From the pn junction to the particle detector

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Outline

- Advantages and disadvantages of semiconductor detectors
- Basic semiconductor properties
- PN junction
- Basic silicon detector design
- Signal formation
- Position resolution
- Microstrip vertex detectors
- Silicon Trackers at LHC
- Future prospects

Advantages of semiconductor detectors

- Silicon detectors are a kind of solid state ionization chamber
  - **10x lower energy per ionization pair : ~3eV** compared to gas (20-40 eV/pair) and scintillators (400-1000 eV to create a photon) → **small signal fluctuations**
  - **High density** =>
    - Large stopping power → **compact detectors**
    - **faster response** (~10ns)
    - **Smaller diffusion effect** (<10 µm) → better achievable **spatial resolution**
- Their use started in the '80s to measure the lifetime of short living particles (charm)
- Use of **planar production** technology and integrated circuit readout
  - standard industrial technology
  - → cheap

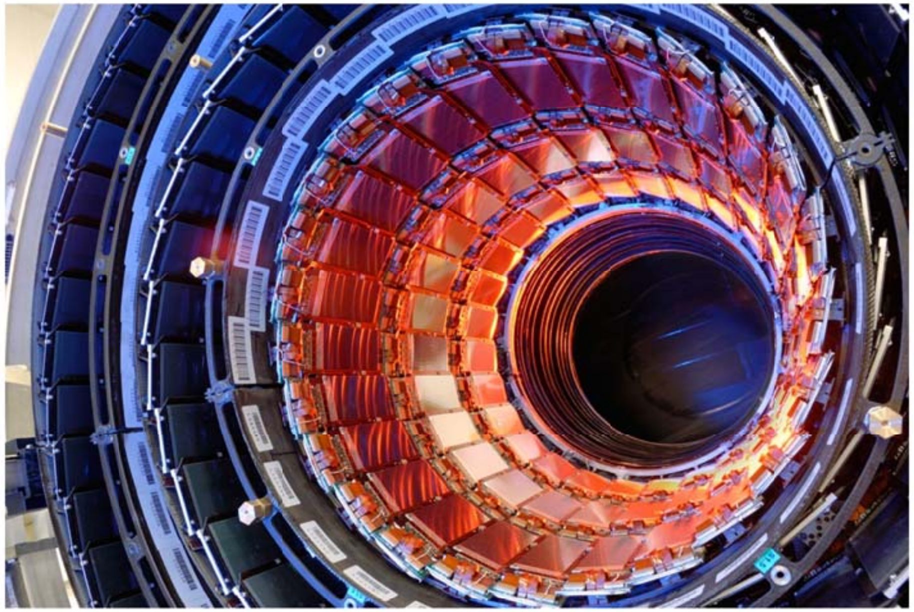
Disadvantages of semiconductor detectors

- No internal amplification
  - → small signals
  - → needs low noise electronics
  - With a few exceptions
- High cost per unit surface
  - Silicon bulk material but also interconnects and electronics
  - Large number of readout channels
  - Large power consumption → cooling is needed

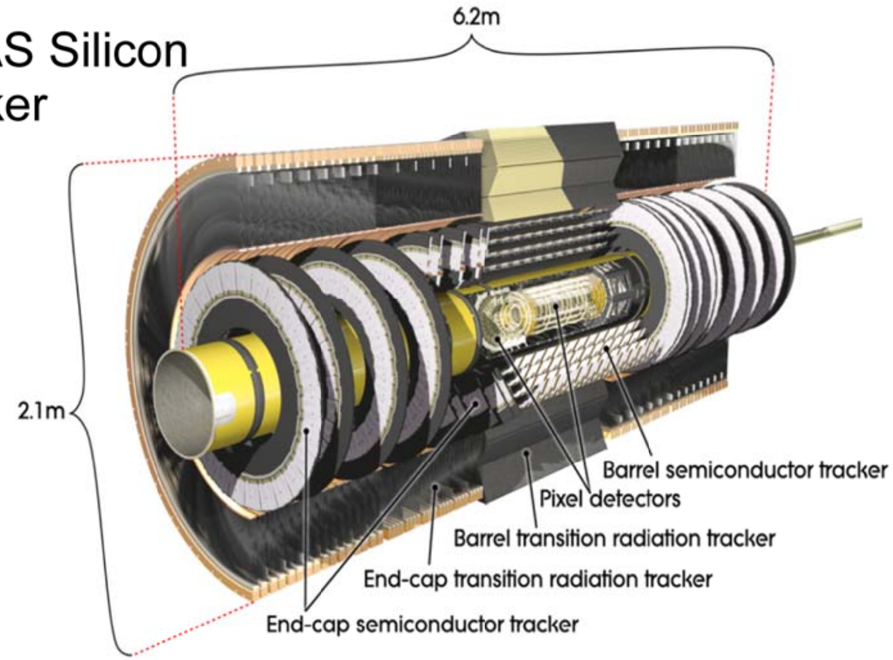
Semiconductor detectors applications

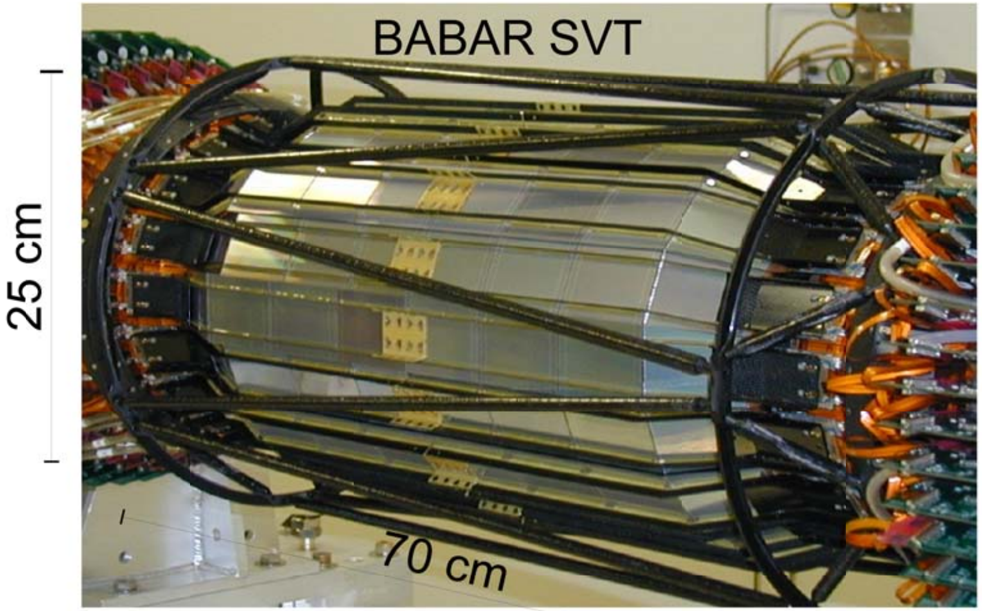
- **Tracking** of charged particles and precision **vertex** reconstruction
- **Energy** measurement up to a few MeV and gamma spectroscopy
- Medicine, security..

CMS Tracker



ATLAS Silicon Tracker

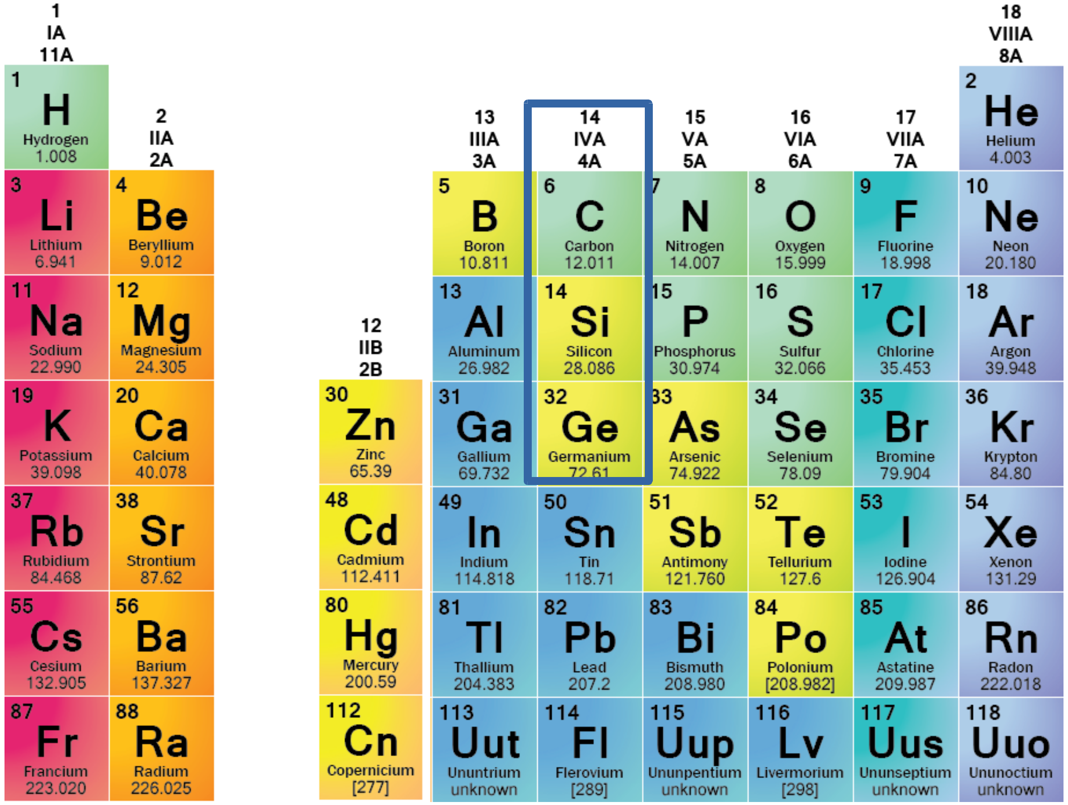




Basic Semiconductor Properties

Types of semiconductors

- Elemental semiconductors:
  - Silicon
    - Room temperature
    - Standard industrial technology for integrated circuits
    - Tracking and Vertexing for HEP experiments
  - Germanium
    - Needs cooling (liquid nitrogen) to reduce thermal generation
    - Nuclear physics gamma spectroscopy

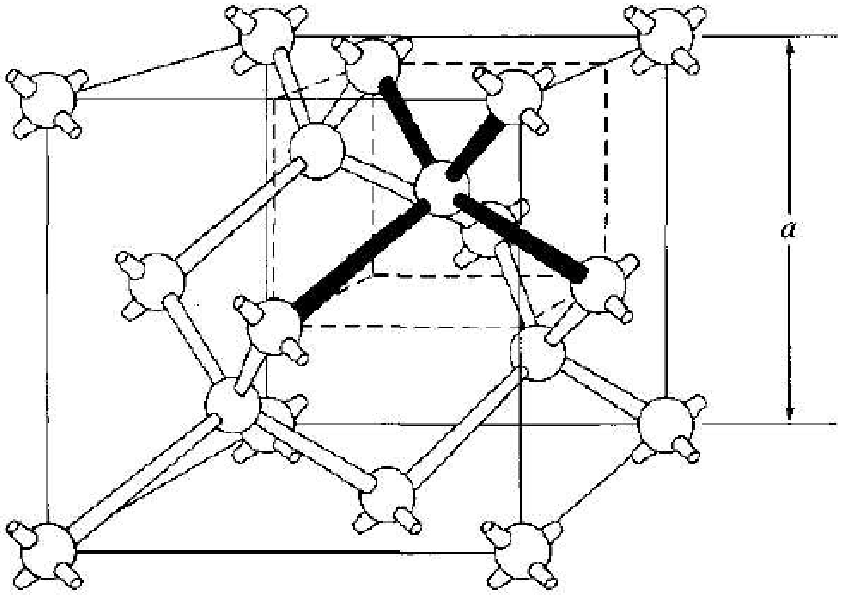


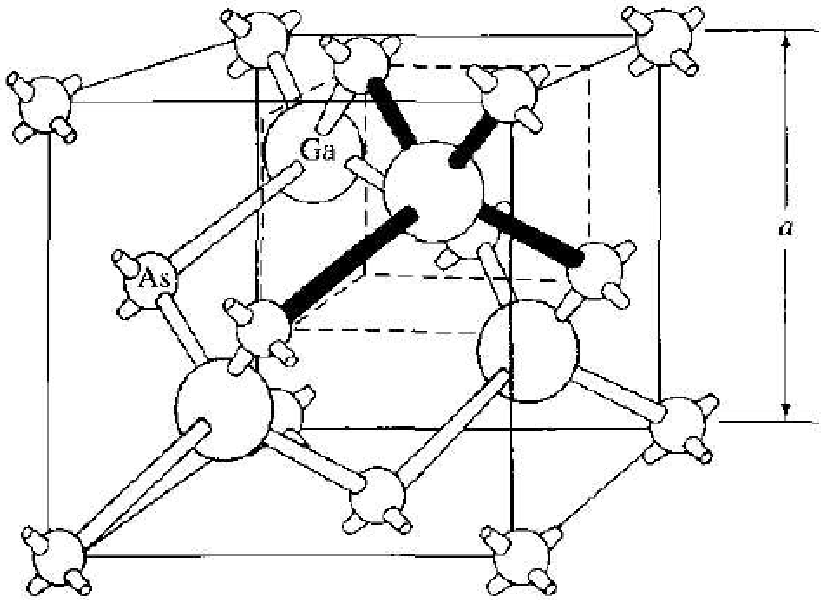
- Cmpound semiconductors
  - IV-IV: SiGe, SiC (UV)
  - III-V: GaAs
  - II-VI: ZnSe , CdTe (High Z)

* usually considered an isolator

Crystal Structure

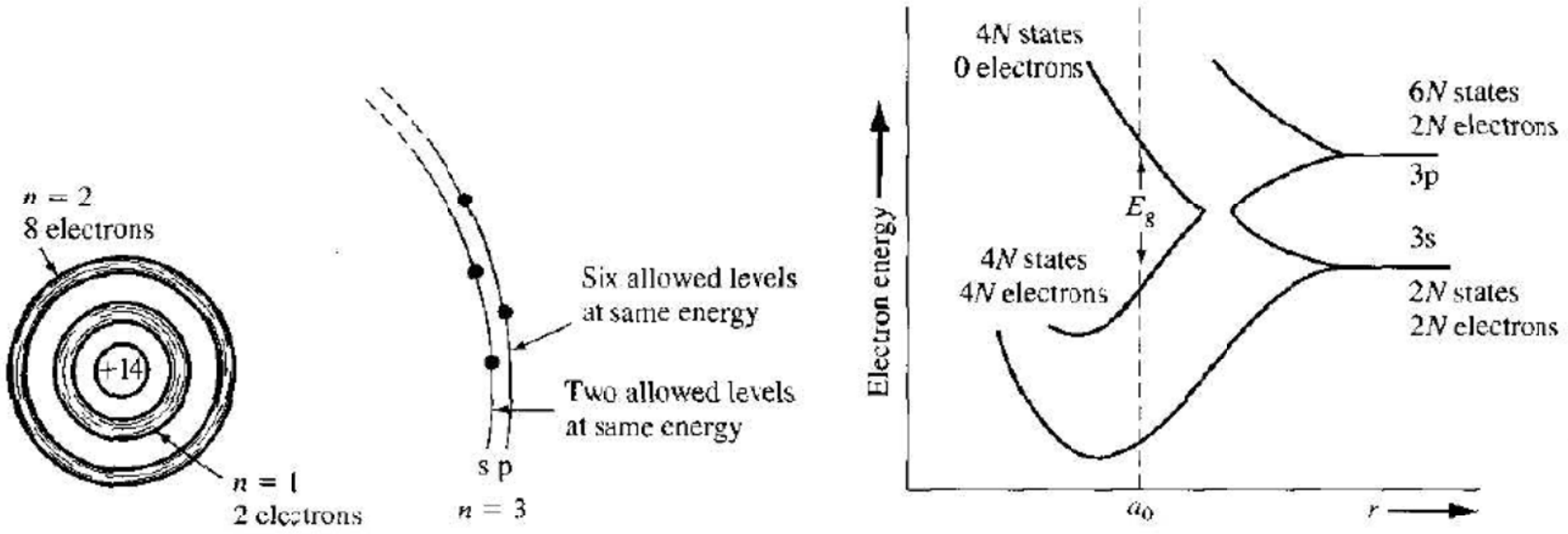
- Many properties relevant for the utilization as detectors are related to the solid state structure of the semiconductor crystal
- Si, Ge and Diamond*
  - Crystal structure is the diamond lattice
  - Each atom surrounded by four neighbors at the corners of a tetrahedron
- III-V es. GaAs
  - Zincblende lattice
  - Two sublattices shifted by one quarter along the diagonal of the cube

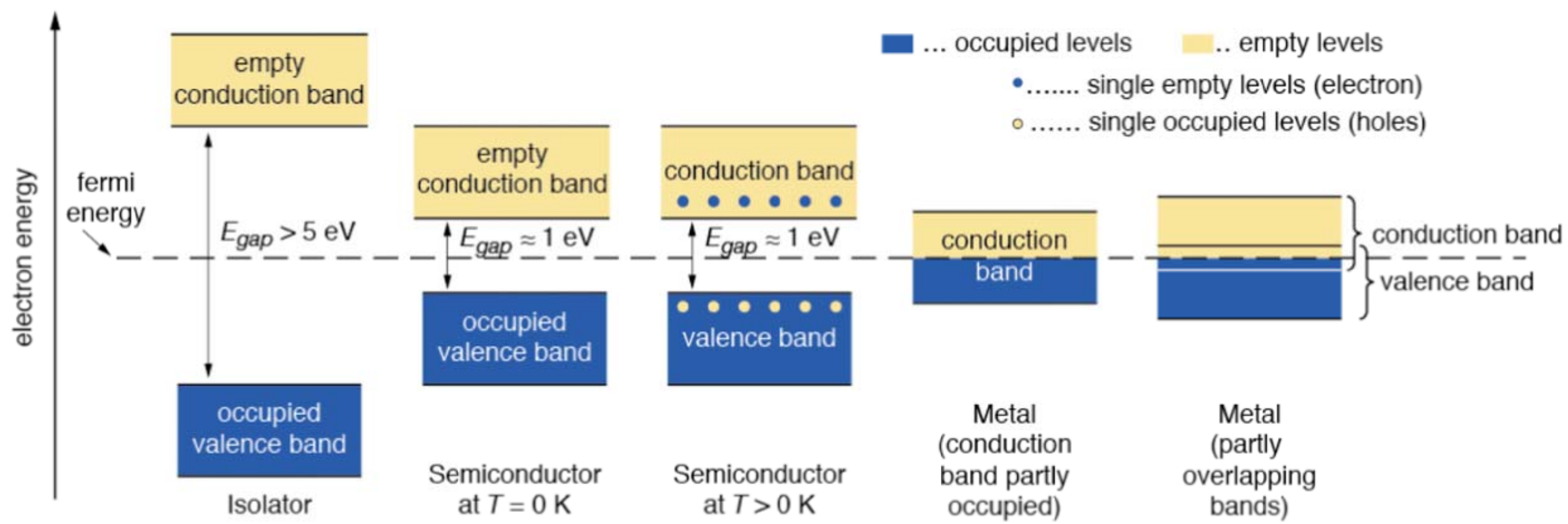




Band Structure

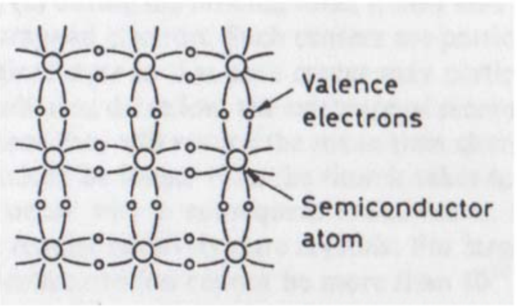
- Periodic arrangement of atoms → formation of allowed and forbidden energy bands



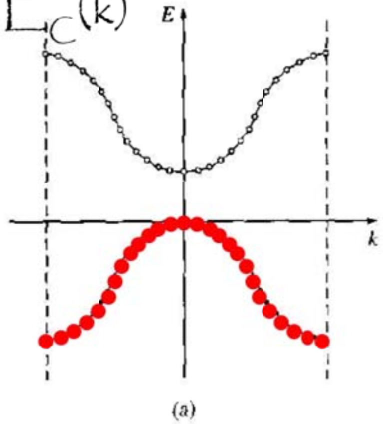


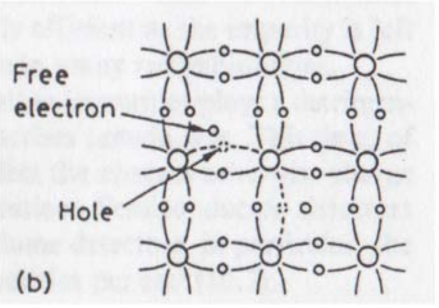
Bond model for free carriers

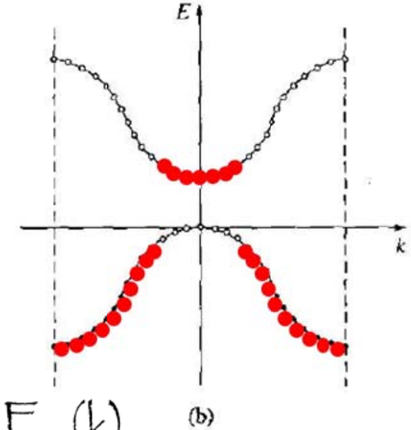
- At 0 Kelvin **all electrons** participate in **covalent** bonds between atoms
  - Are in the **valence band**
- At **higher temperatures electrons** can jump to the **conduction band**
  - Are free to move with a mass determined by the curvature of $E_C(k)$
- A **hole** with positive charge is left behind. It can be easily occupied by neighboring electrons
  - **Net effect is the movement of a positive charge** with a mass determined by the curvature of the $E_V(k)$



$E_C(k)$







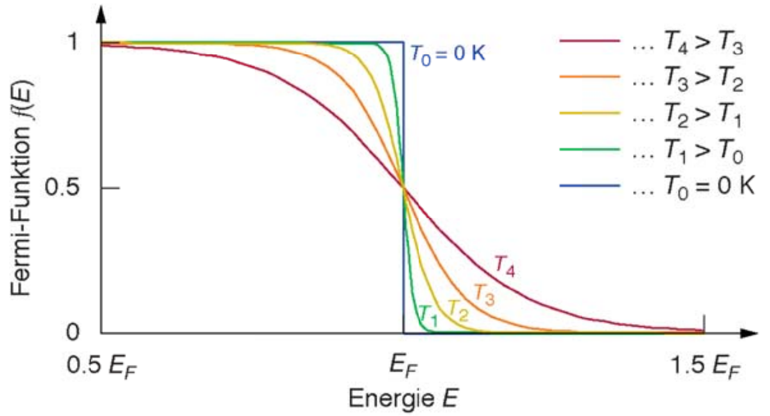
$E_V(k)$

=> conduction is due both to holes and electrons

Fermi level

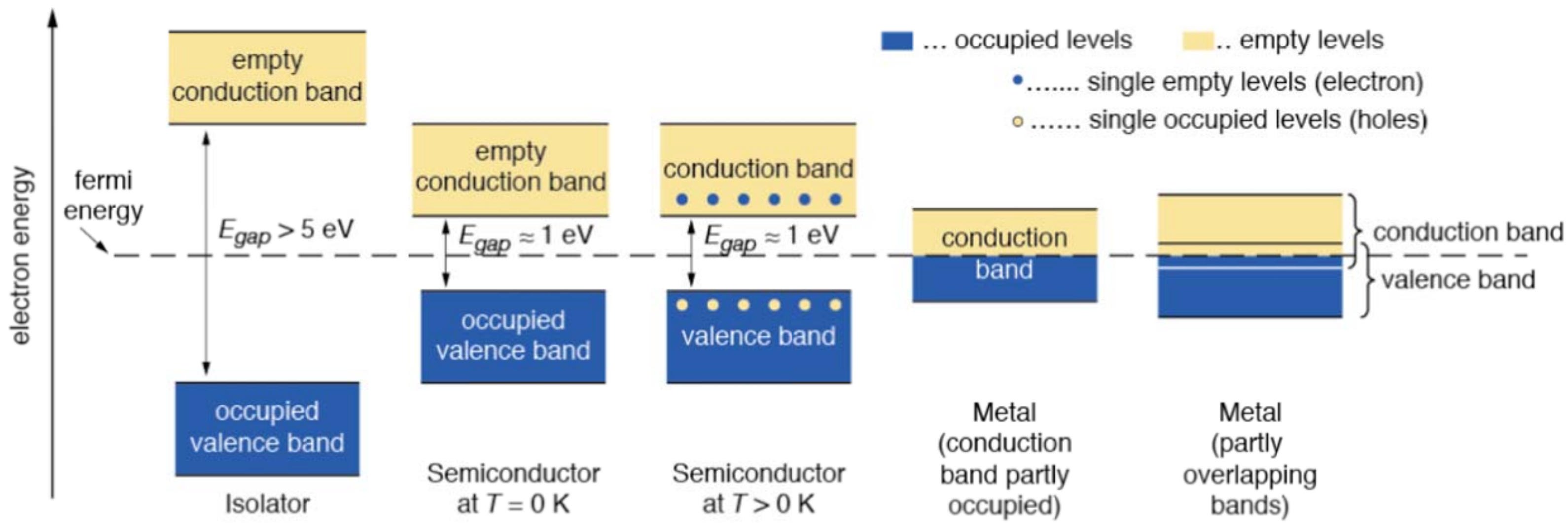
- The occupation of the states is described by the Fermi-Dirac statistics

$$f_F(E) = \frac{1}{1+e^{\frac{E-E_F}{KT}}}$$

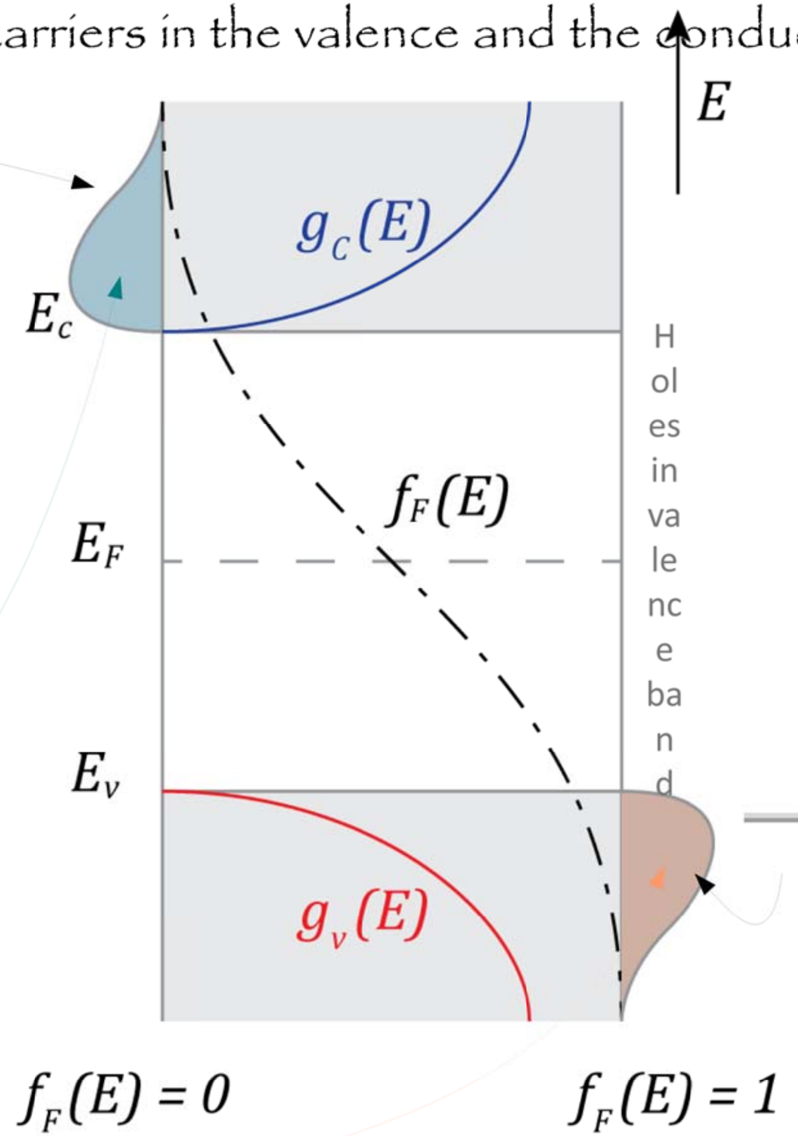


- The Fermi level is the energy level that has 50% probability of being occupied

- For semiconductors and isolators is in the bad gap, for metals is in the band gap



- The density of available quantum states and the Fermi function determines the number of charge carriers in the valence and the conduction band



The area is proportional to the electron and hole volume density

Intrinsic carrier concentration

- Extremely pure semiconductors acre called "intrinsic"
- At thermal equilibrium the density of electrons and holes is equal $n_e = n_h = n_i$
- The carrier density is $n_i = \sqrt{Nc\,Nv}\, e^{\frac{-Eg}{2KT}} \propto T^{3/2} e^{\frac{-Eg}{2KT}}$

Table 4.2 | Commonly accepted values of n_i at $T = 300$ K

		Eg
Silicon	$n_i = 1.5 \times 10^{10}$ cm^{-3}	1.12 eV
Gallium arsenide	$n_i = 1.8 \times 10^{6}$ cm^{-3}	1.43 eV
Germanium	$n_i = 2.4 \times 10^{13}$ cm^{-3}	0.67 eV

- For silicon there is ~ 1 electron every 10^{12} atoms
- The **intrinsic Fermi level** in a pure semiconductor is near the **center of the gap**
- In general even in non pure semicondutors $np = n_i^2$
  - where n and p are the concentrations for negative and positive carriers

Carrier mobility and resistivity

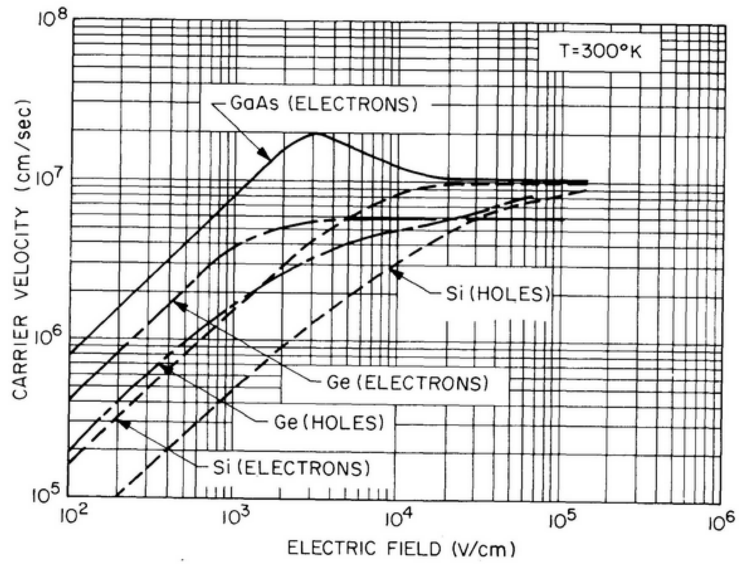
$$\vec{v}_e = \mu_e \vec{E} \qquad \mu_e = \frac{e\,\tau_e}{m^*_n}$$

$$\vec{v}_h = -\mu_h \vec{E} \qquad \mu_h = \frac{e\,\tau_h}{m^*_h}$$

m* is the effective mass
τ is the average time between collisions
μ is the mobility

For Si@300K $\mu_e = 450\,cm^2/Vs$

$\mu_h = 1450\,cm^2/Vs$



$$\vec{J}_{drift} = e(\mu_n n + \mu_p p)\vec{E} \qquad \rho = \frac{1}{e(\mu_n n + \mu_p p)}$$

For pure Si@300K $n = p = 1.45\,10^{10}\,cm^{-3}$ $\rho = 230\,k\Omega cm$

How to change the electrical properties, for example increase the conductivity?

Properties summary

Material → Property ↓	Si	Ge	GaAs	GaP	CdTe	Diamond*
Z	14	32	31;33	31;15	48;52	6
ρ(g/cm^3)	2.328	5.326	5.32	4.13	5.86	3.52
Eg(eV) at 300K	1.11	0.66	1.42	2.26	1.44	5.47-5.6
ε_r	11.9	16	12.8	11.1	10.9	5.7
μ_e at 300K (cm^2/Vs)	~1450	3900	8500	<300	1050	1800
μ_h at 300K (cm^2/Vs)	~450	1900	400	<150	100	1200
Resistivity 300K(Ωcm)	2.3 10^5	47	~10^8		~10^9	>10^{42}
Breakdown field (V/cm)	3 10^5	~10^5	4 10^5	10^6		3 10^7
Energy to create eh pair	**3.62**	**2.9**	**4.2**	**~7**	**4.43**	**13.25**

Source: http://www.ioffe.rssi.ru/SVA/NSM/Semicond/ ; S.M.Sze, *Physics of Semicon. Devices* , J. Wiley & Sons, 1981,
J. Singh, Electronic & Optoelectronic Properties of Semiconductor Structures, Cambridge University Press, 2003

Constructing a Detector

One of the most important parameter of a detector is the **signal-to-noise-ratio** (SNR). A good detector should have a large SNR.
However this leads to **two contradictory requirements**:

- **Large signal**
  - low ionization energy -> small band gap
- **Low noise**
  - very few intrinsic charge carriers -> large band gap

An optimal material should have $E_g \approx 6$ eV.

In this case the conduction band is almost empty at room temperature and the band gap is small enough to create a large number of e^-h^+ pairs through ionization.

Such a material exist, it is Diamond. However even artificial diamonds (e.g. CVD diamonds) are too expensive for large area detectors.

22 May 2011 Thomas Bergauer (HEPHY Vienna)

An interesting point (cont.)

Constructing a Detector (cont.)

Let's make a simple calculation for silicon:

- Mean ionization energy I_0 **= 3.62 eV**,
- mean energy loss per flight path of a mip ***dE/dx*** **= 3.87 MeV/cm**

Assuming a detector with a thickness of $d = 300\ \mu\text{m}$ and an area of $A = 1\ \text{cm}^2$.

- **Signal of a mip in such a detector:**

$$\frac{dE/dx \cdot d}{I_0} = \frac{3.87 \cdot 10^6\,\text{eV/cm} \cdot 0.03\text{cm}}{3.62\text{eV}} \approx 3.2 \cdot 10^4\ \text{e}^-\text{h}^+\text{-pairs}$$

- **Intrinsic charge carrier in the same volume** ($T = 300$ K):

$$n_i\, d\, A = 1.45 \cdot 10^{10}\,\text{cm}^{-3} \cdot 0.03\text{cm} \cdot 1\text{cm}^2 \approx 4.35 \cdot 10^8\ \text{e}^-\text{h}^+\text{-pairs}$$

Result: The number of thermal created e^-h^+-pairs (noise) is four orders of magnitude larger than the signal.

We have to remove the charge carriers

-> Depletion zone in reverse biased **pn junctions**

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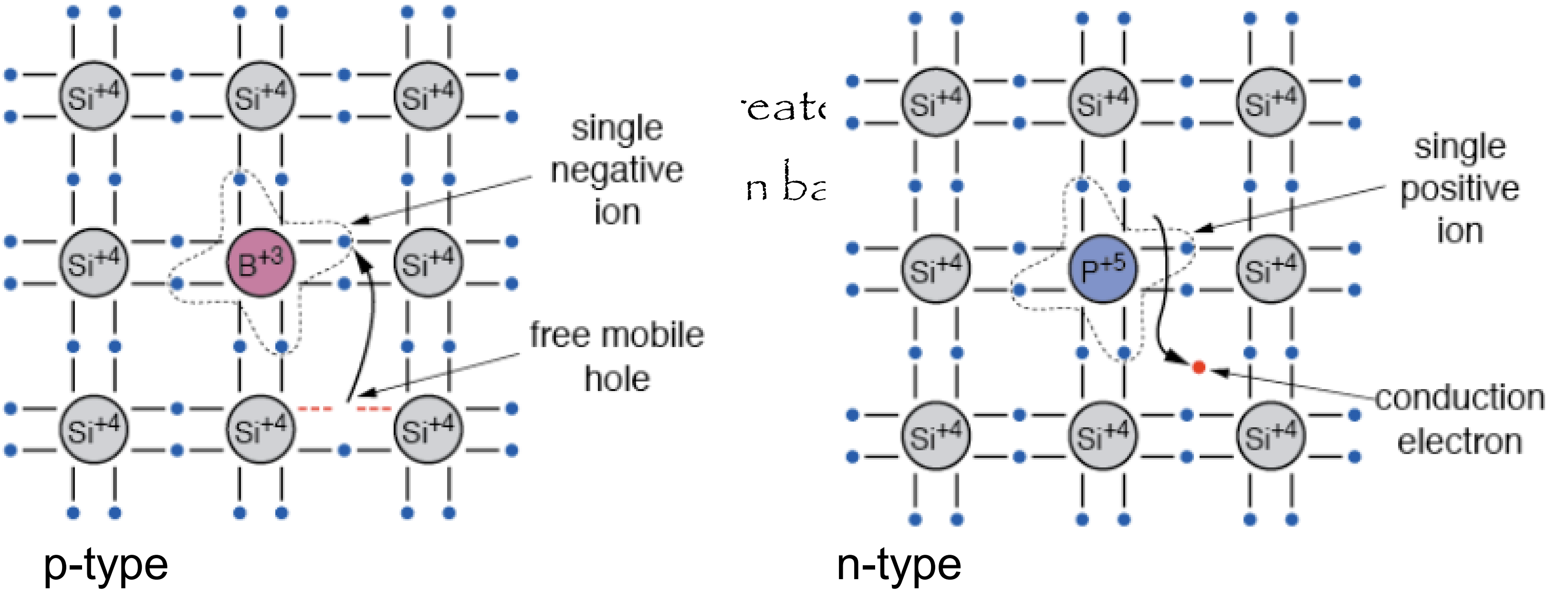
PN Junction

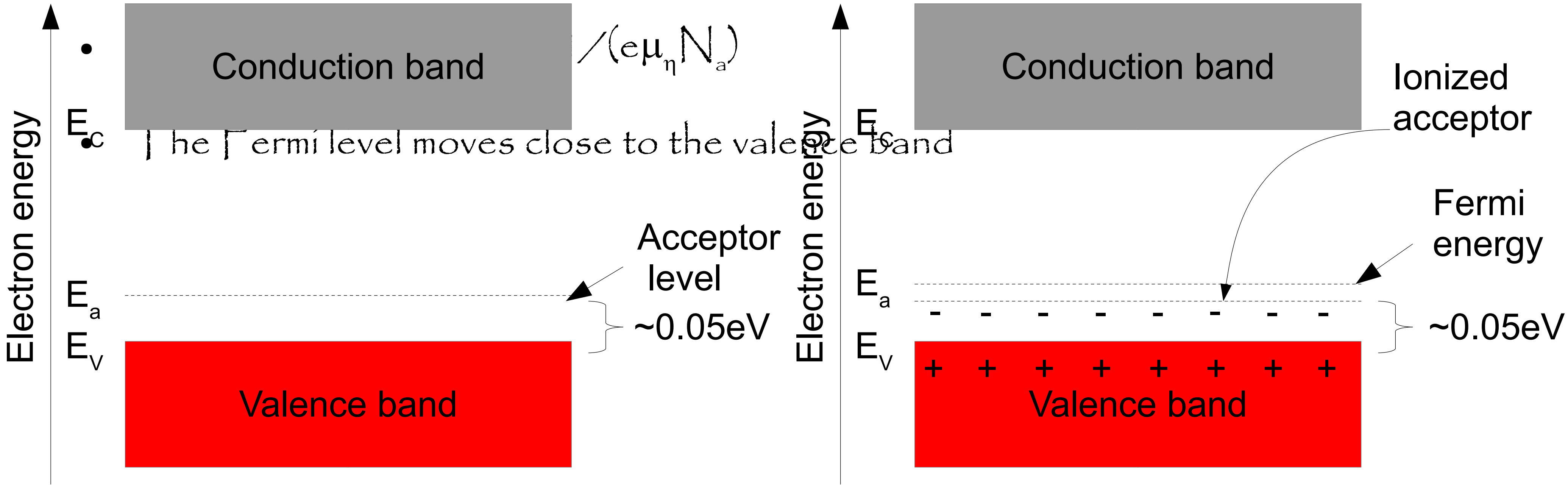
Doping

- Doping consists in adding to pure semiconductor crystal small amounts elements with three(B, Ga, Al, In) or five electrons in the outer shell (P, As, Sb): these are called **extrinsic semiconductors**
- They tend to integrate in the lattice forming four covalent bonds with the surrounding silicon atoms therefore:
  - Group III elements (eg B) tend to create holes in the valence band tend to capture electrons in the conduction band; they are called **acceptors** and the
  - eat n ba



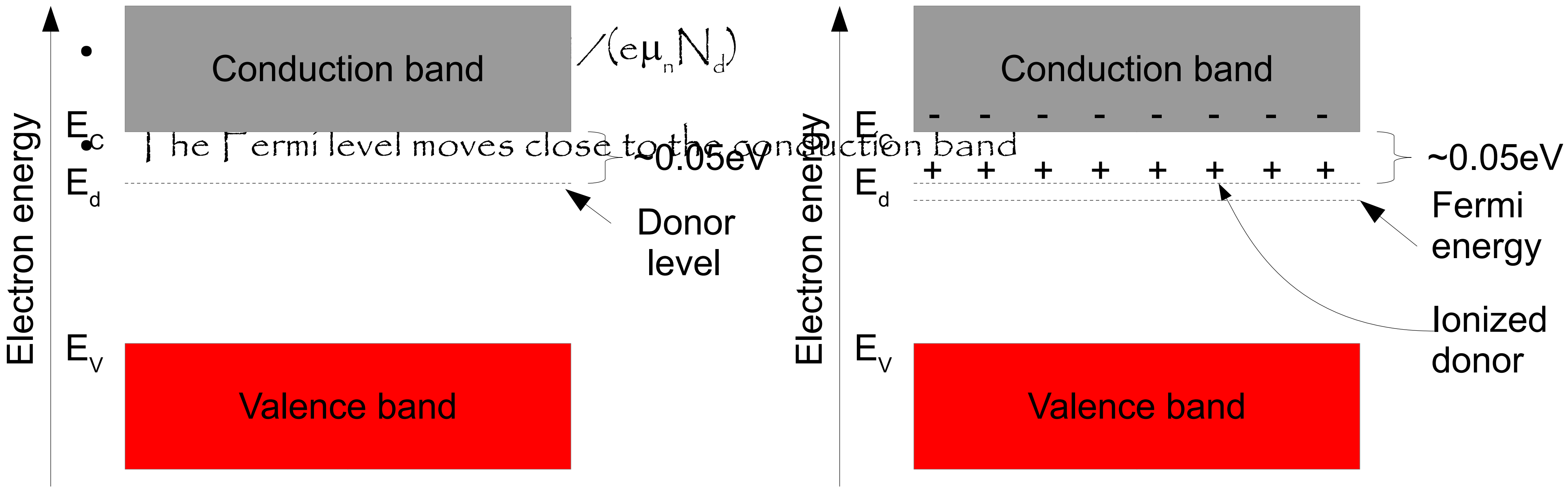
Carrier concentration in p-type semicondutors

- P-type dopants generate energy levels near the valence band
- At room temperature they are ionized and increase the hole carriers concentration
- If the density of dopants is $N_a >> n_i$ the effective carrier concentration of majority carriers is $p = N_a$
- The hole concentration (minority carriers) is reduced to $n= ni^2/N_a$
- $/(e\mu_\eta N_a)$
- The Fermi level moves close to the valence band

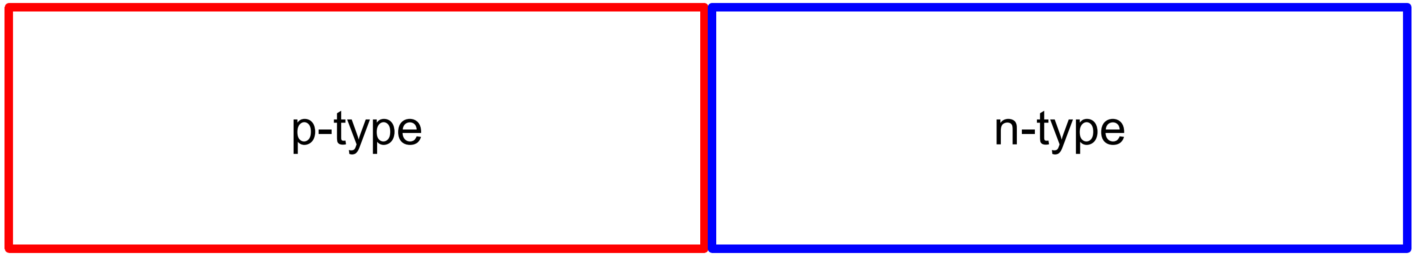


Carrier concentration in n-type semicondutors

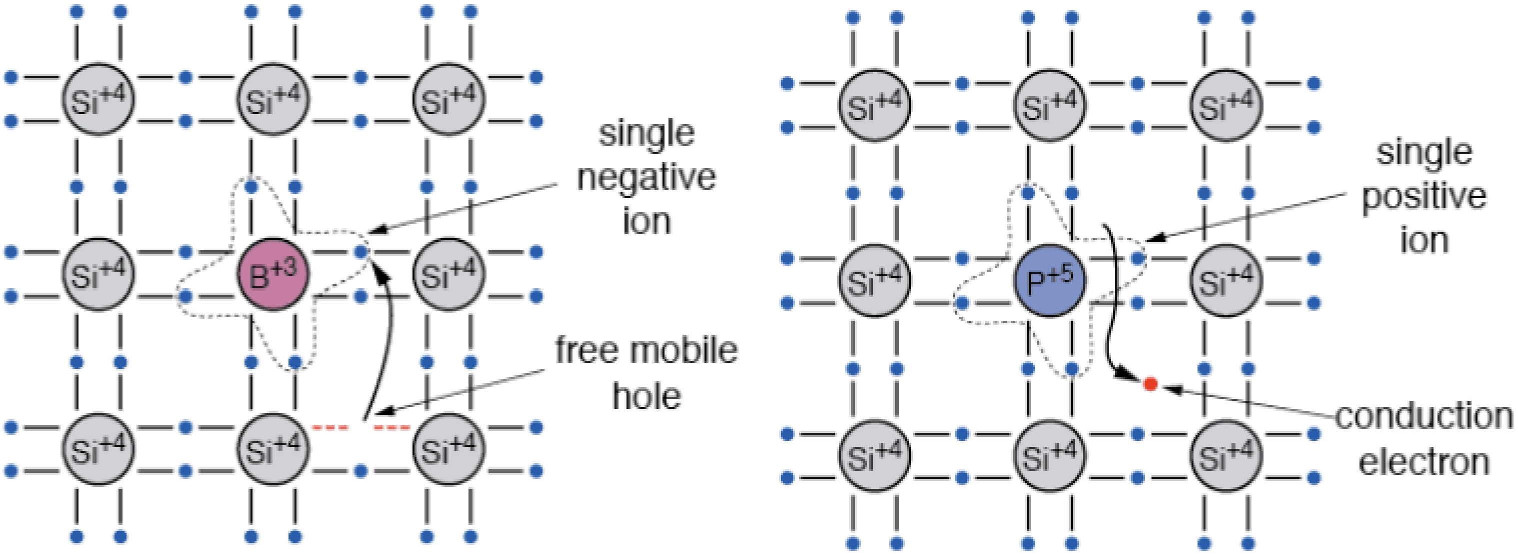
- N-type dopants generate energy levels near the conduction band
- At room temperature they are ionized and increase the electron carriers concentration
- If the density of dopants is $N_d >> n_i$ the effective carrier concentration of majority carriers is $n = N_d$
- The hole concentration (minority carriers) is reduced to $p = ni^2/N_d$
- $/(e\mu_n N_d)$
- The Fermi level moves close to the conduction band



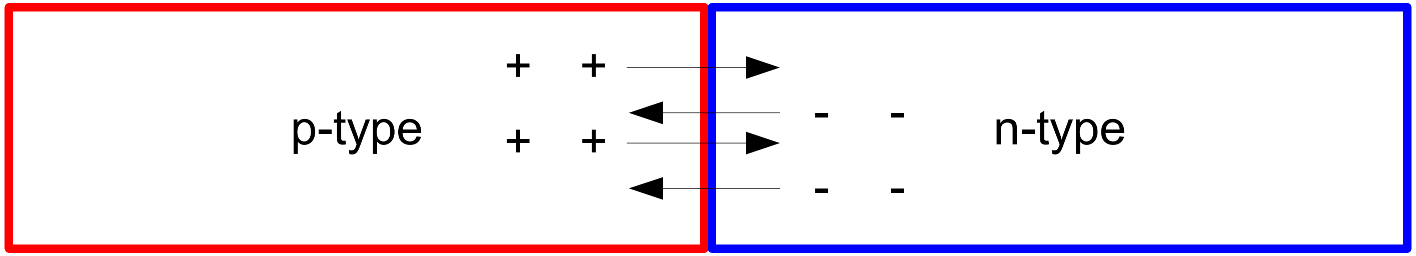
P-N junction



- We can create a PN junction by diffusing donors and acceptor elements into an intrinsic semiconductor
- In p-type there is excess positive carriers, in n-type there is excess negative carr.

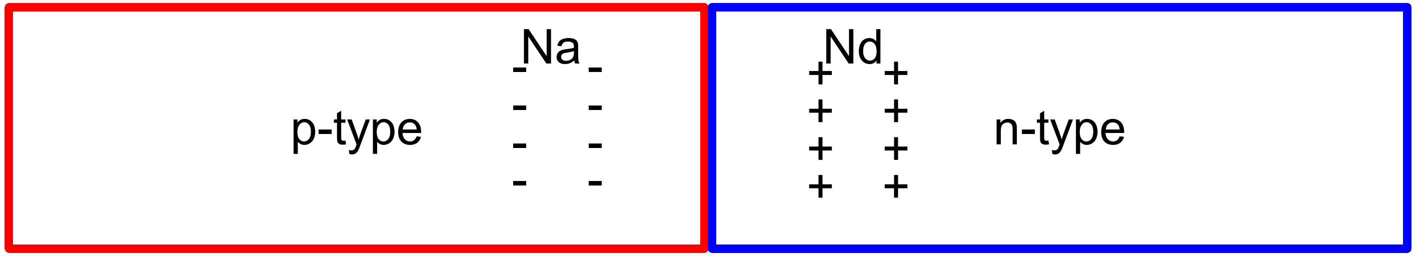


P-N junction



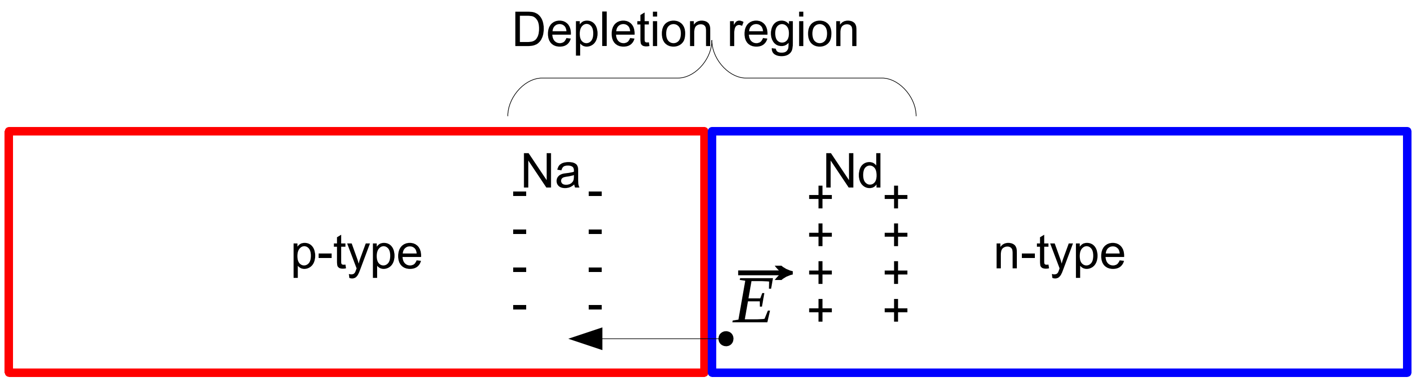
- We can create a PN junction by diffusing donors and acceptor elements into a semiconductor
- At the interface the difference in electron and holes concentration causes diffusion of excessive carriers to the other material until equilibrium is reached and the Fermi energy become the same

P-N junction



- We can create a PN junction by diffusing donors and acceptor elements into a semiconductor
- At the interface the difference in electron and holes concentration causes diffusion of excessive carriers to the other material until equilibrium is reached and the Fermi energy become the same
- The remaining ions create a region of space charge and an electric field which stops further diffusion
- The charge density is equal to the acceptor and donor densities Na, Nd

P-N junction



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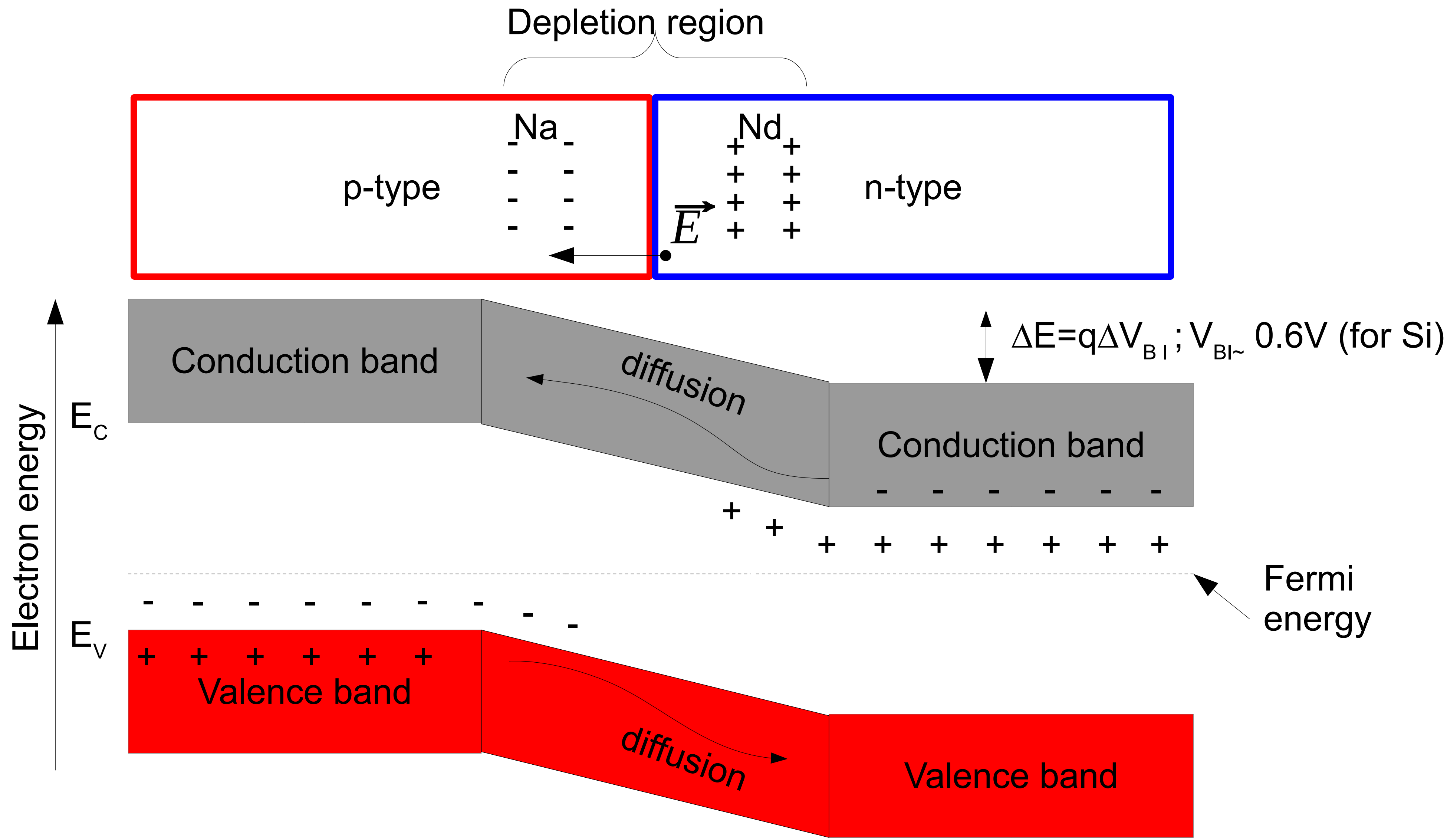
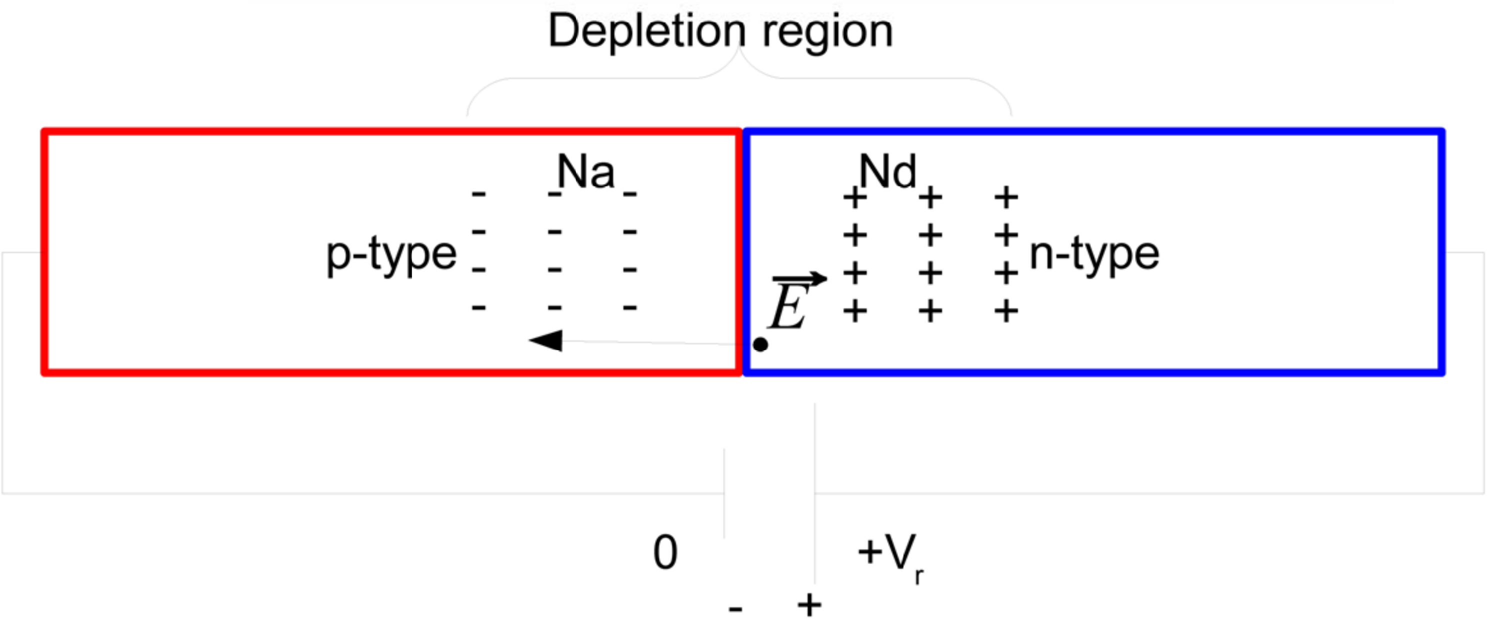
- At the interface the difference in electron and holes concentration causes diffusion of excessive carriers to the other material until equilibrium is reached and the Fermi energy become the same
- The remaining ions create a region of space charge and an electric field which stops further diffusion
- In the space charge region there are no free of charge carriers: **depletion region**

P-N junction

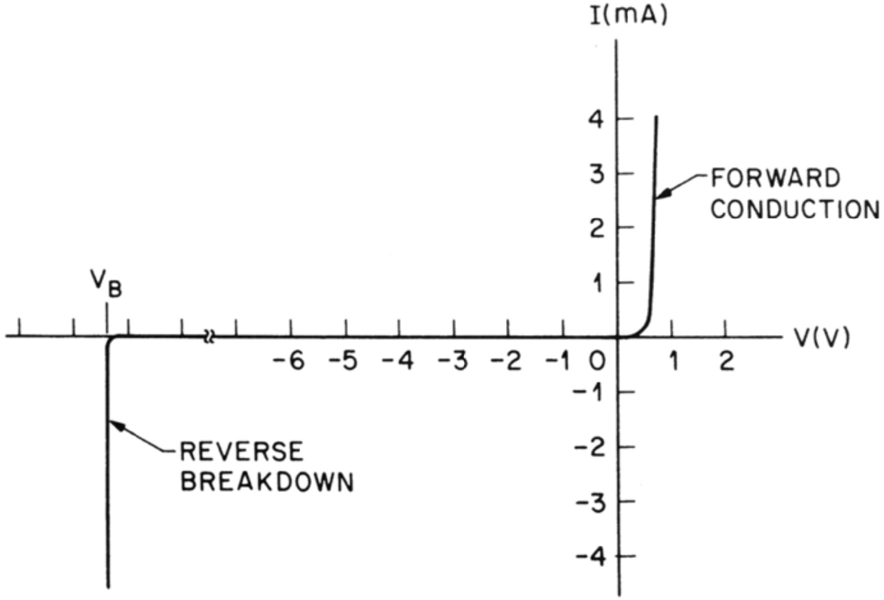


- The energy of the bands shift in order to keep the Fermi energy uniform

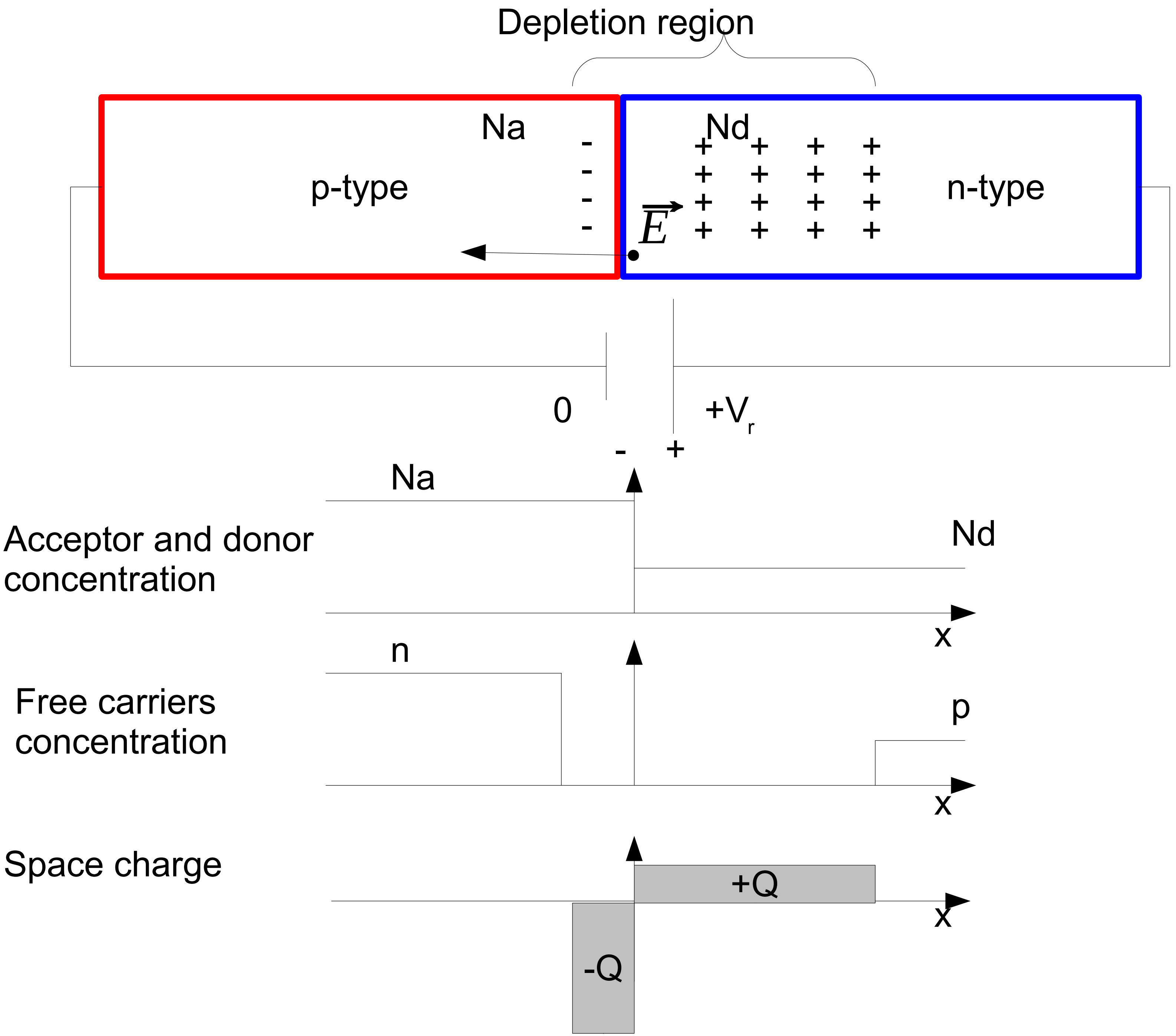
Reverse biased P-N junction



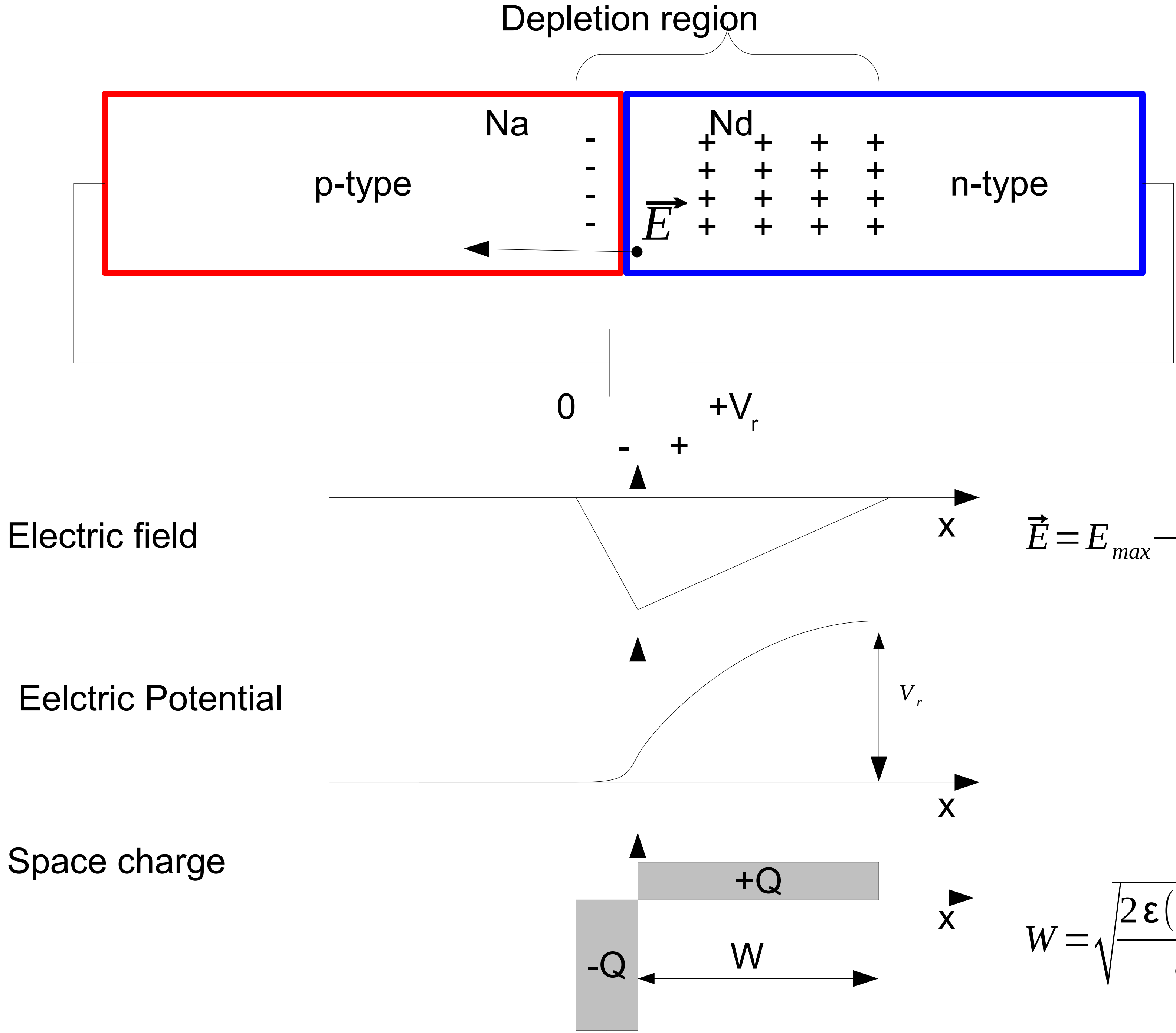
- A positive voltage to the n side with respect to the p side removes holes and electrons from the depletion zone => increase the size of the depletion zone
- The current is very small (leakage current due to thermal generation and/or diffusion) => good signal/noise



Reverse biased P-N junction with asymmetric doping



Reverse biased P-N junction with asymmetric doping



$$\vec{E} = E_{max} - \frac{eN_{eff}}{\varepsilon} x$$

$$W = \sqrt{\frac{2\varepsilon (V_r + V_{BI})}{e\, N_{eff}}}$$

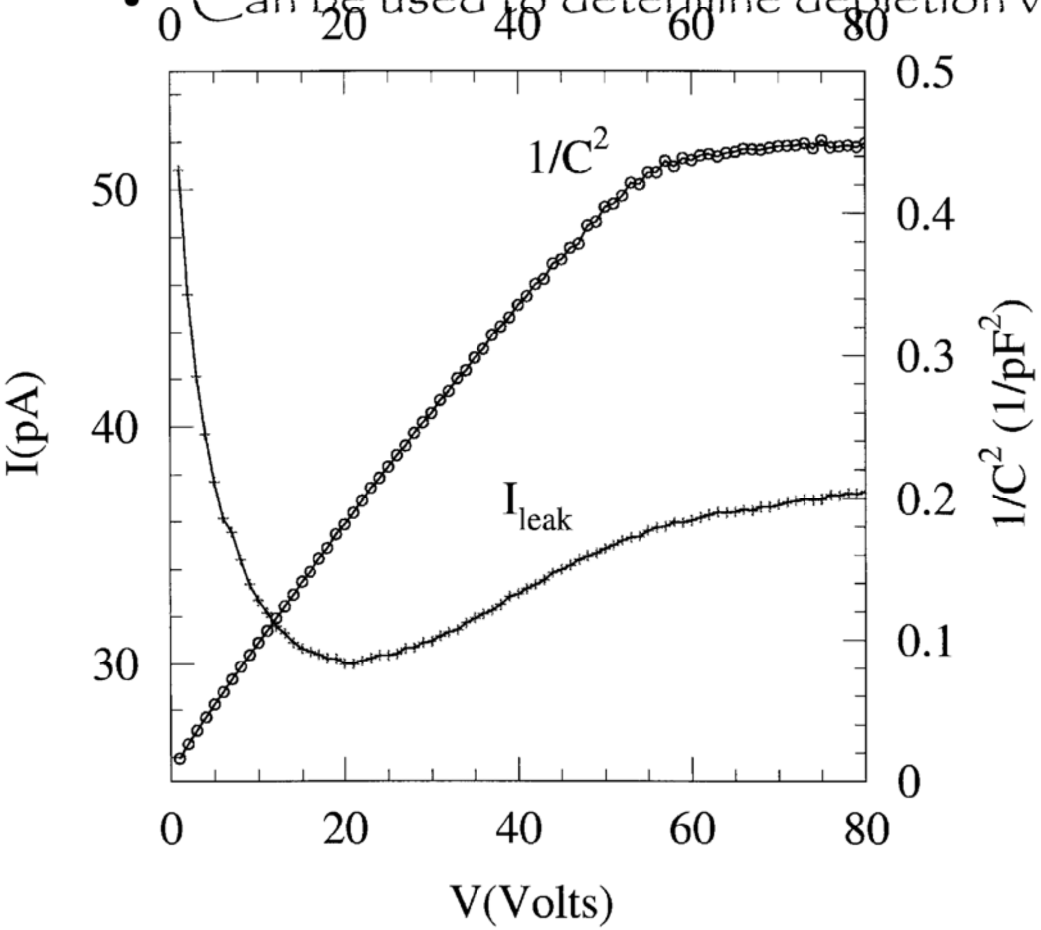
Typical PN Junction

- A typical PN junction in high purity silicon detector
  - Neff(p+) = 2.5 10^{16}cm^{-3}, Neff(bulk)=10^{12}cm^{-3}
  - Wp=0.2μm, Wbulk=28μm
- PN junction is reverse biased until the whole depth of the detector is depleted
  - Typical thickness W=300μm
  - Vdepl = 68V
- Max thickness is given by breakdown voltage
  - Si $\quad E_{BR}=3\,10^{5}\,V/cm\,;\quad N_{eff}=1\,10^{12}\,cm^{-3}\,;\quad W_{max}=\frac{\varepsilon\,E_{BR}}{e\,N_{eff}}=2\,cm$

Detector characterization

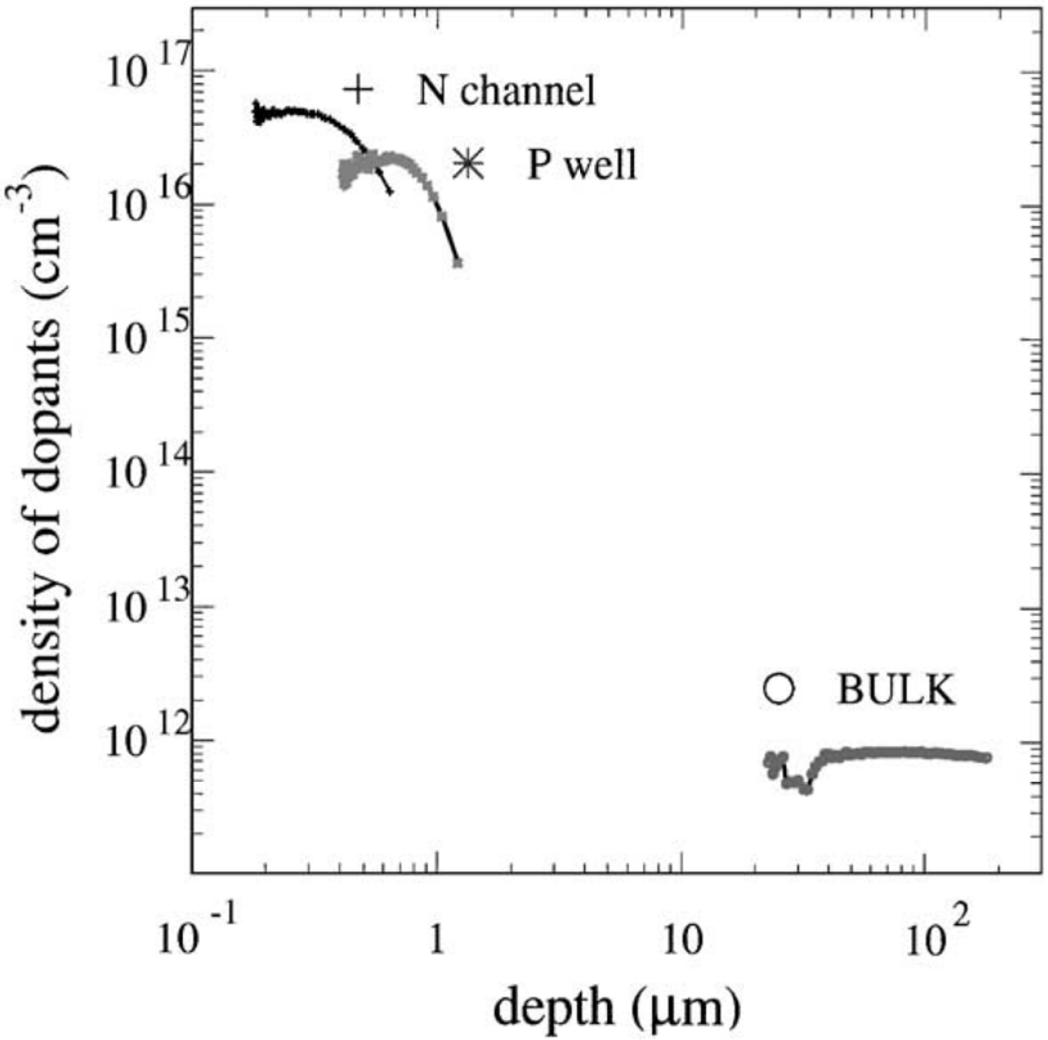
- Detector capacitance is due to parallel plate geometry
- $1/c^2$ proportional to $Vr+V_{BI}$
- Can be used to determine depletion voltage

$$C=\frac{\varepsilon A}{W}=\sqrt{\frac{\varepsilon e N_{eff}}{2(V_r+V_{BI})}}A$$



- Diode area A= 3.14 mm²
- $V_{depl} \approx 65$ Volts
- $I_{leak}(65V) \approx 30pA$ (<1nA/cm²)
- Current at low V due to hole diffusion (L_{diff}>1 cm)

Doping profiles



$$C=\frac{\varepsilon A}{W}=\sqrt{\frac{\varepsilon e N_{eff}}{2(V_r+V_{BI})}}A$$

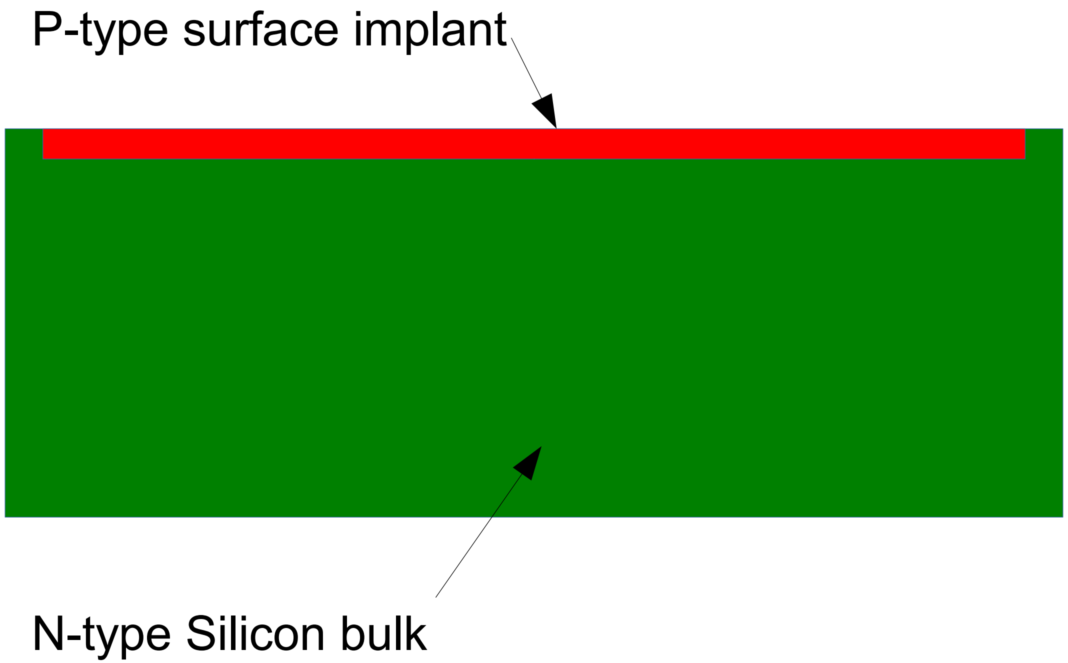
$$(V_r+V_{BI})=\frac{\varepsilon e N_{eff}}{2}\left(\frac{A}{C}\right)^2$$

- Dopant density as extracted from pin-diode test structure
- $1/c^2 \Rightarrow \rho(w)$
- $\rho(bulk) \approx 1\ 10^{12}$
- $\rho(pwell) \approx 2.5\ 10^{16}$
- $\rho(nch) \approx 7\ 10^{16}$

Basic detector design

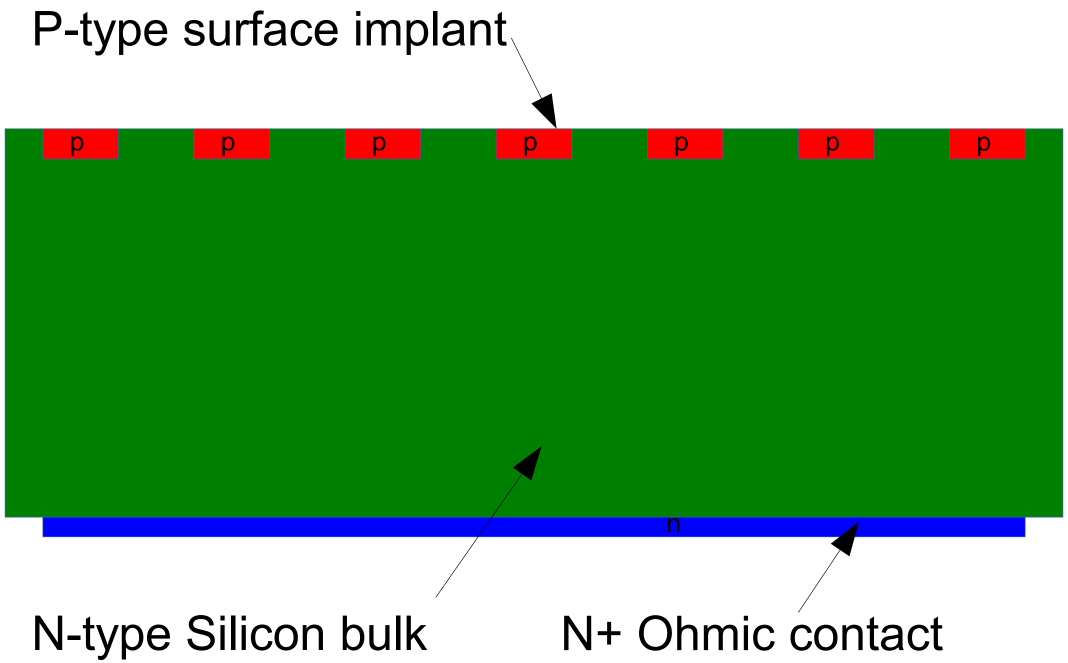
A Basic silicon detector

- Take a pn diode



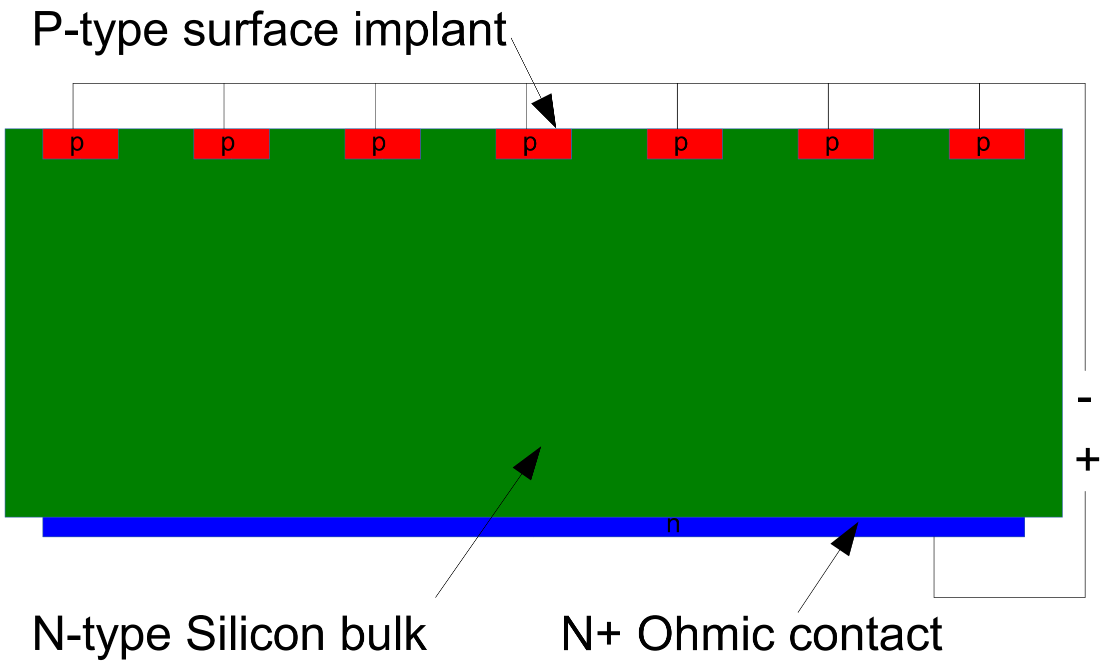
A Basic silicon detector

- Take a pn diode
- Segment it
- Add a back contact



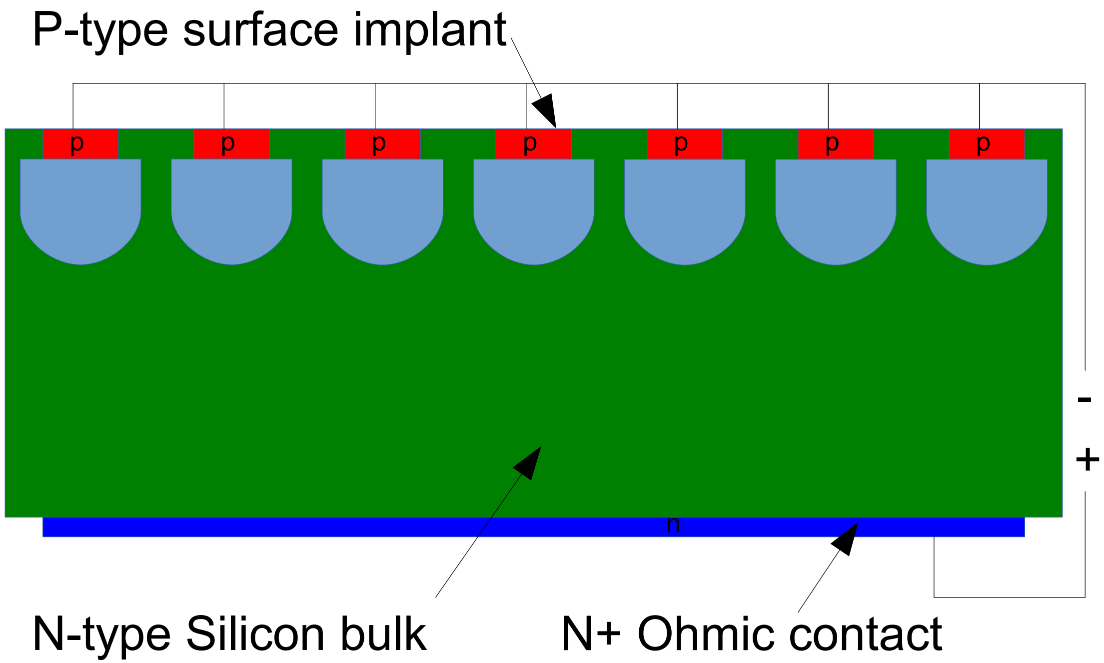
A Basic silicon detector

- Take a pn diode
- Segment it
- Add a back contact
- Apply reverse voltage



A Basic silicon detector

- Take a pn diode
- Segment it
- Add a back contact
- Apply reverse voltage
- Depletion zone grows from pn junction towards back side



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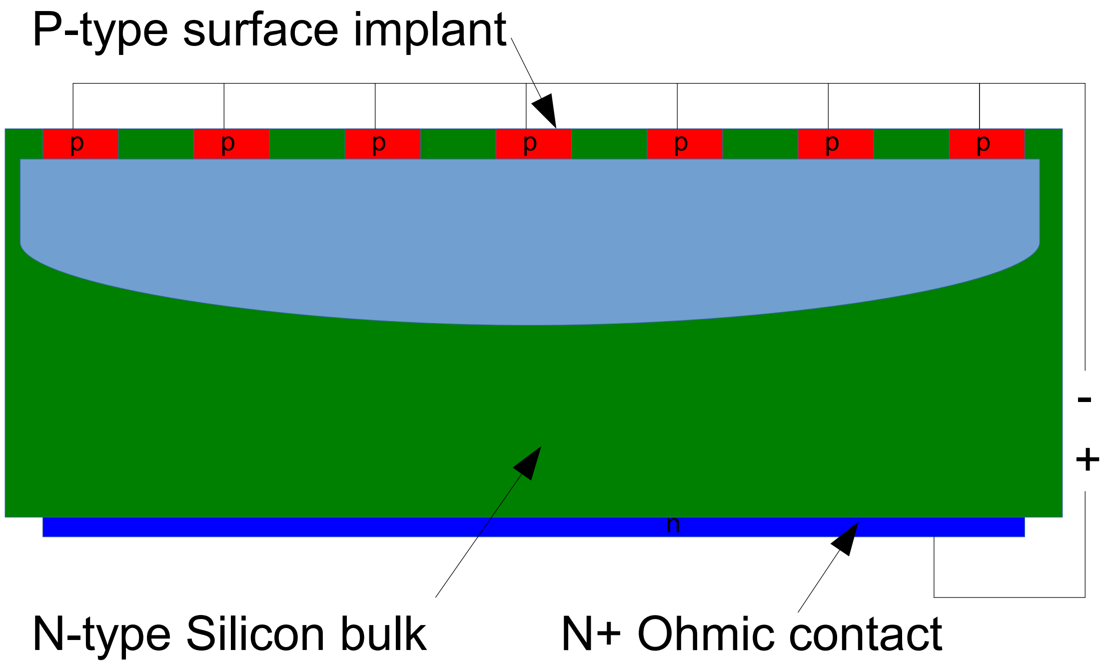

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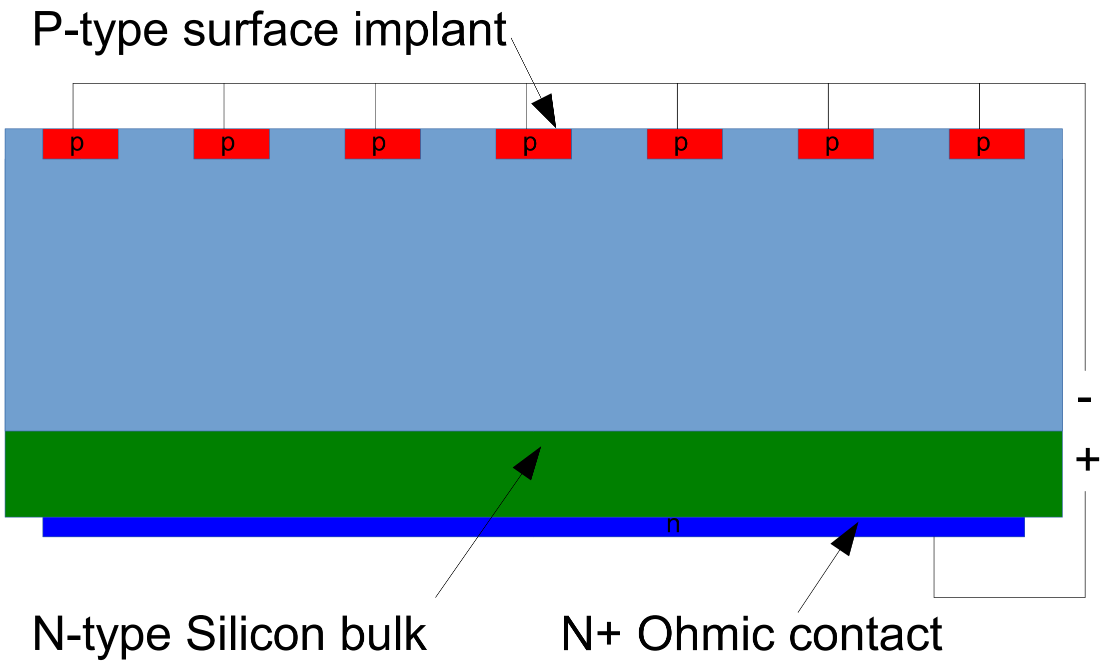

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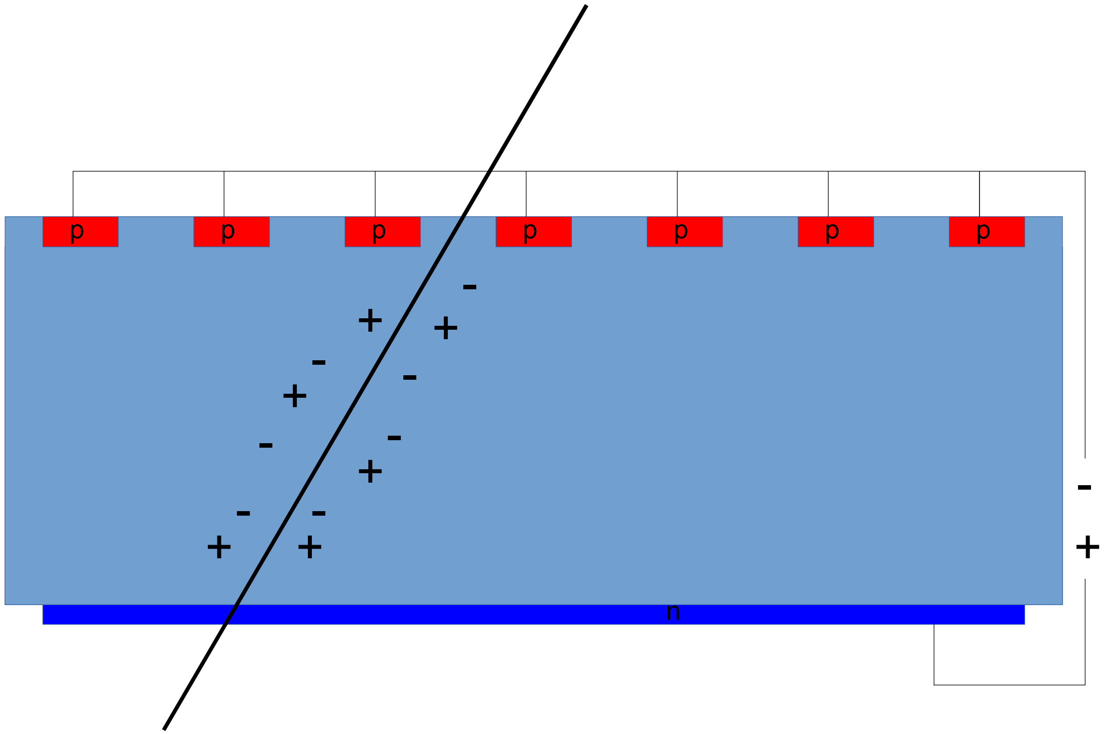
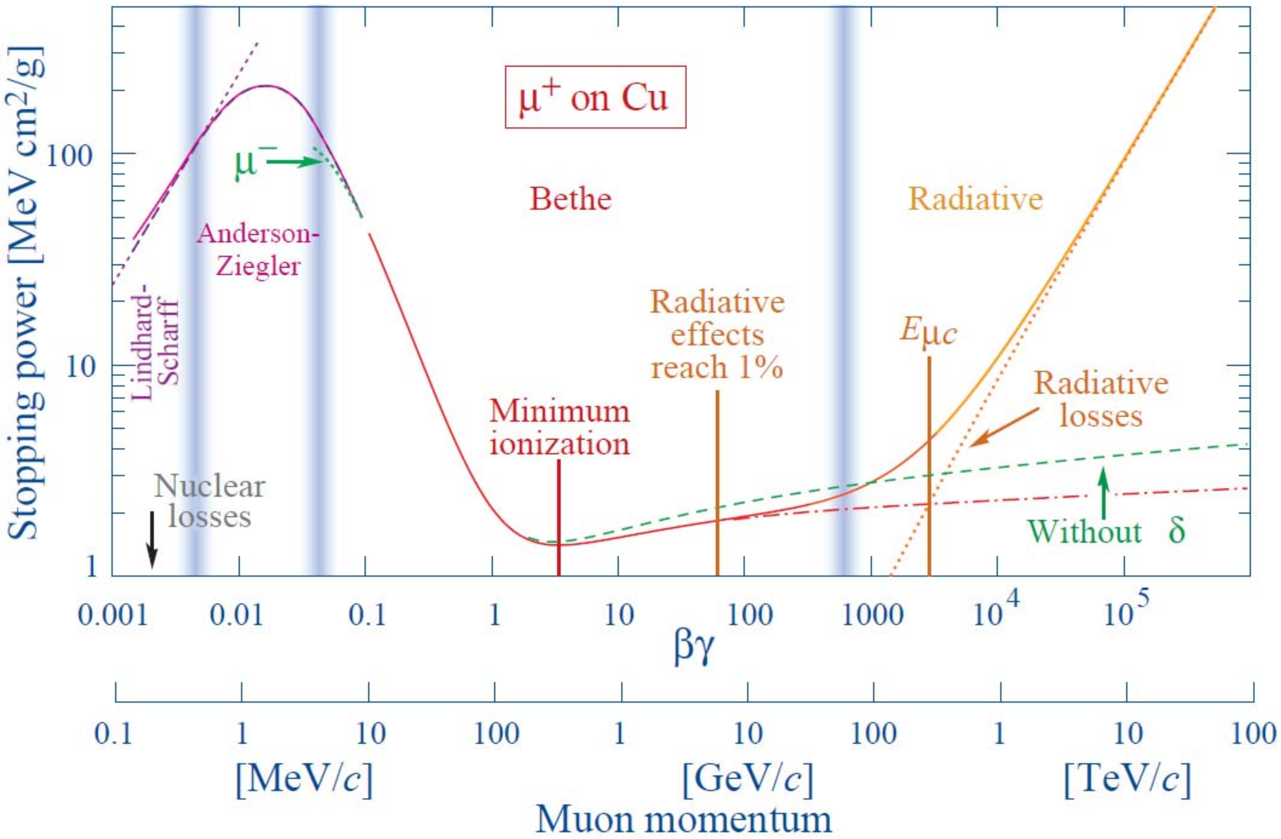


- Minimum ionizing particle generates electron hole pairs

Signal formation and position resolution

Ionizing energy loss

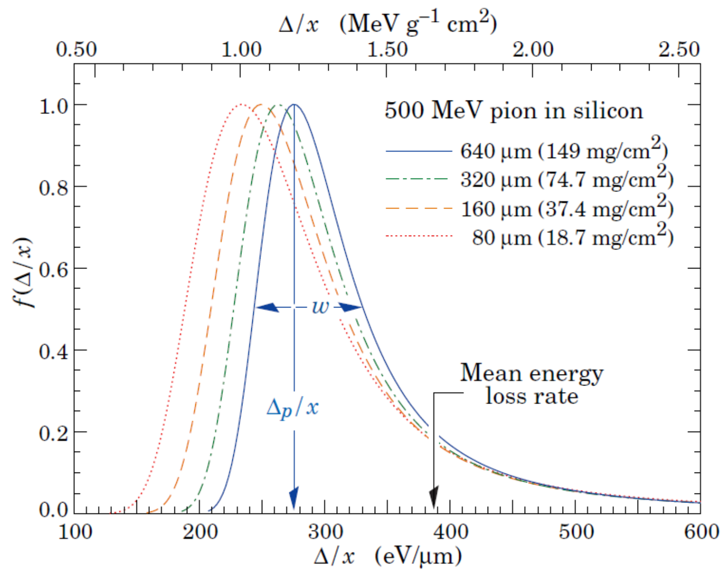
$$-\left(\frac{dE}{dx}\right)_{coll} = 2\pi N_A r_e^2 m_e c^2 \rho \frac{Z}{A}\frac{z^2}{\beta^2}\cdot\left[\ln\left(\frac{2m_e c^2\gamma^2\beta^2 W_{max}}{I^2}\right) - 2\beta^2 - \delta - 2\frac{C}{Z}\right]$$



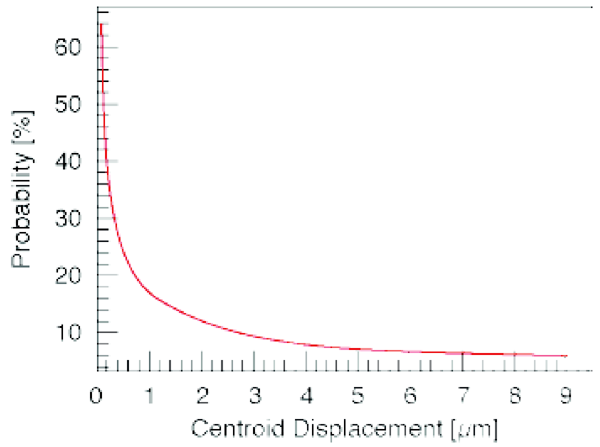
$$-\frac{1}{\rho}\frac{dE}{dx} \approx 1,5\frac{\text{MeV}}{\text{g cm}^{-2}}$$

Ionization signal and Fluctuations in energy loss

- The energy required to create an electron hole pair is bigger that the bad gap because some energy is lost in vibrations of the lattice
  Eeh=3.62eV
- In a thin (300μm) silicon detector the distribution of energy loss is described by a Landau function
- The Landau function has an asymmetric distribution with tails at large energy losses
  - Most probable value is better defined experimentally
  - Most probable energy loss in 300 μm silicon is 79keV = 22'000 pairs → 73eh pairs/μm
  - Mean energy loss is 116keV = 32'000 pairs → 107eh pairs/μm



Displacement probability (calculation) of the charge center of gravity due to δ-electrons:



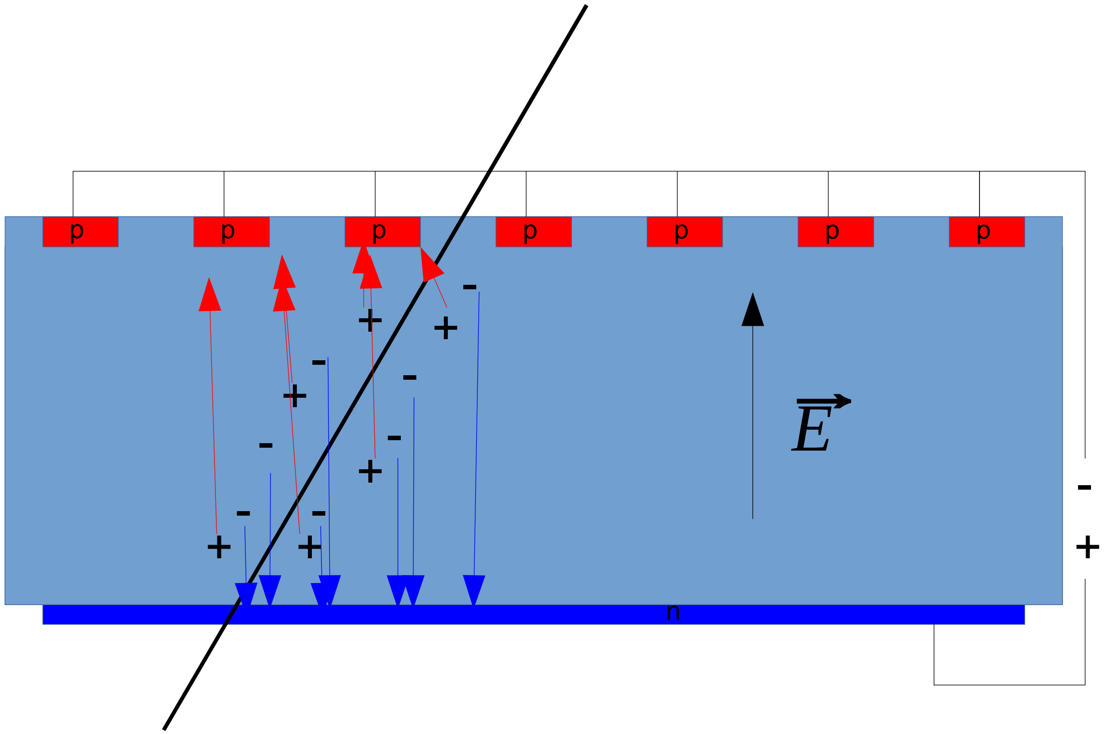
A. Peisert, *Silicon Microstrip Detectors*, DELPHI 92-143 MVX 2, CERN, 1992

Intrinsic energy resolution

- Energy resolution depends on statistical fluctuations of the number of pairs produced
- Energy loss is due to ionization and lattice exitations
- However if a particle is completely absorbed the total energy is fixed (event by event) therefore this introduces a correlation between the number of ionizations and the number of lattice excitations. Since the number of phonons is large its relative fluctuation is small
- As a result the fluctuation in the number of ionizations is smaller than the one derived from Poisson statistics (E_i= energy to create eh pair)
- $$\frac{\sigma(E)}{E}=\sqrt{\frac{FE_i}{E}}$$
- F~0.1 for Si and Ge
- E_{alpha}=5MeV → σ(E)=3.5kEV [ignoring electronics noise][check numbers!]

A Basic silicon detector

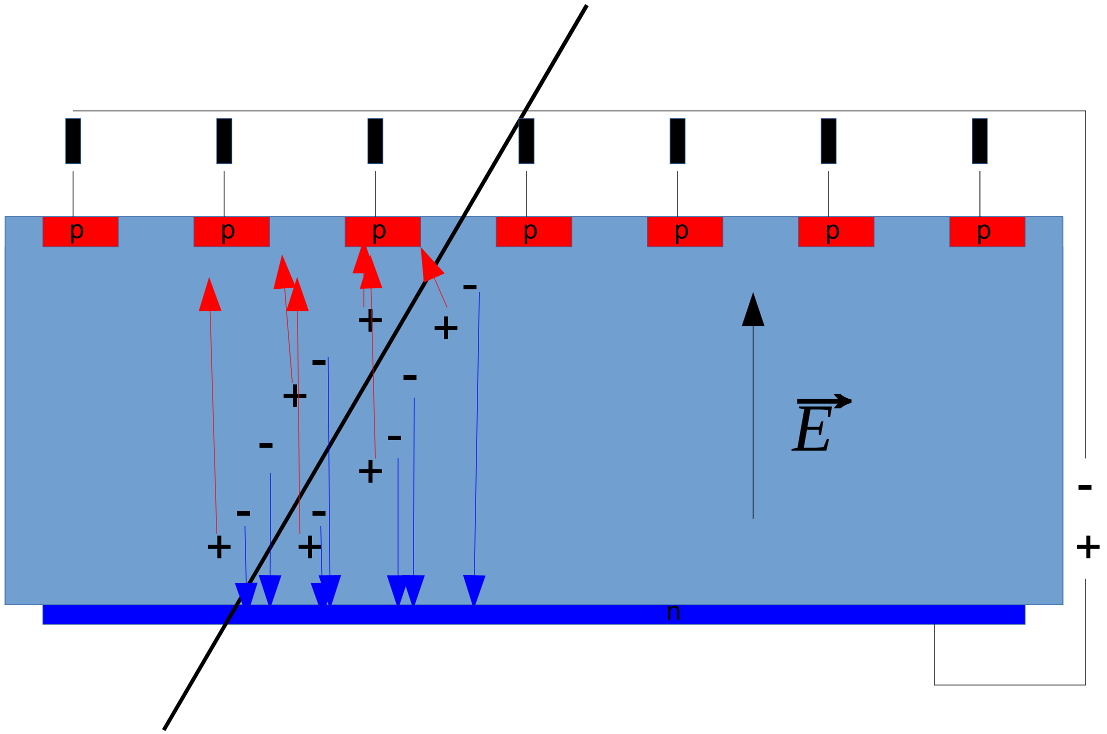
- Take a pn diode
- Segment it
- Add a back contact
- Apply reverse voltage
- Depletion zone grows from pn junction towards back side

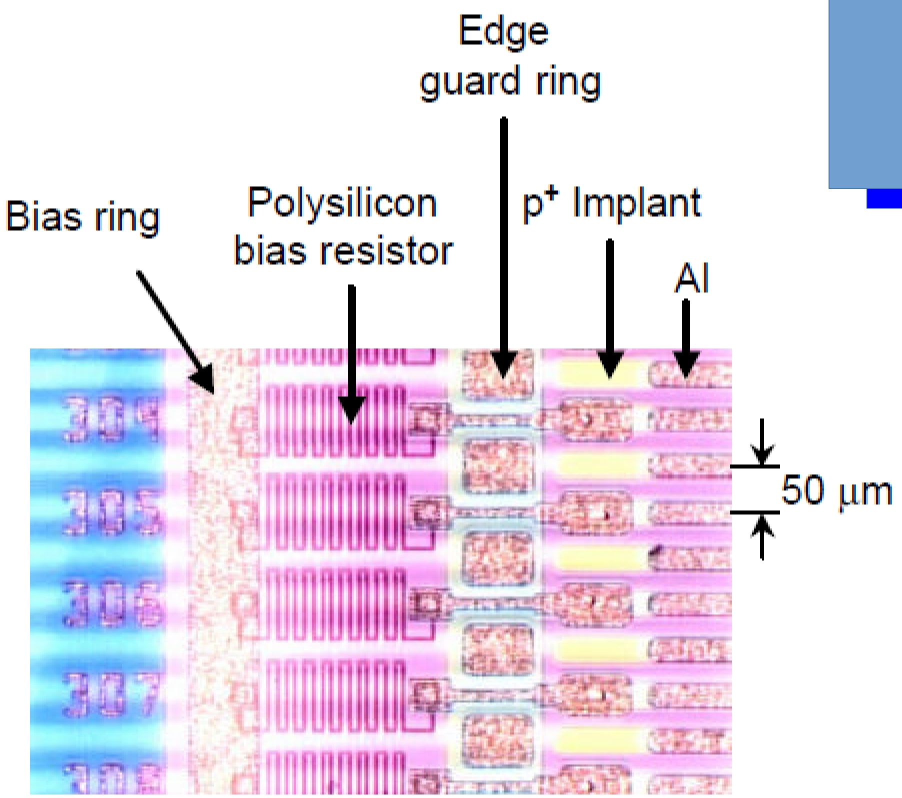


- Minimum ionizing particle generates electron hole pairs
- Charges drift toward the electrodes and induce a signal

A Basic silicon detector

- Bias resistors to decouple strips
- R~MΩ

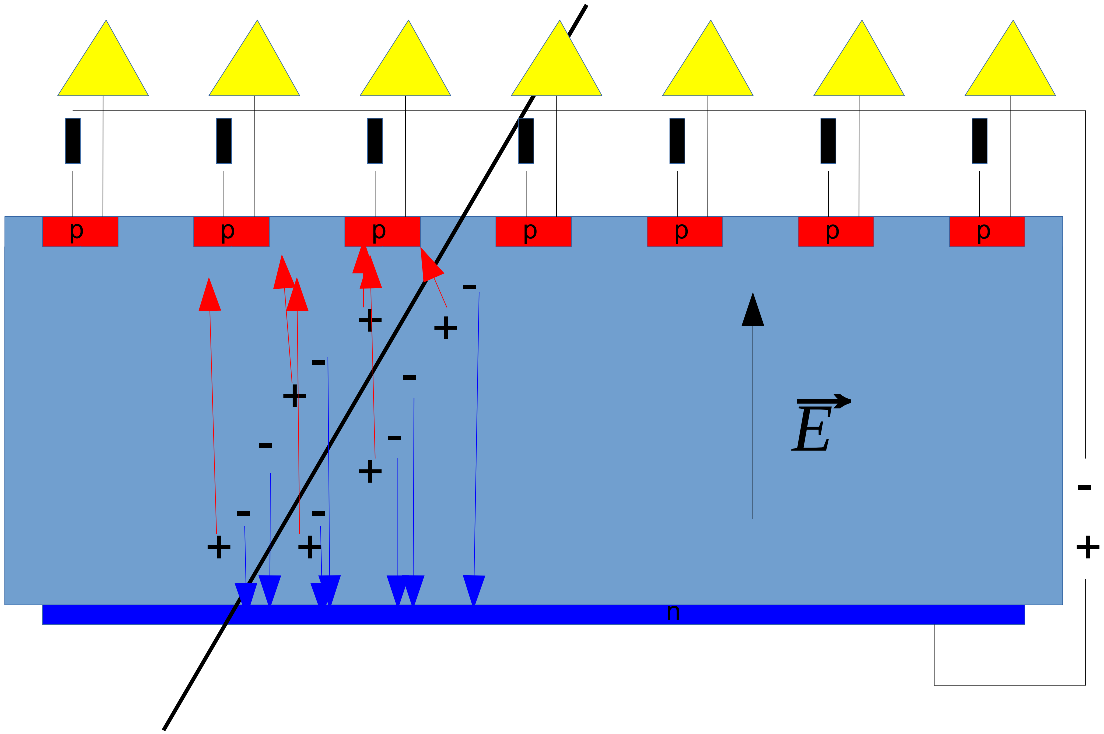




p+ strip side

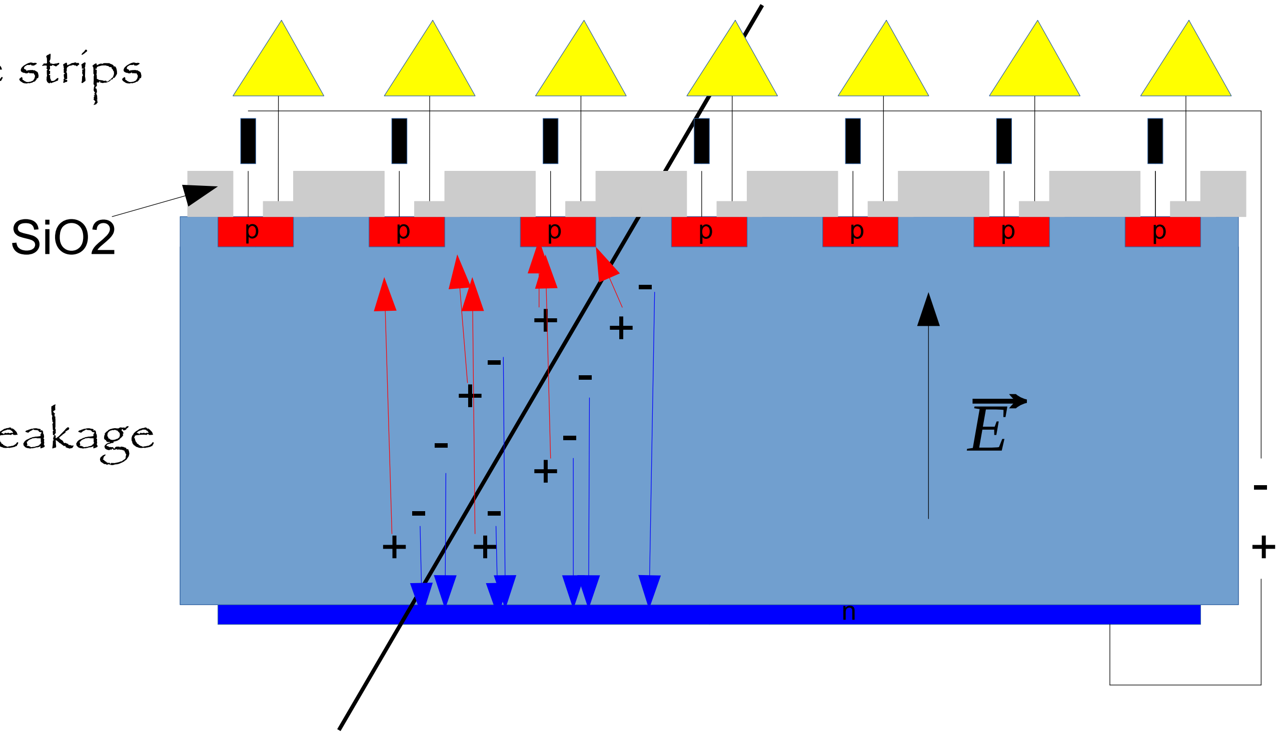
A Basic silicon detector

- Bias resistors to decouple strips
- R~MΩ
- Amplify the signal



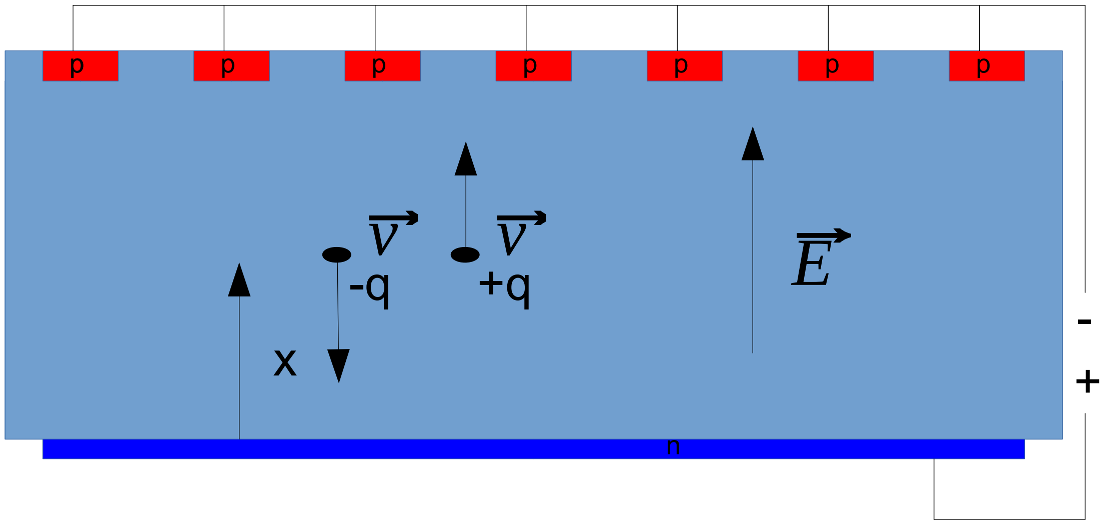
A Basic silicon detector

- Bias resistors to decouple strips
- R~MΩ
- Amplify the signal
- Add a capacitor to block leakage current



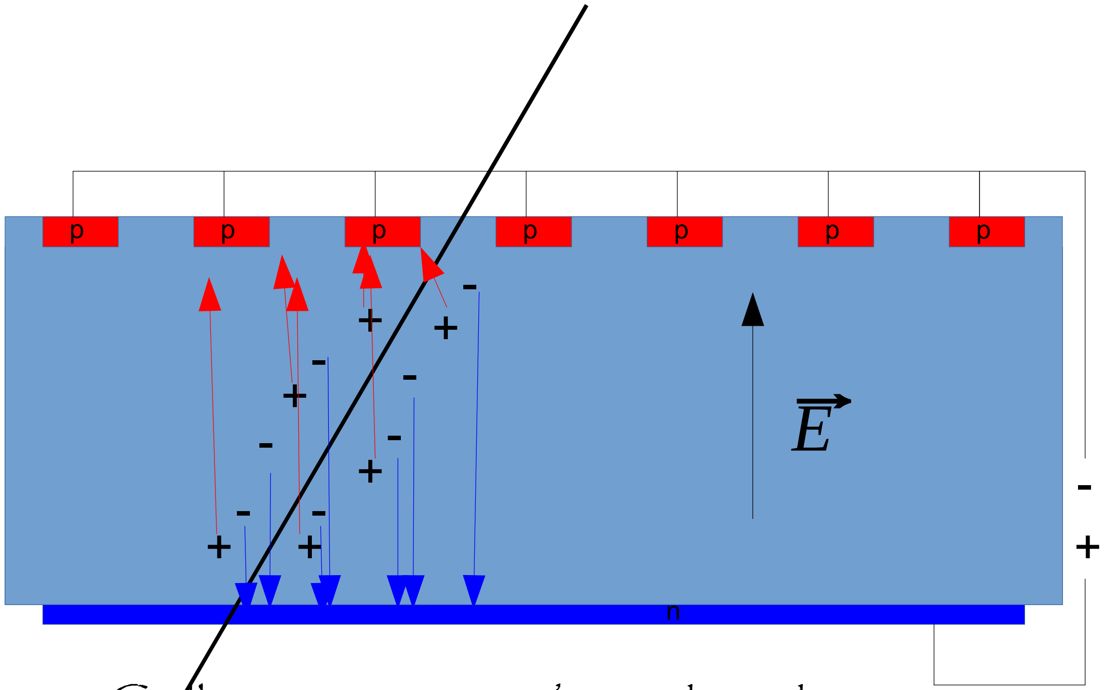
Signal formation

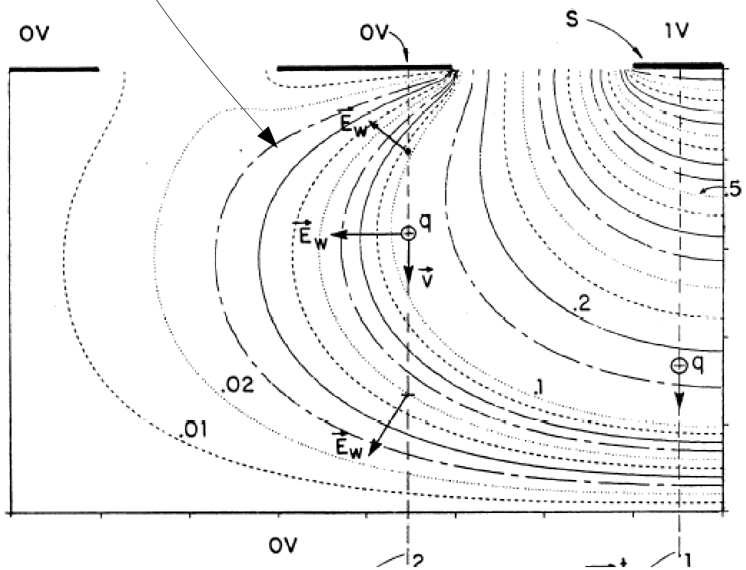
- Moving charge carriers induce a current signal on the electrodes
- In a simplified parallel plate geometry the induced current is given by the Ramo theorem
- $$\delta Q_p = -q\frac{\delta x}{W} = -\delta Q_n$$
  $$I_p = -q\frac{v_x}{W} = -e\frac{\mu E_x}{W} = -I_n$$



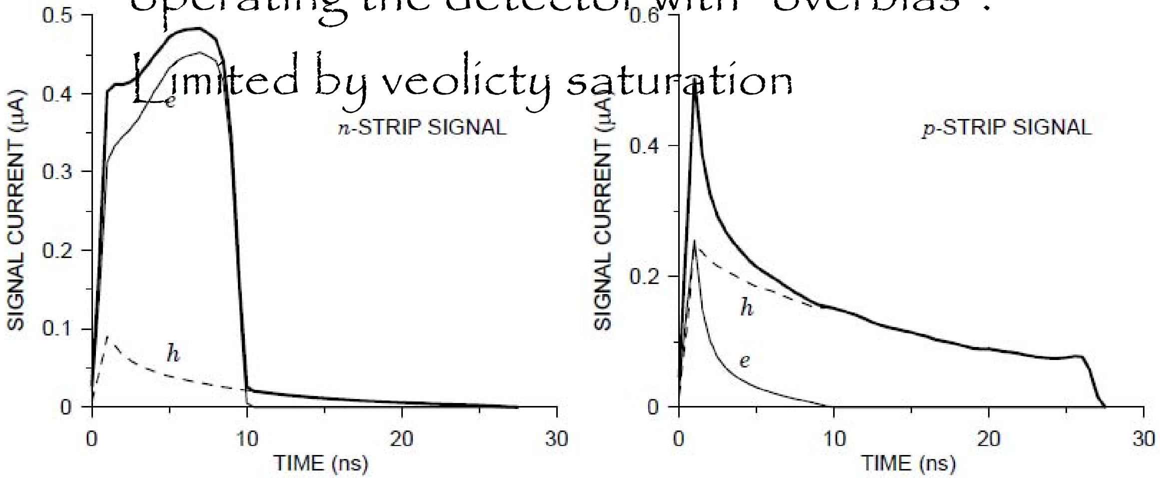
- → carriers induce signal when they move
- → both electrons and hole induce a negative current on the p strips and a positive signal on the n strips
- Current signal is bigger when charge is near p strip because the field is bigger
- Induced charge is the same for electrons and holes, collection time is different

- In a strip detector the field is not uniform near the strips so a weighting field has to be used to compute the signal
- In addition a track transversing the detector creates pairs along the trajectory



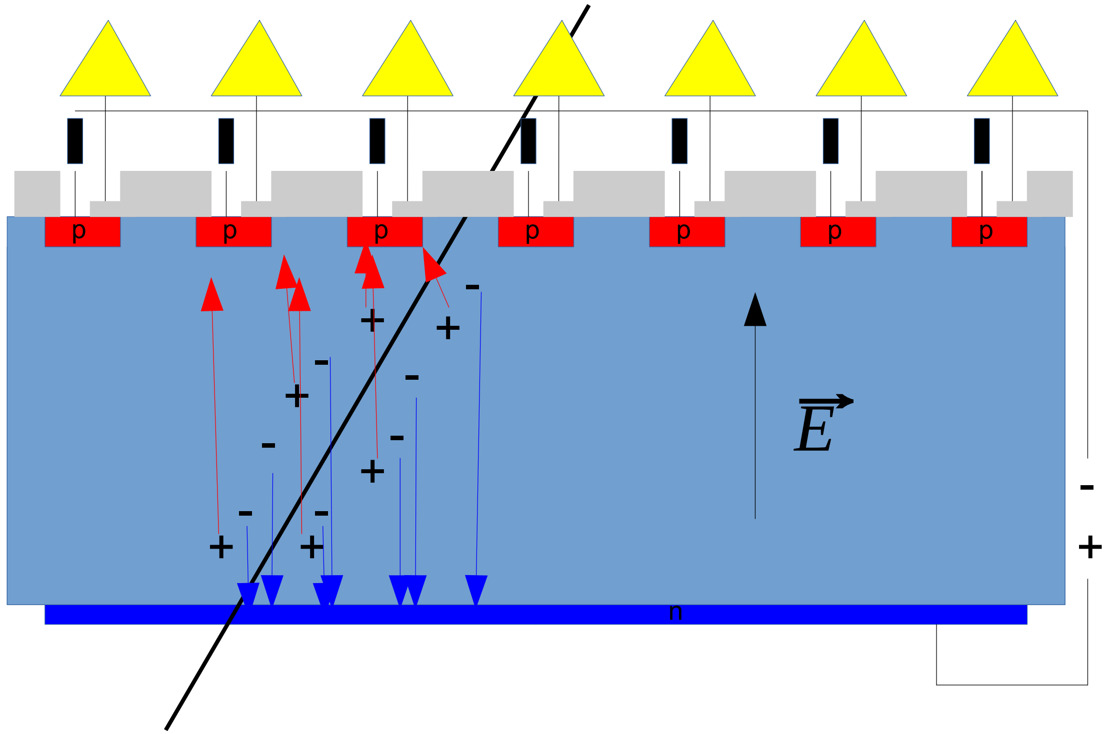


- Collection time can be reduced operating the detector with "overbias". Limited by veolicty saturation



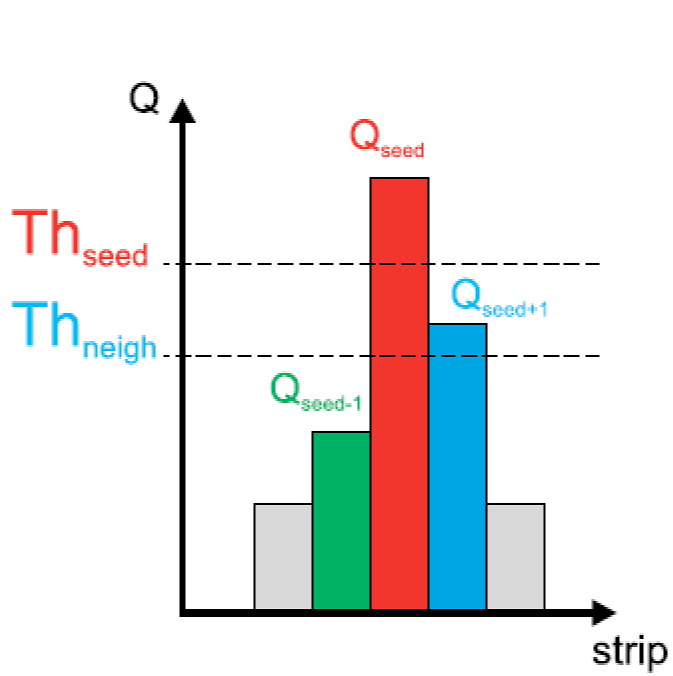
Position resolution

- Most important performance parameter of tracking detectors
- Lmited by
  - Delta rays (already mentioned)
  - Diffusion
  - Binary or analogue readout
  - Strip pitch
  - Signal/noise ratio



Position resolution

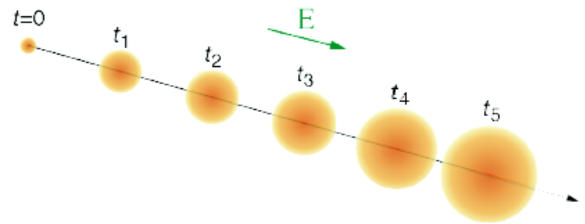
- Resolution for a single strip hit $\sigma(x) = \frac{pitch}{\sqrt{(12)}}$
- More than one strip is hit => cluster
- Analogue readout allows interpolation between strips => improves resolution
- Resolution limited by fluctuations due to noise
  - Few μm have been obtained in test beams



- Diffusion
  - While the ionization charge drifts towards the electrodes diffusion widens the cloud of charge

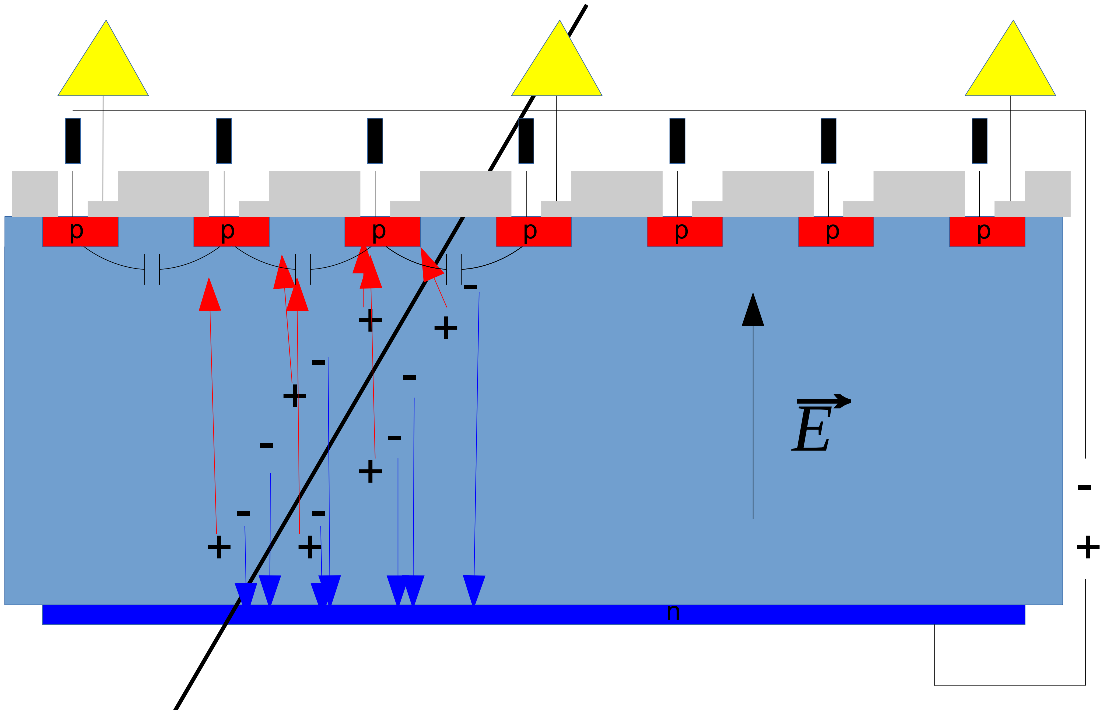
    $\sigma_D = \sqrt{(2 D t_c)}; \quad D = \frac{KT}{e}\mu$

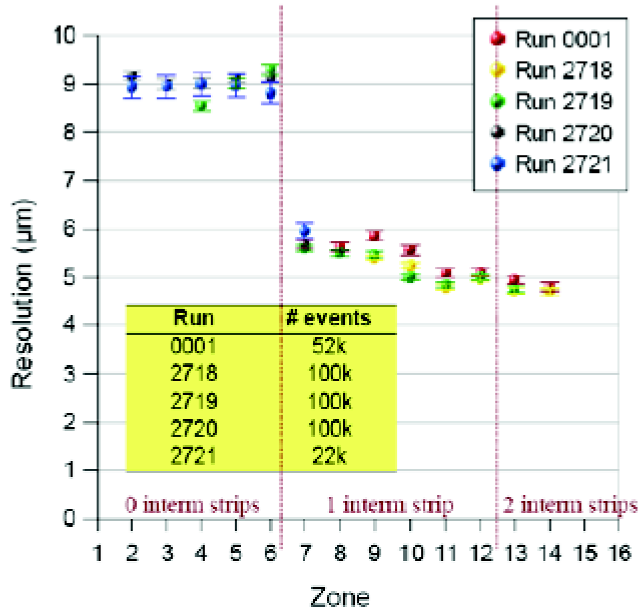
  - Since D~μ and t~1/μ → σ_D is equal for electrons and holes
  - Diffusion acts differently depending on where the ionization is generated



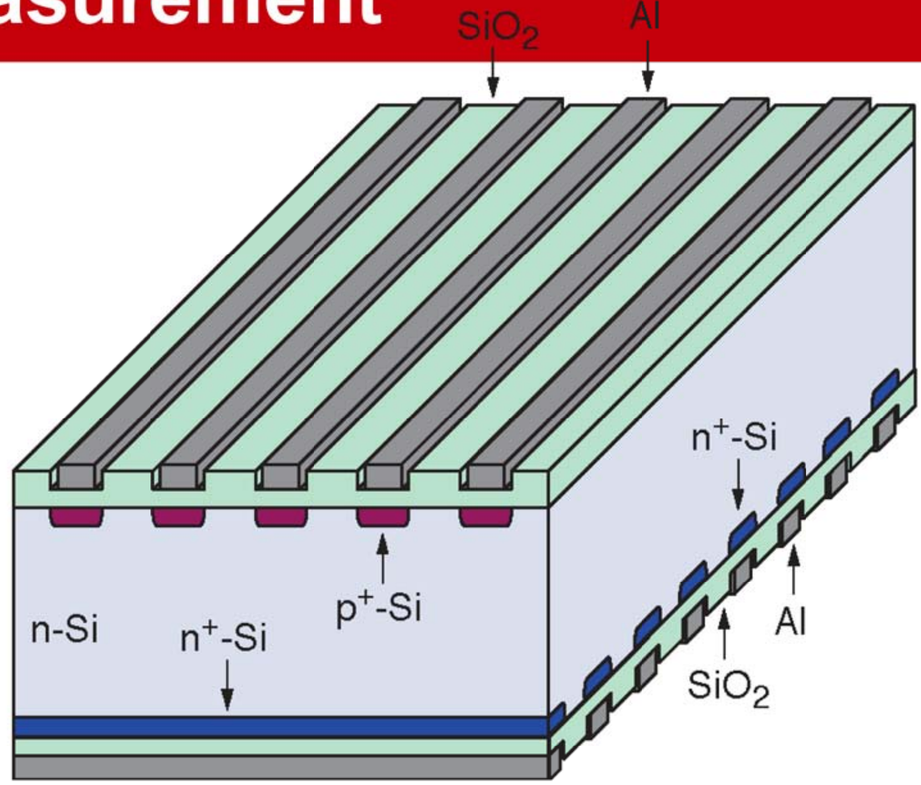
Floating strips

- Strip pitch determines the single strip resolution but requires large number of electronics channels and large power
  - Introduce strip not connected to front-electronics in between readout strips
  - The signal is transferred by capacitive coupling to the readout strips
  - Use analog readout to recover the position precision
  - Example:pitch 50µm





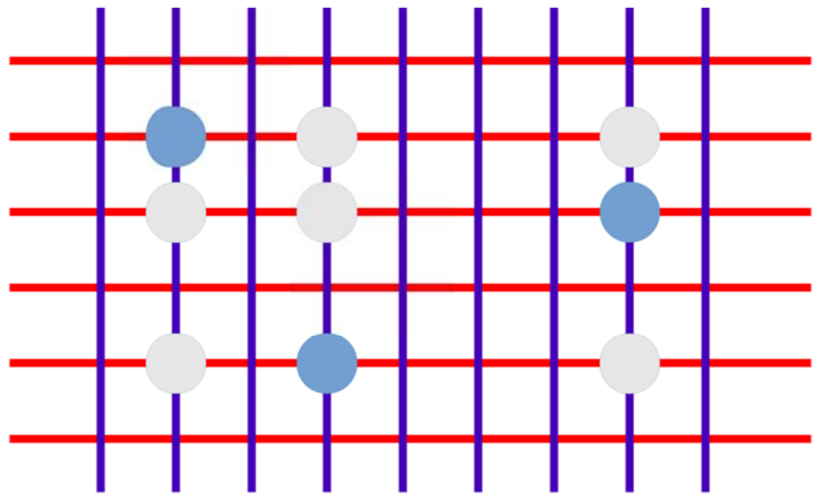
2D position measurement



- Second coordinate can be measured by adding a second layer of detectors with strip in the orthogonal direction
- For e+e- experiments where material budget is important this is not efficient
- → double sided strip detectors
- Needs special strip insulation on n side
- Complicated manufacturing
- Position reconstruction is affected by ambiguities

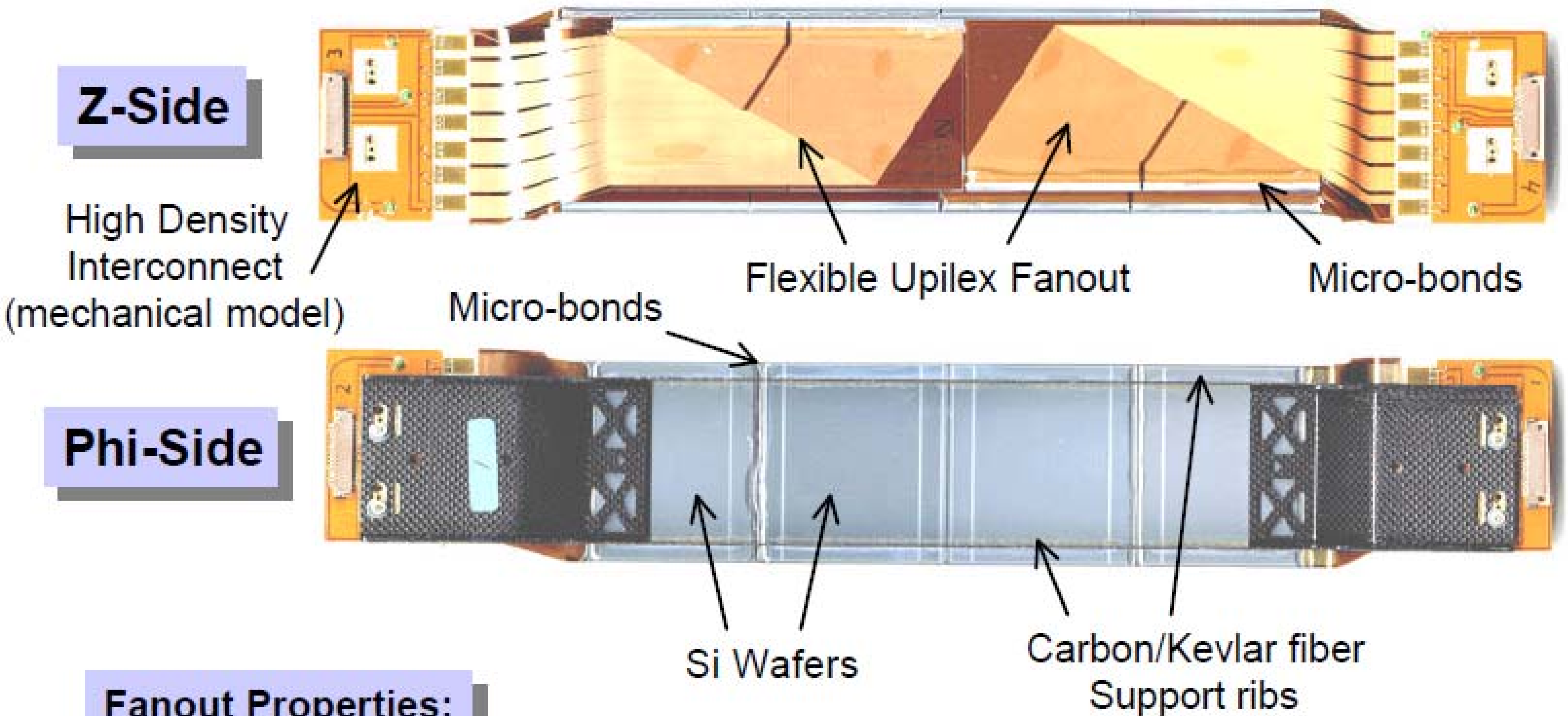
  Real hits

  Ghost hits



Double sided strip detectors

- Needs also routing for signals
  - Fanout circuits

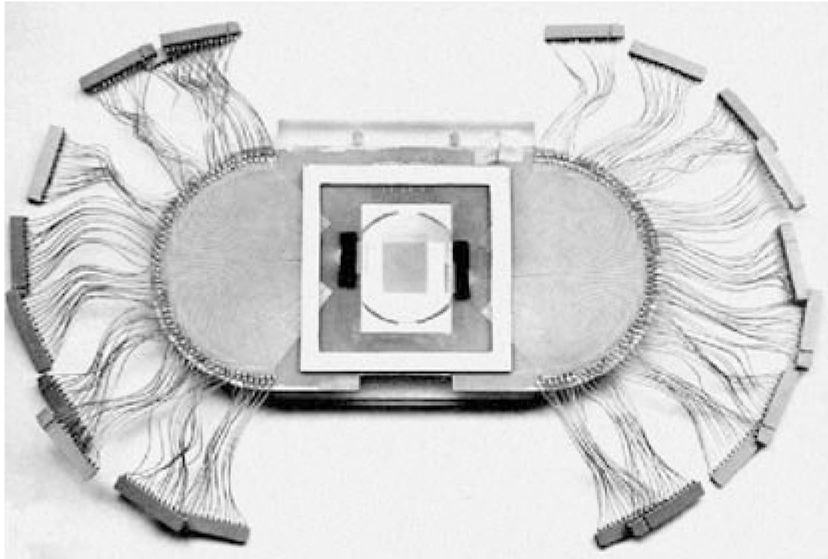


Fanout Properties:
- < 0.03 % X_0
- 0.52 pF/cm

Microstrip vertex detectors

Microstrip detectors

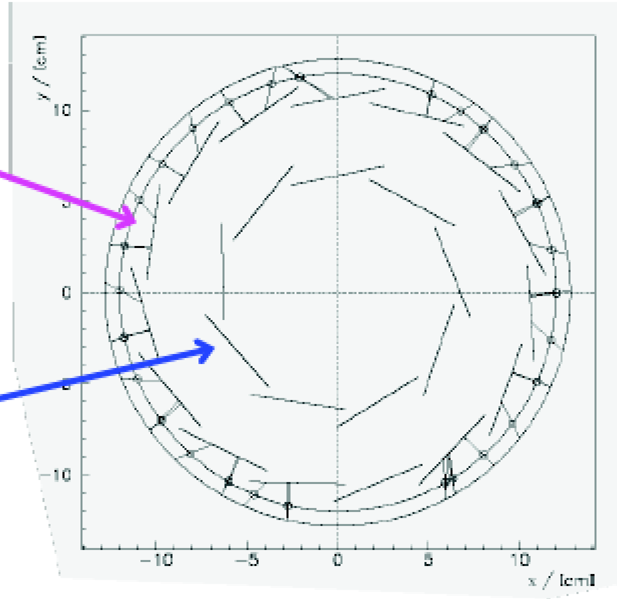
- First strip detector was built by CERN Munich group
- Was fabricated using a commercial planar process
- First proof of principle of the use of a position sensitive silicon detector in HEP experiment
  - NA11 (1980)
  - Resolution of 4.5µm reading out every 3rd strip
  - 24 cm^2 area
  - Aim: measuring charm lifetime



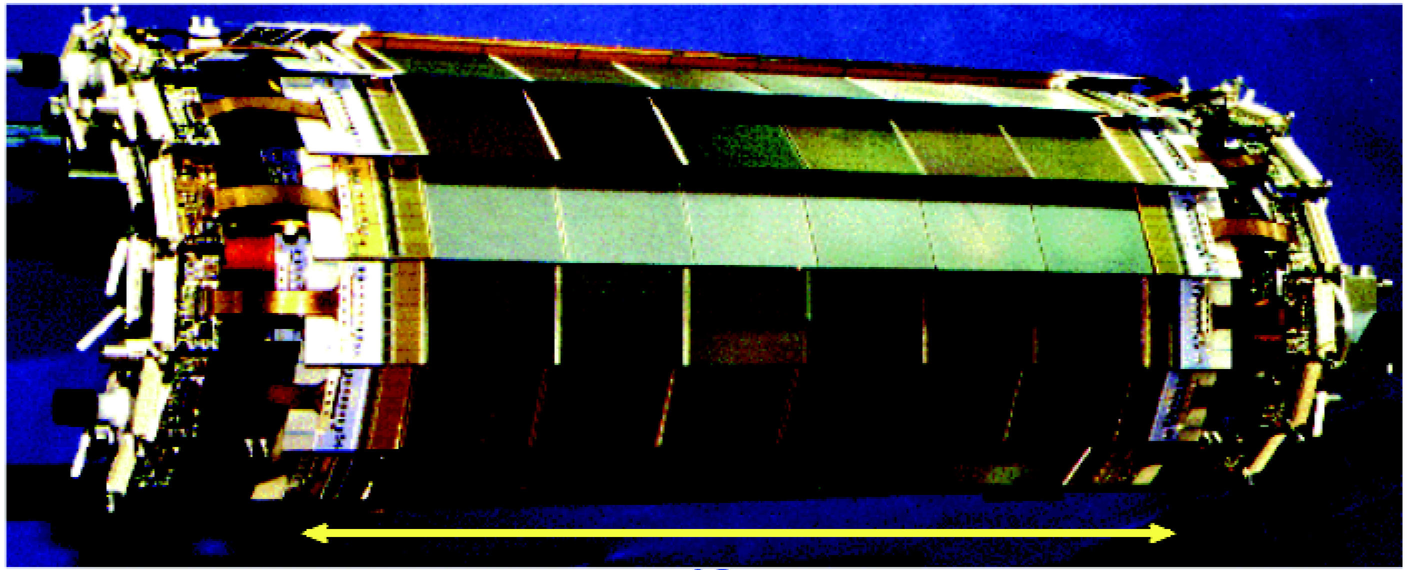
Aleph vertex detector

- **ALEPH**
  - 2 cylindrical layers at 6.3, 10.8 cm

60 modules with
2 sensors/module
double-sided strips
d=300 μm



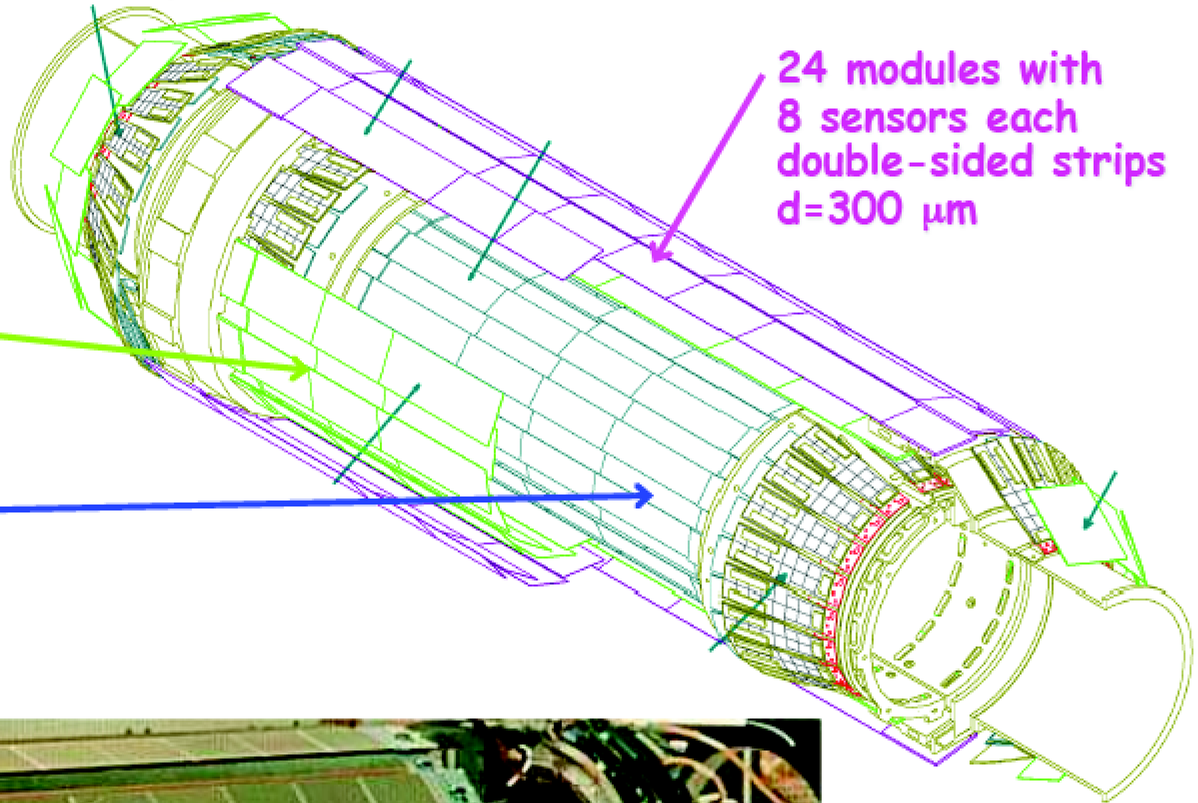
36 modules with
2 sensors/module
double-sides strips
d=300 μm



40 cm

Delphi Vertex detector

- DELPHI
  - 3 cylindrical layers at 6.3, 9.0, 10.9cm

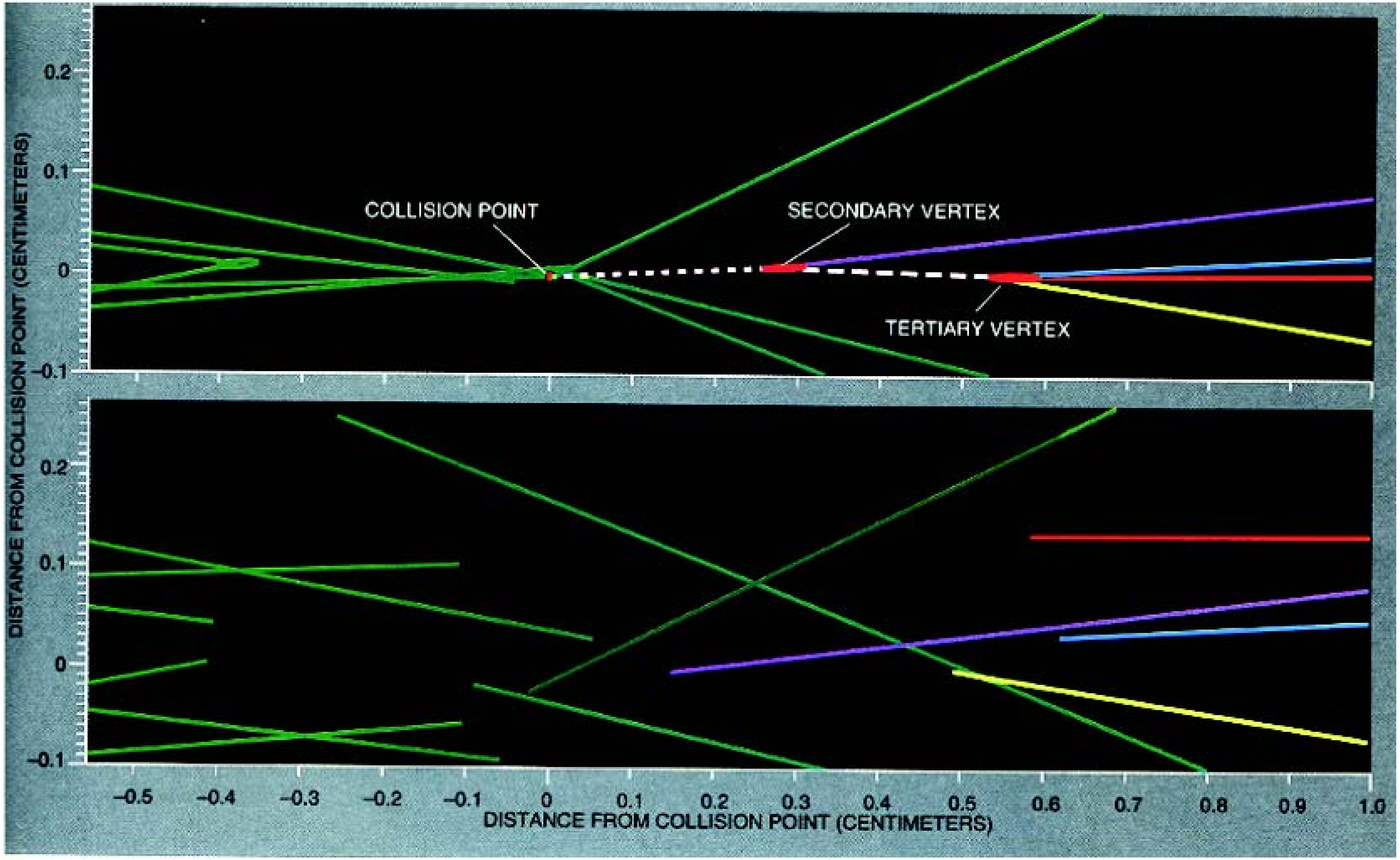


24 modules with
8 sensors each
double-sided strips
d=300 μm

20 modules with
8 sensors each
double-sided strips
d=300 μm

24 modules with
4 sensors each
single-sides strips
d=300 μm

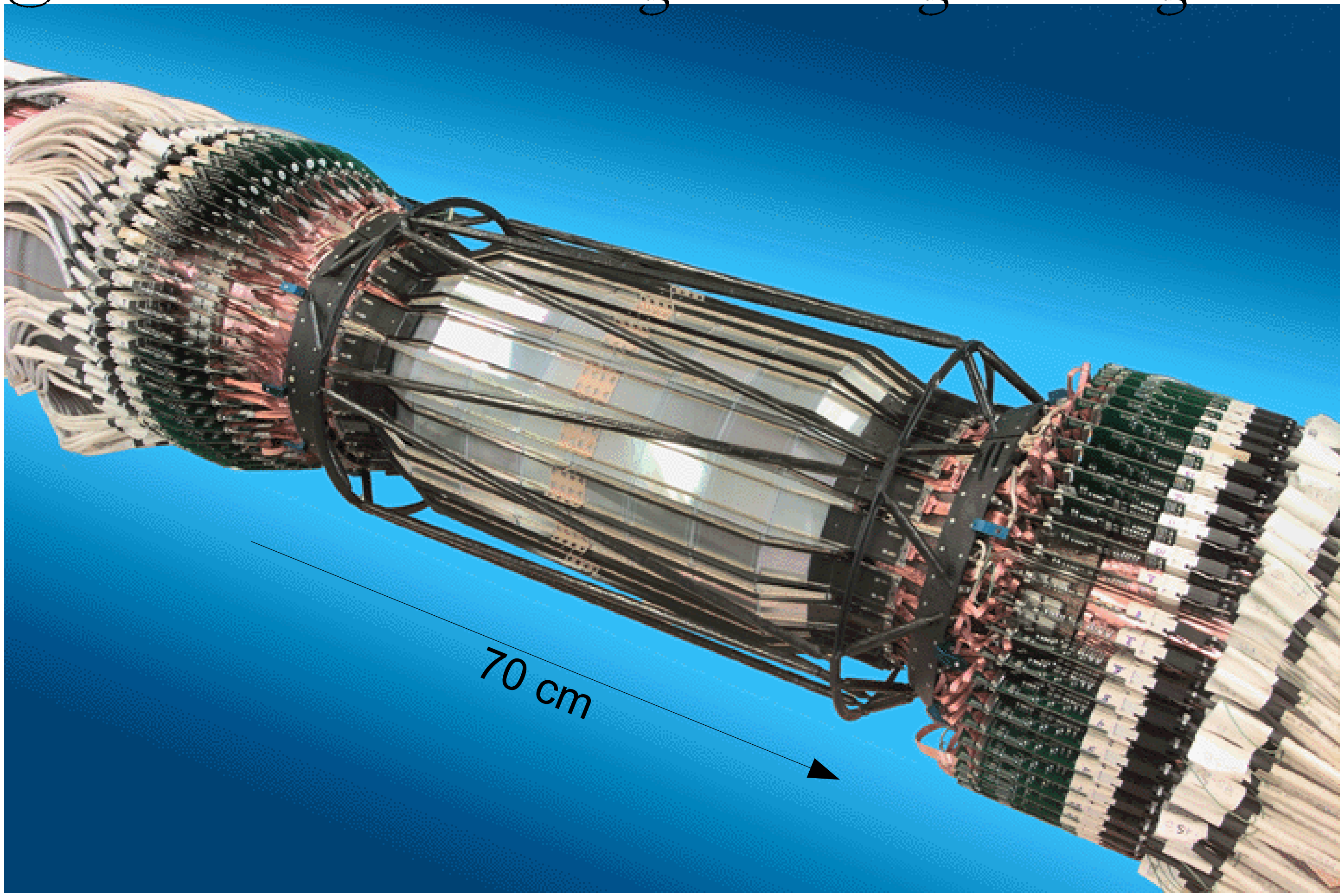
The Power of the Vertex detector (ALEPH)



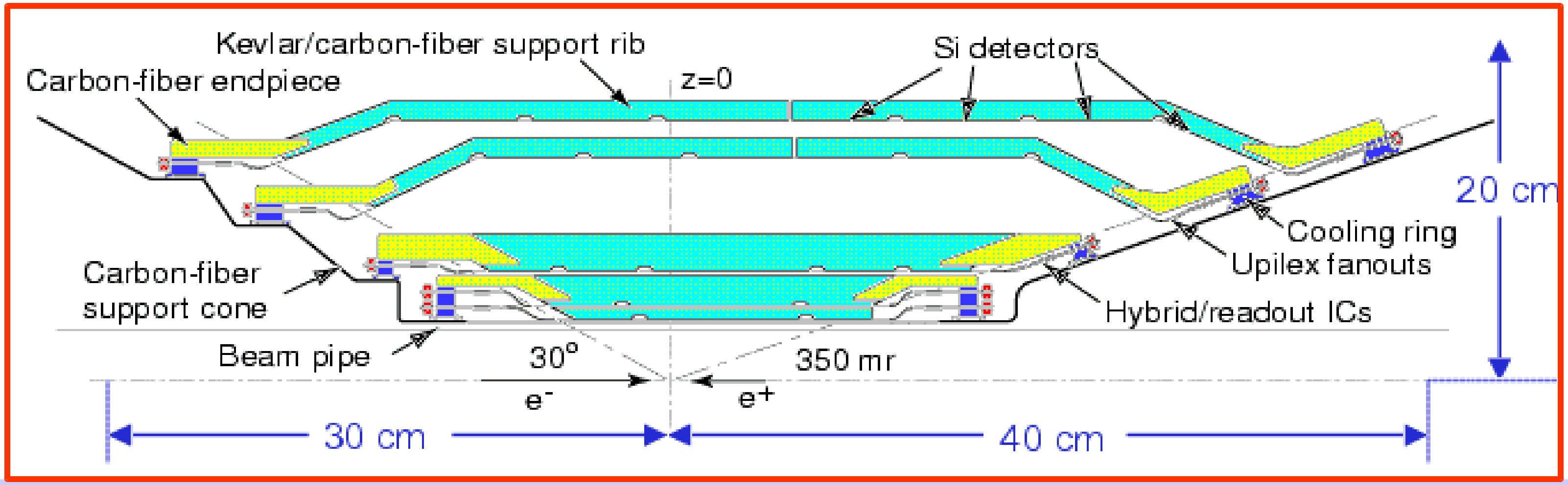
BABAR Silicon Vertex Tracker

5 layers - Silicon Surface 457 cm^2 in L1 – 2089 cm^2 in L5

Shift of focus from vertexing to vertexing + tracking



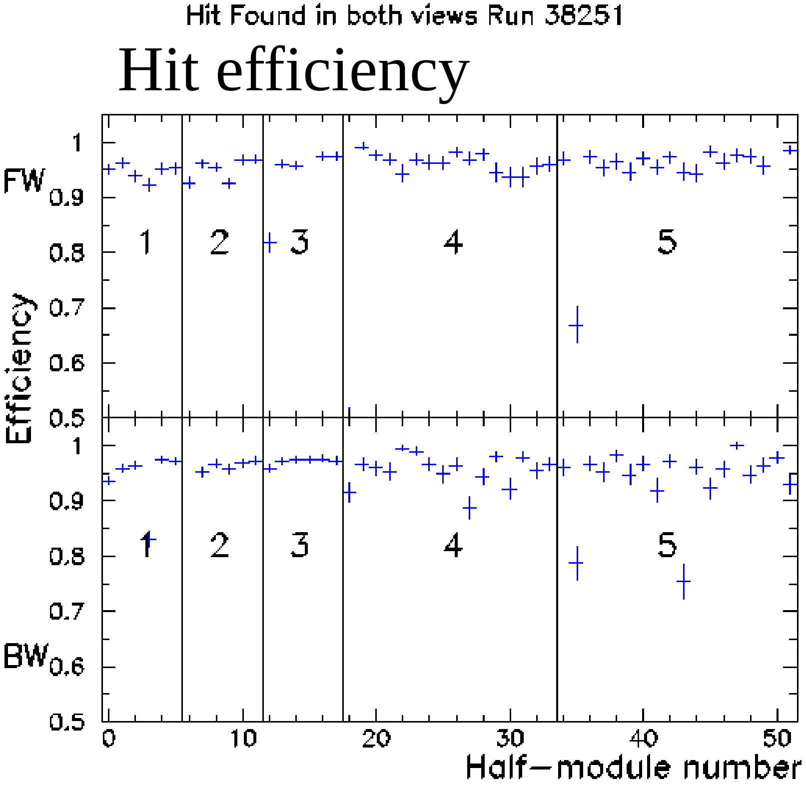
BABAR Silicon Vertex Tracker



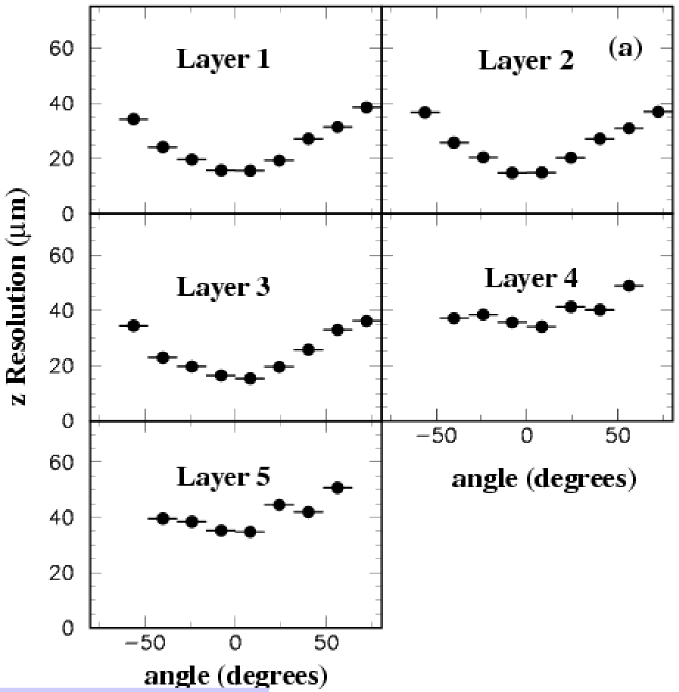
- Double sided n-bulk silcon sensors, 6-30 kΩ cm
- 5 layers: radius from 3.3 → 14.6 cm
- Arch shaped outer layer modules to reduce L_{rad}
- Stand alone tracking for 70 MeV< pt < 120 MeV
- Angular acceptance limited by bending magnets

SVT Hit Performance

Hit efficiency



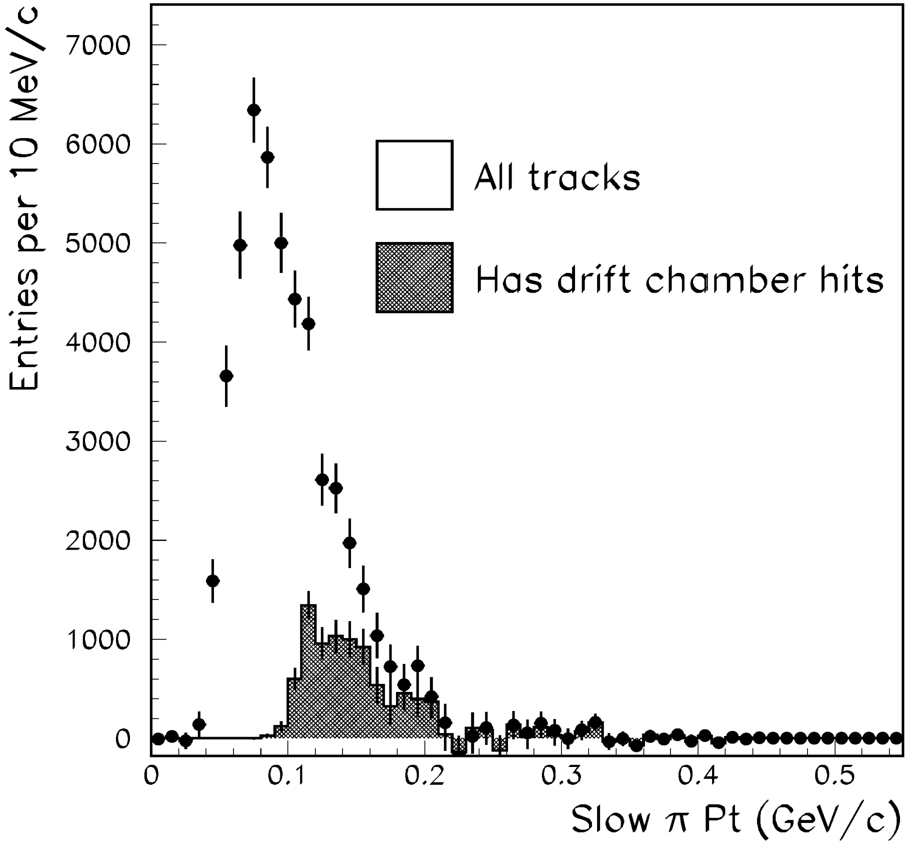
Hit resolution on z side

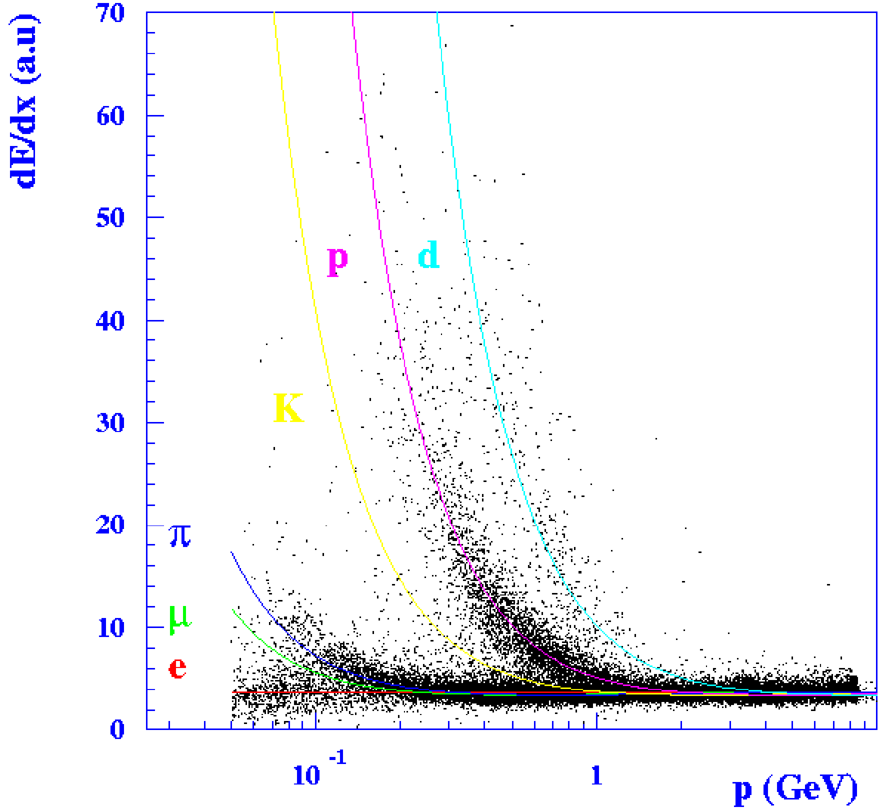


- Hit Efficiency tipically 97%
- Hit Resolution for pt>1 GeV/c, ⊥ wafers
  - Layer 1-3: 10-15 μm
  - Layer 4-5: 30-40 μm

SVT Tracking and PID performance

- Soft π efficiency >70% for pt>50 MeV/c
- Use pulse height height measurement to extract dE/dx
- 2σ separation between kaons and pions up to 500 MeV/c and between kaons and protons up to 1 GeV/c





Radiation damage will be the limiting factor to the lifetime of the SVT

Two different aspects:

A) Radiation damage to the sensors:

Instantaneous

-Creation of p-stop shorts => inefficiency

From integrated radiation (bulk damage)

-Increase in leakage current => shot noise

-Change in the depletion voltage and type-inversion => electronics noise

-Damages to the crystalline structure => decrease in charge collection efficiency

B) Radiation damage to the electronics:

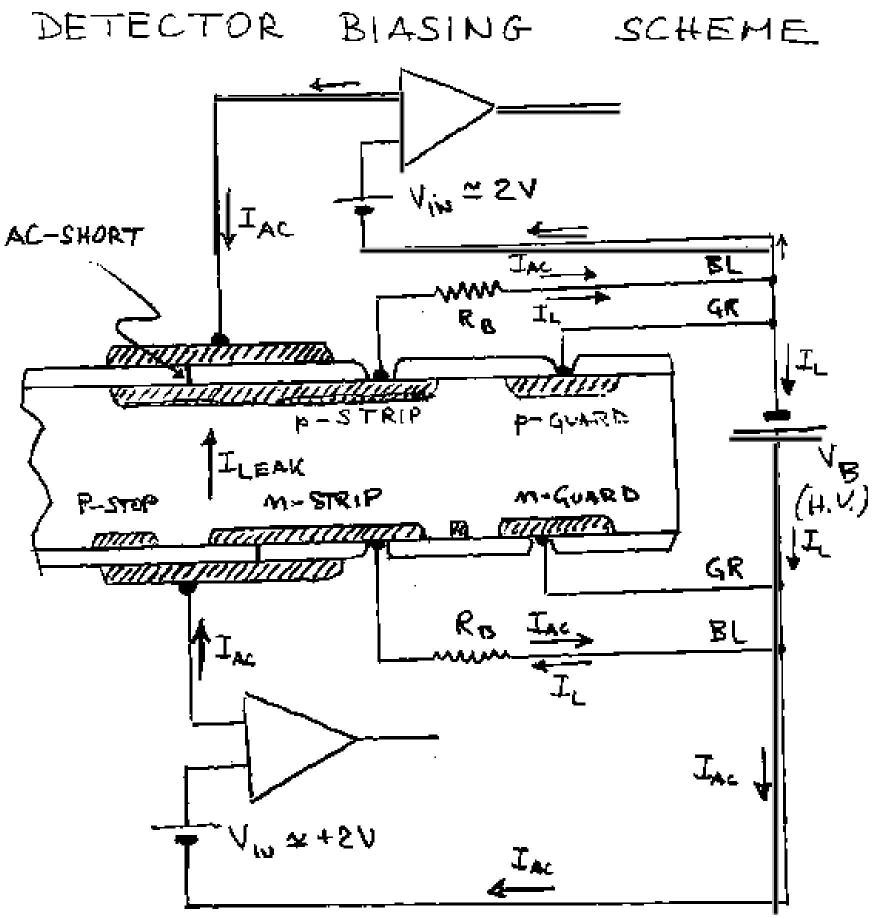
-Increase in noise => decrease S/N

-Decrease in gain => decrease S/N

-Digital failures => inefficiency

All these issues have been addressed in the past with projects aimed to quantify the impact on the SVT operation and lifetime

Instantaneous radiation damage to the sensors



Intense burst of radiation
=>discharge of detector capacitor
=>Vbias (40V) momentarily drops across the coupling capacitors
-deposited charge needed

$$Q_R = \left(C_D + \frac{C_N C_P}{C_N + C_P}\right) V_{Bias} \approx 2.6\ nC/strip$$

on a time scale < $\tau = R_{Bias} * C_{det}$ ~1ms

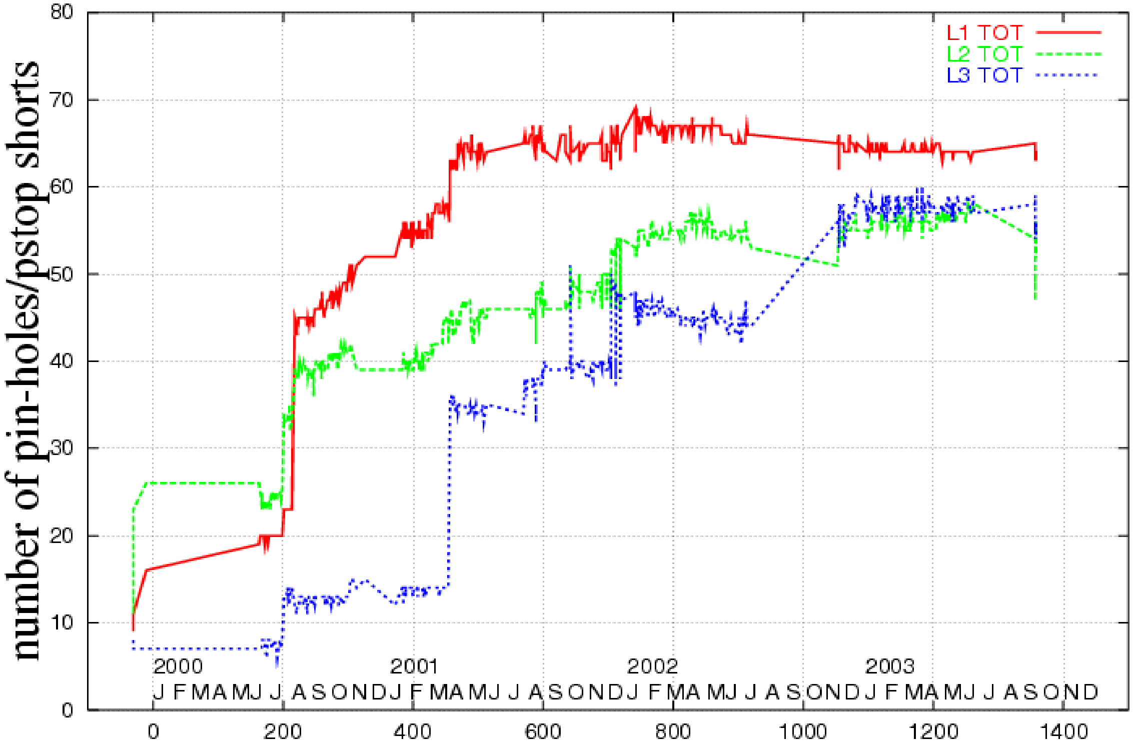
=> critical radiation: 1 Rad/1 ms

Damage Rate

-All the sensors have been tested for AC breakdown up to 20V during construction

-A later study on detectors with a pitch similar to the SVT inner layers has shown an expected rate of failures of about 1-2%

The effect has been observed in the real system: 65 pin-holes / 20k channels in L1,2



Bulk damage: increase in Si leakage current

This effects implies an increase in the noise and a potential problem to bias the detector to very high voltages

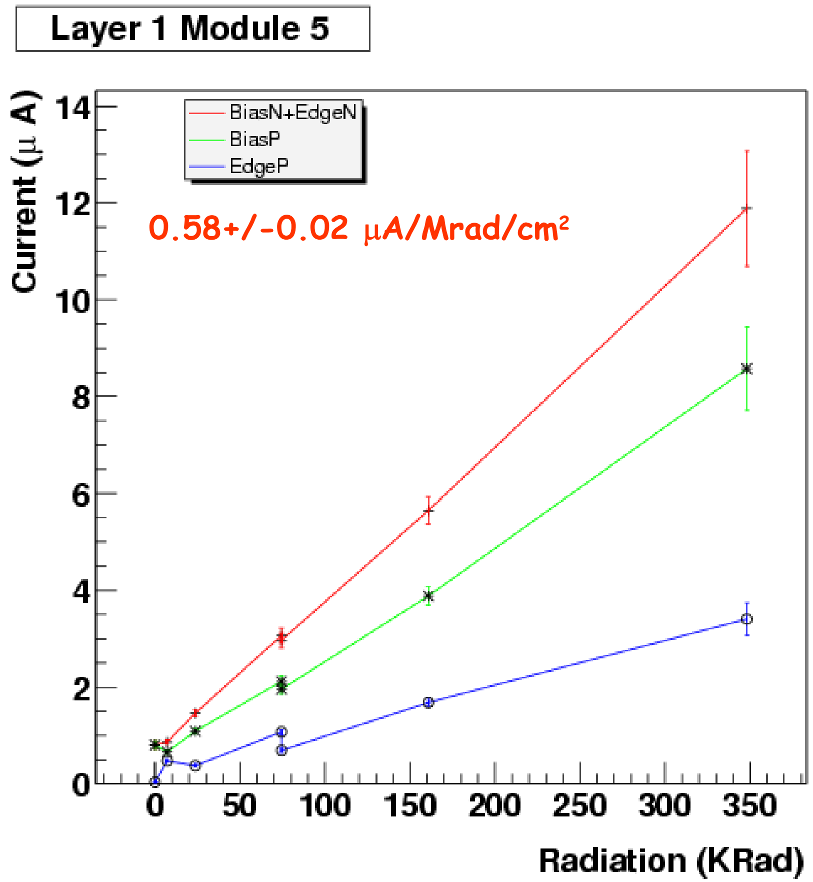
-Measuring the leakage current of SVT Si wafers vs. time allows to evaluate the radiation damage

-I-V measurements performed since 1999

-Current measured @ 40V and the radiation dose estimated from the nearby PIN diode

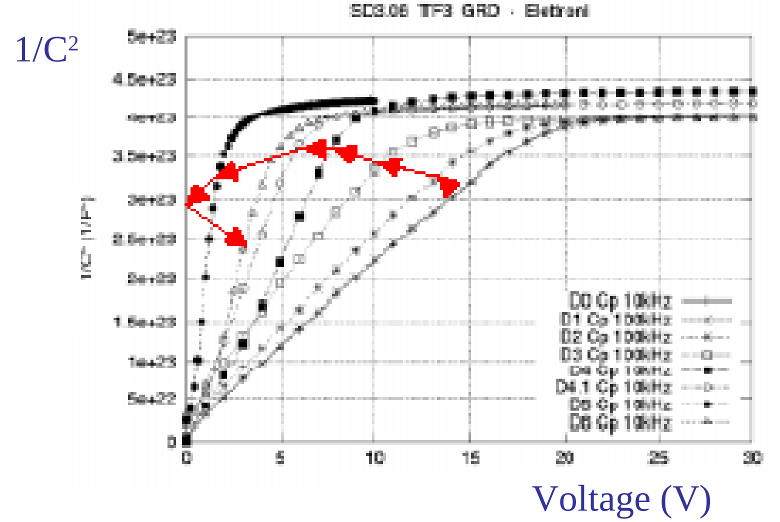
0.5-0.7 mA/Mrad/cm2 @ T=17^{o}C

=> 1mA hardware limit is not an issue

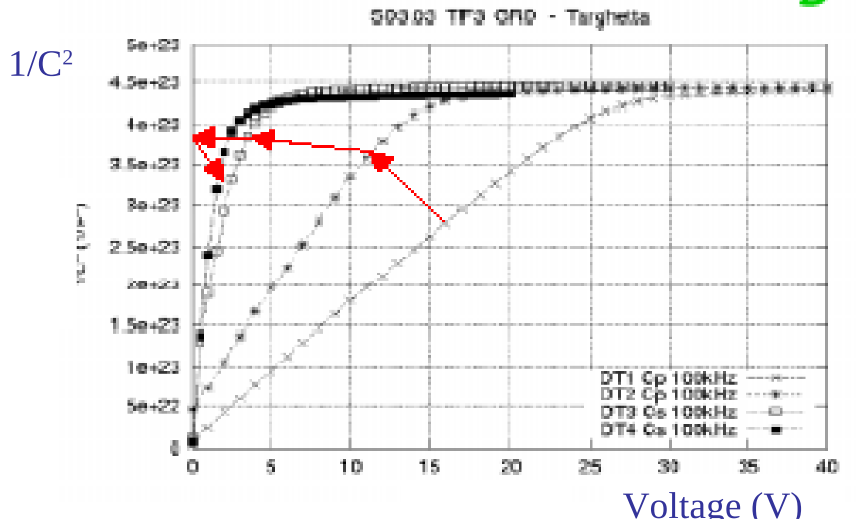


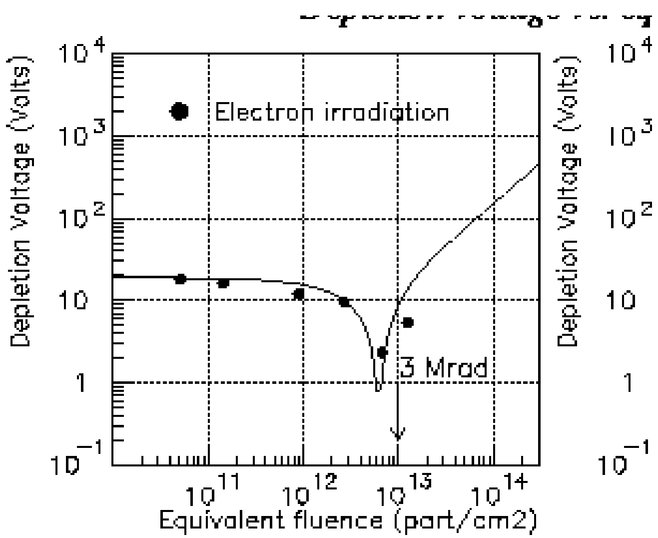
Bulk damage: depletion voltage

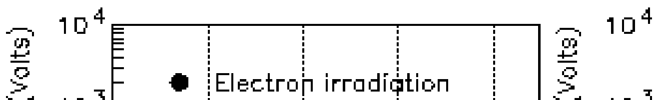
electron beam



electron beam on Cu target





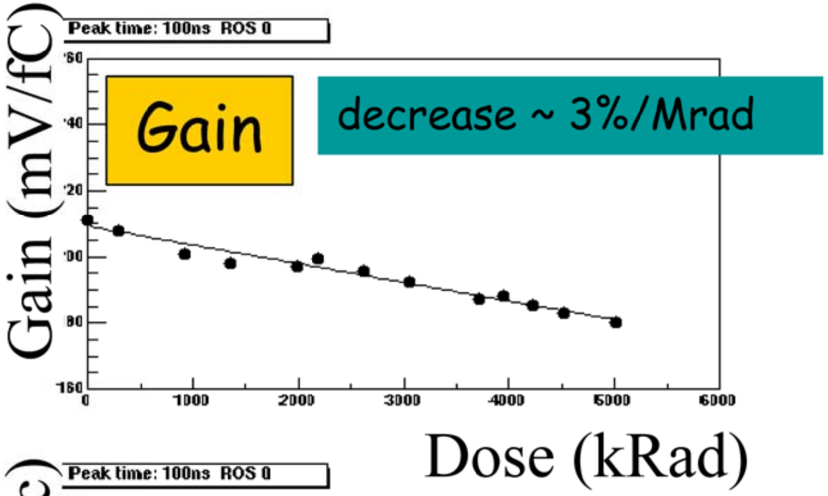


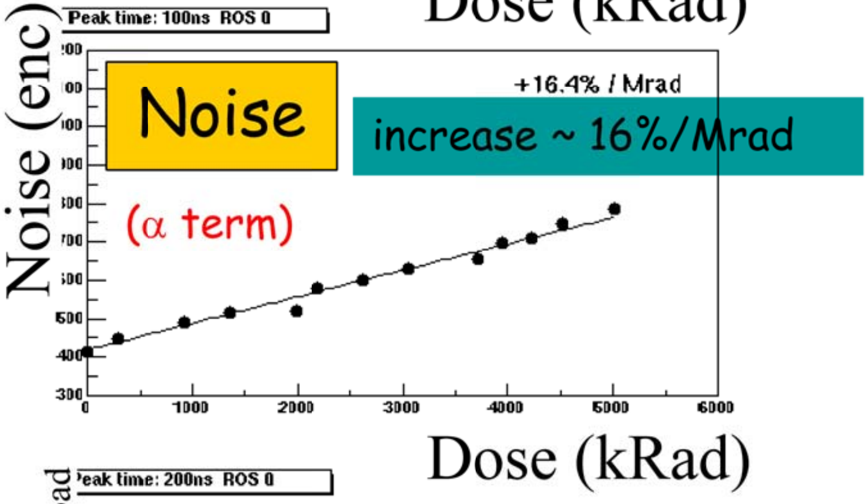
Irradiation with 0.9 GeV e^- beam at Elettra (Trieste, 2000-2001)

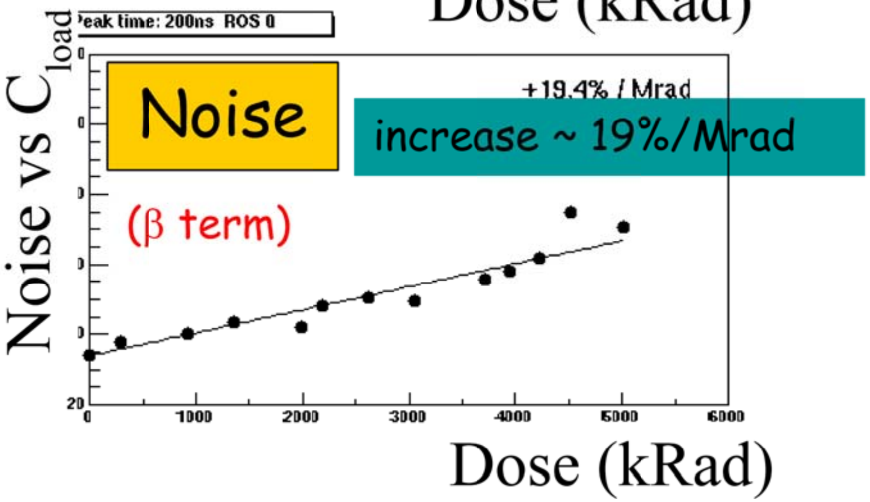
- C^{-2} vs V curve indicates type-inversion results in ~ agreement with NIEL scaling hypothesis (not obvious): 3MRad
Leakage current increase of order 2 μA/Mrad/cm^2 (T=23 °C) in agreement with measurement in the real SVT

After type-inversion up to 5MRad detector electrical properties still look OK

Irradiation tests on the Atom chips







Radiation tests performed on Atom chips in 2001 using Co^{60} sources at SLAC and LBL

Chips powered and running during irradiation

$$\boxed{noise = \alpha + \beta\, C_{load}}$$

Foreseen decrease of signal/noise down to a factor 2 (mid plane). This determines an upper limit on the ATOM chips lifetime (5Mrads).

No digital failure observed up to 5 MRads

Noise Prediction

Instantaneus damage to Silicon:

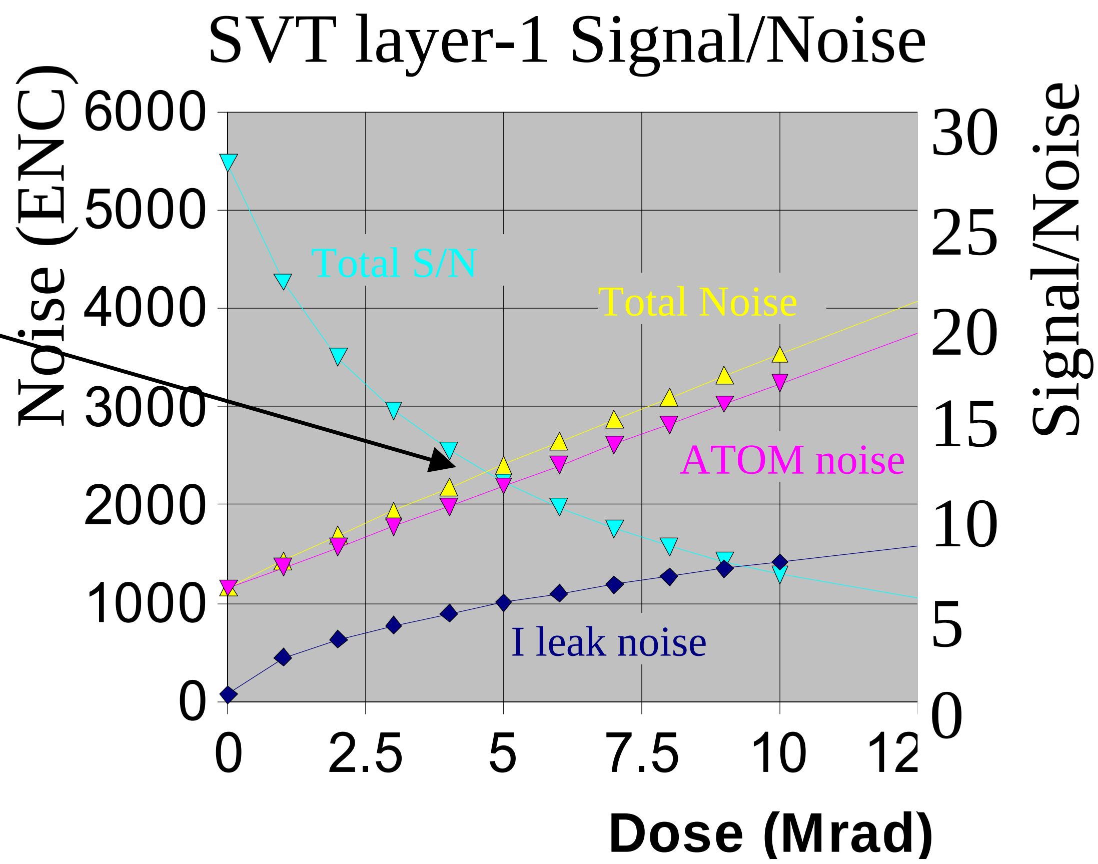
OK (also for Trickle Inj.)

FEE chips damage:

signal/noise	OK up to 5 Mrad
digital funct.	OK up to 5 MRad
Offset	(in progress)

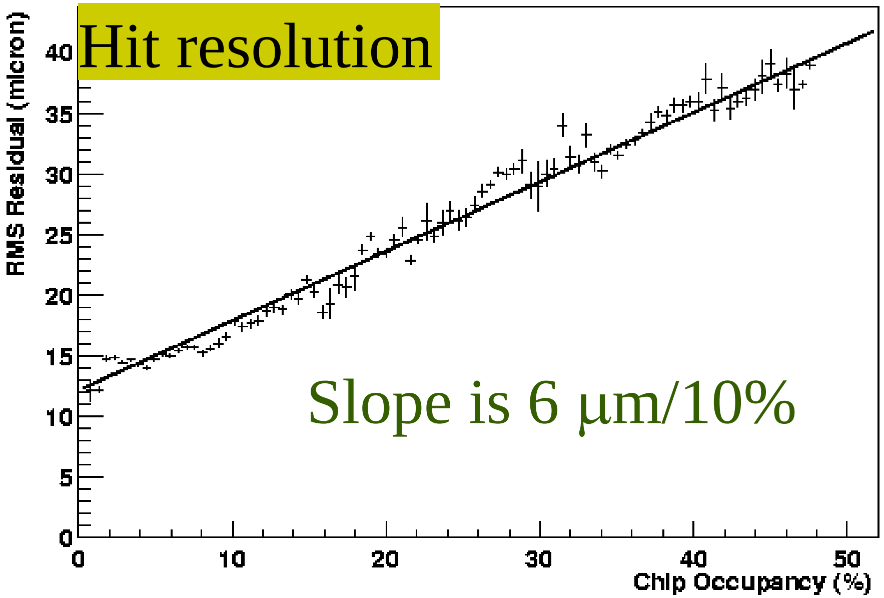
Bulk damage to Silicon:

V_depl	OK up to 10 Mrad
I_leak	OK > 10 MRad
CCE	(in progress)

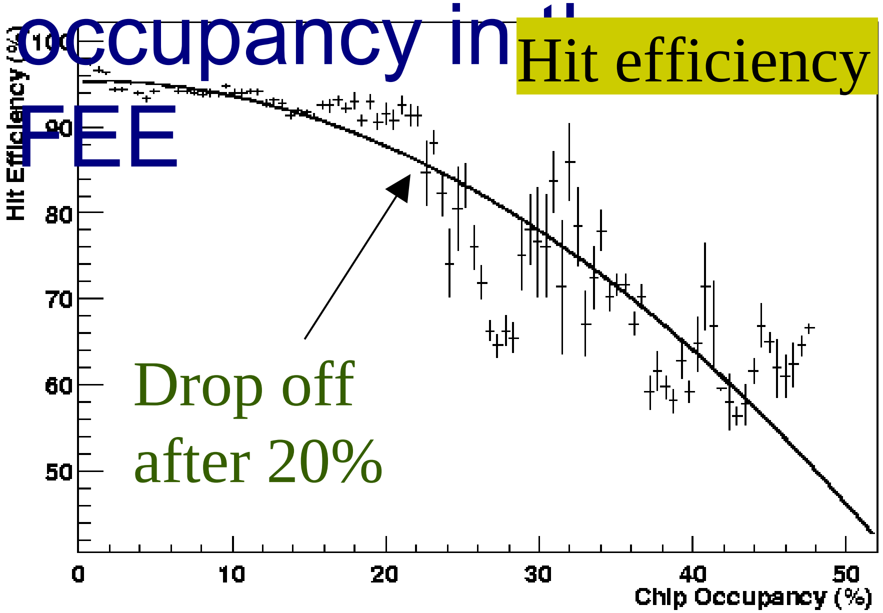


Performance with high background

- Look at hit efficiency and hit resolution as a function of occupancy in the FEE



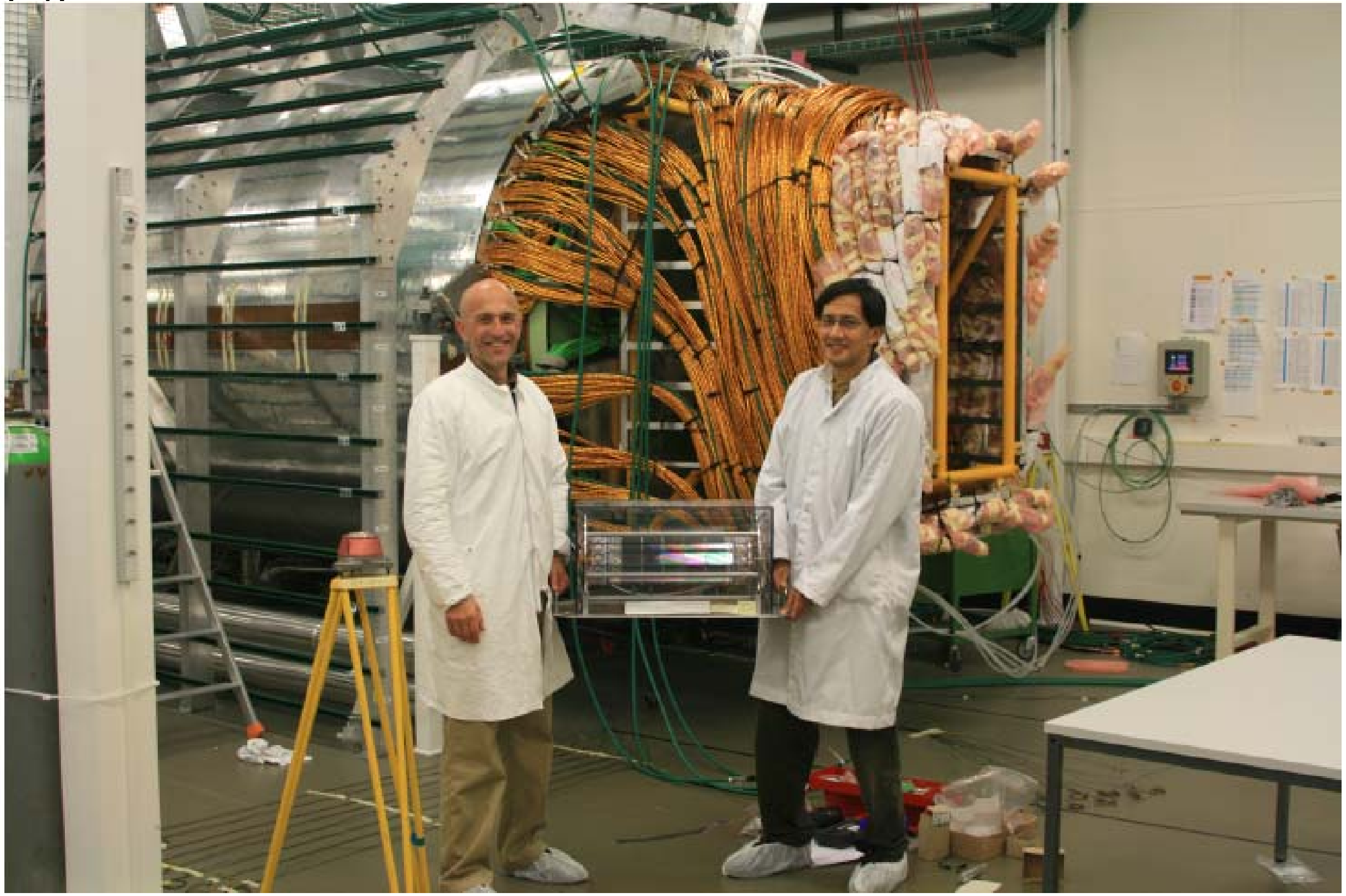
- The effect is expected to be significant in 1/10 of layer 1



LHC Trackers

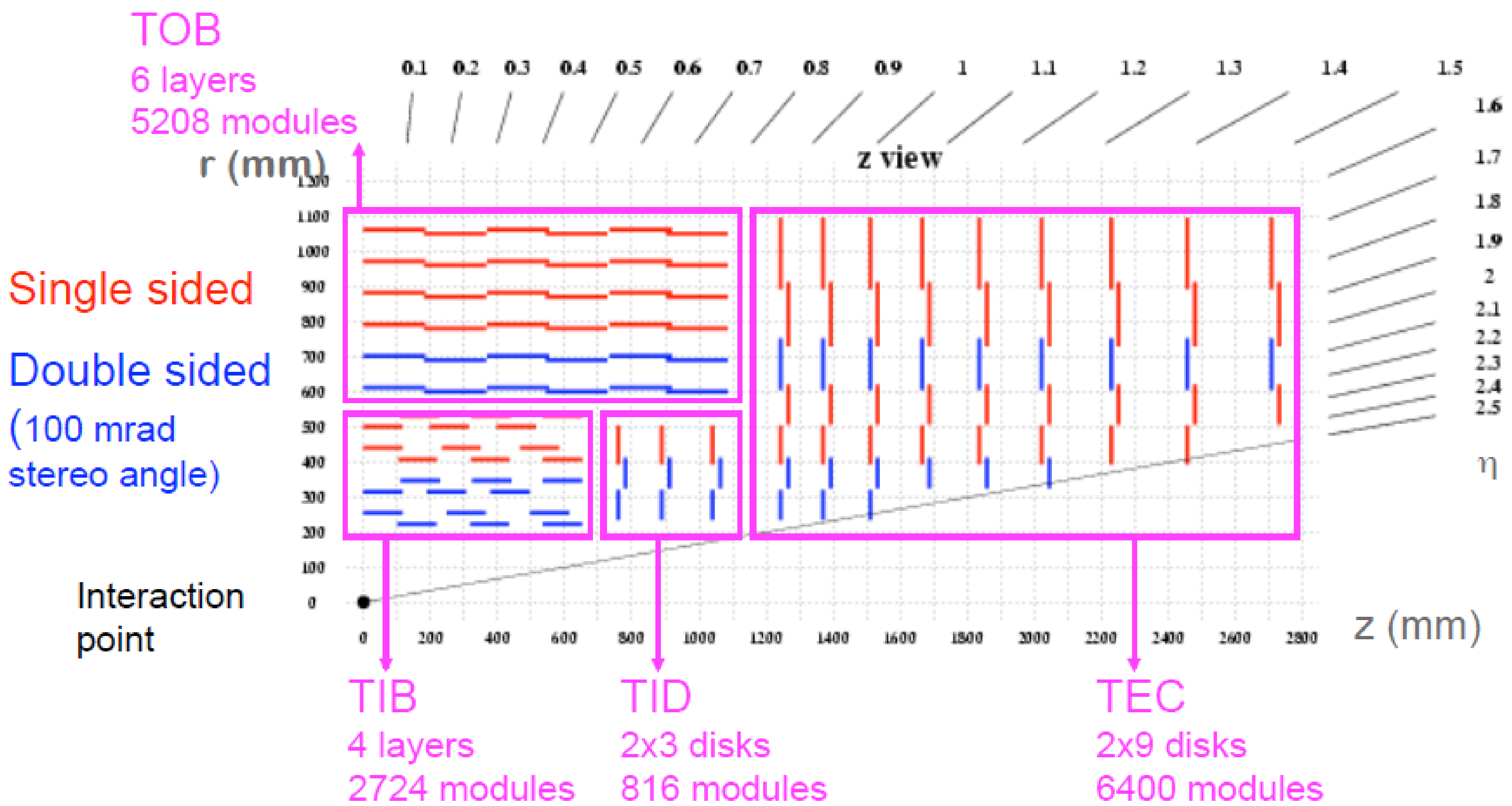
Tevatron and LHC

- Emphasis shifted from vertexing to tracking in a large volume: CMS vs DELPHI



- Detector modules, readout electronics and services inside tracking volume → material budget constraints

CMS Tracker layout



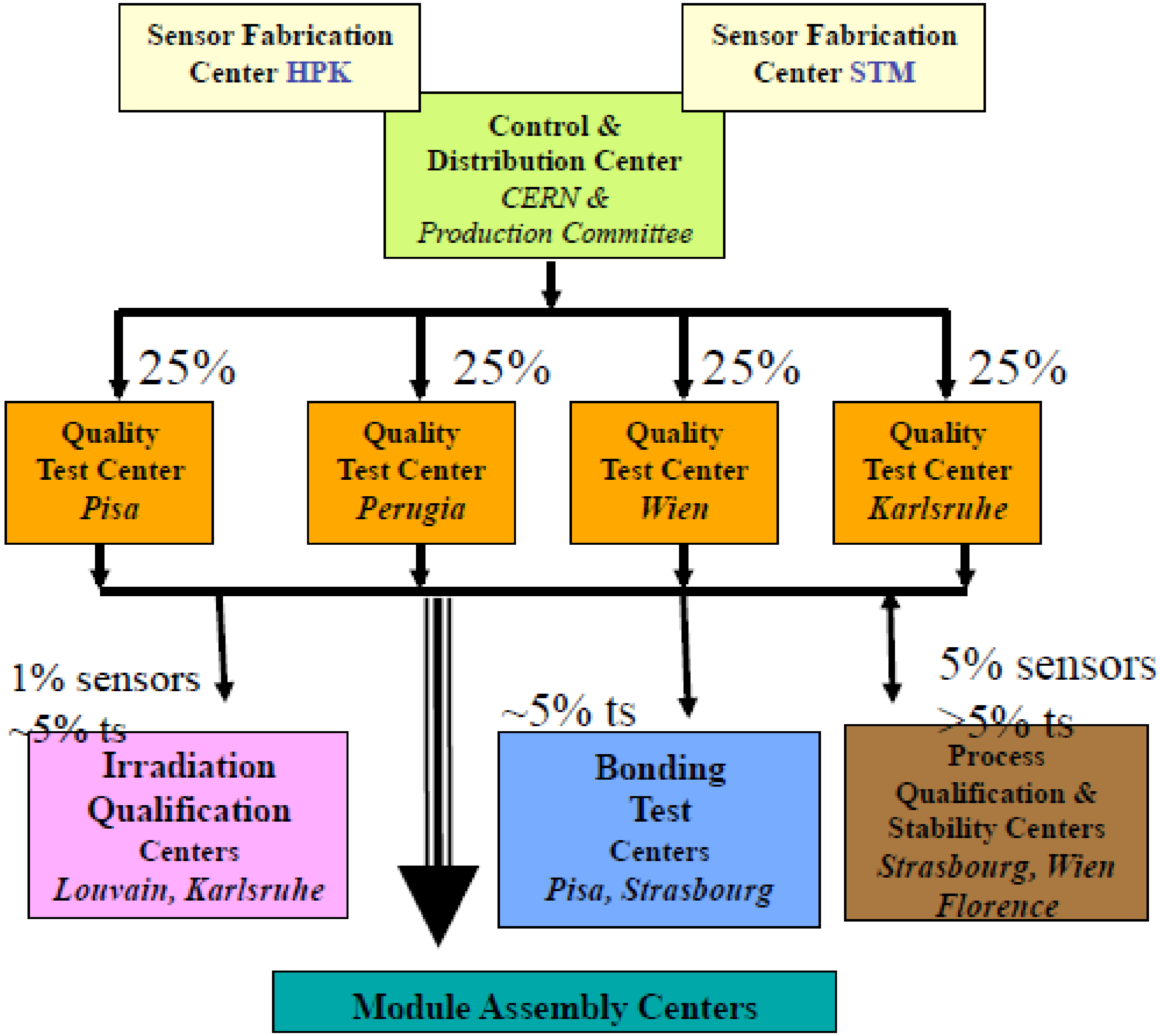
Barrel: strips parallel to beam
End cap: strips in radial direction

200 m^2 of silicon sensors
→ Industry involvement + 25 institutes

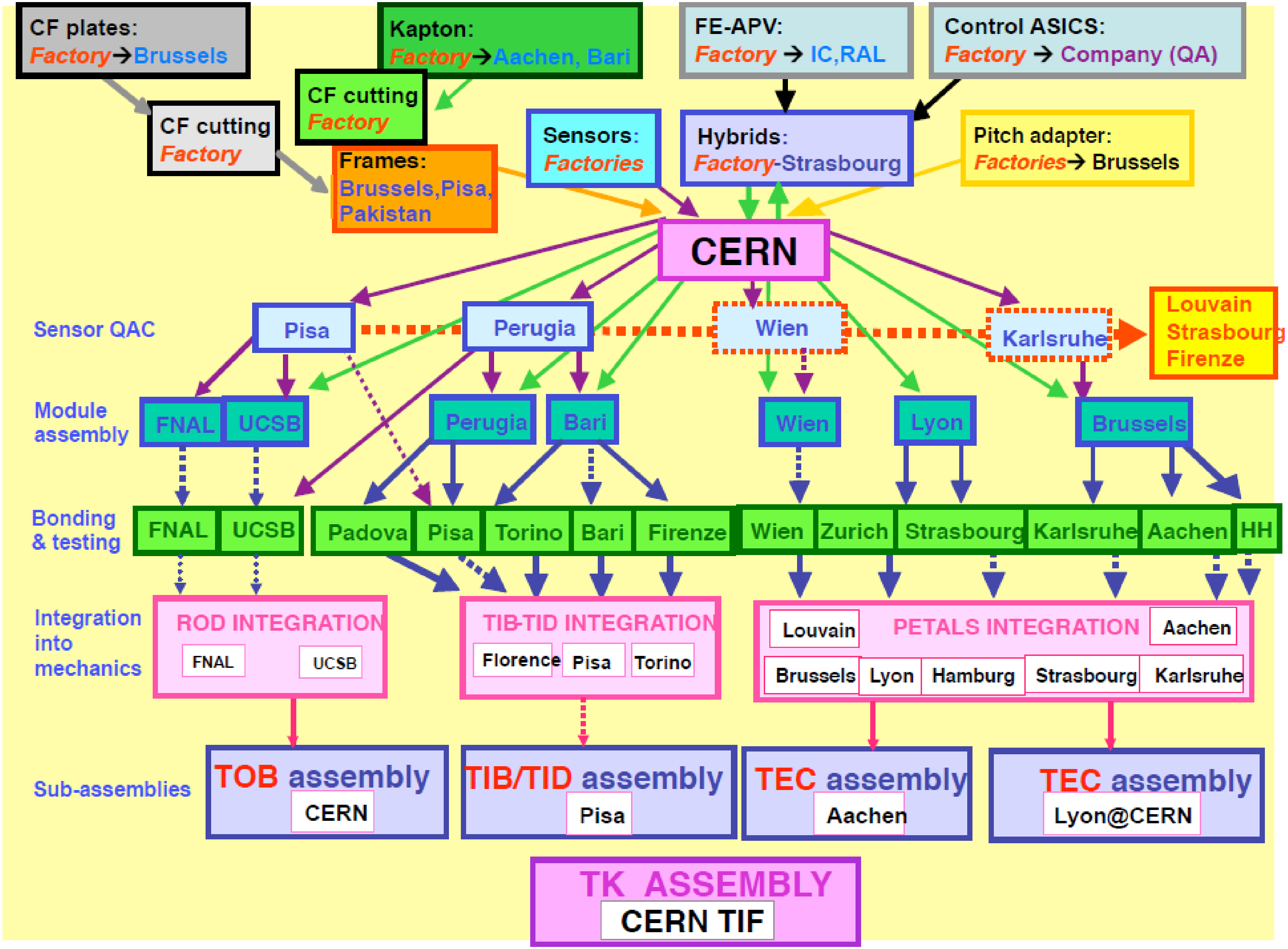
Silicon Sensors

- Two producers:
  - Hamamatsu Photonics (Japan)
  - ST Microelectronics (Italy)
- Four main Test centers
  - Supported by smaller tests in different locations
  - Irradiation
  - Bonding tests
  - Process Qualification & Longterm stability

Complex logistics



CMS contruction simple process...



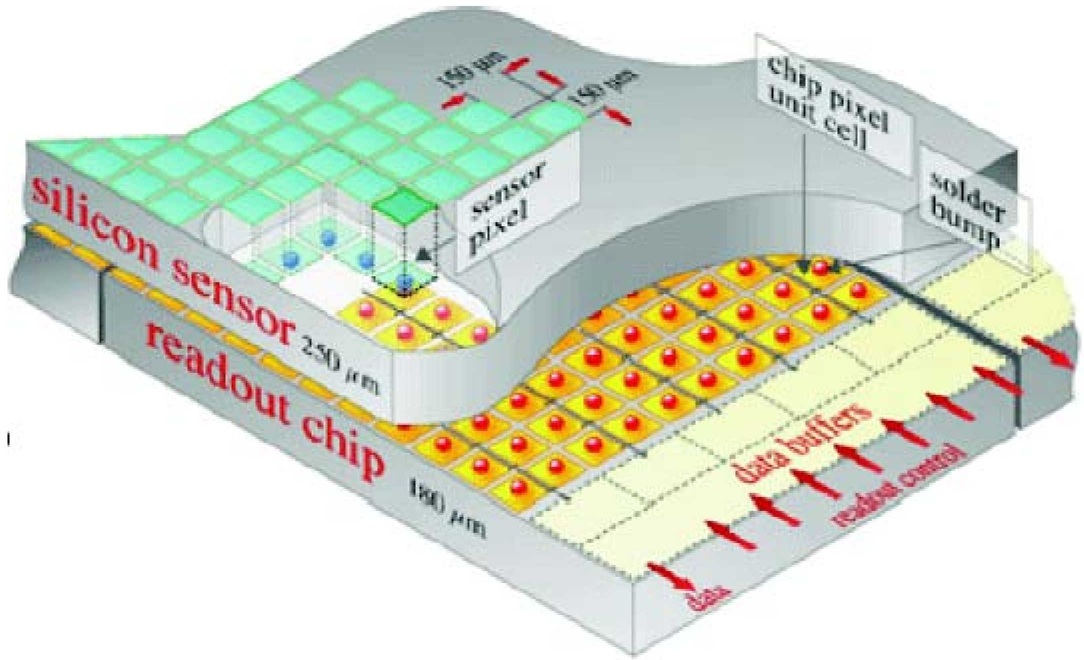
Pixel detectors

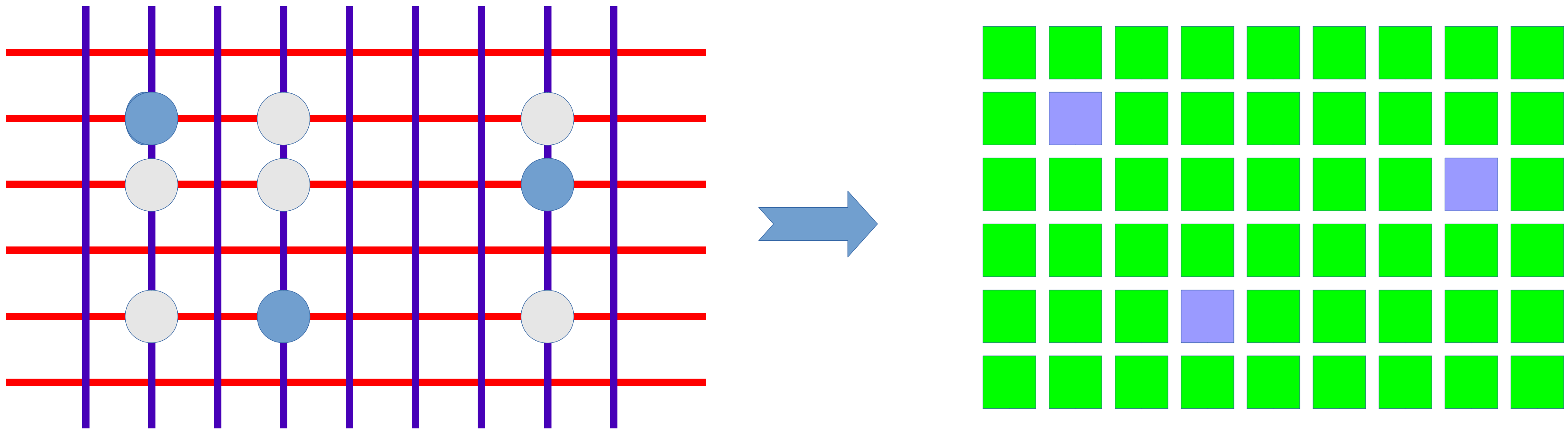
- The principle of pixel detectors is an array of small independent Si pads
- Provide unambiguous hit

  even in high occupancy
- Small pixel area →

  small capacitance (1fF/pix) →

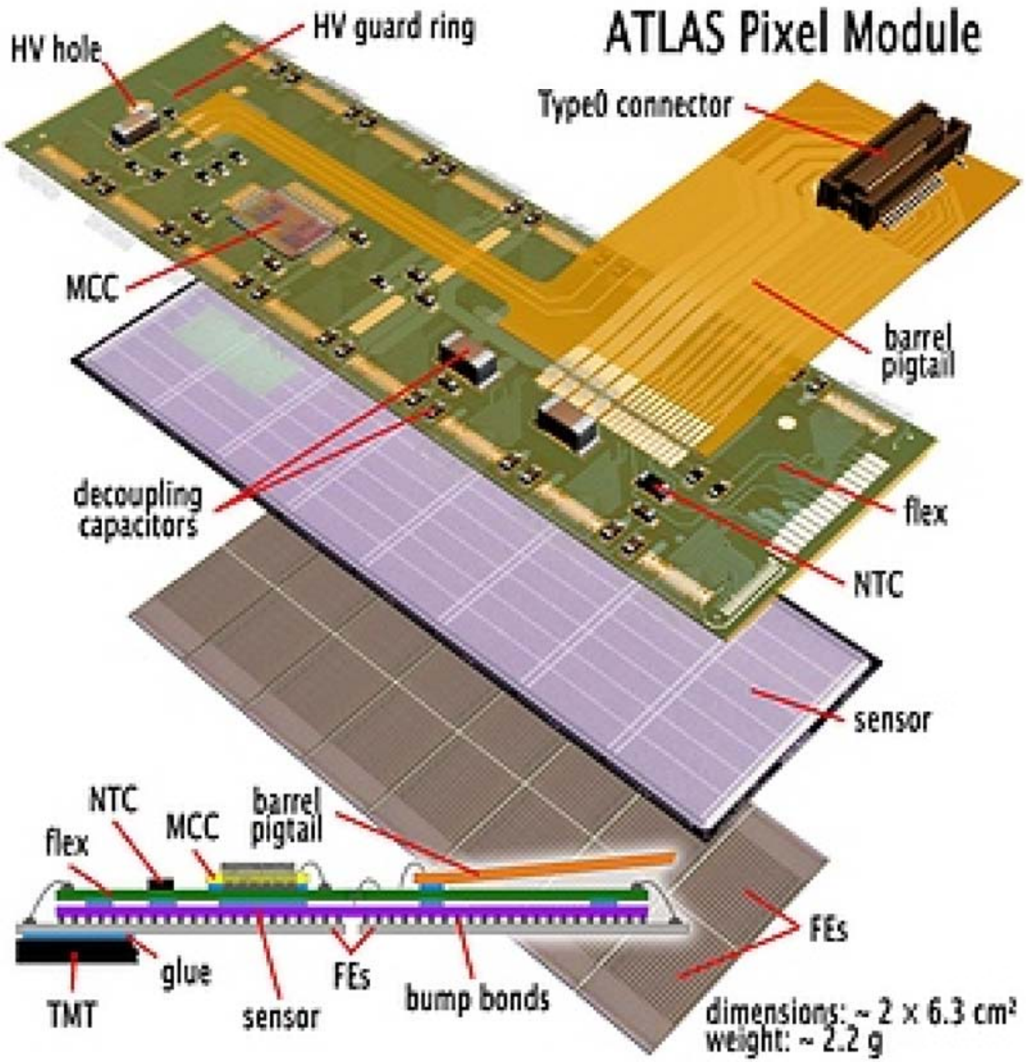
  large signal to noise (~100:1)





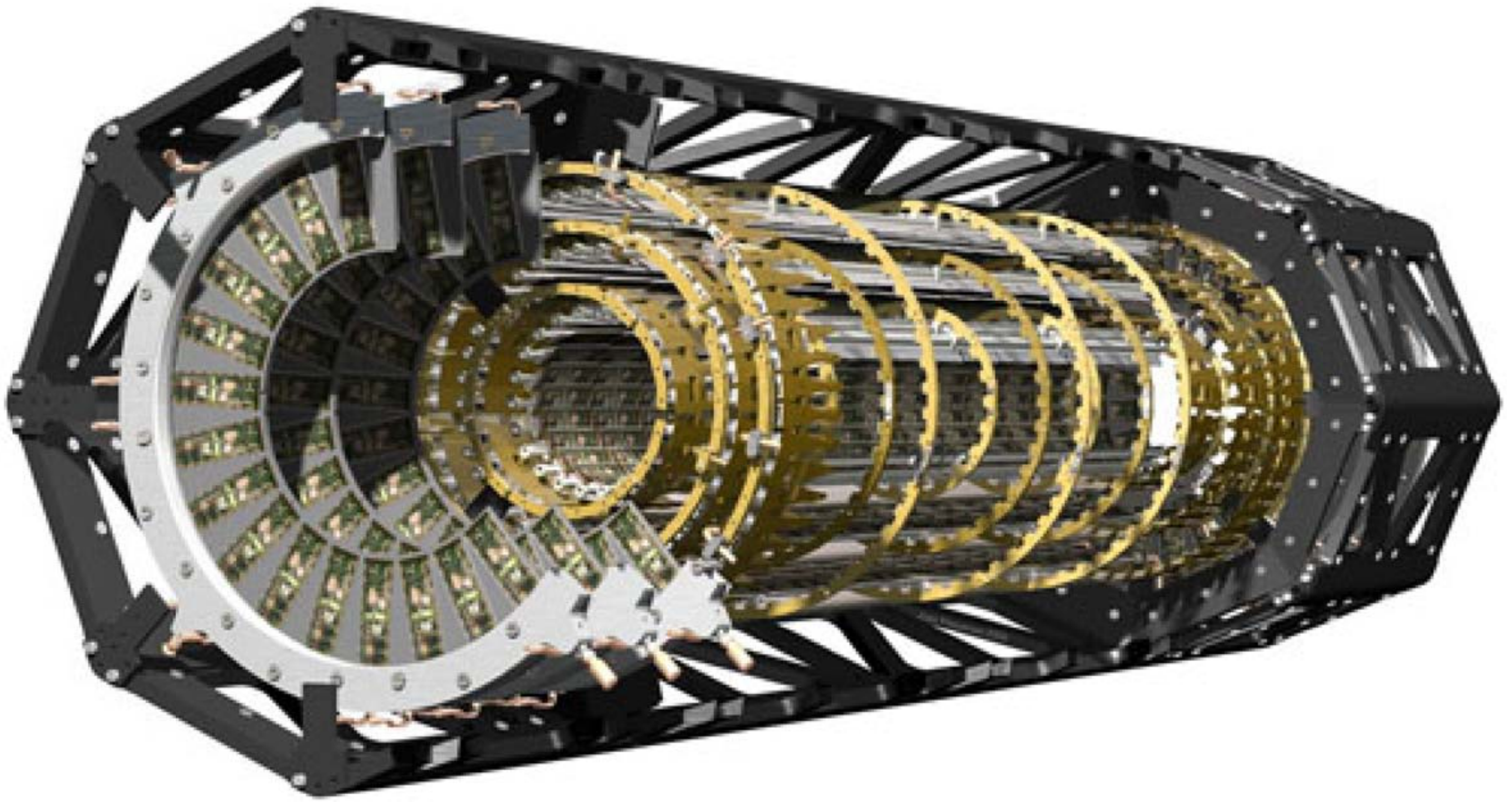
Pixel detectors

- Disadvantages
  - Large number of electrical connections
  - Large power consumption → cooling
- Expensive to cover large area
  - Suitable for innermost region near collision region where hit density is highest



ATLAS Pixel detector

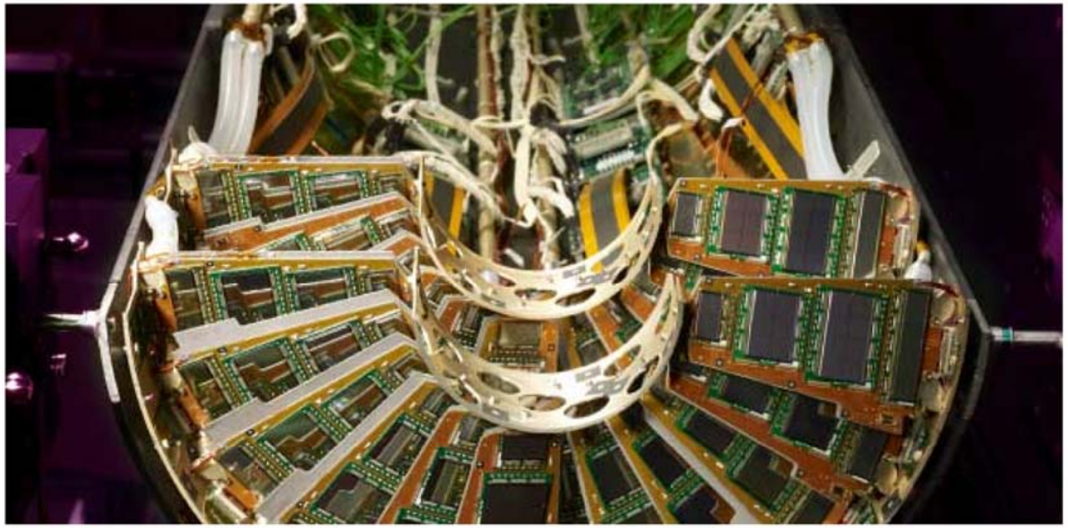
- 3Barrerls (5-12cm) and 3 disks (r=9-15cm)
- 80M pixels, 1.7m^2 area
- Radiation hard up to 5 10^{14} neutrons/cm^2
- Independent installation

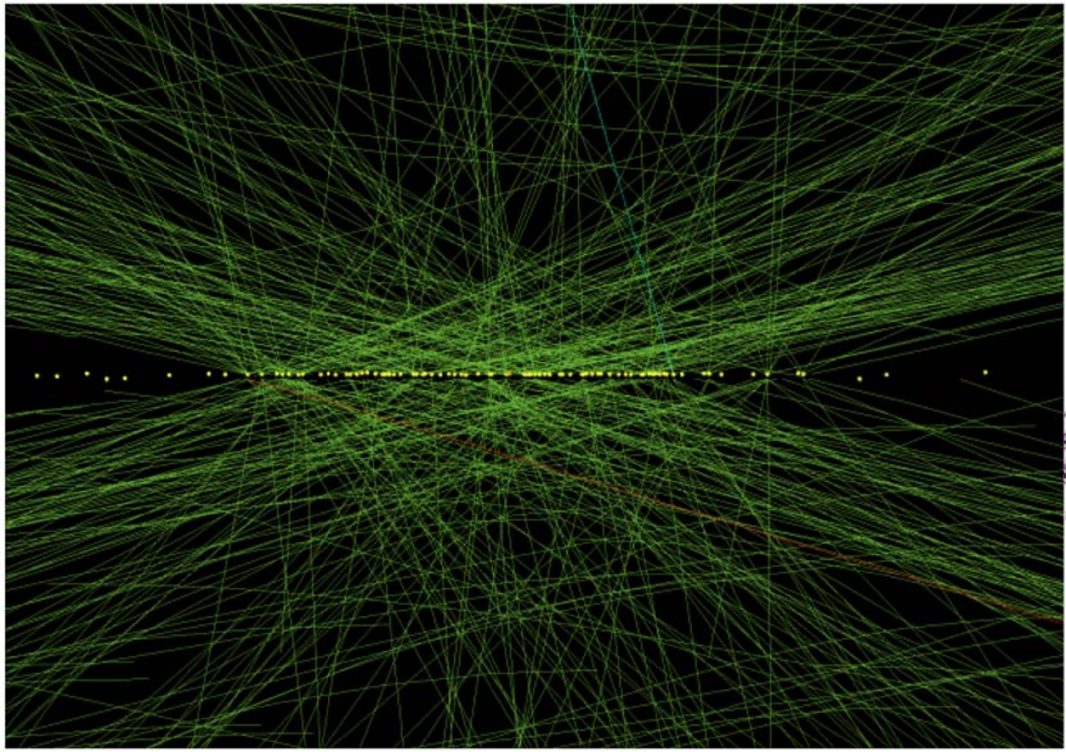


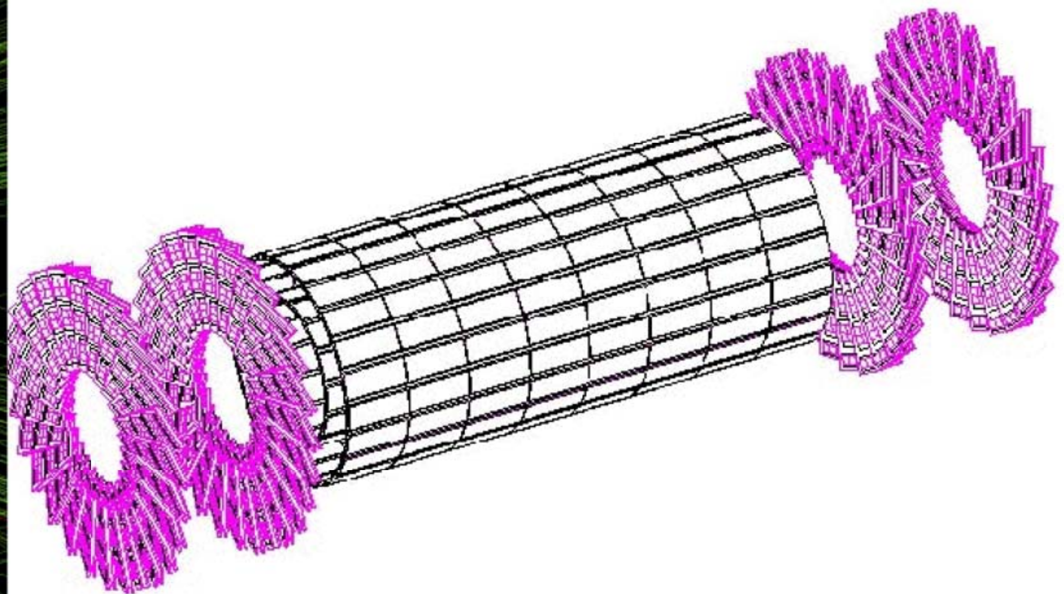
CMS Pixel detector

- 3 Barrels (4-11cm), 2 disks
- 65 M pixels
- An event from high pileup

  run

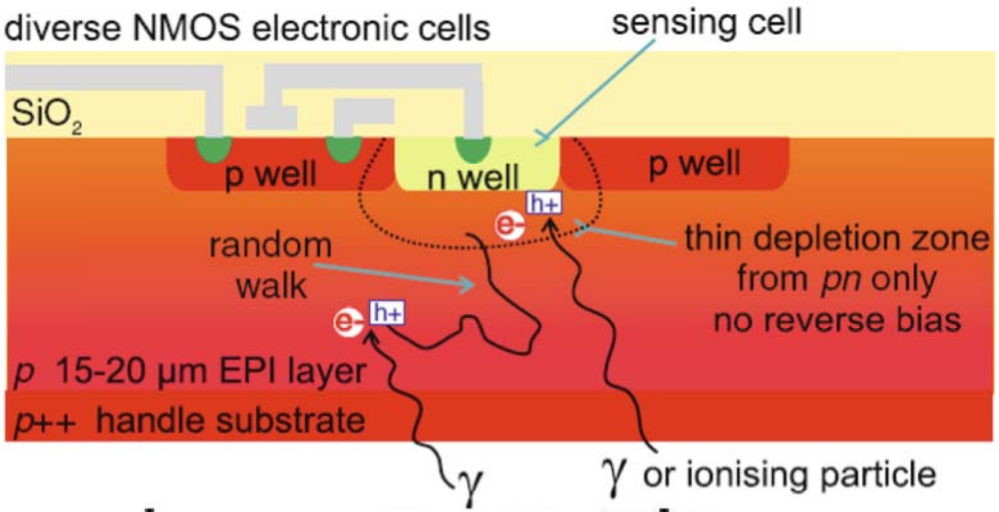




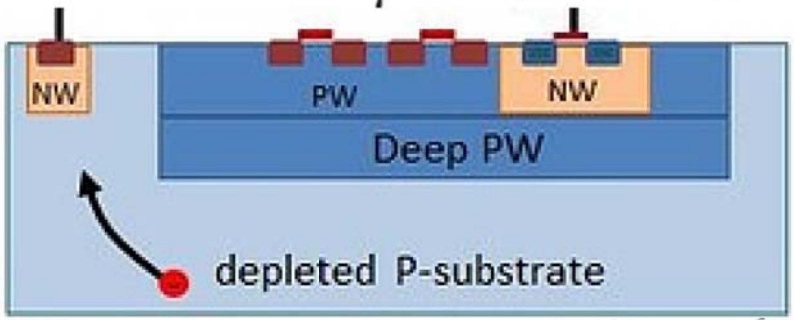


Future prospects

- Monolithic active pixels sensors (MAPS) on standard CMOS substrate are very promising candidates for experiments with moderate timing and radiation hardness requirement.

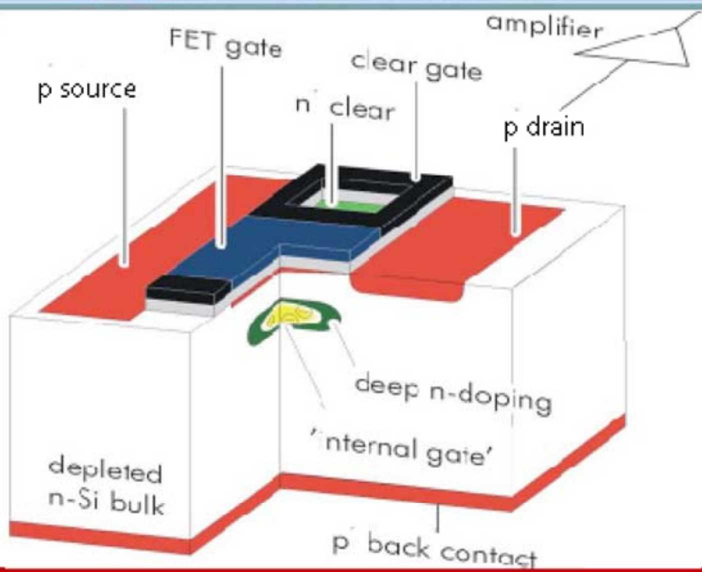


- DMAPS depleted active pixels
  Faster but more complex due to high resistivity silicon substrate



- DEPFET : field effect transistors on top of fully depleted bulk

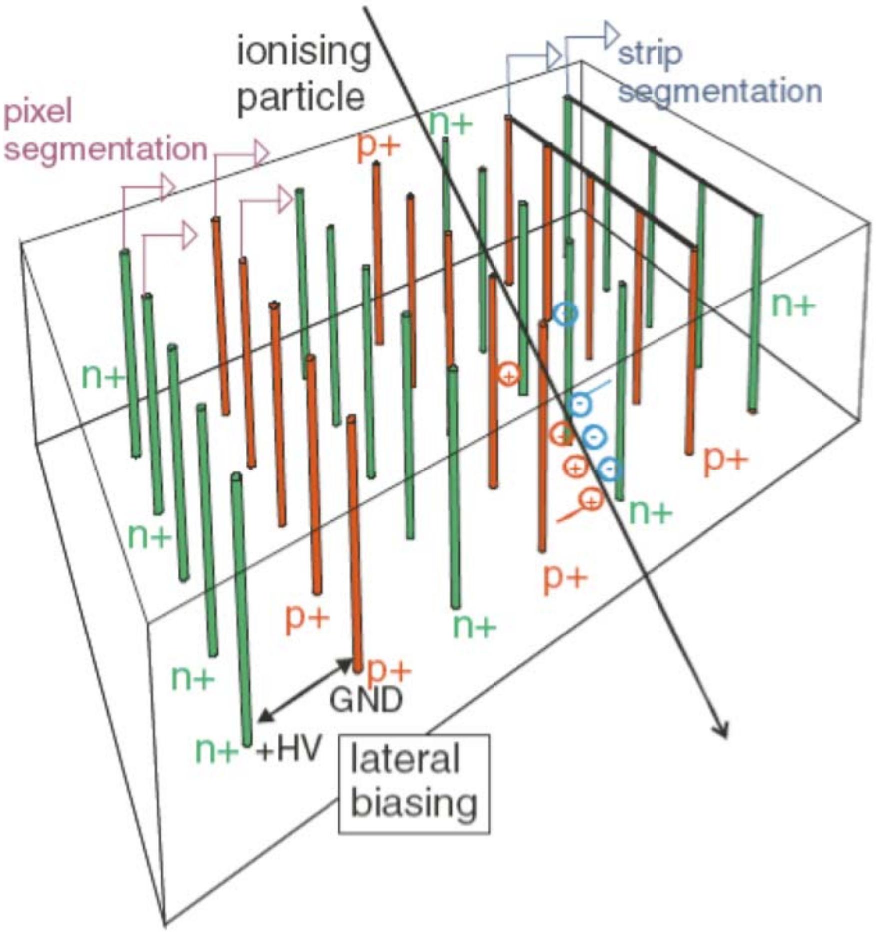
  Combines sensor and amplifier



Future prospects

- Non planar detectors
- Deep holes are etched into the silicon
  - filled with n+ and p+ material.
  - Voltage is applied between
  - Depletion is sideways
- Small distances between the electrode
- Very low depletion voltages
- Very fast, since charge carries travel

  shorter distances



- Very radiation tolerant detectors, in discussion for inner detector layers at SLHC.

More's Law for silicon trackers….