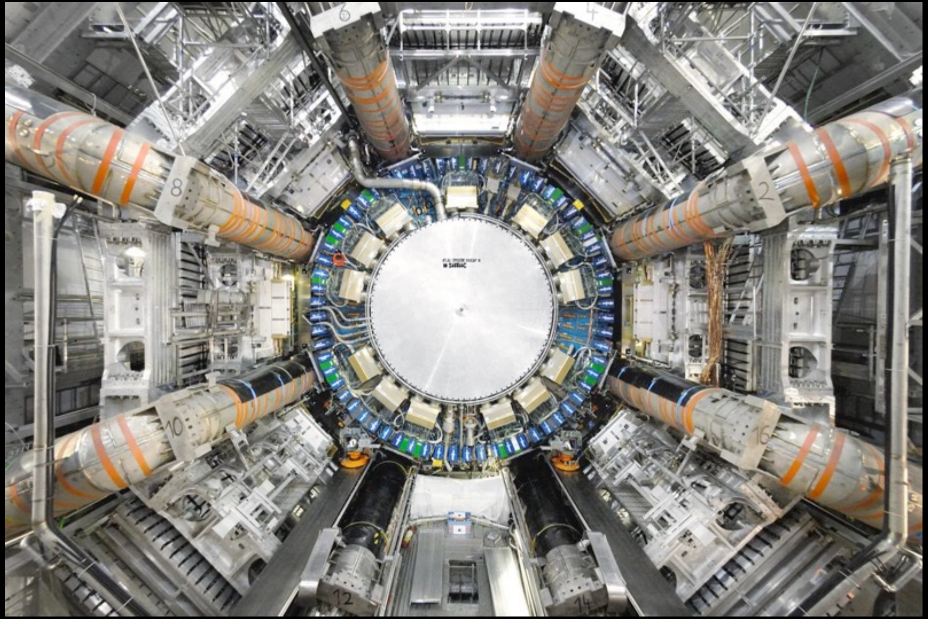
VERTEX DETECTORS

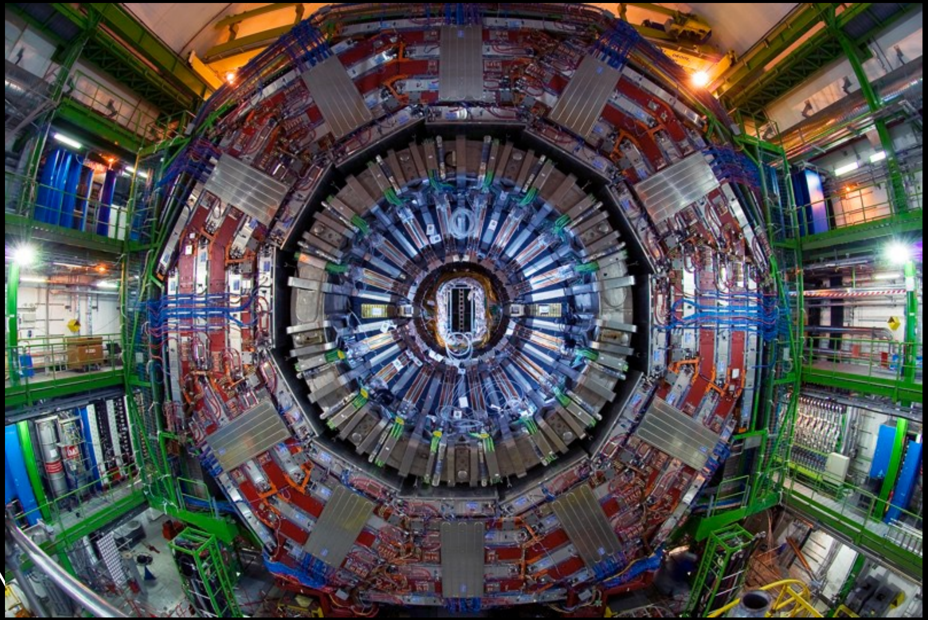
Daniela Bortoletto

- Today
  - –Foundation of silicon sensors
  - –Planar strip and pixel sensors
- Tomorrow : Novel technologies
  - –3D: ultra radiation hard sensors (already used in LHC)
  - –LGADS and 3D: ultra fast detectors
  - –Monolithic sensors: ultra low mass sensors

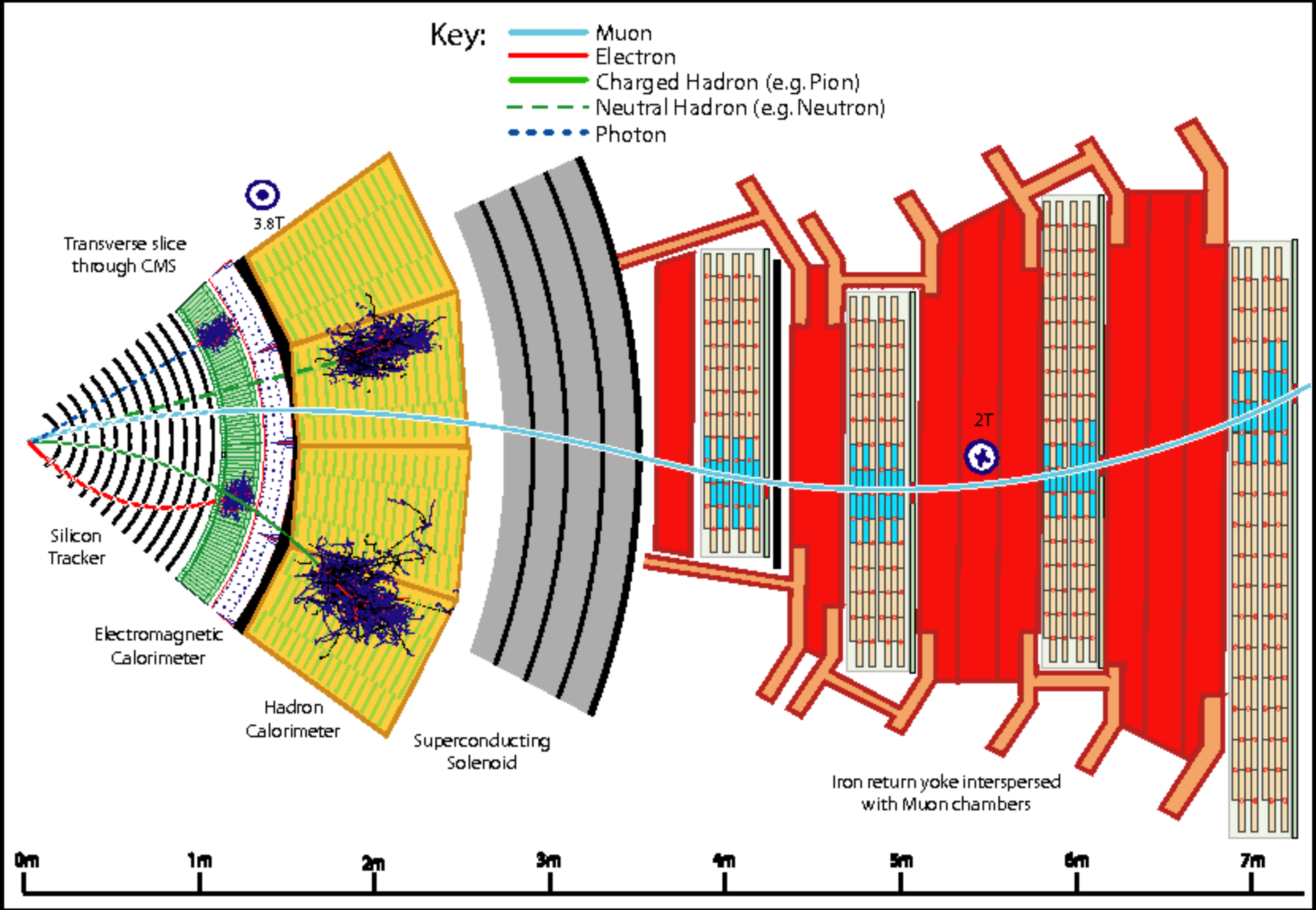
The role of silicon detectors

- Provide high precision measurements of charged particles' position to:
  - Determine their trajectories in a B field and therefore measure their momentum (R[m]=p[GeV/c]/(0.3B[T]))


ATLAS


CMS

The role of silicon detectors



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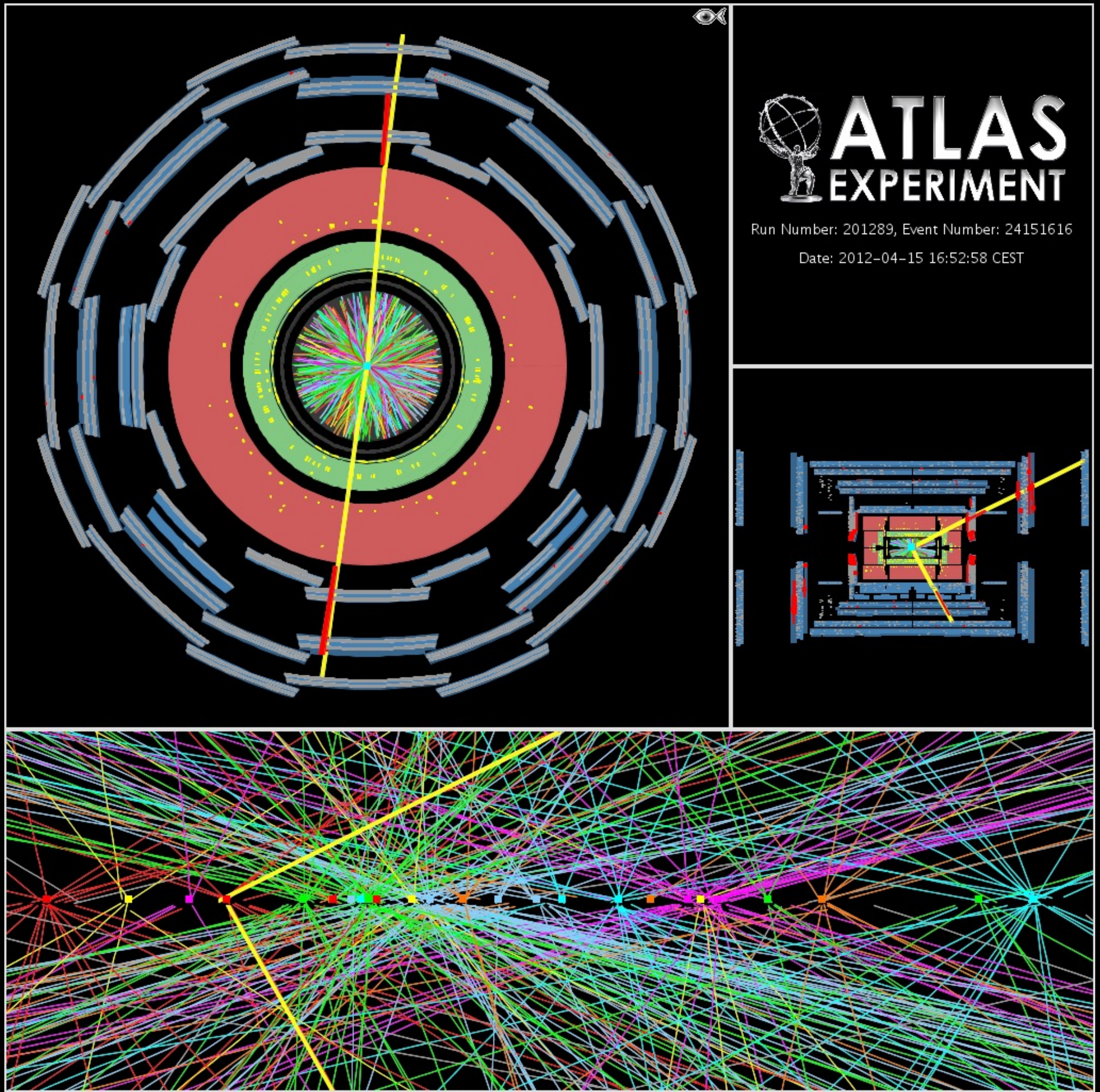

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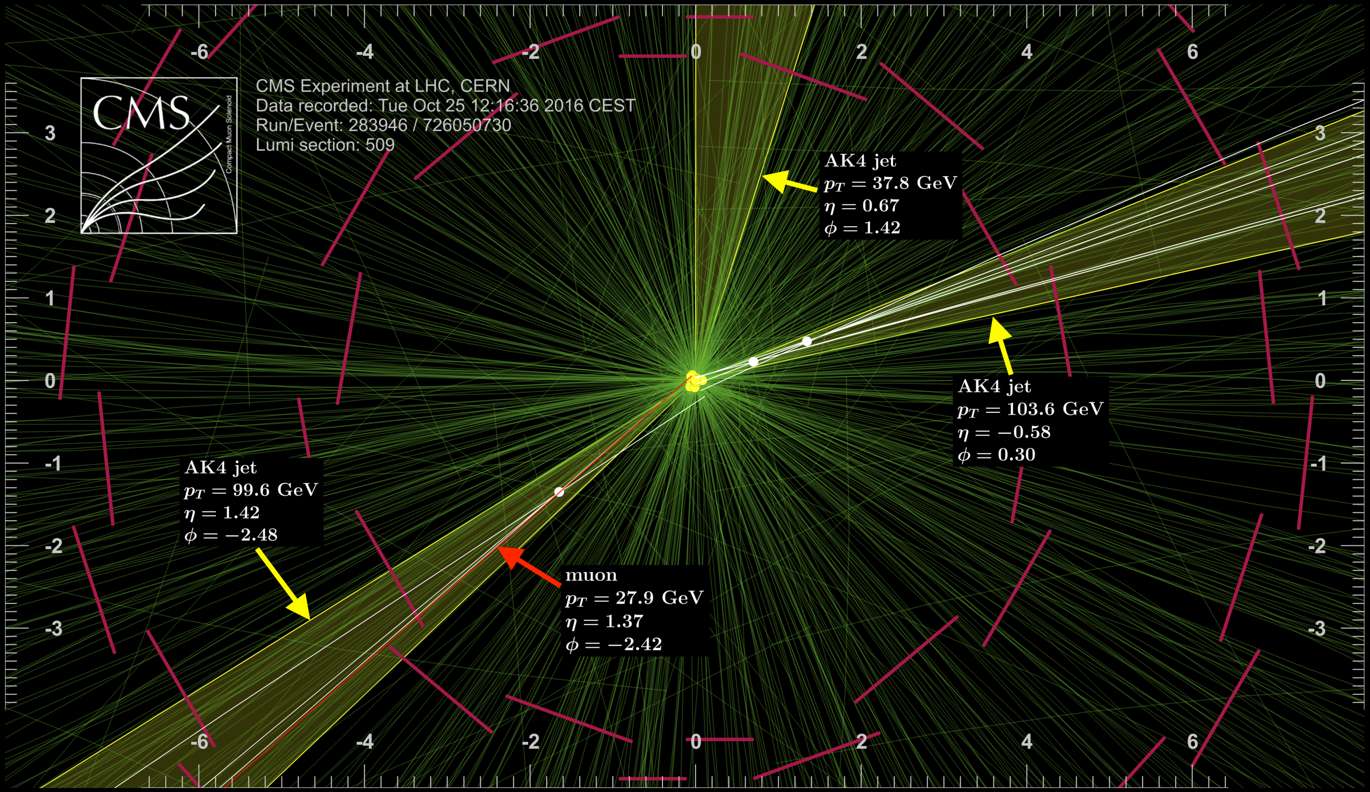
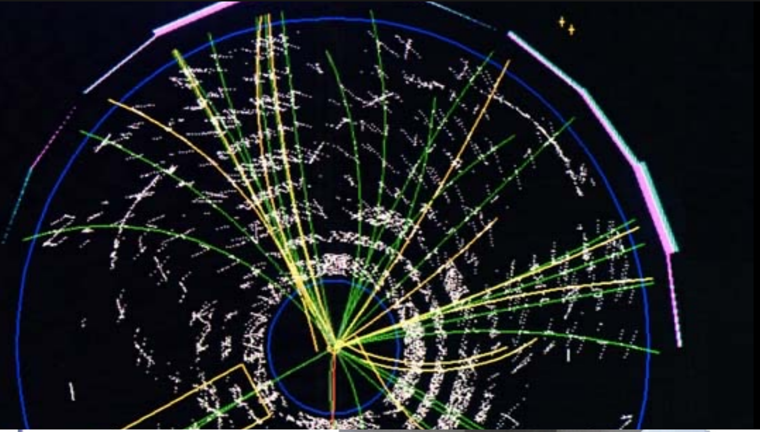
  - Reconstruct secondary vertices ($d = \beta\gamma c\tau$) due to heavy quarks and τ leptons
  - Measure impact parameter of tracks

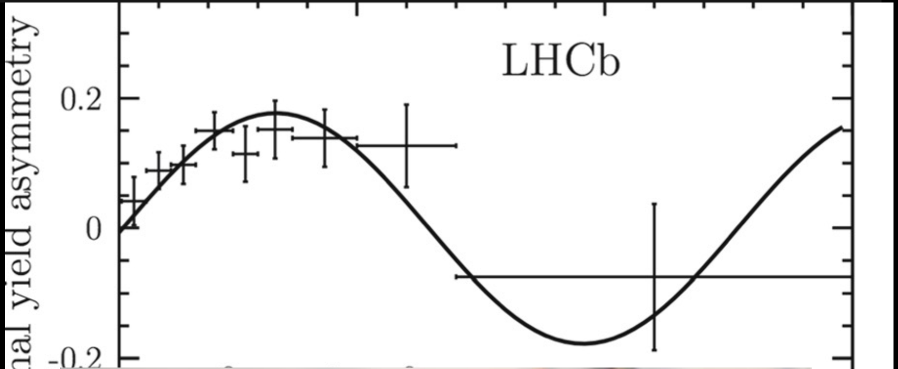


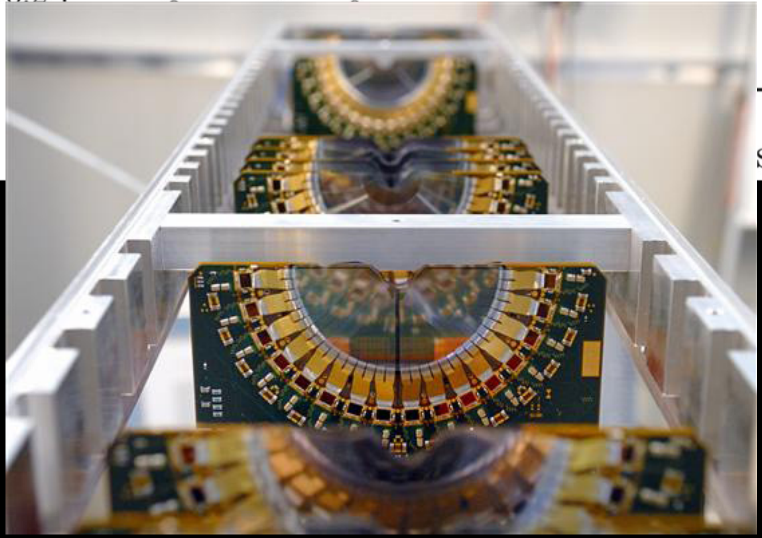
Silicon Detectors discovery enablers

1995 -Top quark (t→Wb) discovery at CDF and D0 at the Tevatron

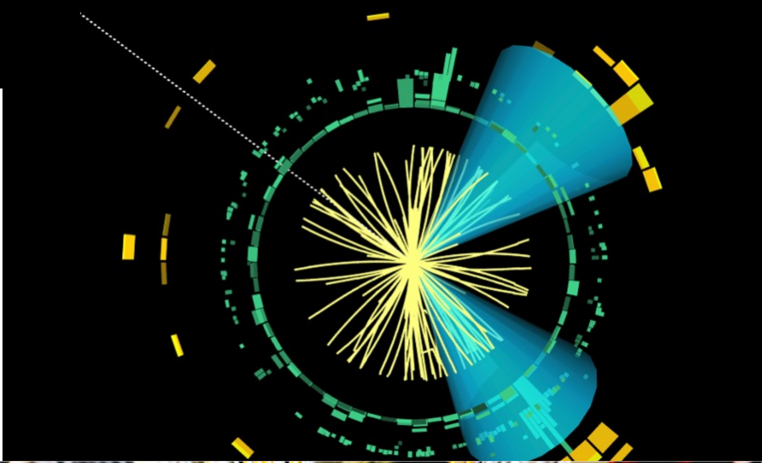


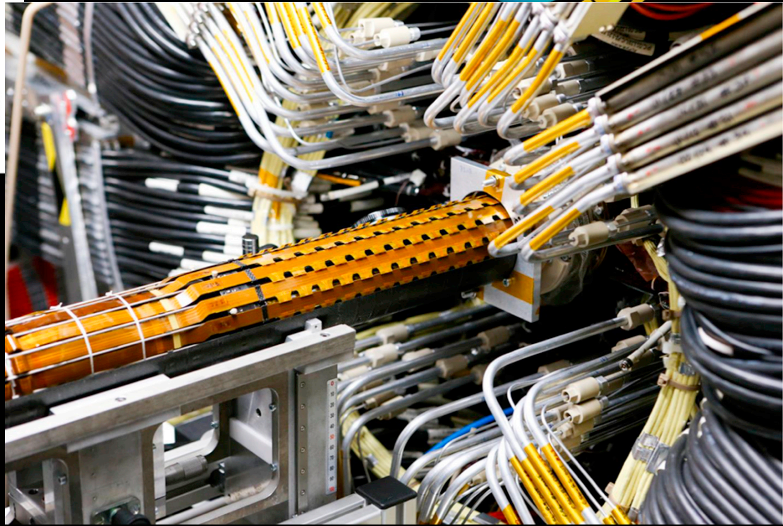
Starting in 2001 the measurements of CP violation b-decays at Belle and BaBar and then LHCb





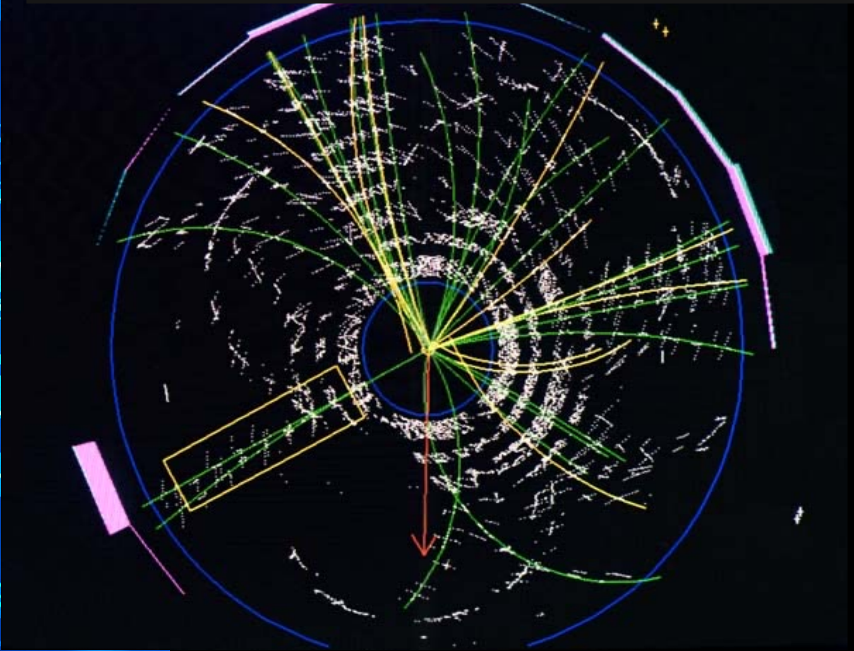
2018 -Discovery of H → bb at the LHC





Silicon Detectors: discovery enablers

1995 -Top quark (t→Wb) discovery at CDF and D0 at the Tevatron



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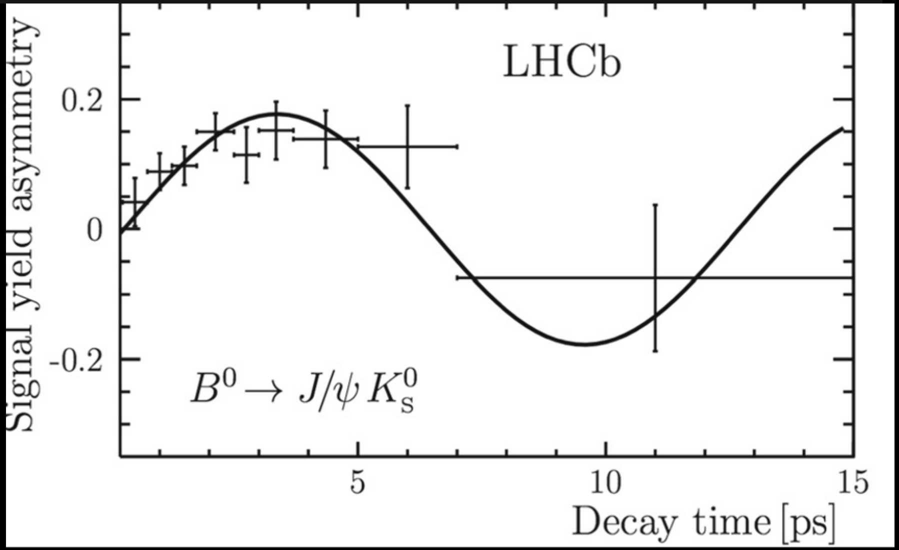
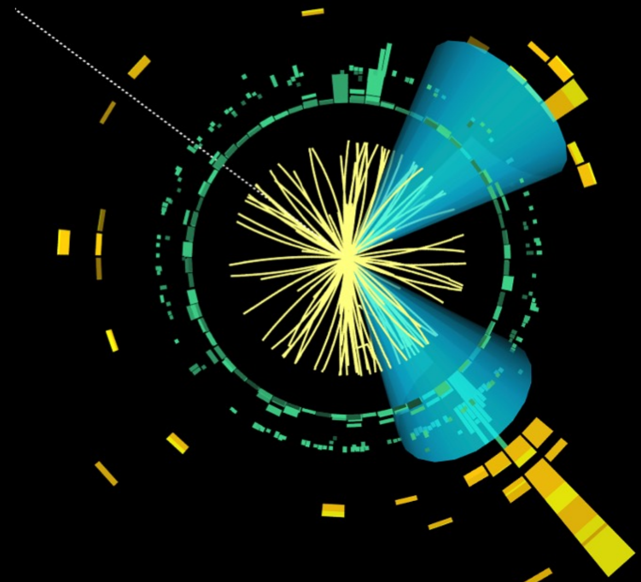
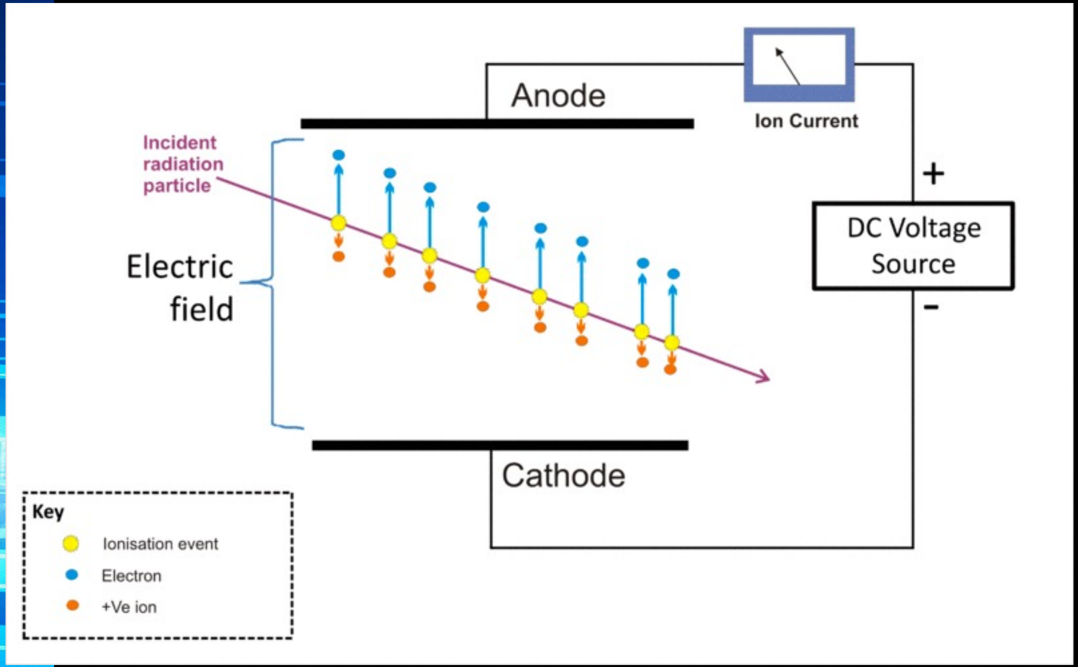


2018 -Discovery of H → bb at the LHC

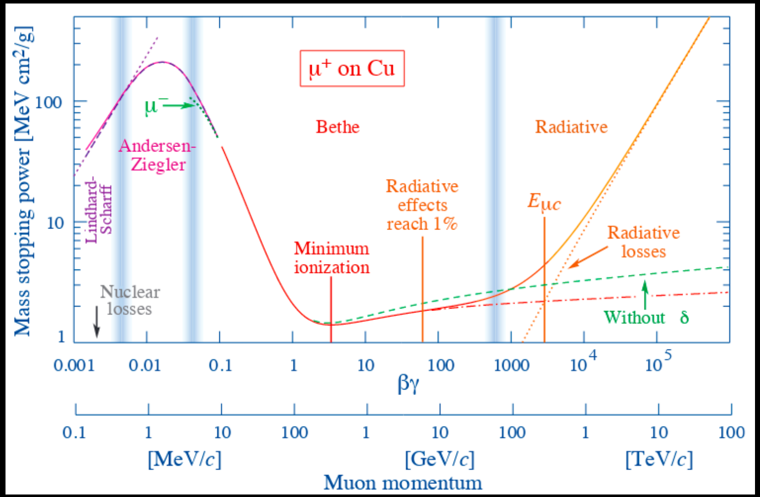


Critical for future discoveries. In the Higgs sector: measuring Hcc and HH(*bbγγ*, *bbττ*, *bbbb*) which is sensitive to the Higgs self coupling

Solid State Detector



$$-\frac{dE}{dx} \cong \left(\frac{e^2}{4\pi\epsilon_0}\right)^2 \frac{4\pi z^2}{m_e v^2} NZ \left[\ln\frac{2m_e v^2}{I} - \ln\left(1-\frac{v^2}{c^2}\right) - \frac{v^2}{c^2}\right]$$



- Working principle of semiconductor detectors relays on ionization due to charge particles or photons on detector material
  - Ionizing radiation creates electron/hole pairs
  - Charge carriers move in applied E field
- Motion induces a current in an external circuit, which can be amplified and sensed. (Integrated, digitized, read out to provide timing and pulse height information)

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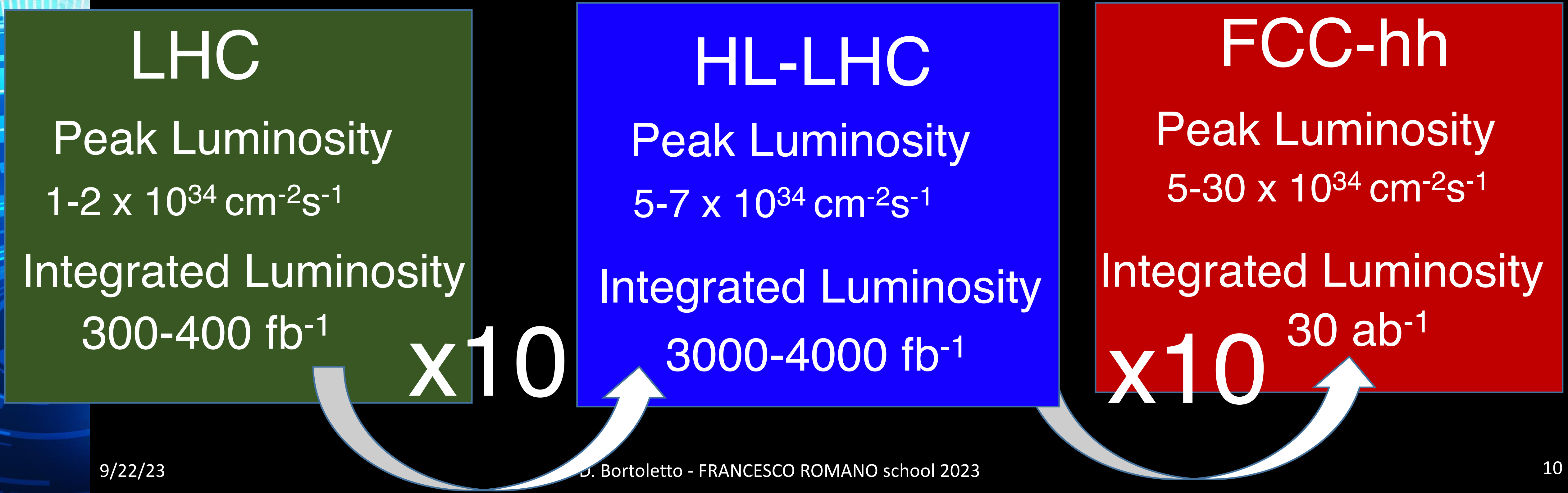
Challenges

- Challenge #1: Seeking new physics, requires probing rare processes thus the production of large amounts of data. The particles produced in each collision also damage the detectors characterizing them
  - Rate of collisions: “instantaneous luminosity” – interactions/cm^2/sec is a critical parameter with high impact on detector design



LHC

Peak Luminosity

$1\text{-}2 \times 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$

Integrated Luminosity

$300\text{-}400\ \text{fb}^{-1}$

x10

HL-LHC

Peak Luminosity

$5\text{-}7 \times 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$

Integrated Luminosity

$3000\text{-}4000\ \text{fb}^{-1}$

x10

FCC-hh

Peak Luminosity

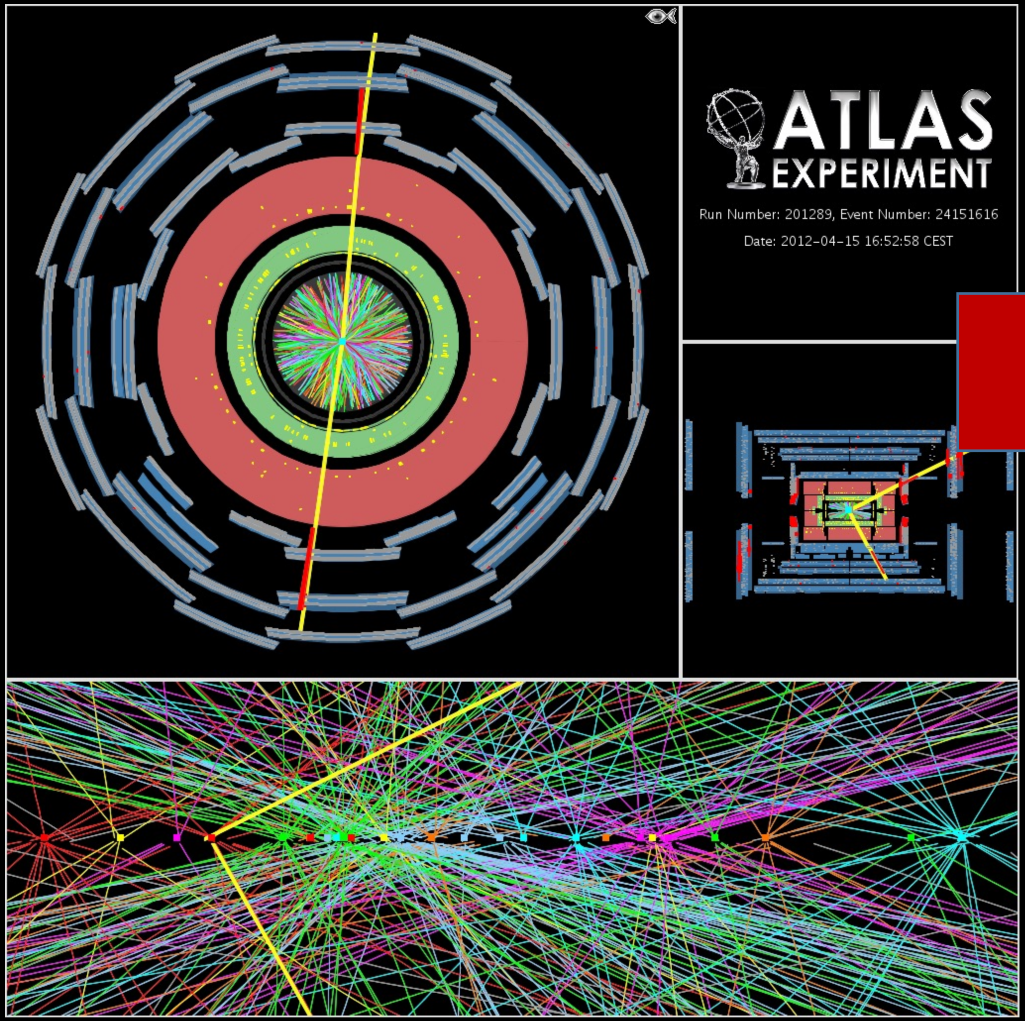
$5\text{-}30 \times 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$

Integrated Luminosity

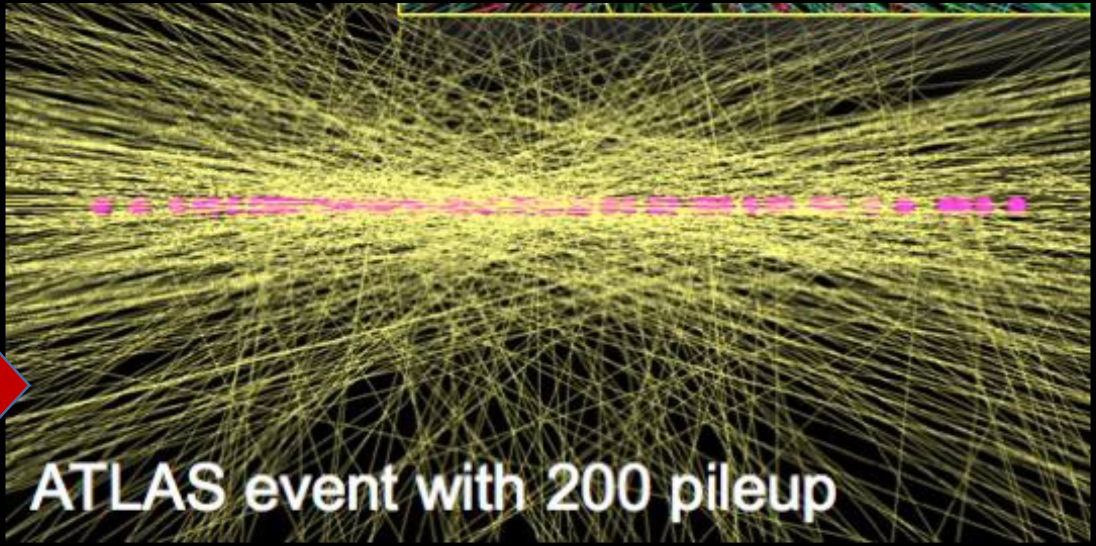
$30\ \text{ab}^{-1}$

The incredible challenge of HL-LHC

Run 2 LHC pileup $<\mu> =$ 37



HL-LHC pileup $<\mu> =$ 200



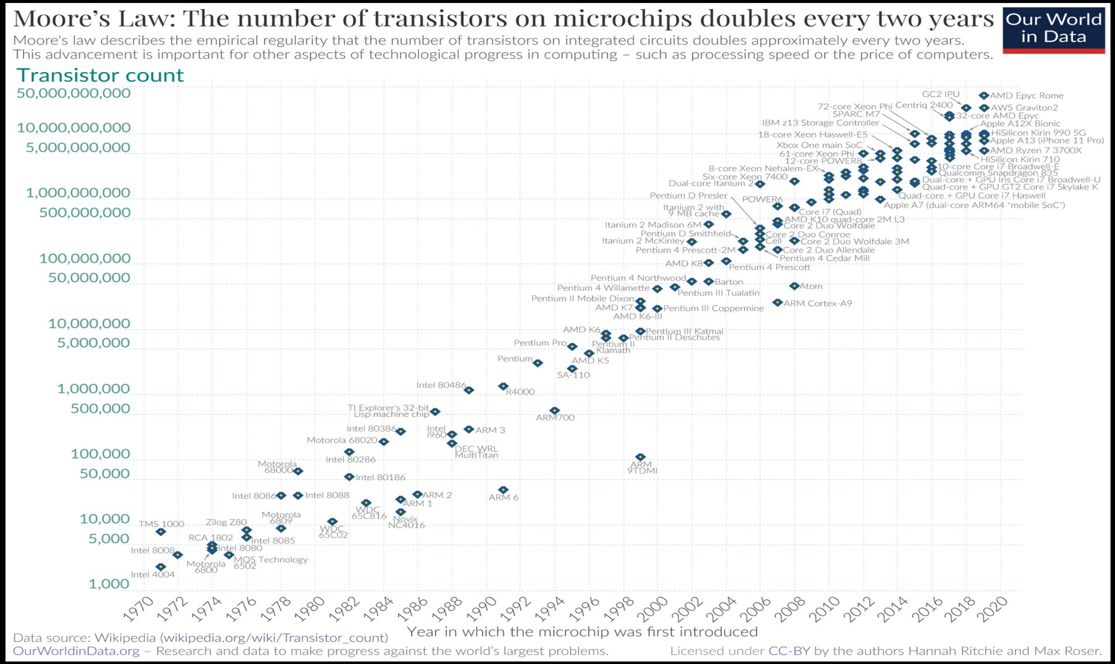
- Radiation levels up to:
  - fluence of $2\text{x}10^{16}$ 1 MeV n_{eq}/cm^2
  - Total Ionizing Dose (TID) ~ 1 Grad
  - Damage due to multitude of particles (charged particles, neutrons, etc…)

Challenges

- Challenge #2: Silicon vertex detectors should be as close as possible to the particle production point(in colliders, the primary vertex or bunch crossing point).
  - Minimum distance $\Longrightarrow$ minimum extrapolation error
  - Tagging jets from heavy quarks
  - Radiation damage: fluence ~ $1/r^n$ $(1.5 < n < 2)$
- Challenge #3: Jets of particles are most compact near the production point, so individual tracks are hardest to resolve at short distances
  - high segmentation (granularity)
- Challenge #3: minimizing multiple scattering.
  - The detector and anything between the primary vertex and the tracker should have minimum mass (including the beam pipe)
  - The detectors are now so thin that can be bent

The advantages of silicon

- Can be patterned in small independent sensing elements O(10μm)
  - High channel density ⇒ low occupancy/channel
  - But the higher the density of the circuit, the harder it is to readout, cool, and to connect mechanically
- Reduced range of secondary electrons in the dense substrate leads to position resolution of a few μm
- Energy to ionize is low (3.6 eV in Si, compared to ~30 eV in a gas) yielding good energy resolution ($\Delta E/E \sim 1/\sqrt{n}$)
- Good signal speed
- Relatively low Z (Z=14) ⇒ good to minimize multiple scattering



Moore's Law: The number of transistors on microchips doubles every two years

Moore's law describes the empirical regularity that the number of transistors on integrated circuits doubles approximately every two years. This advancement is important for other aspects of technological progress in computing – such as processing speed or the price of computers.

Data source: Wikipedia (wikipedia.org/wiki/Transistor_count)
OurWorldinData.org – Research and data to make progress against the world's largest problems.
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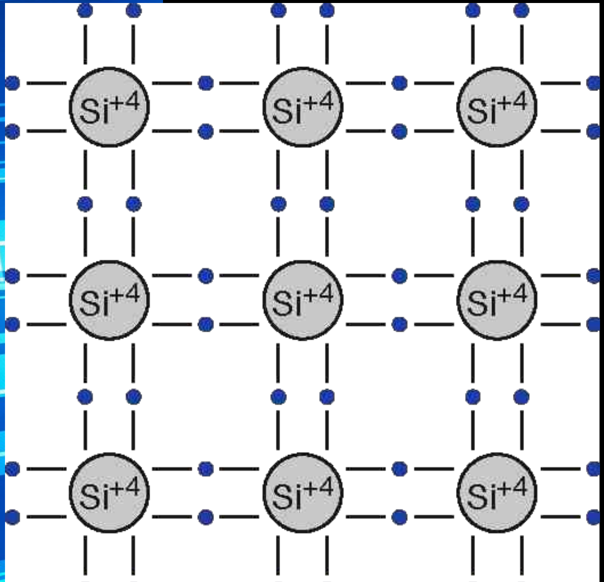
$$\theta_{\mathrm{rms}}^{\mathrm{proj}} = \sqrt{\langle\theta^2\rangle} = \frac{13.6\ \mathrm{MeV}}{\beta c p} z \sqrt{\frac{x}{X_0}}\left[1 + 0.038\ln(x/X_0)\right]$$

$$X_0 \cong \frac{716.4\ g \cdot cm^{-2}\ A}{Z(Z+1)\ln\left(287/\sqrt{Z}\right)}$$

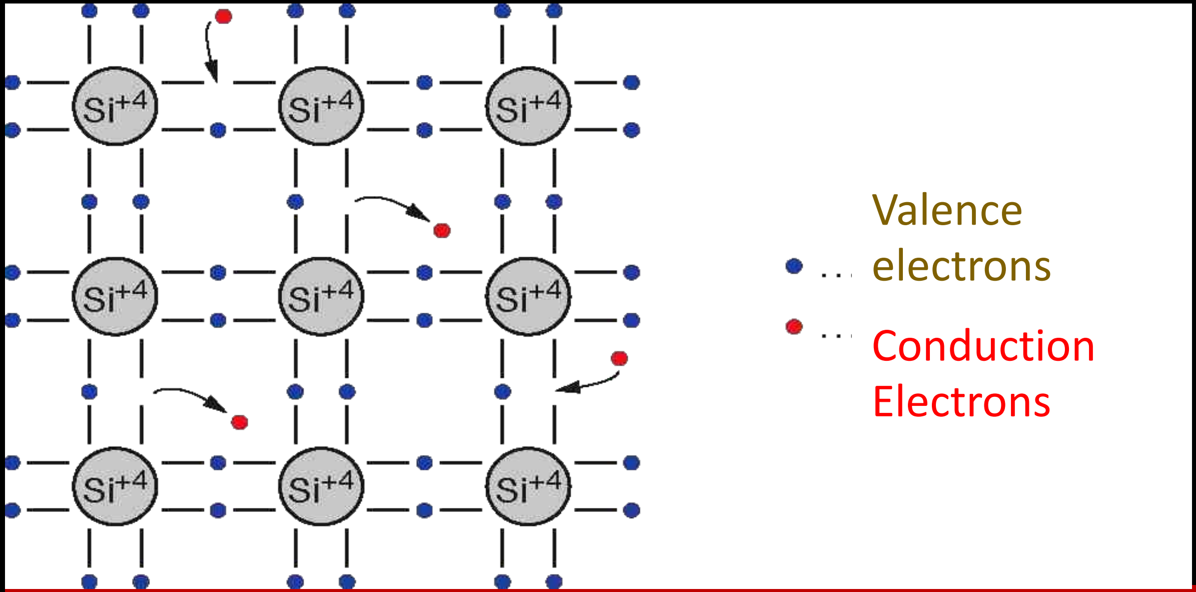
In g/cm must multiply by density to get a length!

Material Properties

- Column IV elemental semiconductor: Each atom has 4 closest neighbors, the 4 electrons in the outer shell are shared and form covalent bonds



- T= 0 K, all electrons are bound

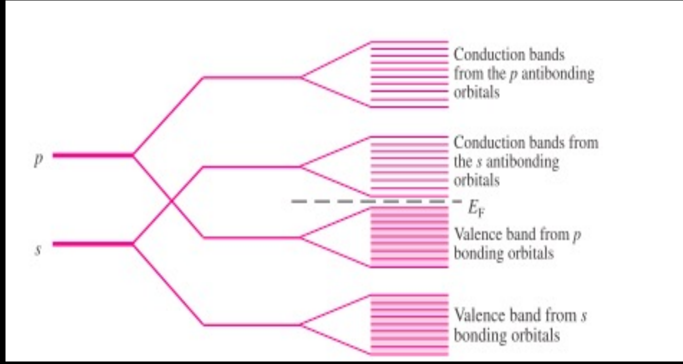


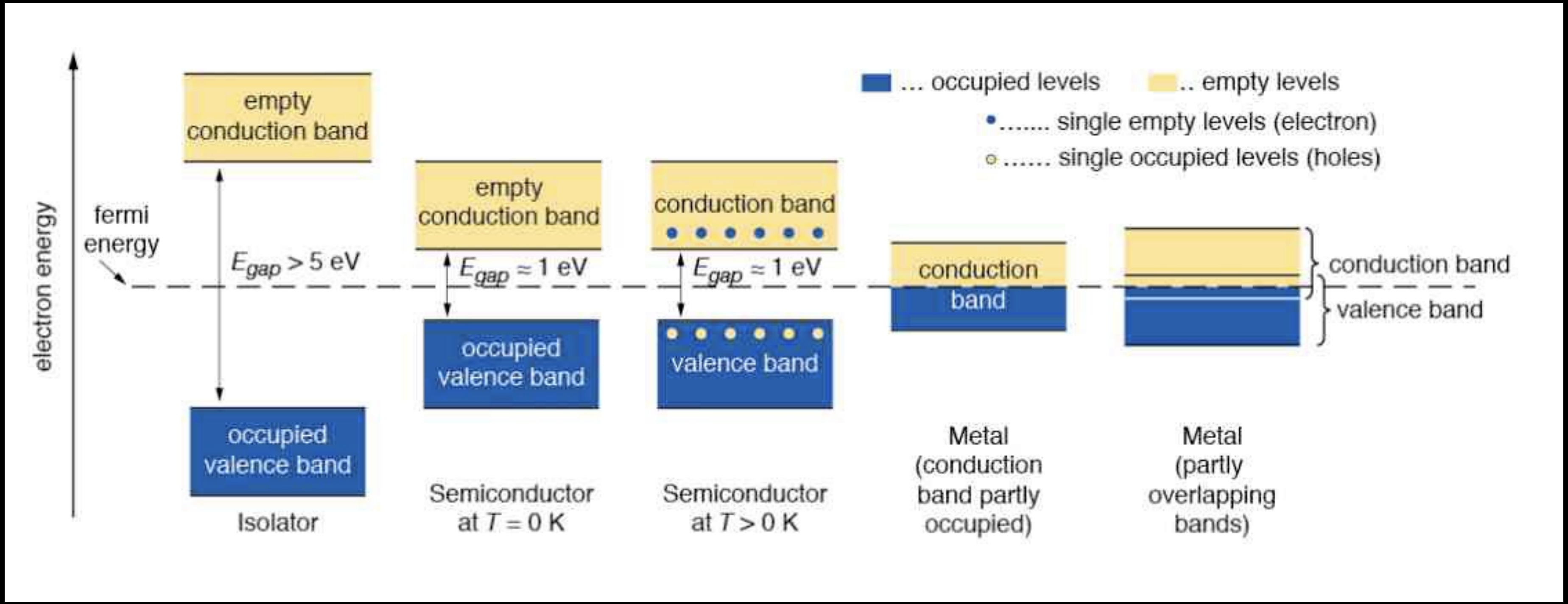
- At T>0K thermal vibrations break some of the bonds and free e^- cause conductivity (electron conduction)
- The remaining open bonds attract other e^-. The “holes” change position (hole conduction)

- To measure charge particles, e- should be produced only by ionization and thermally produced e- must be reduced:
  - lower T (used for germanium)
  - choose a crystal with high bond strength (diamond)
  - sweep away free charge by applying a voltage across the crystal

Energy Bands

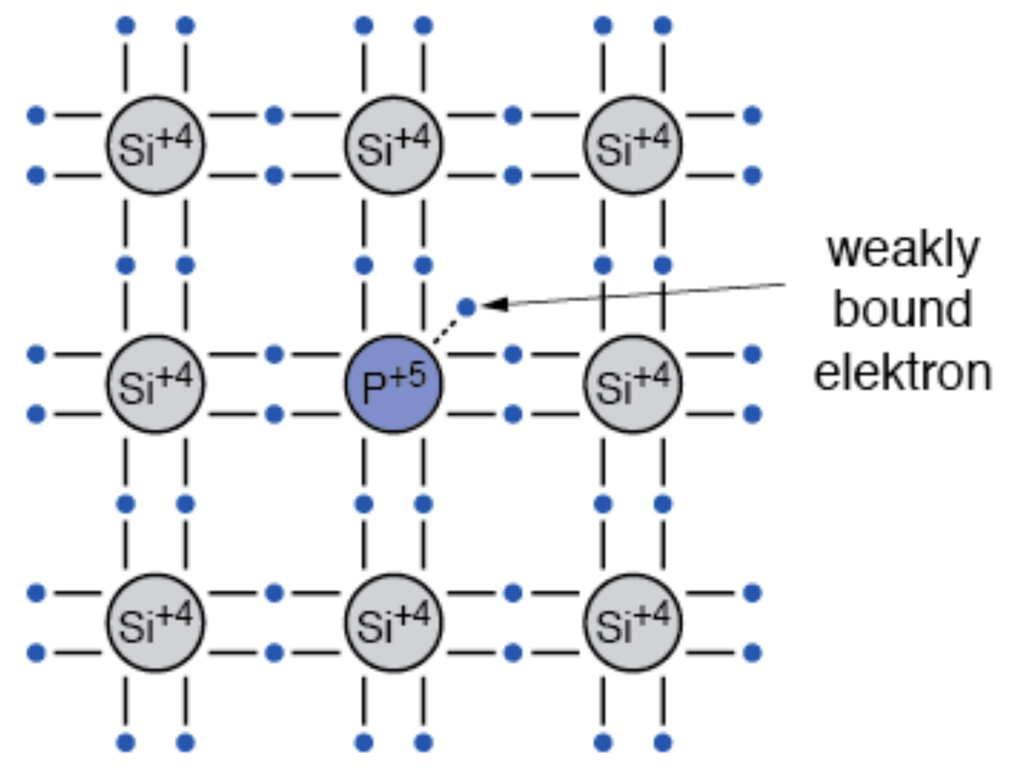
- In an isolated atom the electrons have only discrete energy levels.
- In solid state materials the atomic levels merge to energy bands.





- In metals the conduction and the valence band overlap, whereas in isolators and semiconductors these levels are separated by an energy gap (band gap). In insulators this gap is large.

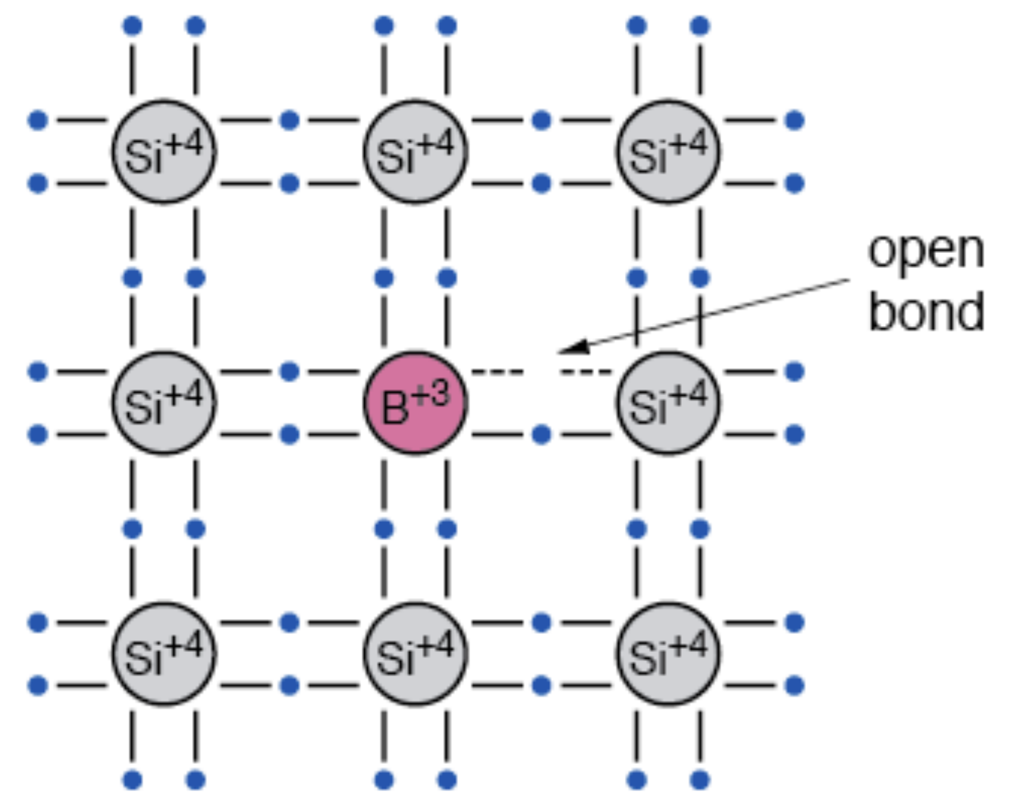
n-type silicon



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

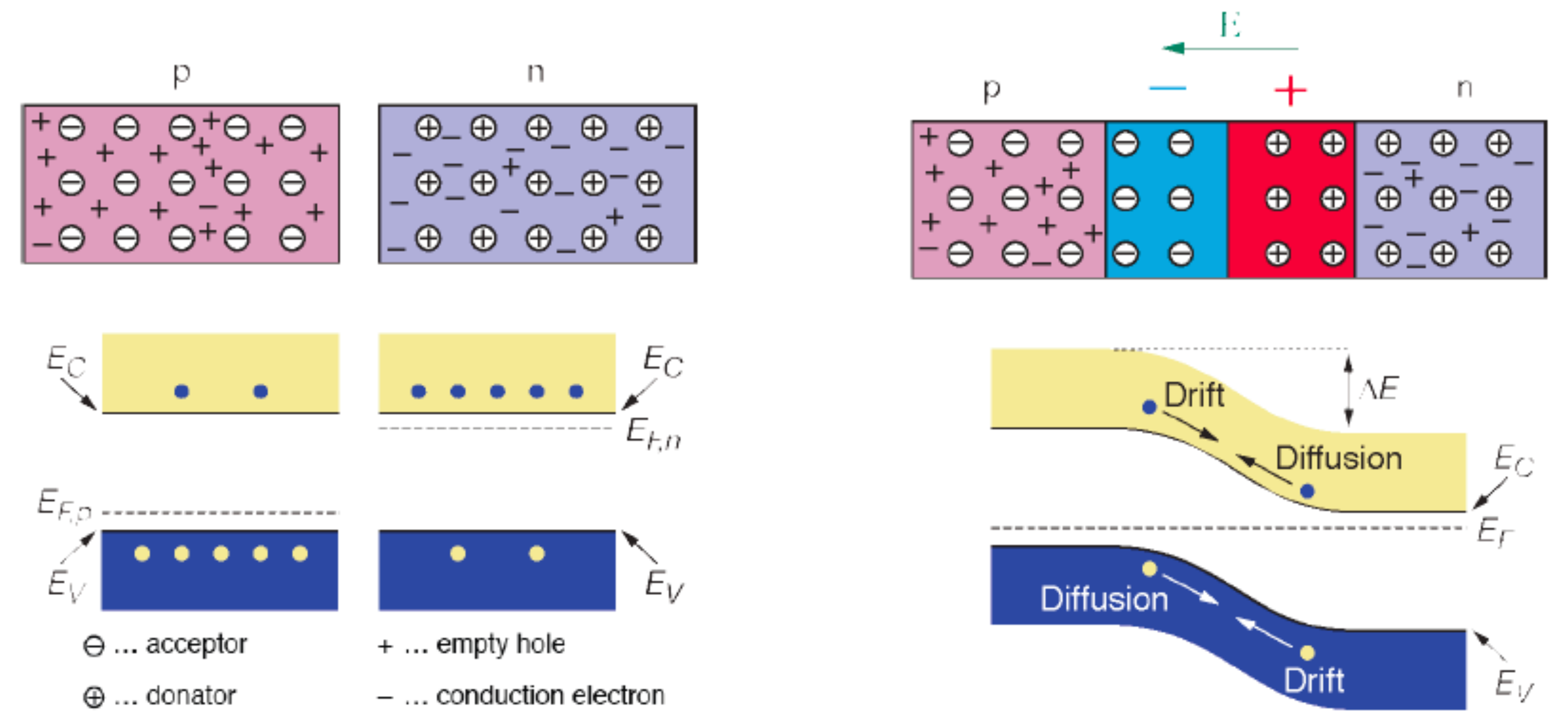
- Replace a small percentage of the silicon atoms in a crystal with Type-V atoms (As, P), and the resulting silicon is called "n-type".
- The crystal is electrically neutral, but one of the dopant's electrons is weakly bound.
- A small perturbation frees it for conduction, leaving a hole. The dopant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

p-type silicon



- Replacing a small fraction of the silicon atoms with Type-III atoms (Al, B) called "acceptors" creates p-type silicon
- The wafer is 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.

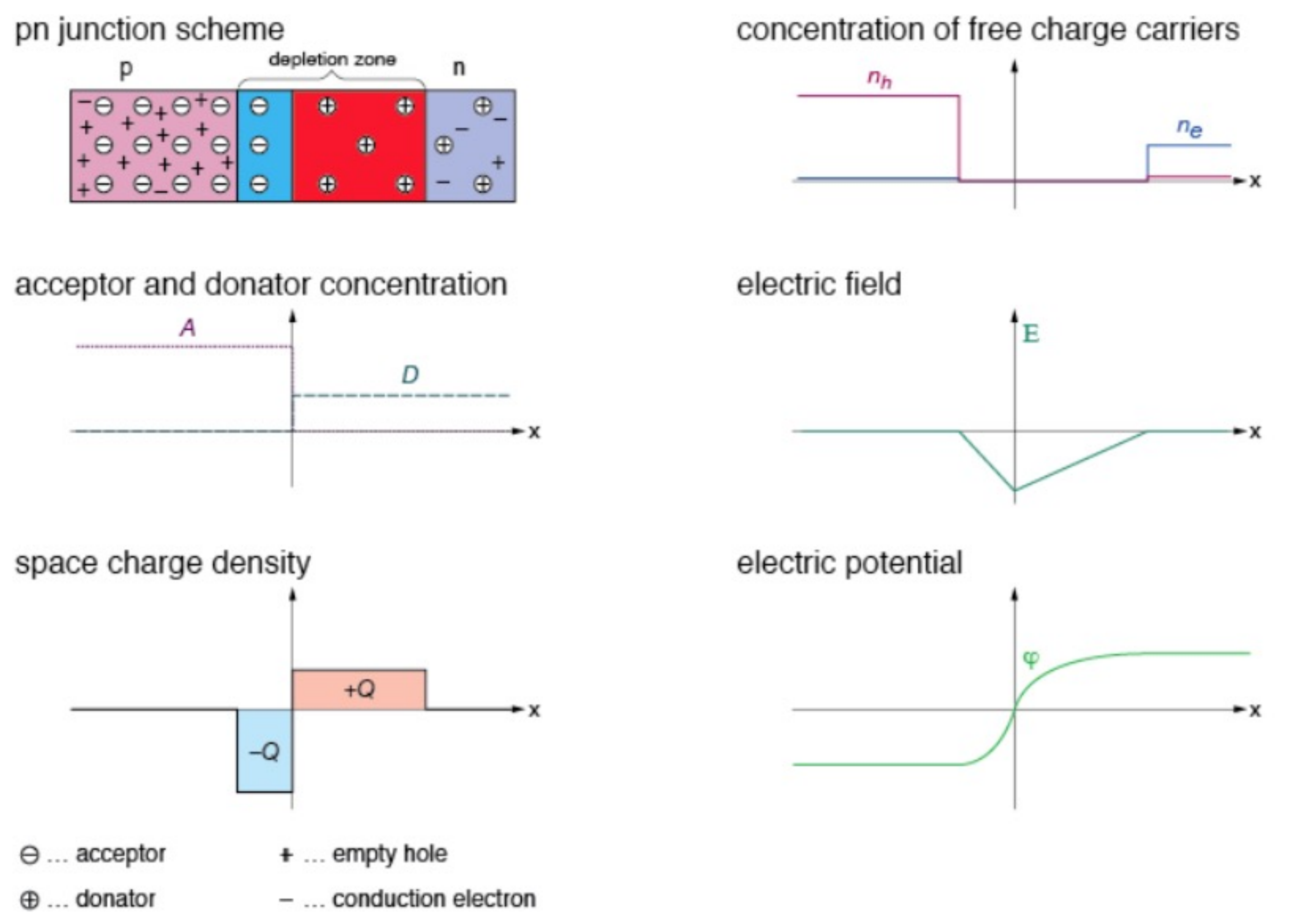
p-n junction


p
n
E_C
$E_{F,n}$
$E_{F,p}$
E_V
E_C
E_V
⊖ … acceptor
⊕ … donator
+ … empty hole
– … conduction electron
E
p
–
+
n
Drift
Diffusion
ΔE
E_C
E_F
Diffusion
Drift
E_V

P-n junction

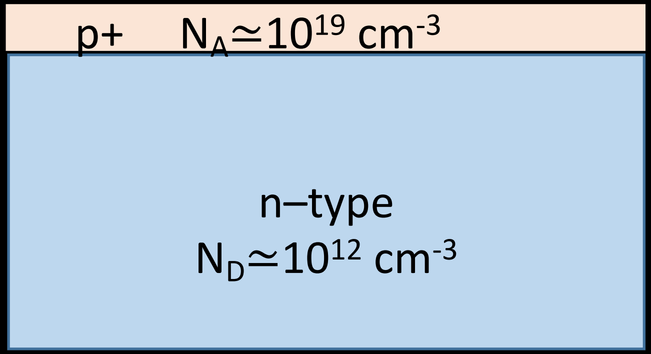
The depleted n-type zone is the tracking sensor.

- 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 interface region, the built-in potential which 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



Principles of a semiconductor detector

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



$$\vec{E} = -\vec{\nabla} V \qquad \boxed{\vec{\nabla} \cdot \vec{E} = \frac{\rho}{\varepsilon\varepsilon_0}} \qquad \rho = eN_{eff}$$

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

N_{eff} = doping concentration = N_{donors}-$N_{acceptors}$

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

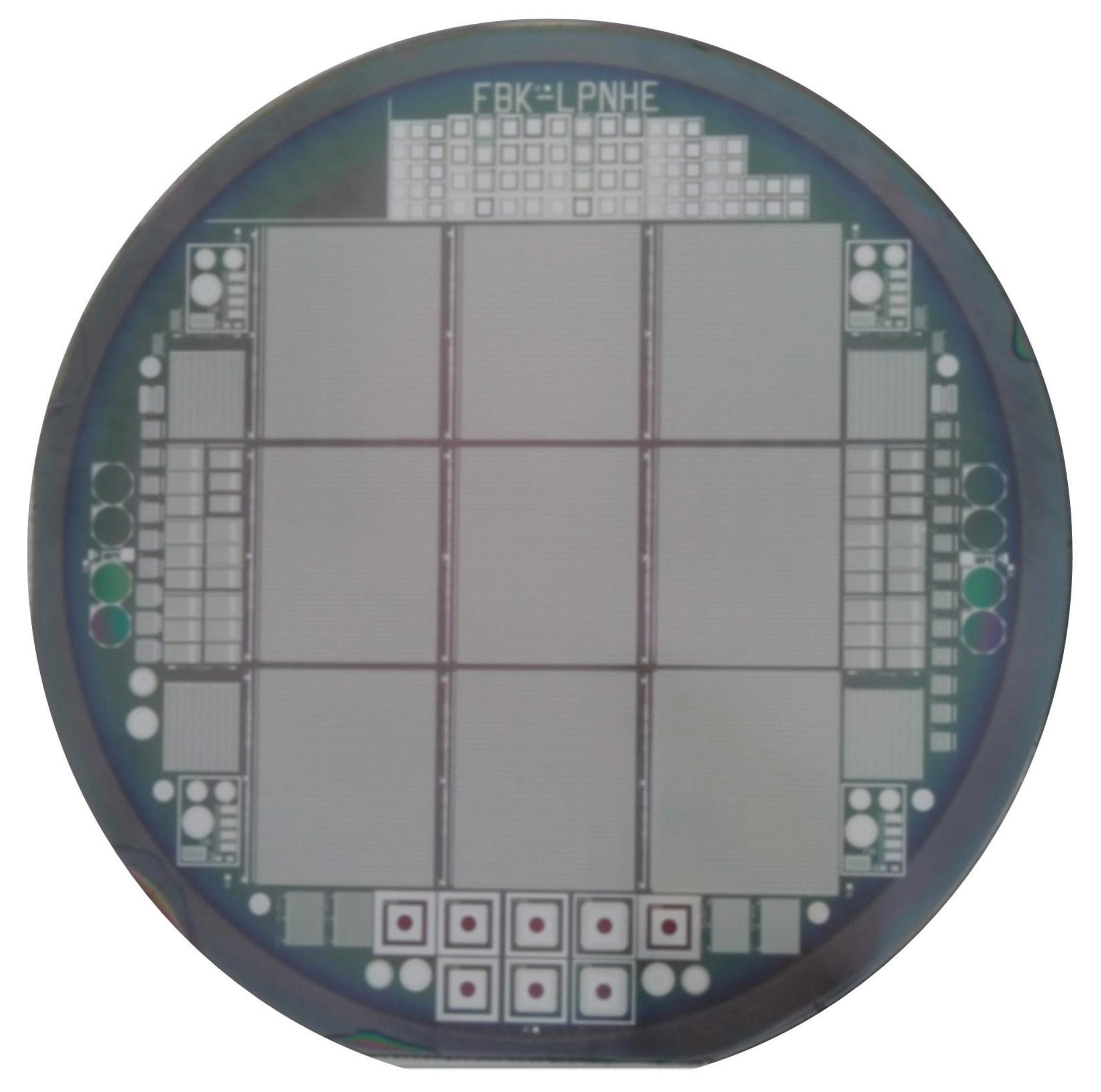
$$\boxed{w = \sqrt{\frac{-2 \cdot V \cdot \varepsilon\varepsilon_0}{e \cdot N_{eff}}} \Rightarrow \sqrt{\frac{2 \cdot V \cdot \varepsilon\varepsilon_0}{e \cdot |N_{eff}|}}}$$

If w = the physical width of the sensor, you reach the depletion voltage

$$\boxed{V_{dep} = w^2 N_{eff} \frac{e}{2\epsilon\epsilon_0}}$$

Silicon sensors

- 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



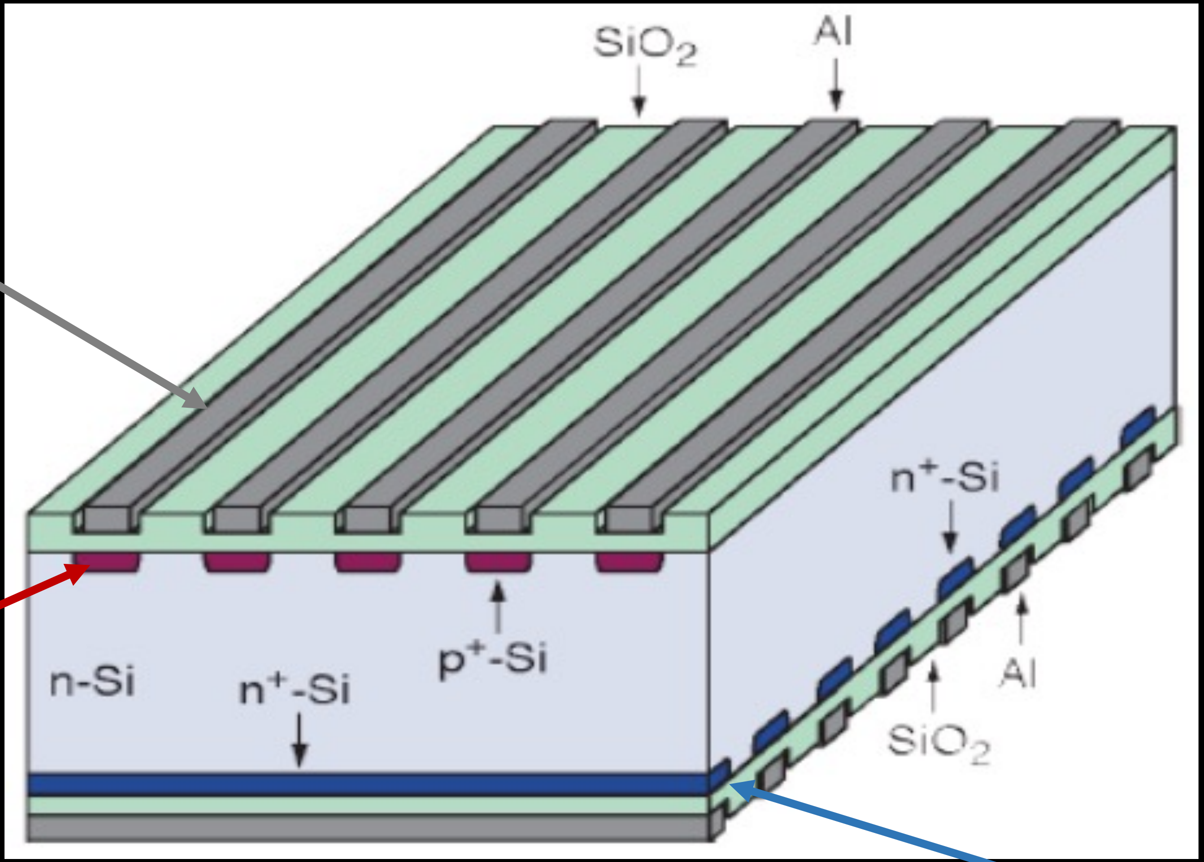
Strip Detectors

- The signal routed to the read-out electronics is often capacitively induced on metal electrodes. The capacitor dielectric is $SiO_2 + Si_3N_4$ (~ 10 pF/cm)

- The pn junction is at the interface of the bulk with these implanted strips ("p^+" means $10^{18} \geq n_{dopant}/cm^3$).

- Under reverse bias, the region depleted of free carriers grows from the junction toward the n+ side ("back side").

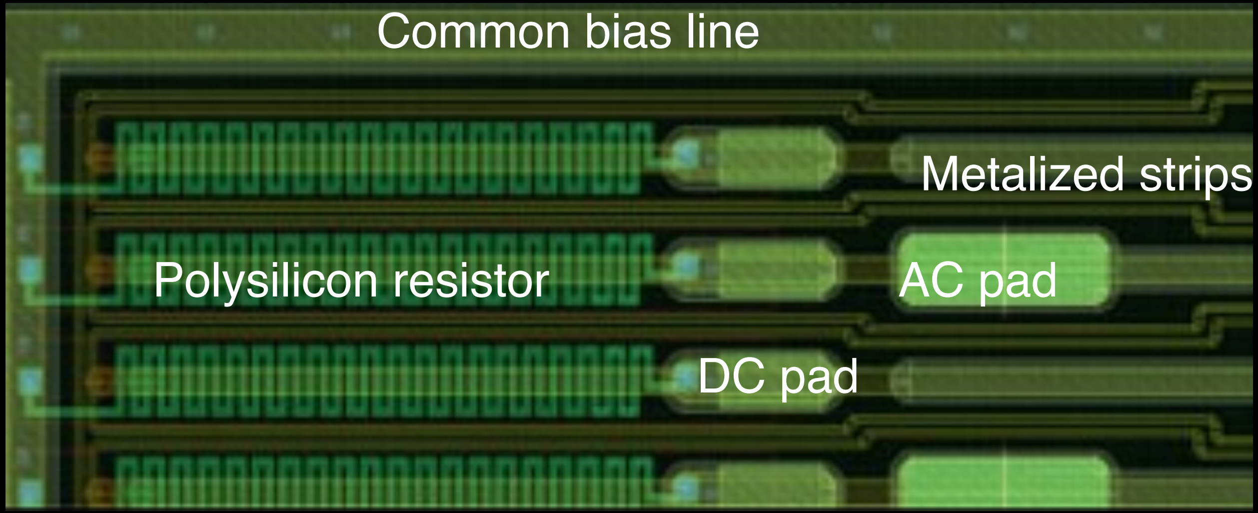
SiO_2 electrically isolates channels.



The back side has also an implant which can be segmented (in "double sided sensors") or not.

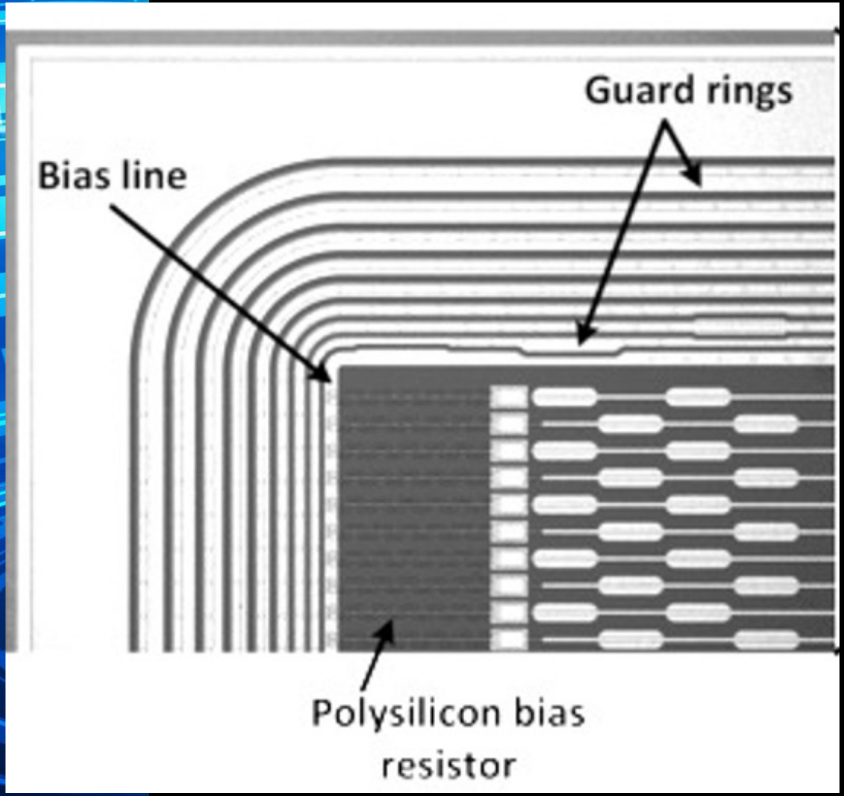
Technical implementation: Biasing

- Strips must be isolated from each other to provide distinct spatial information and they must be biased
- Solution: apply the bias potential to the strip through a very high resistivity (>1 MΩ) resistor (“the polysilicon bias resistor”)
- Depending on width and length a resistor of up to $R \approx 20$ MΩ is achieved ($R = R_s \cdot \mathit{length/width}$) *with* $R_s \approx 250$ kΩ/□

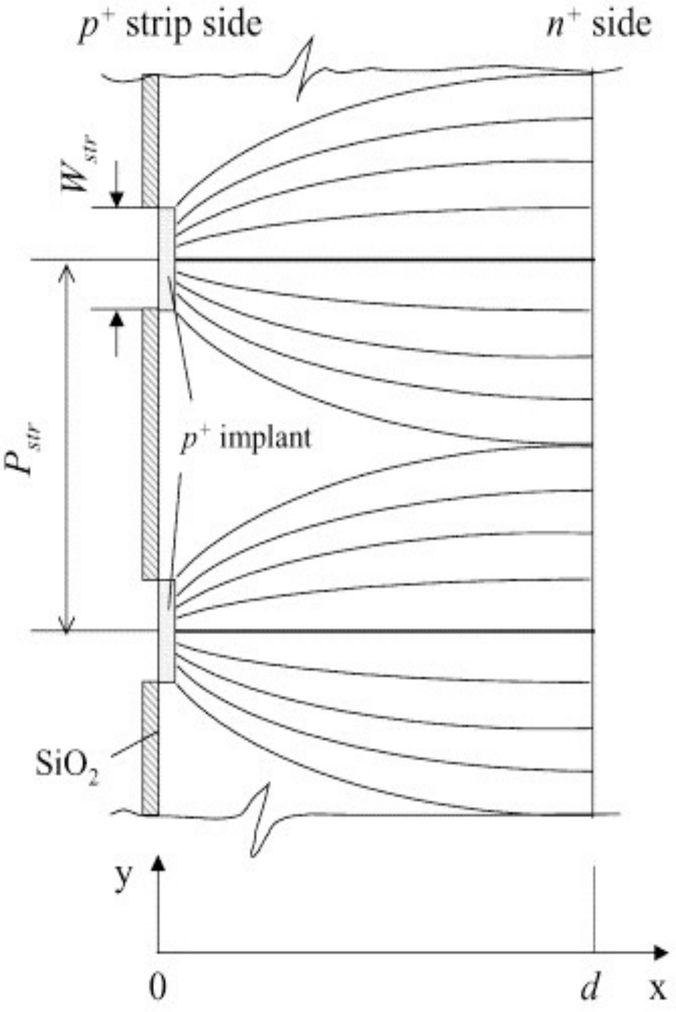


Technical implementation: Guard rings

- 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 instability.

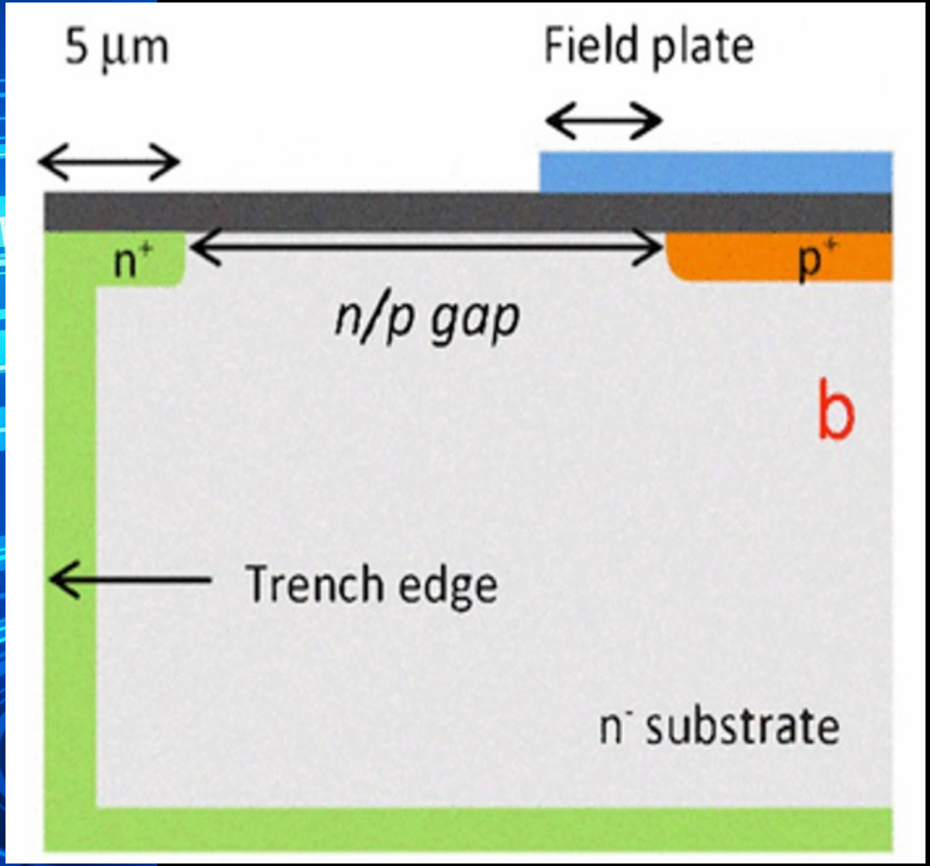


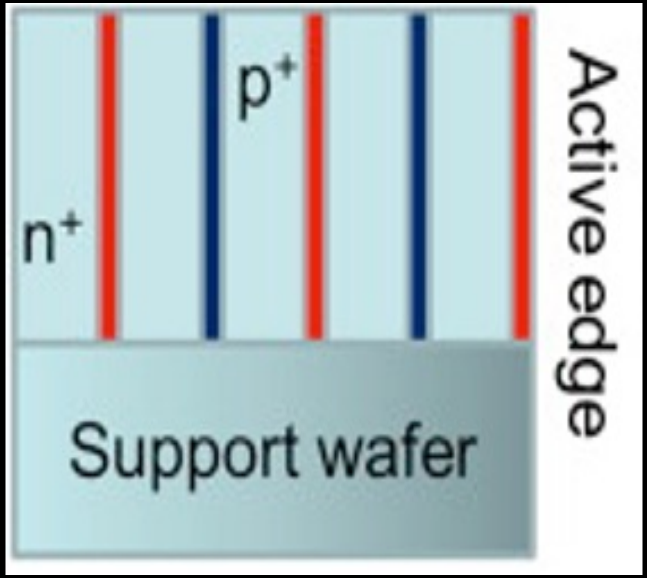
- Guard rings: One or more ring shaped p-n junctions that surround the sensor array and are covered by metal
- For p-implants in n-bulk: bias the n-side, ground the active area and innermost guard ring.
- The rings distribute the diode's field beyond the diode's perimeter, reducing the gradient of V



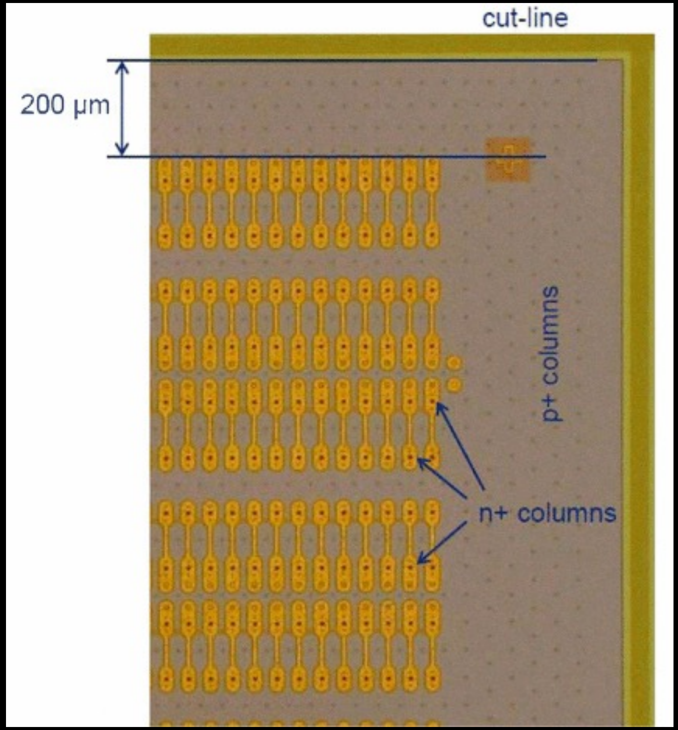
Technical implementation: Active edges

- 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 side





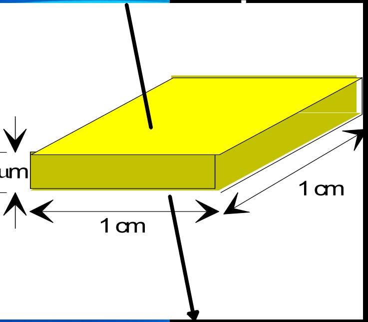
Often adopted for 3 D sensors



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.

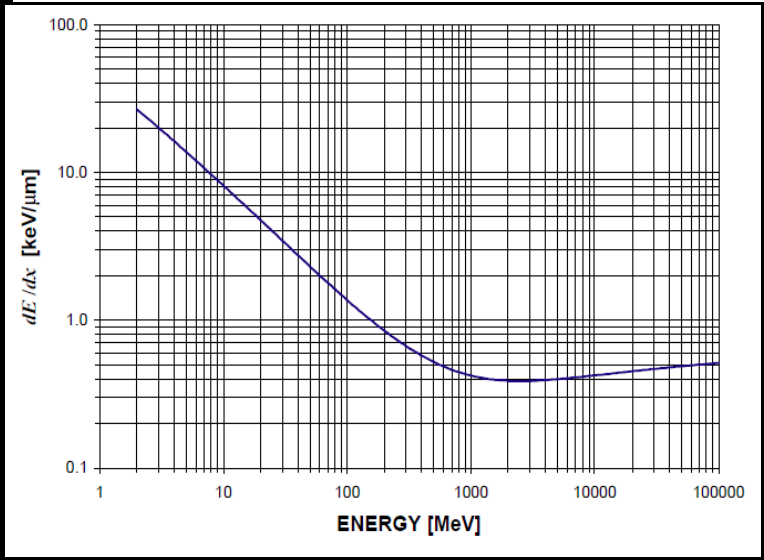
Signal in Silicon

- A minimum ionizing particle traversing Si loses energy at rate dE/dx = 3.87 MeV/cm.
- The mean ionization energy for silicon is $E_0 = 3.62$ eV.
- For A = 1 cm² and thickness d = 300 microns, the mean signal



$$\frac{(dE/dx)d}{E_0} = \frac{3.87\times10^6 eV/cm\times0.03cm}{3.62} = 3.2 \times 10^4 \text{ e-h pairs}$$

<dE/dx> of Protons in Silicon



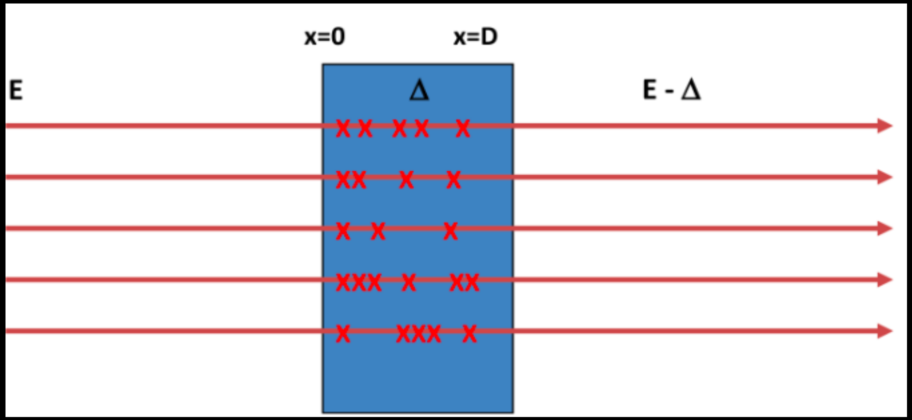
- In an undepleted, undoped ("intrinsic") semiconductor, the densities of holes and electrons are equal. In silicon at temperature 300K they are both $1.45 \times 10^{10}/cm^3$. Scaling to a thickness *d* = 300 microns yields 4.35×10^8 thermal (noise) e-h pairs which would swamp the signal.

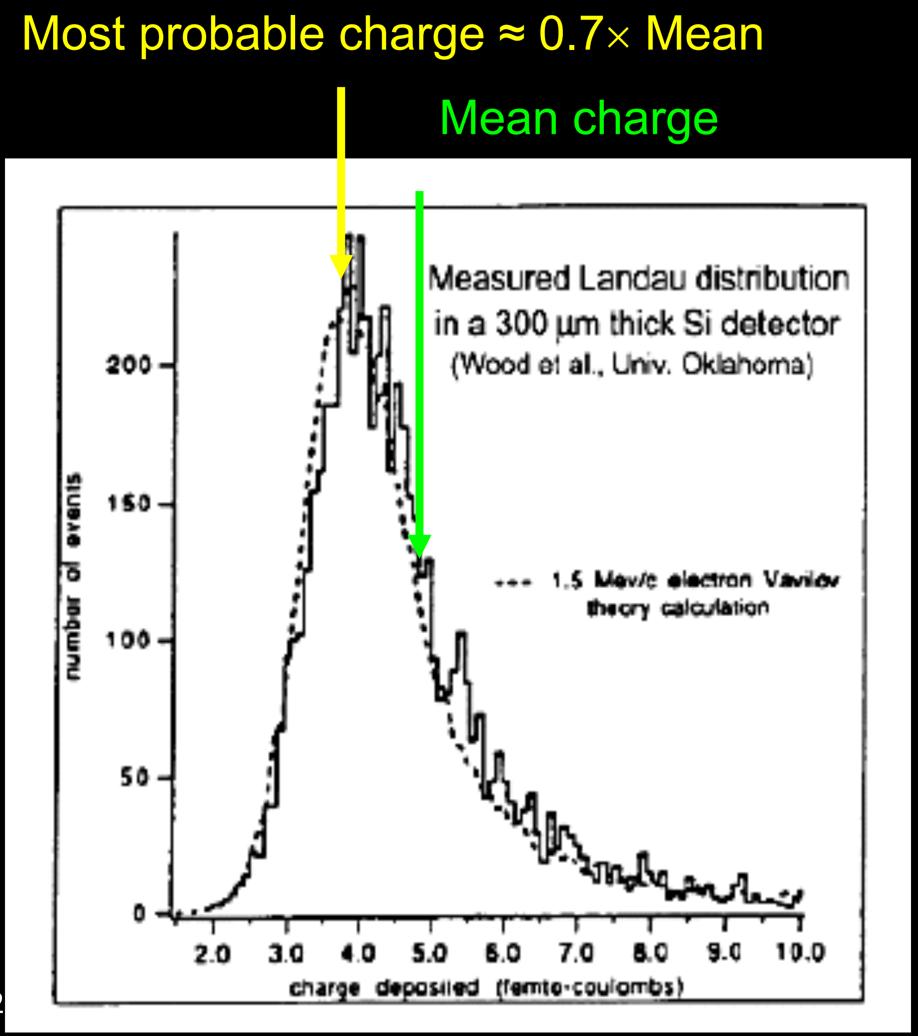
$$n_i dA = 1.45\cdot10^{10}\, cm^{-3}\cdot 0.03cm\cdot 1cm^2 \cong 4.35\cdot10^8 \text{ e-h pairs}$$

Depletion is critical

Landau distribution

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





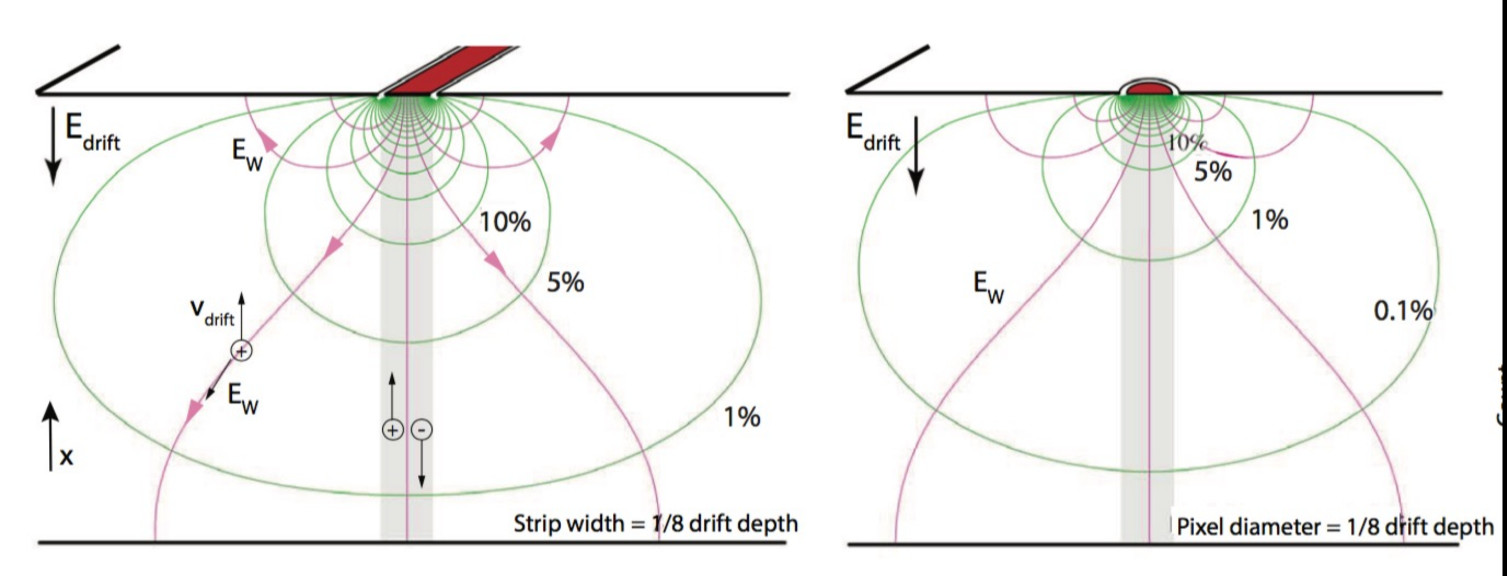
- The Landau distribution combines #collisions in a finite medium (Poisson distribution) with energy transfer per scatter (includes “straggling function” for high-energy delta-electron transfer).

- Most probable = 72 e-h pairs /μm
- Mean= 108 e-h pairs/μm.

Induced current– Shockley-Ramo

All signals in particle detectors are due to induction by moving charges.
Once the charges have arrived at the electrodes the signals are ‘over’.
The drift is recorded - the height of the signal is linear proportional to the velocity of the charge

$$i_s(t) = \boldsymbol{q\vec{E}_W\vec{v}}\big(\boldsymbol{x(t), y(t), z(t)}\big) = q\boldsymbol{\vec{E}_W} \cdot \boldsymbol{\mu\vec{E}}$$



- In diode/large pad detector with a linear field electrons and holes contribute the same to the electrode (pad)
- In fine segmented sensors pixel and strip the electrical fields concentrate at the electrodes and that is why we say that we collect holes, or we collect electrons

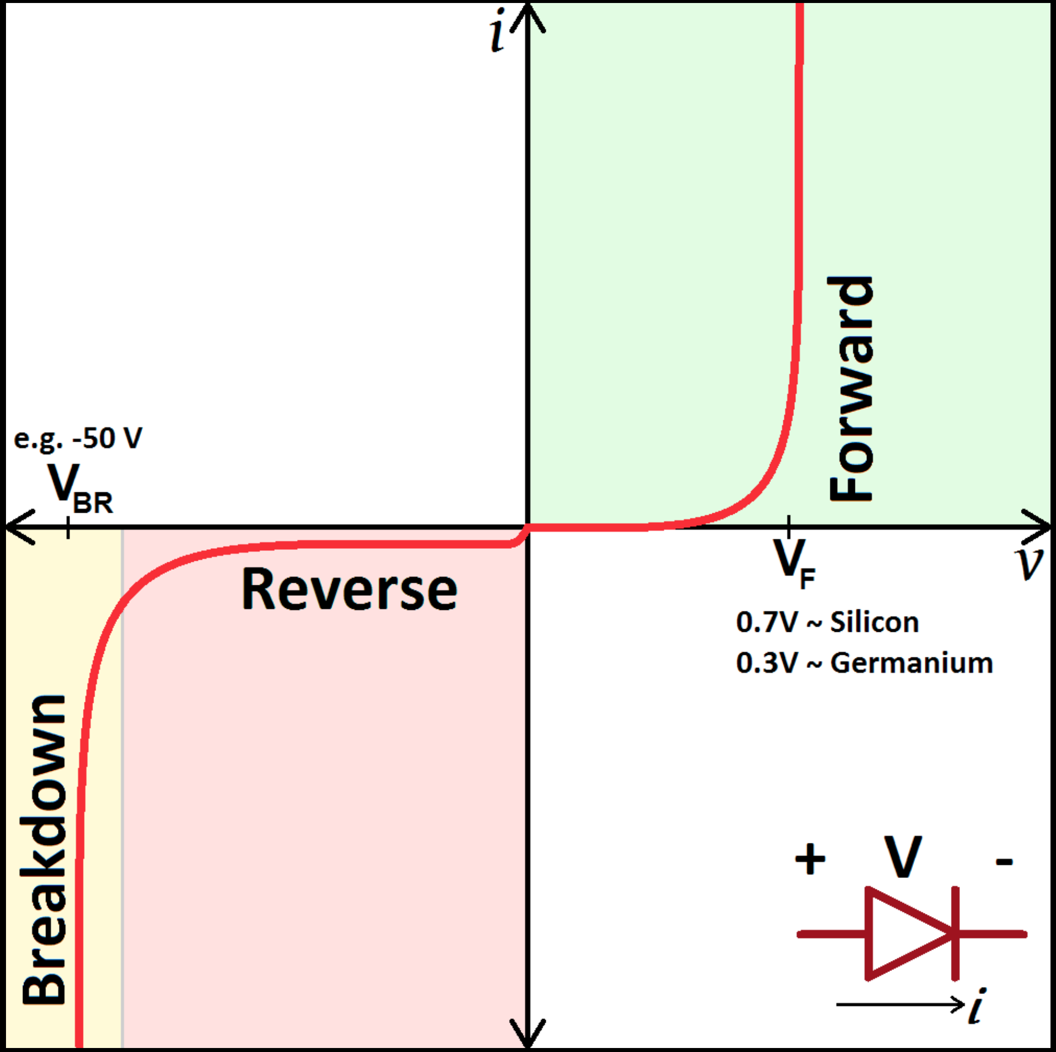
Leakage Current

- The leakage current is due to thermal generation in the depleted region

$$I \propto T^{3/2} \exp\left(-\frac{E_g}{2kT}\right) \text{ x Volume}$$

and diffusion from the undepleted region

- This current is a diagnostic of the quality of the crystal and a source of noise.
- The current versus voltage ("IV") characteristic of a detector is the first measurement to check that a sensor is operating properly and to find the range of safe bias voltages.



Keep leakage current low (approximately doubles for ≈ 8°C increase in temperature)

Capacitance

- The sensor presents a capacitance to the read-out chip amplifier which depends on the depth *w* of the depletion region

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

$$\frac{dw}{dV} = \sqrt{\frac{\varepsilon\varepsilon_0}{2e\left|N_{eff}\right|V}}$$

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

$$Q = e\left|N_{eff}\right|Aw$$

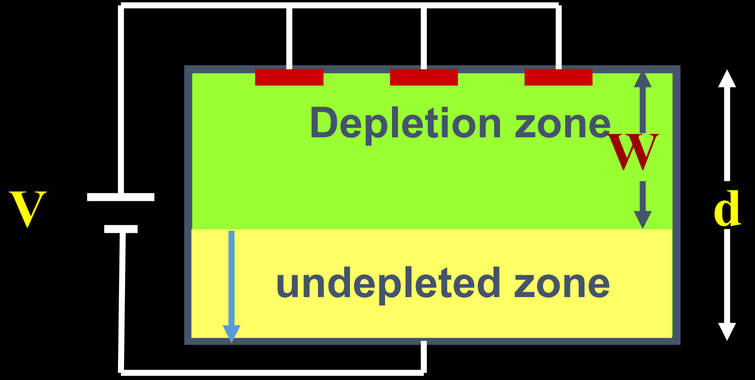
$$\frac{dQ}{dw} = e\left|N_{eff}\right|A$$

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

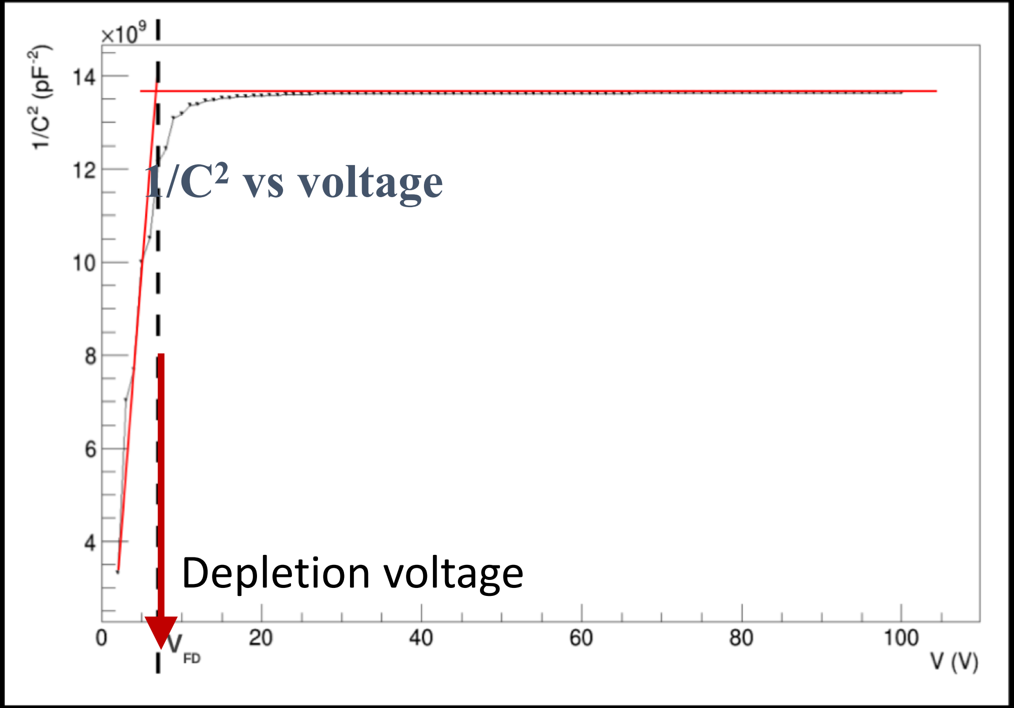
$$C \sim V^{-1/2}$$

- 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.”)

Capacitance



$$\frac{1}{C^2} \propto \begin{cases} V_{bias} & \text{if } V_{bias} < V_{FD} \\ D^2 & \text{if } V_{bias} \geqslant V_{FD} \end{cases}$$

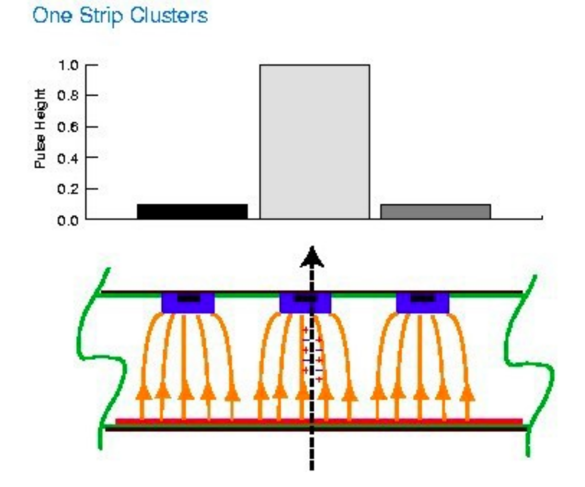


Resolution: Rule of the thumb

- Modern typical thickness 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

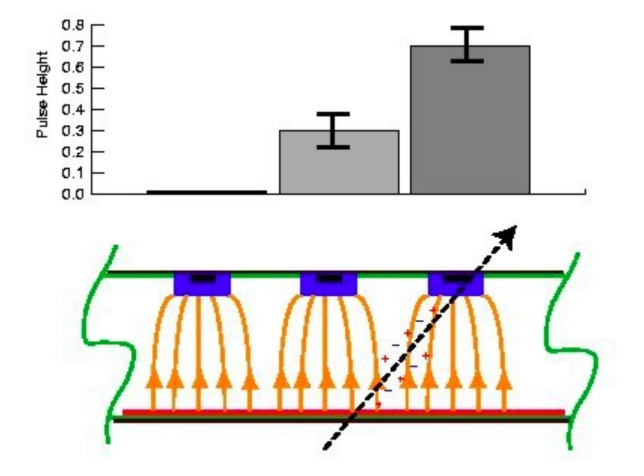
- A typical strip pitch is p = 50 µm.

- For binary charge readout on a single strip, the position resolution is σ = p/√12.



$$\sigma^2 = \int_{-p/2}^{p/2} \frac{x^2}{p} dx = \frac{p^2}{12}$$

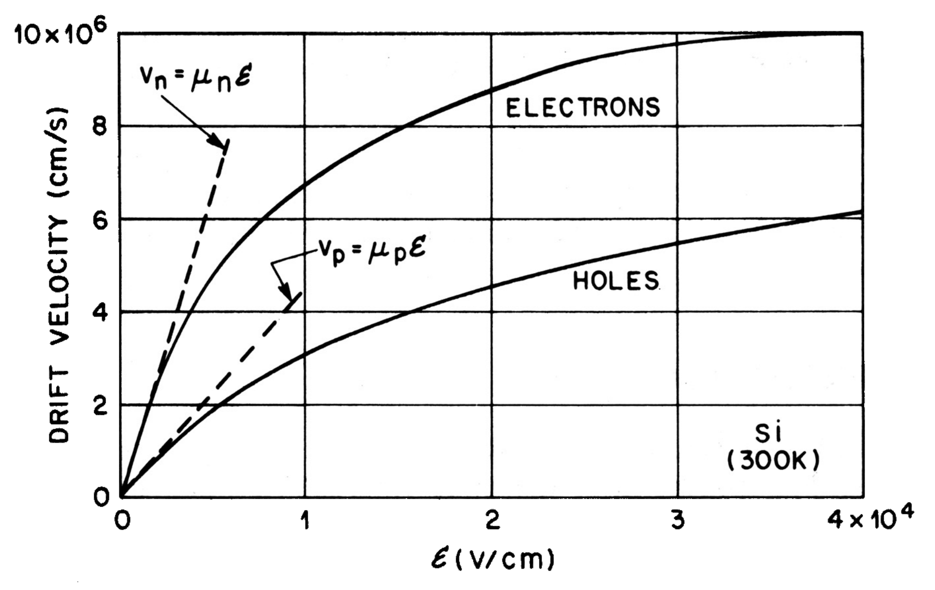
- If the charge is shared over multiple strips, with analog readout, resolution improves

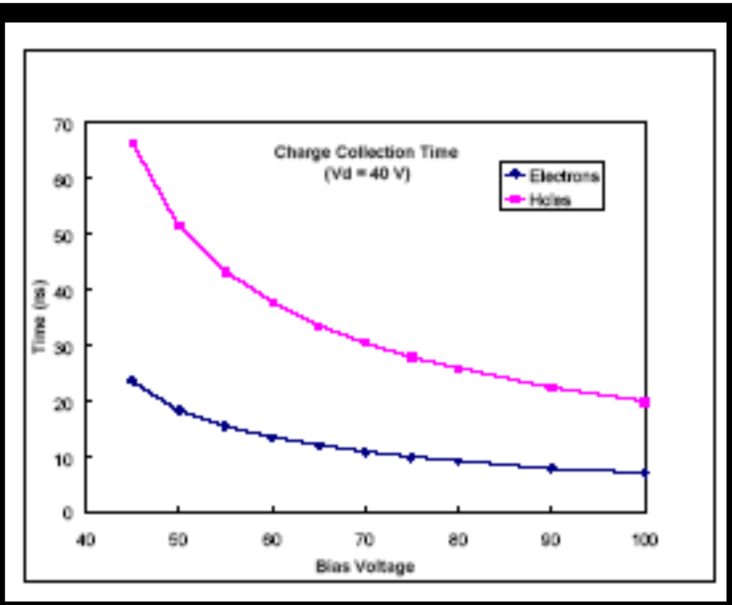


Collection of electrons/Holes

- The sensor can be designed to collect the electrons, the holes, or both.
- The mobility of a carrier is given by $\mu = E\tau/m$ where m = effective mass, τ = mean time between collisions, e = electron charge.
- Electrons have higher mobility:
  - $\mu_e = 1400\ \mathrm{cm^2/Vs}$
  - $\mu_h = 450\ \mathrm{cm^2/Vs}$

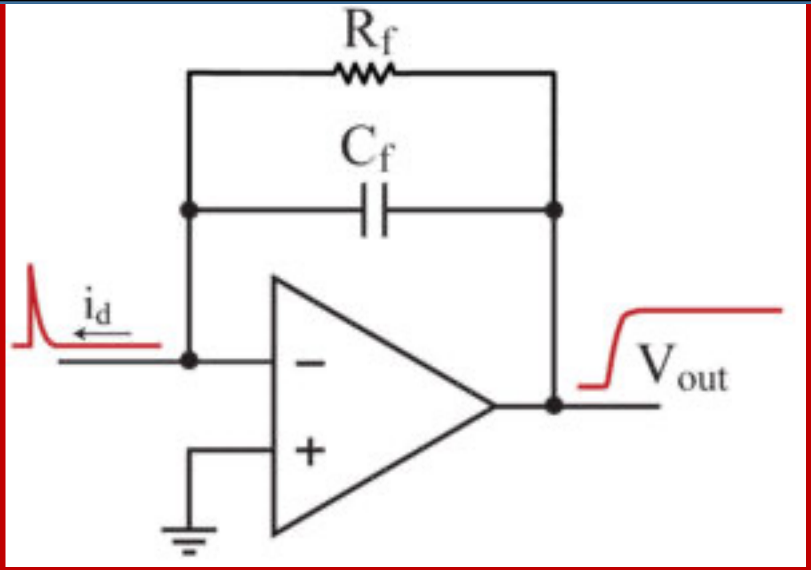
  and are collected faster.
- Before saturation, their velocities depend simply on the applied field E: $v_{e,h} = \mu_{e,h} E$





Readout

- The signal of a silicon detector is often readout by a charge sensitive amplifier



$$V_{out}(t) \propto Q(t) = \int^{t} i_d \, d\tau$$

$$V_o = \frac{Q_D}{C_f}$$

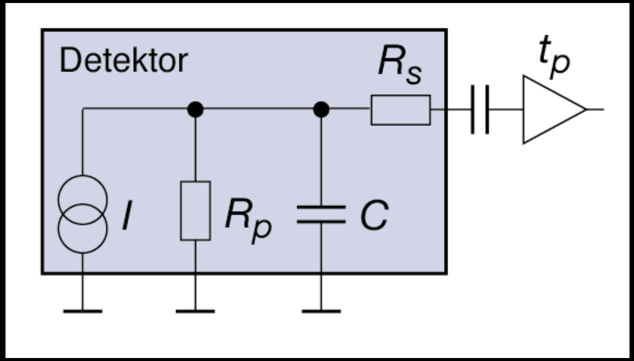
$$\tau_f = R_f C_f$$

- The most simple CSA has a feedback capacitor C_f between the input and output which stores the charge from the detector.
- The gain of the preamplifier is $1/C_f$.
- The resistor in parallel with the feedback capacitor can be used to reset the CSA
- Each pulse of current from the detector causes on output voltage proportional to the integral of the detector current

Noise contributions

The most important noise contributions are:

1. Leakage current (ENC_I)
2. Detector capacity (ENC_C)
3. Det. parallel resistor (ENC_{Rp})
4. Det. series resistor (ENC_{Rs})



Alternate circuit diagram of a silicon detector.

The overall noise is the quadratic sum of all contributions

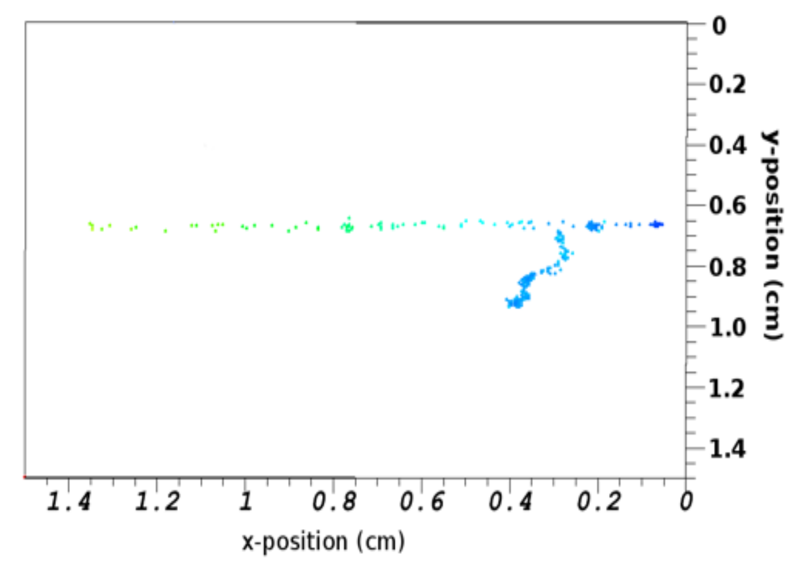
$$ENC = \sqrt{ENC_C^2 + ENC_I^2 + ENC_{Rp}^2 + ENC_{Rs}^2}$$

S/N

- The experiment goal is to maximize signal/noise
  - Capacitance C (interstrip, bulk, coupling...). Equivalent noise charge $ENC_C \sim C$. This contribution is often inversely as the pre-amplifier integration time ⟹ long integration time (but this is restricted by the accelerator beam structure)
  - Leakage current. $ENC_I \sim \sqrt{I_{leakage} t_p}$ where t_p is the “peaking time” of the amplifier
  - Thermal noise in the bias resistor of resistance R: $ENC_{Rp} \sim \sqrt{kT t_p / R_P}$
  - Series resistance in the aluminium traces and connection to the amplifier: $ENC_{Rs} \sim \sqrt{R_s / t_p}$
- To optimize S/N in strip detectors: minimize capacitance, minimize leakage current, maximize bias resistance, minimize the resistive connection to the amplifier.
- For pixel detectors the critical parameter is Signal/Threshold. Typical contemporary front end electronics threshold ~ 2500 e^-.

Drift/Diffusion and position resolution

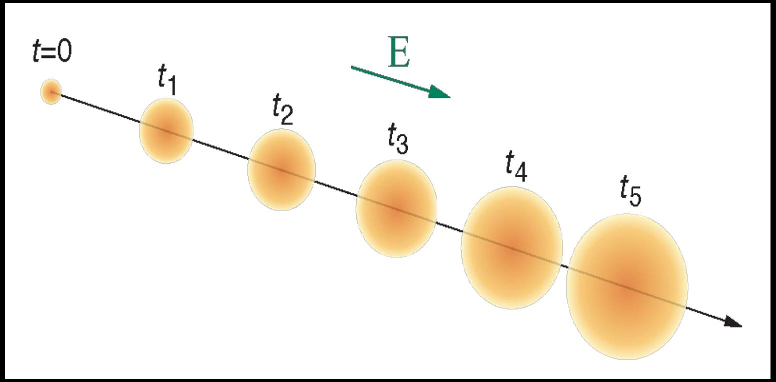
- The shape of the Landau distribution indicates that the ionization deposited in the detector includes statistical variation. (E.g., a delta-ray production due to a hard collision with an electron will redirect the track.)



- The ionization e$^-$ and h drift along the E field to the electrodes, but at the same time they diffuse. Diffusion broadens the cluster.
- The width ("root-mean-square") of the distribution is given as:

$$\sigma_D = \sqrt{2Dt} \quad \text{with:} \quad D = \frac{kT}{e}\mu$$

t … drift time
D … diffusion coefficient
k … Boltzmann constant
T … temperature
e … electron charge
μ … charge carrier mobility



Note: $D \propto \mu$ and $t \propto 1/\mu$, hence σ_D is equal for e$^-$ and h$^+$.

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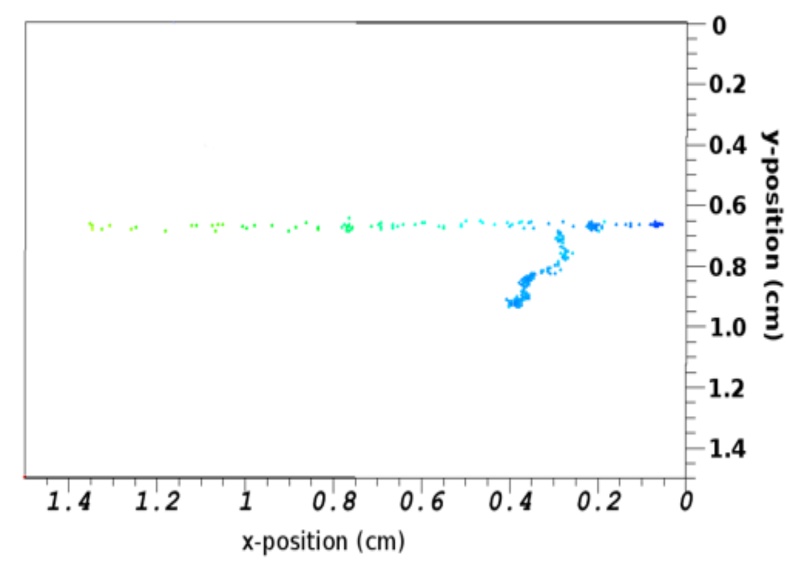

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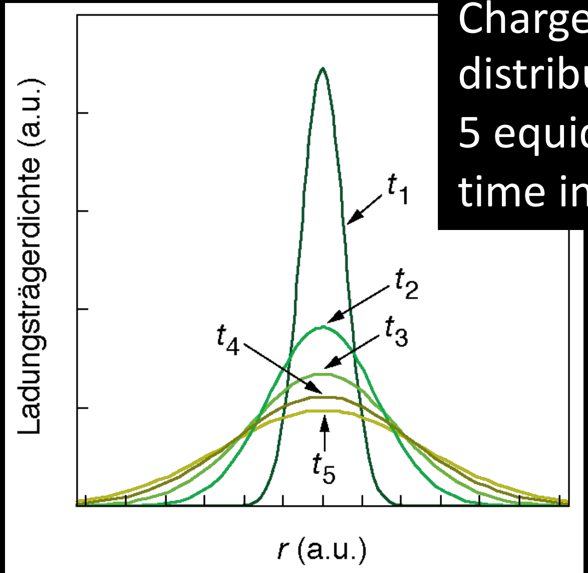
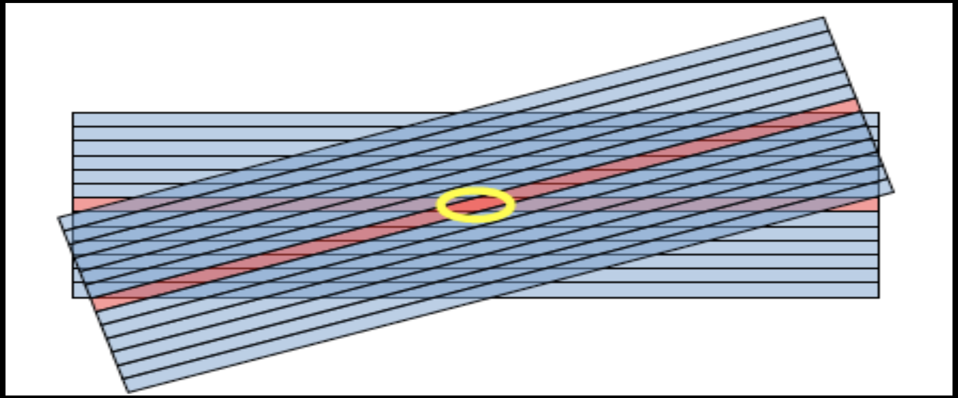
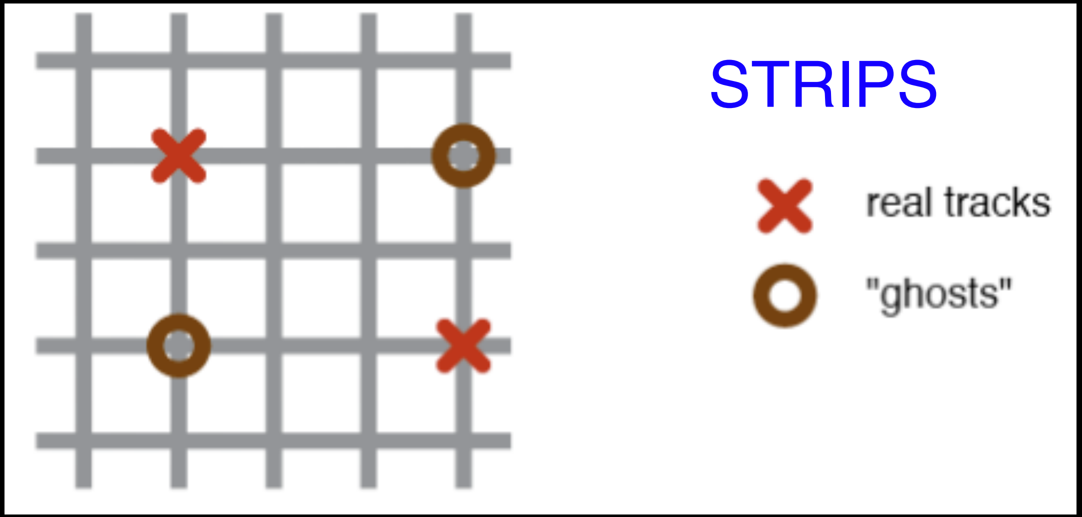


Charge density distribution for 5 equidistant time intervals:

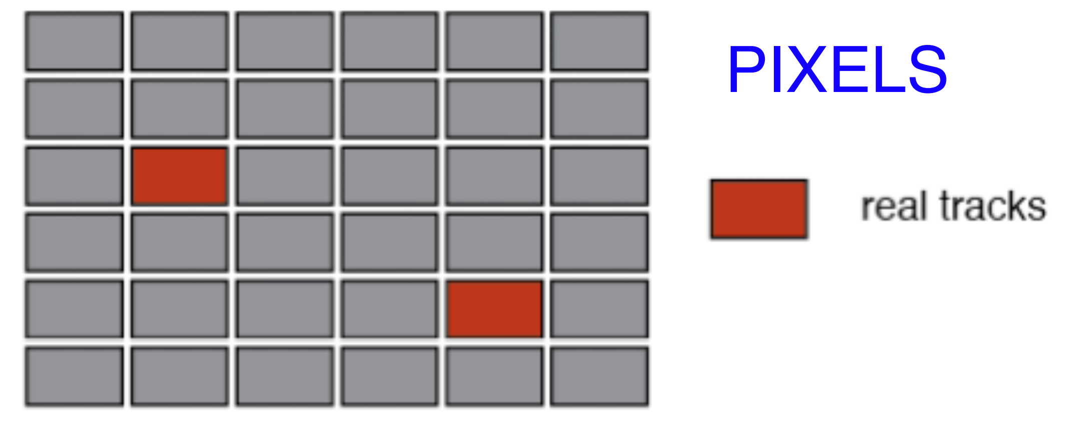
Strips versus Pixels

- A strip detector measures 1 coordinate only. Two orthogonal/angled arranged strip detectors could give a 2-dimensional position of a particle track.



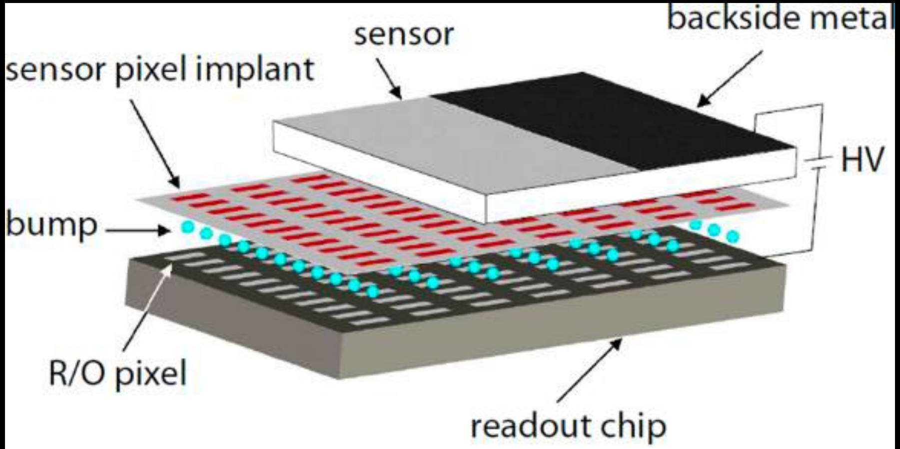


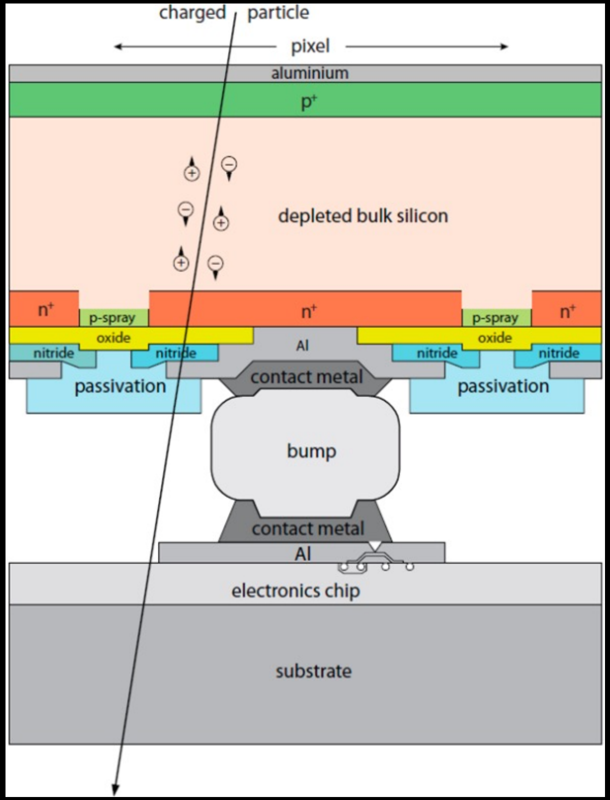
- Pixel detectors produce unambiguous hits!
  - Large number of electrical connections and large power consumption.

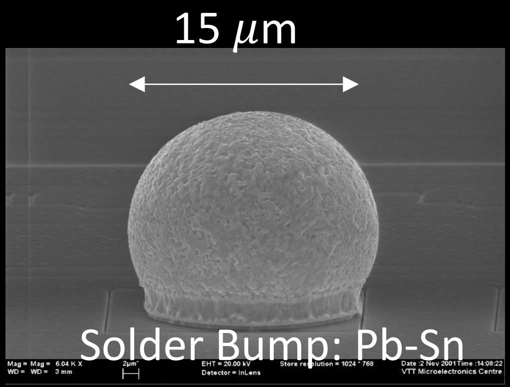


Hybrid Pixel detectors

- Advantage
  - Small pixel area
    - Low capacitance (≈1 fF/Pixel)
    - large signal-to-noise ratio (e.g. 150:1).
  - Small pixel volume
    - low leakage current (≈1 pA/Pixel)
    - DC coupling
- **Disadvantages:**
  - Large number of readout channels
  - Large bandwidth
  - Large power consumption
  - Bump bonding is costly and complex
- n^+-on n for the LHC
  - Electron have faster collection time





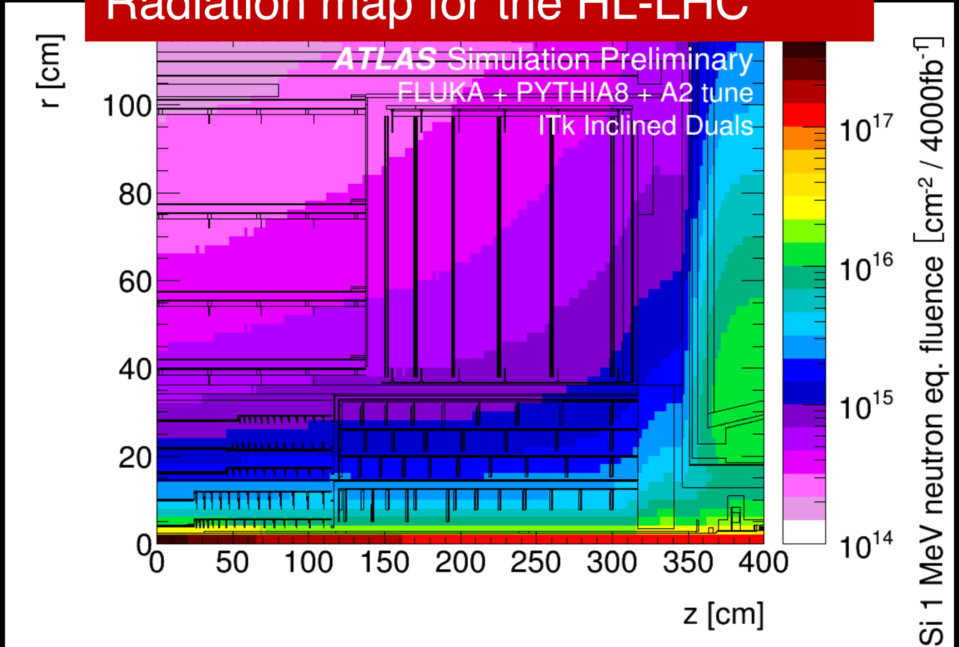


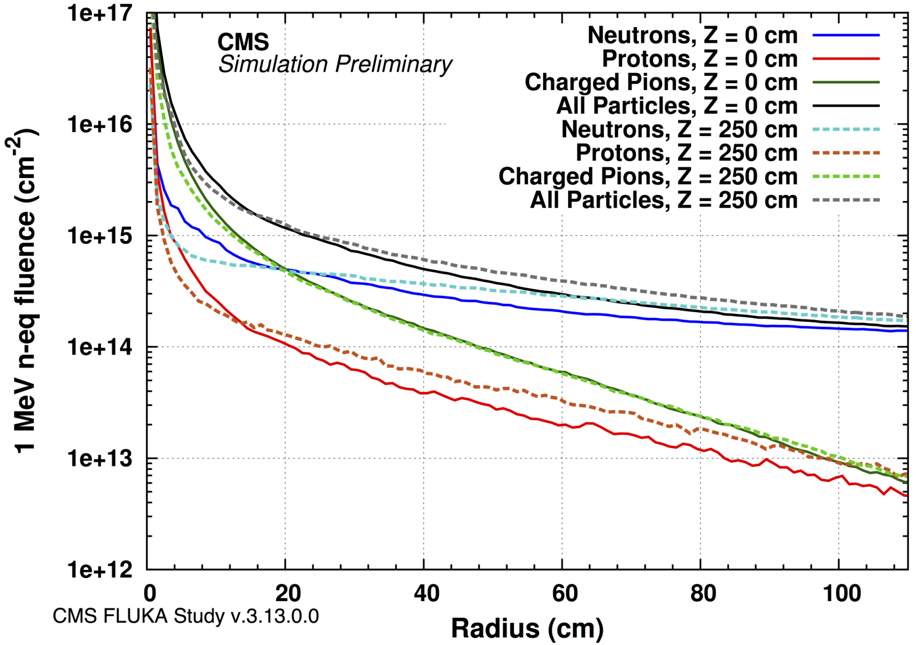
(VTT/Finland)

Radiation damage

- n_{eq}/cm^2 depending upon the distance from the interaction point.
- Radiation sources in a particle collider:
  - The main source of charged radiation: collisions at the interaction point, so their fluence $\Phi \sim 1/r^2$.
  - The main source of neutrons: backsplash from the calorimeter, so their Φ depends on shielding and design.
- Two types of effects: bulk damage (Non Ionizing energy loss) and surface damage (ionizing energy loss)

Radiation map for the HL-LHC



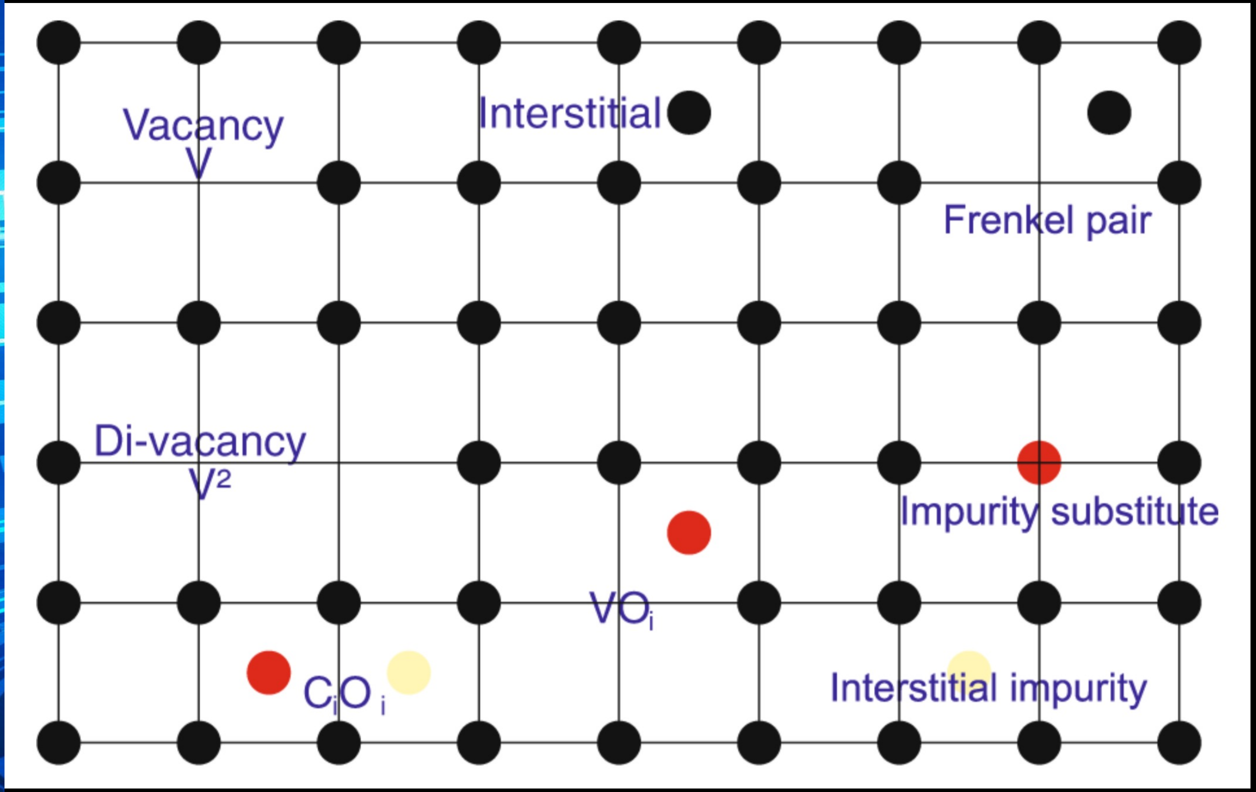


Bulk and surface damage

- Radiation induced damage in the semiconductor bulk are dislocated atoms from their position in the lattice (Non ionizing energy loss). Such dislocations are caused by massive particles.
  - Bulk damage is primarily produced by neutrons, protons and pions (NIEL)
- In SiO_2 such dislocations are not important because the material is amorphous. The radiation damage in the SiO_2 is due to the charges generated in the oxide which cannot disappear due to the insulating nature and lead to local concentrations of these charges.
  - Radiation damage in the oxide is primarily produced by photons and charged particles. (Ionizing energy loss).

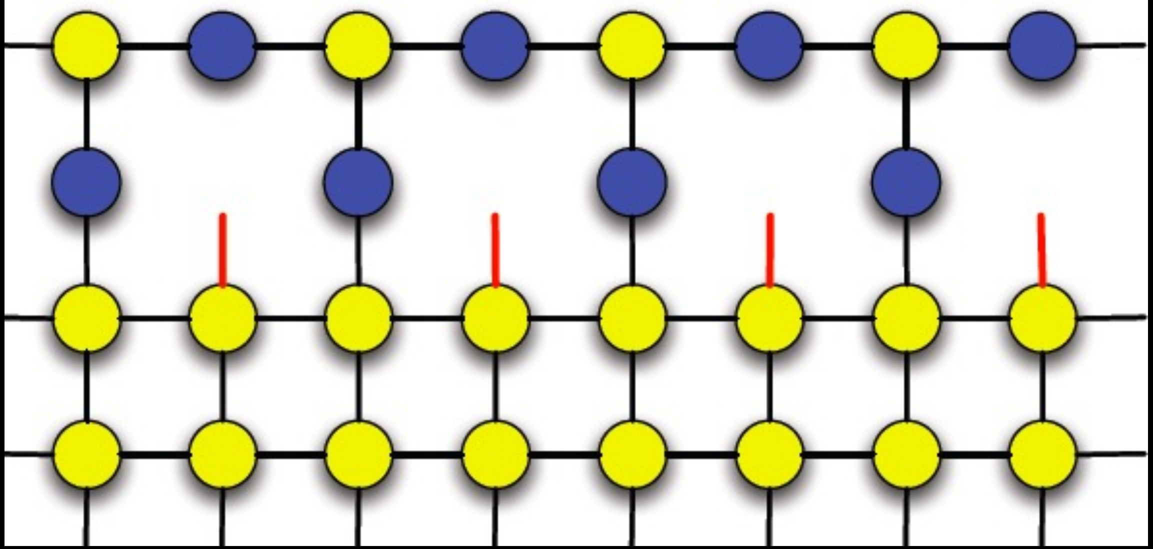
Radiation damage

- Non ionizing energy loss (NIEL)
  - – Atomic displacement caused by p,n,**π**
  - – Frenkel pair E~25eV, Defect cluster E~5keV



- Affects mainly the sensors and measured in 1 MeV n_{eq}

- Ionizing energy loss
  - – Proportional to absorbed radiation dose
  - – Measured in 1 Gy = 100 rad

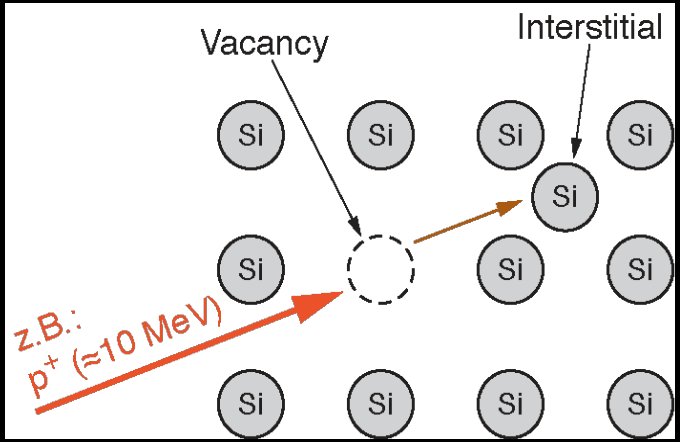


- The interface states become filled and saturate at about 100 kRad so for the sensors this is not as severe a problem as the bulk damage. But surface damage is a major challenge for readout electronics.

Point defects

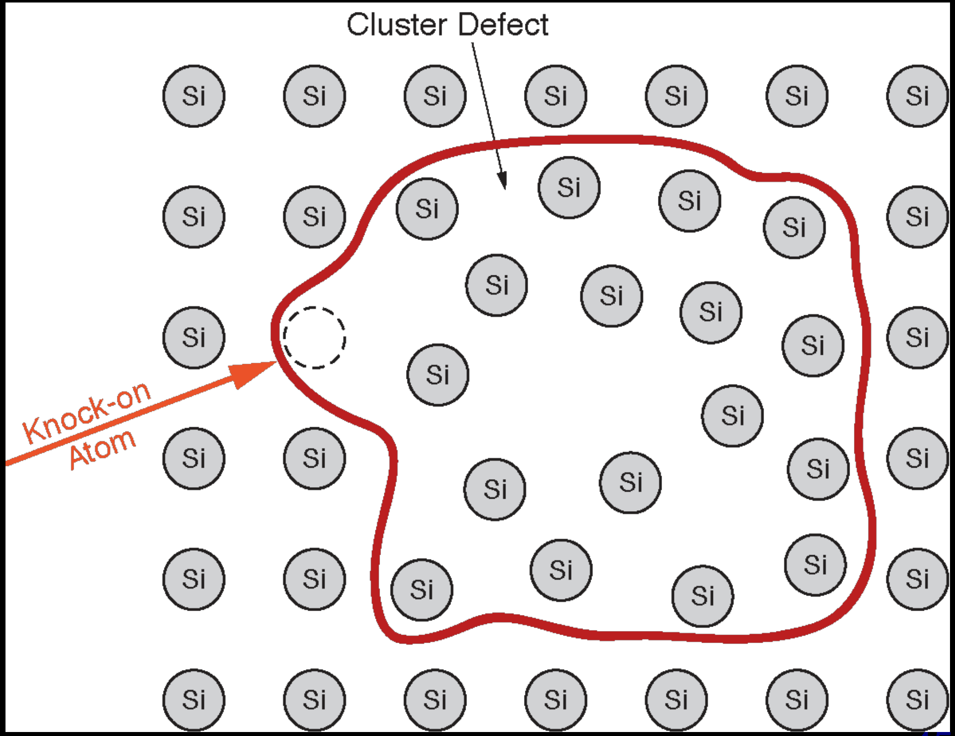
- A displaced silicon atom produces an empty space in the lattice (Vacancy, V) and in another place an atom in an inter lattice space (Interstitial, I).
- A vacancy-interstitial pair is called a Frenkel-defect.

Frenkel-defect



Cluster defects

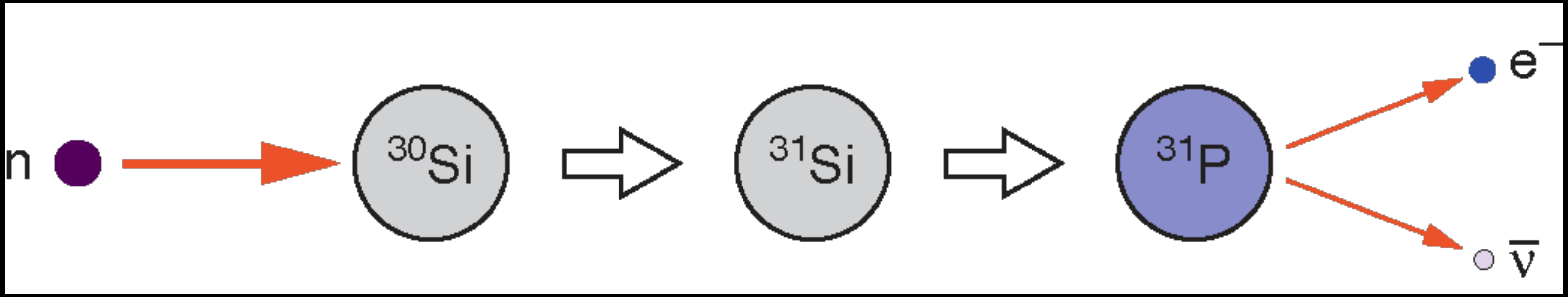
- In hard impacts the primary knock-on atom (PKA) displaces additional atoms. These defects are called cluster defects.
- The size of a cluster defect is approximately 5 nm and consists of about 100 dislocated atoms.
- For high energy PKA cluster defects appear at the end of the track when the atom looses the kinetic energy and the elastic cross section increases.



Atom transformations

- Particles can also interact strongly

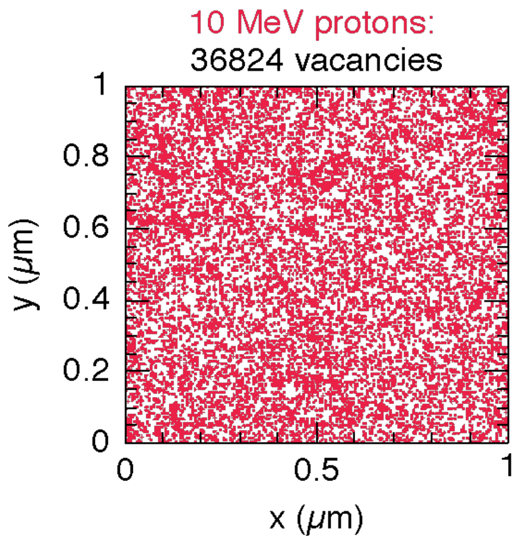
- An example is the transformation of a silicon atom in a phosphor atom with the subsequent beta decay:

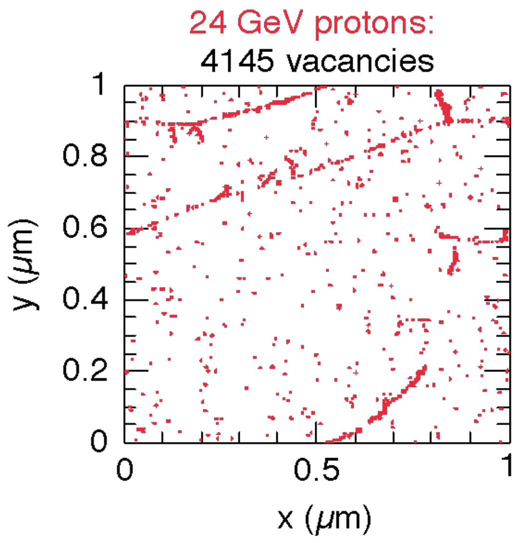


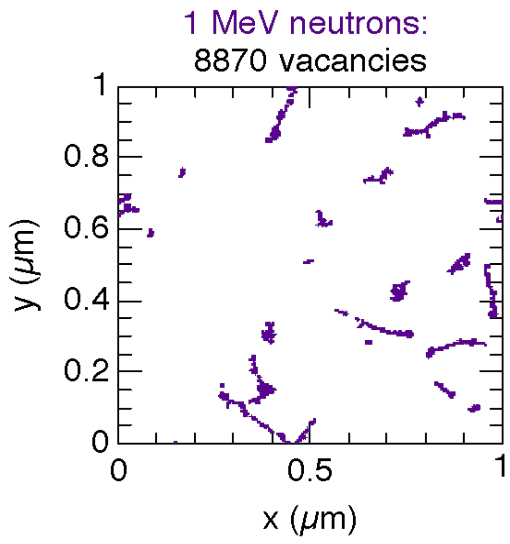
- If the transformed atom remains in the correct lattice position this atom acts as a regular dopant – either as donor or acceptor.

Dependence on type and energy of radiation

Type and frequency of defects depends on the particle type and the energy.
Simulation of vacancies in 1 μm thick material after an integrated flux of 10^{14} particles per cm^2:







Many vacancies produced

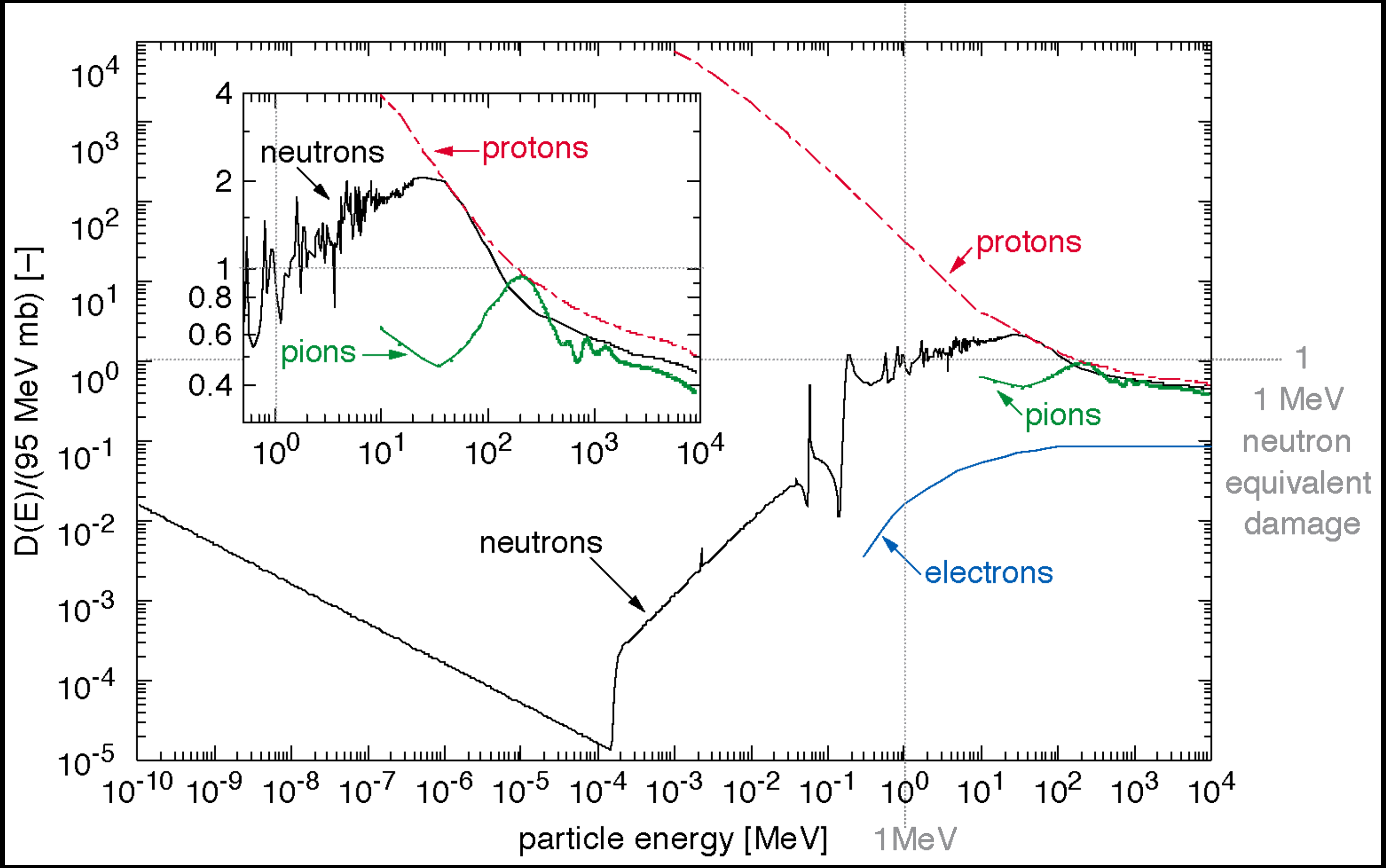
Less vacancies, a significant part of the energy is consumpted to produce cluster deffects

Very few vacancies, energy of the neutrons is used up to produce cluster defects.

M. Huhtinen, *Simulation of Non-Ionising Energy Loss and Defect Formation in Silicon*, Nucl. Instr. Meth. A **491**, 194 (2002)

Damage function for different particles

D(E) in the plot below is divided by 95 mb to be normalized to the damage caused by 1 MeV neutrons



G. Lindström, *Radiation Damage in Silicon Detectors*, Nucl. Instr. Meth. A **512**, 30 (2003)

Hardness factor

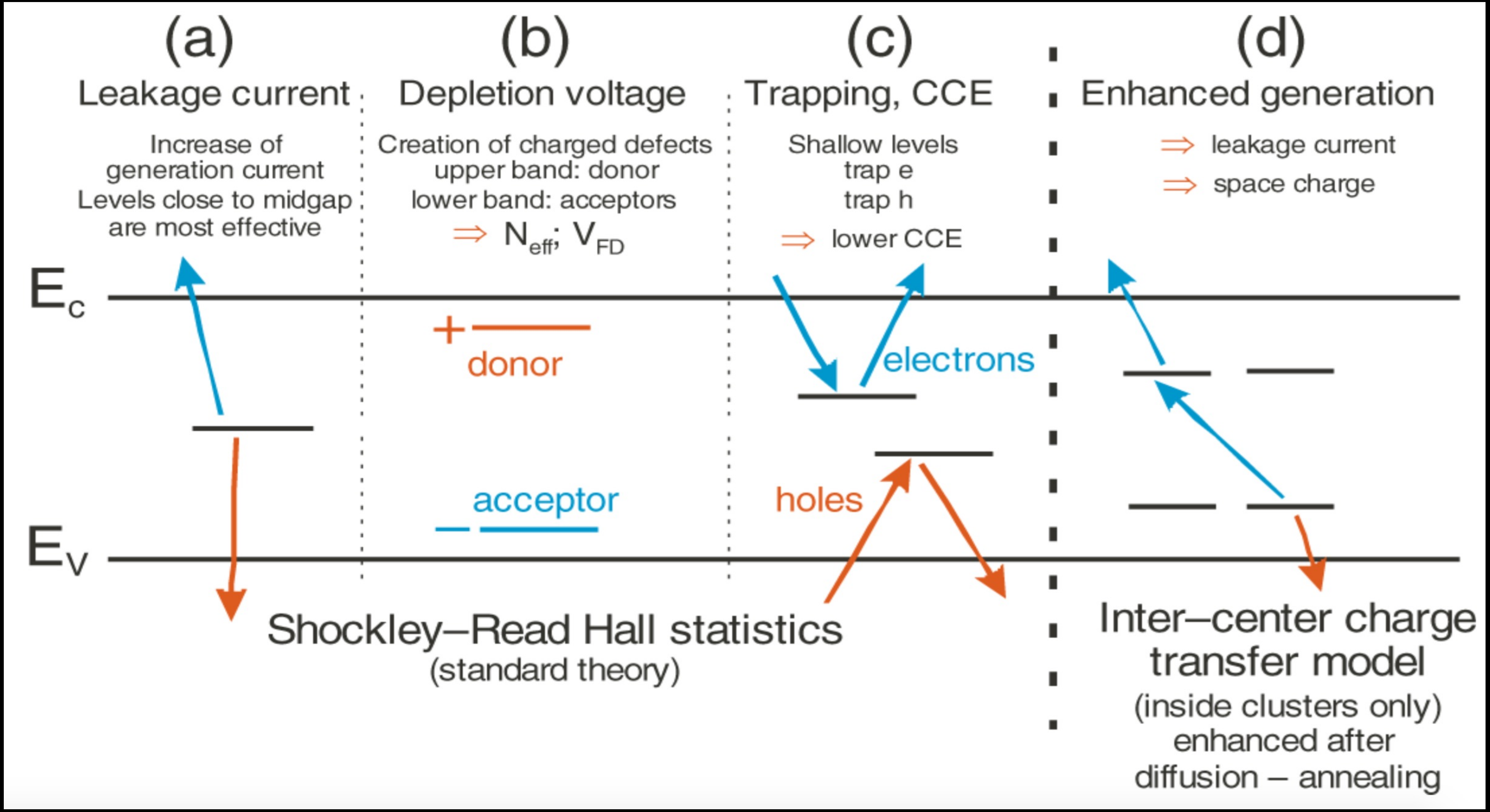
- Using the damage function one can define for each particle (radiation) a hardness factor .
- κ is the ratio of the irradiation damage of a particular particle compared to the irradiation damage due to flux of mono energetic 1 MeV neutrons :

$$\kappa = \frac{\int D(E)\,\Phi(E)\,dE}{D(E_{\text{neutron}} = 1\text{MeV})\int \Phi(E)\,dE}$$

- $D(E_n = 1$ MeV) is fixed to be 95 MeV mb.
- The integrated equivalent flux n_{eq}(1 MeV neutrons) can therefore be calculated as:

$$\Phi_{eq} = \kappa \cdot \Phi$$

Radiation effects (RD50)



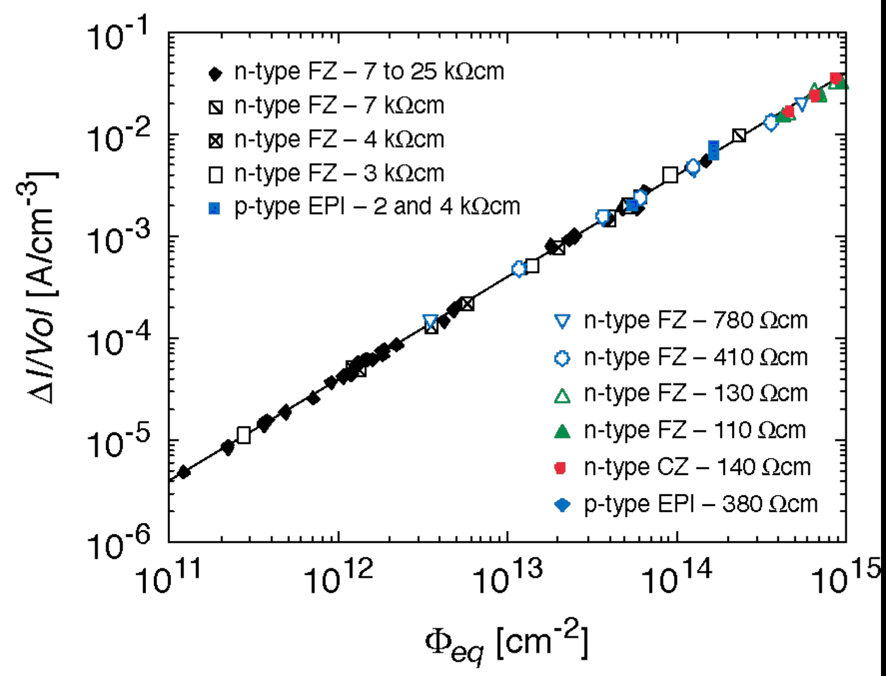
Leakage current increase

- Irradiation induced leakage current increases linear with the integrated flux:

$$\frac{\Delta I}{Vol} = \alpha \cdot \Phi_{eq}$$

- α is the current related damage rate.
- The current increase is due to production of generation-recombination centers in the semiconductor's bandgap.
  - It is largely independent of the material type.
  - Depends on temperature, the time between exposure to radiation and measurement (annealing).
  - $\alpha \approx 4 \cdot 10^{-17}$ A/cm.
  - Current measured after 80 min. annealing at 60 C

Leakage current causes stochastic noise in the amplifier. To maintain S/N you must operate the detectors cold. ATLAS pixel operates at -10 ºC, strips at 0 ºC

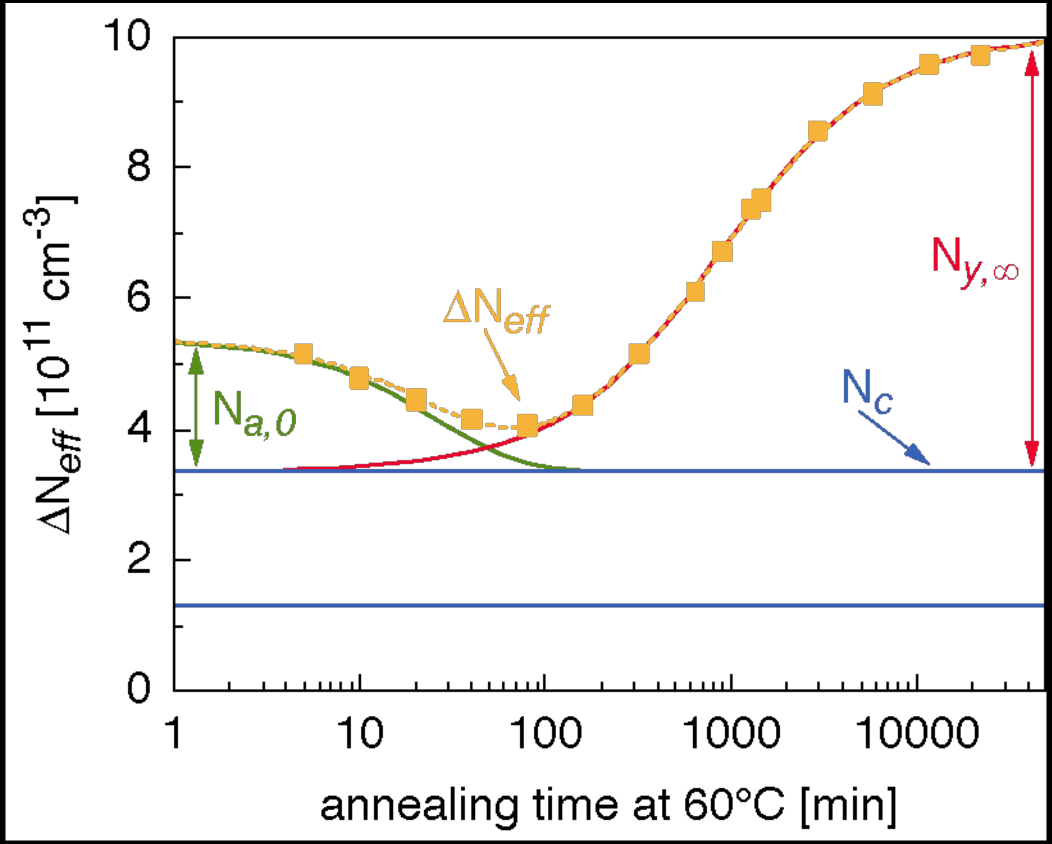


M. Moll, *Radiation Damage in Silicon Particle Detectors*, PhD-Thesis (1999)

In ten years of LHC operation the currents of the innermost layers increases by 3 orders of magnitude!

Changes in the effective dopant concentration

- $\Delta Neff\ (\Phi) = \Delta(N_{donor} - N_{acceptor}) = N_C + N_a + N_Y$ 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" insignificant after 2 days at room temperature
  - $N_Y = gY\Phi(1 - e^{-t/\tau(Y)})$: "reverse annealing." Its value begins at 0 for t = 0 and grows to saturate at $gY\Phi$ as t approaches ∞



G. Lindström, *Radiation Damage in Silicon Detectors*, NIM A **512**, 30 (2003)

- 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.

- Impact of the operating temperature of the LHC detectors
- An irradiated detector has to remain cooled down even in non operating periods

Type inversion

- Irradiation produces mainly acceptor defects and removes donor type defects.
- In a n-type silicon the effective doping concentration $N_{eff} = N_D - N_A$ decreases until it type invert (n type Si becomes p type Si)
- Then N_{eff} *and* $V_{depletion}$ increase linearly with the fluence

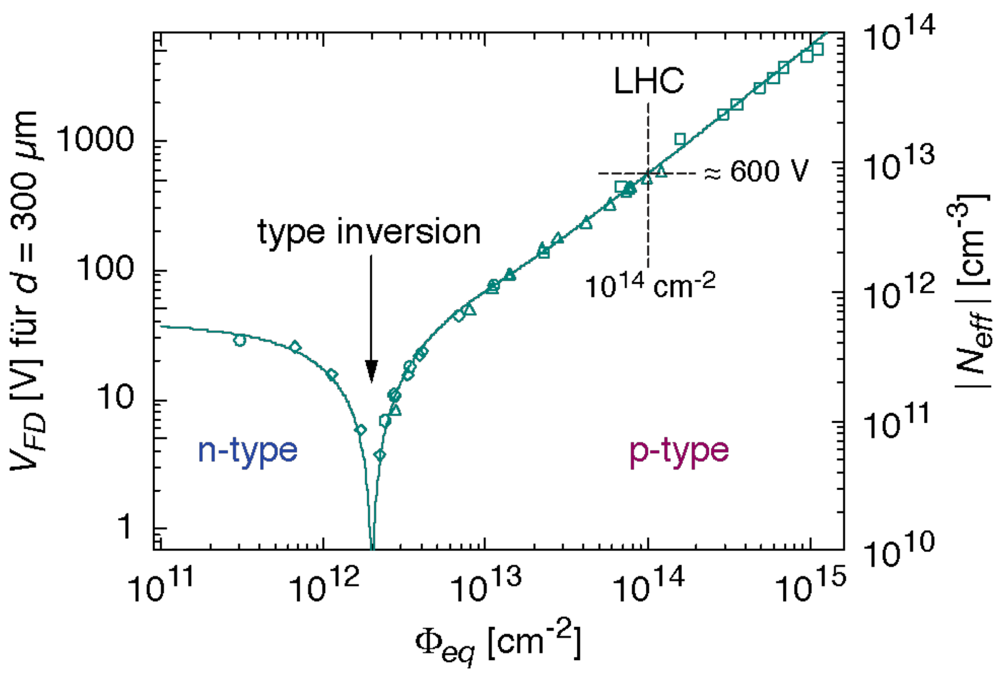
G. Lindström, *Radiation Damage in Silicon Detectors*, Nucl. Instr. Meth. A **512**, 30 (2003)

Initial n-type silicon

$$V_{\mathrm{FD}} \sim \frac{e}{2\varepsilon_0\varepsilon_r} N_D d^2$$

After irradiation

$$V_{\mathrm{FD}} = \frac{e}{2\varepsilon_0\varepsilon_r} |N_{eff}| d^2$$



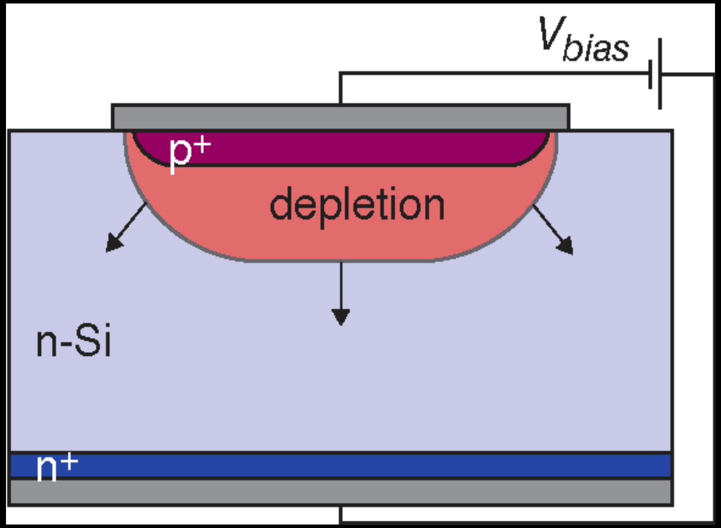
- V_{depl} and I_{eakage} both depend upon fluence Φ, so power consumption (heat generated) ~ fluence Φ^2.
- This has significant impact on cooling and power.

Operation before and after type inversion

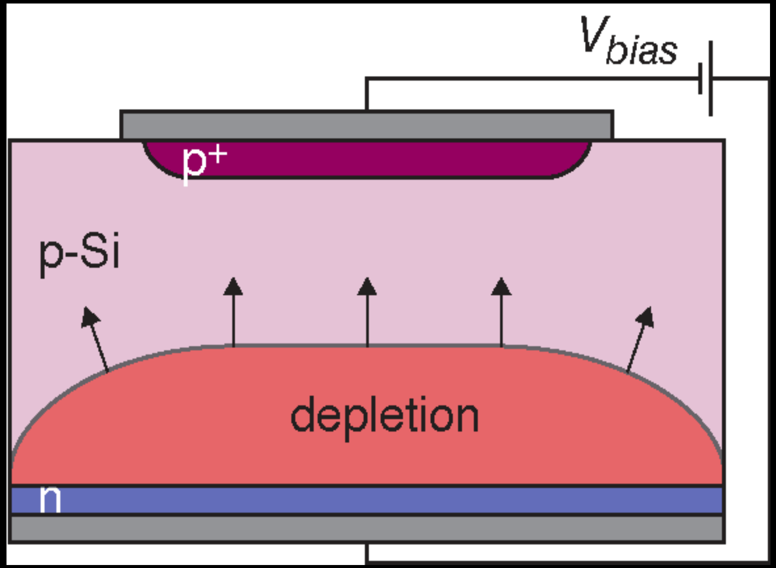
- “p-on-n” sensors (p implants n-bulk): depletion zone grows from the p-implants to to the backplane n-implant.
- These detectors can be operated underdepleted if necessary as the signal orming depletion region is always in contact with the segmented strips.

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

Unirradiated detector:



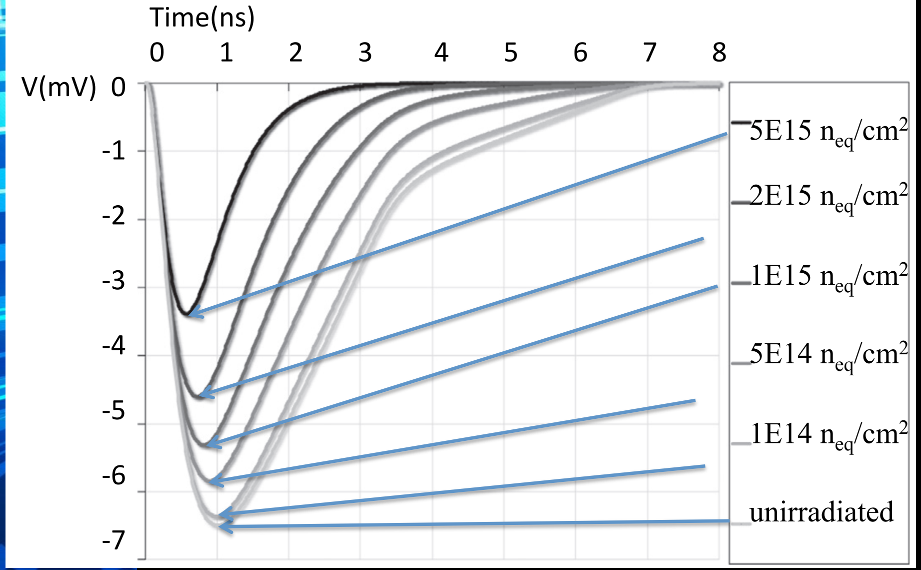
Detector after type inversion:



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

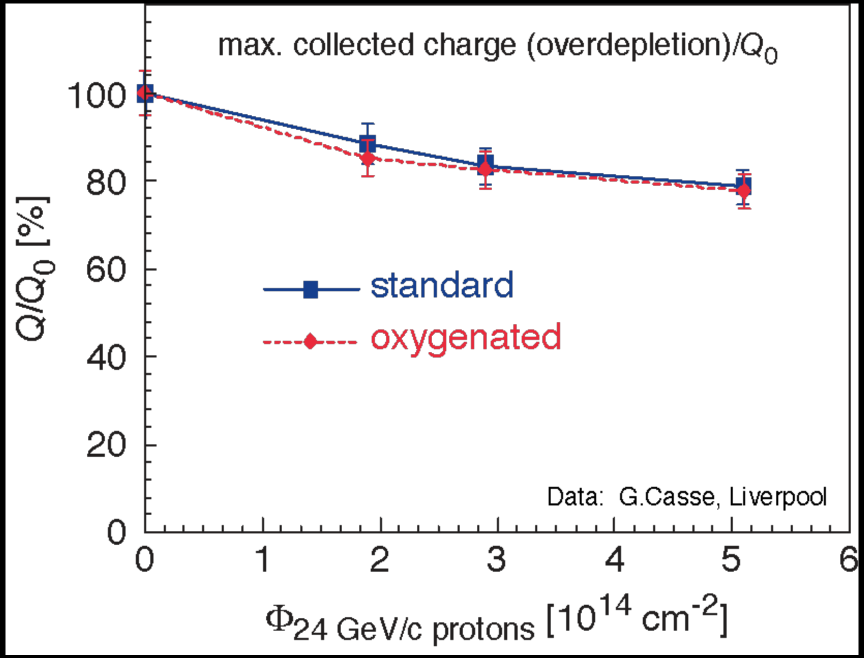
Charge collection efficiency

- Irradiation creates defects with energy levels deep inside the band gap that are as trapping centers.
- Charge carriers are trapped in these levels and are released after some time (depending on the depth of the energy level).
- Charges released with delay are not measured within the integration time of the electronics and the detector signal is reduced



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

Charge collection efficiency, detector irradiated with $5 \cdot 10^{14}$ protons/cm^2 (24 GeV). Within the readout time of 25 ns only 80% of the signal is observed:



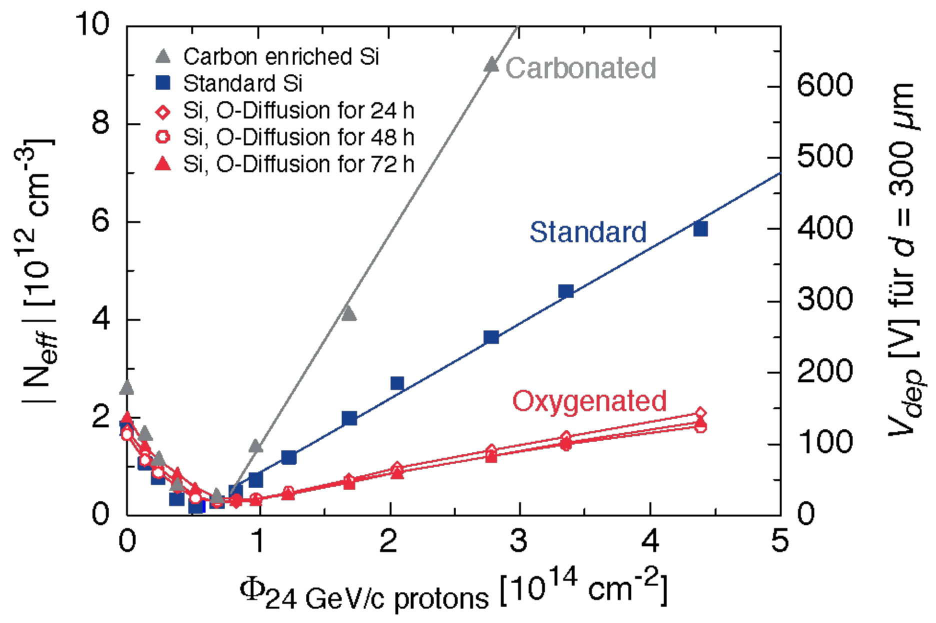
M. Moll, *Development of Radiation Hard Sensors for Very High Luminosity Colliders - CERN RD50 Project* VERTEX2002, Hawaii (Nov., 2002)

Overdepletion can compensates the reduced charge collection efficiency

Material engineering

- Introduction of impurity atoms, initially electrically neutral, can combine to secondary defects and modify the radiation tolerance of the material.
  - Silicon enriched with carbon makes the detector less radiation hard.
  - Oxygen enriched silicon (e.g. Magnet Czochralski Si) is more radiation hard with respect to charged hadrons (no effect for neutrons)

Irradiation with 24 GeV protons, no annealing

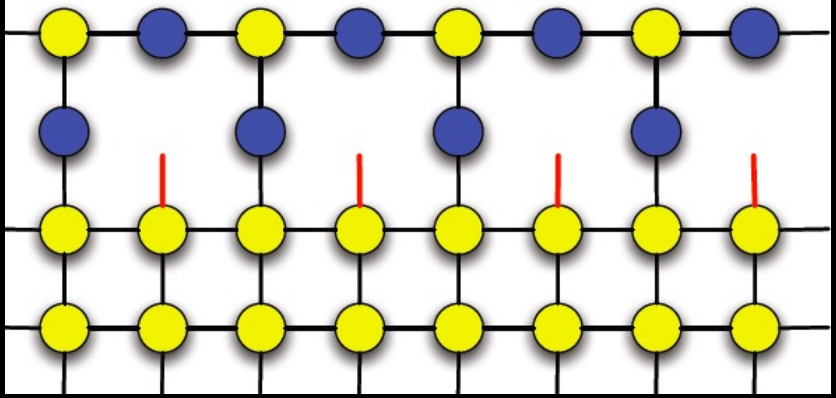


G. Lindström, *Radiation Damage in Silicon Detectors*, NIM A **512**, 30 (2003)

Oxygen enriched Si used for pixel detectors in ATLAS and CMS.

Ionizing damage

- Within the band gap of amorphous oxide (8.8 eV compared to 1.12 eV in Si) a large number of deep levels exist which trap charges for a long time.
  - The mobility of electrons in SiO_2 is much larger than the mobility of holes
  - Electrons diffuse out of the oxide, holes remain semi permanent fixed
- The oxide becomes positively charged due to these fixed oxide charge yielding
  - Reduced electrical separation between implants
  - Increase of interstrip capacitance
  - Increase of detector noise
  - Worsening of position resolution
  - Increase of surface leakage current

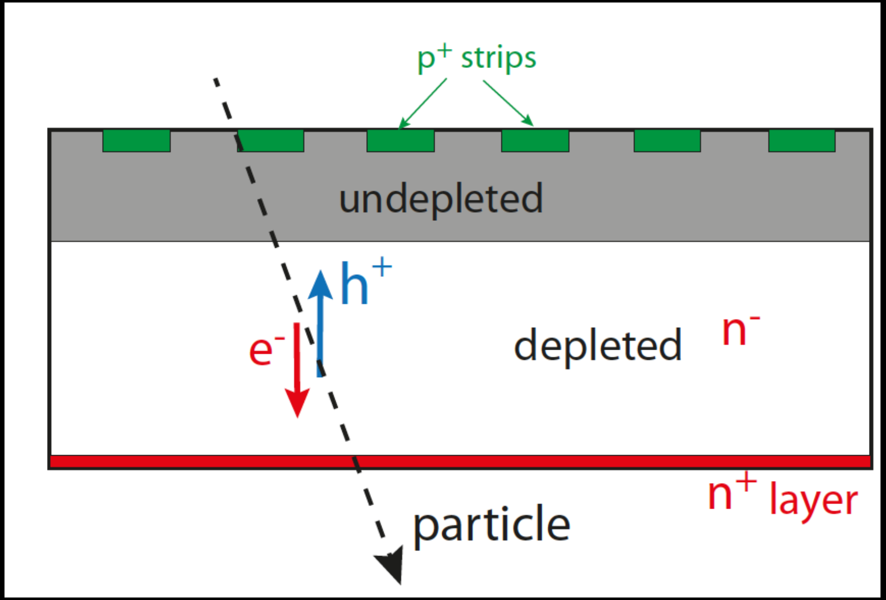


- Proportional to absorbed radiation dose
- 1 Gy = 1 J/kg = 100 rad = 10^4 erg/g (energy loss per unit mass)

Ionizing dose Affects both detector and electronics

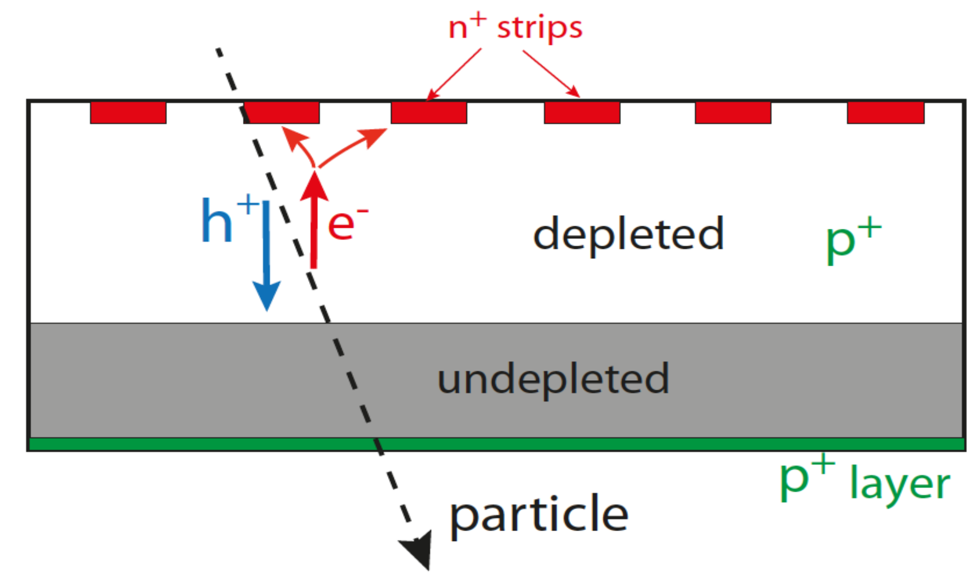
Silicon detectors for HL-LHC

- LHC and pre-LHC: p^+ in n



- Consequences:
  - signal loss
  - resolution degradation due to charge spreading

- For HL-LHC upgrade: n^+ in p

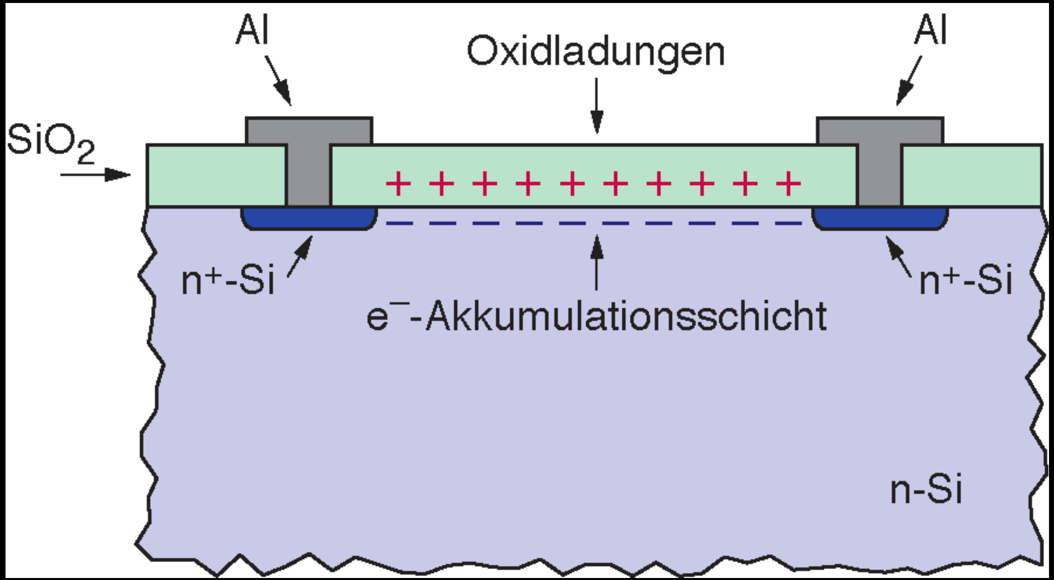


- Advantages:
  - faster charge collection (electrons have higher v_{drift})
  - Less signal and CCE degradation

p – type substrates used for both strips and pixels

n-side Isolation

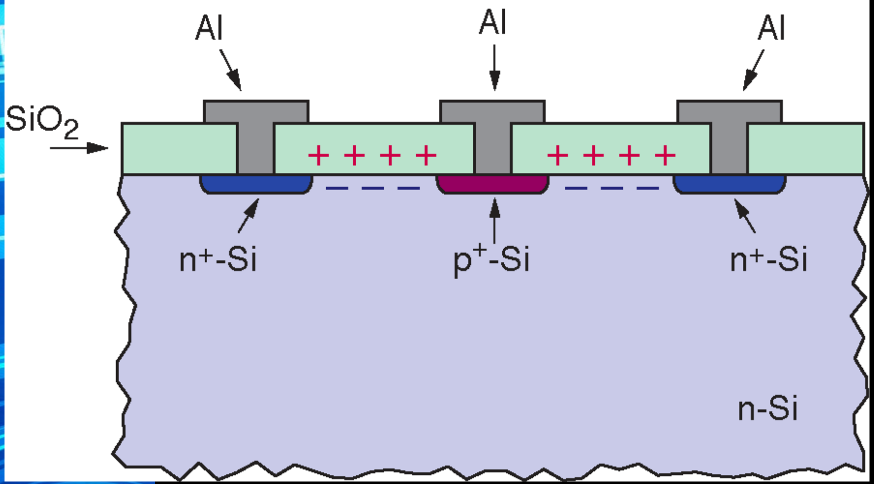
- Problem with n$^+$ segmentation:
  - Layer of static, positive oxide charges in the Si-SiO$_2$ interface.
  - These positive charges attract electrons forming an accumulation layer underneath the oxide.
  - n$^+$ strips are no longer isolated from each other
  - Charges generated by through going particle spread over many strips and no position measurement possible.
  - Interrupt accumulation layer using p$^+$-stops, p$^+$-spray or field plates.



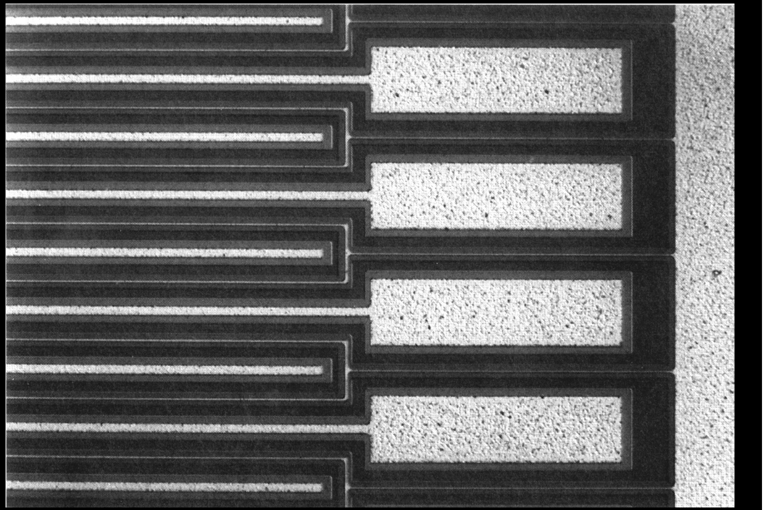
Critical for pixel –detectors at the LHC which have n+ implants on n-silicon

p^+-stops

- p^+-implants (p^+-stops, blocking electrodes) between n^+-strips interrupt the electron accumulation layer.
- Interstrip resistance reaches again GΩ.



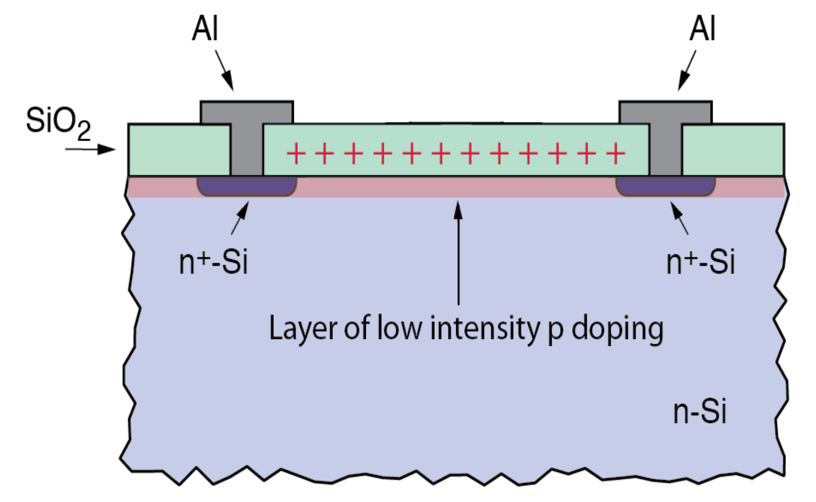
A. Peisert, *Silicon Microstrip Detectors*, DELPHI 92-143 MVX 2, CERN, 1992



J. Kemmer and G. Lutz, *New Structures for Position Sensitive Semiconductor Detectors*, Nucl. Instr. Meth. A **273**, 588 (1988)

p-sprays

- p doping as a layer over the whole surface which disrupts the e^- accumulation layer.



- A combination of p-stops and p-spray can also be used