SEMICONDUCTOR DETECTORS

LECTURE 4 PART 2

CONTENT

REFERENCES

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- Doris Eckstein,
  "Semiconductor detectors"
  Lecture at DESY, 2012
- Kolanoski, Wermes
  "Teilchendetektoren", 2015
- Kleinknecht,
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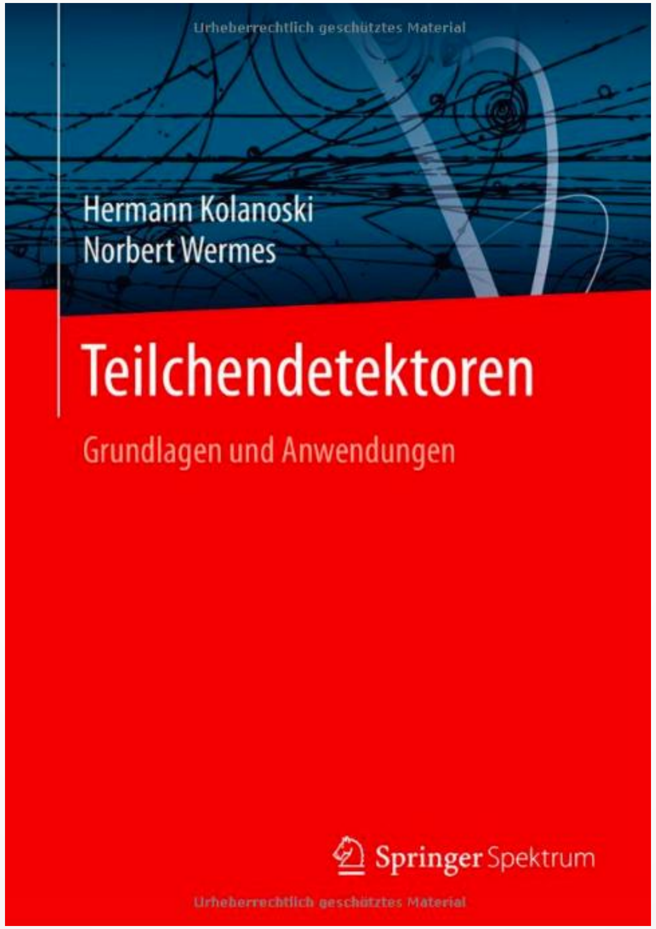


1. INTRODUCTION

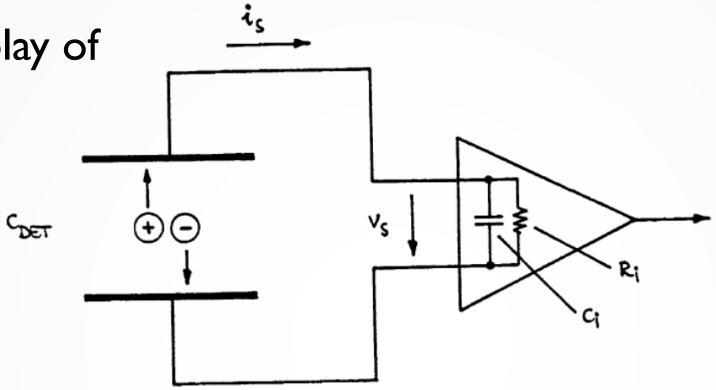
1.1 SEMICONDUCTOR DETECTORS

- Where are semiconductor detector used?
  - Nuclear Physics
    - Energy measurement of charged particles in the MeV range
    - Gamma spectroscopy:
      precise determination of photon energy
  - Particle Physics
    - Tracking or vertex detectors, precise determination of particle tracks and decay vertices
    - recently: high granularity calorimetry
  - Satellite Experiments
    - Tracking detectors
  - Industrial Applications
    - Security, Medicine, Biology,...

+ Semiconductor detectors have a high density
+ large energy loss in a short distance
+ Diffusion effect is smaller than in gas detectors resulting in achievable position resolution of less than 10 µm
+ Low ionization energy (few eV per e-hole pair) compared to
  - gas detectors (20-40 eV per e-ion pair) or
  - scintillators (400-1000 eV to create a photon).
+ Large experience in industry with micro-chip technology (silicon).
+ Easy integration with readout electronics (identical material)
+ High intrinsic radiation hardness
- No internal amplification, i.e. small signal
- High cost per surface unit
  - Not only the silicon itself
  - High number of readout channels:
    Large power consumption and cooling

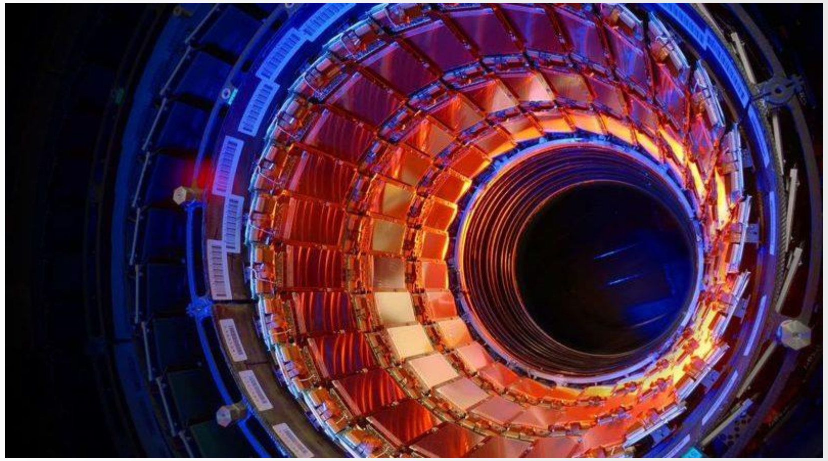
1.2 SILICON –OPERATING PRINCIPLE

- Most semi-conductor detectors work on the principle of an ionization chamber.
- The challenge is to find the best interplay of material, sensor geometry, supply/readout electronics, cooling, and detector geometry

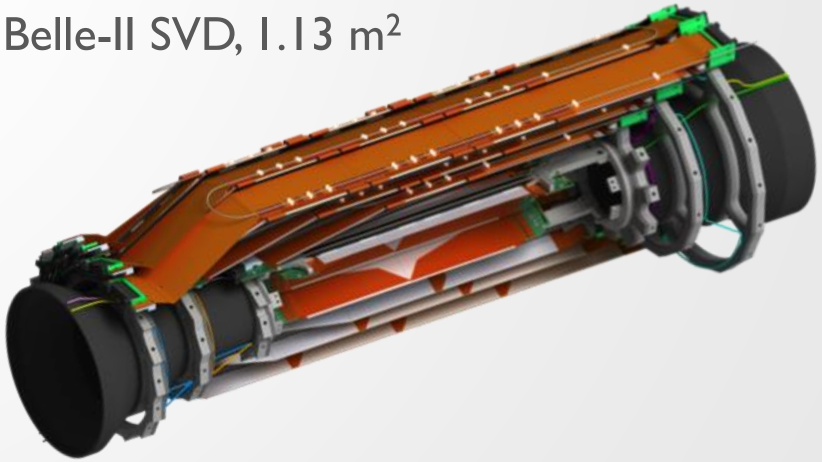


- properties of Silicon semiconductors:
  - moderate bandgap E_g = 1.12 eV
  - minimum energy to create e/h pair = 3.6 eV which is low compared to gases used for ionization chambers or proportional counters (e.g. Ar E_{ion} = 15 eV)
- High density and atomic number (Bethe Bloch!)
  - Higher specific energy loss ⟶ Thinner detectors are possible Of course, Landau fluctuations become important.
- High carrier mobility ⟶ Fast!
  - Less than 30 ns to collect entire signal
- SiO_2 is a good dielectric with good control in the fabrication process
- Industrial fabrication techniques (however, only few vendors if requirements are specific)

CMS tracker, 200 m^2

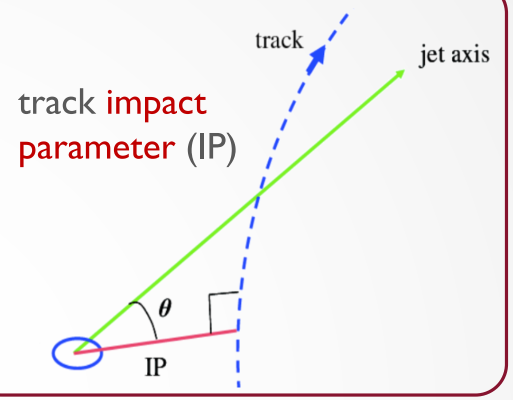


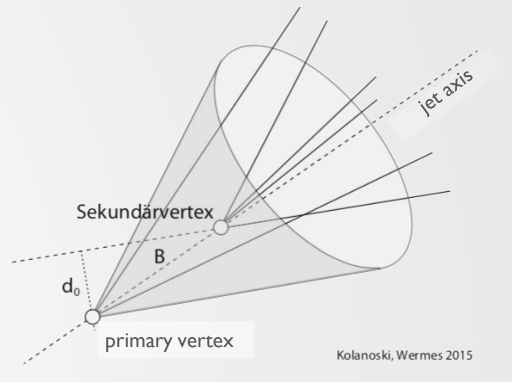
Belle-II SVD, 1.13 m^2



1.3 MAIN OBJECTIVES OF TRACKING DETECTORS

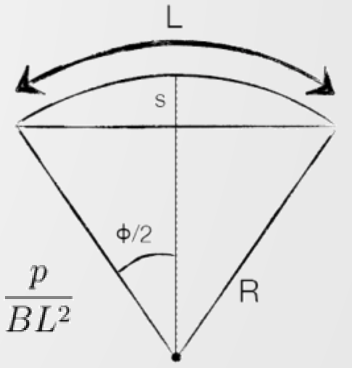
- Objective: Track particles without disturbing them
- Determine position of primary and secondary vertex.
  - Need superb position resolution ⟶ Highly segmented
  - Need large signal (no intrinsic amplification)
  - Thin, close to interaction point





- Determine particle momentum by measuring track curvature.
- Low mass of the detector is needed:
  - Minimize multiple scattering of detector, readout, cooling / support.
- In summary, the measurements are points in space, used to deduce
  - vertex location of primary collisions and secondary decays
  - track momenta
  - impact parameters, decay lengths

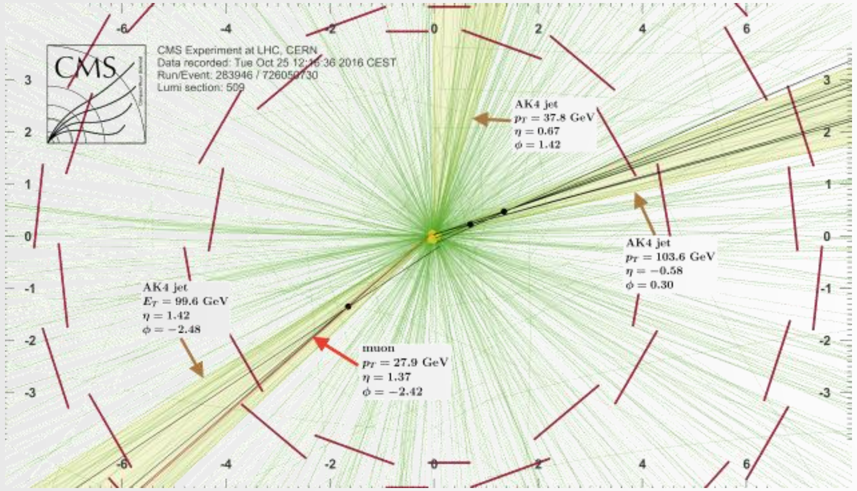
spectrometer momentum measurement (see later)

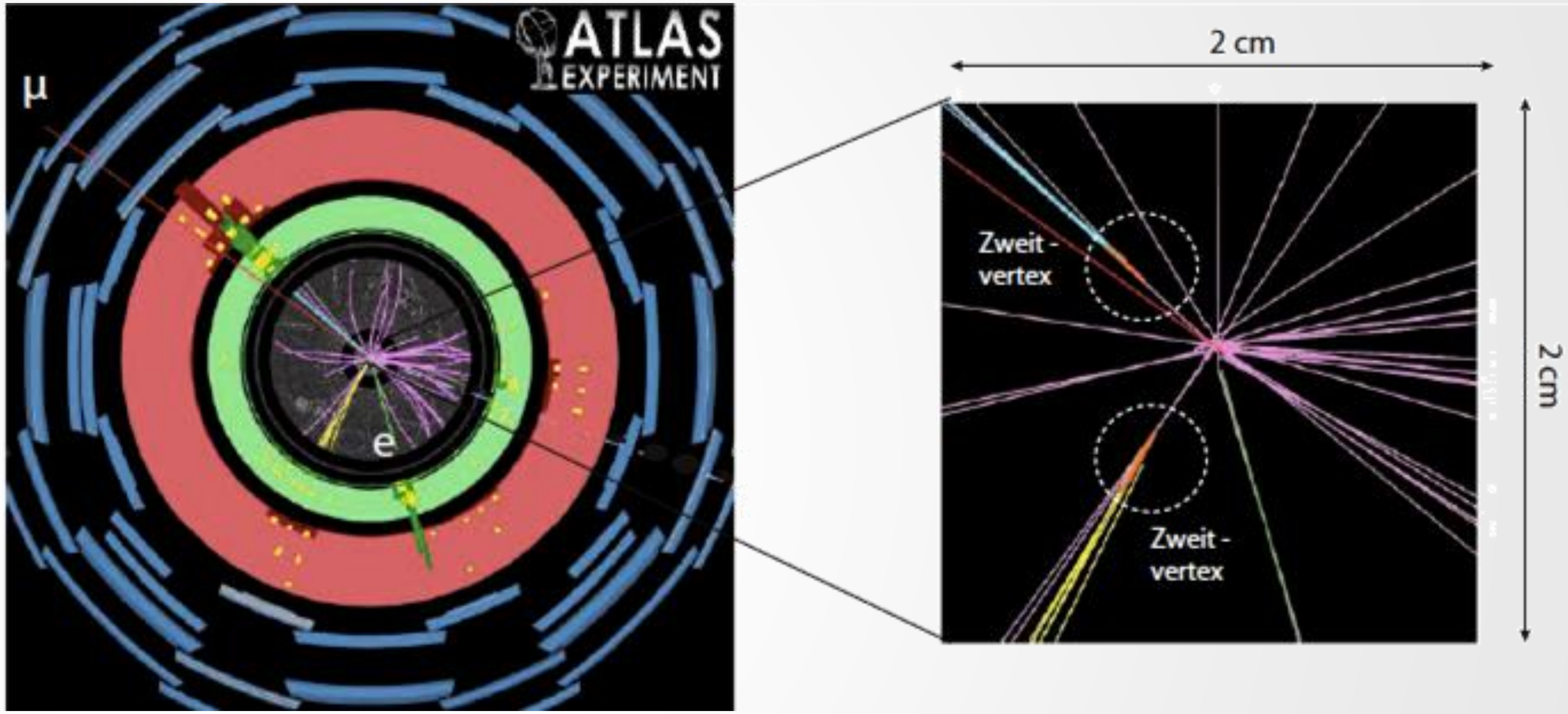


$$\frac{\sigma_p}{p} = \frac{\sigma_s}{s} = \frac{8\sigma_s}{0.3}\frac{p}{BL^2}$$

1.4 MAIN APPLICATIONS: TRACKING, VERTEXING, B-TAGGING

CMS event





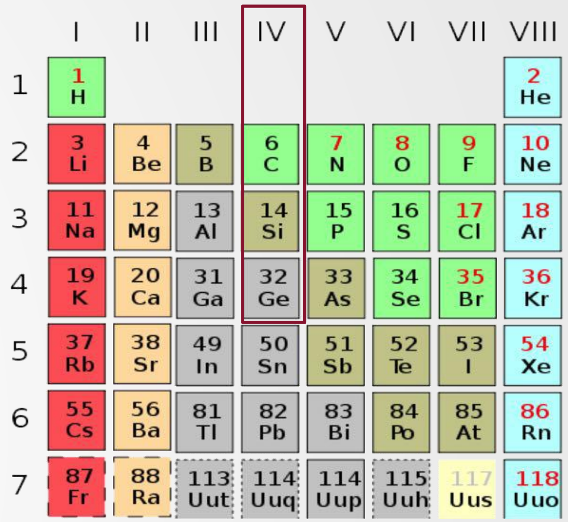
- Pixel and strip tracking detectors in large collider experiments are often onion-shaped and operate in a high magnetic field. The tracks are reconstructed and primary collision vertices are identified.
- Secondary vertices (e.g τ lepton from Z: $\beta\gamma$ = p/m = 45.5GeV/1.78 GeV, cτ=87μm, $\beta\gamma c\tau$ = 2.2 mm) can be identified with impact parameter resolutions of 10μm (100 GeV) to 100μm (1 GeV) for meter-sized detectors!

2. SEMICONDUCTORS

2.1 TYPES OF SEMICONDUCTORS

- Elementary semiconductors
  - Germanium
    - Used in nuclear physics and DM searches (Needs liquid nitrogen cooling due to small band gap of 0.66 eV)
  - Silicon
    - Can be operated at room temperature
    - Synergies with micro electronics industry
    - Standard material for vertex and tracking detectors in high energy physics
  - Diamond (CVD or single crystal):
    - Allotrope (=differ by crystal structure) of C
    - Large band gap (requires no depletion zone)
    - very radiation hard
    - Disadvantages: low signal and high cost

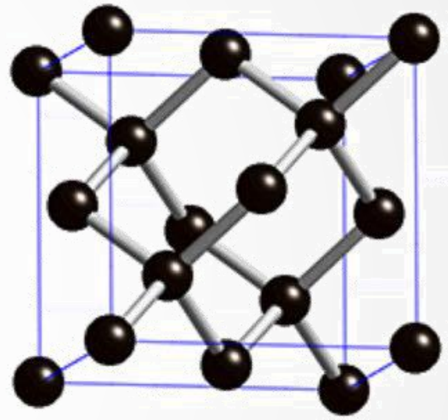
- Compound semiconductors
  - two or more atomic elements
  - depending on the column in the periodic system differentiate:
    - IV-IV (e.g. SiGe, SiC),
    - III-V (e.g. GaAs, direct)
    - II-VI compounds (CdTe, ZnSe)
  - important III-V compounds:
    - GaAs: Faster and probably more radiation resistant than Si.
    - Drawback is less experience in industry and higher costs.
    - others: GaP, GaSb, InP, InAs, InSb, InAlP
  - important II-VI compounds:
    - CdTe: High Z (48+52) hence very efficient to detect photons (Remember: $\gamma \longrightarrow e^{\pm}e^{\mp} \propto Z^2$)
    - ZnS, ZnSe, ZnTe, CdS, CdSe, $Cd_{1-x}Zn_xTe$, $Cd_{1-x}Zn_xSe$



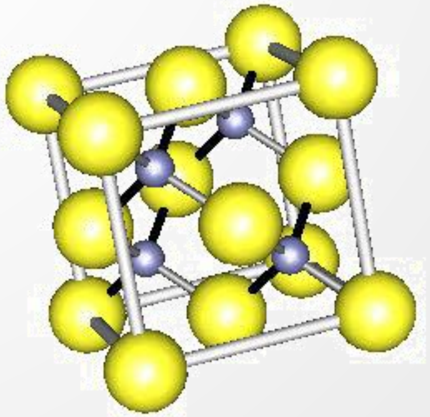
2.2 CRYSTAL STRUCTURE OF SEMICONDUCTORS

- Si, Ge and diamond
  - Group IV elements
  - Crystal structure: diamond lattice
    - two nested sub-lattices
  - shifted by one quarter along the diagonal of the cube.
  - Each atom is surrounded by four equidistant neighbors.
  - Lattice parameter a = 0.54 nm for Si
- Most III-V semiconductors (e.g. GaAs)
  - zincblende lattice
  - similar to the diamond lattice
  - except that each sub-lattice consists of one element.
  - GaAs is a ‘direct’ semiconductor (in comparison to most others), the creation of e/h pairs needs no energy transfer to the lattice (This efficiency is exploited in LEDs).

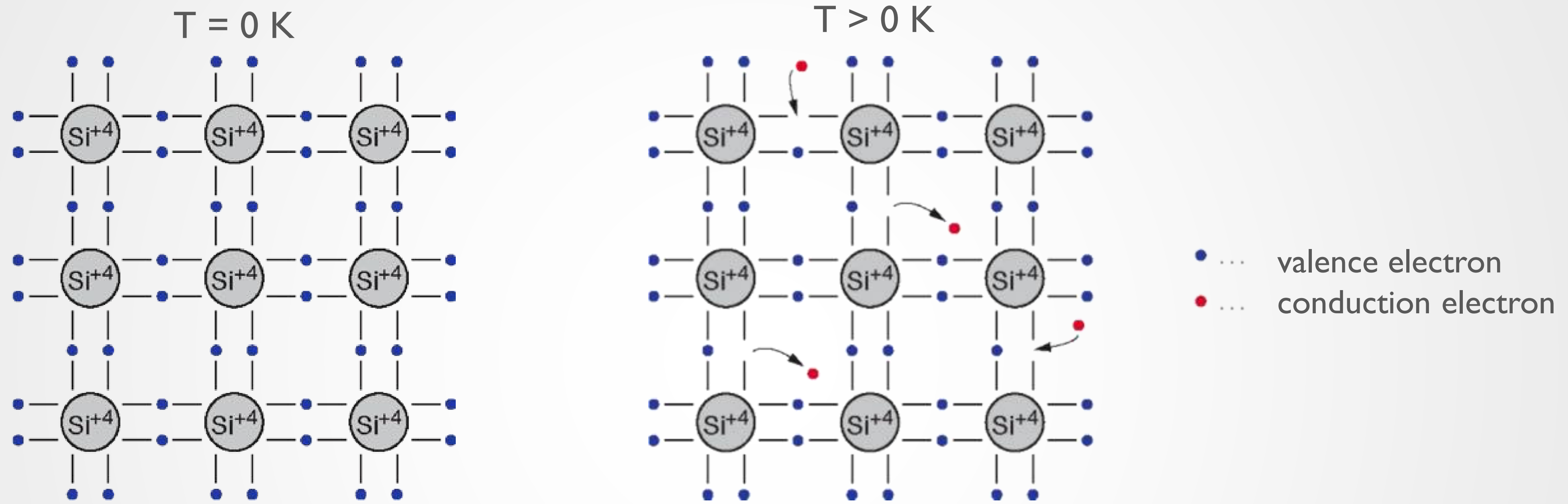
diamond lattice:
two face-centred cubic lattices



Zincblende lattice



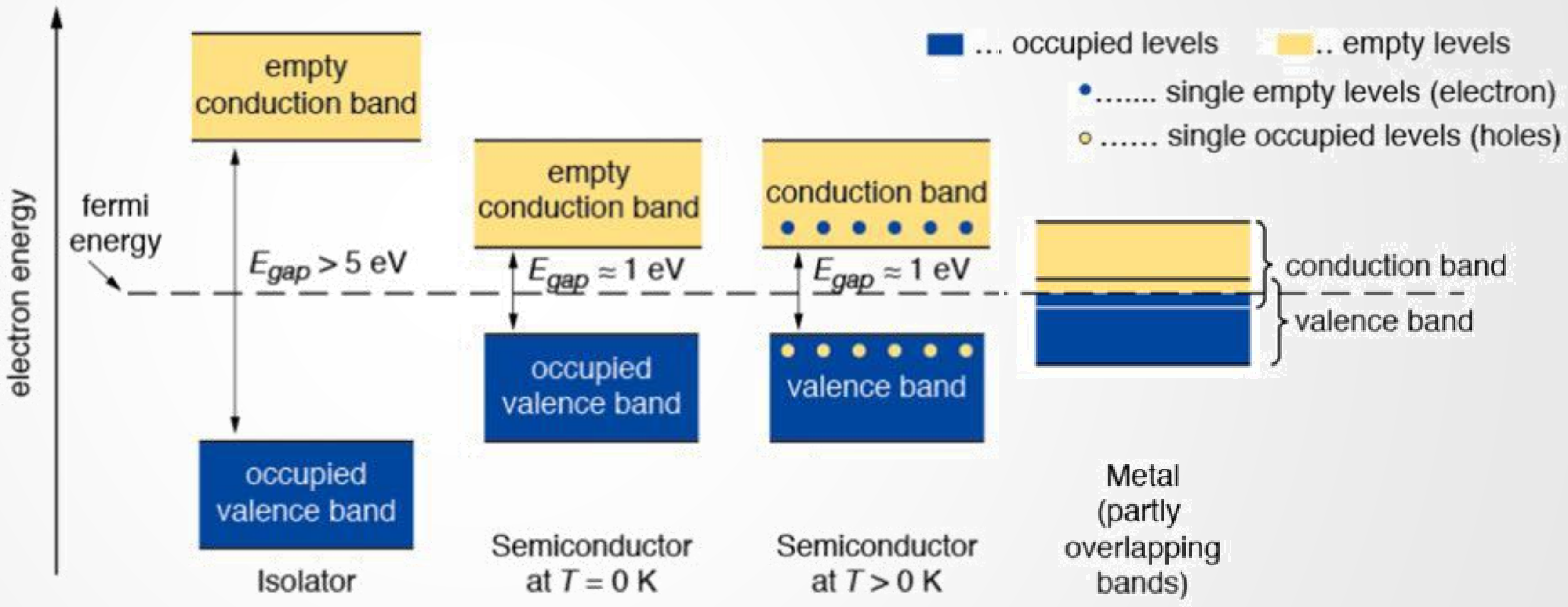
2.3 BOND MODEL OF SEMICONDUCTORS



- Each atom has 4 closest neighbors, the 4 electrons in the outer shell are shared and form covalent bonds.
  - At low temperature all electrons are bound (valence electrons)
- For T > 0 K, thermal vibrations break some of the bonds ⟶ free e^- cause conductivity (electron conduction)
- The remaining open bonds attract other e^- ⟶ The "holes" change position (hole conduction)
- The dynamic of electrons and holes differs, because of the different interactions with the surrounding atoms.

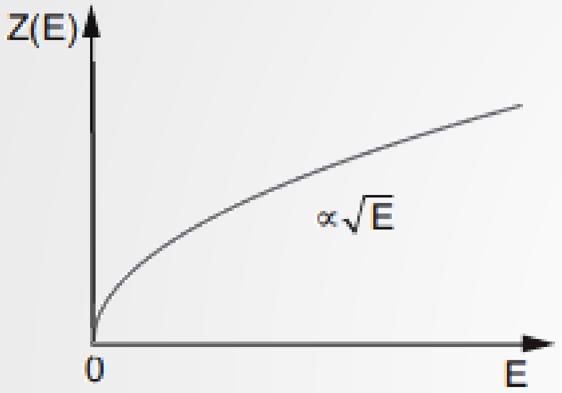
2.4 ENERGY BANDS

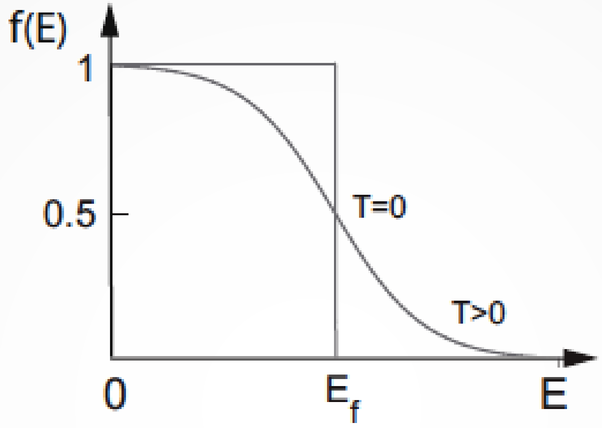
- In an isolated atom the electrons have only discrete energy levels.
- In solid state materials, the atomic levels merge to energy bands (meV differences)
- In metals, the conduction and the valence band overlap. In isolators and semiconductors these levels are separated by an energy gap (band gap).
- In isolators, this gap is large.

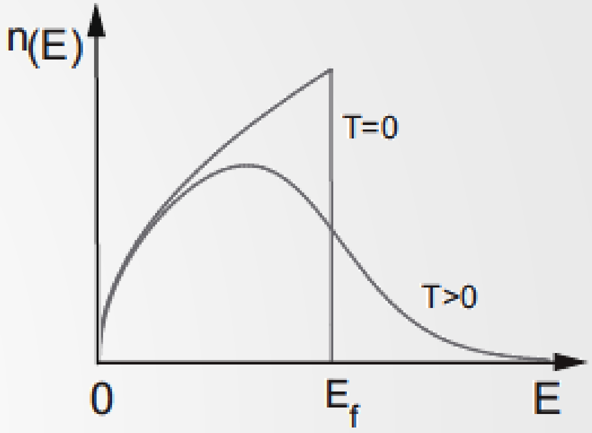


- The Fermi energy E_f is the level of 50% occupancy.
- Equilibrium: constant Fermi level

2.5 ELECTRONS AND HOLES IN A SEMICONDUCTOR







- The density of states above a threshold grows with √E (see backup)

$$Z(E)\,dE = 4\pi\left(\frac{2m_{\text{eff}}}{h^2}\right)^{3/2}\sqrt{E}\,dE\,.$$

where m_{eff} is the effective electron or hole mass that describes the different dynamics of e^- and h^+.

- The occupation of energy levels for spin-1/2 particles is given by the Fermi-Dirac distribution.

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

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

- For T=0, there is a sharp threshold at the Fermi energy.

- The number density (per volume and energy) of electrons or holes is given by

$$n(E)\,dE \;=\; Z(E)\,f(E)\,dE$$

- Integrate this over energy for the total number density …

2.5 ELECTRONS AND HOLES IN A SEMICONDUCTOR

- For $E-E_f > kT$, expanding the exponential and integrating over $E>E_L$ (for electrons) or $0<E_V$ (for holes) the number densities (per volume) for electrons and holes become

$$n = 2\left(\frac{m_{\mathrm{eff},n}\, kT}{2\pi\hbar^2}\right)^{\frac{3}{2}} \exp\left(-\frac{E_L - E_f}{kT}\right) = N_L \cdot \exp\left(-\frac{E_L - E_f}{kT}\right)$$

$$p = 2\left(\frac{m_{\mathrm{eff},p}\, kT}{2\pi\hbar^2}\right)^{\frac{3}{2}} \exp\left(-\frac{E_f - E_V}{kT}\right) = N_V \cdot \exp\left(-\frac{E_f - E_V}{kT}\right)$$

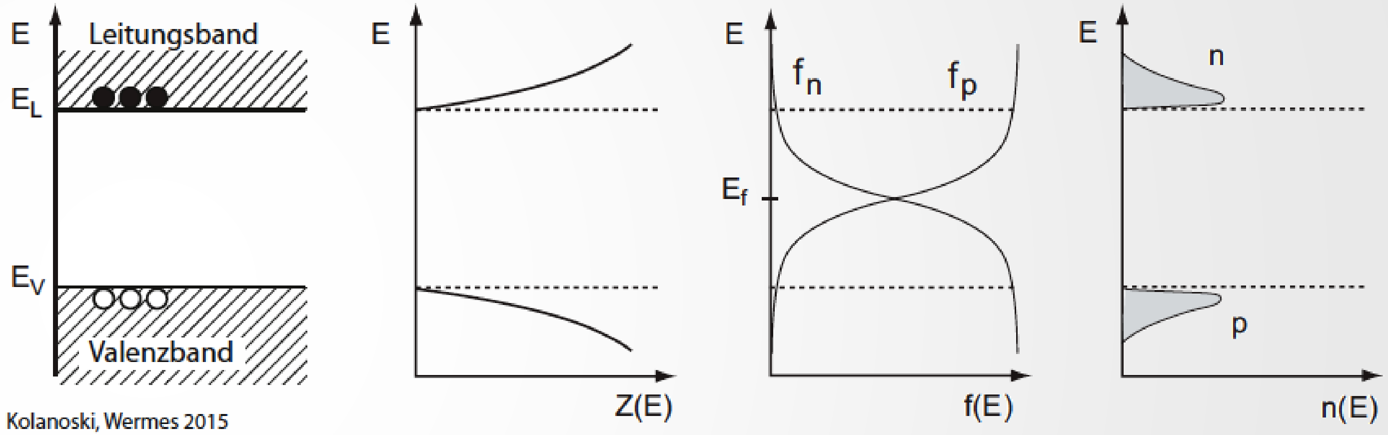
where Si at 300K

$$N_L = 2\left(\frac{m_{\mathrm{eff},n}\, kT}{2\pi\hbar^2}\right)^{\frac{3}{2}} \approx 3.05 \cdot 10^{19}\,\mathrm{cm}^{-3}$$

$$N_V = 2\left(\frac{m_{\mathrm{eff},p}\, kT}{2\pi\hbar^2}\right)^{\frac{3}{2}} \approx 2.55 \cdot 10^{19}\,\mathrm{cm}^{-3}$$

are the effective e (h) state densities of in the conduction (L) and valence (V) band.

- Si@300K: $m_{eff}(e)=1.14\ m_e$, $m_{eff}(h)=1.01\ m_e$



Kolanoski, Wermes 2015

- In equilibrium $n = p = n_i$
  and therefore $n \cdot p = n_i^2 = const.$
- The product $n_i^2 = np = N_L N_V \exp\left(-\frac{E_G}{kT}\right)$
  is independent of E_f but $\propto T^3$.
  (holds also if the concentrations are modified by doting)
- 'Intrinsic' carrier concentration for pure Si: $n_i = 1.01\ 10^{10}\ \mathrm{cm}^{-3}$
  at room temperature ($\exp(-E_g[\mathrm{Si,300K}]/2kT) \approx 4\ 10^{-10}$)

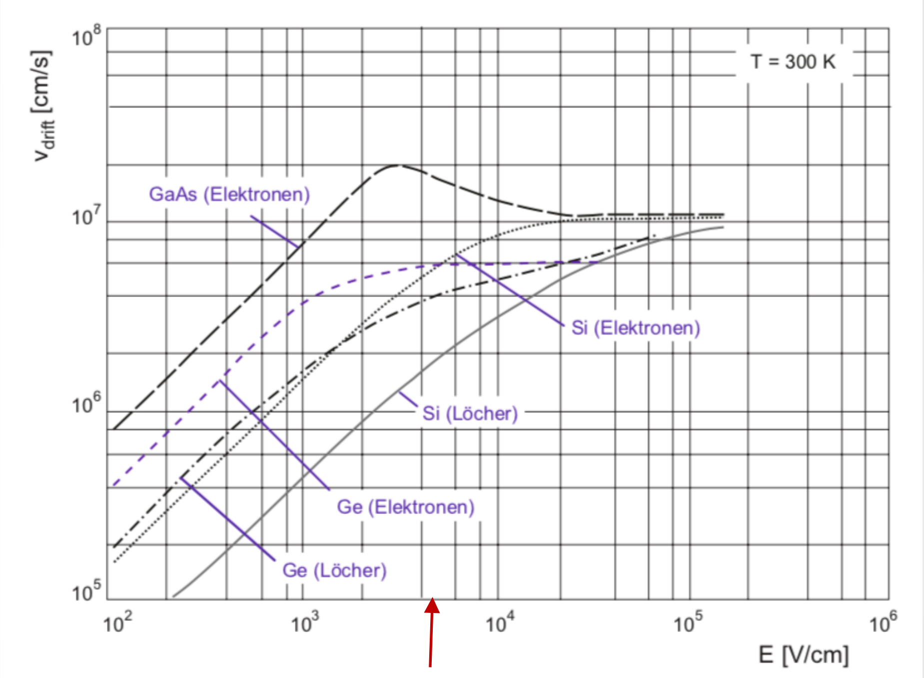
2.6 DRIFT VELOCITY, RESISTIVITY AND MEAN FREE PATH

- Because of the small Si band-gap E_g=1.12 eV, there are ≈ 10^{10} /cm^3 charge carriers at room temperature.
- With 10^{22} Atoms / cm^3, about 1 in 10^{12} atoms is ionized
- Drift velocity: $\nu_n = \mu_n |\vec{E}|,$ $\nu_p = \mu_p |\vec{E}|$
- Mobility: $\mu_n = \frac{e\,\tau_n}{m_{n,\text{eff.}}}$ $\mu_p = \frac{e\,\tau_p}{m_{p,\text{eff.}}}$
- Specific resistivity $\boldsymbol{\rho}$ is a measure of the Silicon purity:

$$\rho = \frac{1}{e(\mu_n n_e + \mu_p n_h)}$$

μ_p(Si, 300 K) ≈ 450 cm^2/Vs
μ_n(Si, 300 K) ≈ 1450 cm^2/Vs

  - $\boldsymbol{\tau}_n$, $\boldsymbol{\tau}_p$ … mean free time between collisions for e^- and holes (carrier lifetime)
  - μ_n, μ_p … mobility for electrons and holes
  - n_e, n_h … charge carrier density for electrons and holes
  - With the charge carrier concentration in pure Si (≈10^{10} cm^{-3}): $\boldsymbol{\rho}$ ≈ 230 kΩ cm
  - If mean free path is lower because of impurities, then $\boldsymbol{\rho}$ increases



Example: Sensor thickness 300μm
U = 100 V, E = 3.3 10^3 V/cm
ν_e = 48 μm/ns

$$t = \frac{d}{v_D} \approx \frac{300\,\mu\text{m}}{50\,\mu\text{m/ns}} \approx 6\,\text{ns}$$

LHC bunch spacing is 25ns!

2.7 SEMICONDUCTOR MATERIAL PROPERTIES

http://www.ioffe.rssi.ru/SVA/NSM/Semicond

Material	Si	Ge	GaAs	GaP	CdTe	Diamond*
Atomic number Z	14	32	31+33	31+15	48+52	6
Mass Number A (amu)	28.086	72.61	69.72+74.92	69.72+30.97	112.4+127.6	12.011
Lattice constant a (Å)	5.431	5.646	5.653	5.451	6.482	3.567
Density ρ (g/cm^3)	2.328	5.326	5.32	4.13	5.86	3.52
E_g (eV) bei 300 K	1.11	0.66	1.42	2.26	1.44	5.47–5.6
E_g (eV) bei 0 K	1.17	0.74	1.52	2.34	1.56	≈ 6
rel. permittivity $\varepsilon_r = \varepsilon / \varepsilon_0$	11.9	16.0	12.8	11.1	10.9	5.7
Melting point (°C)	1415	938	1237	1477	1040	3527
eff. e^--mass (m_n/m_e)	0.98, 0.19	1.64, 0.08	0.067	0.82	0.11	0.2
eff. hole mass$^+$ (m_h/m_e)	0.16	0.044	0.082	0.14	0.35	0.25

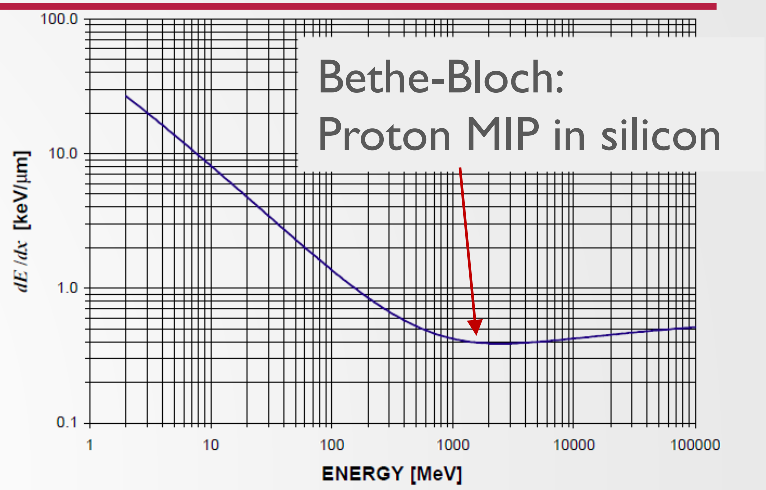
2.7 SEMICONDUCTOR MATERIAL PROPERTIES

http://www.ioffe.rssi.ru/SVA/NSM/Semicond

Material	Si	Ge	GaAs	GaP	CdTe	Diamond*
eff. density of states in conduction band n_{CB} (cm^{-3})	$3 \cdot 10^{19}$	$1 \cdot 10^{19}$	$4.7 \cdot 10^{17}$	$2 \cdot 10^{19}$		$\approx 10^{20}$
eff. Density of states in valence band n_{VB} (cm^{-3})	$1 \cdot 10^{19}$	$6 \cdot 10^{18}$	$7 \cdot 10^{18}$	$2 \cdot 10^{19}$		$\approx 10^{19}$
Electron mobility μ_e bei 300 K (cm^2/Vs)	~1450	3900	8500	< 300	1050	1800
Hole mobility μ_h bei 300 K (cm^2/Vs)	~450	1900	400	< 150	100	1200
instrins. charge carrier density at 300 K (cm^{-3})	$1.45 \cdot 10^{10}$	$2.4 \cdot 10^{13}$	$2 \cdot 10^{6}$	2		$\approx 10^{-27}$
instrins. resistivity at 300 K (Ω cm)	$2.3 \cdot 10^{5}$	47	$\approx 10^{8}$		$\approx 10^{9}$	$\geq 10^{42}$
Breakdown field (V/cm)	$3 \cdot 10^{5}$	$\approx 10^{5}$	$4 \cdot 10^{5}$	$\approx 10^{6}$		$3 \cdot 10^{7}$
Mean E to create an e^-h^+ pair (eV), 300 K	3.62	2.9	4.2	≈ 7	4.43	13.25

2.8 CONSTRUCTING A DETECTOR?

- Optimize the signal-to-noise ratio leads to contradictory requirements:
  - Large signal ⟶ low ionization energy ⟶ small band gap E_g
  - Low noise ⟶ 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 ionization e/h pairs.
  - Diamond has $E_g \approx 6$ eV! Artificial diamonds (CVD – Chemical Vapor deposition) too expensive for large detectors.



- All other materials have too many charge carriers in the conduction band. Example with 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 µm and an area of A = 1 cm².
  - MIP signal: $\frac{\mathrm{d}E/\mathrm{d}x \cdot d}{I_0} = \frac{3.87 \cdot 10^6\,\mathrm{eV\ cm^{-1}} \cdot 0.03\,\mathrm{cm}}{3.62\,\mathrm{eV}} \approx 3.2 \cdot 10^4\,\mathrm{e^-/h^+\ pairs} \approx 5\,\mathrm{fC}$
  - Charge carriers in same volume at T=300K:

$$n_i\,\mathrm{d}A = 1.01 \cdot 10^{10}\,\mathrm{cm^{-3}} \cdot 0.03\,\mathrm{cm} \cdot 1\,\mathrm{cm}^2 \approx 3.0 \cdot 10^8\,\mathrm{e^-/h^+\ pairs}$$

- Thermally produced charge carriers are 10^4 more abundant!
- Solution: remove them in reverse-biased pn-junctions.

2.9 DOPING

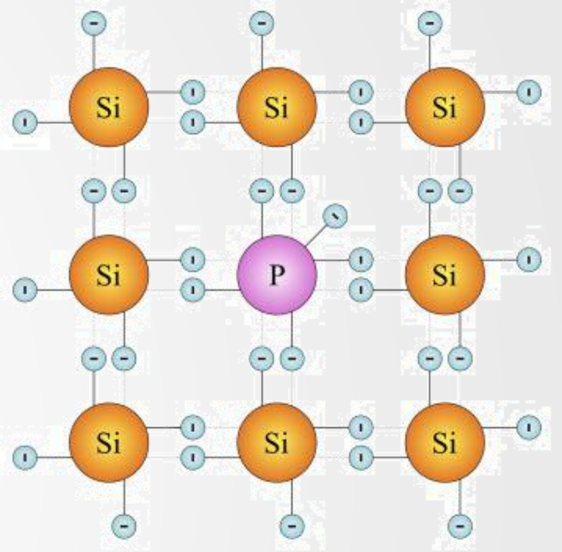
- A pn junction consists of n and p doped substrates:
  - Doping is the replacement of a small number of atoms in the lattice by atoms of neighboring columns from the periodic table
  - These doping atoms create energy levels within the band gap and therefore alter the conductivity.

Nomenclature:

- An un-doped semiconductor is called an intrinsic semiconductor
  - For each conduction electron exists the corresponding hole.
- A doped semiconductor is called an extrinsic semiconductor.
  - Extrinsic semiconductors have a abundance of electrons or holes.

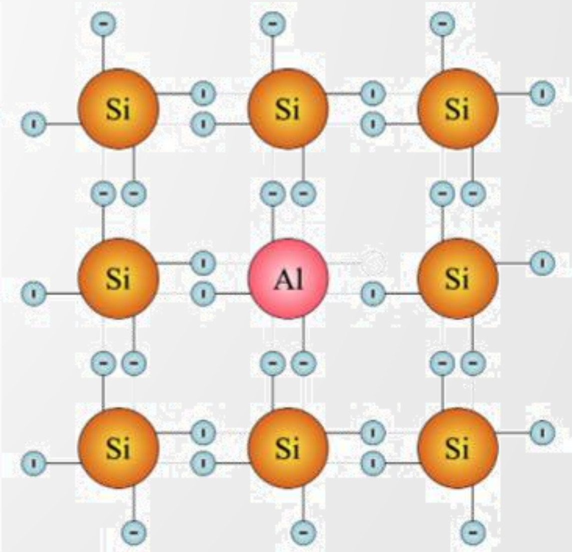
n-type

- Dopants: Elements with 5 valence electrons, e.g. Phosphorus
- electron donators
- electron abundance



p-type

- Dopants: Elements with 3 valence electrons, e.g. Aluminum
- electron acceptors
- electron shortage



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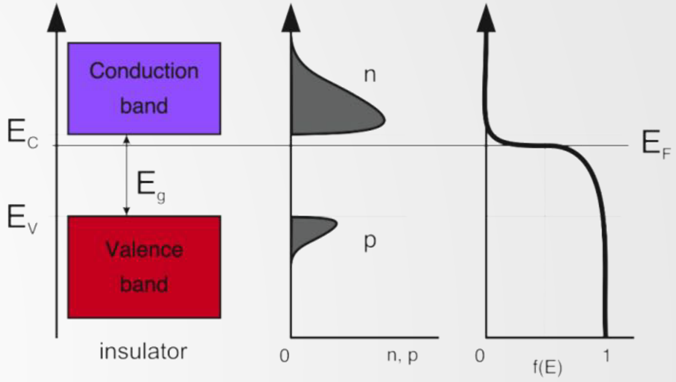

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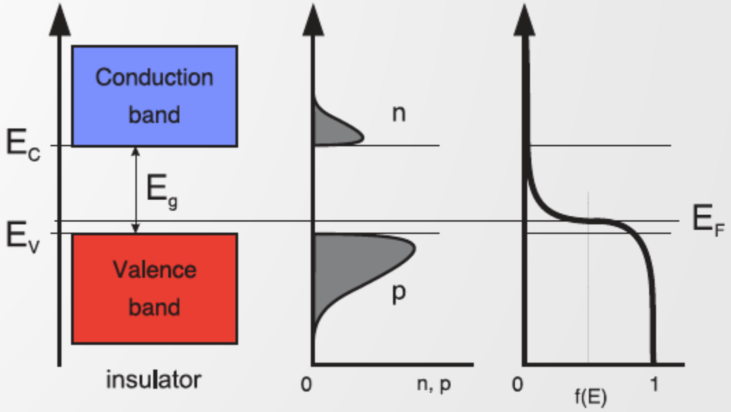
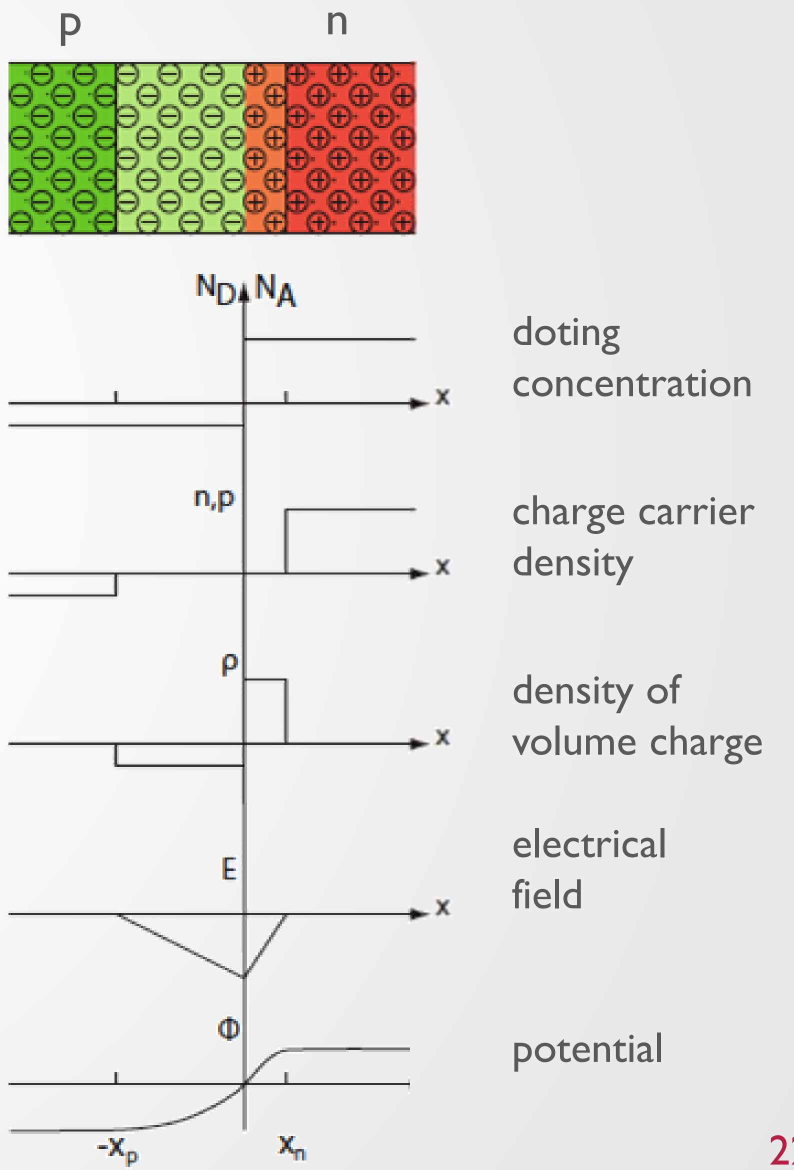
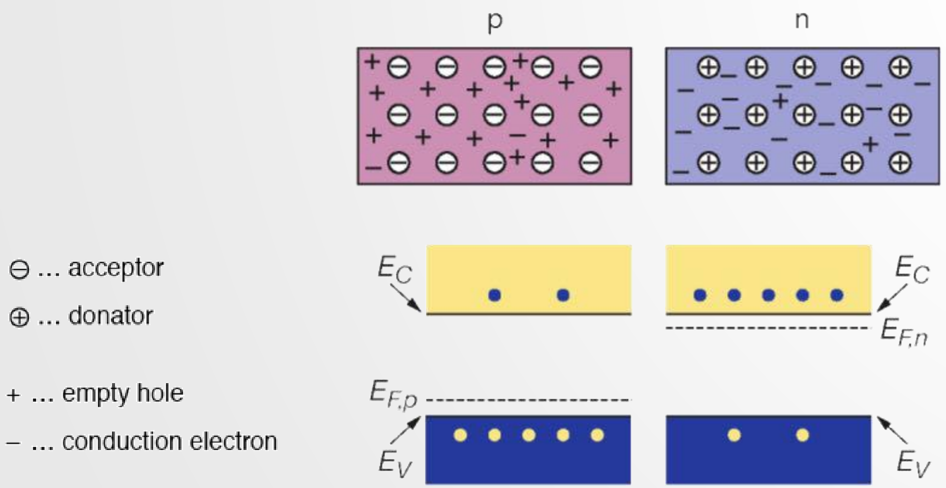
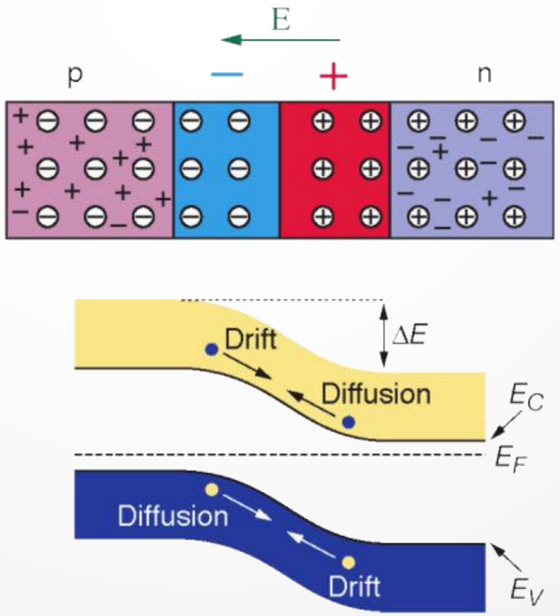


2.10 P-N JUNCTION

- At an n-type and p-type semiconductor junction, the difference in the Fermi levels cause diffusion of excessive carries to the other material until thermal equilibrium is reached.
    - At this point the Fermi level is equal. The remaining ions create a space charge region and an electric field stopping further diffusion.
    - The stable space charge region is free of charge carriers and is called the depletion zone.

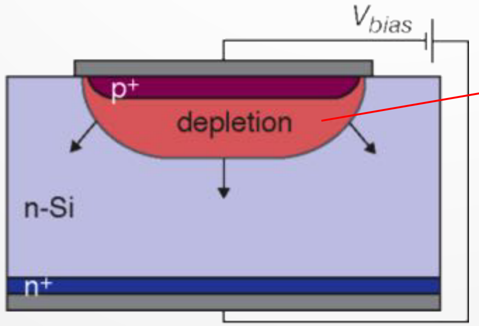


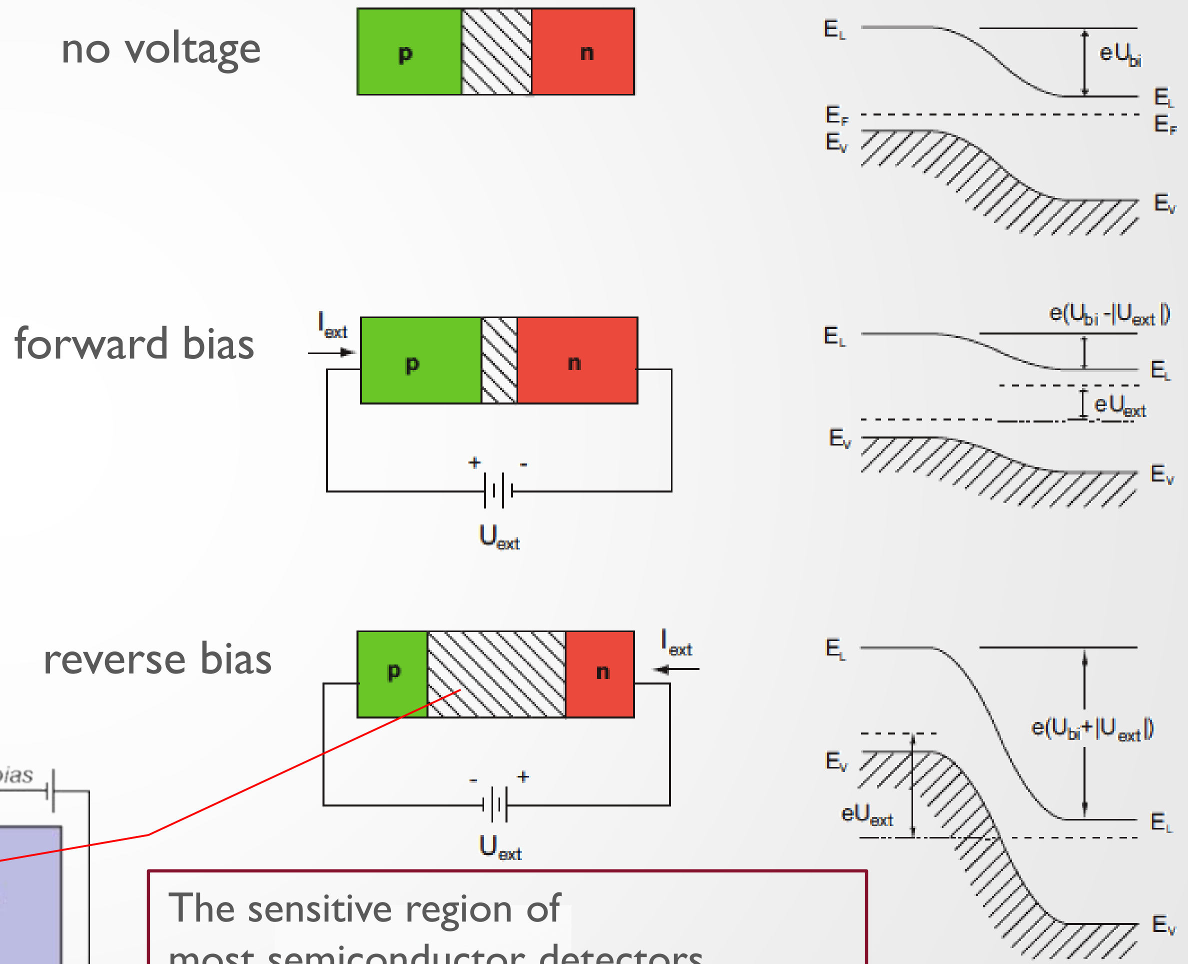




2.11 P-N JUNCTION IN REVERSE BIAS

- Electrically, a p-n junction is a diode.
- Applying a voltage U_{ext} in the forward direction pushes charge carriers into the depleted zone
  - The width of the zone is reduced
- Semiconductor detectors are operated in reverse direction: The external voltage increases the width of the depletion zone
- Example of a Typical Si p-n junction:
  - $N_a = 10^{15}\ \mathrm{cm}^{-3}$ in p+ region
  - $N_d = 10^{12}\ \mathrm{cm}^{-3}$ in n bulk.
  - Without external voltage:
    - $W_p = 0.02\ \mu\mathrm{m}$, $W_n = 23\ \mu\mathrm{m}$
  - Reverse bias voltage of 100 V:
    - $W_p = 0.4\ \mu\mathrm{m}$, $W_n = 363\ \mu\mathrm{m}$



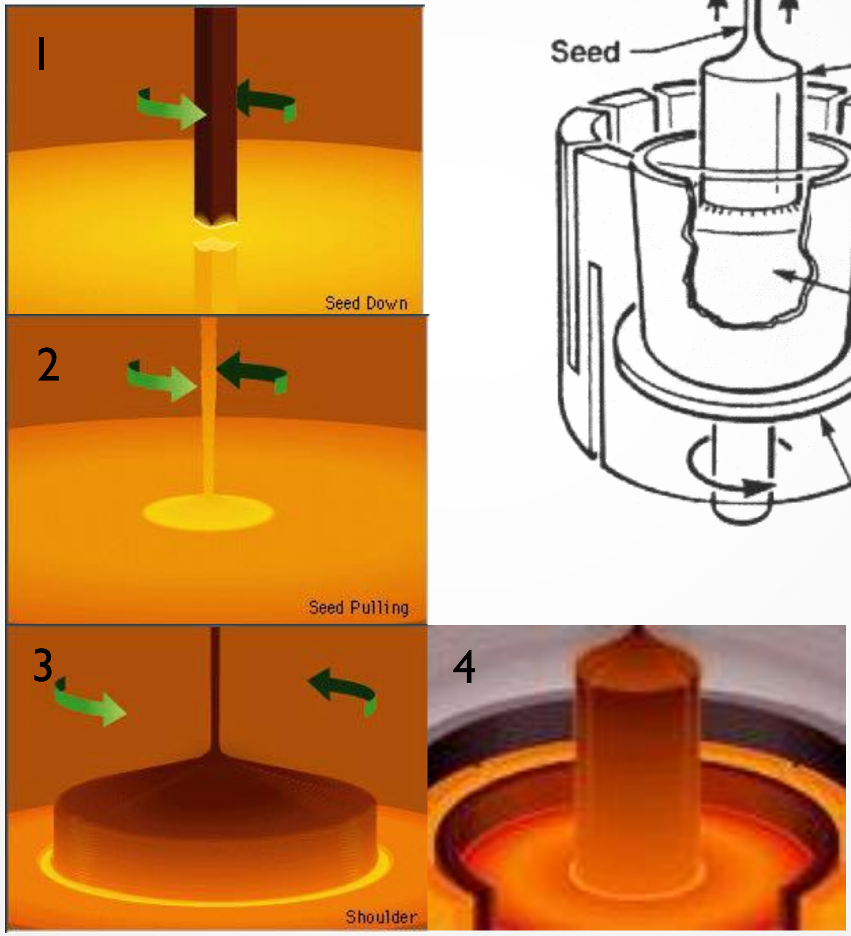


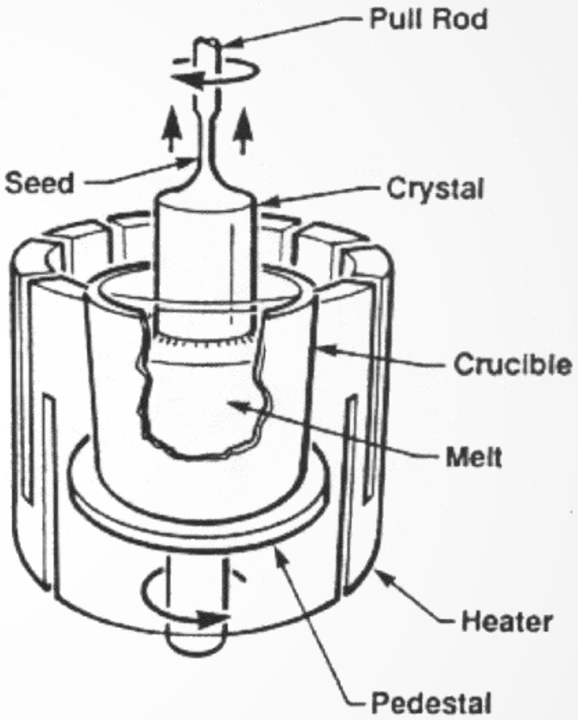
The sensitive region of most semiconductor detectors is the depleted region of a p-n junction operated in reverse bias mode.

3. DETECTOR APPLICATIONS

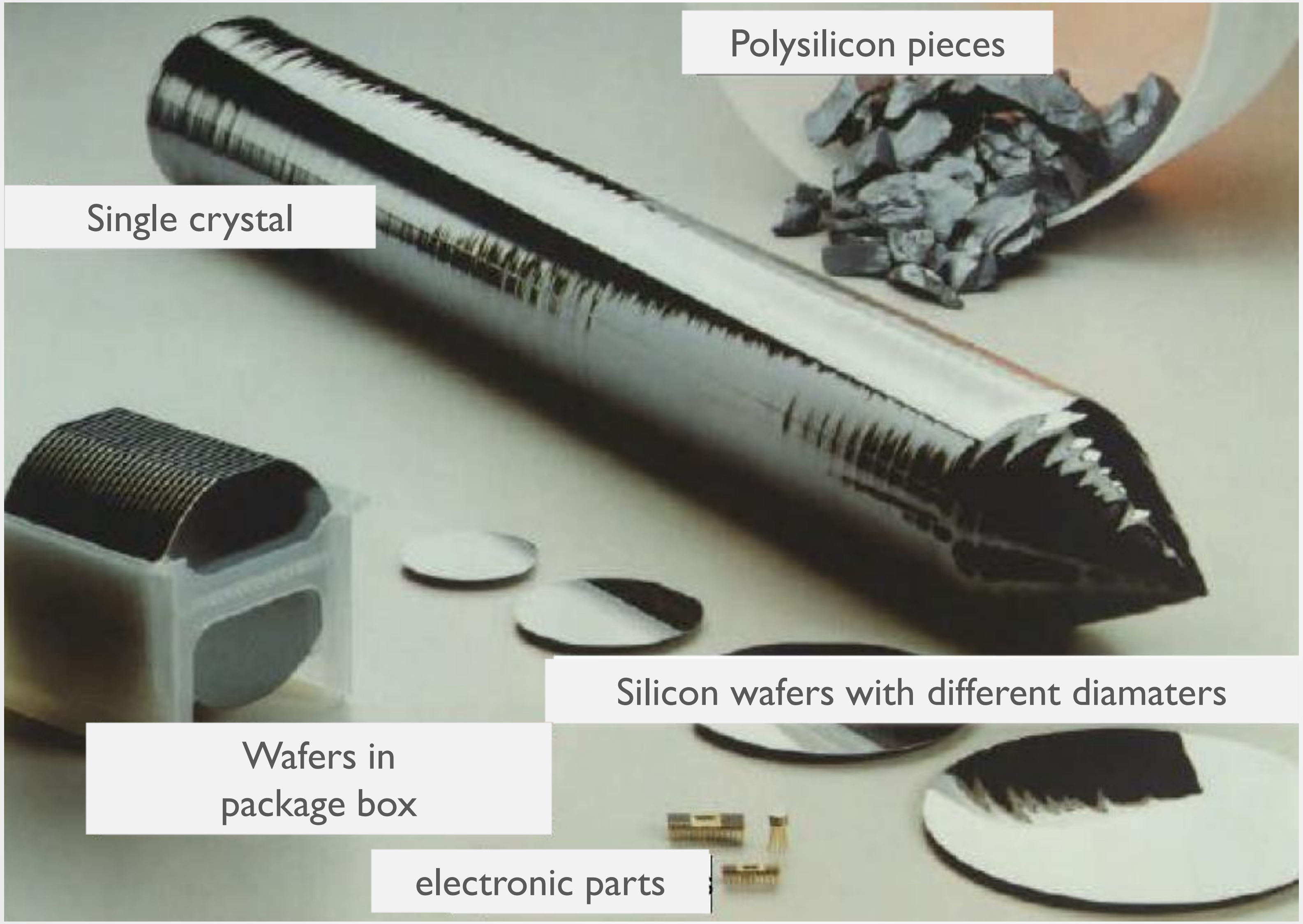
3.1 MANUFACTURING

- The Ingot ('Rohblock') is manufactured in the Czochralski process for crystal growth of Si, Ge, GaAs
- Melt silicon at 1425°C
  - Add impurities (dopants)
  - Spin and pull crystal
  - several 100 kg!
- Slice into wafers
  - 0.25mm to 1.0 mm thick
  - polish
  - 6" and up to 8" wafers



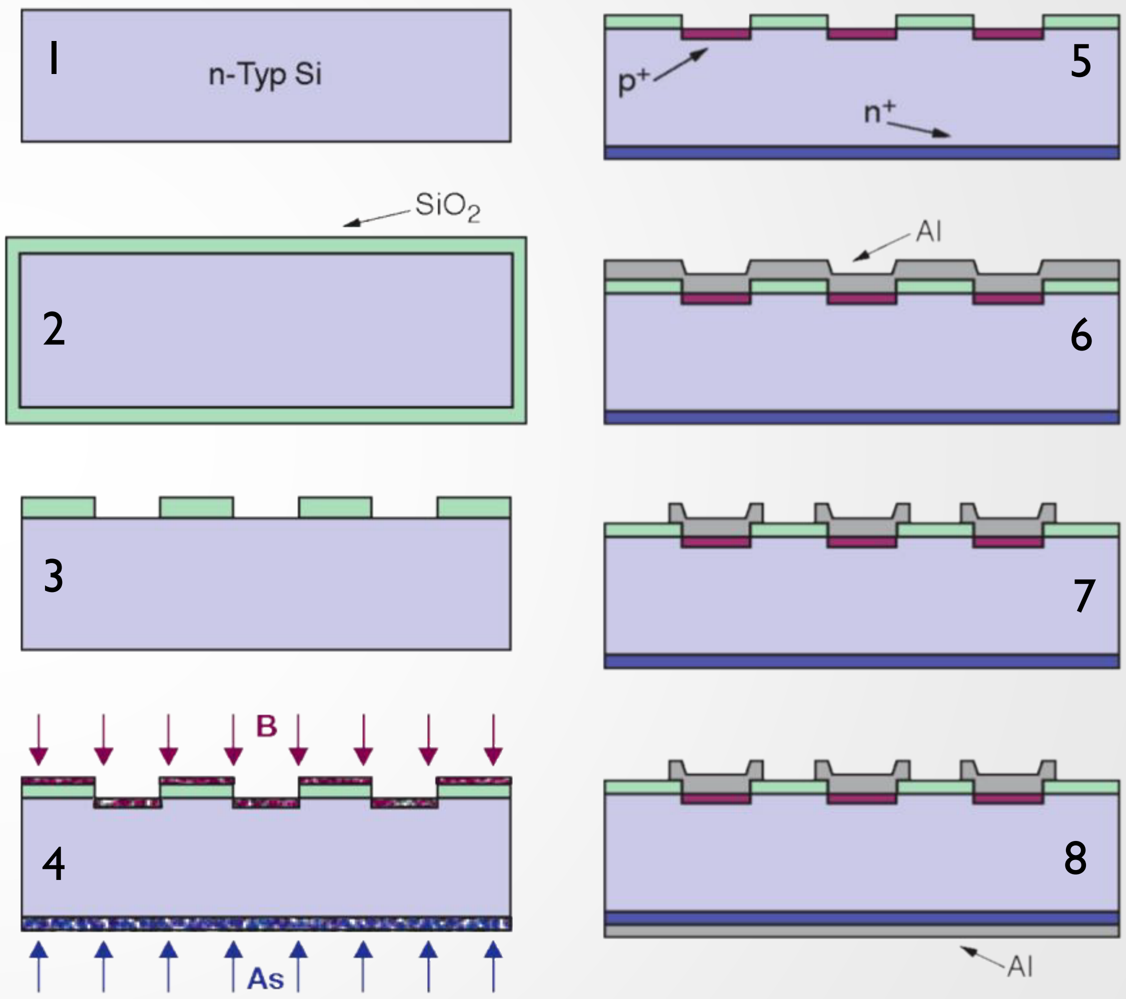


3.1 MANUFACTURING



3.2 THE PLANAR PROCESS

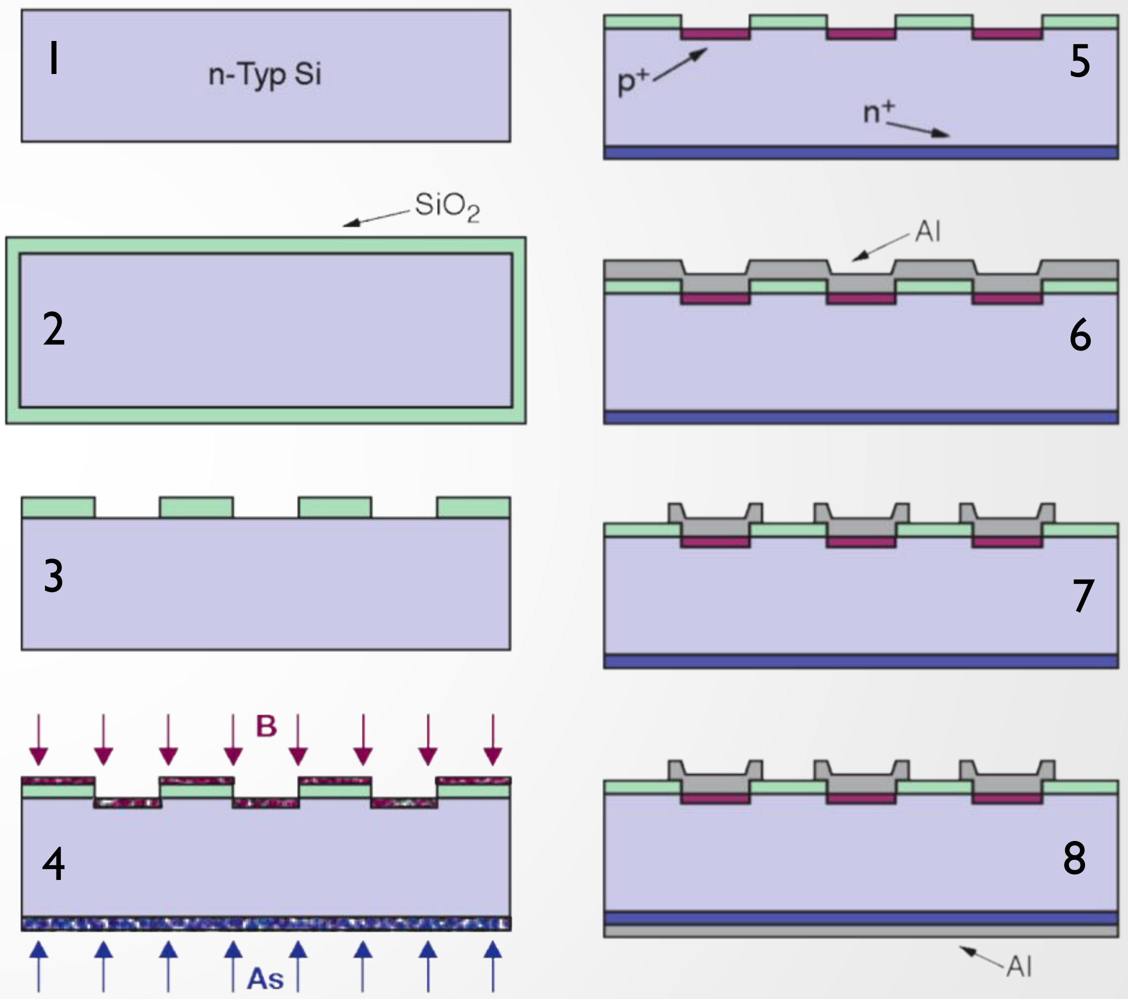
1. Starting Point: single-crystal n-doped wafer ($N_D \approx 1–5 \times 10^{12}$ cm^{-3})
2. Surface passivation by SiO_2-layer (approx. 200 nm thick). E.g. growing by (dry) thermal oxidation at 1030°C.
3. Window opening using photolithography technique with etching, e.g. for strips
4. Doping using either
   - thermal diffusion (furnace)
   - Ion implantation
     - p+-strip: Boron, 15 keV, $N_A \approx 5 \times 10^{16}$ cm^{-2}
     - Ohmic backplane: Arsenic, 30 keV, $N_D \approx 5 \times 10^{15}$ cm^{-2}



3.2 THE PLANAR PROCESS

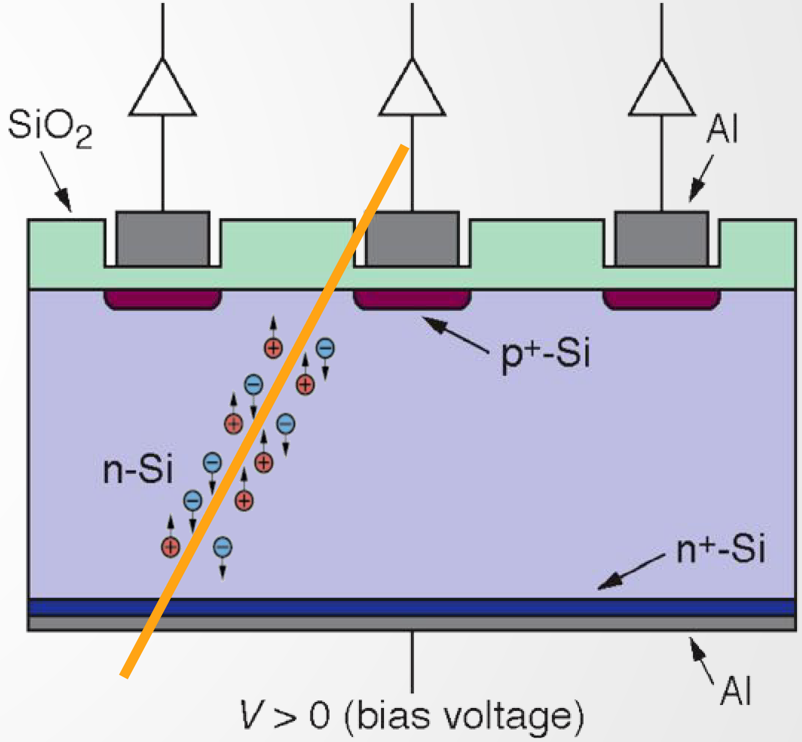
5. After ion implantation: Curing of damage via thermal annealing at approx. 600°C (activation of dopant atoms by incorporation into silicon lattice)
6. Metallization of front side: sputtering or CVD
7. Removing of excess metal by photolithography: etching of non covered areas
8. Full-area metallization of backplane with annealing at approx. 450°C for better adherence between metal and silicon

Last step: wafer dicing (cutting)

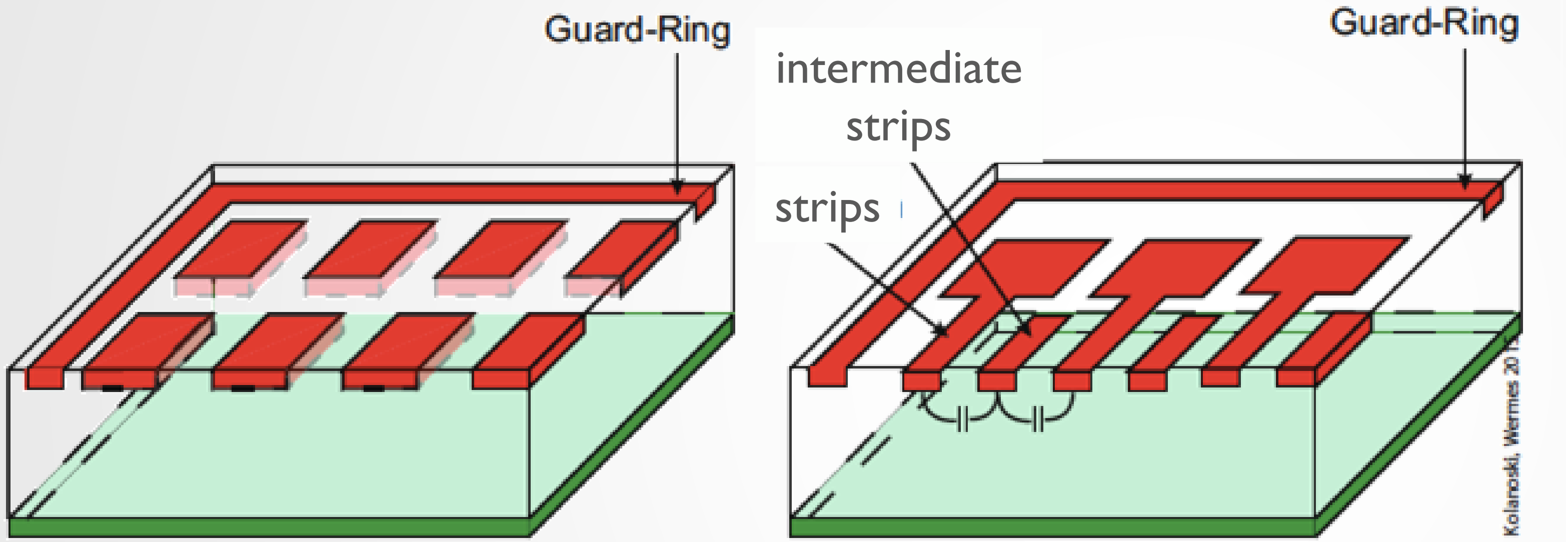


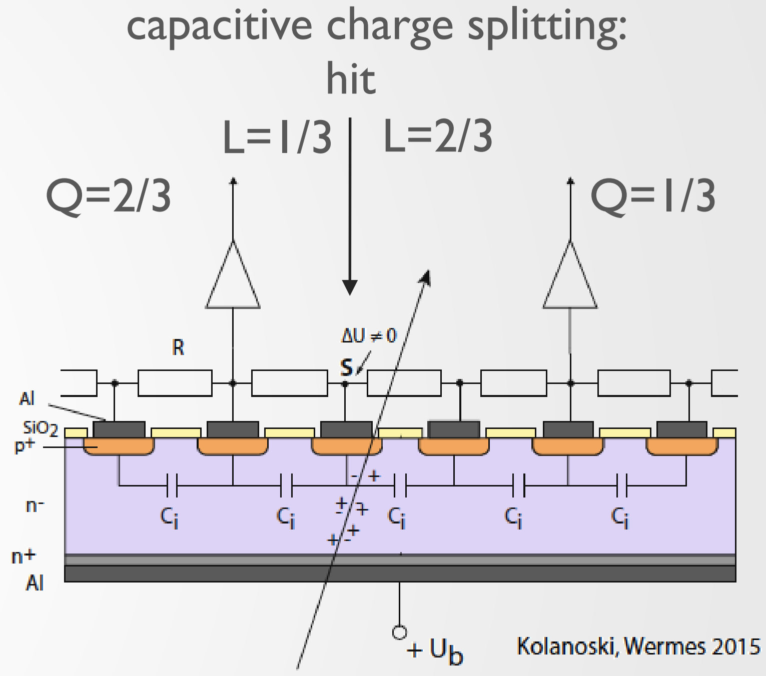
3.3 TYPICAL DETECTOR

- Charged particles traversing sensor create e-/h+ pairs in the depletion region
  - These charges drift to the electrodes
  - The drift (current) creates the signal which is amplified by an amplifier connected to each strip (Shockley-Ramo theorem!)
  - The SiO_2 dielectric shields the bias potential (AC coupling)
  - From the signals on the individual strips the position of the through going particle is deduced (next two slides)
- Typical n-type Si strip detector:
  - n-type bulk: r > 2 kΩ cm
  - thickness 300 µm
  - Operating voltage < 200 V.
  - n+ layer on backplane to improve ohmic contact to metal
  - Aluminum metallization



3.4 PIXEL AND STRIP SENSOR GEOMETRY



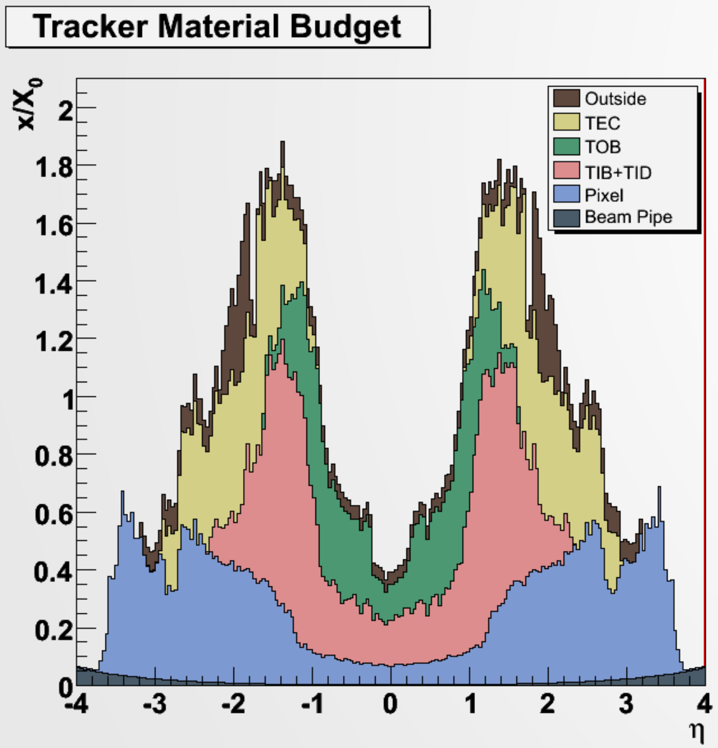


The most common use case divide the sensor in:

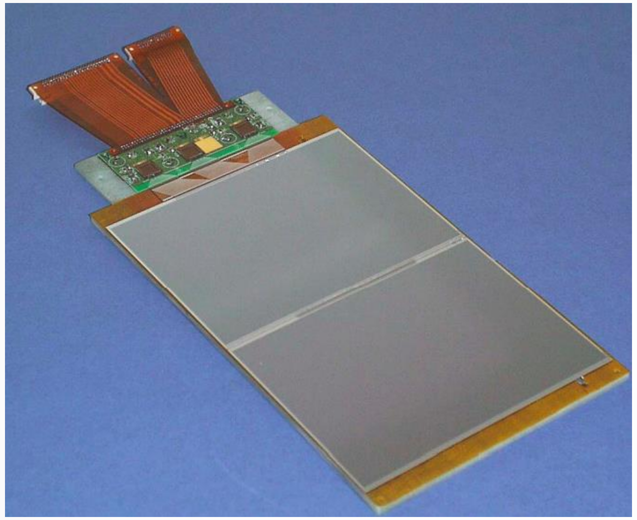
- pixels (pads) of ~100 μm. ATLAS pixel detector: 50 μm x 250 μm / 400 μm, CMS pixel detector: 100 μm x 150 μm. Useful for highest spatial resolution very close to the collision vertex.
- strip detectors have less channels (N instead of N^2). Connectors to electronics can be on one side of the sensor.
- Capacitive charge splitting reduces the number of needed amplifiers

3.5 SILICON STRIP DETECTORS

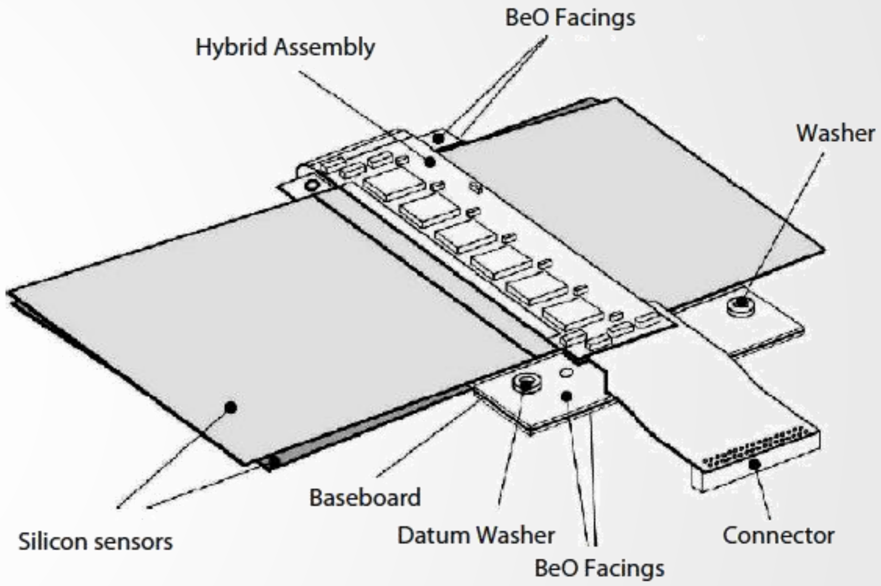
- The sensor, electronics, supply, cooling, constitute 1.5 X_0!



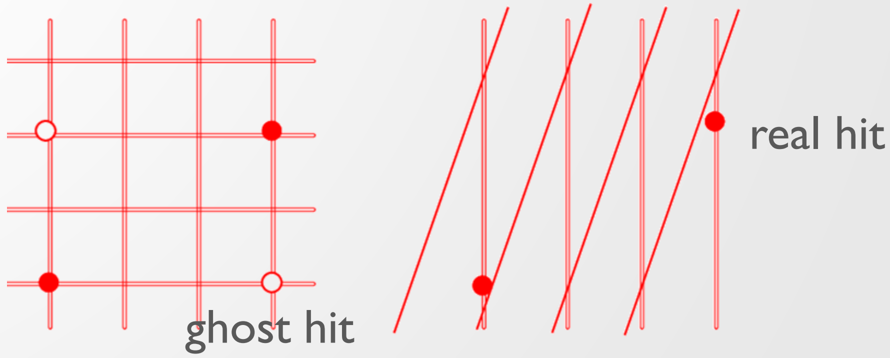
CMS strip tracker detector module stereo angle 100 mrad



ATLAS SCT double-sided module, 40 mrad crossing angle



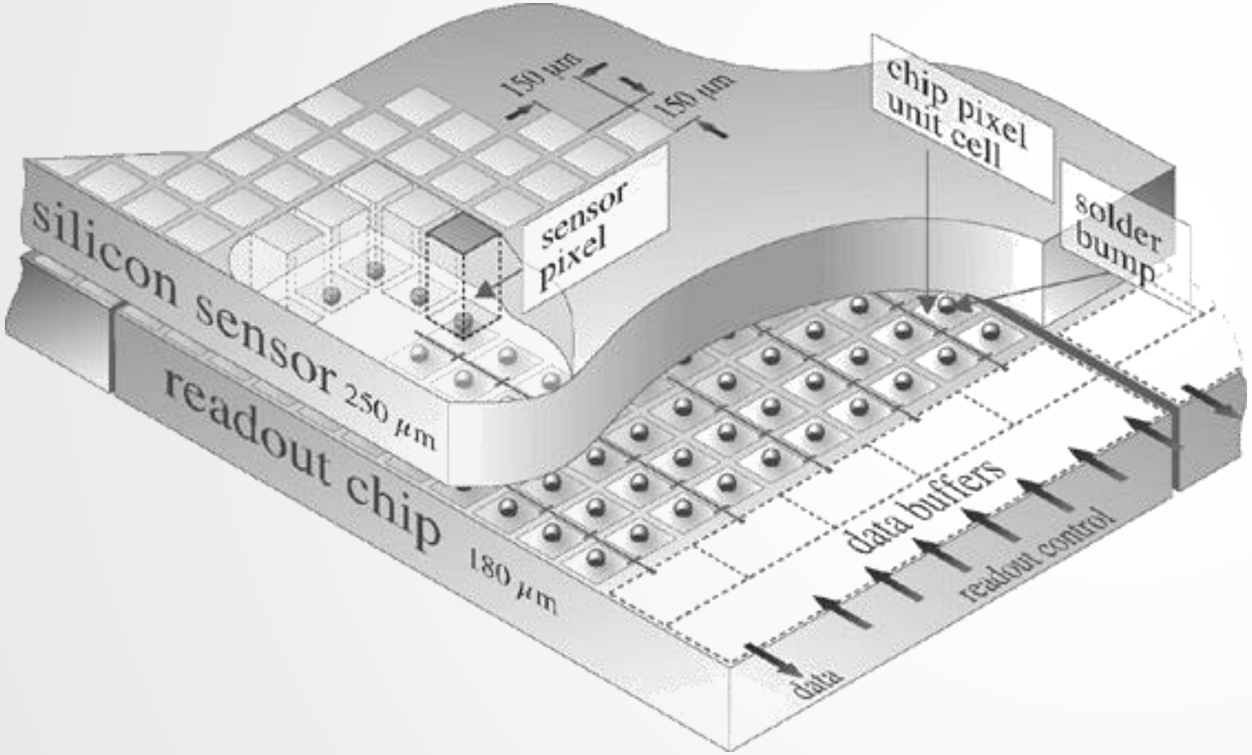
two-sided strip detectors create ghost hits at high occupancy. Smaller angles than 90° reduce ghost hit density

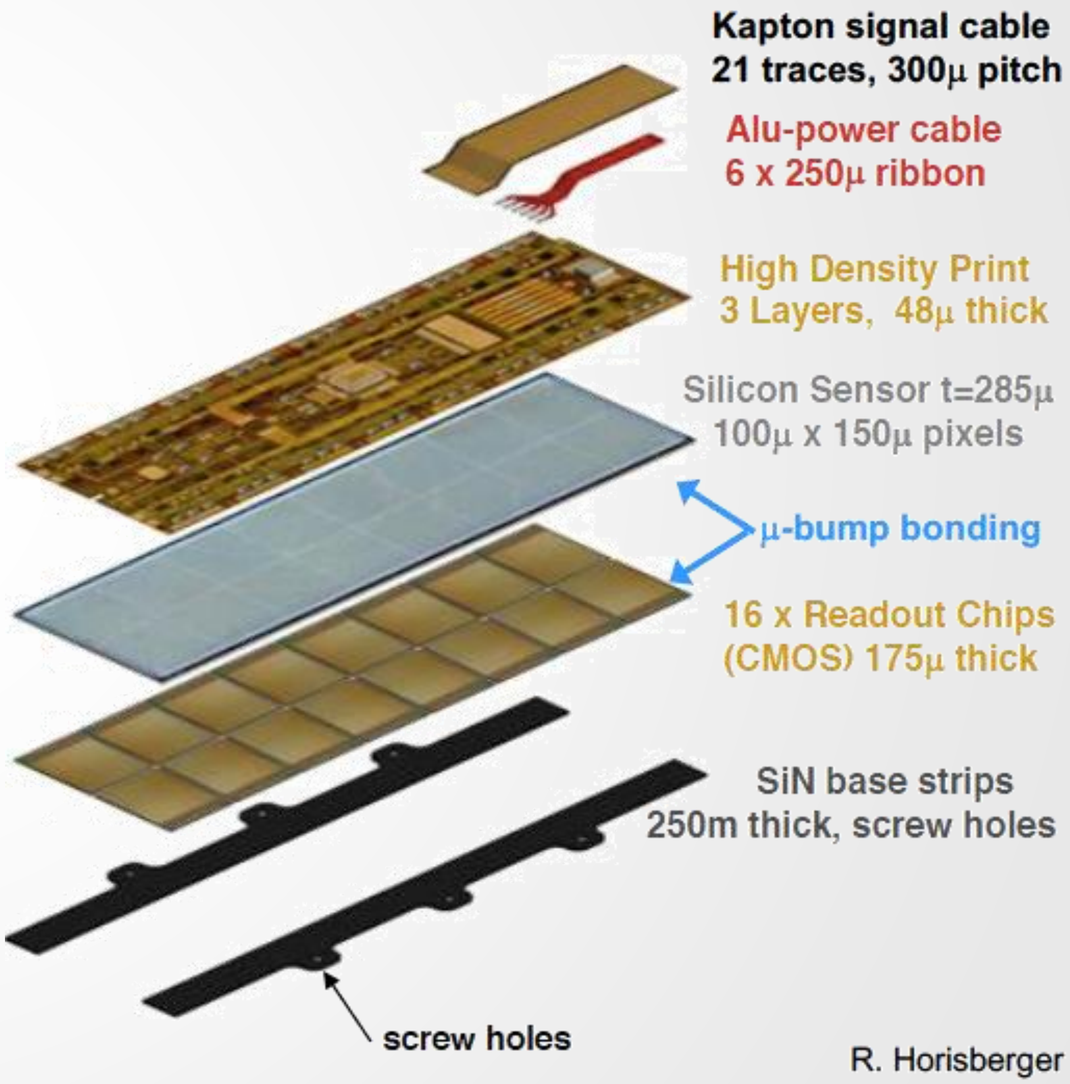


3.6 HYBRID PIXEL DETECTORS

arXiv:0911.5434

- Most current silicon detectors are hybrid:
- ‘Bump bonds’ connect the sensor to the electronics





- Highly sensitive and error prone process
- Difficult to test the sensors before bump bonding

3.6 HYBRID PIXEL DETECTORS

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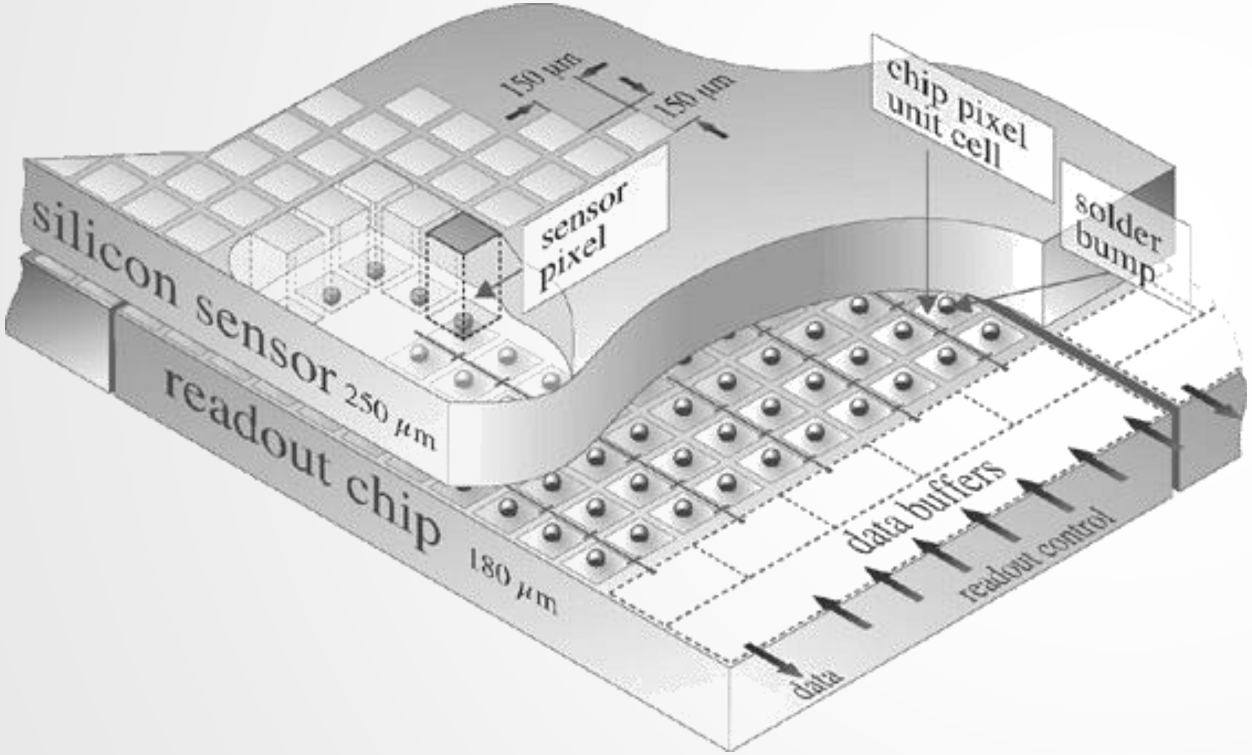

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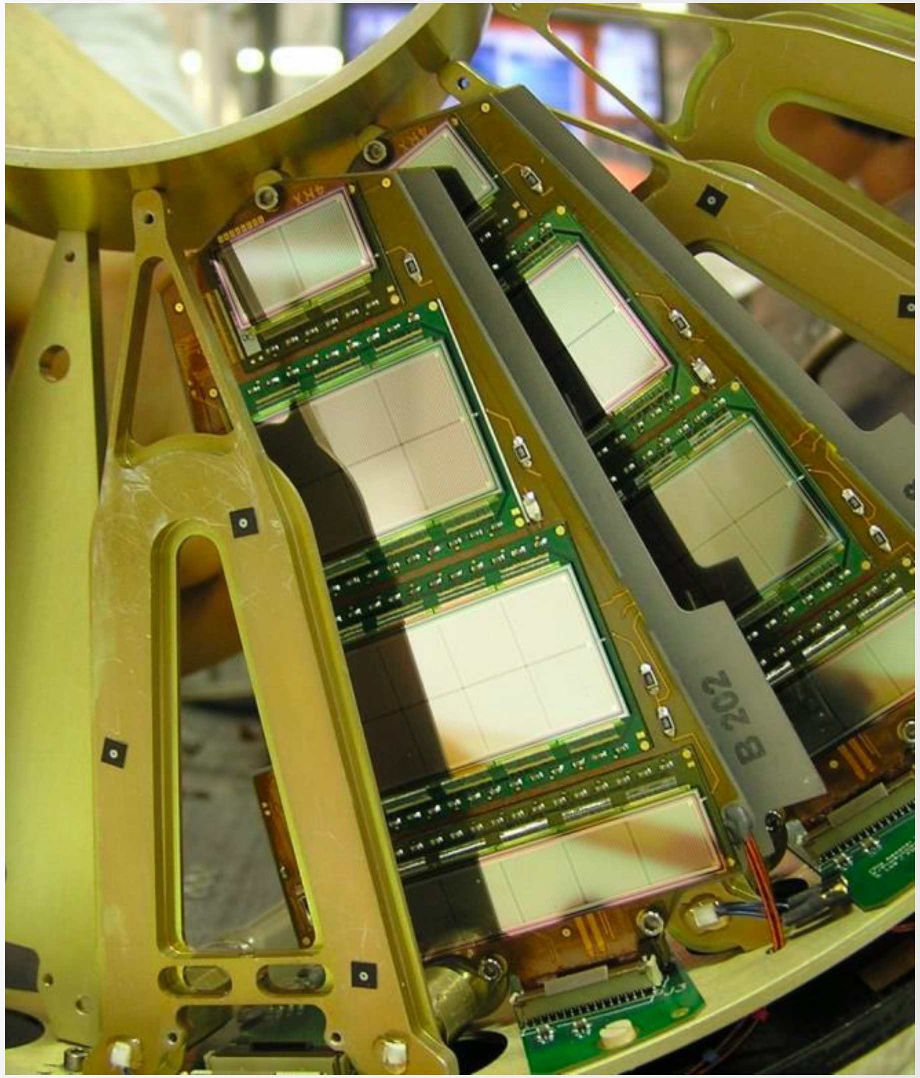
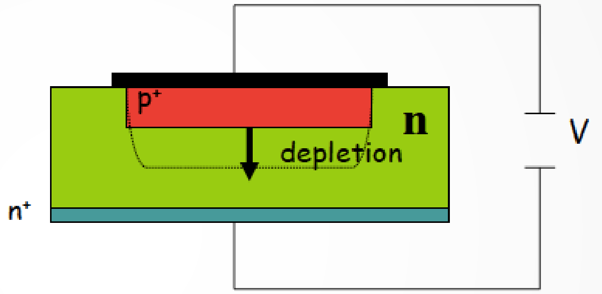


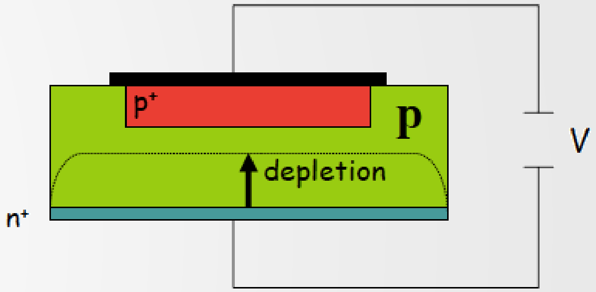
3.7* OPERATION AND TYPE INVERSION

- During operation in high density environments, enormous fluxes of charged and neutral particles effectively dope the sensor material: n^- bulk can change to p^+ bulk!
- Therefore, the maximum voltage for full depleting changes.
- The $p^+/n/n^+$ type changes to $p^+/p/n^+$ and the depletion region changes side
- Pure sensor material has high resistivity. Continued irradiation damage reduces the resistivity of the sensor.
  - For full depletion, high voltages (200-1000 V) are needed and then increase the leakage current.
  - The leakage current reduces the signal resolution.
- If the sensor is irradiated so much that the full depletion can not be achieved, a type-inverted sensor is at the end of the life-time (charge carriers need to reach the readout on the top plane)

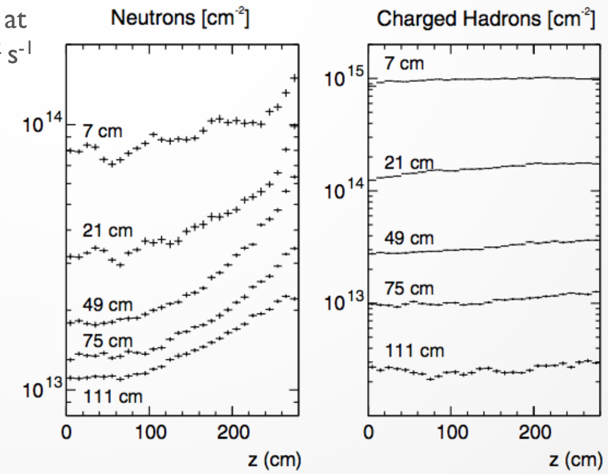
before inversion:

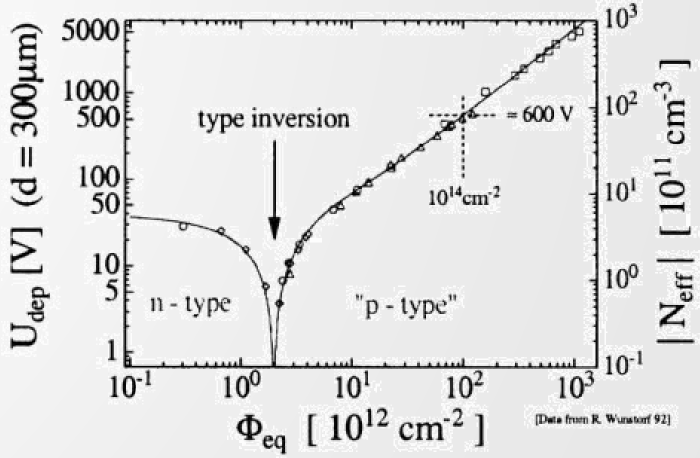


after inversion:

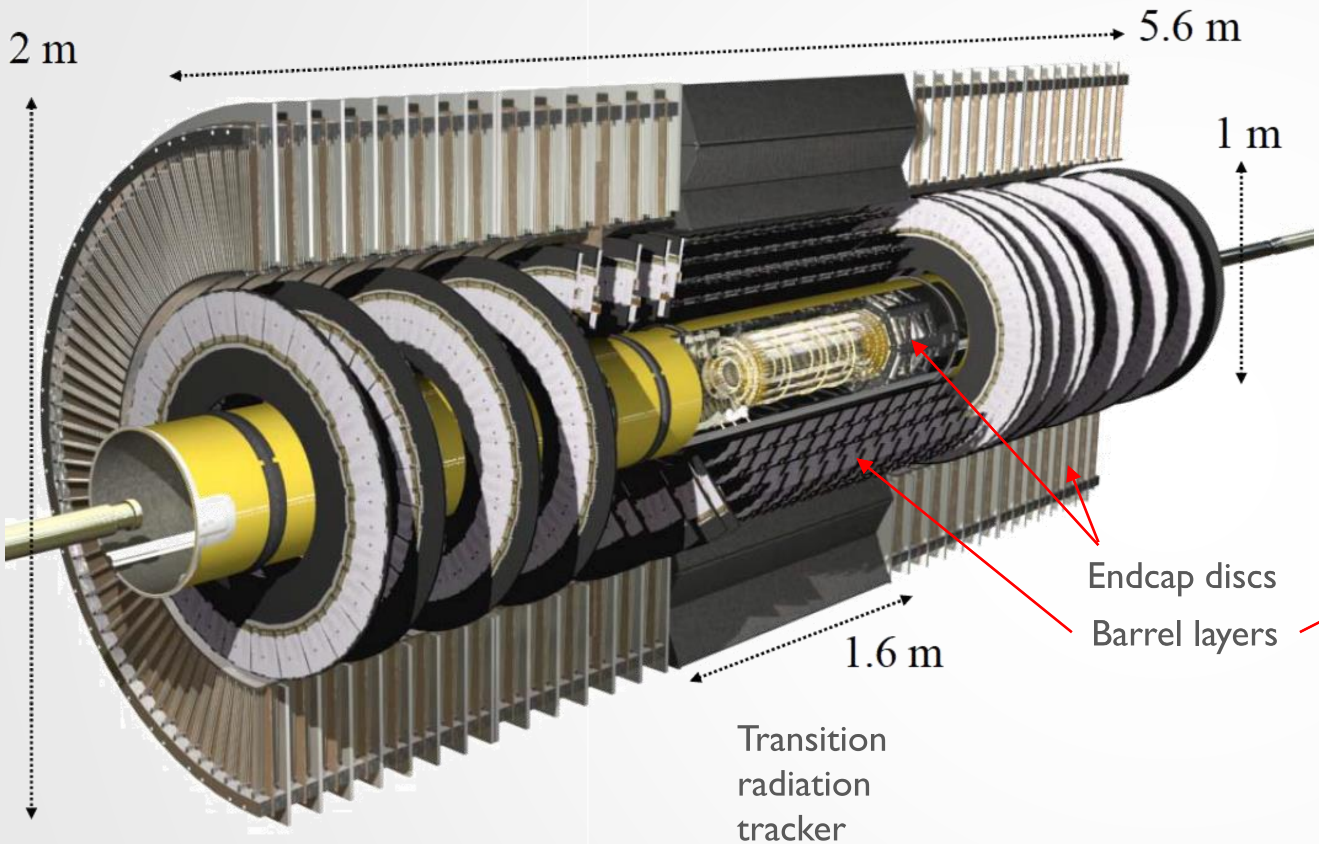


1 year at 1e34 cm^{-2} s^{-1}





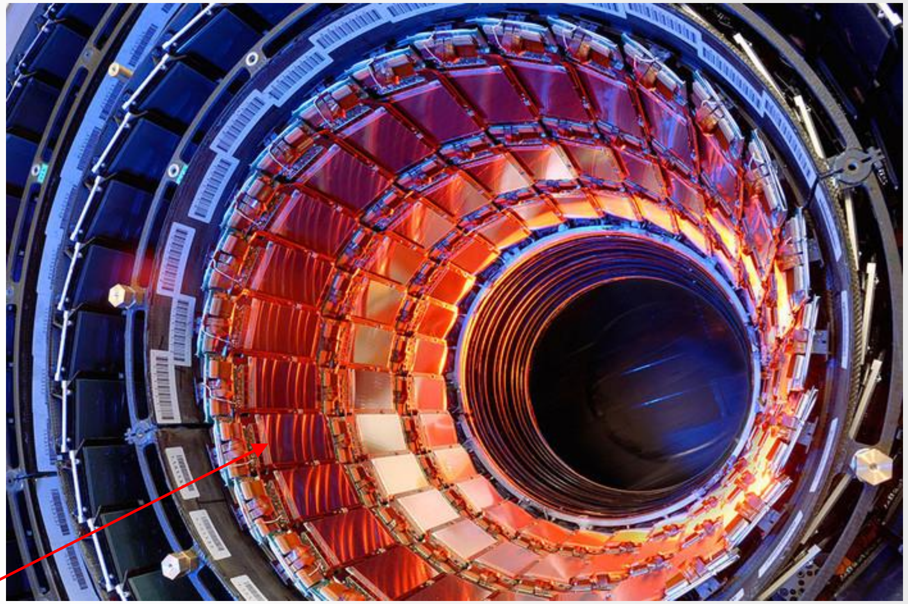
3.8 ATLAS AND CMS SILICON TRACKERS

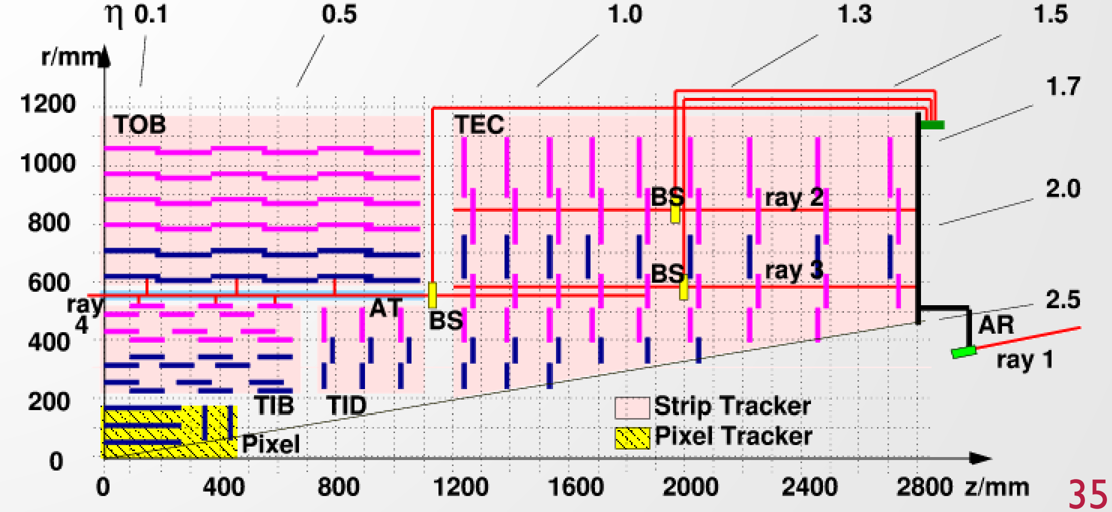


Endcap discs

Barrel layers

Transition radiation tracker





ATLAS Silicon Tracker SCT (top)

17 thousand silicon sensors (60 m²)
6 M silicon strips (80 µm x 12.8 cm)
80 M pixels (50 µm x 400 µm)

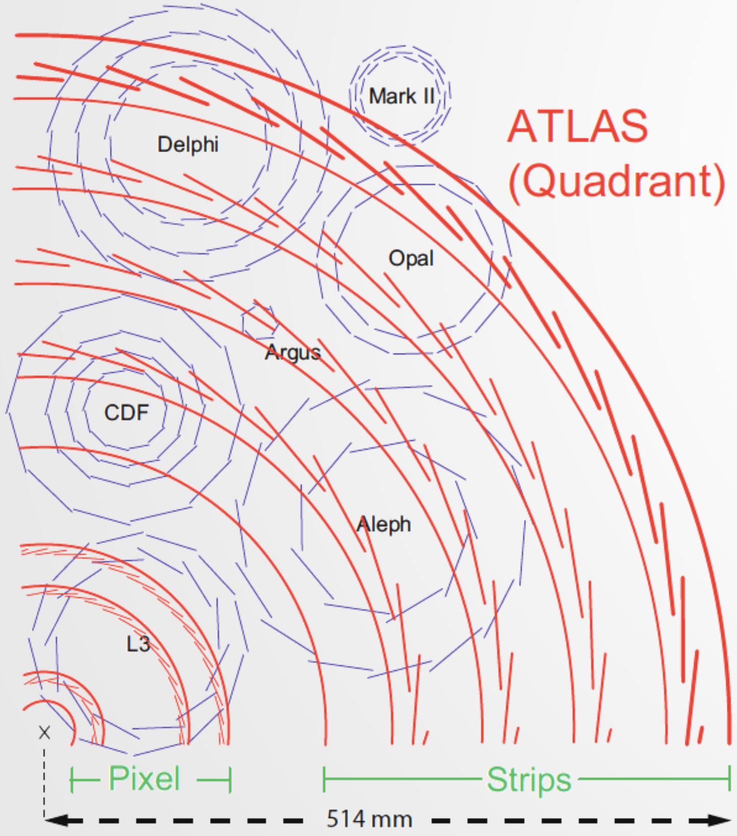
CMS (right)

24k sensors (210m^2)
now 124M pixels (100μm x 150 μm)
9.6M strips

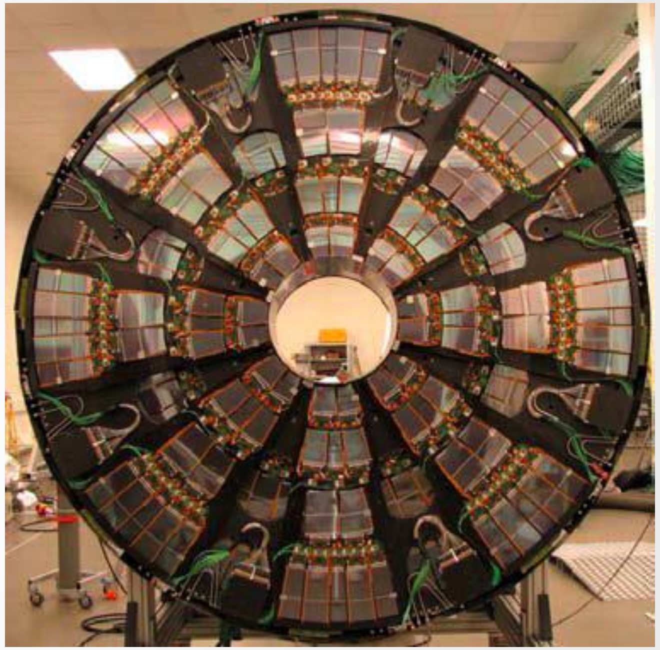
3.9 RECENT SILICON DETECTORS

- Silicon detectors have become much larger over time.

Comparison of existing trackers:



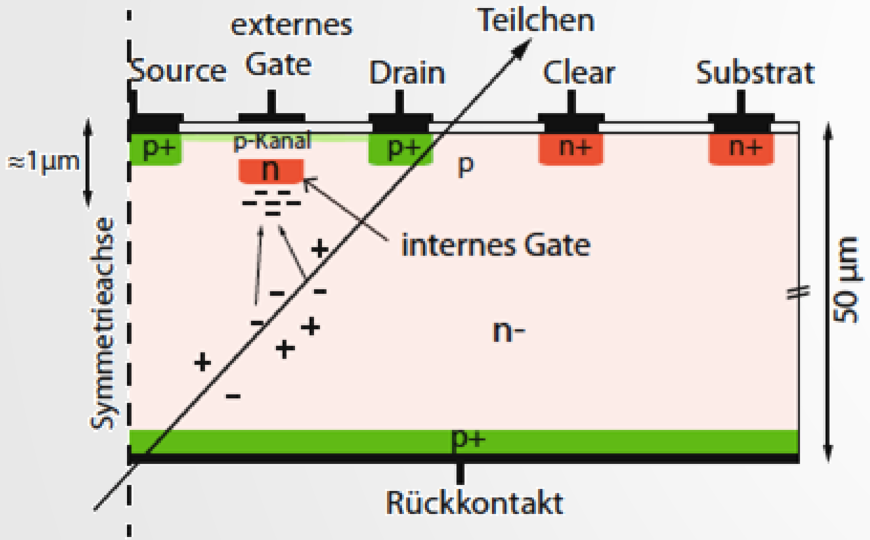
CMS Tracker endcap: Silicon strip detector operating at 25ns, high magnetic field and high radiation levels



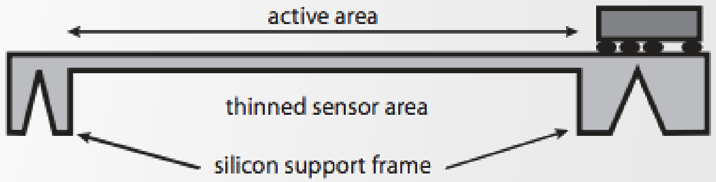
The movable LHCb 'Velo' Detector. Specialized for secondary vertex reconstruction.
Each sensor contains 2048 strips in radial or azimuthal direction.
The innermost layer is 7mm from the beam!

3.10 DEPFETS AND BELLE PIXEL DETECTOR

- The Depfet (Depleted field effect transistor) is an amplification transistor combined with pixel sensor, realized as a p-type MOSFET (Source/Gate/Drain below)
- A voltage between the subtrate and the back plane creates a potential minimum behind the n-doted internal gate. Here, the signal electrons are collected.



Belle-II Pixeldetector



Illustrative cross section through a PXD module. The silicon in the active area is thinned to 50 µm, 450 µm thick silicon rims are left on the module sides for stability.

- The collected charge is measured via the source-drain voltage
- Repeated readout possible, very low noise – down to a single e^- !
- Positive voltage on clear gate removes charge carriers.

4. SPECTROMETER MEASUREMENTS

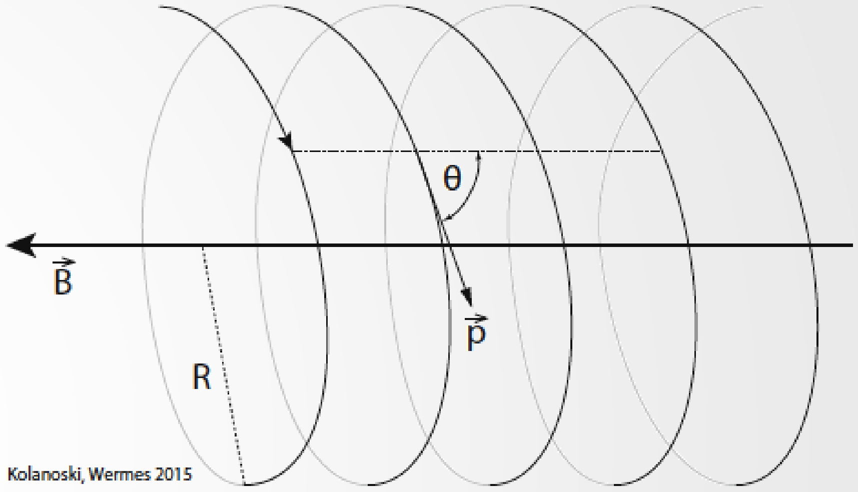
4.1 KINEMATIC IN SPECTROMETER MEASUREMENTS

- The Lorentz force on a charged particle is:

$$\vec{F} = \dot{\vec{p}} = q\left(\vec{v} \times \vec{B}\right) \qquad \Rightarrow \qquad \dot{\vec{v}} = \frac{q}{\gamma m}\left(\vec{v} \times \vec{B}\right)$$

which we can solve for the velocity by an ansatz.

$$\begin{aligned} v_1 &= v_T \cos(\eta\,\omega_B\,t + \psi_0)\,, \\ v_2 &= -v_T \sin(\eta\,\omega_B\,t + \psi_0)\,, \\ v_3 &= v_3\,. \end{aligned}$$



- The solution for the cyclotron frequency ω_B and the transverse velocity v_T is

$$\omega_B = \frac{|q|\,B}{\gamma m}, \qquad \eta = \frac{q}{|q|}, \qquad v_T = \sqrt{v_1^2 + v_2^2}\,.$$

- Integrating once more:

$$\begin{aligned} x_1 &= \frac{v_T}{\eta\,\omega_B}\sin(\eta\,\omega_B\,t + \psi_0) + x_{10}\,, \\ x_2 &= \frac{v_T}{\eta\,\omega_B}\cos(\eta\,\omega_B\,t + \psi_0) + x_{20}\,, \\ x_3 &= v_3\,t + x_{30}\,. \end{aligned}$$

- So we have

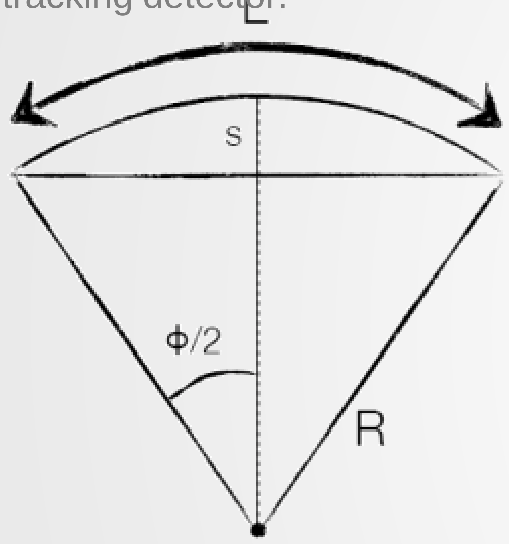
$$R = \sqrt{(x_1 - x_{10})^2 + (x_2 - x_{20})^2} = \frac{v_T}{\omega_B} = \frac{\gamma\,m\,v_T}{|q|\,B} = \frac{p_T}{|q|\,B}$$

$$\frac{1\mathrm{eV}}{c} = \frac{1.610^{-19}\mathrm{CV}}{3 \cdot 10^8 \frac{\mathrm{m}}{\mathrm{s}}} = 0.53310^{-27}\frac{\mathrm{kg\ m}}{\mathrm{s}}$$

$$\boxed{p_T\left[\frac{\mathrm{GeV}}{c}\right] = 0.3RB, \quad R = \frac{p}{0.3B}}$$

4.1 KINEMATIC IN SPECTROMETER MEASUREMENTS

Sketch of a trajectory of a charged particle traversing a tracking detector:



- The momentum measurement of the track of a charged particle can be though of as the measurement of the Sagitta s of a circular track

$$s = R - R\cos\frac{\phi}{2} \simeq R\frac{\phi^2}{8}, \text{ with } \phi = \frac{L}{R}$$

$$s = \frac{L^2}{8R}, \qquad R = \frac{L^2}{8s}$$

$$\frac{\sigma_p}{p} = \frac{\sigma_s}{s} = \frac{8\sigma_s}{0.3}\frac{p}{BL^2}$$

Example: L = 4 m, B=1 T p=1 TeV/c
R = 3300 m and s = 0.6 mm.
Requiring σ_p/p= 10% need σ_s = 60 μm.

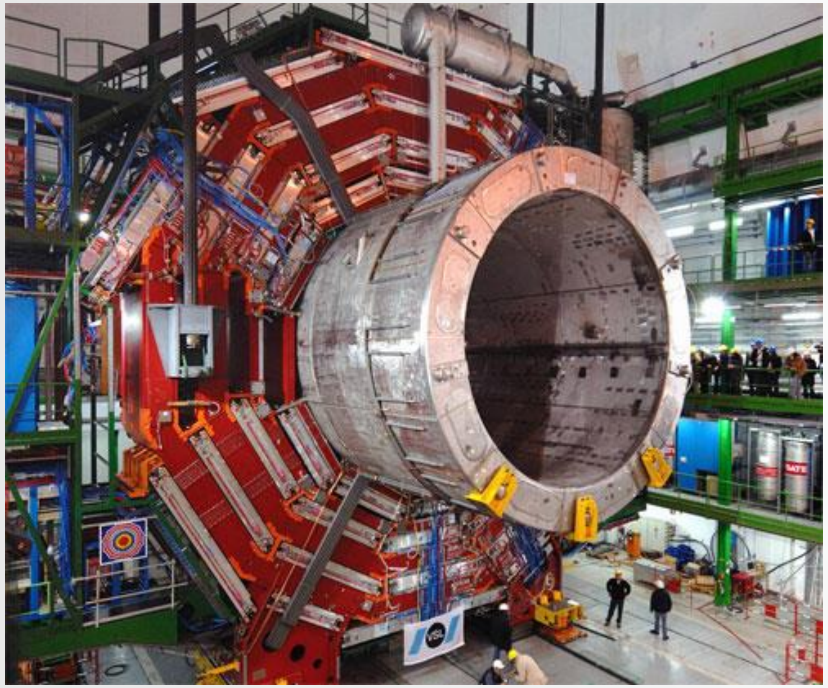
- The resolution on the saggita s of a path of length L of a trajectory with radius R determines the momentum resolution.
- A long lever arm L and a high magnetic field B are needed

- ATLAS and CMS, use different ways to realize a low relative uncertainty
- ATLAS: momentum measurement of μ with contribution from two different detectors
  - 2T solenoid for momentum measurement of charged tracks
  - toroid magnet at the μ-system for momentum measurement of μs
- CMS: 4T solenoid magnet for charged track momentum measurement.

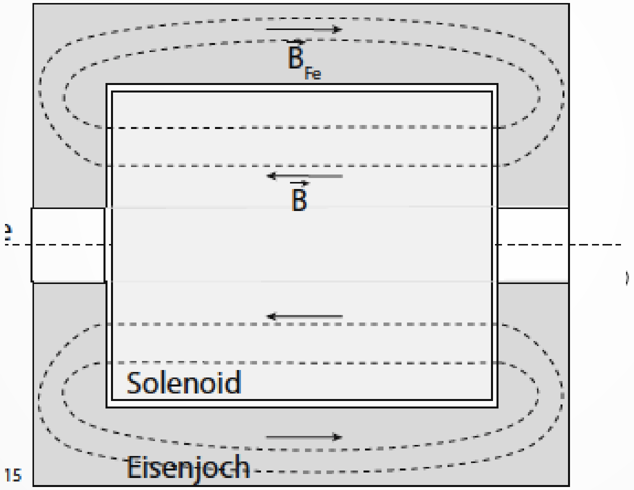
	CMS	ATLAS
σ_{d_0}(1 GeV)	90 μm	75 μm
σ_{d_0}(1 TeV)	9 μm	11 μm
σ_p/p(1 TeV)	0.7 %	1.3 %
σ_p/p(0.1 TeV)	1.5 %	3.8 %

4.2 ATLAS AND CMS MAGNETS

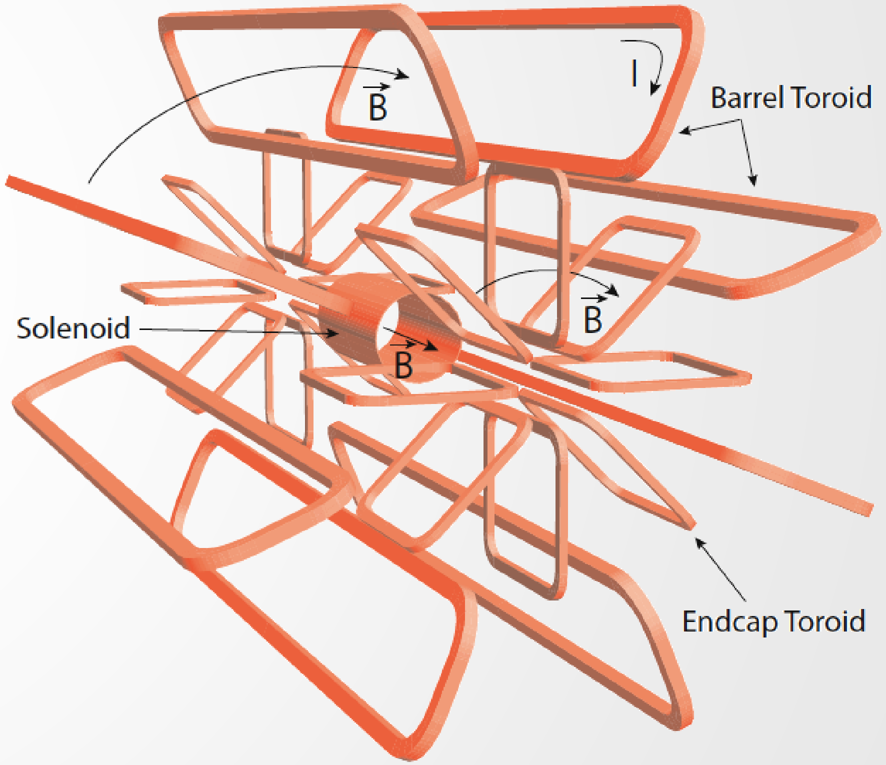
CMS solenoid



CMS solenoid field lines



ATLAS toroids and central solenoid



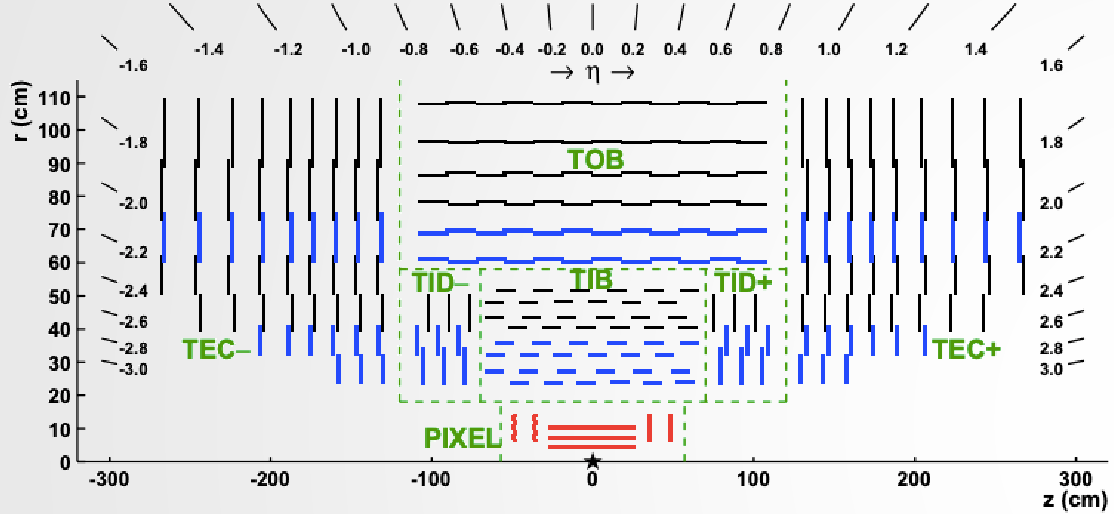
4.3 MAGNETS IN EXPERIMENTS

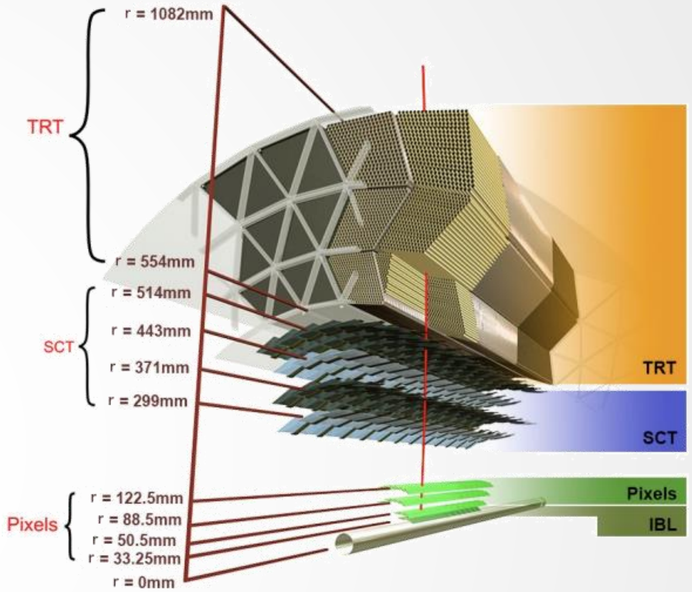
- Comparison of main characteristics of experimental magnets.
- Most recent magnets are superconducting.
- ATLAS
  - NbTi at 4.7 K
  - 2 T solenoid
  - toroid for the muon system, providing on average 0.5 T
- CMS
  - NbTi at 4K
  - largest superconducting magnet ever built
  - 3.8 T solenoid, iron return yoke

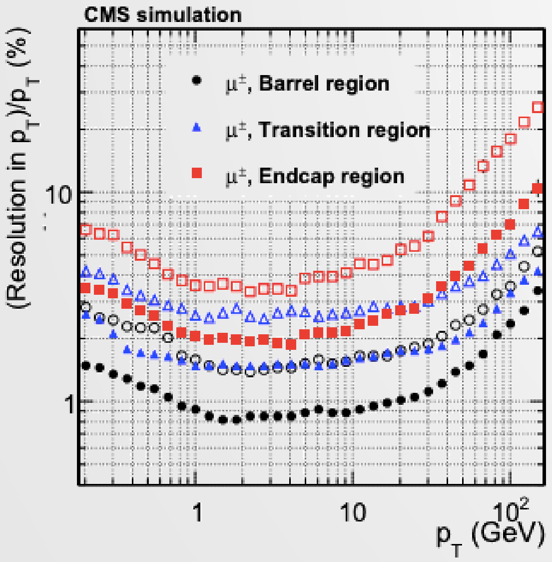
experiment	lab	B [T]	radius [m]	length [m]	x/X0	energy [MJ]	E/M [kJ/kg]	P [MW]
superconducting magnets								
CDF*	Tsukuba/Fermi	1.5	1.5	5.07	0.84	30	5.4	
CLEO-II*	Cornell	1.5	1.55	3.8	2.5	25	3.7	
ALEPH*	Saclay/CERN	1.5	2.75	7	2	130	5.5	
DELPHI*	RAL/CERN	1.2	2.8	7.4	1.7	109	4.2	
ZEUS*	INFN/DESY	1.8	1.5	2.85	0.9	11	5.5	
H1*	RAL/DESY	1.2	2.8	5.75	1.8	120	4.8	
BELLE*	KEK	1.5	1.8	4		42	5.3	
ATLAS	CERN	2	1.25	5.3	0.66	38	7	
CMS	CERN	4	6	12.5		2600	12	
normally conducting magnets								
TASSO*	DESY	0.5	1.35	4.4	1.2			2.8
MARK II*	SLAC	0.5	1.56	4.05	1.3			1.8
ARGUS*	DESY	0.8	1.4	2.8				2
OPAL*	CERN	0.435	2.18	6.3	1.7			5

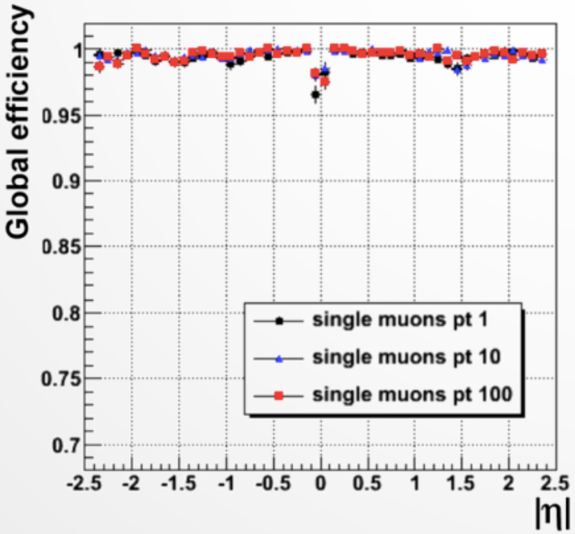
* no longer in operation

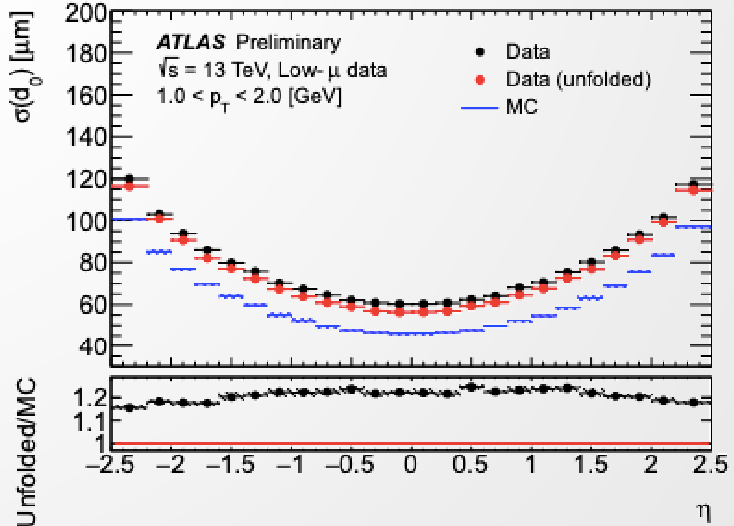
4.4* TRACK RECONSTRUCTION PERFORMANCE - EXAMPLES





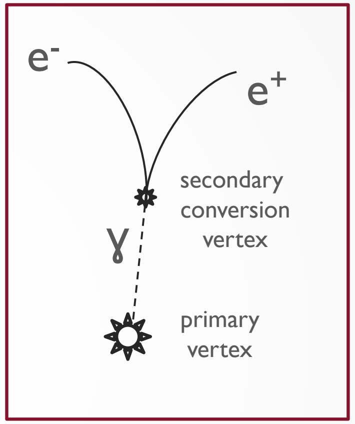


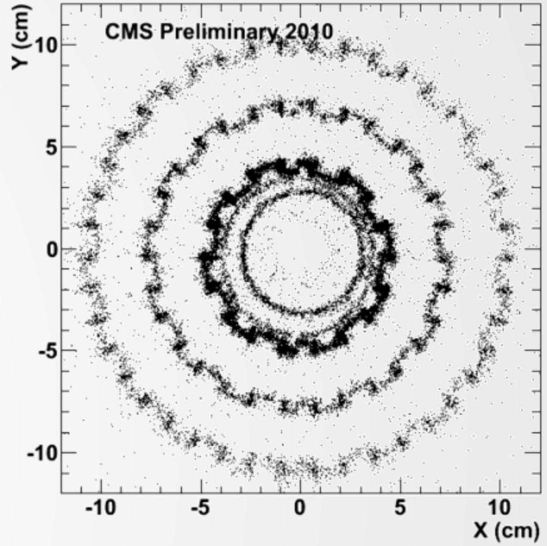


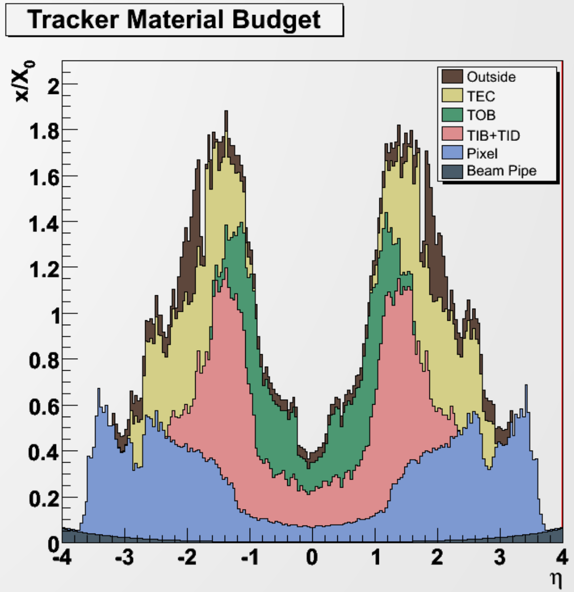


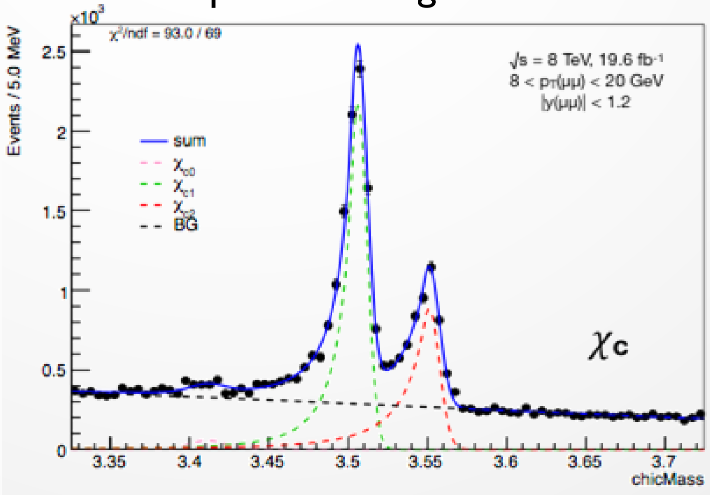
4.5* EXAMPLE: P-WAVE QUARKONIA VIA CONVERTED PHOTONS

- Quarkonia are quark bound states of quarks and an ideal test-bed for QCD
- J/Ψ are s-wave and χ_c are the p-wave bound states§
- $\chi_c \longrightarrow J/\Psi + \gamma$ and a precise measurement of the mass, momentum and polarization, requires reconstruction of all final state particles with 0.1%-level resolution
- The s-wave quarkonia decay to muon pairs with excellent resolution
- For the low energetic γ in the p-wave quarkonia decay, the calorimetry does not have good enough resolution.
- Trick: select events where the photon converts to e^+/e^- and exploit tracking resolution!
- Tracker has 1-1.5 X_0 radiation lengths of material budget
- $O(10^{-3})$ resolution for conversion photons
- Conversion vertices can be used to map the actual material budget of the detector









THE END!

DENSITY OF STATES FOR SEMICONDUCTORS

- Start with the number of momentum states in a unit volume V=1:
  Between momenta p and p+dp there are $4\pi p^2$ dp states within a spherical shell.
- Phase space is quantized in units of h^3, and thus, for a spin-1/2 particle with two spin configurations, the density of states is $Z(p)\,dp = 2\frac{4\pi p^2\,dp}{h^3}$.
- For non-relativistic momenta we find

$$\frac{dE}{dp} = \frac{d}{dp}\left(\frac{p^2}{2m_{\text{eff}}}\right) = \frac{p}{m_{\text{eff}}}$$

$$\Rightarrow dp = \frac{m_{\text{eff}}}{p}\,dE = \frac{m_{\text{eff}}}{\sqrt{2m_{\text{eff}}E}}\,dE$$

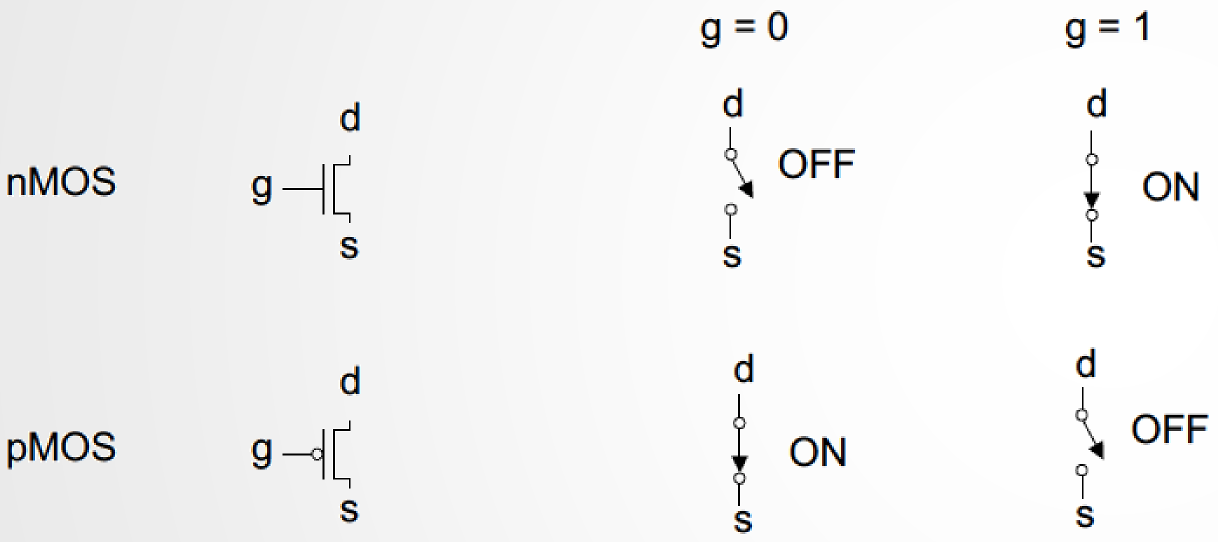
$$\Rightarrow 4\pi p^2\,dp = 4\pi(2m_{\text{eff}}E)\frac{m_{\text{eff}}}{\sqrt{2m_{\text{eff}}E}}\,dE$$

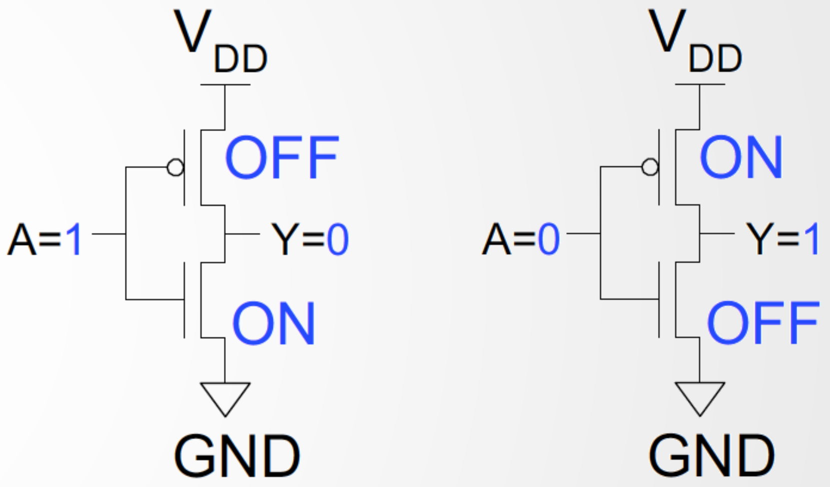
and finally

$$\boxed{Z(E)\,dE = 4\pi\left(\frac{2m_{\text{eff}}}{h^2}\right)^{3/2}\sqrt{E}\,dE.}$$

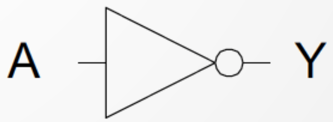
HV/HR CMOS DETECTORS

- We can view MOS (metal-oxide-semiconductor) transistors as electrically controlled switches
  - Voltage at gate controls path from source to drain





- If 'A' is the input and 'Y' the output, two n/pMOS transistors form an inverter.



A	Y
0	**1**
1	0

- The idea is to put industrial cMOS electronics directly onto the silicon sensor. No hybrid. No bonding.

INVERTER CROSS SECTION

- Typically use p-type substrate for nMOS transistor
- Requires n-well for body of pMOS transistors
- First amplification happens already on the sensor
- Cheaper and less electronics needed