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Introduction to Silicon Detectors

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Outlook

- Introduction to physics of Si and detection
- Examples of detectors
- Radiation effects and system issues
- Conclusions

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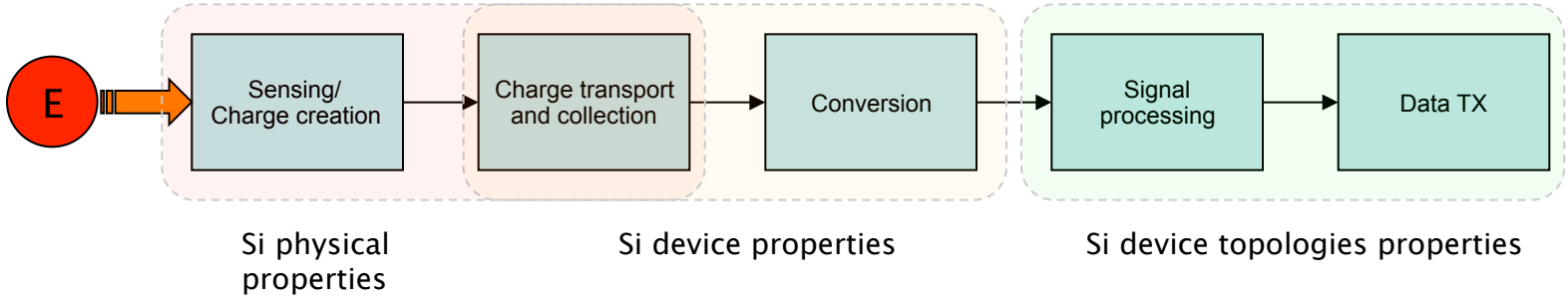
Introduction

The Si detection chain



all the boxes of the detection chain process based upon Silicon

Detector physics:
Silicon physical and electrical properties
Detection principles
Transport mechanisms
Conversion

Detector examples:
Strips, pixels
MAPS
ATLAS SCT

Detector system issues:
Detection efficiency
Power

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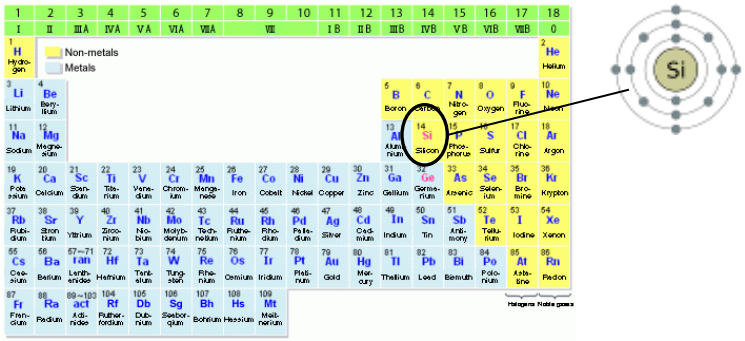
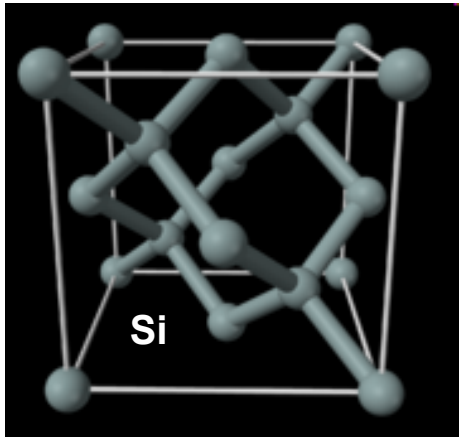
Silicon properties



After Oxygen, Silicon is the 2nd most abundant element in Earth's crust (>25% in mass)

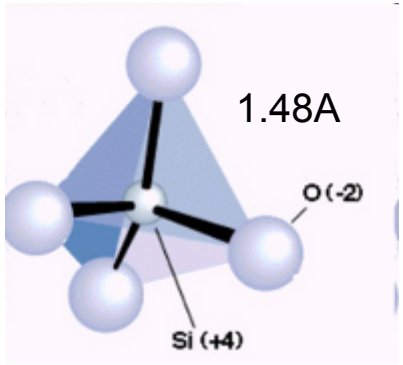


The crystalline structure is diamond cubic (FCC), with lattice spacing of 5.43 A

•Polysilicon consists of small Si crystals randomly oriented; in α-Si there is no long range order.

Apart from its abundance, that makes it also cheap, the key to success of Si is related to its oxide SiO_2, an excellent insulator (BV ~ 10^7 V/cm).

*Micro crystals but the flexible bond angles make SiO_2 effectively an amorphous: its conductivity varies considerably (charge transport in SiO_2 via polaron hopping between non-bonding oxygen 2p orbitals)



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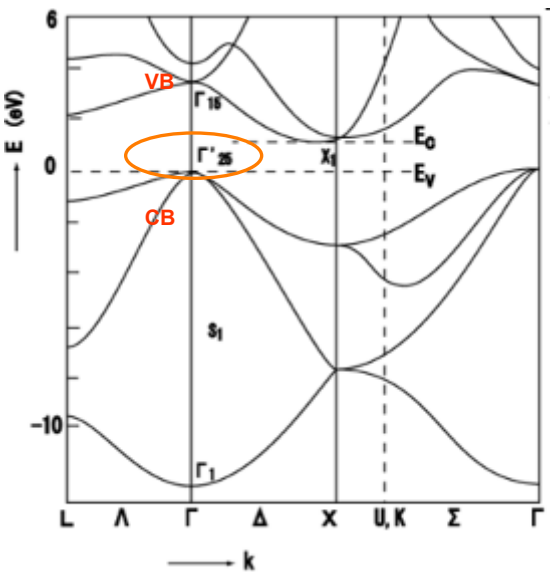
Silicon electrical properties

Silicon Band structure

The electronic band structure can be obtained by solving many-body SE in presence of periodic potential of the crystal lattice: (normally 1 electron SE in periodic potential neglecting electron interactions) : Bloch functions

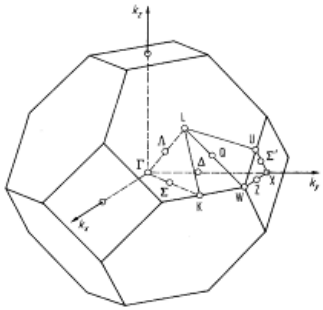
$$(T+U)\psi = E\psi \Rightarrow \psi_{n,k}(r) = u_{n,k}(r)e^{jk\cdot r} \mapsto E_n(k)$$

~ a wave associated with free motion of electrons modulated by the periodic solution $u_{n,k}$. The energy E is periodic in k so is specified just within the 1st unit WS cell of the reciprocal lattice (the Brillouin zone).



➔The appearance of Band Gap, separating CB and VB

➔The 6 CB minima are not located at the center of 1st Brillouin zone, INDIRECT GAP



1st Brillouin zone of Diamond lattice

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Silicon electrical properties

The detailed band structure is complicated: usually quasi-equilibrium simplifications are sufficient to study the charge transport.
Assuming that the carriers reside near an extremum, the **dispersion relationship E(k) is almost parabolic**:

$$E(k) = \frac{\hbar^2 |k|^2}{2m_0^*} \rightarrow g(E) = \frac{(2m_0^*)^{3/2}}{2\pi^2\hbar^3}\sqrt{E - E_o}$$

$$E(k) = \frac{\hbar^2 |k|^2}{2m_0^*} \rightarrow \langle v \rangle = \frac{1}{\hbar}\nabla_k E(k) = \frac{\hbar k}{m_0^*} = \frac{\langle p \rangle}{m_0^*}$$

$$\hbar \frac{dk(t)}{dt} = \hbar \frac{d\langle p \rangle}{dt} = \langle -\nabla_r V \rangle \cong F$$

➔Under the assumptions of small variation of the electric field, the carrier dynamics resembles that one of a **free particle**, with appropriate simplifications.
➔The **effective mass approximation** takes into account the periodic potential of the crystal by introducing an effective carrier mass (averaged over different longitudinal and transverse masses) . The lower the mass, the higher mobility ($\mu \propto 1/m^*$)

A similar approach is used to calculate the E(k) for phonons.

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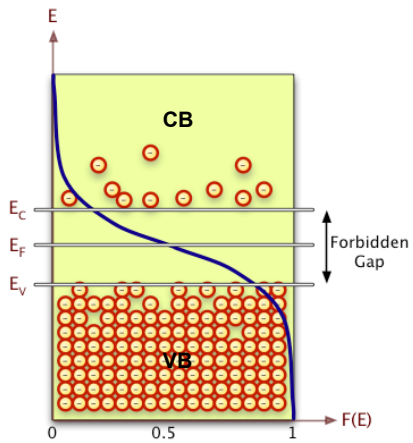
Silicon electrical properties



The **carrier density** is calculated from:

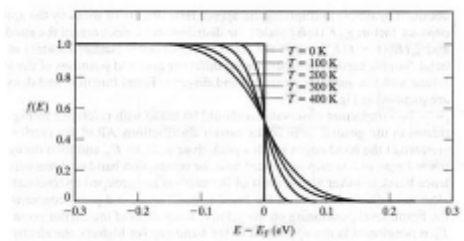
- The density of states g(E), which depends on dimension;
- The distribution function F(E);

Only partly filled bands can contribute to conduction: carrier density in CB and VB.
At equilibrium the carrier density is obtained by integrating the product:

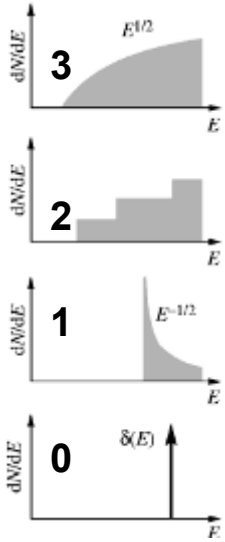
$$n_D = \int g_D(E) F(E) dE \cong N_{C/V} e^{-(Ec-Ev)/kT} = n_i = p_i$$

$$F(E) = \frac{1}{1 + \exp\left(\frac{E - E_F}{kT}\right)}$$

$$pn = n_i^2 = N_C N_V e^{-(E_g)/kT} \cong 10^{20} \quad @\, T = 300K$$



*Fermi level: energy level @ 50% occupancy



The density of states $g_D(E)$ depends on the dimension

In intrinsic Si a creation of e in CB leaves behind a hole in VB, that can be treated as an e with positive charge and mobility of the band where it resides

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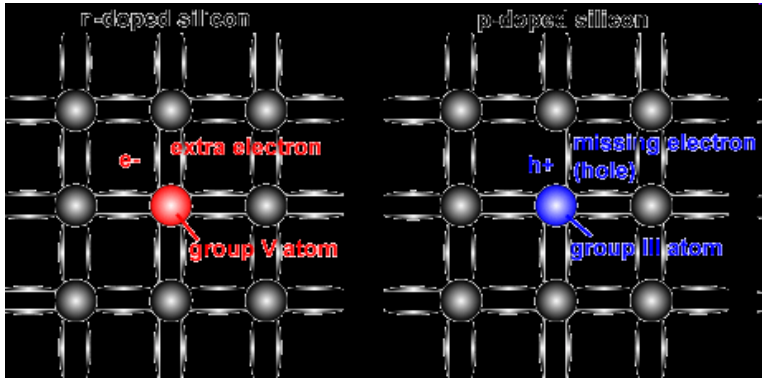
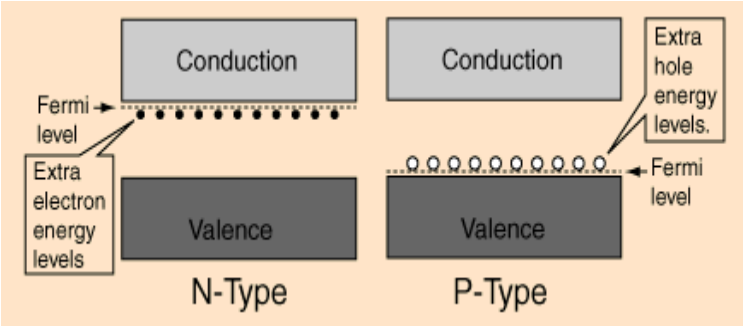
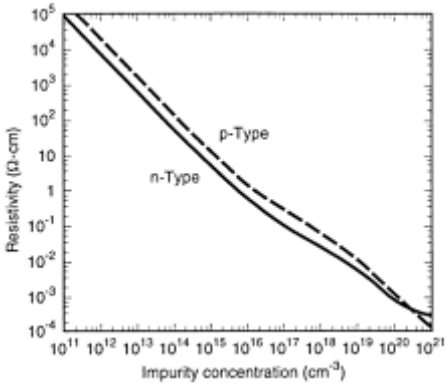
Silicon electrical properties







➔Conduction of Si intrinsic @ T = 300K:

$\sigma = q(\mu_n + \mu_p)\, n_i = 3.04\times10^{-6}$mho-cm ->**329kOhm-cm**

➔By adding atoms of **dopants**, which require little energy to ionize (~10's mEV, so thermal energies @ ambient temperature are enough) we can change by many orders of magnitude the carrier concentration.

➔Doping concentration: 10^{12} to 10^{18} cm^{-3}
In crystalline Si ~ $5*10^{22}$ atoms cm^{-3}
In equilibrium and for non degenerate case
the relationship between carrier concentration and E is the same as in the intrinsic case:

$$pn = n_i^2 = N_C N_V e^{-(E_g)/kT} \cong 10^{20} @ T = 300K$$

$$e.g.: N_D = 10^{17} \Rightarrow pn \cong pN_D \rightarrow p \cong \frac{n_i^2}{N_D} = 10^3$$

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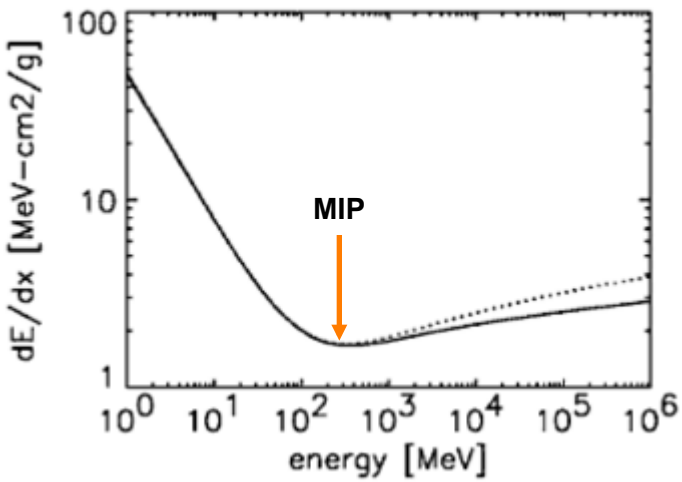
Detection principles

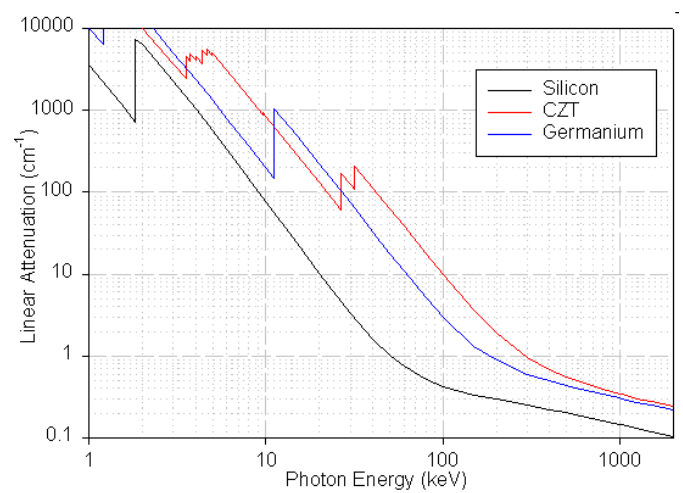
Detection principles:

A: **Ionization**: by imparting energy to break a bond, electrons are lifted from VB to CB then made available to conduction. Most exploited concept (ionization chambers, microstrip, hybrid pixels, CCD, MAPS…)

B: **Excitation:** Charge or lattice (acoustic or optical phonons) some IR detectors, bolometer



α



$$-\frac{dE}{dx} = \frac{4\pi}{m_e c^2} \cdot \frac{nz^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\varepsilon_0}\right)^2 \cdot \left[\ln\left(\frac{2m_e c^2 \beta^2}{I \cdot (1-\beta^2)}\right) - \beta^2\right]$$

Photon interaction $I(z) = I_o e^{-\alpha(E)z}$

Bethe-Bloch formula for stopping power gives the rate of energy loss/unit length for charged particles through matter

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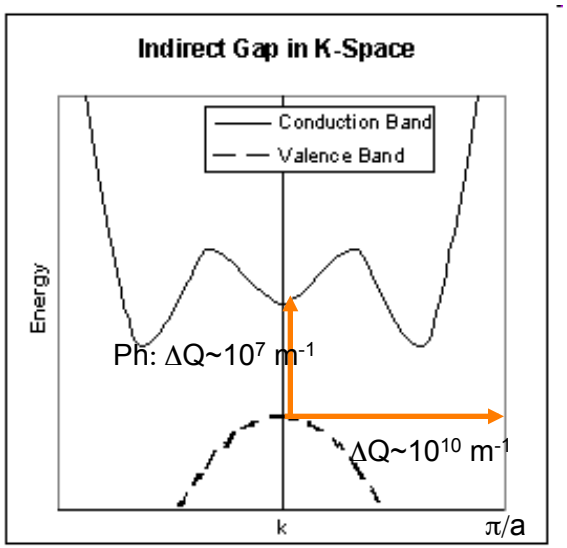
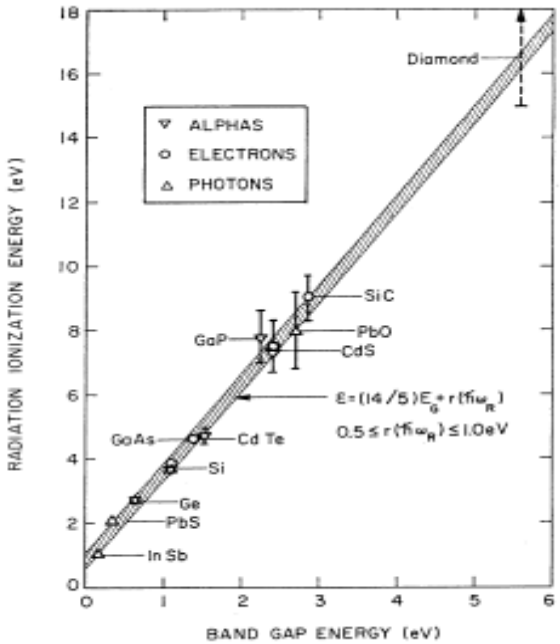
Detection





The indirect BG semiconductors require higher energy than naively expected from their band gap for charge excitation, because energy and momentum must be conserved (Phonon-assisted pair creation/recombination)

➔ In Si an average of **3.6** eV is required for pair creation

Detection

MIP charge density

$$n = \frac{dE}{dx}\rho\frac{1}{\varepsilon_i}\frac{1}{\pi\cdot R^2} \cong 3\cdot 10^{15}\,cm^{-3}$$

$$R = \hbar\frac{\gamma\cdot v}{\langle I\rangle} \cong 110nm$$

A MIP forms an ionization trail of radius R when traversing Si, creating ~ 80e$^-$/µm

$$\lambda \cong \frac{h}{\sqrt{2\cdot m\cdot E}} << 10^{-15}\,cm$$

$$L \cong 0.5 - 1\cdot 10^{-7}\,cm$$

➔Low injection regime:
The associated wavelength is **much smaller** than mean free path:
Each charge is independent from each other;
Carrier dynamics does not need QM
The generated charge is too small to affect the internal electric field

Photoelectric charge density

$$I(z) = I_o e^{-\alpha(E)z}$$

$$n_\lambda(z) = \frac{P_{in}}{h\nu}\eta\alpha(\lambda)e^{-\alpha(\lambda)z} \cong 5.6\cdot 10^6 e^- / \mu m$$

An optical power of -60dBm (= 1nW) of 1keV photons generates ~ 6*10^{6}e−/µm

➔High injection regime:
Plasma effects
The internal electric field can be affected by the generated charge

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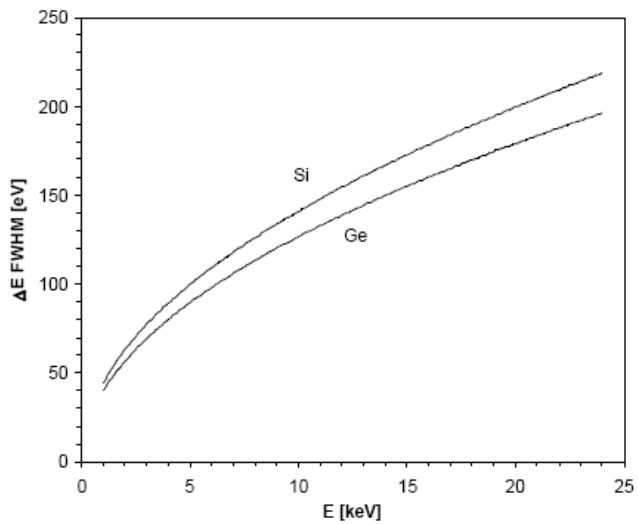
Detection

The variance in signal charge σ_i associated to the ionization process is related to the phonon excitation



Intrinsic resolution of Si and Ge based detectors

$$\sigma_i = \sqrt{\frac{E_o}{\varepsilon_i}} \underbrace{\sqrt{\frac{E_{pn}}{E_i}\left(\frac{\varepsilon_i}{E_i} - 1\right)}}$$

Fano factor ~0.1 in Si

High resolution requires smaller band gap (ε_i), direct or **small phonon excitation energy**

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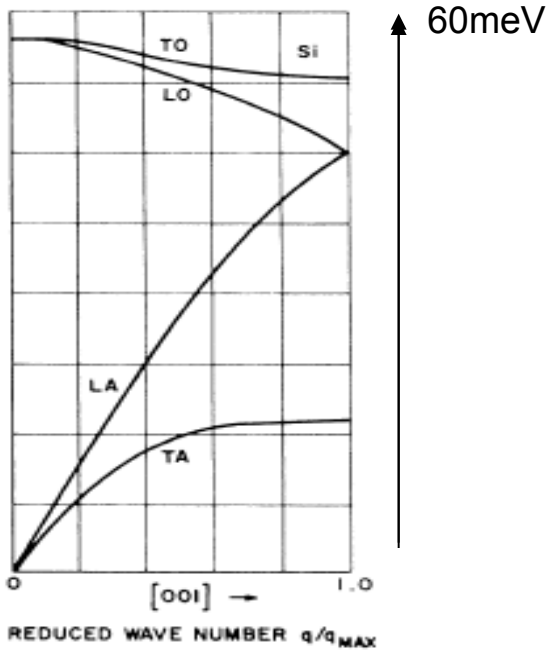
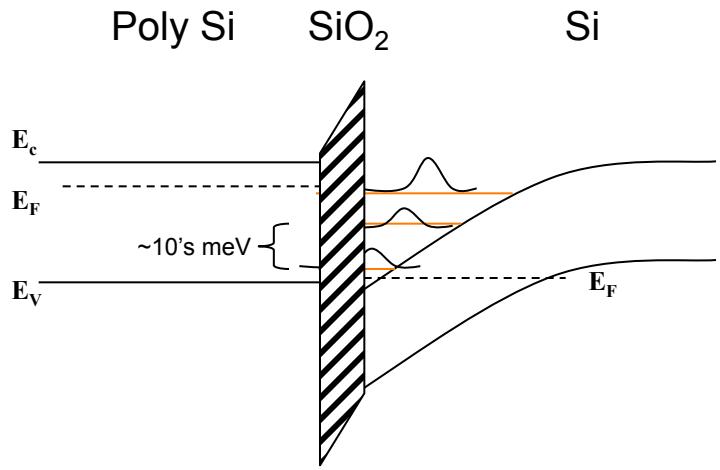
Detection

B: **Excitation:**





Eigenvalues separation in quantized structures ~ 10's meV

Dispersion relation for phonons in Si
Phonon excitation energy ~ 10 meV : much lower threshold

Charge transport

Charge transport:
Once the charge has been created in the material, the next step is its **collection**:
The charge transport description relies on semi-classical **BTE** (continuity equation in 6D phase space)

$$\frac{\partial f(\bar{r},\bar{k},t)}{\partial t}+\frac{1}{\hbar}\nabla_k E(\bar{k})\cdot\nabla_r f(\bar{r},\bar{k},t)+\frac{F}{\hbar}\cdot\nabla_k f(\bar{r},\bar{k},t)=\left.\frac{\partial f(\bar{r},\bar{k},t)}{\partial t}\right|_{coll}+S(\bar{r},\bar{k},t)$$

$$n(\bar{r},t)=\frac{1}{V}\int_k f(\bar{r},\bar{k},t)$$ Q conservation

$$J(\bar{r},t)=-\frac{q}{V}\int_k v(\bar{k})f(\bar{r},\bar{k},t)$$ P conservation

$$W(\bar{r},t)=\frac{1}{V}\int_k E(\bar{k})f(\bar{r},\bar{k},t)$$ E conservation

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Charge transport

Under (many) simplifying assumptions the 1st moment of BTE gives the **DD** model (The 'semiconductor equations'):

Drift term

Diffusion term

$$J_n = \underline{qn\mu_n E(r)} + \underline{qD_n \nabla n}$$

$$J_p = qp\mu_p E(r) - qD_p \nabla p$$

$$\frac{\partial n}{\partial t} = \frac{1}{q}\nabla \cdot J_n + U_n$$

$$\frac{\partial p}{\partial t} = -\frac{1}{q}\nabla \cdot J_p + U_p$$

$$\nabla \cdot \varepsilon \nabla V = -\left(p - n + N_D^+ - N_A^-\right)$$

➔**DD** expresses <u>momentum</u> conservation: it becomes invalid when sharp variation in energy of carriers occur (due to F for example: deep submicron devices)
When feature size is 0.'sμm the **DD** model becomes invalid: higher moments required

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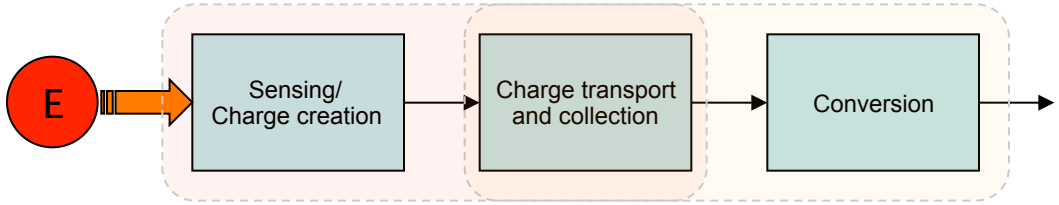
Half summary

Under a number of assumptions, the description of the detection processes in semiconductor detectors can be hugely simplified:



Si physical properties

Si device properties

Physical characteristics:

Quasi equilibrium;

Homogeneity;

'Room' temperature;

Non degenerate Si;

Charge generation:

Ionization: Small injection, QM not needed;

Stopping power, average ionization energy

Charge transport:

Big devices, DD adequate;

Small injection, electric field as static;

Under conditions of
- quasi stationary conditions
- non degenerate semiconductor
- not small feature size
- low injection
- …

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Detectors examples

PN junction

Strip / pixel detectors

HEP, Scientific applications

Monolithic Active Pixel Sensors (MAPS)

Consumer and scientific applications

Charge Coupled Devices (CCD)
Imaging, scientific and consumer applications

RAL PPD has (is) actively involved with all these detector technologies

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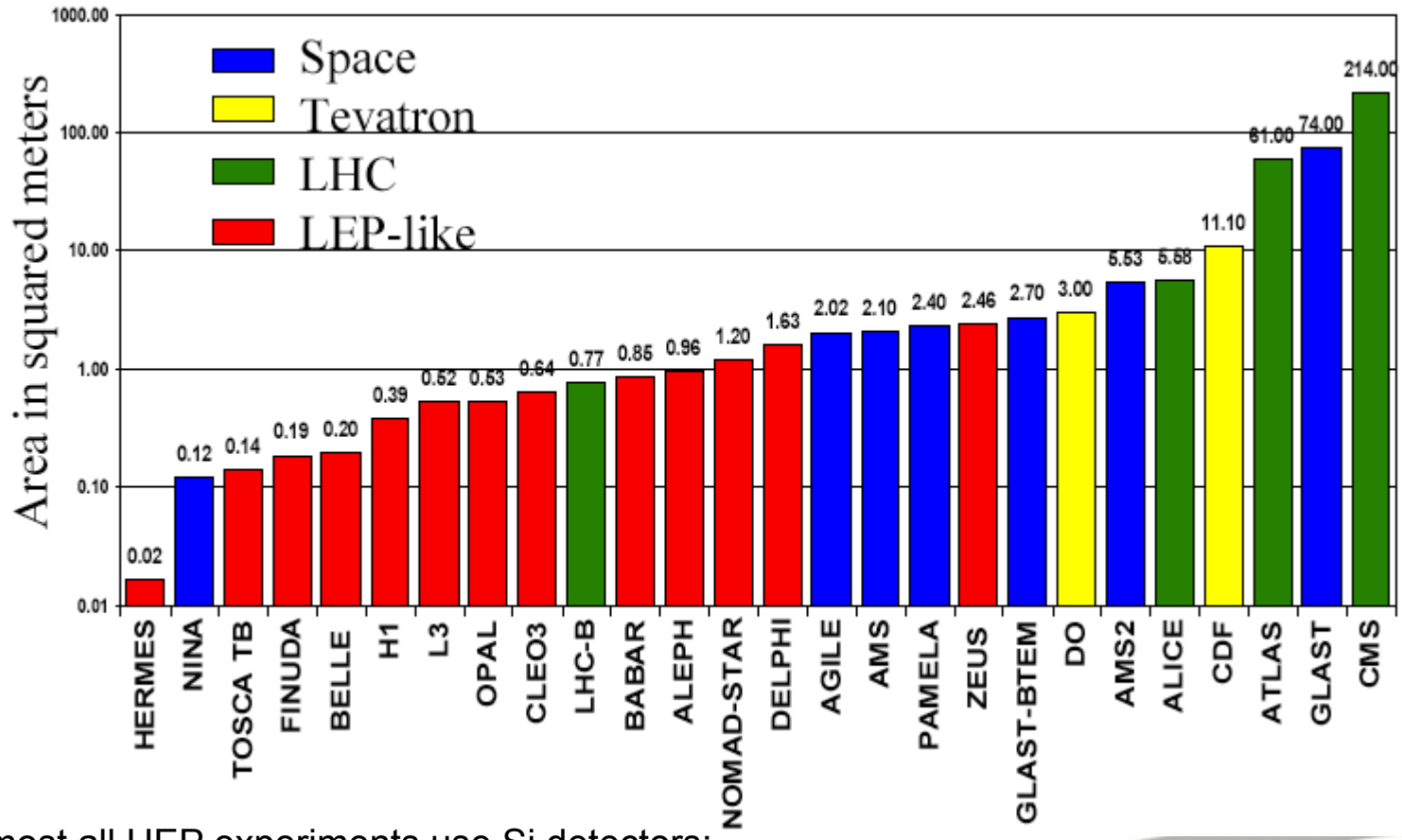
Detectors examples

Use of Si detectors



➔Almost all HEP experiments use Si detectors:
The high density track region usually covered by pixel detectors; by strip at larger radius (cost reason)

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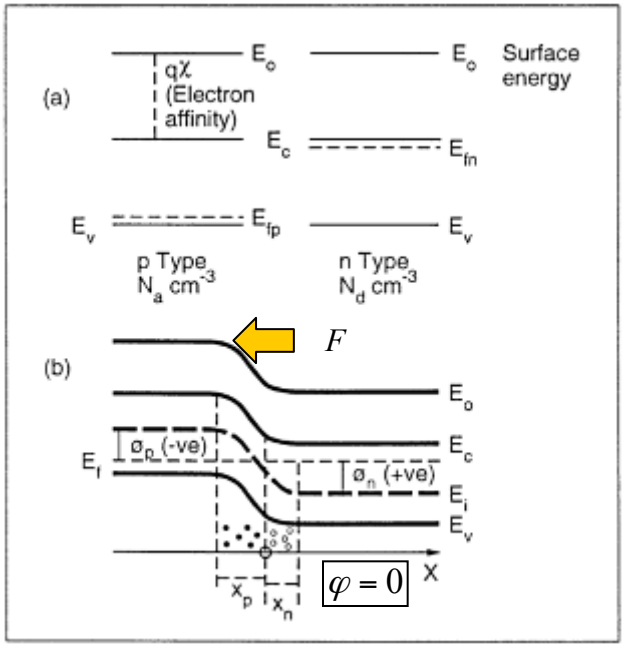
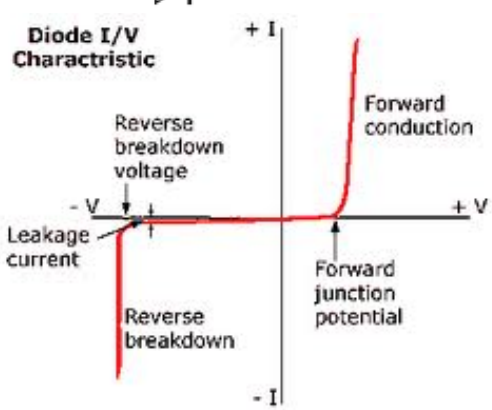
Signal conversion: The PN junction





Homojunction: two pieces of <u>same</u> semiconductor materials with <u>different</u> doping levels:

- In equilibrium, the Fermi level equalizes throughout the structure
- thermal diffusion of charge across the junction leaves a depleted region, with the ionized dopants : an electric potential Φ, and a field F, develops across
- the charge concentration depends exponentially on energy, or Φ:

In equilibrium J = 0

$$0 = qn\mu_n E(r) + qD_n \nabla n \rightarrow n = n_0 e^{\frac{\Delta\varphi}{V_t}}$$

$$0 = qp\mu_p E(r) - qD_p \nabla p \rightarrow p = p_0 e^{-\frac{\Delta\varphi}{V_t}}$$

- by applying a small voltage to decrease the barrier, the charge increases exponentially
- by applying a voltage to increase the barrier, the depleted region increases

➔**Unidirectionality** of current characteristics

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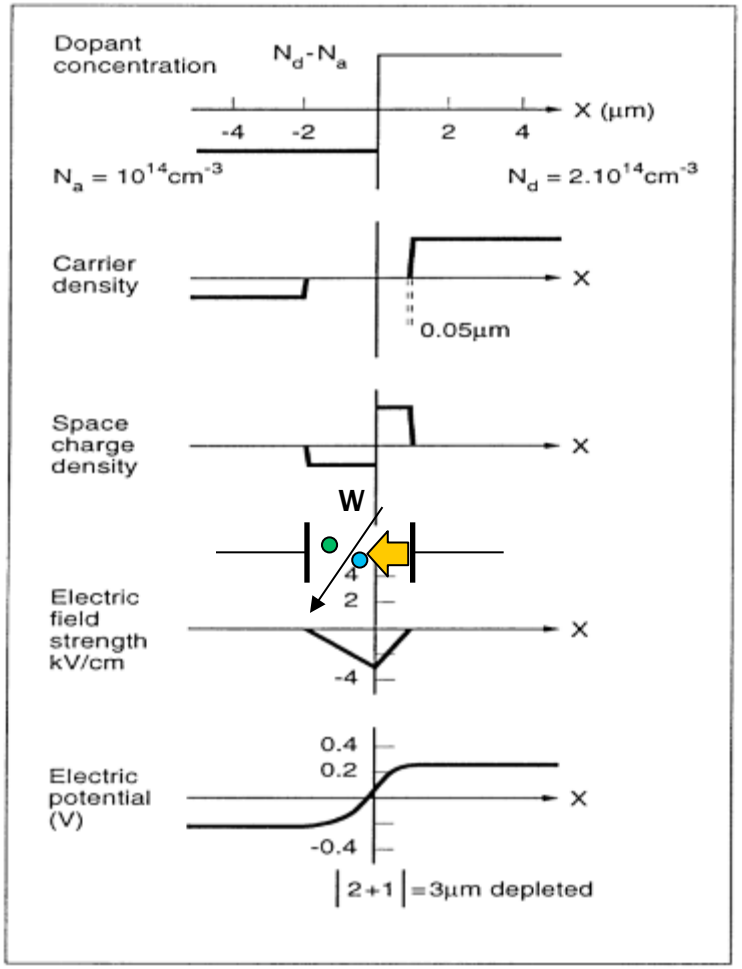
Signal conversion: The PN junction



- when charge is generated in the depleted region is swept across by the electric field sustained by the ionized dopants and the biasing.

➔ PN junction as signal converter: <u>capacitor</u> with a F across

➔ A PN junction with a <u>large depleted region</u> can be used to efficiently collect radiation generated charge (Solid state ionization chamber)

Depletion width $$W = \sqrt{\frac{2\varepsilon V_b}{q}\frac{N_a + N_d}{N_a \cdot N_d}}$$

To achieve large W high field region:
- Low doping (high resistivity),N_a or N_d
- Large voltages V_b

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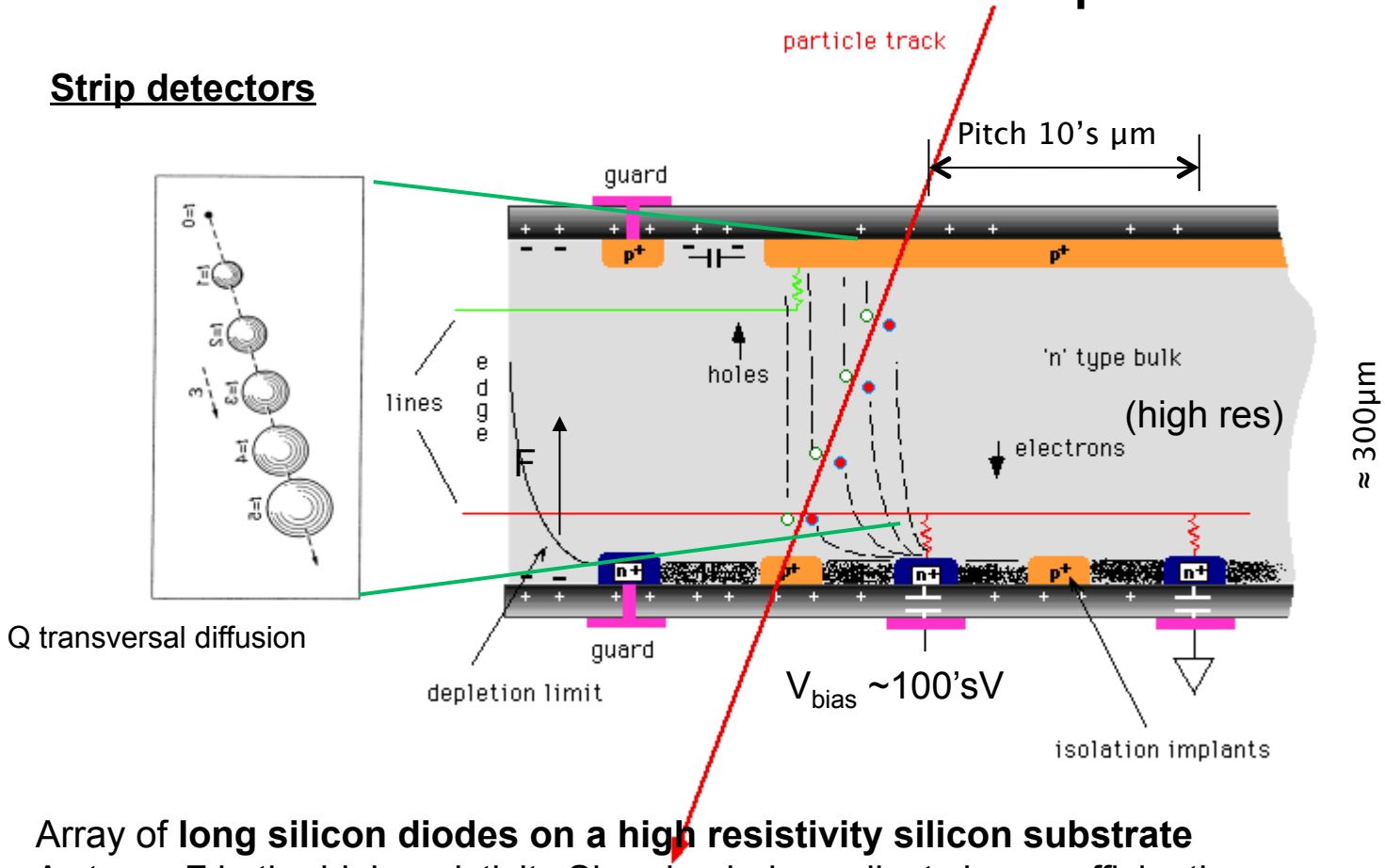
Detectors examples

Strip detectors



Q transversal diffusion

Array of **long silicon diodes on a high resistivity silicon substrate**
A strong F in the high resistivity Si region helps collect charge efficiently.

➔ The high resistivity Si is not usually used in mainstream semiconductor industry:
Hybrid solution: sensor (high resistivity Si) connected (wire/bump-bonded) to the readout electronic (low resistivity Si)

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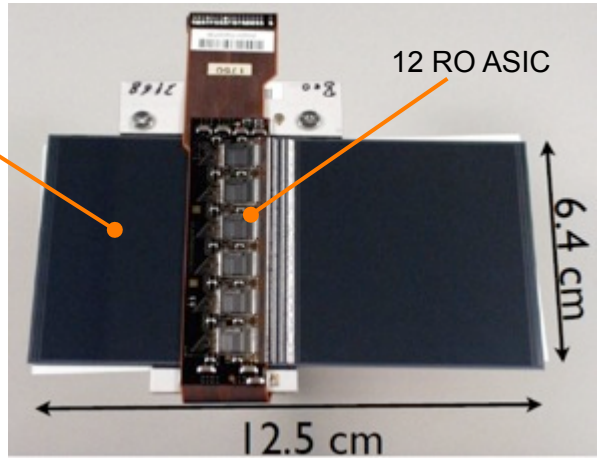
Detectors examples



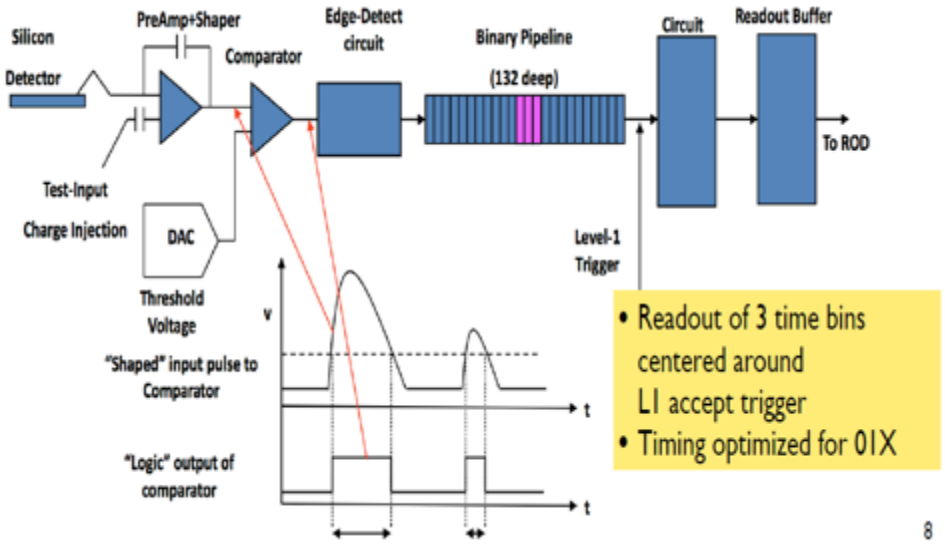
ATLAS SCT RO ASIC (ABCD3TA)

128 channels/ASIC

RAD-HARD DMILL technology

ASICS glued to hybrid

40 MHz Ck



ATLAS SCT

4 single-sided p-on-n sensors

2x2 sensors daisy chained

Stereo angle 40 mrad

Strip pitch 80 μm

768 channels/side

Binary RO

Bias Voltage up to 500 V

Operating temperature -2 C

Space point resolution: rPhi 17μm / z 50 μm

Power consumption: 5.6 W (initially) to 10 W (after 10y)

Rad hard up to $2x10^{14}$ 1-MeV n eqv/cm^2

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Detectors examples

ATLAS SCT

61 m^2 of Si

6.3 * 10^6 channels

50 kW total power consumption

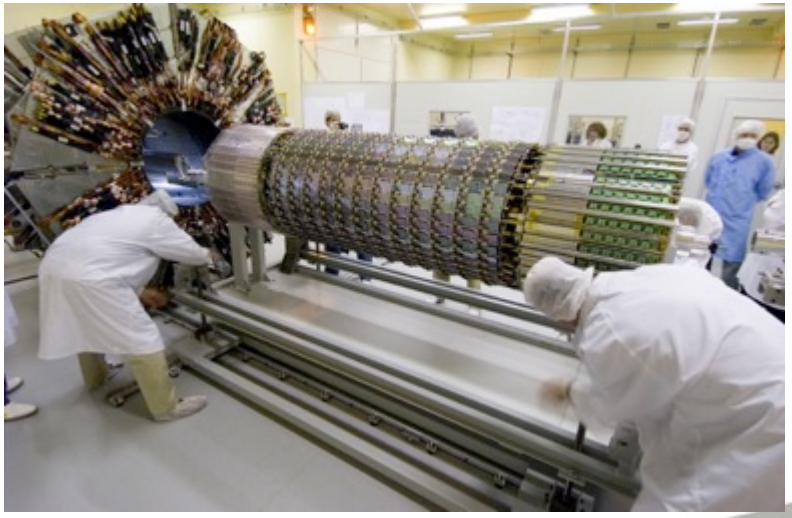
1 barrel

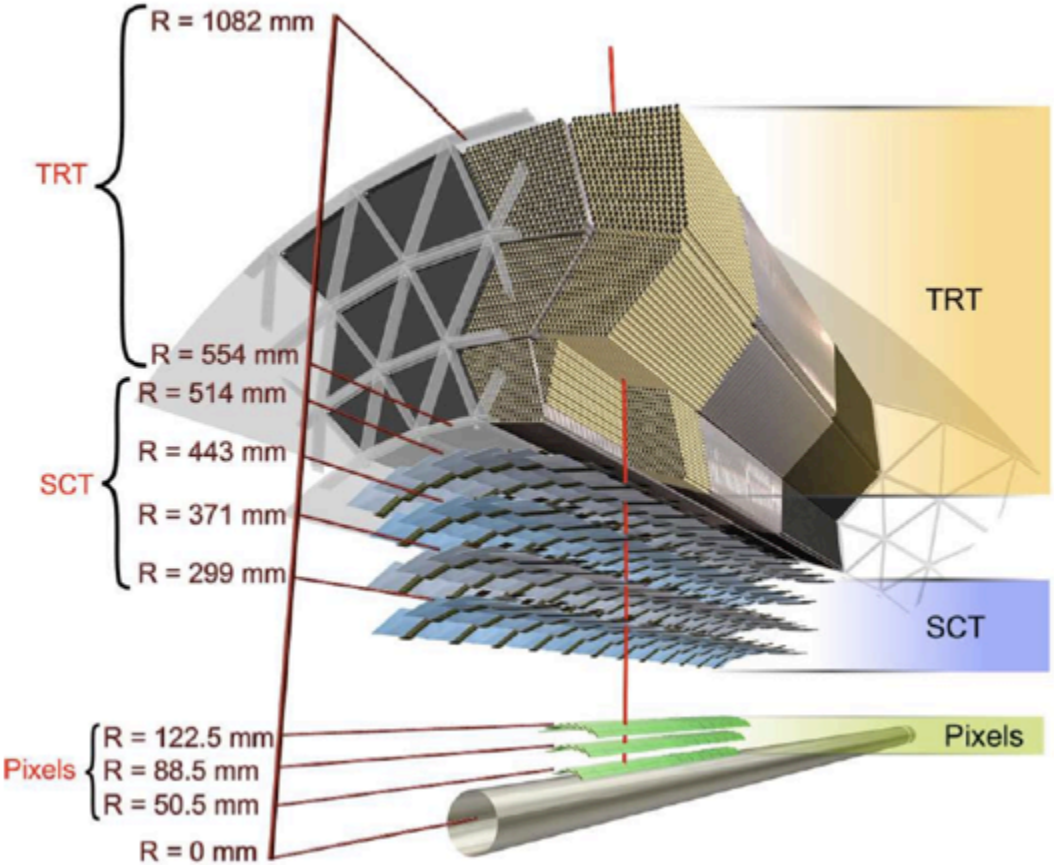
- 4 layers
- 2100 modules

2 endcaps

- 9 disks/each
- 988 modules

2 T solenoidal field





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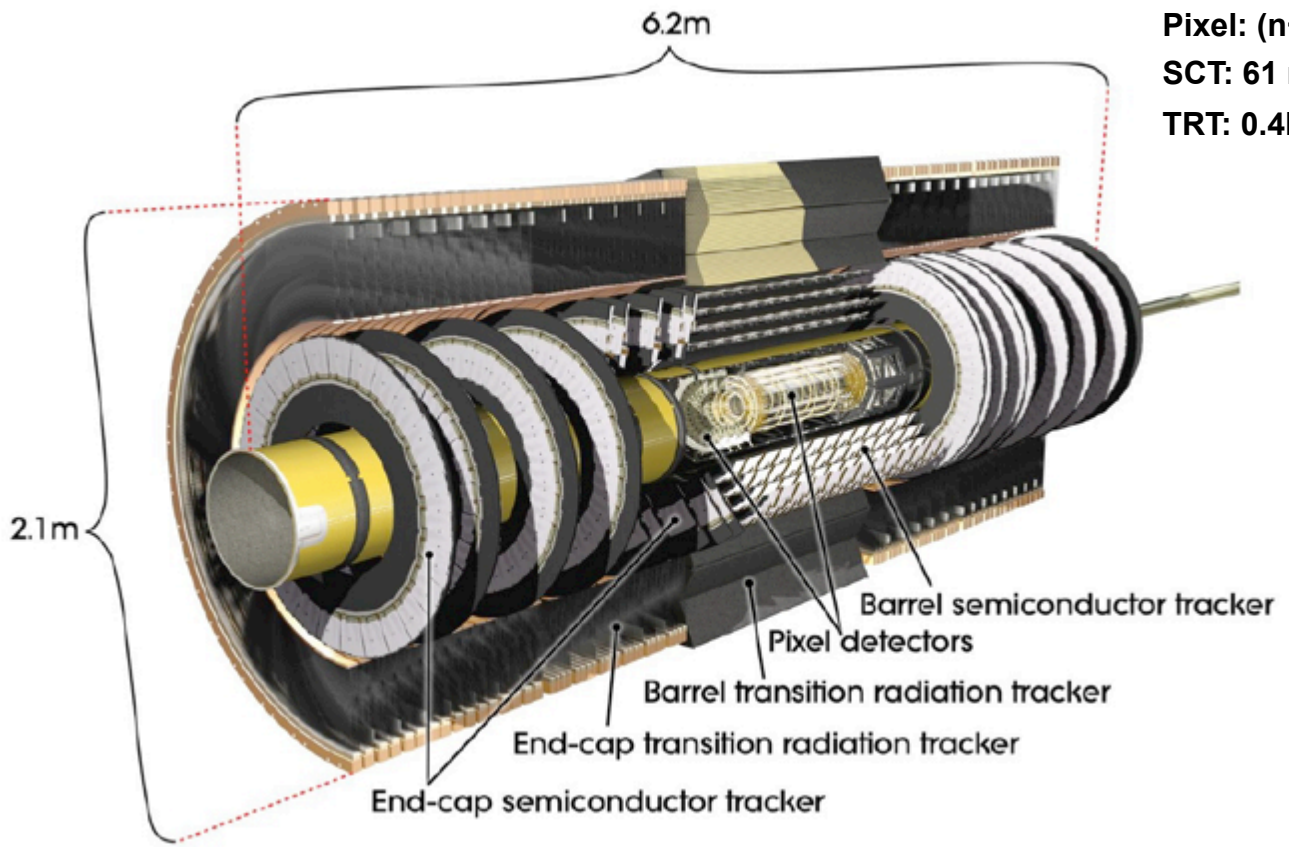
Detectors examples

ATLAS Tracker overview



Pixel: (n+ on n) 1.8m^2, 80M channels

SCT: 61 m^2 6.3Mchannels

TRT: 0.4M channels

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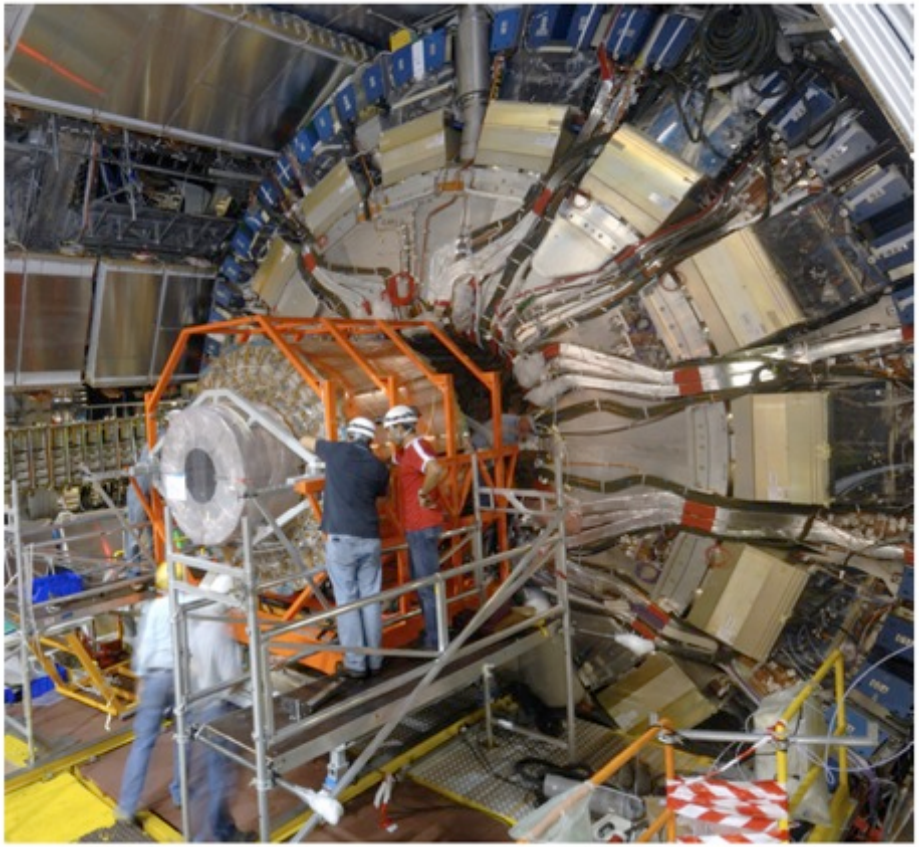
Detectors examples

Barrel insertion in the ATLAS Cavern



ATLAS SCT - Red cables : power cables

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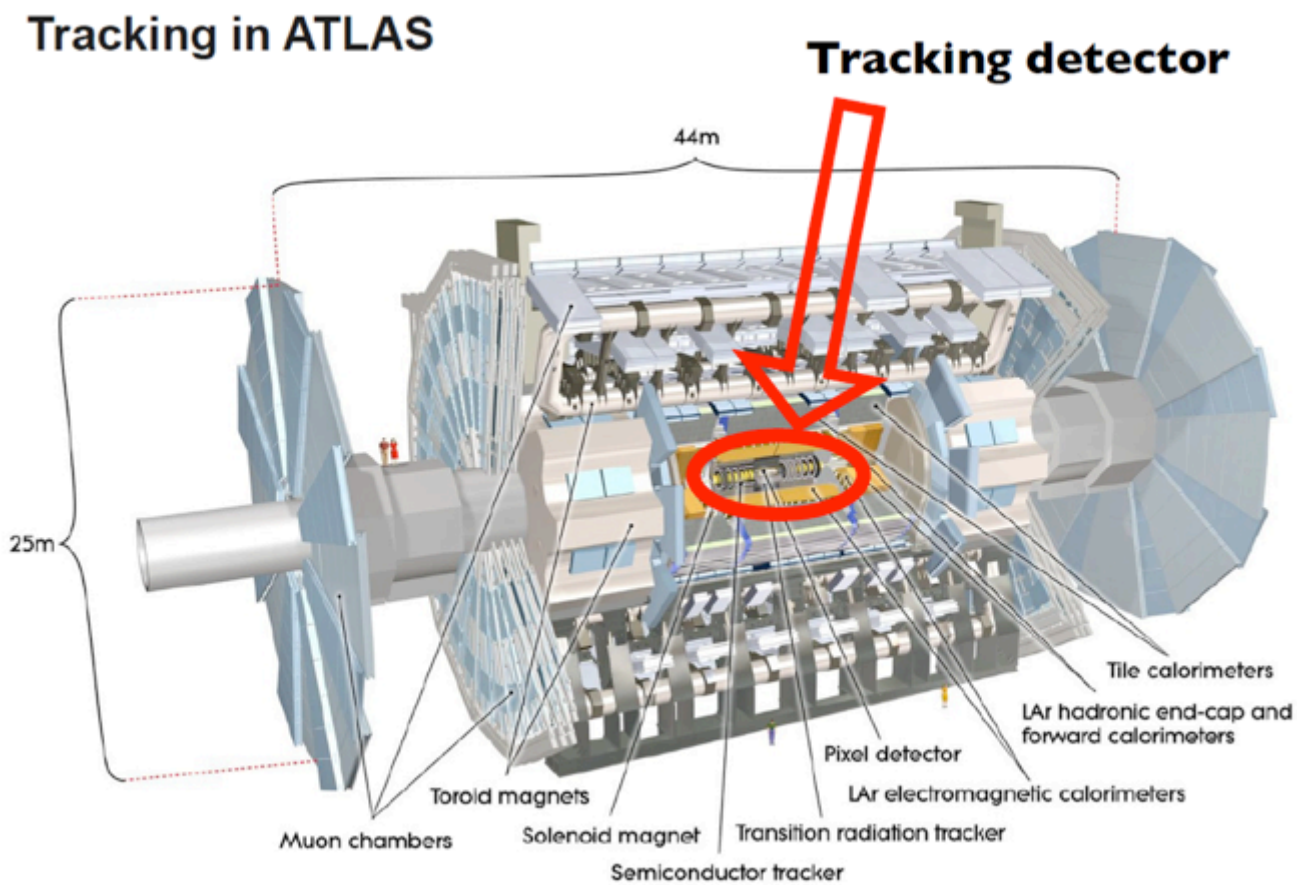
Detectors examples



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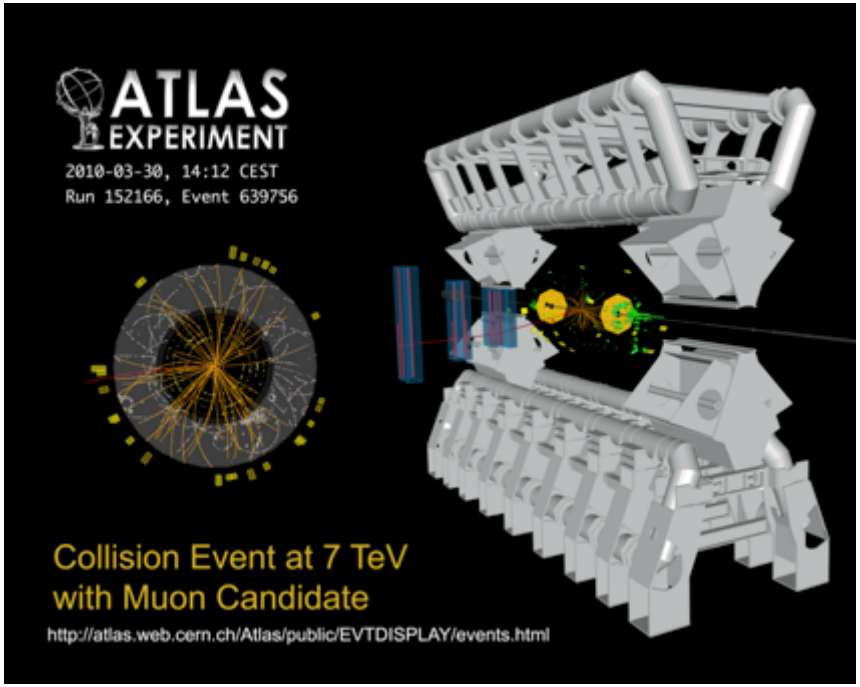
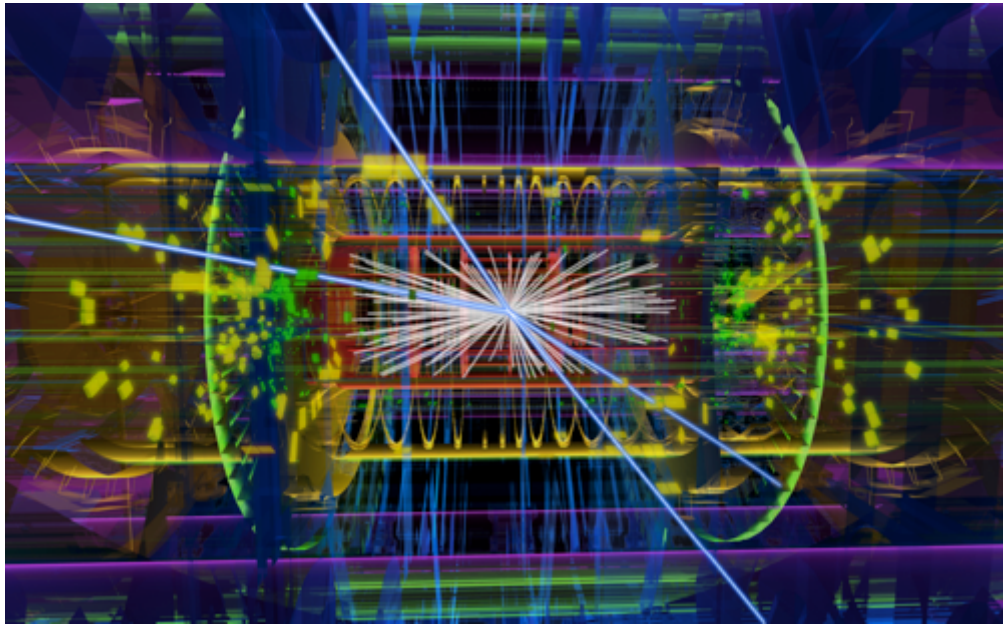
Detectors in operation





An ATLAS event with 4 muons. The four muons are picked out as long blue tracks.

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Detectors in operation

- 4088 modules with 6.3 million readout channels

➡ 99 % are operational

Disabled Readout Components	Endcap A	Barrel	Endcap C	SCT	Fraction (%)
Disabled Modules	5	10	15	30	0.73
Disabled Chips	5	24	4	33	0.07
Masked Strips	3,364	3,681	3,628	10,673	0.17
Total Disabled Detector Region					0.97

	Endcap A	Barrel	Endcap C	SCT	Fraction (%)
Total	5	10	15	30	0.73
Fraction (%)	0.5	0.2	1.5	0.7	
Cooling	0	0	13	13	0.32
LV	0	6	1	7	0.17
HV	4	1	1	6	0.15
Readout	1	3	0	4	0.10

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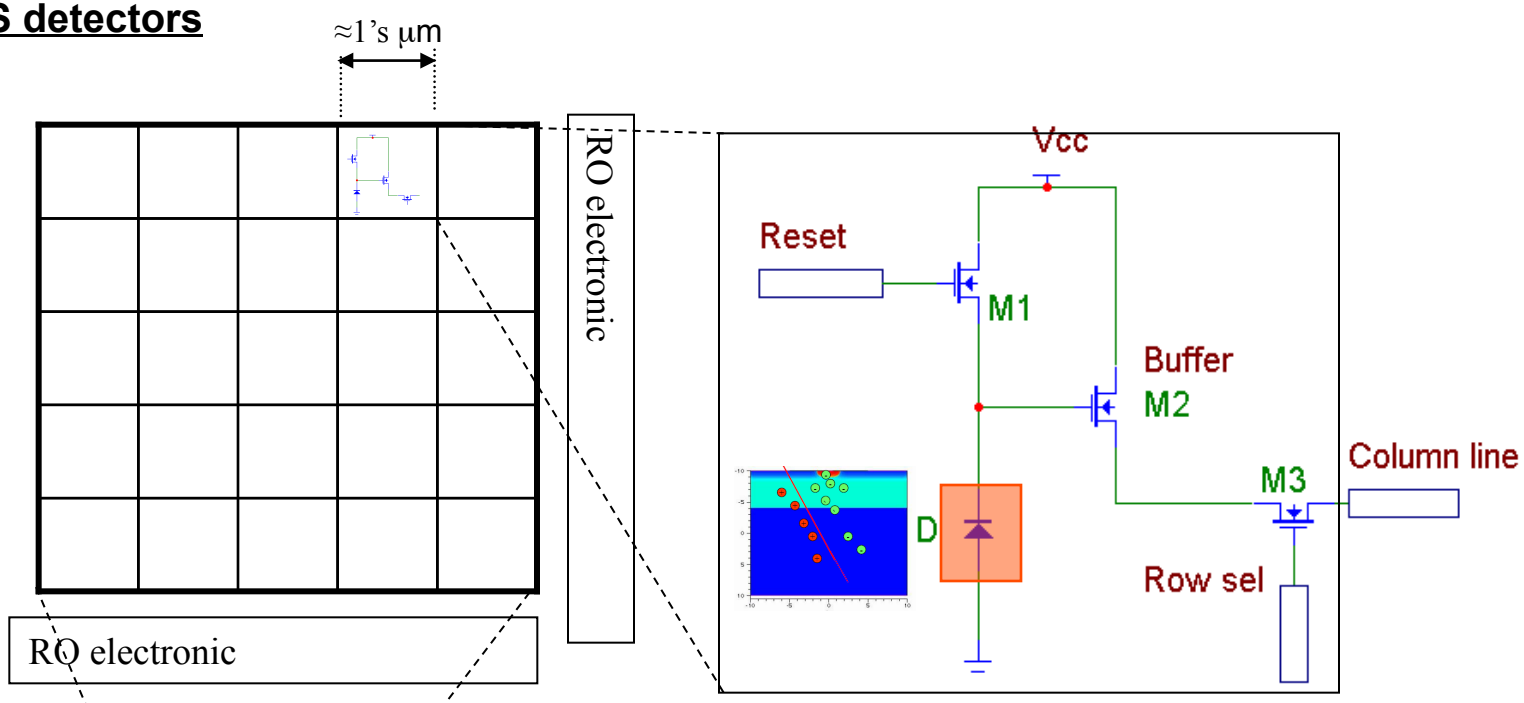
Detectors examples

MAPS detectors



3T (3MOS) MAPS structure

2 D array of pixels

➔ Monolithic **solution**: detector and readout integrated onto the same substrate

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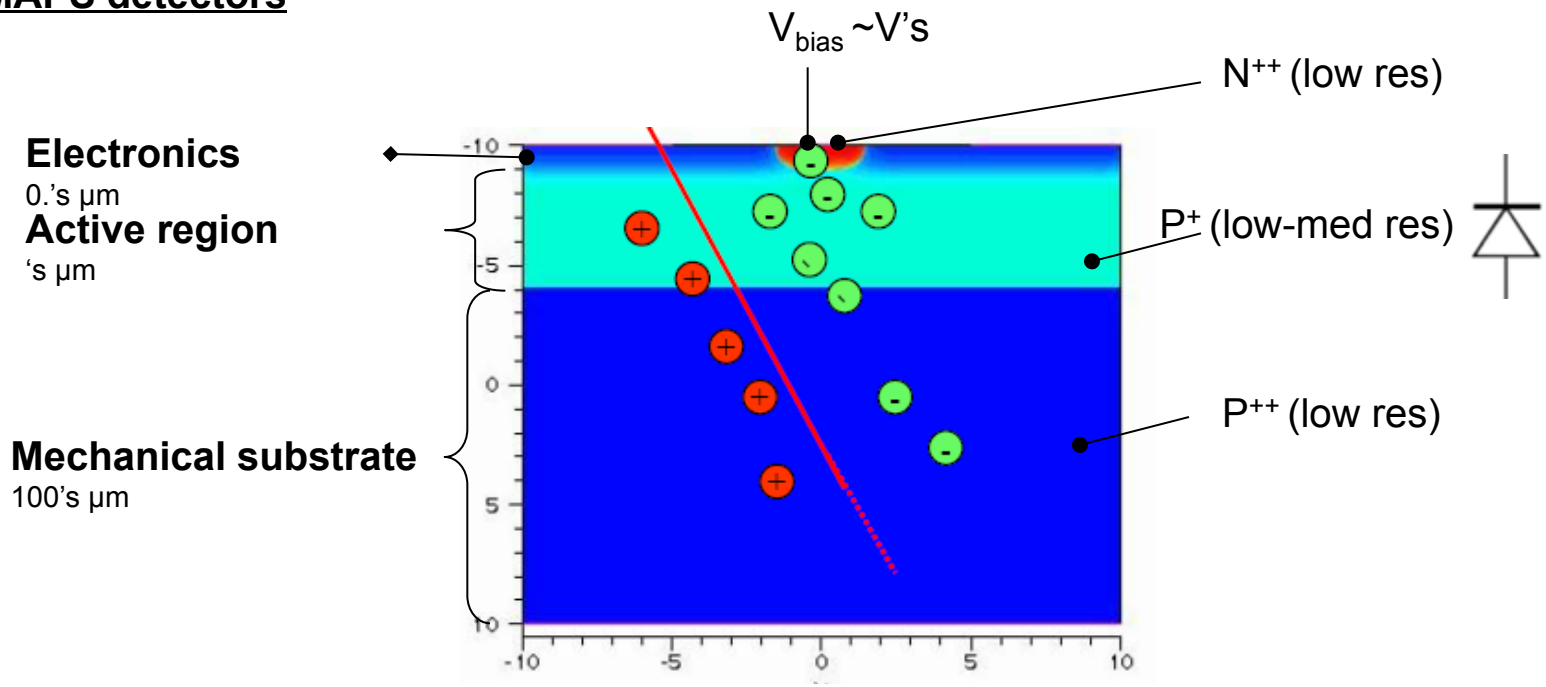
Detectors examples

MAPS detectors

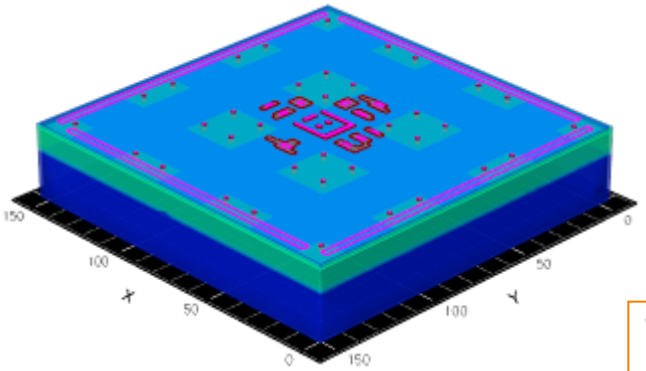


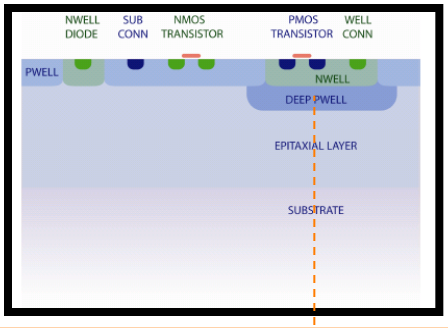
➔ The charge generated in the thin active region moves mainly by diffusion :
'Long' collection time
Small signal
Low radiation hardness

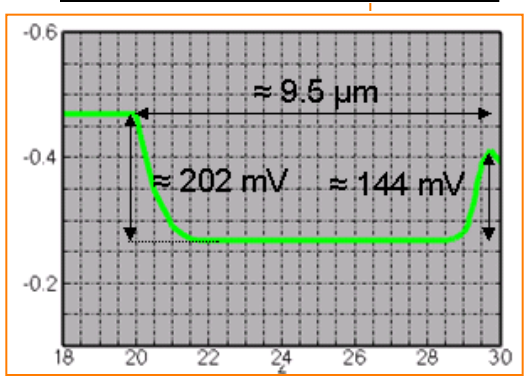
➔However, complex circuit topologies allow DSP on pixels for low noise performances (≈ some e^- noise)

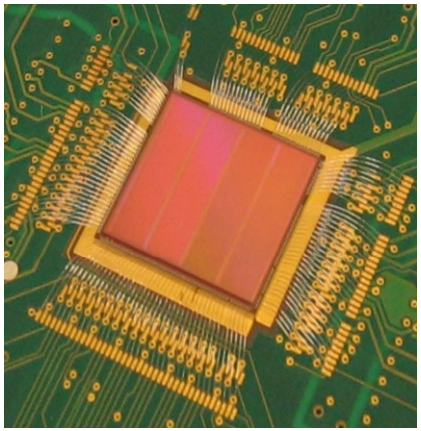
Detectors examples

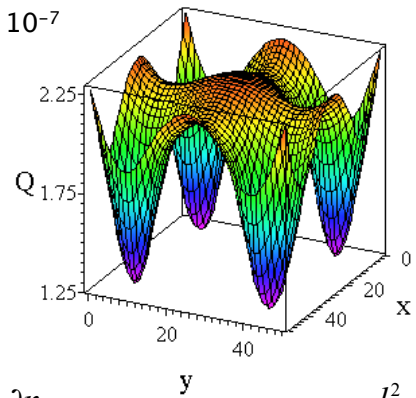
Example of MAPS detectors:











$$\frac{\partial n}{\partial t} \cong D_n \nabla^2 n + U_n \rightarrow t_{coll} \cong \frac{l^2}{D_n}$$

Charge collection time (s) in MAPS vs. perpendicular MIP hit

TPAC 1 pixel size 50x50 μm^2
Chip size ~1cm^2
Total pixels 28k
>8Meg Transistors

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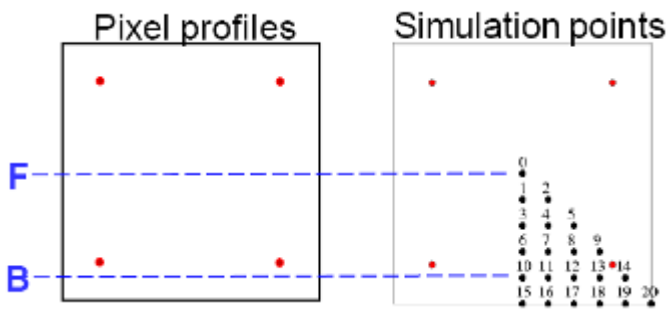
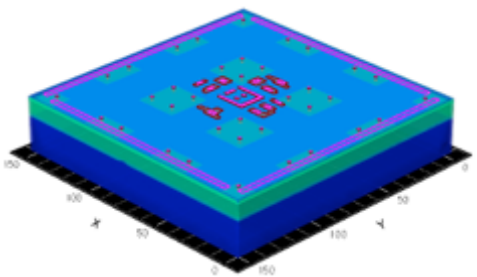
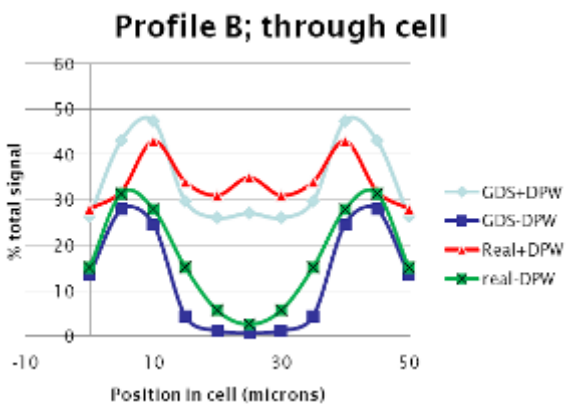
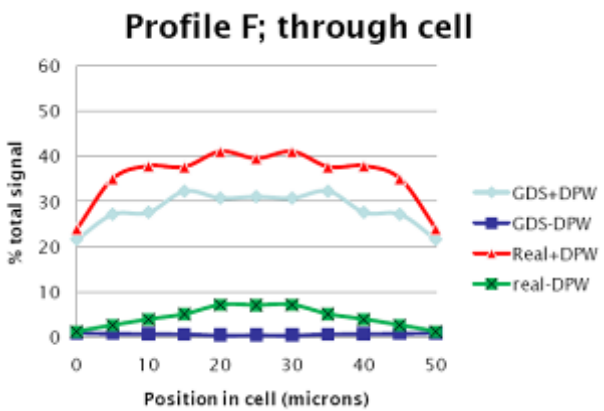
Detectors examples

Example of charge collection in MAPS: simulated MIP vs.1064nm laser 2x2 μm^2 5ns pulse









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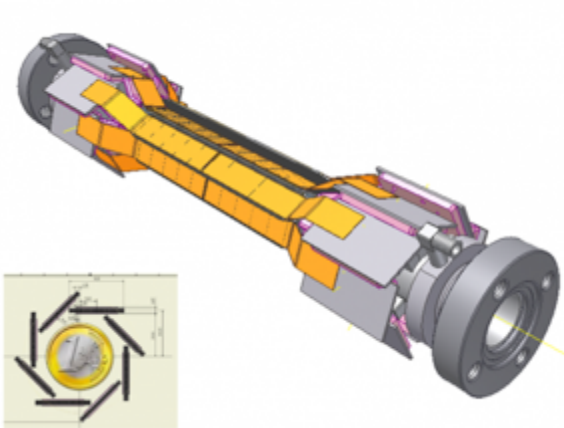
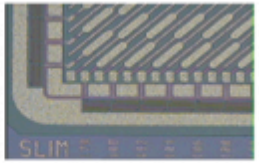
Detectors example

Proposed use of MAPS (50x50 μm^2) sensors in SuperB Vertex Tracker

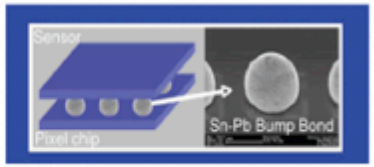


Complexity

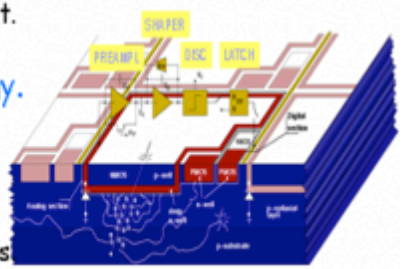
- **Striplets option:** mature technology, not so robust against background occupancy.
  - Marginal with background rate higher than ~ 5 MHz/cm^2
  - Moderate R&D needed on module interconnection/mechanics/FE chip (FSSR2)



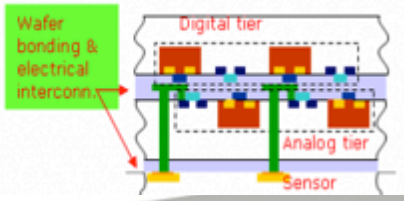
- **Hybrid Pixel option:** viable, although marginal.
  - Reduction of total material needed!
  - Reduction in the front-end pitch to 50x50 μm^2 with data push readout (developed for DNW MAPS)
  - → FE prototype chip (4k pixel, ST 130 nm) now under test.



- **CMOS MAPS option:** new & challenging technology.
  - Sensor & readout in 50 μm thick chip!
  - Extensive R&D (SLIM5-Collaboration) on
    - Deep N-well devices 50x50μm^2 with in-pixel sparsification.
    - Fast readout architecture implemented
  - CMOS MAPS (4k pixels) successfully tested with beams



- **Thin pixels with Vertical Integration:** reduction of material and improved performance.
  - Two options are being pursued
    - DNW MAPS with 2 tiers
    - Hybrid Pixel: FE chip with 2 tiers + high resistivity sensor



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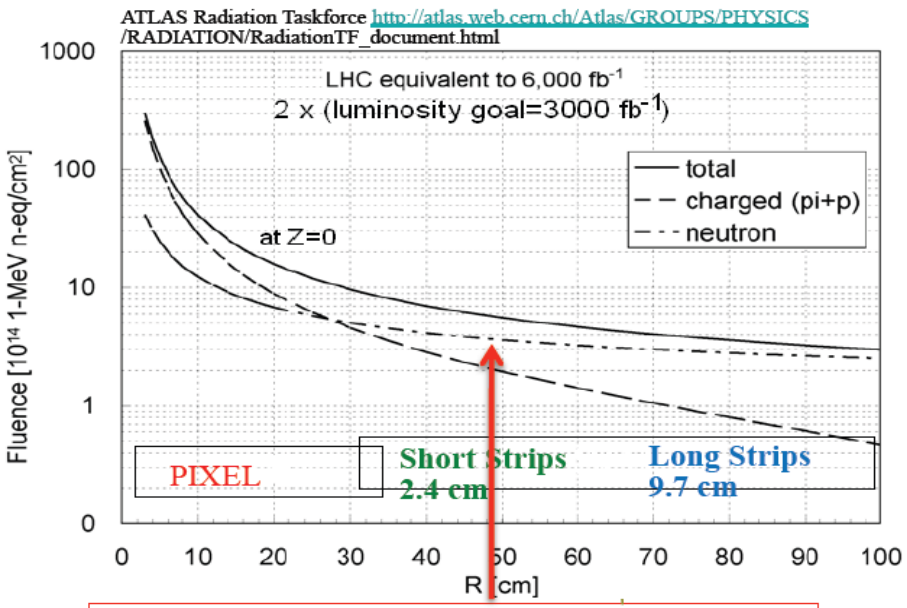
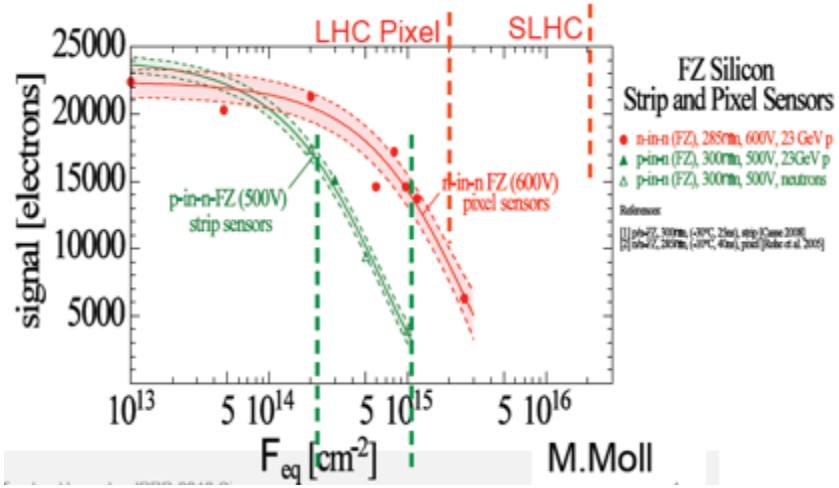
Radiation damage

In HEP and space applications the detectors are exposed to high level of dose of radiation:
LHC: 10's Mrad (100kGy) over 10 years of operation
N.B.: 1 rad/cm^3 Si ~10^{13}e/h pairs
Lethal dose: 5 Gy Total Body Irradiation





Main damage in strip layers due to neutrons

Radiation damage

Radiation environment in LHC experiment

	TID	Fluence 1MeV n eq. [cm^{-2}] @ 10 years
ATLAS Pixels	50 Mrad	1.5×10^{15}
ATLAS Strips	7.9 Mrad	2×10^{14}
CMS Pixels	~24Mrad	~6×10^{14} *
CMS Strips	7.5Mrad	1.6×10^{14}
ALICE Pixel	250krad	3×10^{12}
LHCb VELO	-	1.3×10^{14}/year**

All values including safety factors.

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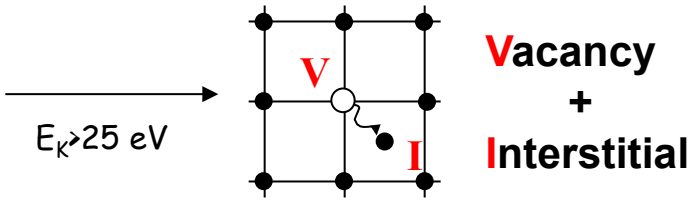
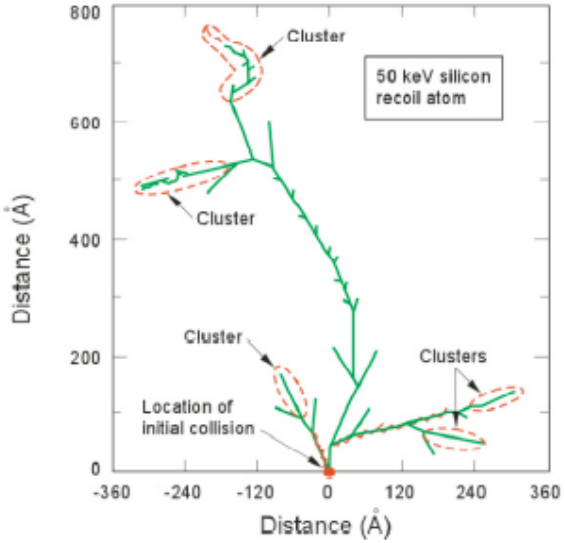
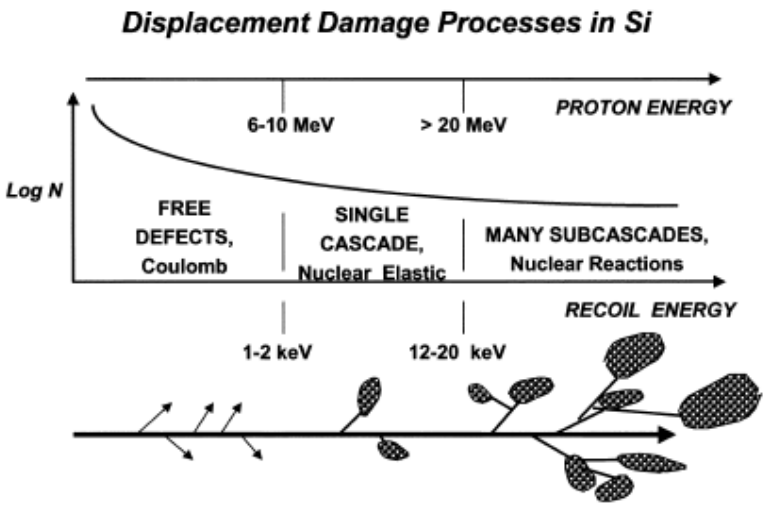
Radiation damage

<u>Microscopic effects</u>: Bulk damage to Silicon :
Displacement of lattice atoms







➔Atoms scattered by incoming energetic particles leave behind vacancies or atoms in interstitial positions (Frenkel pairs).
Low energy particle ~ point defects
High energy particles ~ cluster defects

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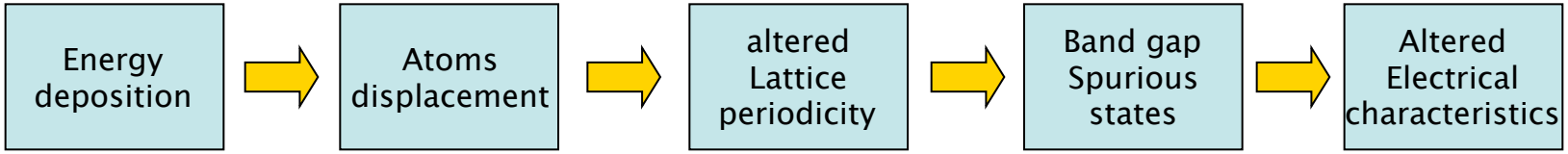
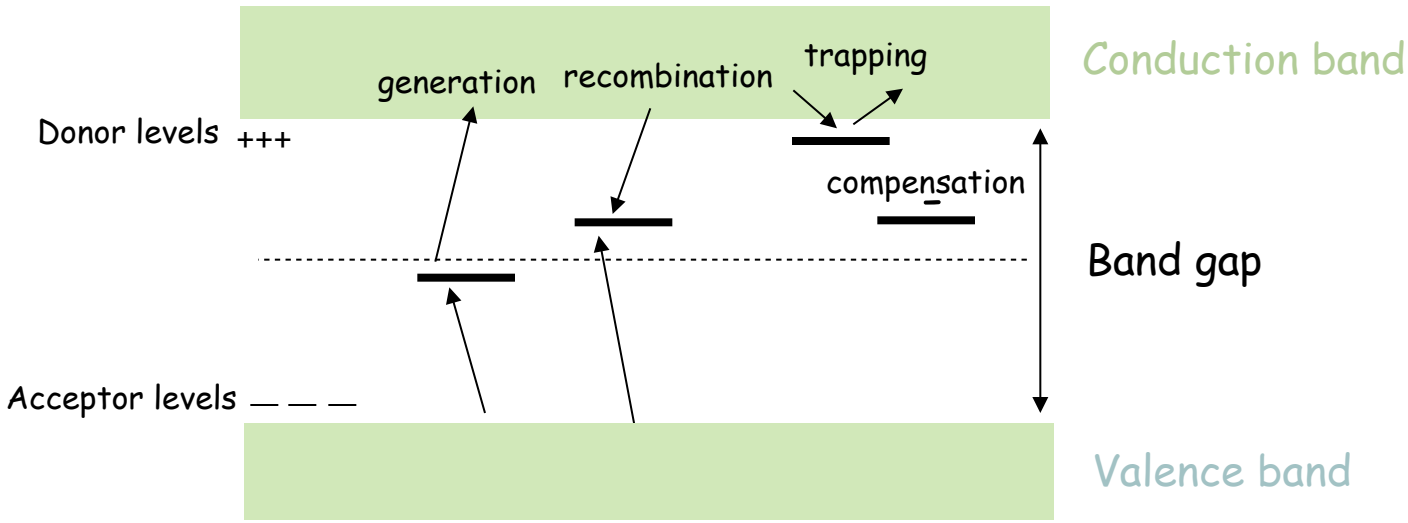
Radiation damage





➔The appearance of spurious band gap states affects the electro/optical characteristics of the device:

- Thermal generation of carriers (increased leakage current)
- Reduced recombination time (quicker charge loss , reduced signal)
- Charge trapping
- Scattering
- Type conversion

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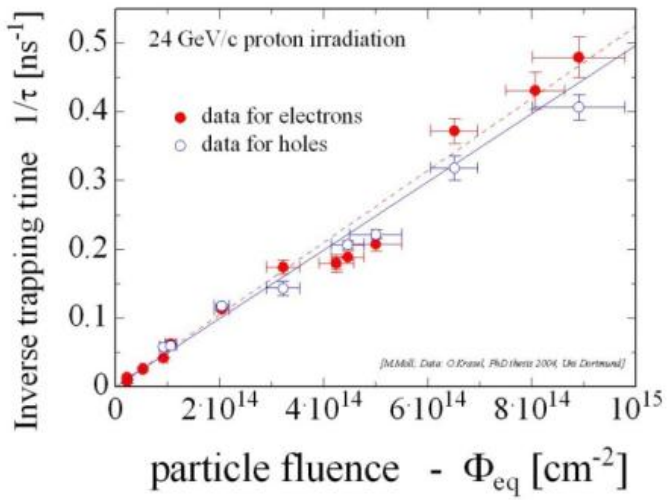
Radiation damage

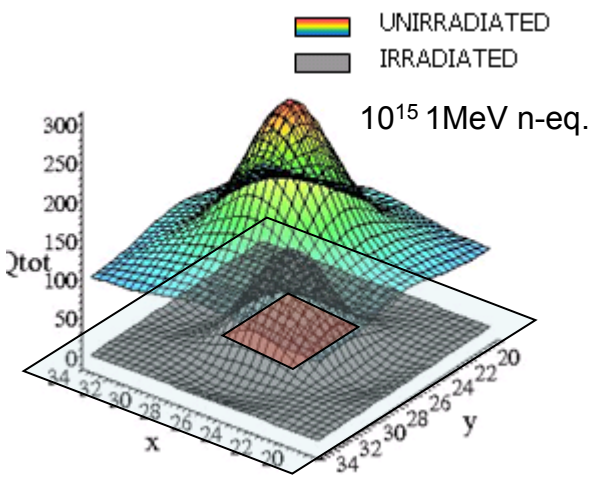
Macroscopic effects:

Charge Collection Efficiency (CCE) is reduced by decreased recombination time and trapping
Noise increases because of increased leakage current
Depletion voltage increases because of type inversion

$$Q_{e,h}(t) = Q_{0e,h} \exp\left(-\frac{1}{\tau_{eff\ e,h}} \cdot t \right)$$

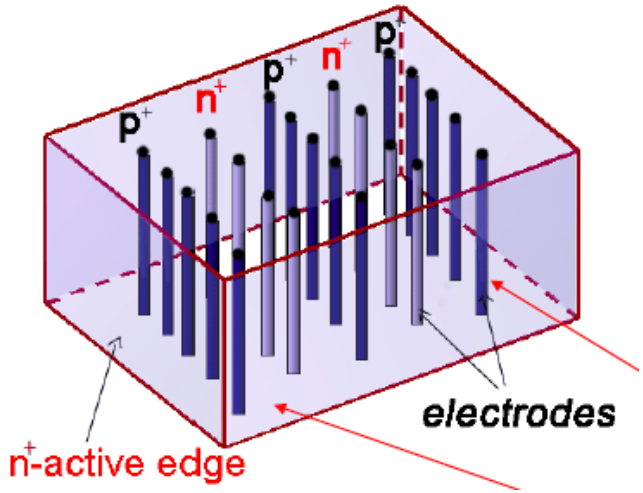


$$\frac{1}{\tau_{eff\ e,h}} \propto N_{defects}$$



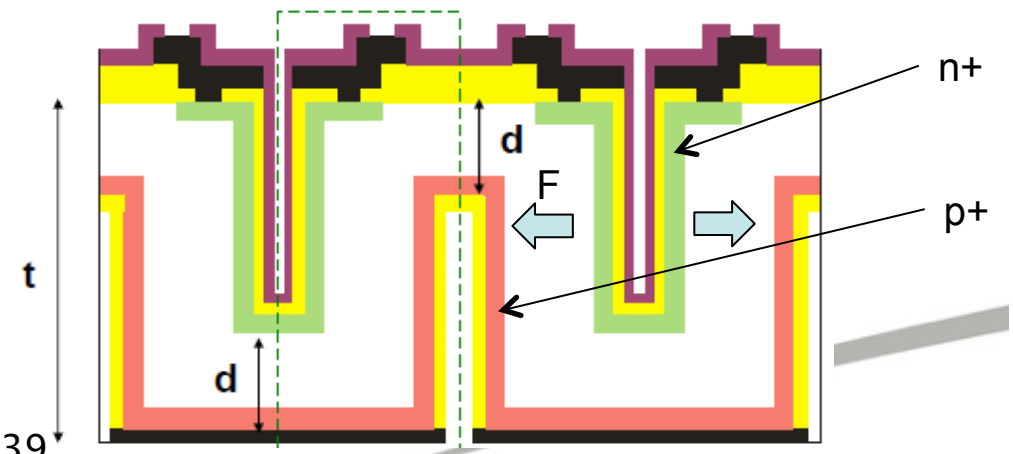
Radiation damage

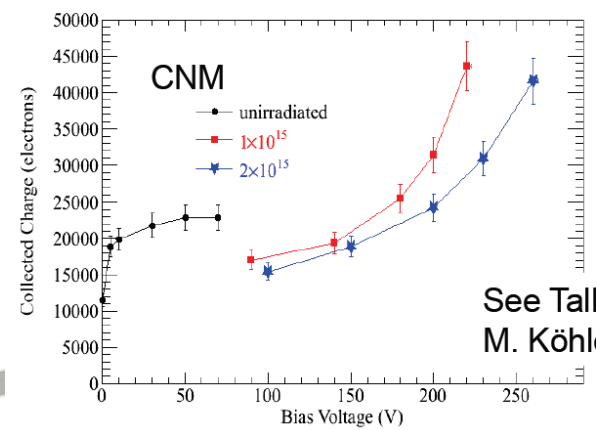
To increase the Radiation Hardness of Sensors:
- Operating conditions (cooler – lower leakage)
- Material engineering (OFZ - Diamond detectors)
- Device engineering (n in n/p – 3D detectors):



- Electrodes in the bulk – lateral collection reduces the drift distance
- Lower depletion voltage – less power consumption
- difficult to manufacture

•3D DDTC similar to 3D but easier to manufacture; also Better mechanical strength.





See Tall
M. Köhl

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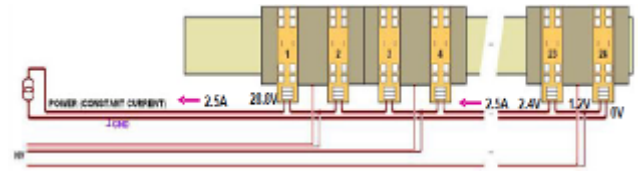
Detector systems

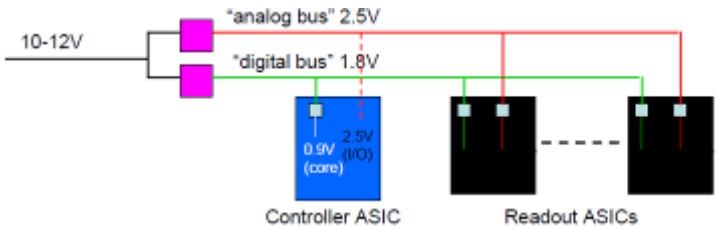
➔HEP experiments: large detector systems
Challenging engineering issues

The ATLAS SCT (semiconductor tracker) detector.
The thick red cables on show feed the detector with half of its power

Alternative powering schemes:



SP



DC2DC

A serial powering (SP) or DC2DC approach can increase efficiency in power distribution compared to a parallel approach

Low power solutions are crucial for future HEP (and others) experiments:

Estimated lowest power consumption for simple generic pixel: ≈10 μW

10μW continuous -> 10μJ energy

Energy deposited by a MIP particle: 0.2 – 10fJ

Required energy/deposited energy >> 10^{10} !!!
'Huge' energy inefficiency

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Conclusions

The field of semiconductor detectors encompasses different scientific and technology fields: solid state physics, nuclear and particle physics, electrical engineering, …

Some of the issues relevant to particle and radiation detectors:

- Development of new detection techniques based on novel and well established semiconductor material: (phonon-based detectors, quantum detectors, compounds, low dimensional)
- Integration with electronics (monolithic solution to achieve more compactness and reduce cost) , 3D structures
- Topologies optimization (power reduction, noise reduction)
- Simulation and modelling;
- Radiation hardness