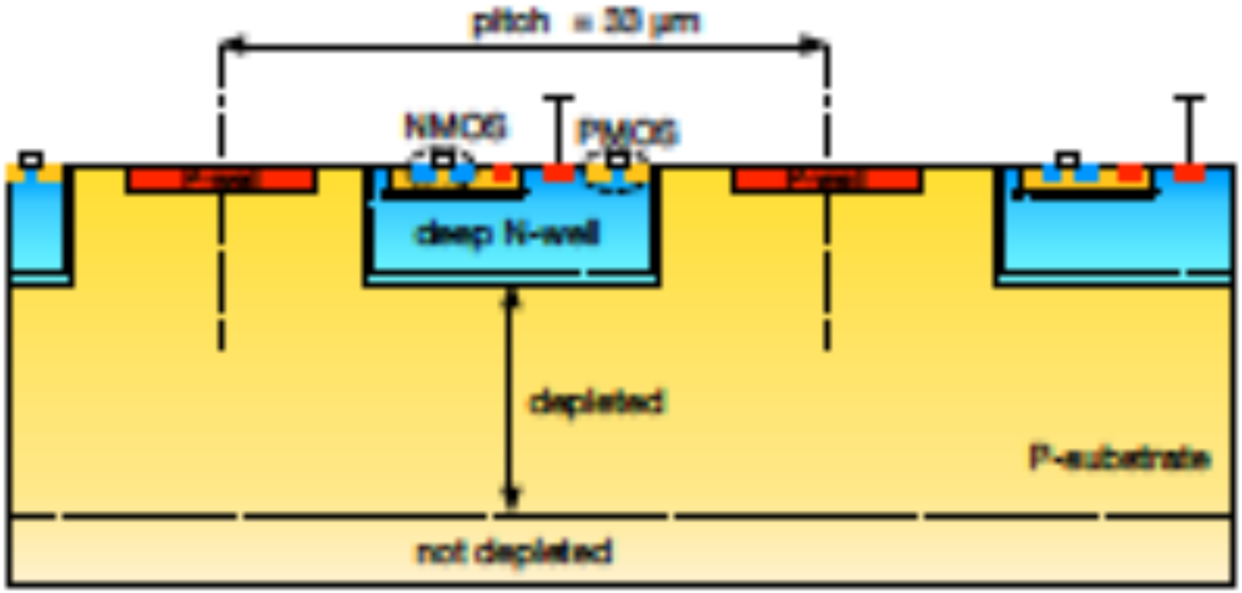
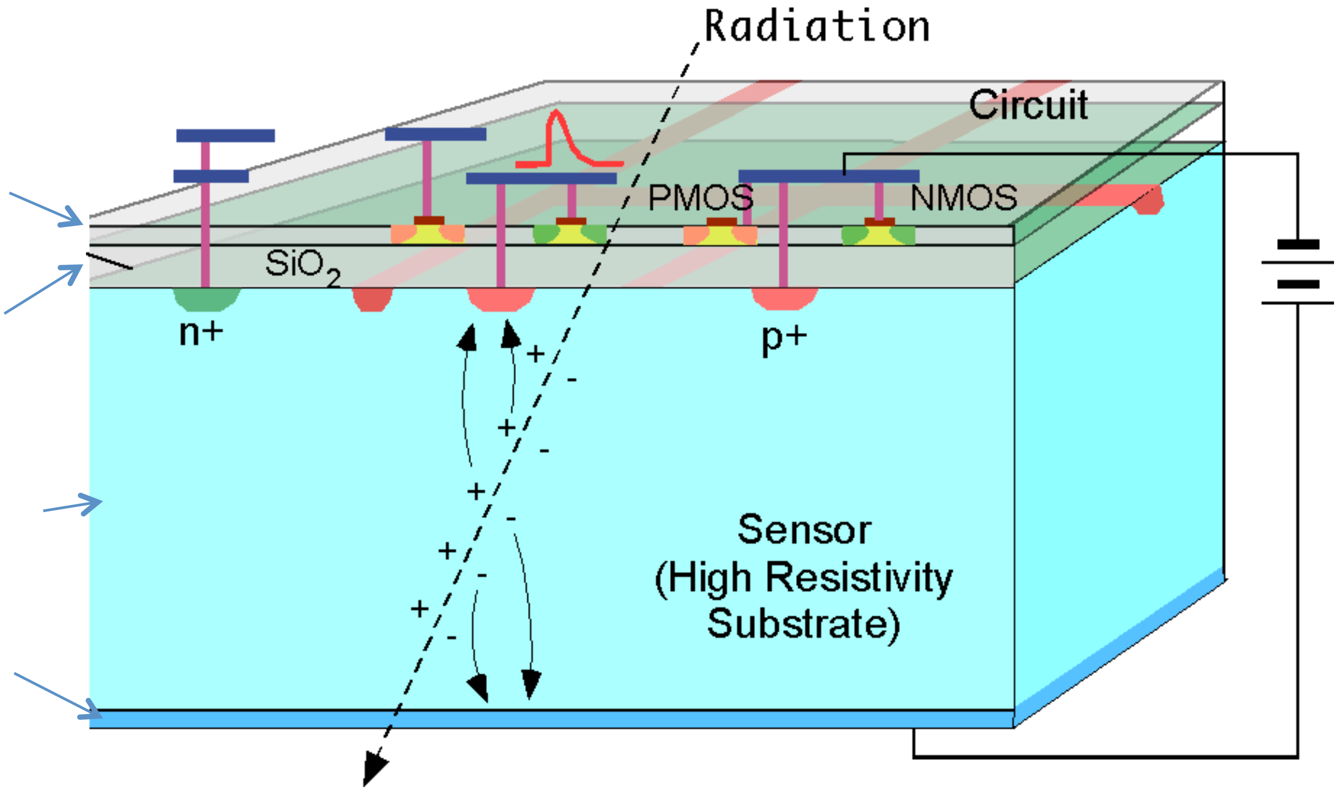


Image taken from: M. Benoit et al., 2018 JINST 13 P02011.

The Silicon on Insulator[1,2] (SoI) sensors overcome the problem of the low signal from only partially depleted sensors by **combining a high resistivity silicon sensor wafer with a low resistivity electronics wafer, chemically bonded together**. Transistors implemented in the electronics wafer are connected to the implant of the sensors, which is fully depleted.



40nm thin CMOS layer

200nm thick BOX

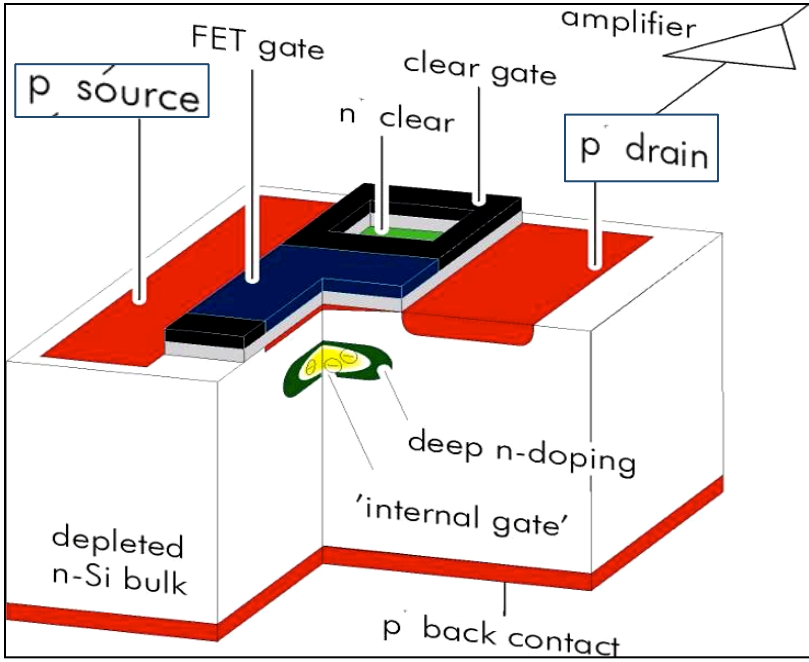
350?m thick high resistivity substrate

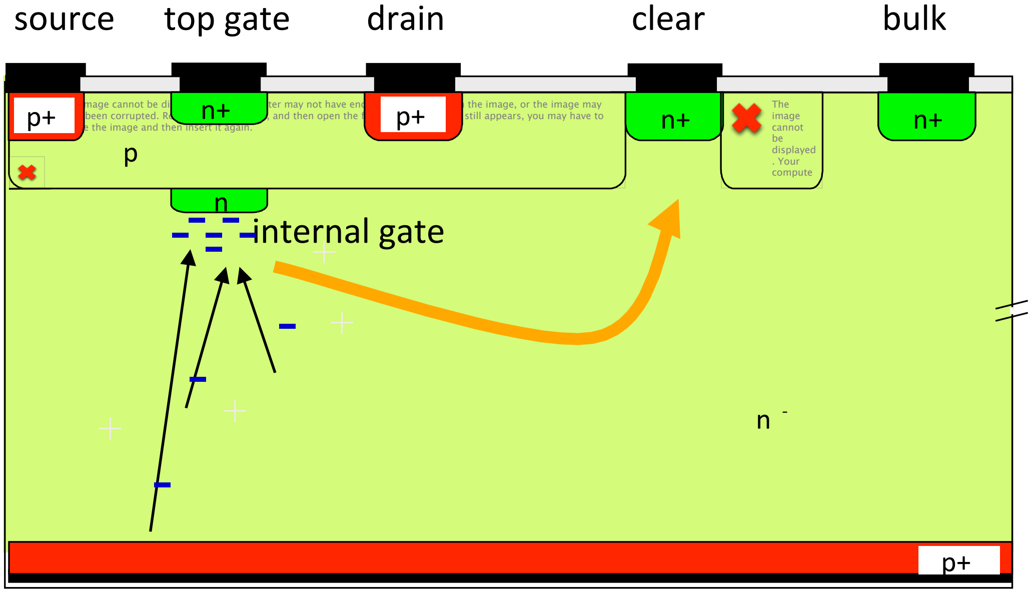
200nm Al back-contact

[1] Y. Arai, et al., Nucl. Instr. and Meth. in Phys. Res. A 623: 186-188, 2010.
[2] J. Marczewski, et al., Nucl. Instr. and Meth. in Phys. Res. A 549: 112-116, 2005.

Image from “A thin fully depleted monolithic pixel sensor in Silicon on Insulator technology,” S. Mattiazzo et al., PIXEL2012.

In ***DEPFET (Depleted P-channel Field Effect Transistor)* detectors**[1] a potential valley for electrons is created underneath the p^+ strips within the n bulk. Accumulated electrons drift underneath the gate of a field effect transistor and modify the source drain current producing a built-in amplification. Following the readout the accumulated electrons have to be swept away by an active clear.





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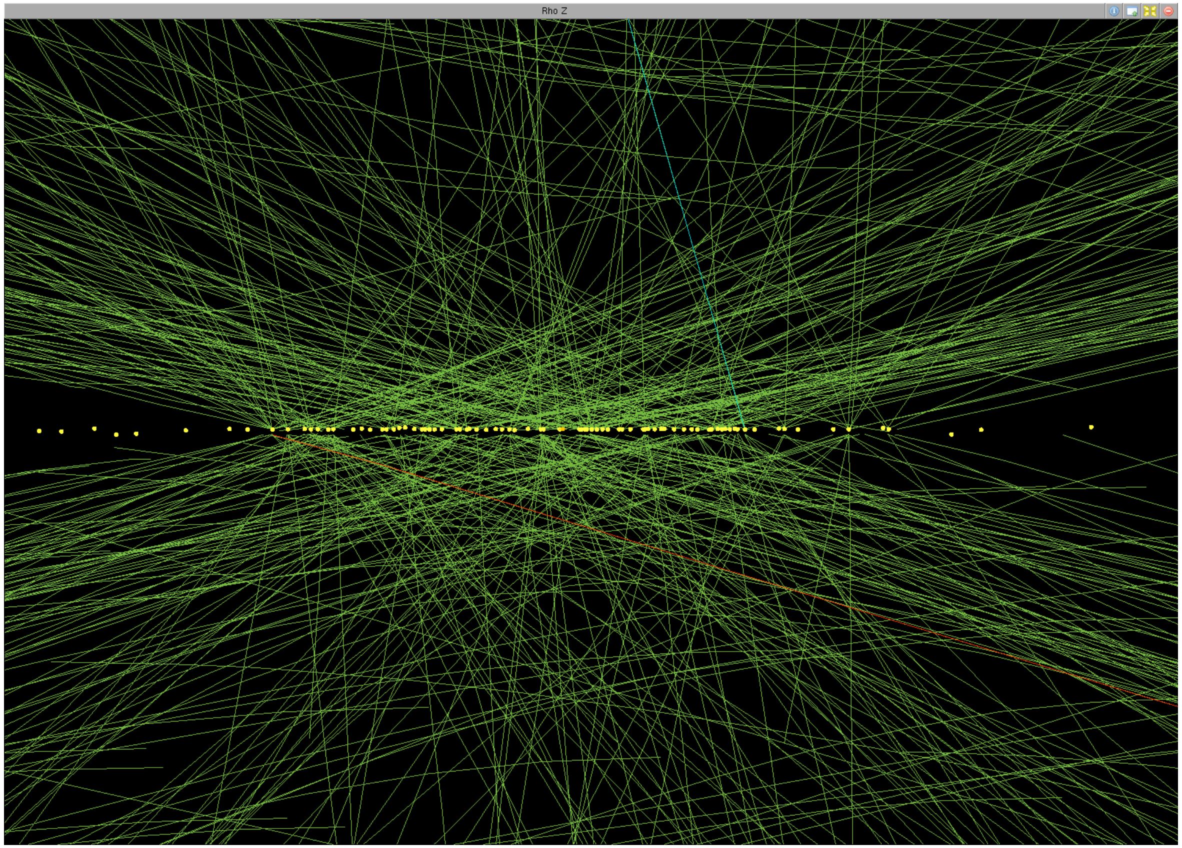
[1] J. Kemmer, G. Lutz, Nucl. Instr. and Meth. in Phys. Res. A 253: 365-377, 1987.

A new technology to resolve multiple interactions at the HL-LHC: **Low Gain Avalanche Detectors, Ultra-fast Silicon Detectors**[1]

The issue: **not every one of these vertices occurred at the same time** – they are separated by tenths of nanoseconds. ***Ultrafast timing detectors can distinguish them – simplifying pattern recognition.***



H. F.-W. Sadrozinski et al., NIM A 730 (2013) 226-231.

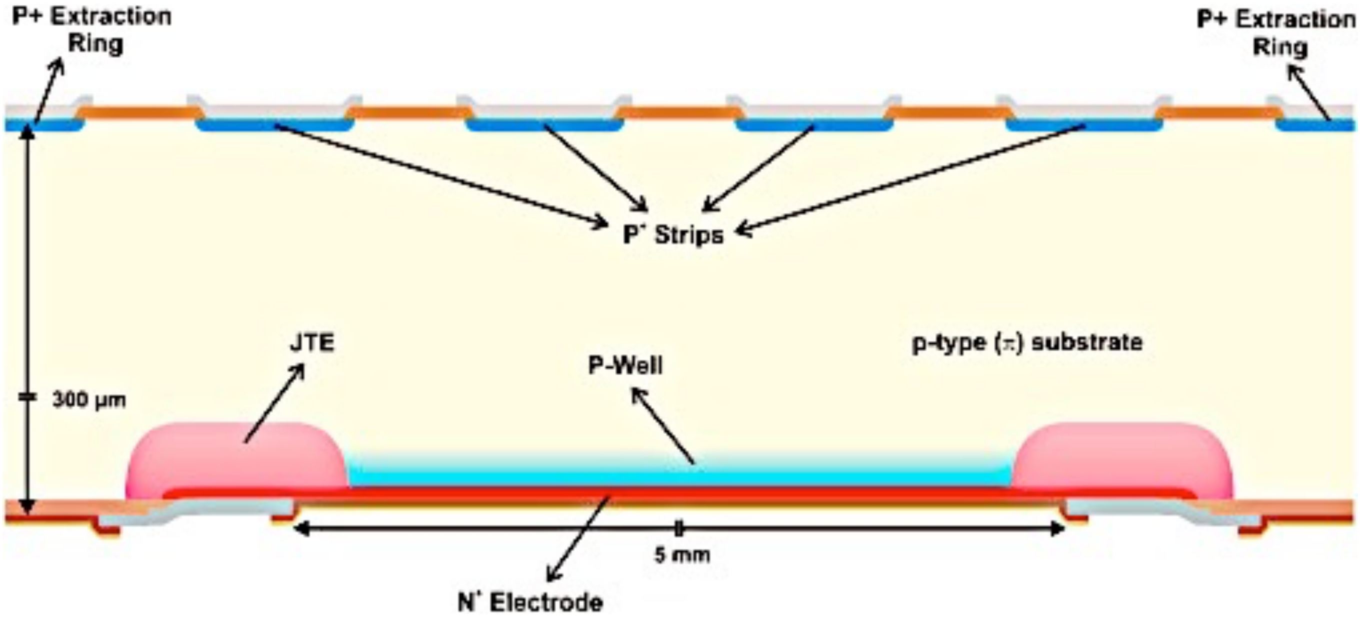
Very thin, high resistivity n-on-p wafers, for fast collection time, to overcome saturation of drift velocity at 10^7 cm/s. Since resolution depends on S/N, boost signal with an extra implantation step to create a p layer just under the n-layer, yielding a localized high field region that amplifies drifting electrons.

Target gain: 10, for high rate operation, good time resolution, excellent position resolution.

Target thickness: 35-50 microns

Target time resolution: 40 psec

Key: minimize slew rate (signal/rise-time), do not amplify hole signal



Top challenge now: radiation hardness

Outlook

Silicon detectors have been central to paradigm-changing particle physics discoveries for over 30 years.

Exciting new technologies are still emerging.

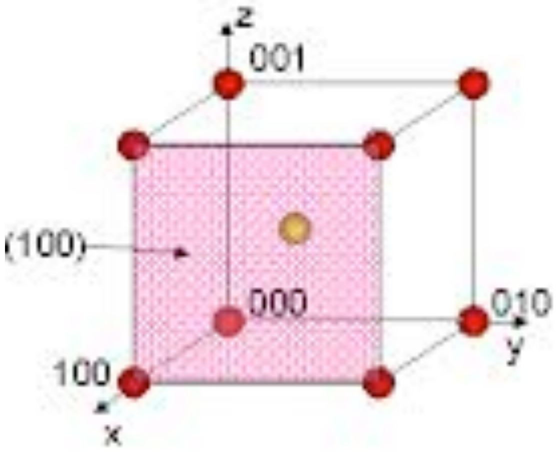
There is so much more to say – we have not even touched upon silicon's applications outside of HEP.

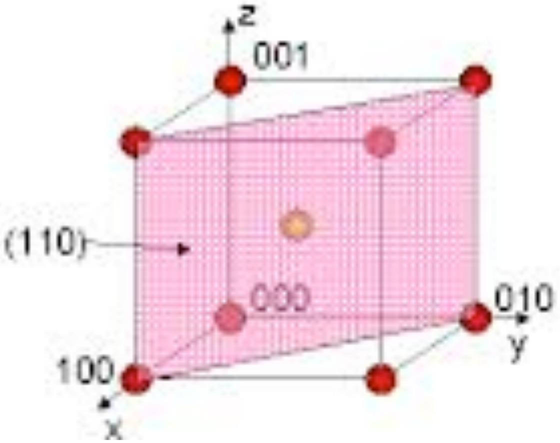
There is room for your contributions everywhere – please join the detector community!

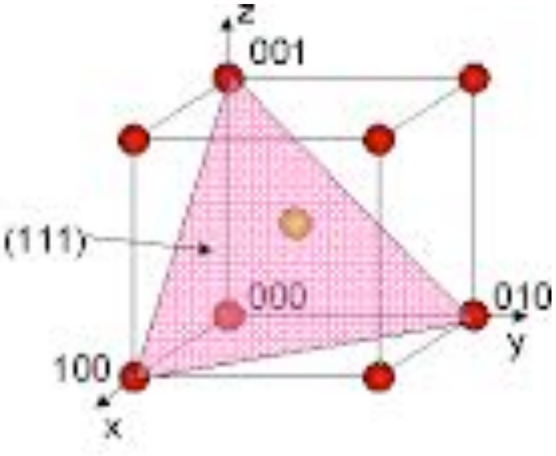
Backup

- Crystal orientation

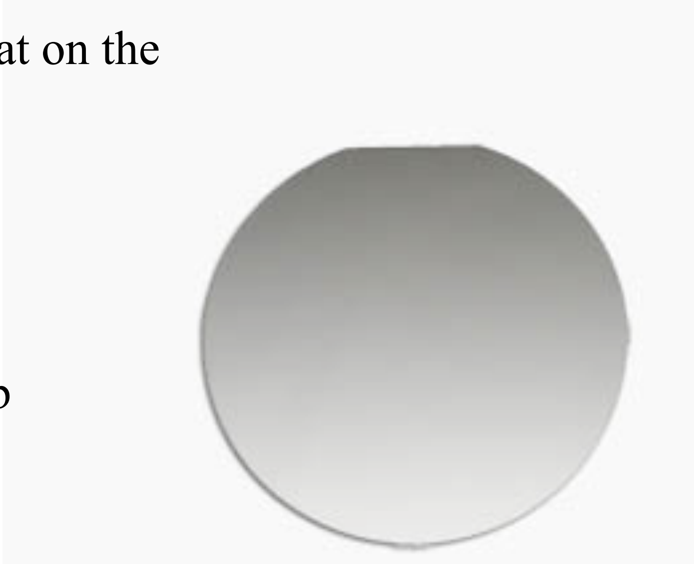
Sensors with features registered along different crystal planes (denoted by Miller indices) may have different electrical characteristics before irradiation but are comparable after irradiation







The crystal orientation is specified by the location of the flat on the silicon wafer.



<111>:

- chosen by CDF SVX, ATLAS SCT

<100>

- chosen by CDF L00, CMS pixels, ATLAS pixels, LHCb

Use of 6-inch wafers is now standard.

Summary on readout noise, from “Pixel Detectors” by L. Rossi et al. (Springer, 2006)

$$\mathrm{ENC} = \frac{\text{noise output voltage (rms)}}{\text{signal output voltage for the input charge of 1e}^-}$$

$$ENC_{tot}^2 = ENC_{shot}^2 + ENC_{therm}^2 + ENC_{1/f}^2$$

$$ENC_{\text{shot}} = \sqrt{\frac{I_{\text{leak}}}{2q}\tau_f} = 56e^- \times \sqrt{\frac{I_{\text{leak}}}{\text{n}A}\frac{\tau_f}{\mu s}}$$

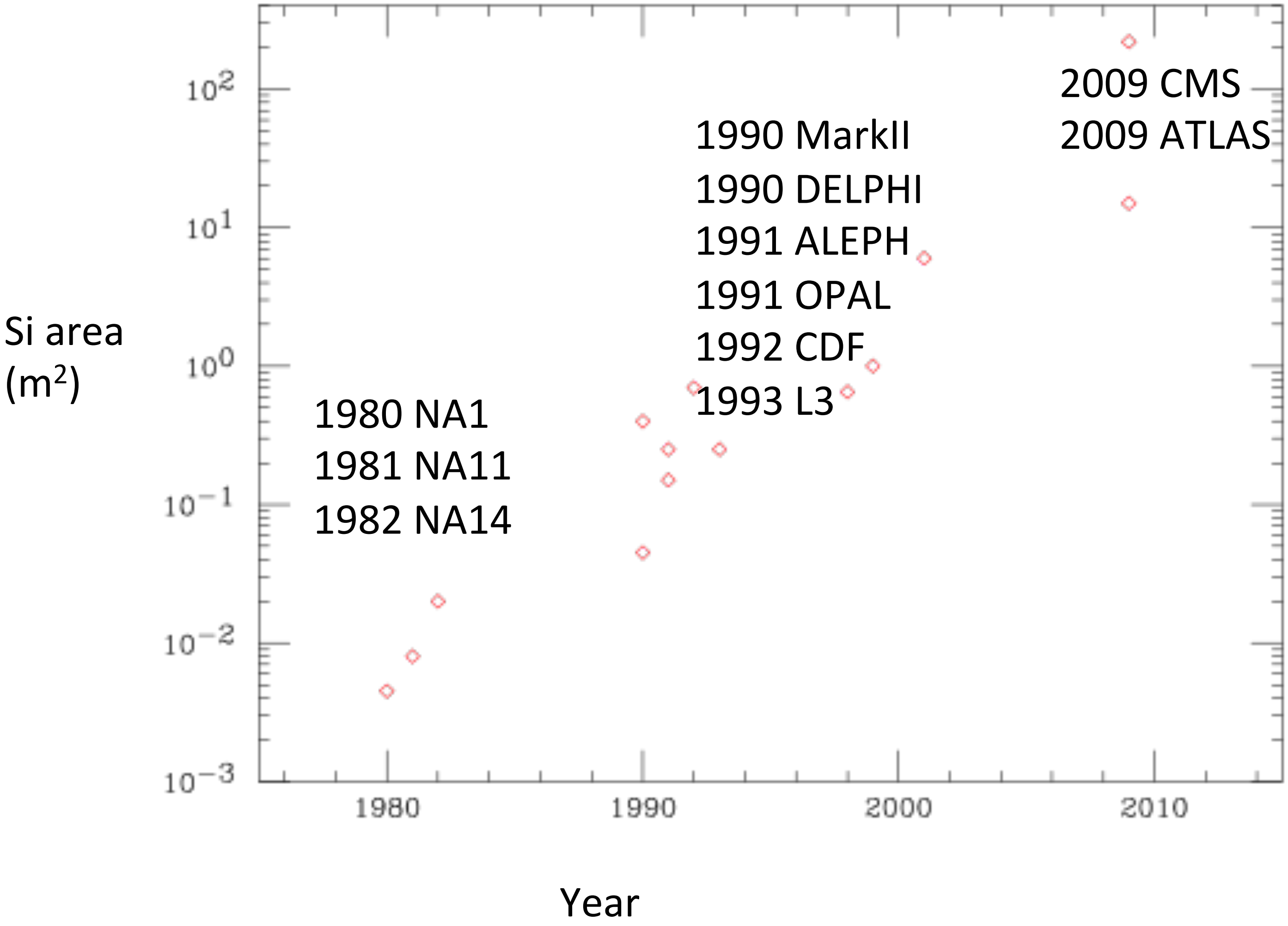
$$ENC_{\text{therm}} = \frac{C_f}{q}\sqrt{\langle v_{\text{therm}}^2\rangle} = \sqrt{\frac{kT}{q}\frac{2C_D}{3q}\frac{C_f}{C_{load}}} = 104e^- \times \sqrt{\frac{C_D}{100\,\text{fF}}\frac{C_f}{C_{load}}}$$

$$ENC_{1/\text{f}} \approx \frac{C_D}{q}\sqrt{\frac{K_f}{C_{ox}WL}}\sqrt{\ln\left(\tau_f \frac{g_m}{C_{load}}\frac{C_f}{C_D}\right)} = 9e^- \times \frac{C_D}{100\,\text{fF}}(\text{for NMOS trans.})$$

W, L = width and length of trans. gate
K_f = 1/f noise coefficient
C_{ox} = gate oxide capacitance

C_f = feedback capacitance
C_{load} = load capacitance
C_D = detector capacitance
τ_f = feedback time constant

Evolution of the scale of silicon detector coverage in HEP experiments



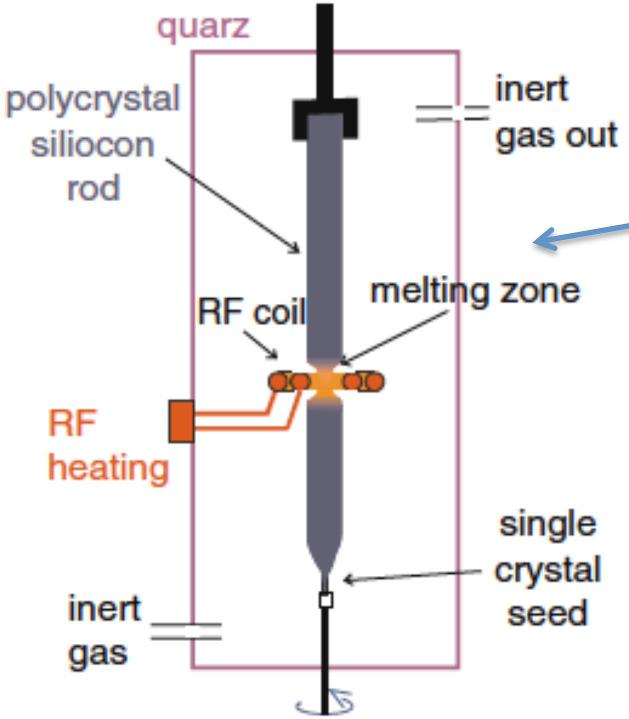
Binary resolution of strip sensor for pitch p

$$\sigma^2 = \frac{\int_{-\frac{p}{2}}^{\frac{p}{2}} (x_r - x_m)^2 D(x_r)\, dx_r}{\int_{-\frac{p}{2}}^{\frac{p}{2}} D(x_r)\, dx_r} = \frac{p^2}{12}$$

$D(x) = 1$ uniform distribution of tracks

$X_m = 0$ pixel centre

Silicon wafer fabrication

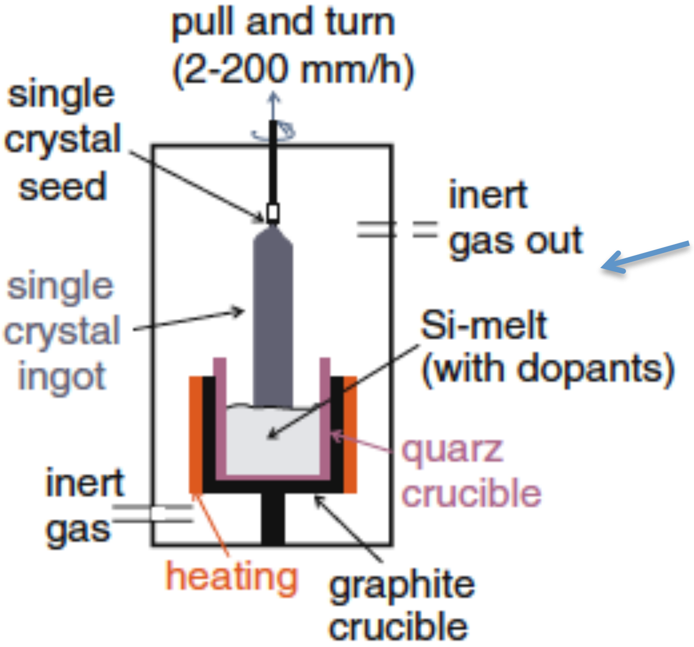


Float Zone

- Using a single Si crystal seed, melt the vertically oriented rod onto the seed using RF power and "pull" the monocrystalline ingot
- Can be oxygenated by diffusion at high T

Epitaxial silicon

- Chemical-Vapor Deposition (CVD) of Silicon
- CZ silicon substrate used a diffusion of oxygen
- Growth rate about 1mm/min
- Excellent homogeneity of resistivity
- 150 mm thick layers produced (thicker is possible)
- price depending on thickness of epi-layer but not exceeding ~ 3 x price of FZ wafer



Czochralski silicon

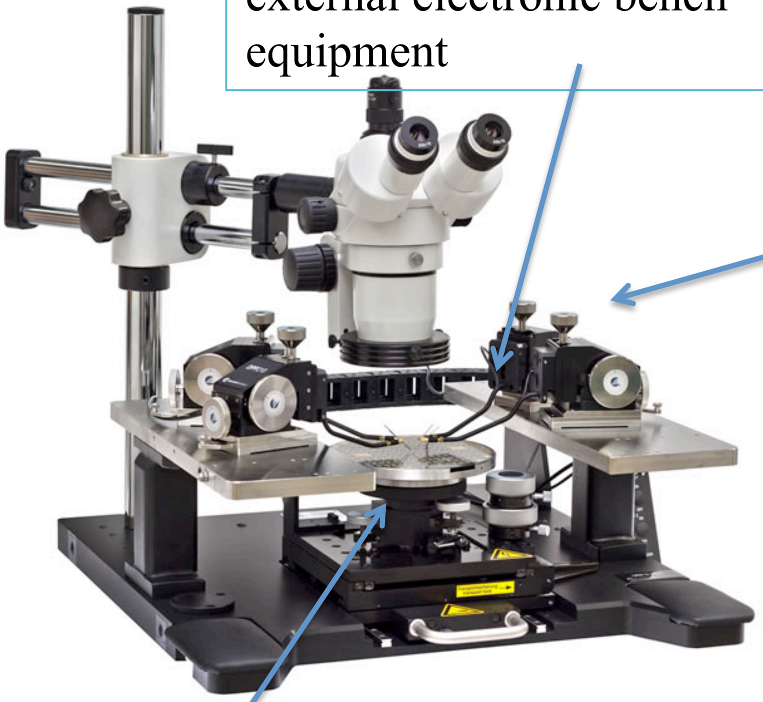
- Pull Si-crystal from a Si-melt contained in a silica crucible while rotating.
- Silica crucible is dissolving oxygen into the melt at high concentration
- Material used by IC industry (cheap). Also available in high purity for use as particle detector (MCz)

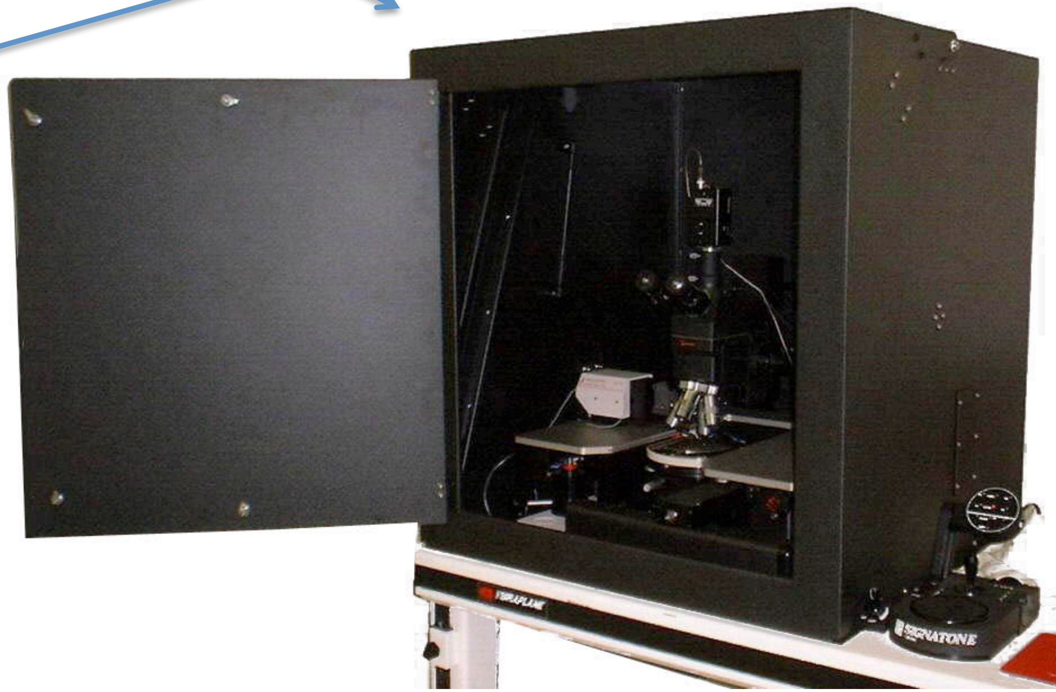
The environment for the experimenter characterizing the sensors

Silicon detectors can operate in air and at room temperature – but **as radiation damage progresses, cooling becomes essential.**

Probes connect individual structures on the sensor to external electronic bench equipment

Silicon is light-sensitive: characterization measurements require a dark enclosure. The standard laboratory facility is **a cleanroom-based probe station in a dark box:**





Vacuum chuck for secure positioning of sensor, can be cooled