Introduction to silicon tracking detectors

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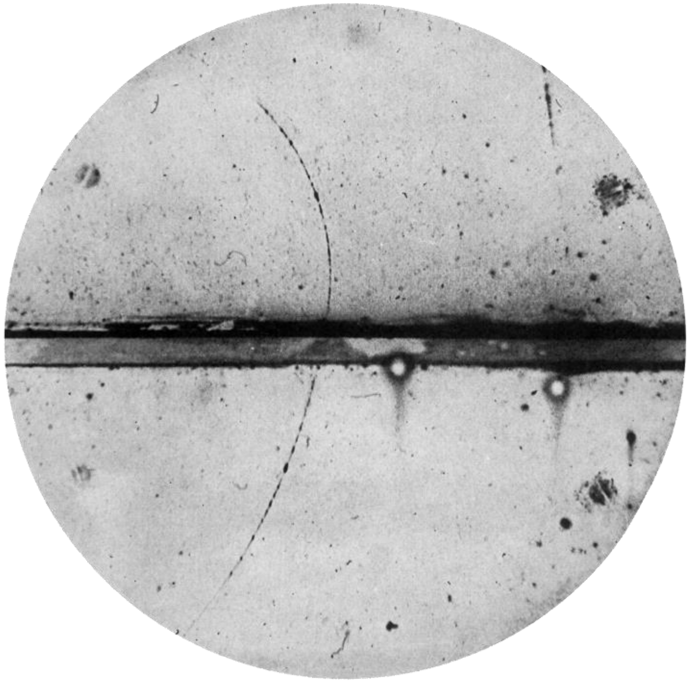
Introduction



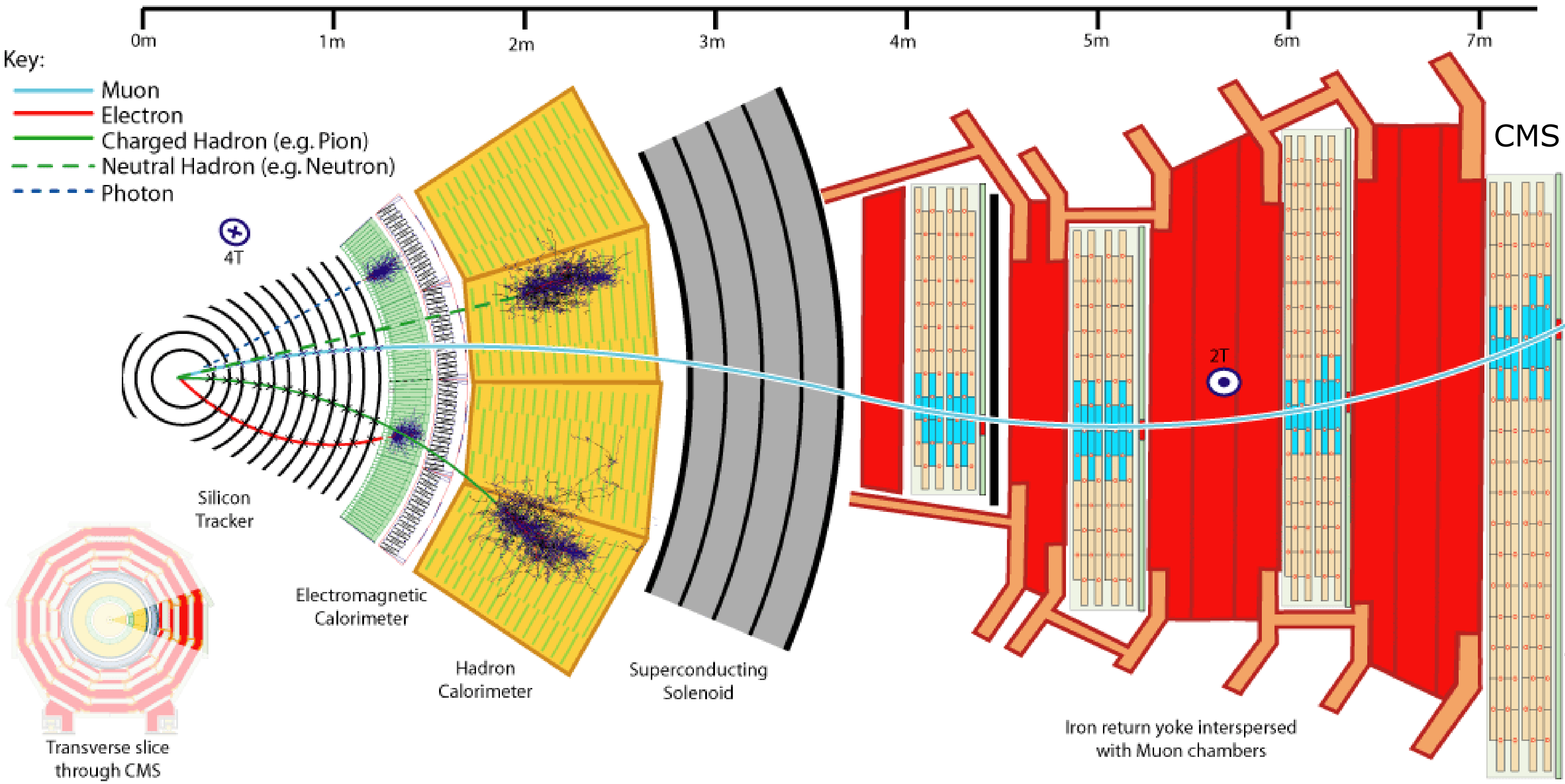
Positron discovery
In cloud chamber
Carl Anderson 1932

Energetic charged particles loose energy by ionizing the medium they are traversing

- Cloud chamber: Ions seed condensation of supersaturated vapor

In silicon we use the same principle but directly measure the charge created by ionization

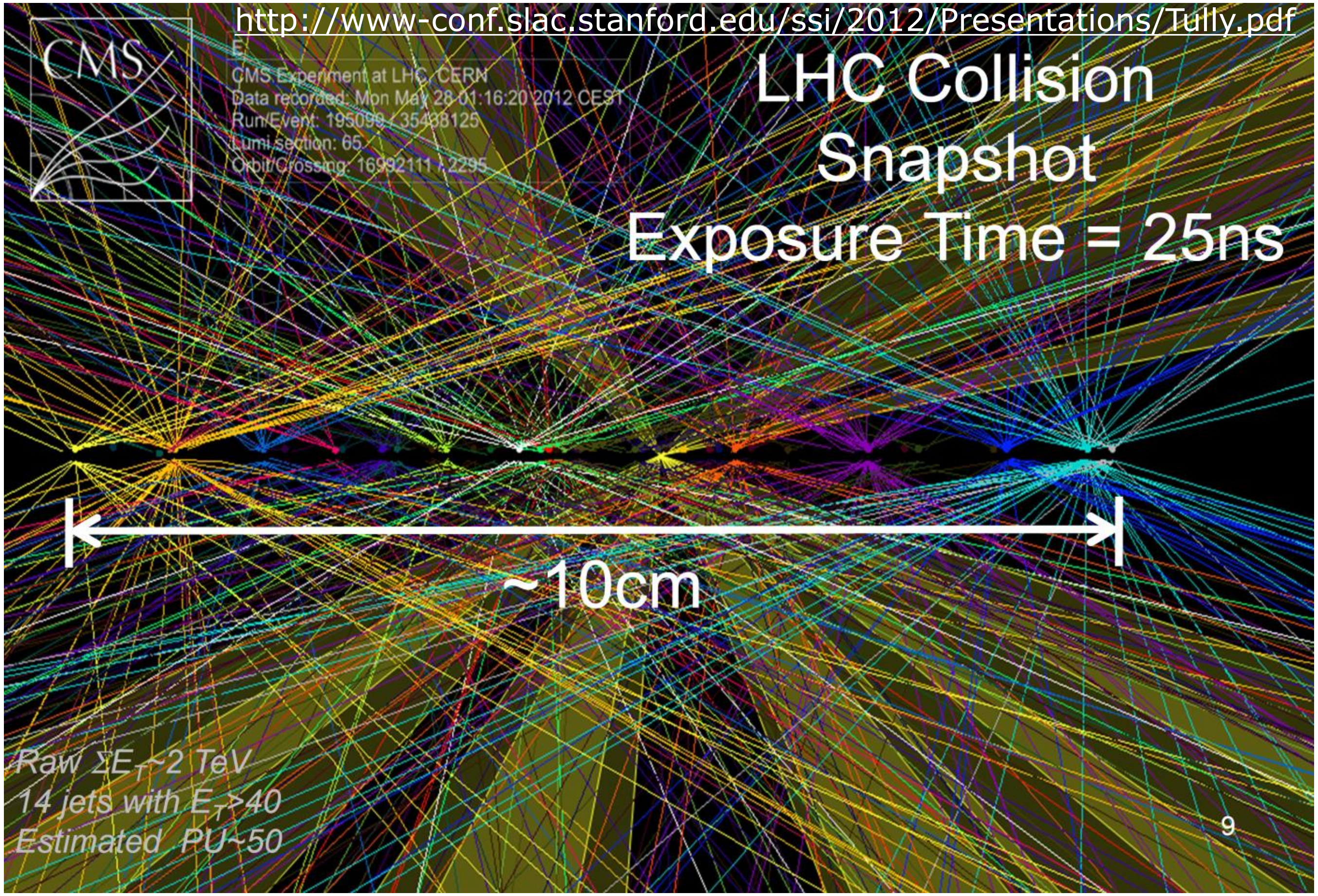
Introduction
Collider experiments



Vertex detectors (trackers) are located around the interaction point of collider experiments

- Most widely used material for trackers is silicon

Introduction
Requirements for high luminosity trackers



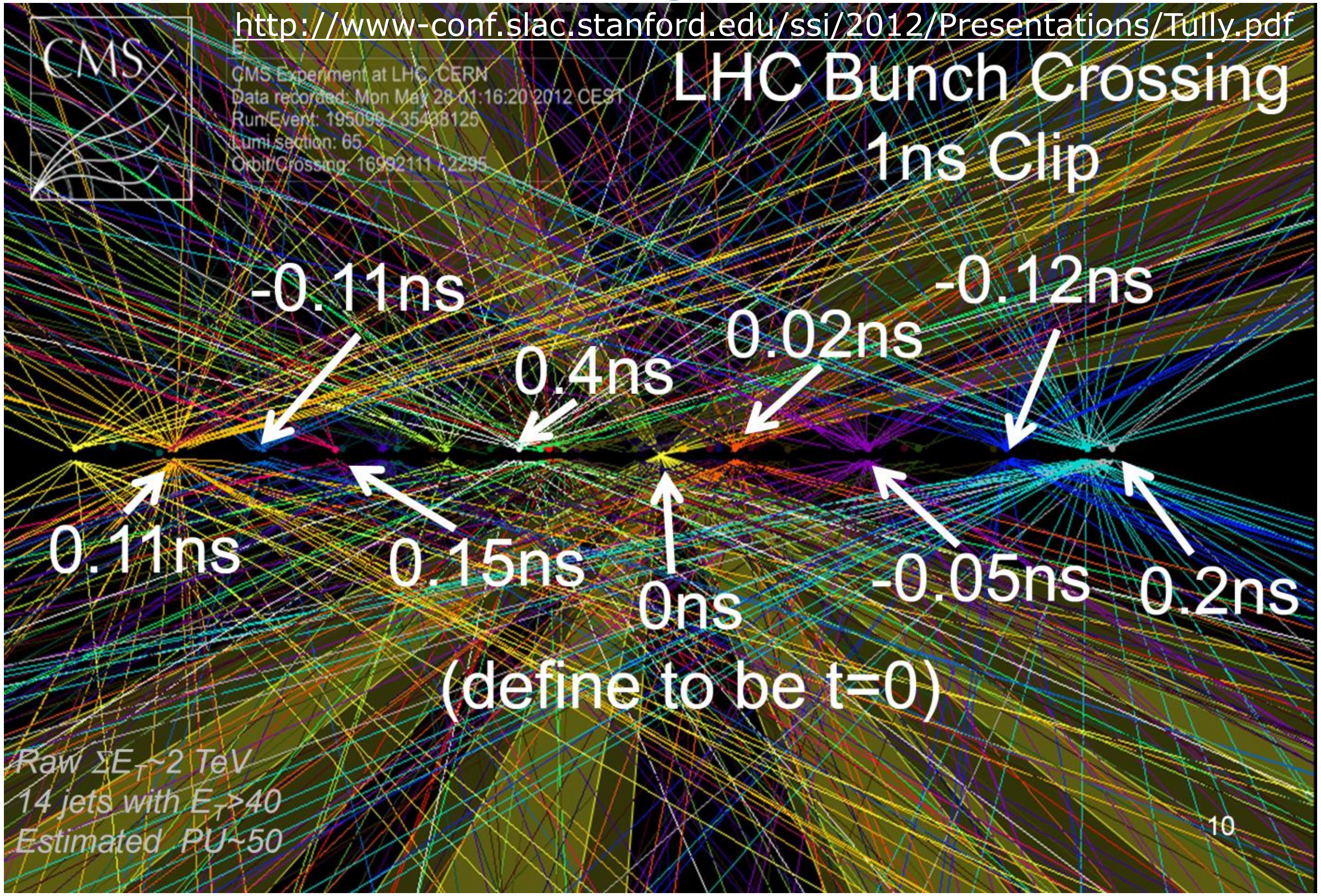
CMS event display w/ 50 pile-up events

HL-LHC: ~200 primary vertices per bunch crossing (pile-up)

In order to assign tracks to primary and secondary vertices we need

- Good spatial resolution (ATLAS: ~10 μm rφ)
- High granularity (down to 25 μm channel pitch)

Introduction
Requirements for high luminosity trackers

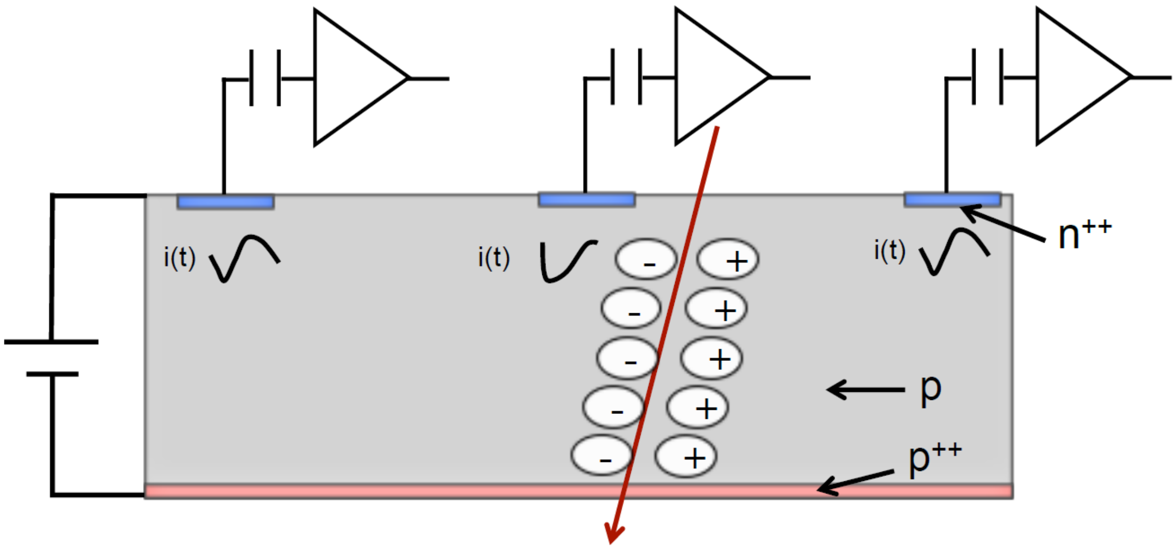


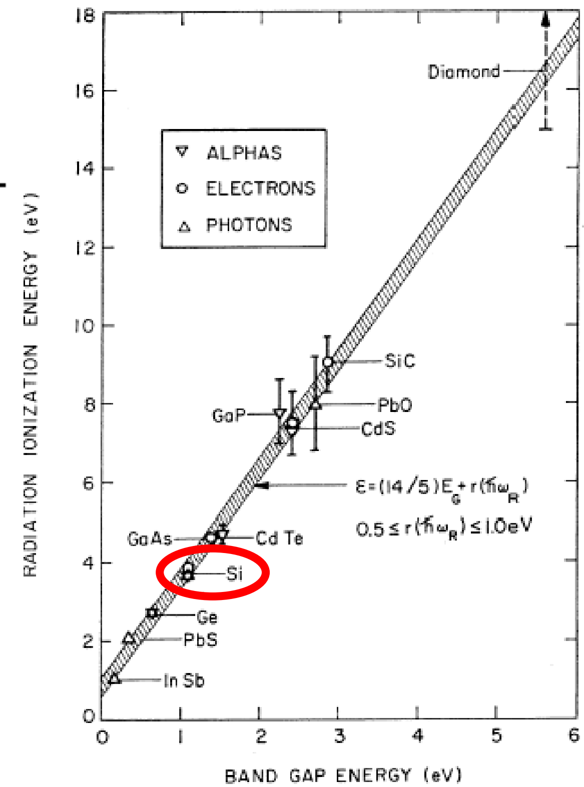
CMS event display w/ 50 pile-up events

Vertex reconstruction for high pile-up can be improve with timing detectors (“4D tracking”)

- Timing resolution of 20-30 ps would improve reconstruction

Silicon sensors
The ionization chamber



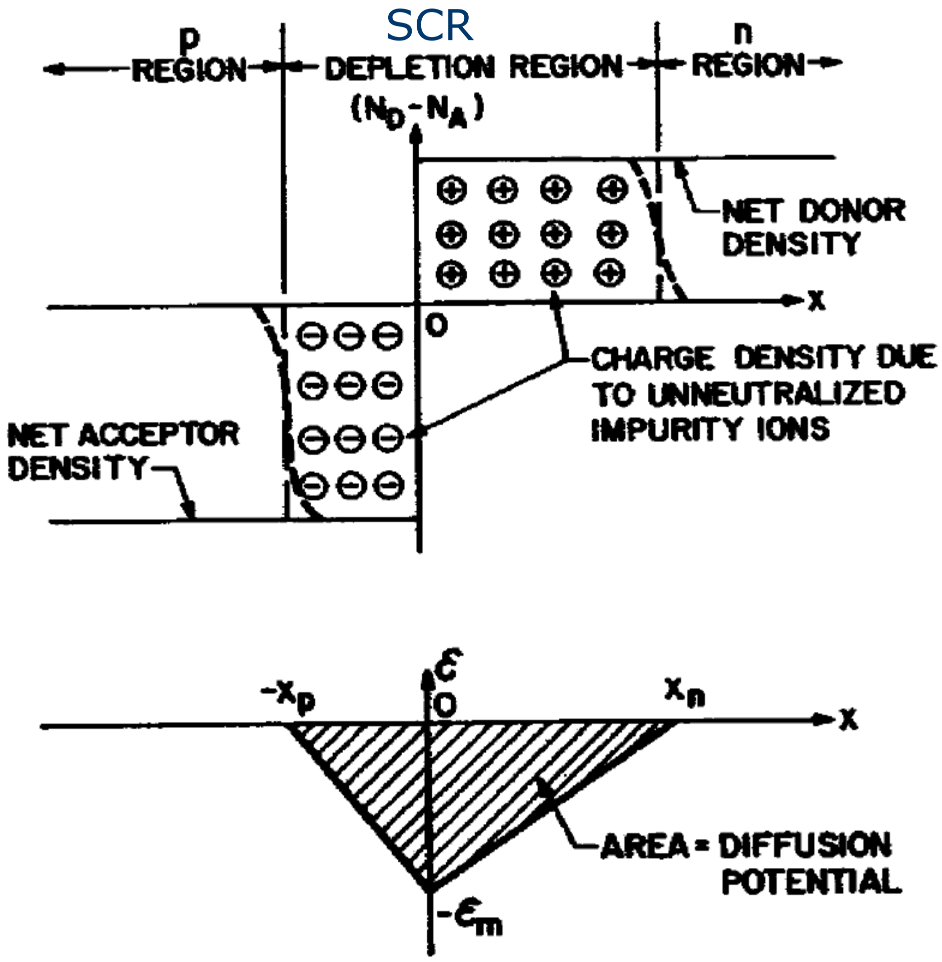


Ionizing particles create free electron-hole pairs in semiconductor which drift to electrodes in applied el. field

Why silicon?

- Low ionization energy: 3.6 eV/e-h, ~80 e-h/µm
- Fast signals: 100 µm/ns saturation velocity
- Availability of Si (8 km² wafers/yr) and technology!

Signal formation in silicon pn junction



Intrinsic Si carrier density

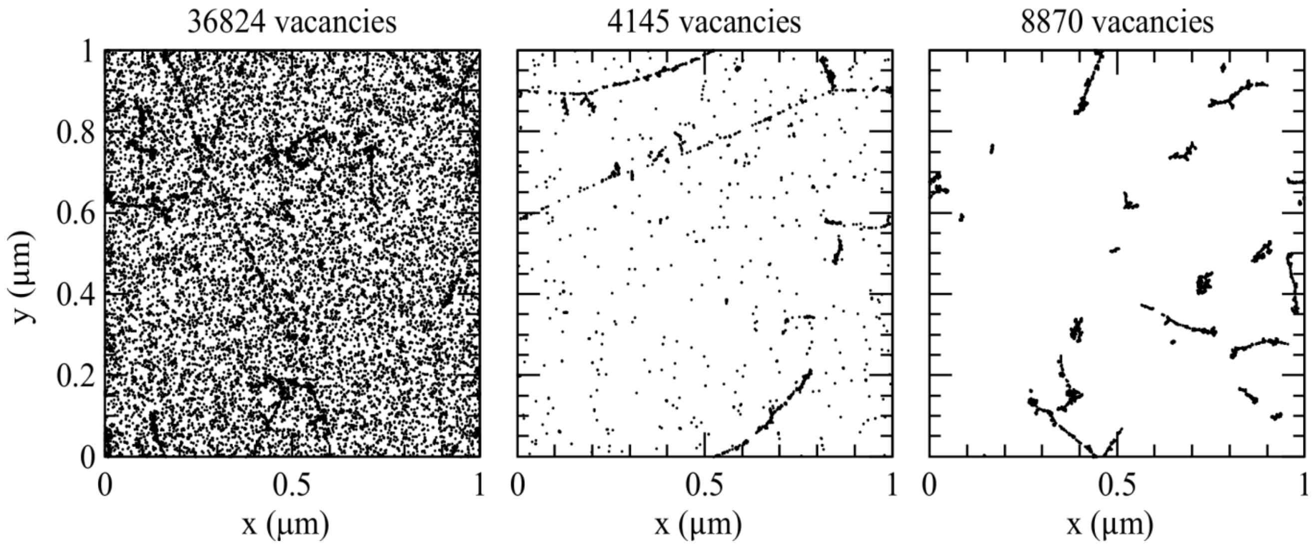
- $n = p = n_i \sim 10^{10}$ cm^{-3}

pn junction:

- Recombination of e and h leaves space charge region SCR
- Reverse bias leads to larger SCR
- SCR has high el. field and a very low free carrier density $n, p \ll n_i$

Ideal to use as low noise detection volume!

Radiation damage in silicon
Defect creation

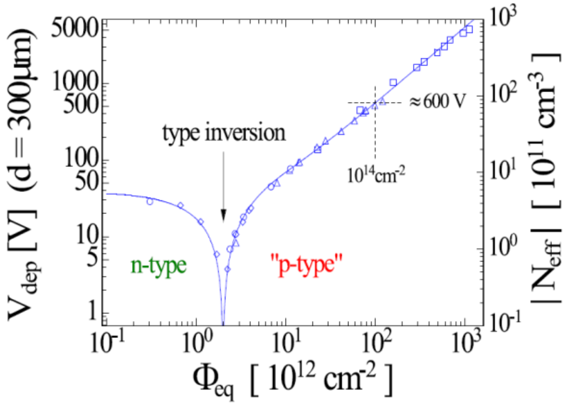


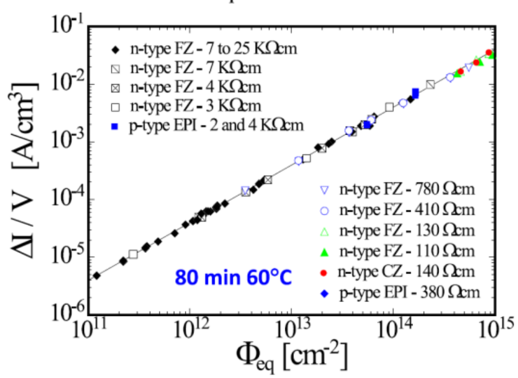
10 MeV p | 24 GeV p | 1 MeV n

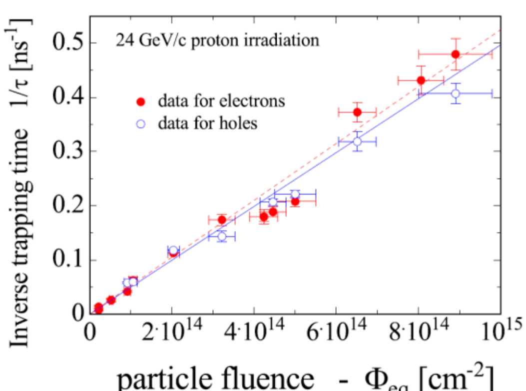
Energetic particles can knock atoms from their lattice position

- Cross section strongly depends on particle type and energy
- Knock-on atom forms Frenkel pair (vacancy-interstitial)
- Frenkel pairs are mobile in the lattice and can recombine or form new defects
- High energy knock-on atoms can create cluster defects with modified lattice

Radiation damage in silicon
Effects on sensor operation







Most significant effects of radiation-induced defects are

Change of the effective doping concentration

- N_D decreases over time
- N_A first decreases and then increases
- Type inversion n→p
- Loss of gain

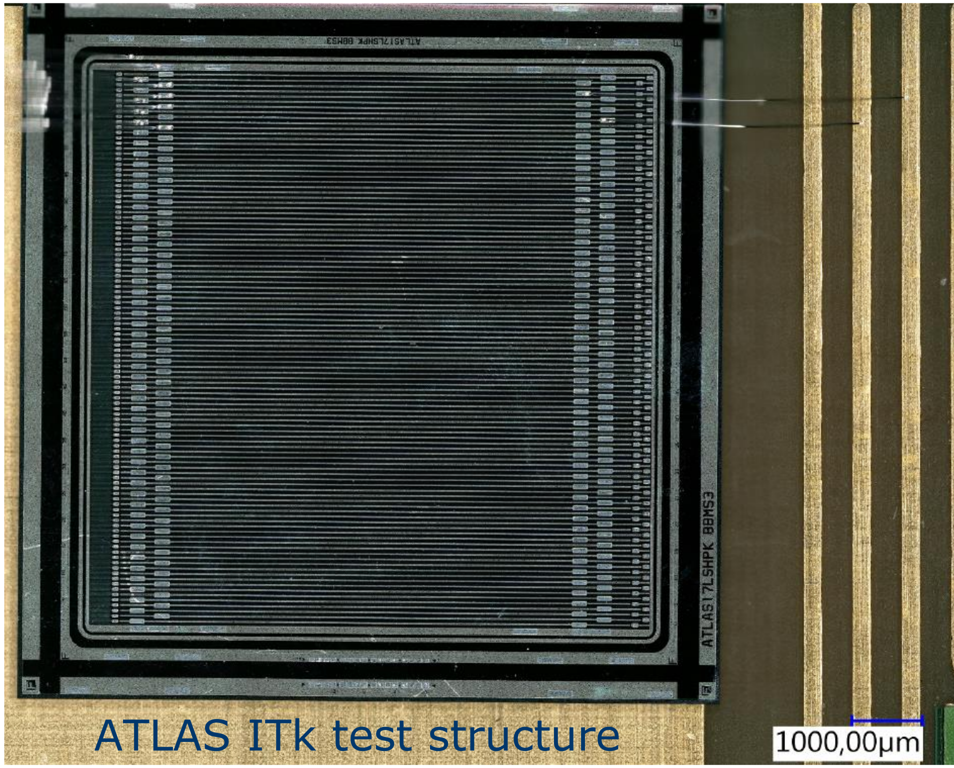
Increase of thermal carrier generation

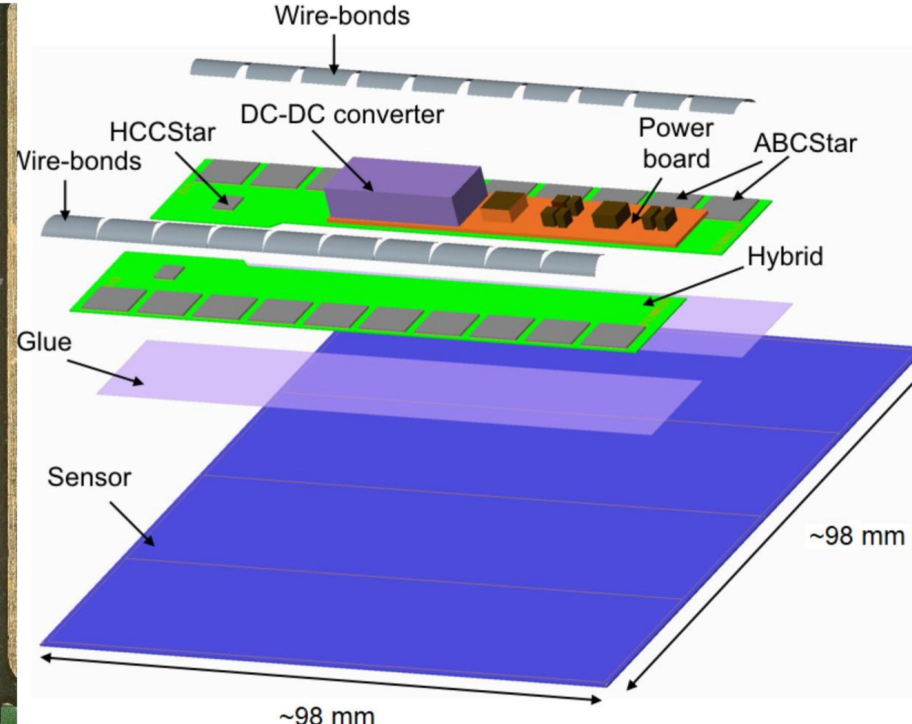
- Current in SCR increases
- Heats the sensors

Trapping of free carriers

- Carriers can only drift for short time
- Signal decreases

Silicon detectors
Strip sensors





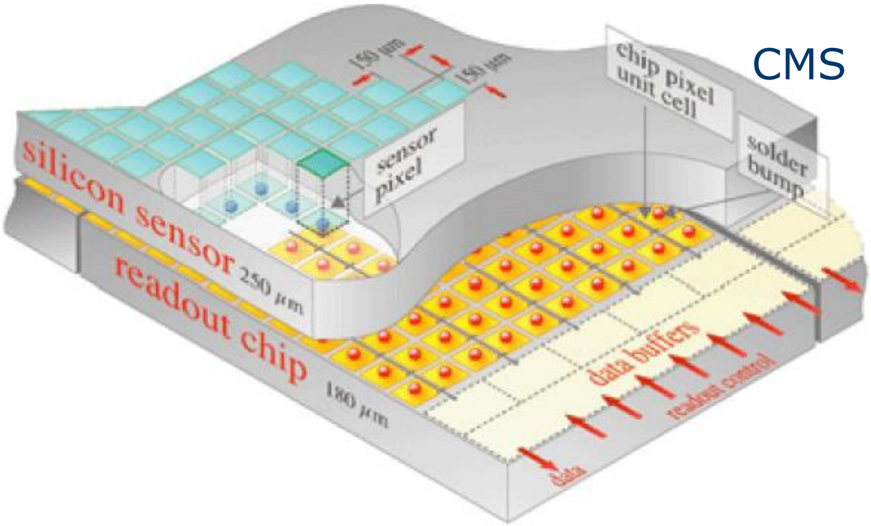
ATLAS ITk strip module

- Mainly used for outer trackers volume w/ $\Phi_{eq} < 10^{16}$ cm^{-2}
- Sandwiched strip sensors with stereo angle can provide x-y tracking
- Read out by ASICs glued on sensor

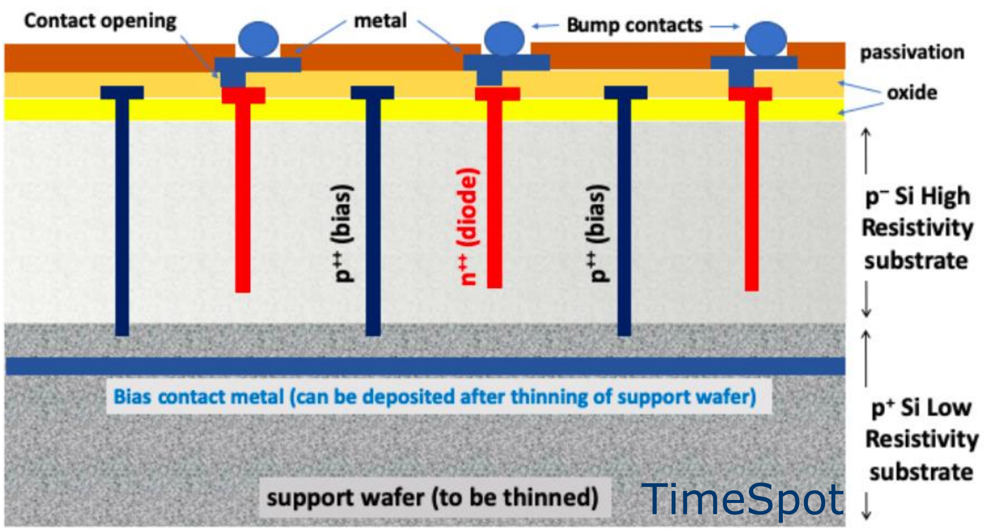
Pros: Proven technology, high spatial resolution, large area, less channels

Cons: Suffers from oxide damage, complicated wire bonding, thick sensors

Silicon detectors
Pixel sensors



CMS

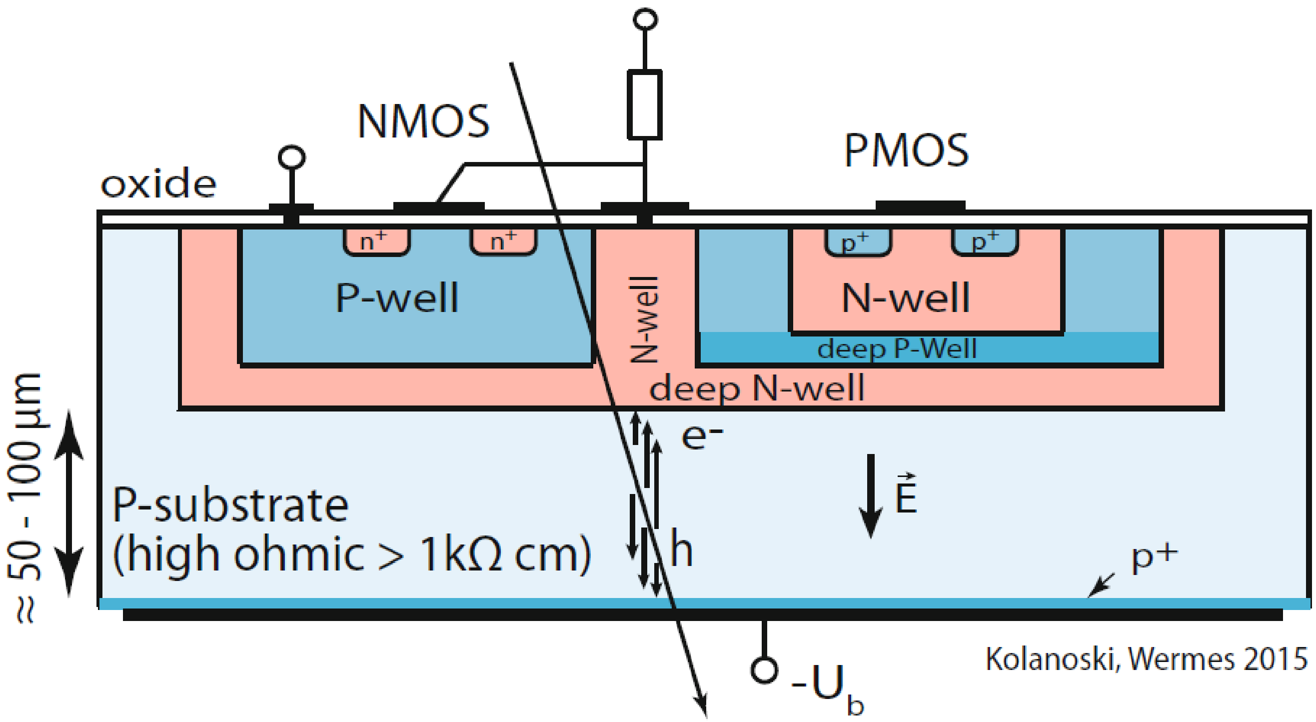


TimeSpot

- Mainly used for inner tracker volume w/ $\Phi_{eq} > 10^{16}$ cm^{-2}
- Pixel matrix directly provides x-y tracking
- Read out by ASICs bump bonded to sensor

Pros: High granularity, very good radiation hardness (3D), thin
Cons: Complicated bump bonding, expensive, small sensors

Silicon detectors
CMOS monolithic sensors



- Mainly used for inner tracker volume w/ $\Phi_{eq} < 10^{15}$ cm^{-2}
- Pixel matrix directly provides x-y tracking
- Read out ASICs integrated in sensor

Pros: High granularity, very thin, flexible, fully integrated
Cons: Difficult to achive full depletion, medium rad. hard, small die size

Summary

Silicon sensors are very versatile for vertex detectors

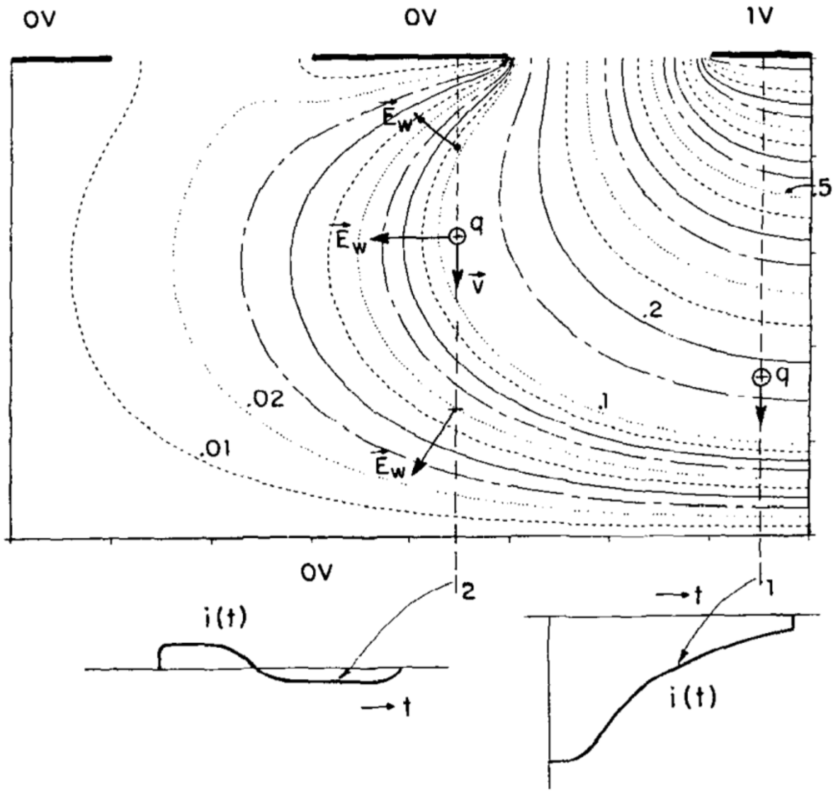
Silicon helps to achieve

- Good spatial resolution → few μm
- Large detector areas → 600 m² silicon CMS HGCAL
- Very high granulatrity → <25 μm pitch
- Thin sensors (50 μm) → low radiation length
- Extremely radiation hard → up to $\Phi_{eq} \sim 5 \cdot 10^{16}$ cm^{-2}
- Very fast signals → down to 20 ps timing capability

Currently the main trends towards faster timing detectors, monolithic sensor, 3D sensors, and sensors with gain

Backup

Signal formation in silicon
Weigthing potential



Weigthing potential in thin strip sensor

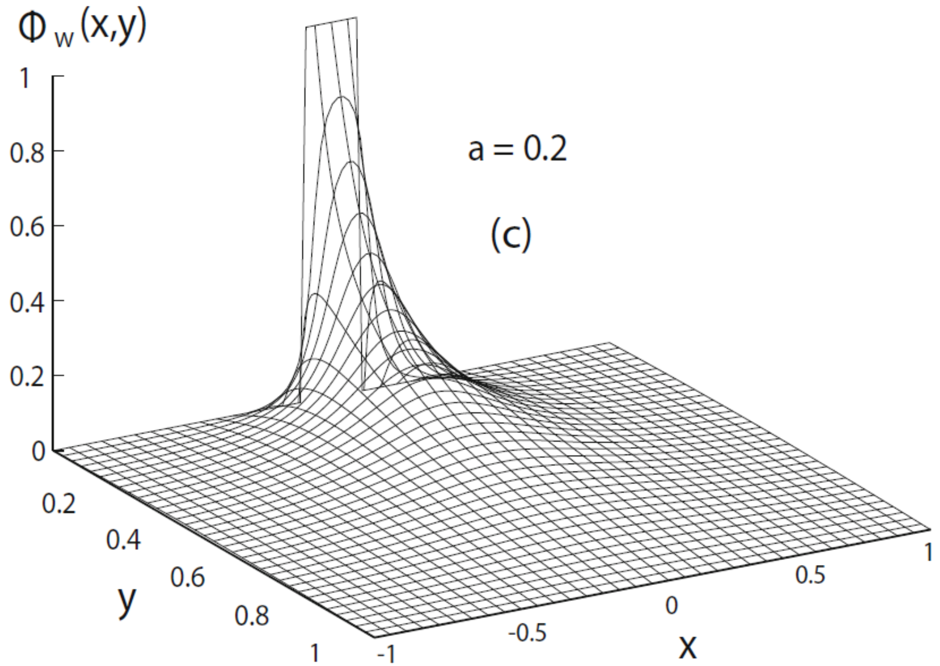
Signal current induced in rightmost strip

Drifting charge carriers induce mirror charges in electrodes and the current induced in an electrode is

$$I = q\overrightarrow{E_w}\vec{v}$$

- Drift near backside ($\Phi_w \rightarrow 0$) hardly contributes to signal
- We want to maximize $\overrightarrow{E_w}\vec{v} = \overrightarrow{E_w} \cdot \mu(\vec{E})\vec{E}$

Signal formation in silicon
Ramo theorem



Kolanoski, Wermes 2015

Weigthing potential
in typical strip sensor

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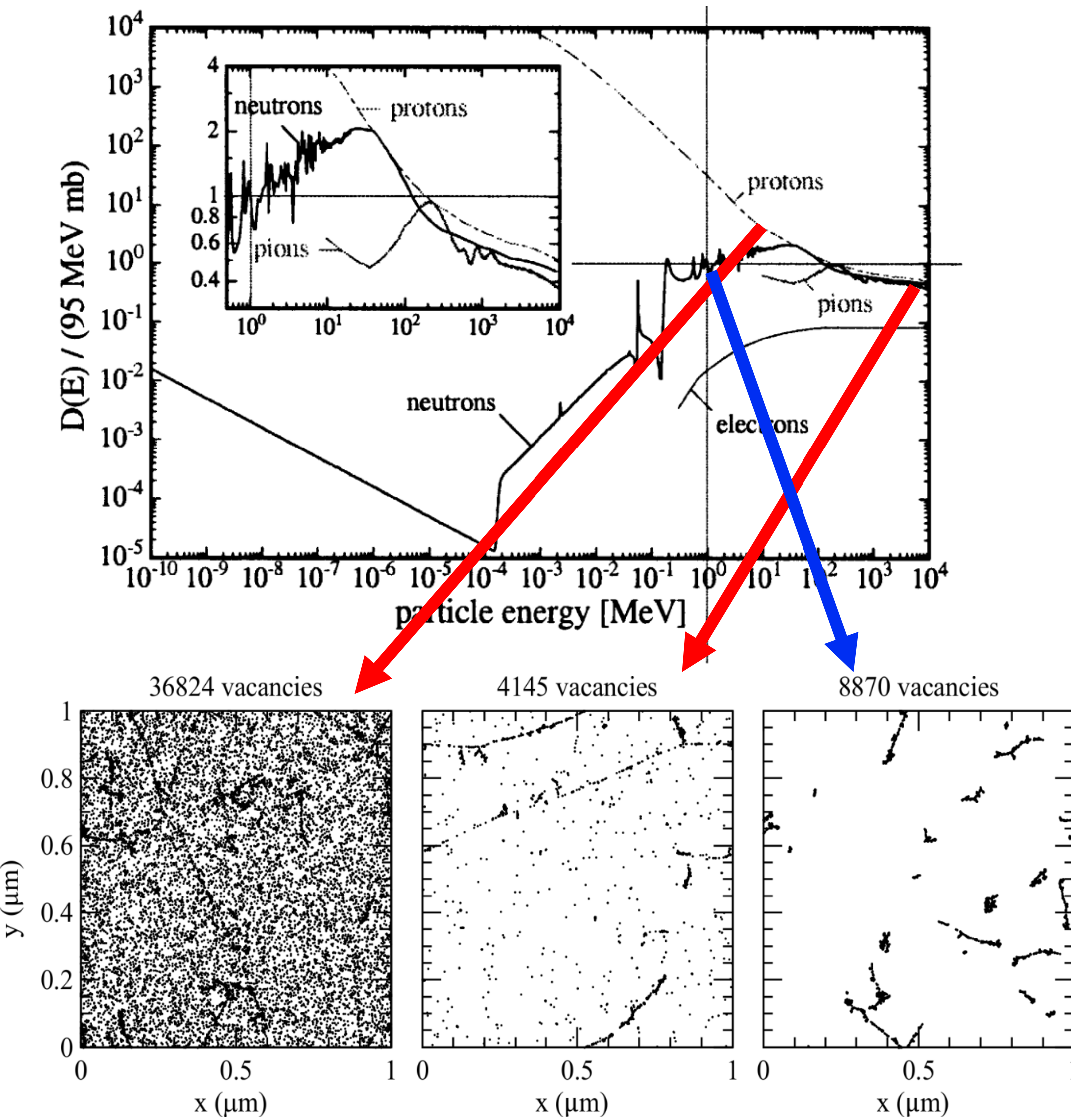
Radiation damage in silicon
Defect creation



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