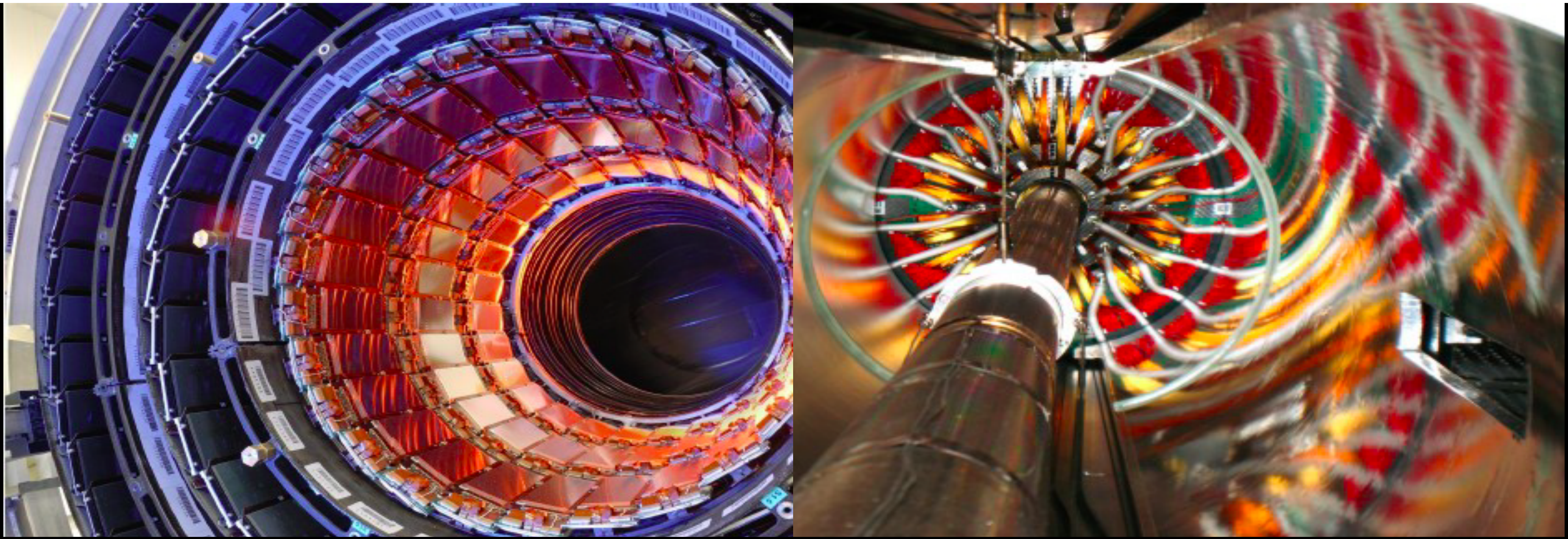
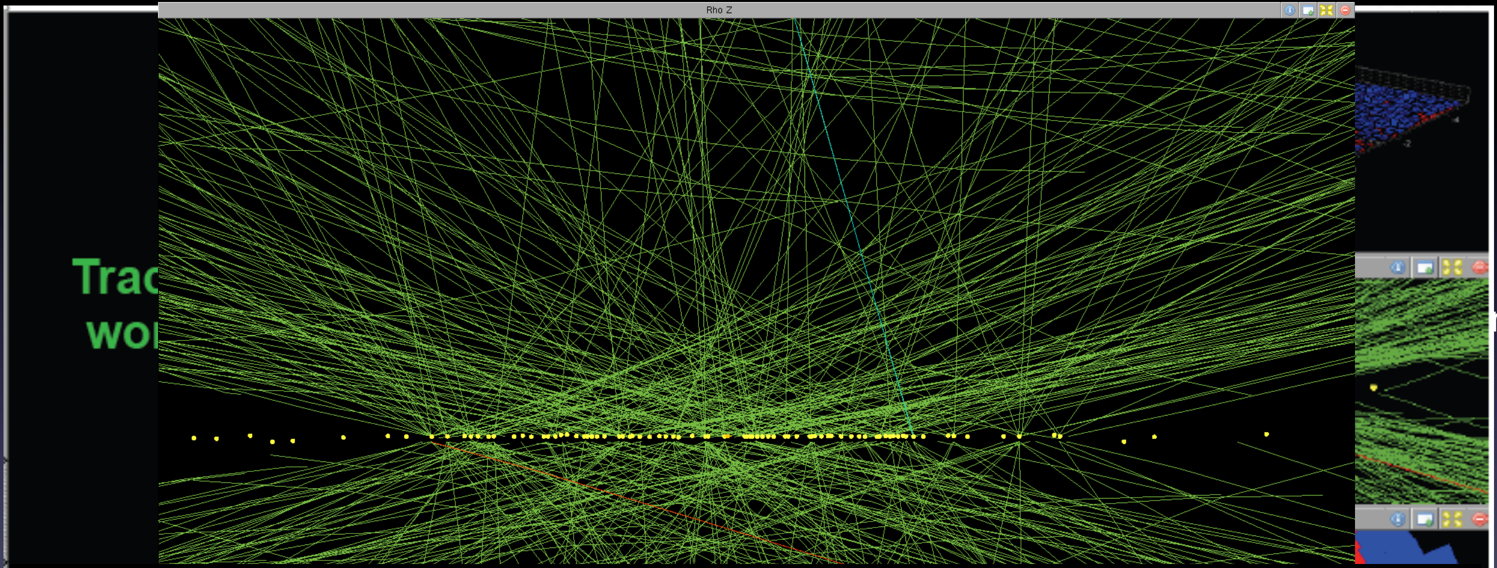


Semiconductor Detectors

Tracking and Vertex Detectors

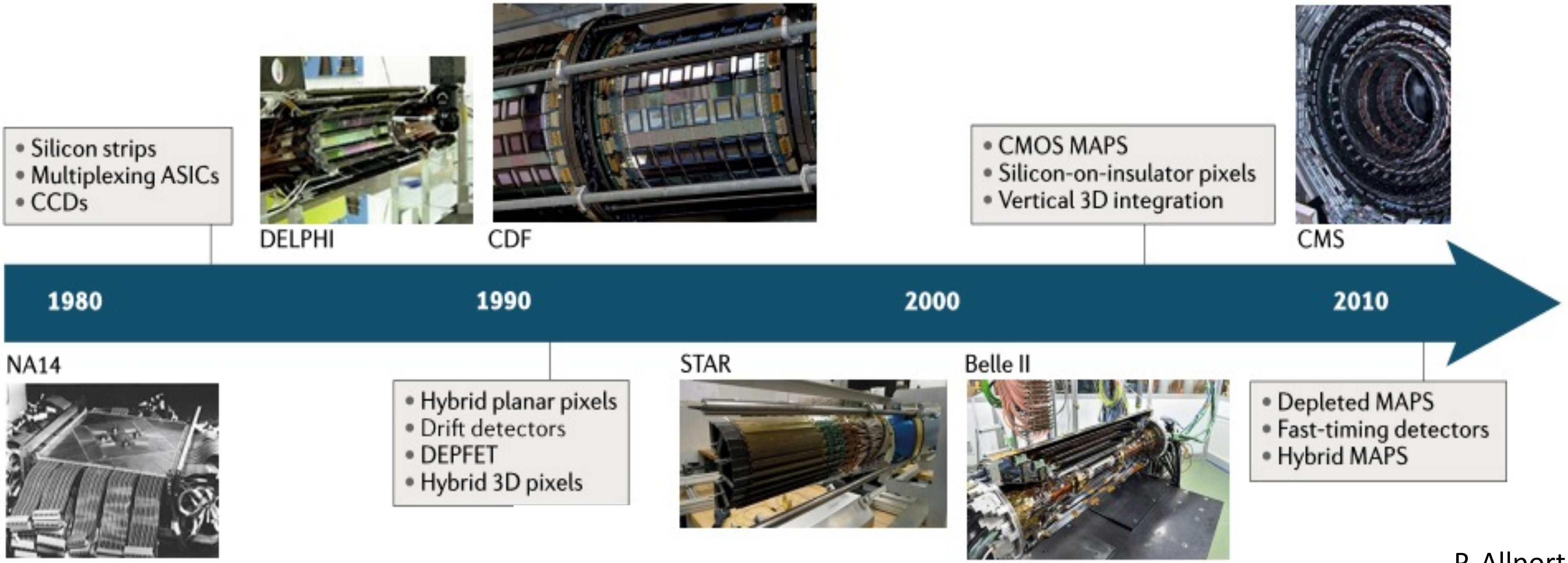
- Solid state detectors especially silicon offer high segmentation
- Determine position of primary interaction vertex and secondary decays



This would have not been possible without semiconductor (pixel and strip) trackers

Solid State Detectors

Many different silicon detector technologies for **particle tracking** have been developed over the last four decades:



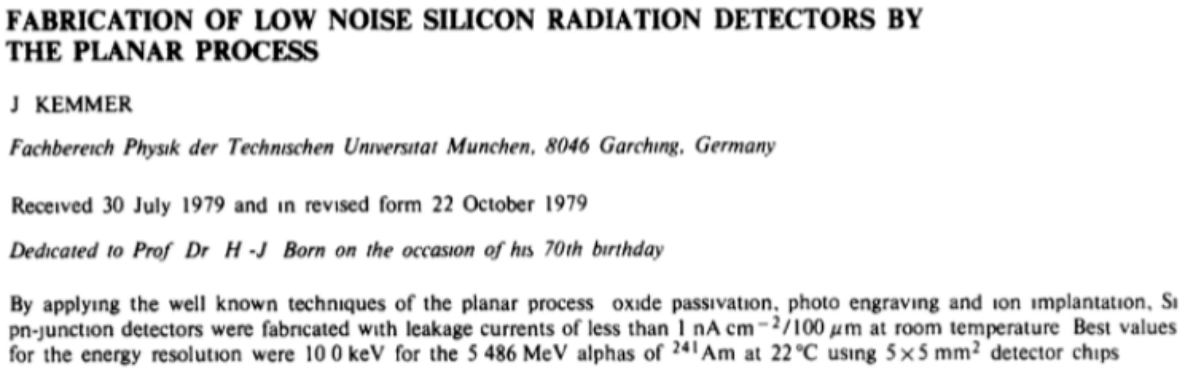
P. Allport

Remarkable: every decade the instrumented areas have increased by a factor of 10 while the numbers of channels in the largest arrays have increased by a factor of 100

- Solid state detectors now more radiation hard and now also used for **calorimetry and time-of-flight**
- **But improved precision, radiation hardness and timing are needed**

The Birth of Silicon Sensors in Particle Physics

J. Kemmer
  Fixed target experiment with a planar diode
  Later strip devices -1980



FABRICATION OF LOW NOISE SILICON RADIATION DETECTORS BY THE PLANAR PROCESS

J KEMMER

Fachbereich Physik der Technischen Universitat Munchen, 8046 Garching, Germany

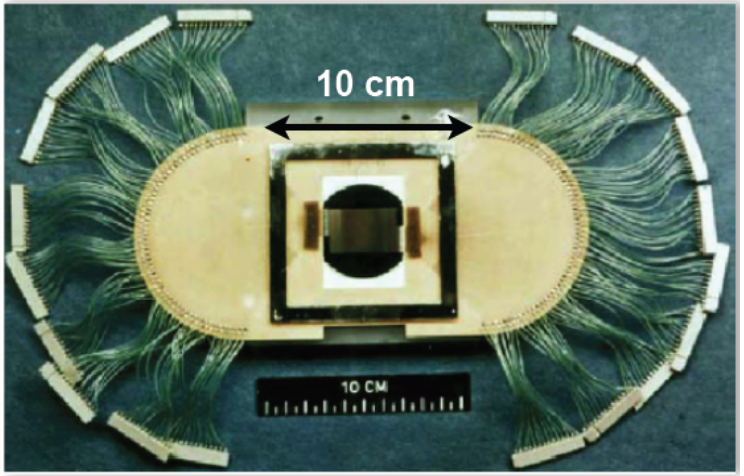
Received 30 July 1979 and in revised form 22 October 1979

Dedicated to Prof Dr H -J Born on the occasion of his 70th birthday

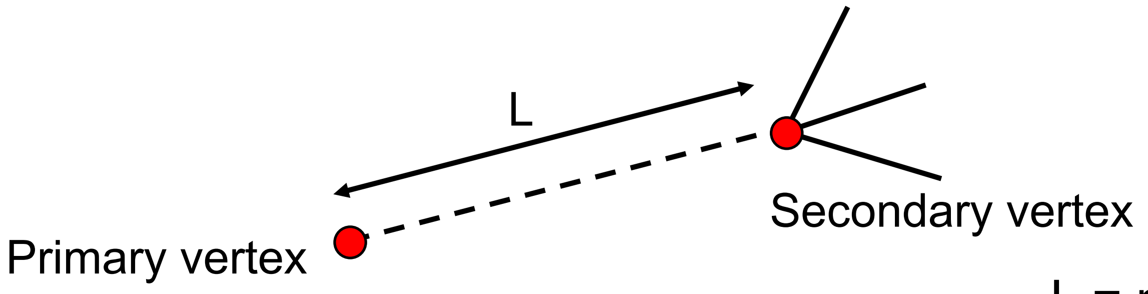
By applying the well known techniques of the planar process oxide passivation, photo engraving and ion implantation, Si pn-junction detectors were fabricated with leakage currents of less than 1 nA cm^{-2}/100 μm at room temperature Best values for the energy resolution were 10 0 keV for the 5 486 MeV alphas of ^{241}Am at 22 °C using 5×5 mm^2 detector chips

NA11 at CERN
First use of a position-sensitive silicon detector in HEP experiment

- Measurement of charm-quark lifetime (decay length 30 μm)
- 1200 diode strips on 24 x 36mm^2 active area
- 250-500 μm thick bulk material
- 4.5 μm resolution



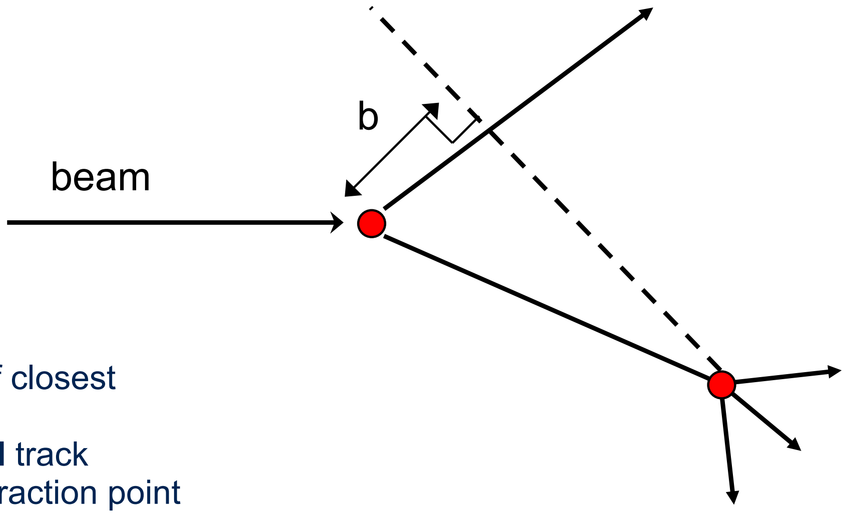
- Particle tracking
- Vertexing
  - primary and secondary vertices
  - decay length
  - impact parameter



$L = p/m\ c\ \tau$

- By measuring the decay length, L, and the momentum, p, the lifetime of the particle can be determined
- Need accuracy on both production and decay point

- σ_b = f(vertex layers, distance from main vertex, spatial resolution of each detector, material before precision measurement, alignment, stability)



b = distance of closest
approach of a
reconstructed track
to the true interaction point

Why Silicon

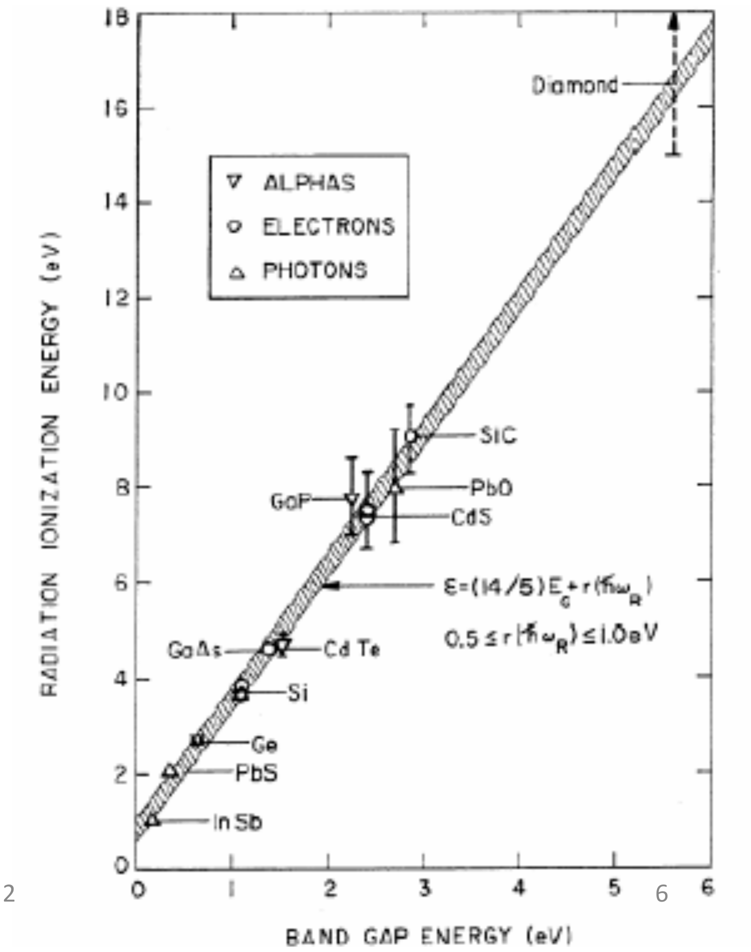
- **Semiconductor with moderate bandgap (1.12eV)**
- **Energy to create e/h pair (signal quanta)= 3.6eV**
  - (c.f Argon gas = 15eV)
  - High carrier yield
  - Better energy resolution and high signal
  - no gain stage required

plus phonon excitation

- **High density and atomic number**
  - Higher specific energy loss
  - Thinner detectors
  - better spatial resolution

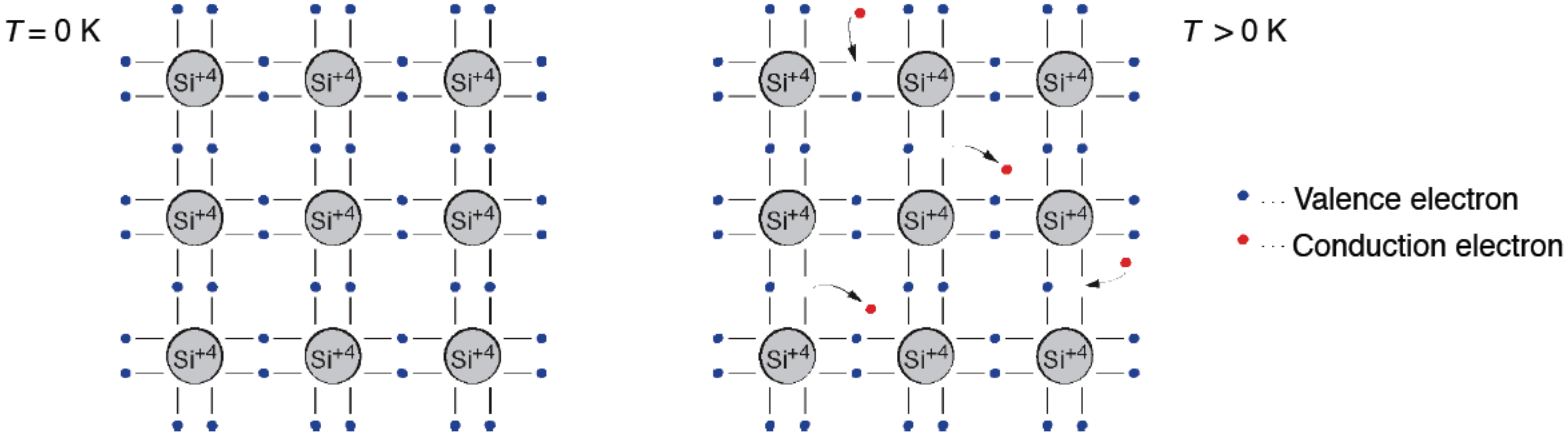
- **High carrier mobility Fast!**
  - Less than 30ns to collect entire signal

- **Large experience in industry** with micro-chip technology
- Intrinsic radiation hardness



Silicon Bond Model

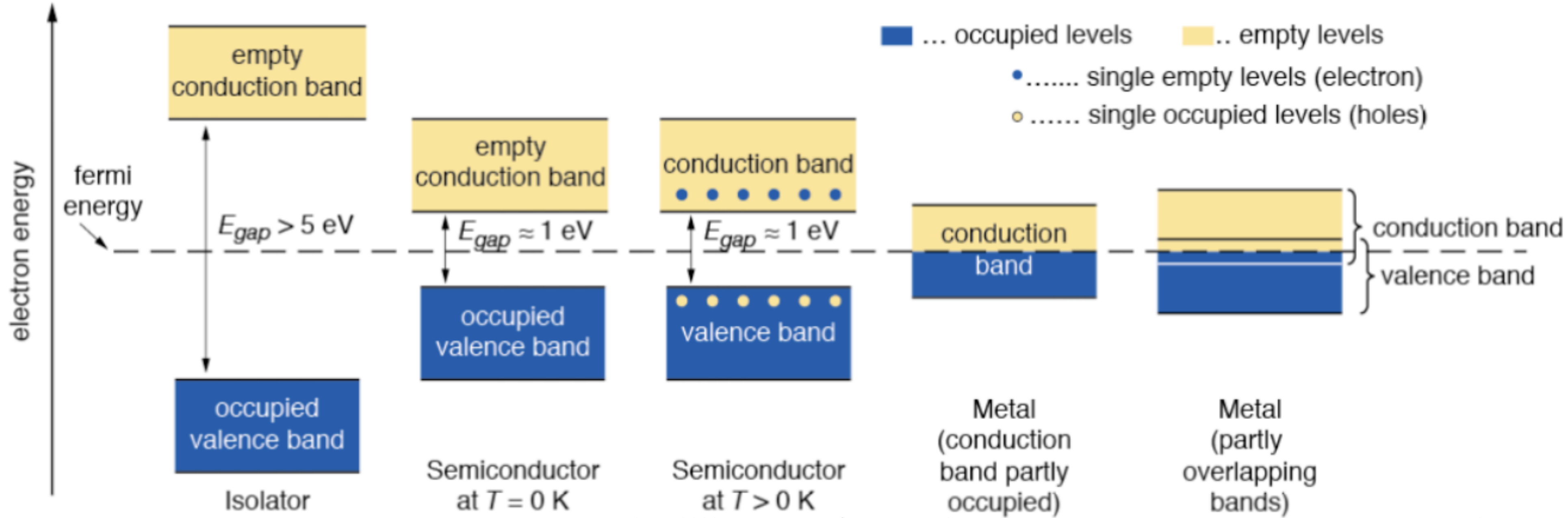
Example of column IV elemental semiconductor:



- Each atom has 4 closest neighbours, the 4 electrons in the outer shell are shared and form covalent bonds.
  - At low temperature all electrons are bound
  - At higher temperature thermal vibrations break some of the bonds
  - free e- cause conductivity (electron conduction)
  - The remaining open bonds attract other e- , “holes” change position (hole conduction)

Energy Bands

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



Intrinsic Carrier Concentration

- Small band gap in semiconductors
  —> electrons already occupy the conduction band at room temperature

- Electrons from the conduction band may recombine with holes

- **thermal equilibrium** is reached between **excitation** and **recombination:**
  - charge carrier concentration $n_e = n_h = n_i$

  —> intrinsic carrier concentration:

$$n_i = \sqrt{N_C N_V} \cdot \exp\left(-\frac{E_g}{2kT}\right) \propto T^{\frac{3}{2}} \cdot \exp\left(-\frac{E_g}{2kT}\right)$$

- In ultrapure silicon the intrinsic carrier concentration is $\mathbf{1.45 \cdot 10^{10}\ cm^{-3}}$

- With approximately 10^{22} Atoms/cm^3 about 1 in 10^{12} silicon atoms is ionized

Material Properties

Drift velocity for electrons: $\vec{v}_n = -\mu_n \cdot \vec{E}$

for holes: $\vec{v}_p = \mu_p \cdot \vec{E}$

Mobility for electrons: $\mu_n = \frac{e\,\tau_n}{m_n}$

for holes: $\mu_p = \frac{e\,\tau_p}{m_p}$

μ_n(Si, 300 K) ≈ 1450 cm^2/Vs

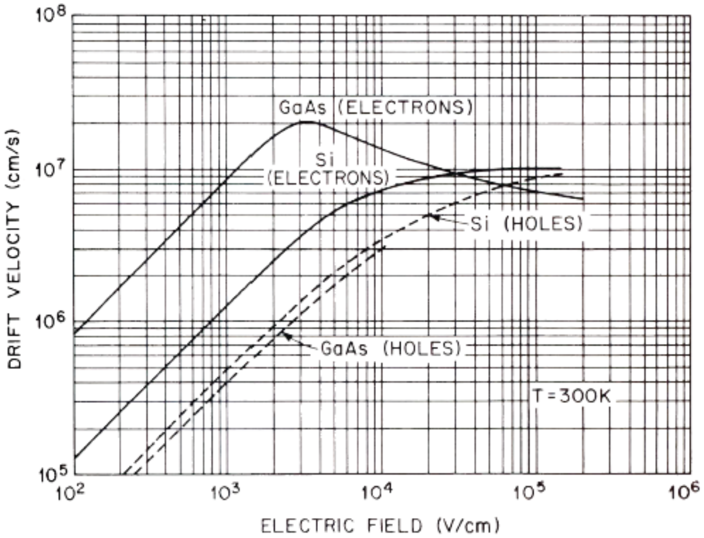
μ_p(Si, 300 K) ≈ 450 cm^2/Vs

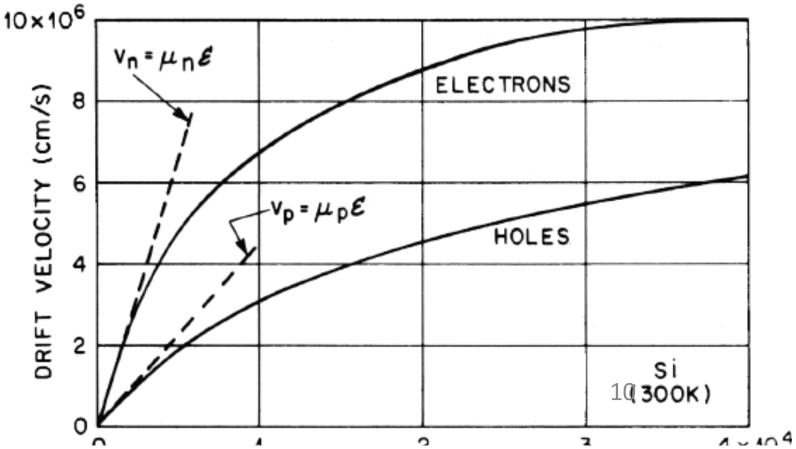
Resistivity: $\rho = \frac{1}{e(\mu_n n_e + \mu_p n_h)}$

With the charge carrier concentration in intrinsic silicon

$n_e = n_h \approx 1.45 \cdot 10^{10}\ cm^{-3}$

—> intrinsic resistivity **ρ ≈ 230 kΩcm**





How to make a detector

Thickness: 0.3mm

Area: 1cm^2

Resistivity: 10$k\Omega$cm

Resistance ($\rho d/A$) : 300Ω

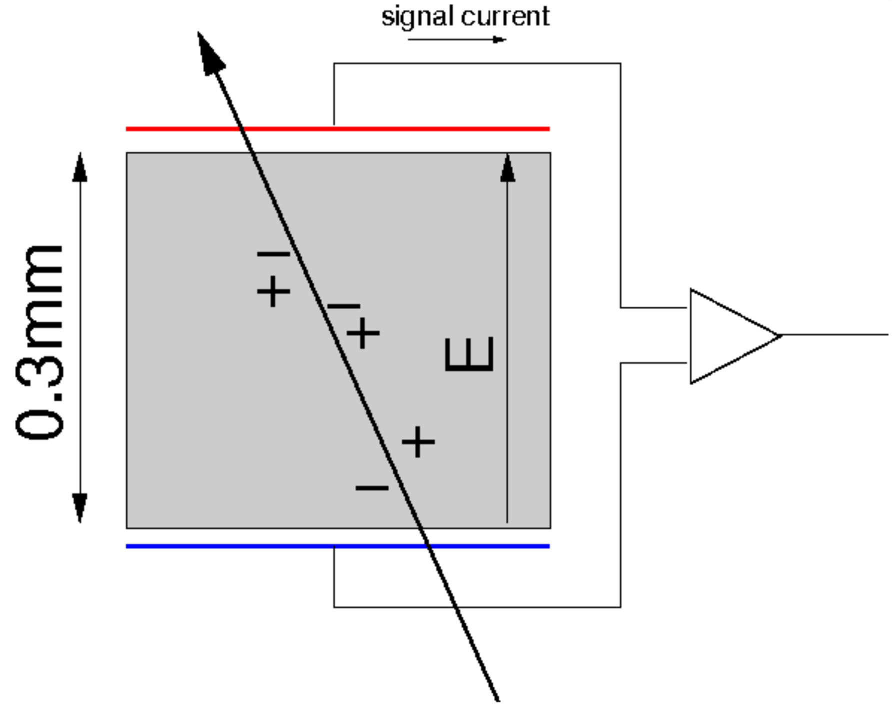
Mobility (electrons): ~1400 cm^2/Vs

Collection time: ~10ns

Charge released: ~25000 e~4fC

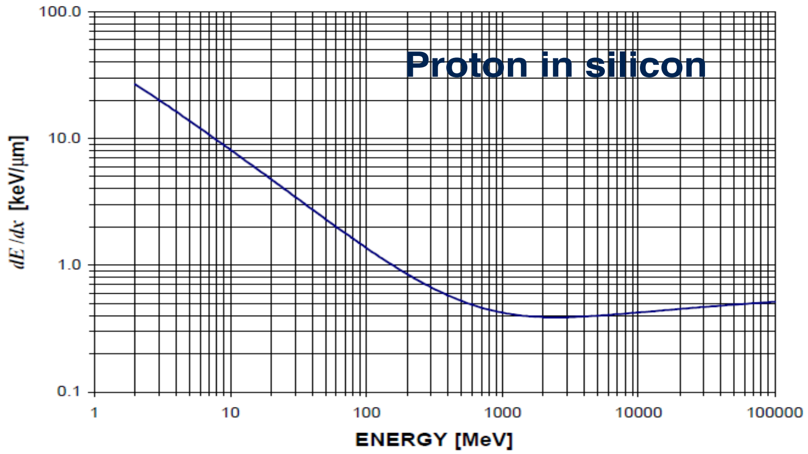
Need an average field of

$E=v/\mu=0.03cm/10ns/1400cm^2/V \sim 21000$ V/cm or V=60V



Is this detector going to work?

How to make a silicon detector



Mean ionization energy ***I₀* = 3.62 eV**

- mean energy loss per flight path of a mip ***dE/dx* = 3.87 MeV/cm**

Assuming same detector with a thickness of *d* = 300 µm and an area of *A* = 1 cm².

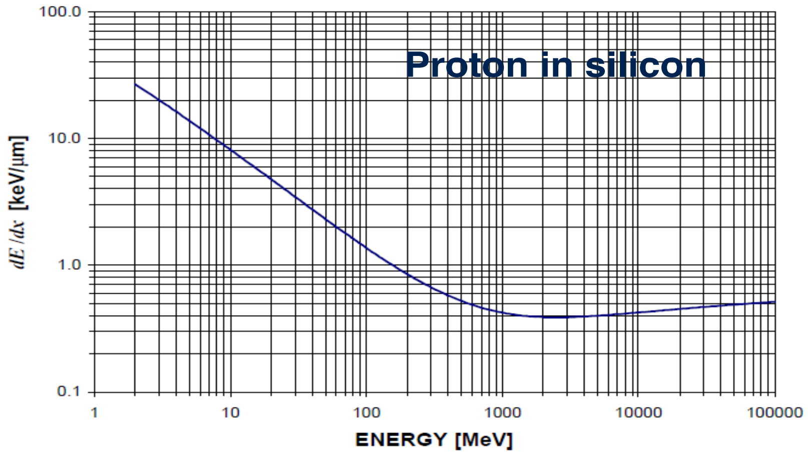
Signal of a mip in such a detector:

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

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

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

How to not make a silicon detector



Mean ionization energy ***I₀*** **= 3.62 eV**

- mean energy loss per flight path of a mip ***dE/dx*** **= 3.87 MeV/cm**

Assuming same detector with a thickness of $d = 300$ µm and an area of $A = 1$ cm^2.

Signal of a mip in such a detector:

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

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

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

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

p-n-junction — Doping

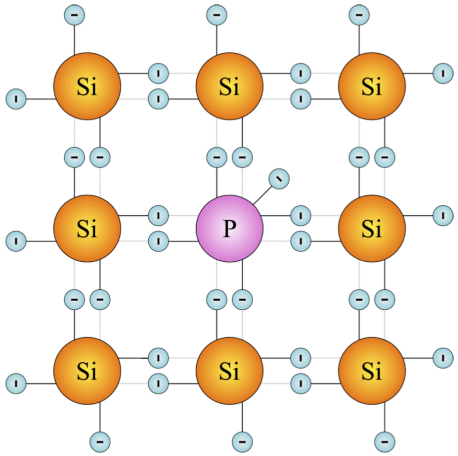
- **Remove the charge carriers by generating a depletion zone in a pn junction**
- **create n- and p-type silicon by doping**

- **Doping:** replacement of a small number of atoms in the lattice by atoms of neighboring columns from the periodic table

—> energy levels within the band gap created

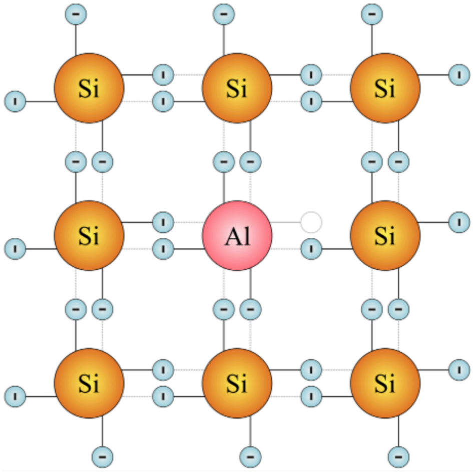
—> conductivity altered

n-type silicon



- **Dopant**: element V atom (e.g. P, As, Sb)
- **Donor**
- 5th valence electron is weakly bound
- **majority carriers**: electrons
- **space charge:** positive

p-type silicon



- **Dopant**: element III atom (e.g. B, Al, Ga, In)
- **Acceptor**
- one valence bond open attracts electrons from neighbouring atoms
- **majority carriers**: holes
- **space charge:** negative

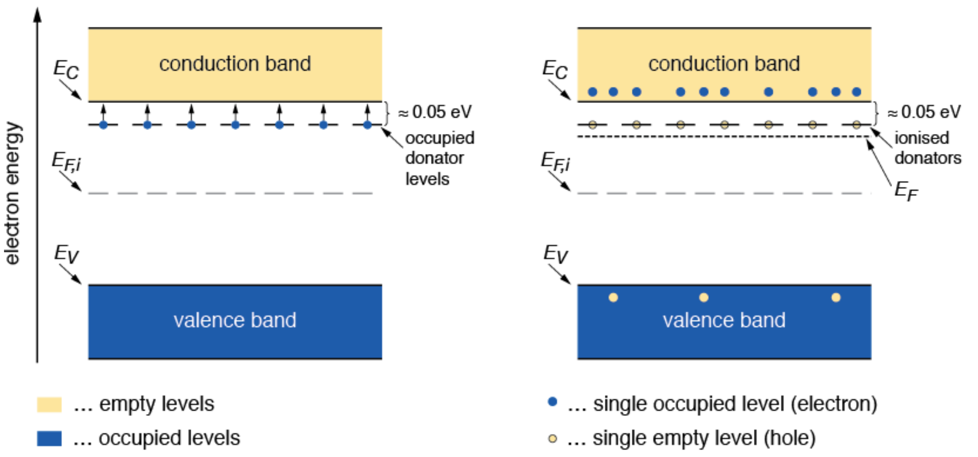
Doping

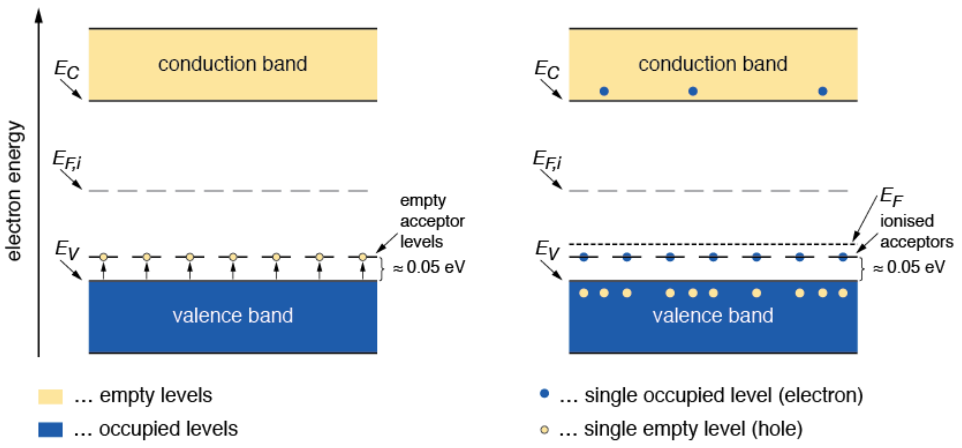
n-type silicon

- Energy level of **donor** just below the edge of the conduction band
- At room temperature most **electrons** are raised to the **conduction band**
- The Fermi level E_F moves up

p-type silicon

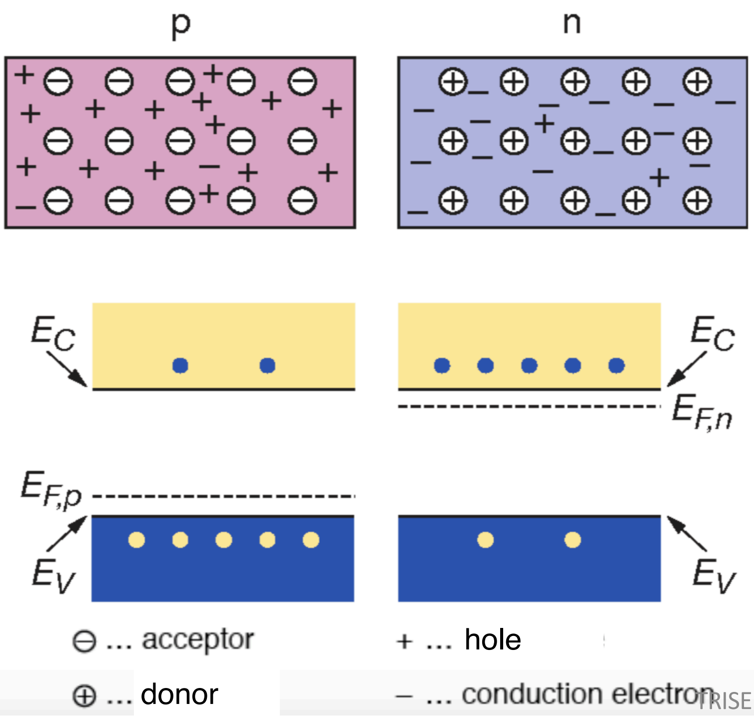
- Energy level of **acceptor** just above the edge of the valence band
- At room temperature most levels are occupied by electrons leaving **holes** in the **valence band**
- The Fermi level E_F moves down

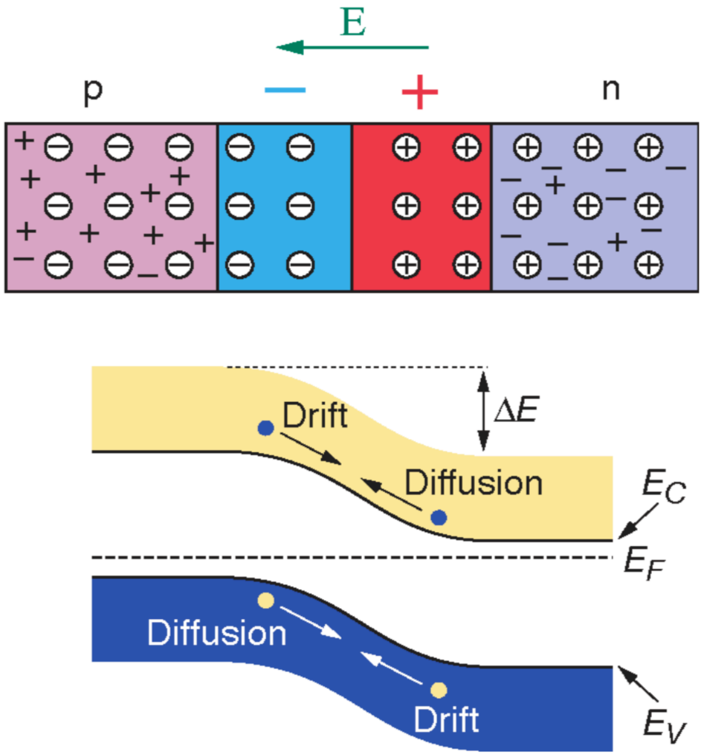




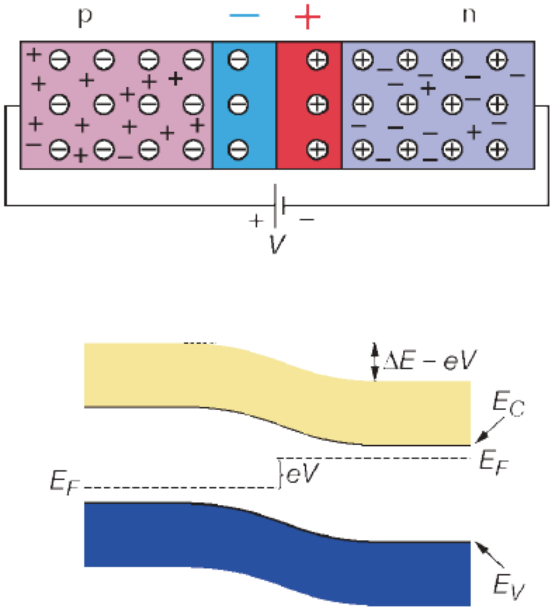
Creating a p-n junction

- Difference in the Fermi levels cause **diffusion of excessive carriers** until thermal equilibrium
- Fermi level is equal
- Remaining ions create a **space charge region** and an **electric field** stopping further diffusion
- Space charge region is free of charge carries —> **depletion zone**

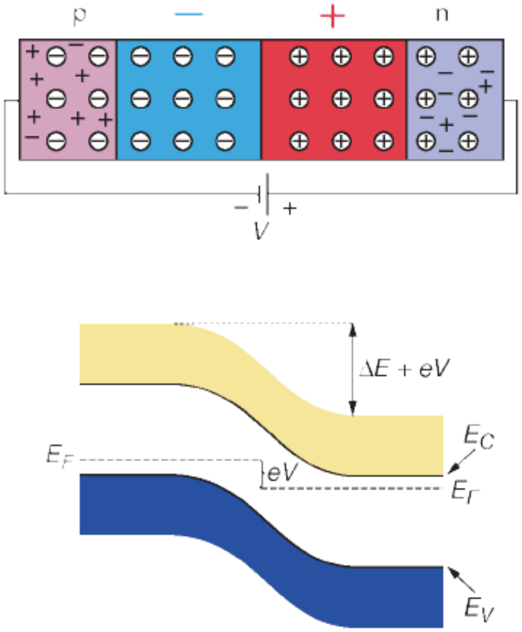




Biased p-n junction or How to really make a silicon detector


p-n junction with forward bias

- External voltage V with + to p and — to n
  —> e- and holes are refilled to the depletion zone
- **depletion zone becomes narrower** (forward biasing)
- **Consequences:**
  - The potential barrier becomes smaller by *eV*
  - Diffusion across the junction becomes easier
  - The current across the junction increases significantly


p-n junction with reverse bias

- External voltage V with — to p and + to n
  —> e- and holes are pulled out of the depletion zone
- **depletion zone becomes larger** (reverse biasing).
- **Consequences:**
  - The potential barrier becomes higher by *eV*
  - Diffusion across the junction is suppressed
  - current across junction is very small (“leakage current”)

Depletion Zone

Effective doping concentration in **typical silicon detector with p+-n junction**

$N_a = 10^{15}$ cm^{-3} in p+ region

$N_d = 10^{12}$ cm^{-3} in n bulk.

Without external voltage: $W_p = 0.02$ µm

$W_n = 23$ µm

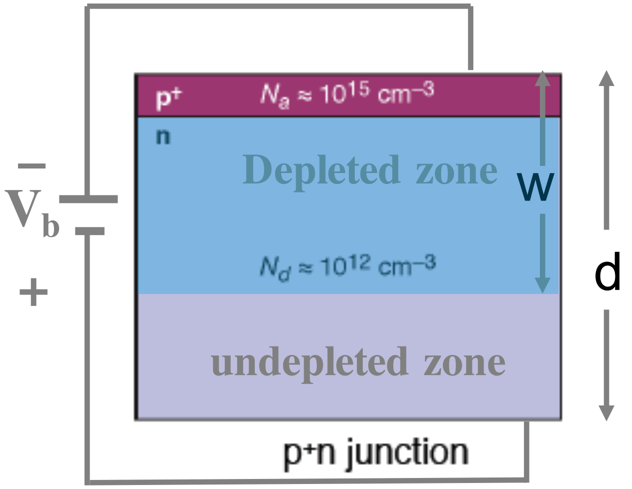
With bias voltage:

$$W = \sqrt{\frac{2\varepsilon V}{q}\left(\frac{1}{N_D} + \frac{1}{N_A}\right)}$$

For a given thickness, Full Depletion Voltage is:

$$V_{fd} = \frac{qN_D W^2}{2\varepsilon}$$

W = 300µm, $N_D = 5\times10^{12}$cm^{-3} –> $V_{fd} = 100$V



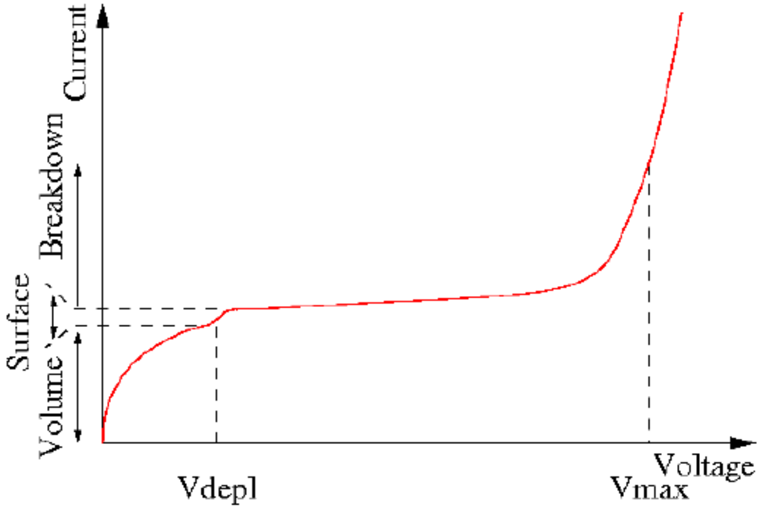
Resistivity: $$\rho = \frac{1}{q\mu_p N_D}$$

High-resistivity material (i.e. low doping) requires low depletion voltage :

FZ sensors:
Doping concentrations: 10^{12}–10^{15}cm^{-3}
Resistivity ~ 5 kΩcm
CMOS:
Doping concentrations: 10^{17} –10^{18} cm^{-3}
Resistivity ~ 1 Ωcm

Properties of the depletion zone

Current of the reverse biased diode



Diffusion current

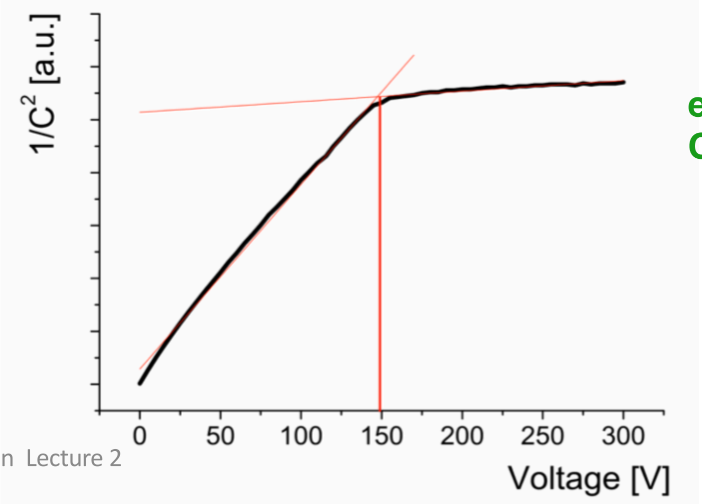
- From generation at surface, interfaces, edge of depletion region
- Negligible for a fully depleted detector

Generation current

- From thermal generation in the depletion region
- Reduced by using pure and defect free material
- Must keep temperature low & controlled

$$j_{gen} = \frac{1}{2} q \frac{n_i}{\tau_0} W \qquad j_{gen} \propto T^{3/2} \exp\left(\frac{1}{2kT}\right)$$

factor 2 every △T= 8K



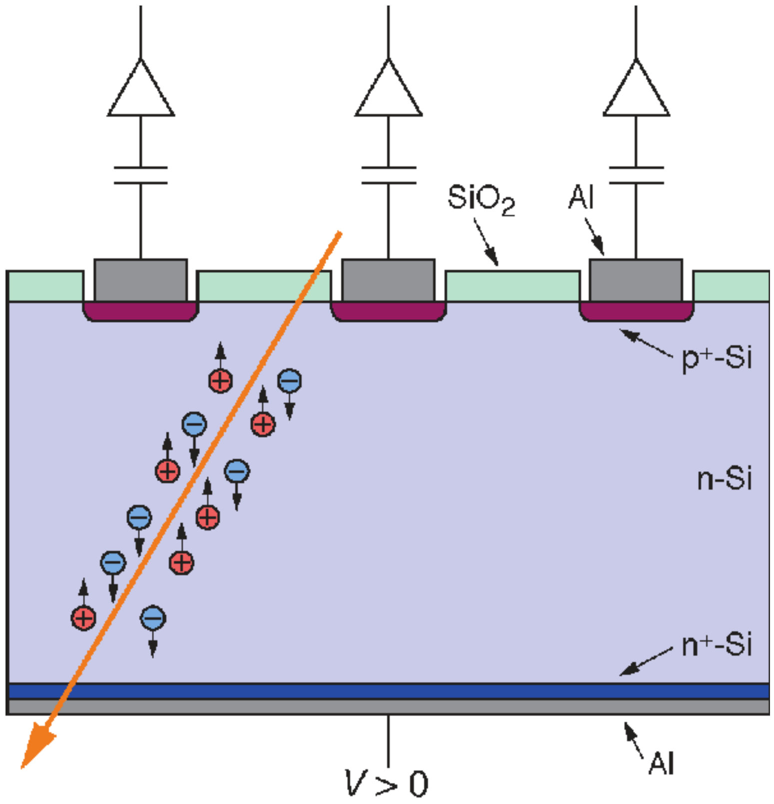
exercise CV/IV

Capacitance of the reverse biased diode

- Similar to parallel-plate capacitor
- Fully depleted detector capacitance defined by geometric capacitance

$$C = \sqrt{\frac{\varepsilon_0 \varepsilon_r}{2\mu\rho|V|}} \cdot A$$

Position Sensitivity - Silicon Strip Detectors (DC)



- Segmenting the implant
  —> one-dimensional position of the traversing particle

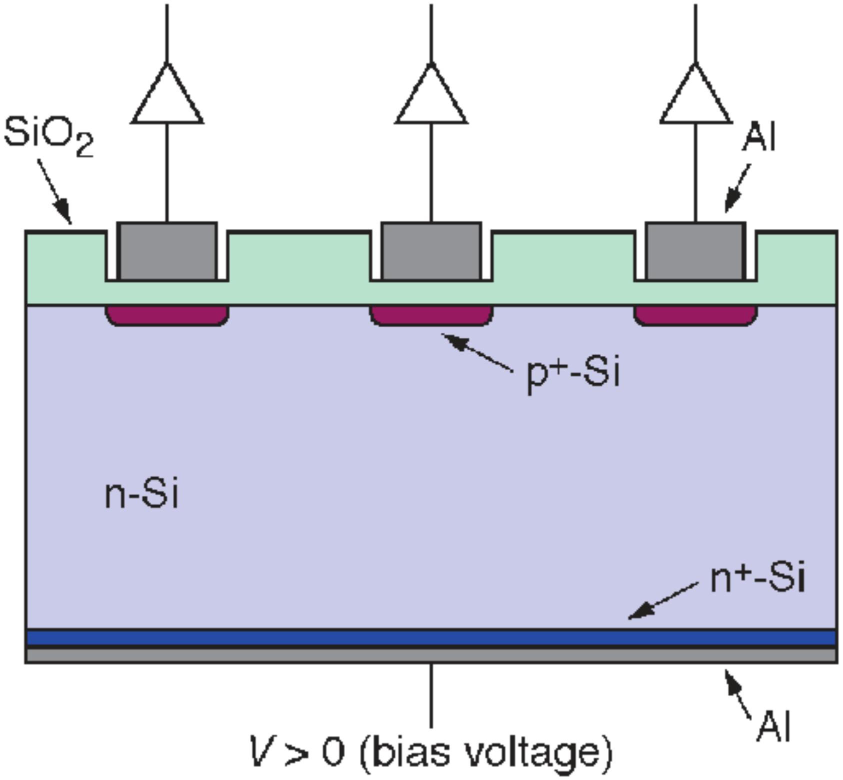
- Simplest version: **DC-coupled** strip detector

- **p-in-n** sensor:
  - Strips are Boron implants (p+)
  - Substrate is Phosphorous doped (~2-10 kΩcm)
- Thickness ~300μm
- $V_{dep} < 200V$

- Backside Phosphorous implant (n+) to establish ohmic contact and to prevent early breakdown

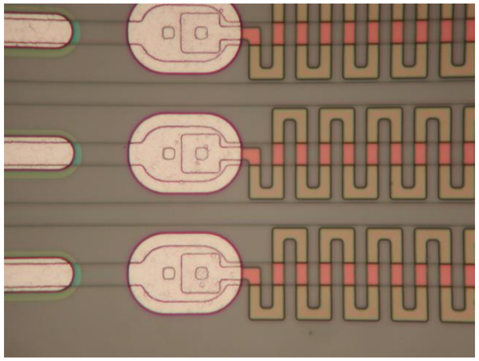
- Highest field close to the collecting electrodes where most of the signal is induced

Position Sensitivity - Silicon Strip Detectors (AC)

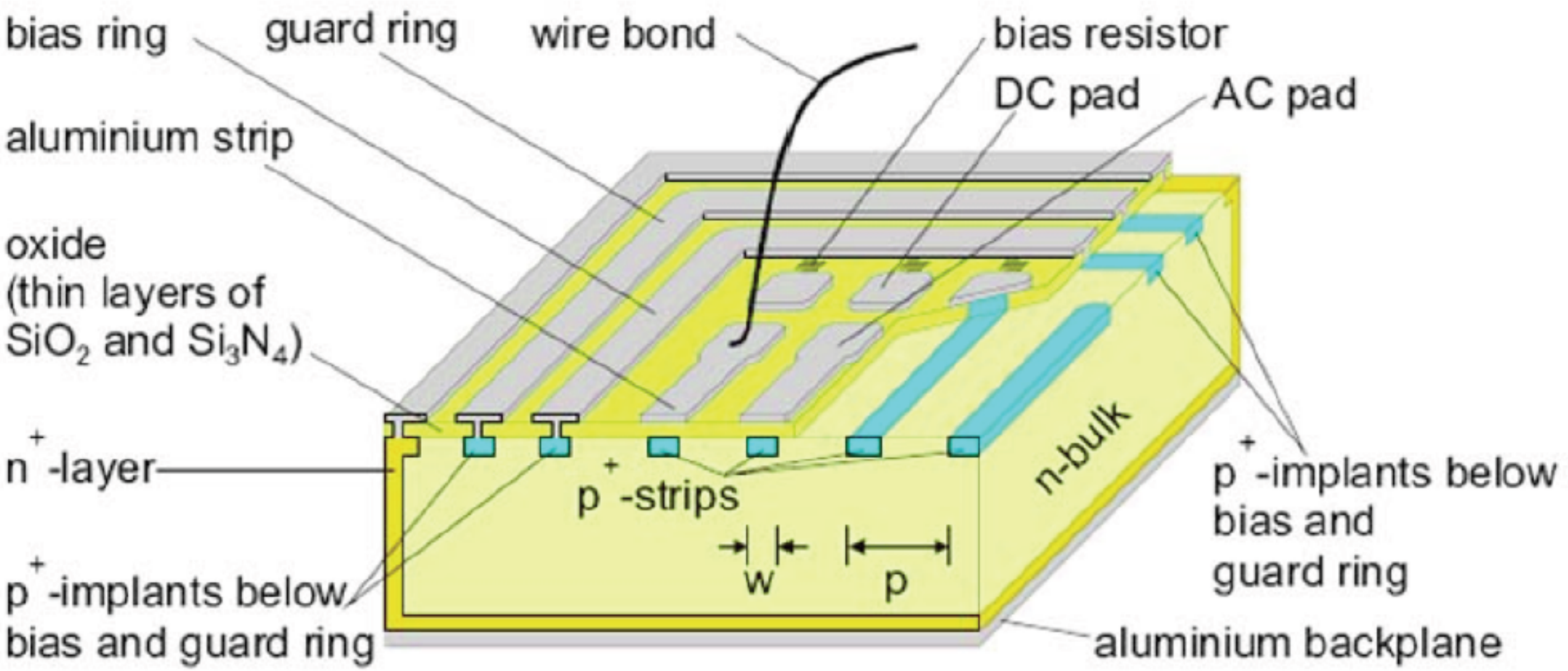


- **AC coupling** blocks leakage current from the amplifier
- Integration of coupling capacitances in standard planar process:
  - Deposition of SiO_2 with thickness of 100–200 nm between p+ and Al strip
- Increase quality of dielectric by a second layer of Si_3N_4

connect bias to strips —>
Long poly silicon resistor
with R>1MΩ



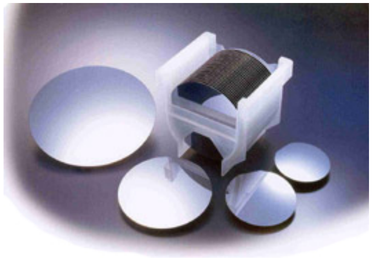
Summary AC coupled strip sensor



Fabrication of Planar Silicon Sensors - Wafers

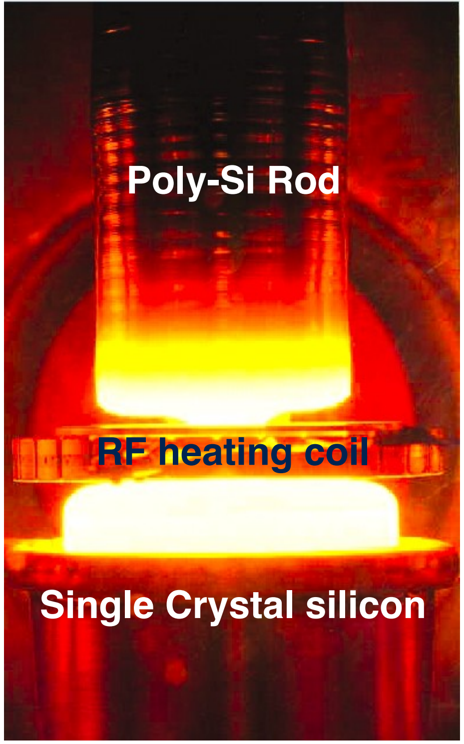
Properties of Si bulk required for detectors:

- 4, 6 or 8 inches
- Lattice orientation <111> or <100>
- high Resistivity 1–10 kΩcm



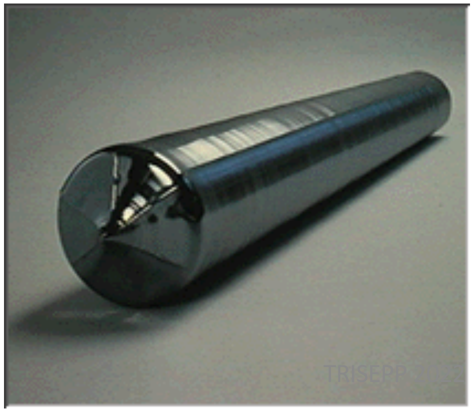
- slice (lap, etch, polish) wafers from ingot

Float Zone process

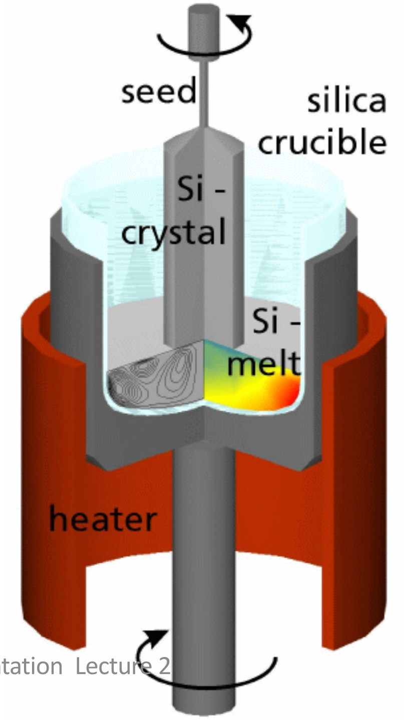


- single crystal seed
- melt the Poly-Si rod and
- ‘pull’ the singe-crystal ingot

mono crystalline Ingot

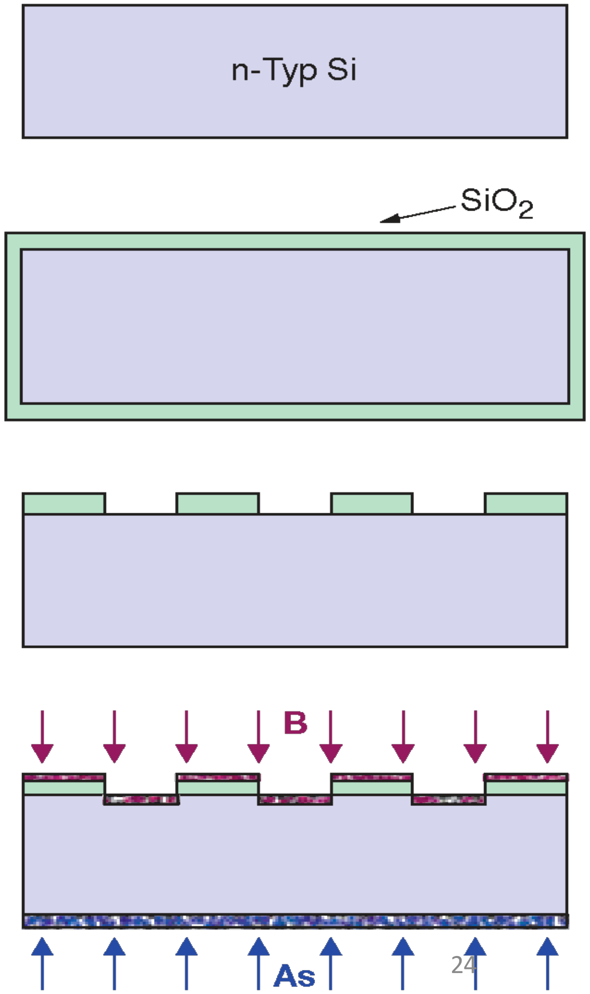


Czochralski process



- Si melt in silica crucible
- ‘pull’ the singe-crystal from melt
- less pure as O (and other) in melt
- used by IC industry
- now also available in higher resistivity

Fabrication of Planar Silicon Sensors - Sensor Fabrication

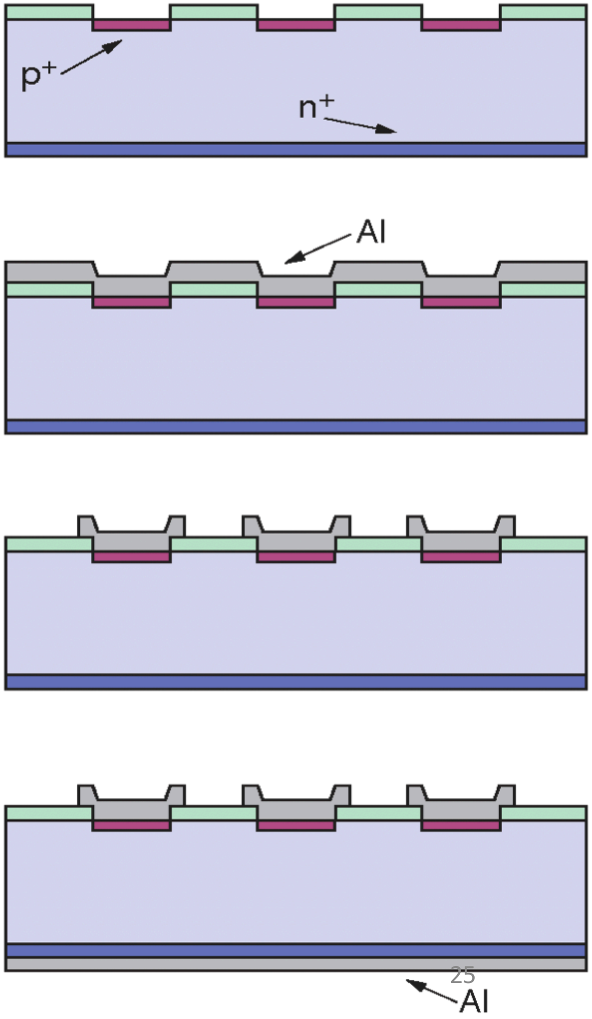


1. Starting Point: single-crystal n-doped wafer ($N_D \approx 1–5 \cdot 10^{12}$ cm^{-3})
2. Surface passivation by SiO_2-layer (approx. 200 nm thick). E.g. growing by (dry) thermal oxidation at 1030 °C.
3. Window opening using **photolithography technique** with etching, e.g. for strips
4. Doping using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

Fabrication of Planar Silicon Sensors - Sensor Fabrication

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

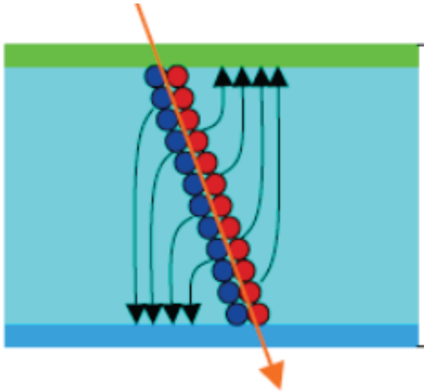
Last step: wafer **dicing** (cutting)



Signal Generation

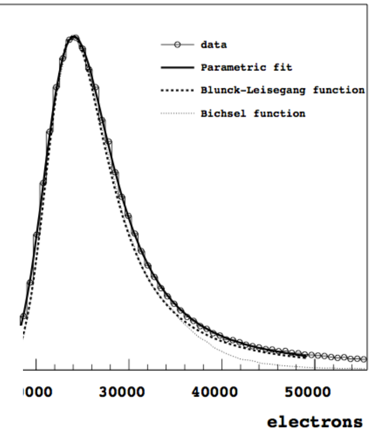
The signal

- depends essentially only on the thickness of the depletion zone and on the dE/dx of the particle
- electron-hole pairs generated along the particle trajectory



Reminder:

- mean energy loss per flight path of a mip dE/dx = 3.87 MeV/cm
- Fluctuations give the famous “Landau distribution”
- The “most probable value” MPV is 0.7 of the mean value
- For 300 μm of silicon, most probable value is ~23400 e- / h pairs

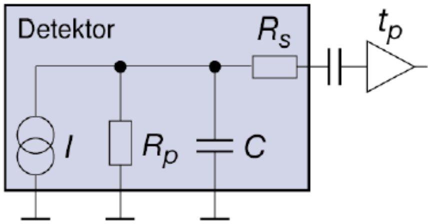


The noise in a silicon detector system

- depends on various parameters: geometry, biasing scheme, readout electronics
- typically given as “equivalent noise charge” ENC
- This is the noise at the input of the amplifier in elementary charges
- Most important wise contributions from:

Leakage current ($\mathrm{ENC_I}$)
Detector capacitance ($\mathrm{ENC_C}$)
Detector parallel resistor ($\mathrm{ENC_{Rp}}$)
Detector series resistor ($\mathrm{ENC_{Rs}}$)

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



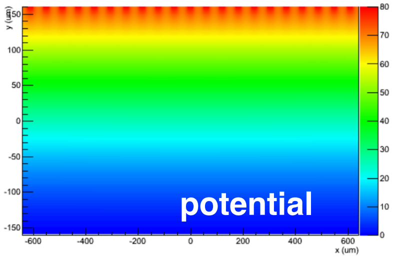
Equivalent circuit diagram of a silicon detector.

exercise
Landau distribution

Signal Collection

Drift under E-field

- p^+ strips on n^- bulk
- p^+ —ve bias
- Holes to p^+ strips, electrons to n+ back-plane
- **E-field determines the charge trajectory and velocity**

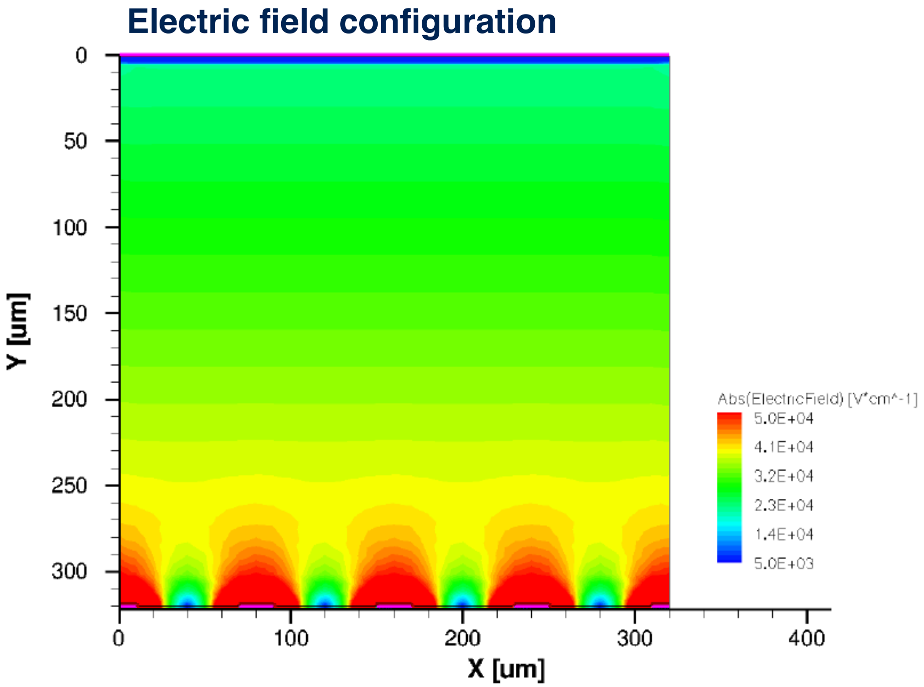


Typical bias conditions

- 100V, W=300μm E=3.3kVcm^{-1}
- Collection time: e=7ns, h=19ns

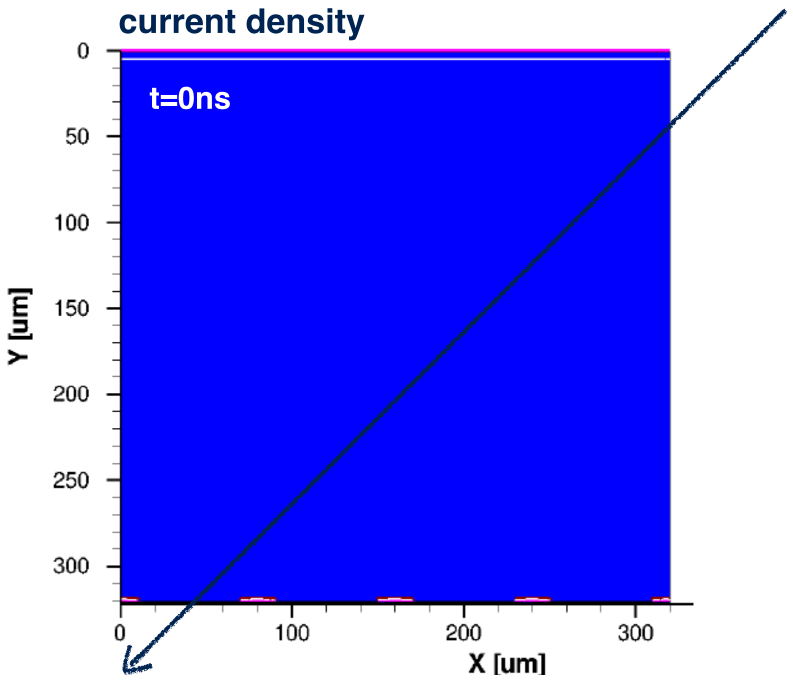
Charge Collection - Simulation

- a typical silicon sensor
- thickness 320 um
- n bulk
- p+ readout strips



Electric field configuration

Simulation with Synopsys TCAD by Thomas Eichorn

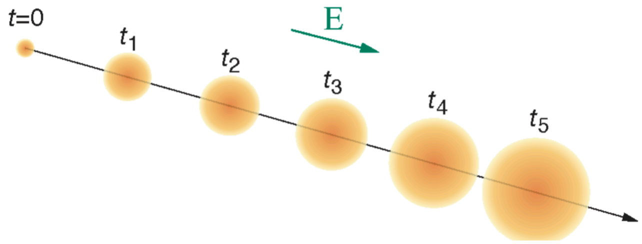


current density

Ionizing particle at 45^{o} incidence

Diffusion and Position Resolution

Diffusion



- Diffusion is caused by random thermal motion
- Width of charge cloud after a time t given by

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

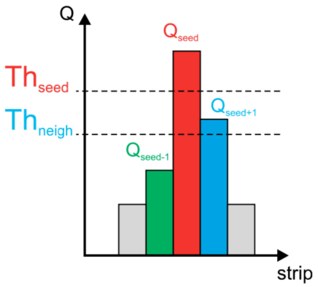
σ_D … width “root-mean-square” of the charge carrier distribution
t … drift time
k … Boltzmann constant
e … electron charge
D … diffusion coefficient
T … temperature
μ … charge carrier mobility

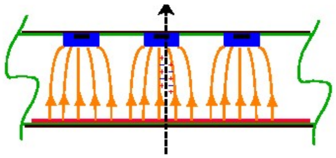
Note: $D \propto \mu$ and $t \propto 1/\mu$, hence σ_D is equal for e^- and h^+.

·Diffusion:Typical value: 8 µm for 300 µm drift.
·Can be exploited to improve position resolution

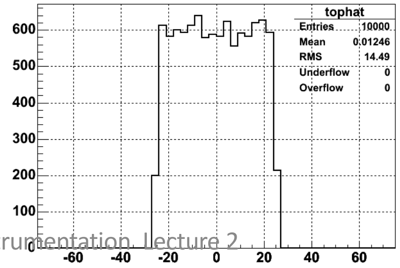
Resolution

digital readout single strip clusters

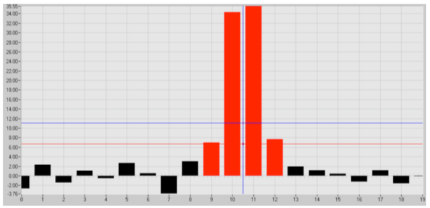


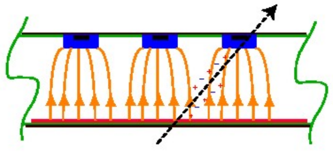


$$\sigma = \frac{\text{pitch}}{\sqrt{12}}$$

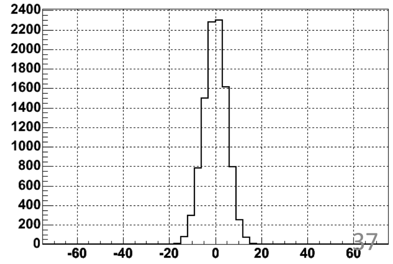


analogue readout multiple strips hit





$$\sigma \approx \frac{\text{pitch}}{1.5 * (S/N)}$$



More on Resolution — how to increase

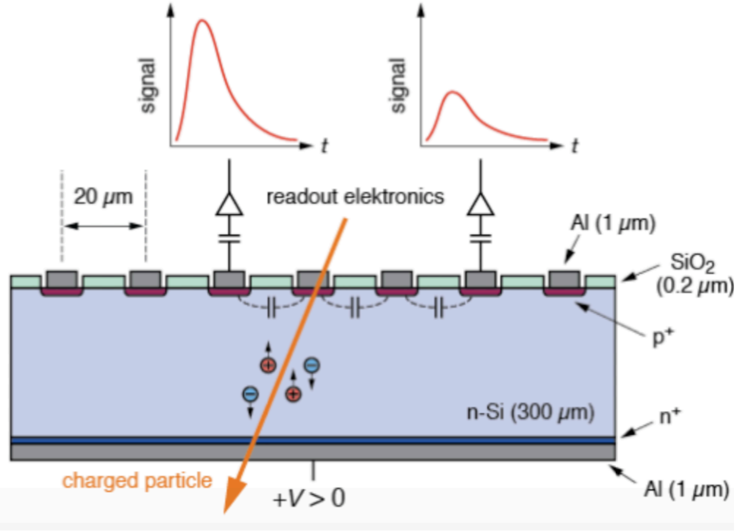
- resolution depends on S/N --> increase S/N
- resolution pitch dependent --> decrease pitch
- draw-back: increased number of readout channels
  increased power dissipation
  increased cost

- resolution better when charge shared on several strips

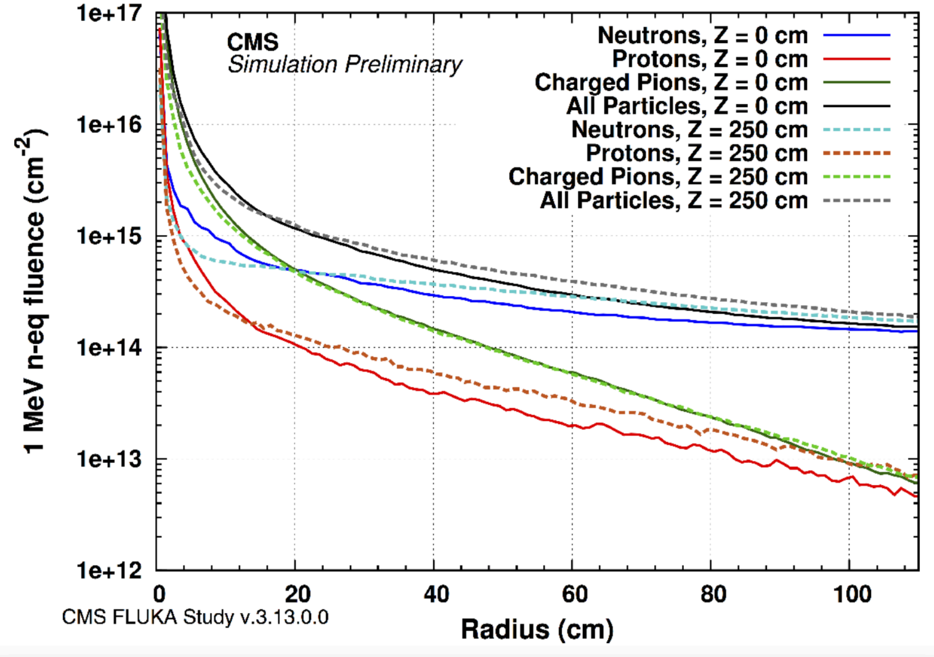
- implementation of **intermediate strips**
  - strips not connected to the readout electronics
  - located between readout strip
  - Signal is transferred by capacitive coupling to the readout strips

  —> more hits with signals on more than one strip

  —> Improved resolution with smaller number of readout channels.



Radiation Damage at the (HL-)LHC



FLUKA simulation of the fluence levels in the CMS Tracker after 3000 fb–1

- at LHC and even more at HL-LHC detector exposed to high levels of radiation
- **radiation fields:**
  - charged particles dominate at small radii
  - neutrons equal or dominant at higher radii
- **strip trackers:** LHC: up to 1.8×10^{14} n_{eq}/cm^2

  HL-LHC: up to 1.1×10^{15} n_{eq}/cm^2
- what happens to silicon sensors?

Φ_{eq}: equivalent fluence
-damage of different particle types
normalized to 1MeV neutrons

Radiation Damage

Particles passing through silicon material loose energy through

- interaction with shell electrons (**I**onizing **E**nergy **L**oss)
  —> **surface damage**
  - local charges accumulate in surface (charges cannot recombine in insulating surface, i.e. SiO_2 and Si/SiO_2 interface, thus it causes damage in the surface)
    —> oxide charges, interface traps
  - damage caused primarily through photons, charged particles
  - fast recombination in silicon bulk —> no damage in the bulk

- Interaction with atomic core or whole atom (**N**on **I**onizing **E**nergy **L**oss)
  —> **bulk damage**

  - Displacement of atoms in the lattice
  - Caused by massive particles as protons, pions, neutrons

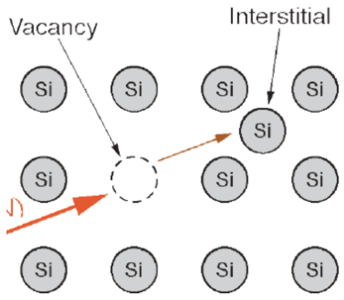
Take away:

IEL
- to first order not relevant for planar sensor
- becomes important for ASICs, monolithic sensors
- becomes important in combination with bulk damage

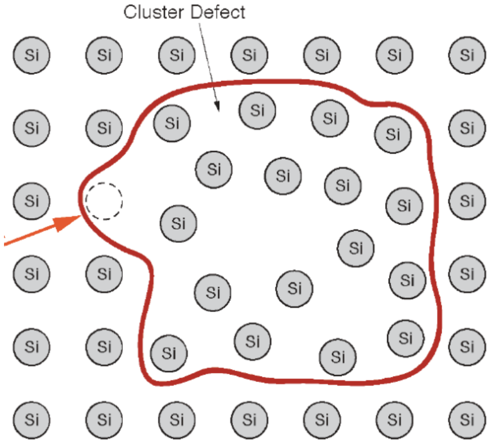
NIEL
- major degradation of sensor properties with irradiation

Bulk Damage

Primary **K**nock on **A**tom displaced out of lattice site

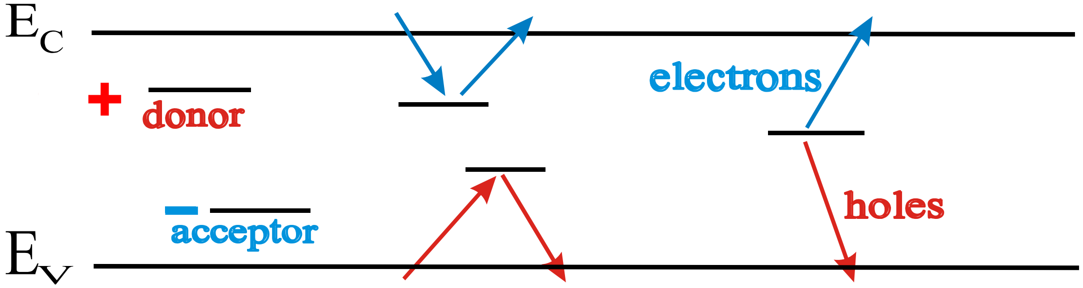


- Interstitials and Vacancies are very mobile at T>150K and migrate through lattice
  - Annihilate --> no damage remaining
  - Reactions with each other and impurities (V_2, V_iO_i,…)
  - Along path of recoil —> formation of more defects
  - at the end clusters formed



- defects in the crystal
- point defects and “cluster” defects

➔ energy levels in the band gap filled



charged defects

deep traps (e and h), recombination centers

deep traps, generation centers

⇒N_{eff} , V_{dep}

⇒ Charge Collection Efficiency

⇒ Leakage current

NIEL Scaling

- **NIEL - Non Ionizing Energy Loss scaling using hardness factors**

Hardness factor k

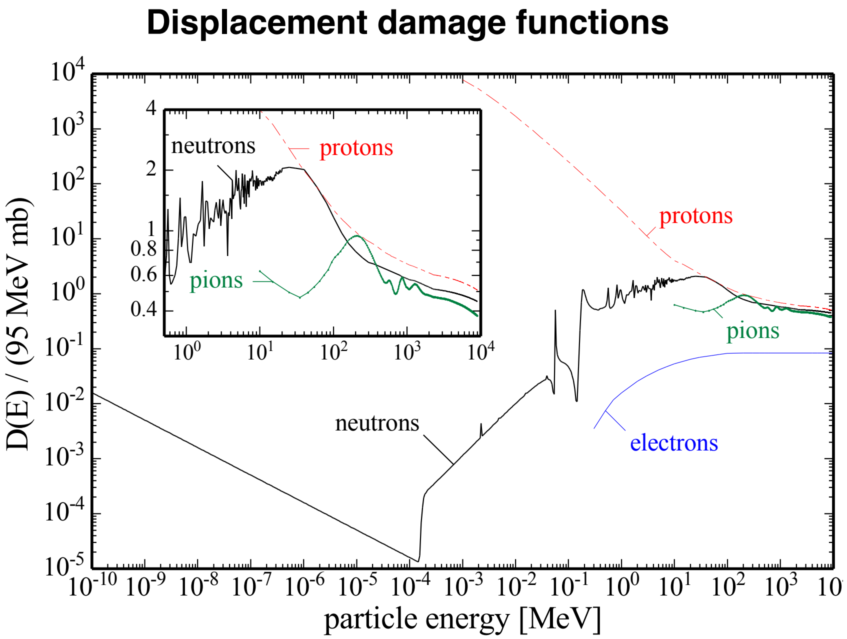
of a radiation field (or monoenergetic particle) with respect to 1 MeV neutrons

$$\kappa = \frac{1}{D(1MeV\ neutrons)} \bullet \frac{\int D(E)\,\phi(E)\,dE}{\int \phi(E)\,dE}$$

- **E** energy of particle
- **D(E)** displacement damage cross section for a certain particle at energy E
  D(1MeV neutrons)=95 MeV·mb
- **Φ(E)** energy spectrum of radiation field

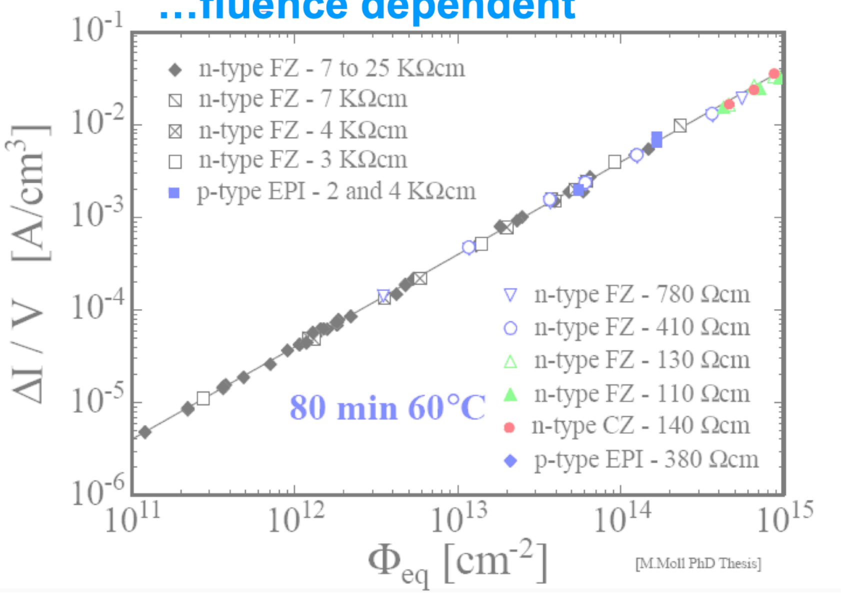
The integrals are evaluated for the interval [E_{MIN},E_{MAX}], being E_{MIN} and E_{MAX} the minimum and maximum cut-off energy values, respectively, and covering all particle types present in the radiation field

NIEL Hypothesis: damage parameters scale with NIEL
1 MeV neutron equivalent


Displacement damage functions

Sensor Properties after Irradiation - Leakage Current

…fluence dependent

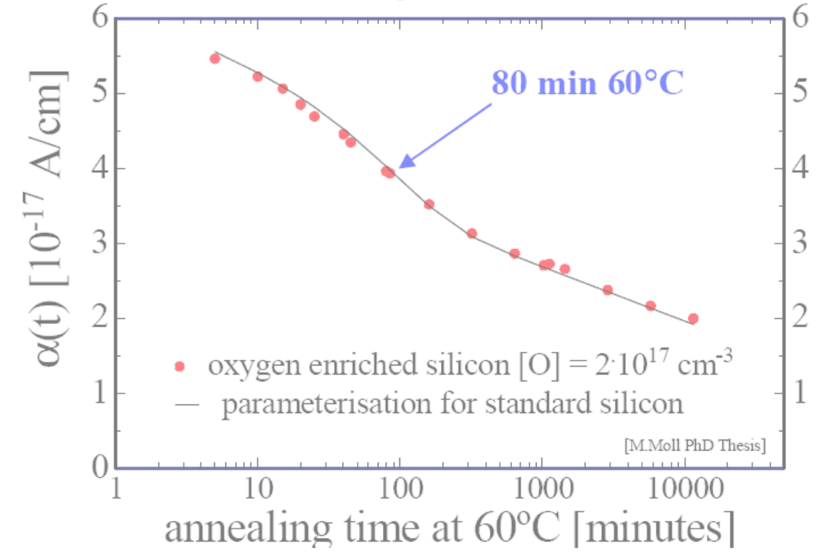


- independent of material
- independent of type of irradiation

- Damage parameter $\boxed{\alpha = \dfrac{\Delta I}{V \cdot \Phi_{eq}}}$

- strong temperature dependence $\boxed{I \propto \exp\left(-{}^{E_g}\!/_{2k_B T}\right)}$

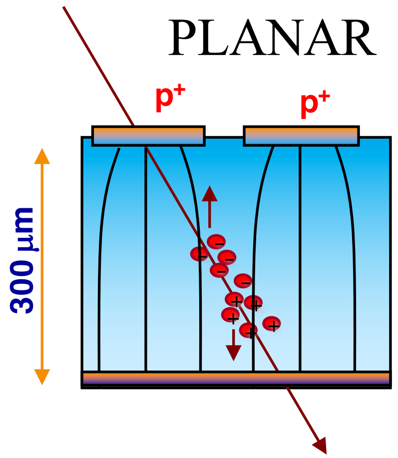
…annealing dependent

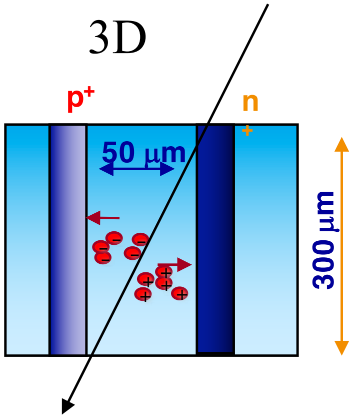


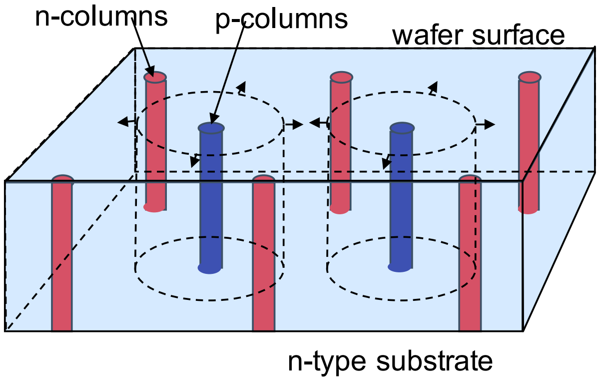
- current decreases with annealing

—> consider annealing
—> run cold

3d Sensor Concept







- 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 electrodes
- Very low depletion voltages
- Very fast, since charge carries travel shorter distances

- etch columns into silicon
- technology developed in the last years
- pixels and strips possible (connect columns of one row into strip)

- disadvantage:
  - geometrical efficiency highly dependant on particle incidence angle

- ATLAS IBL deployed 3d sensors in more forward (backward) region

Radiation Hardness - Comparison

Irradiation with Neutrons

- p-side readout: holes
- n-side readout: electrons

- electrons better than holes

- MCz better than FZ due to higher oxygen content

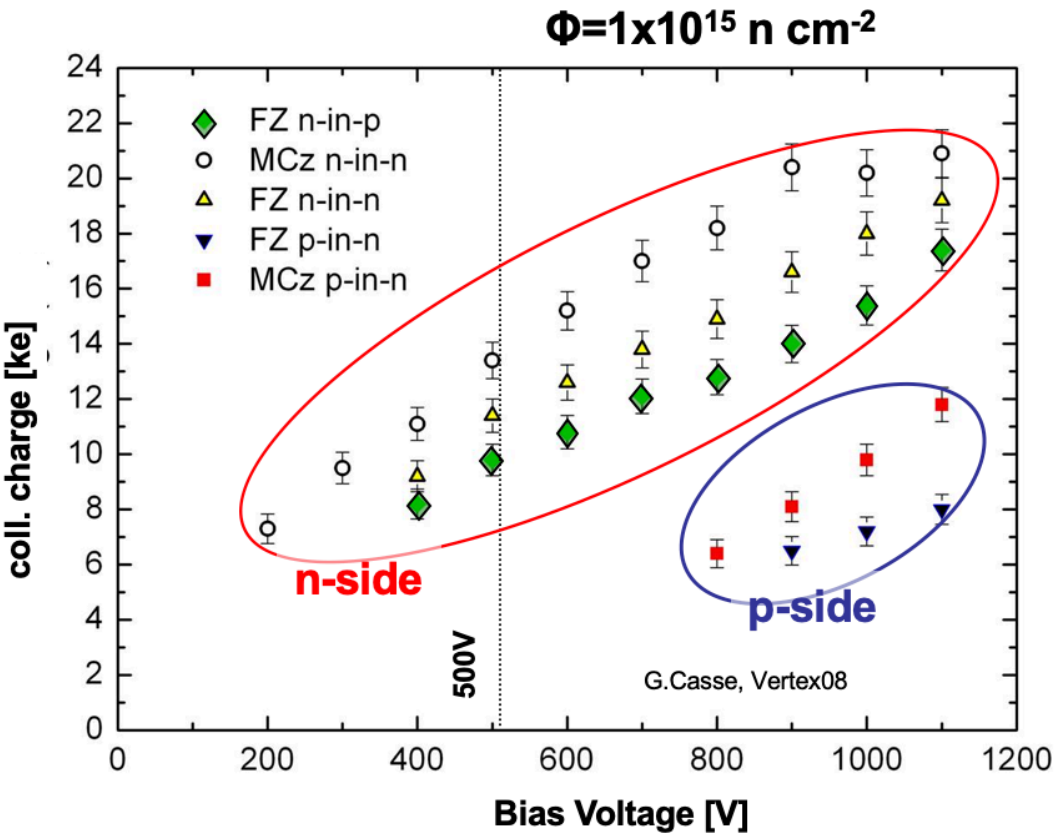
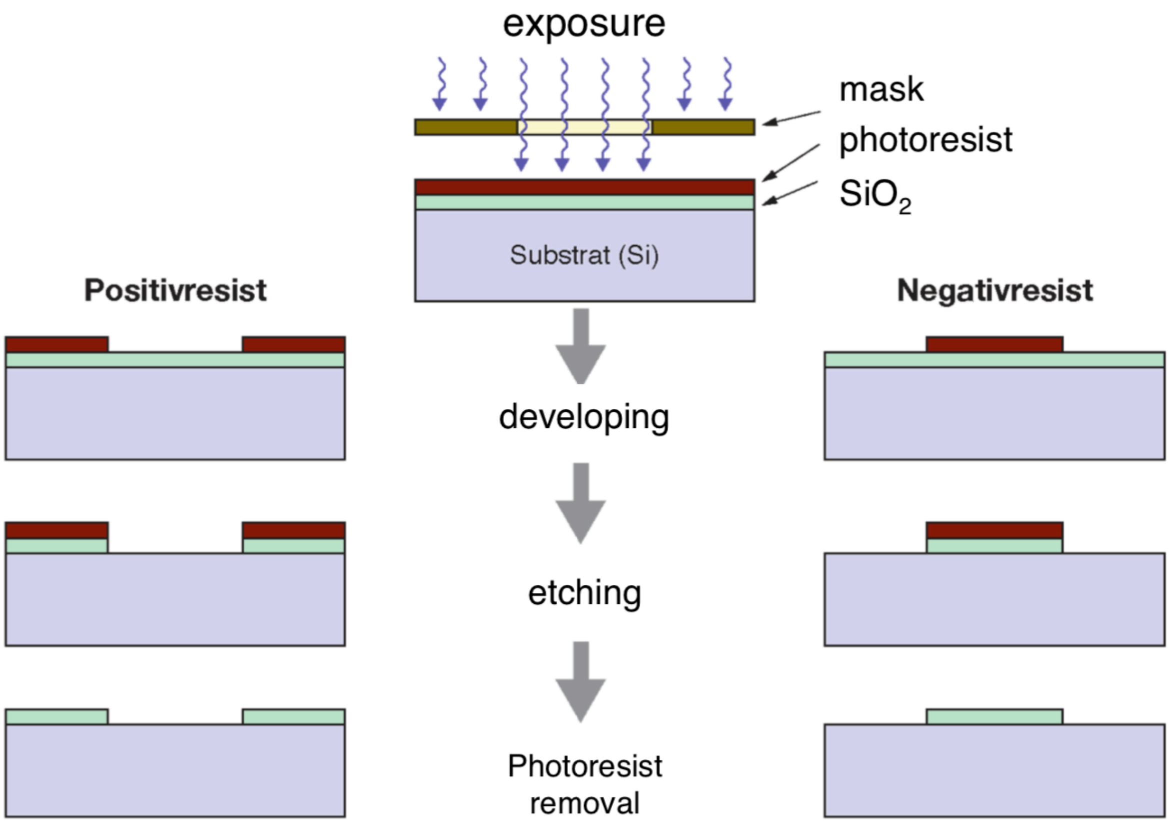


Photo-Lithography



Fermi distribution, Fermi levels

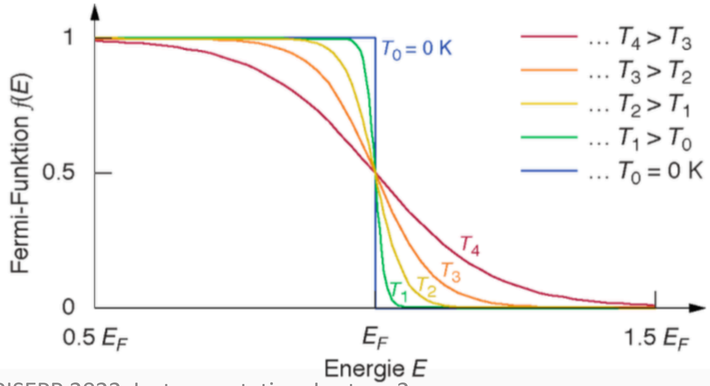
Fermi distribution $f(E)$ describes the **probability that an electronic state with energy E is occupied by an electron**.

$$f(E) = \frac{1}{1 + e^{\frac{E-E_F}{kT}}}$$

The **Fermi level E_F** is the energy at which the **probability of occupation is 50%.** For metals E_F is in the conduction band, for semiconductors and isolators E_F is in the band gap

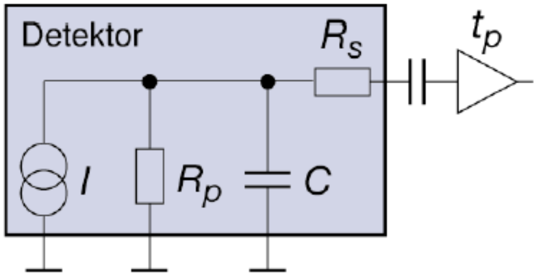
Fermi distribution function for different temperatures
$T_4 > T_3 > T_2 > T_1 > T_0 = 0$ K

$T_0 = 0$ K: saltus function



Noise

- The most important noise contributions are:
  - Leakage current (ENC_I)
  - Detector capacitance (ENC_C)
  - Detector parallel resistor (ENC_{Rp})
  - Detector series resistor (ENC_{Rs})



Equivalent circuit diagram of a silicon detector.

- The overall noise is the quadratic sum of all contributions:

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

Germanium:

- Used in nuclear physics
- Needs cooling due to small band gap of 0.66 eV (usually done with liquid nitrogen at 77 K)

Silicon:

- Can be operated at room temperature
- Synergies with micro electronics industry
- Standard material for vertex and tracking detectors in high energy physics

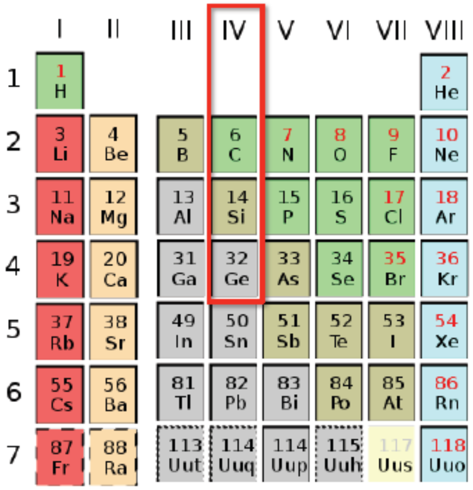
Diamond (CVD or single crystal):

- Allotrope of carbon
- Large band gap (requires no depletion zone)
- very radiation hard
- Disadvantages: low signal and high cost

Compound Semiconductors

- **Compound semiconductors consist of**
  - two (binary semiconductors) or
  - more than two

  atomic elements of the periodic table.



- **Depending on the column in the periodic system of elements one differentiates between**
  - IV-IV- (e.g. *SiGe*, *SiC*),
  - III-V- (e.g. *GaAs*)
  - 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.
  - GaP, GaSb, InP, InAs, InSb, InAlP
- **important II-VI compounds:**
  - ***CdTe***: High atomic numbers (48+52) hence very efficient to detect photons.
  - ZnS, ZnSe, ZnTe, CdS, CdSe, Cd1-xZnxTe, Cd1-xZnxSe

What we need

high resolution, high granularity

low material for minimal multiple scattering

high speed

low power consumption

radiation hardness