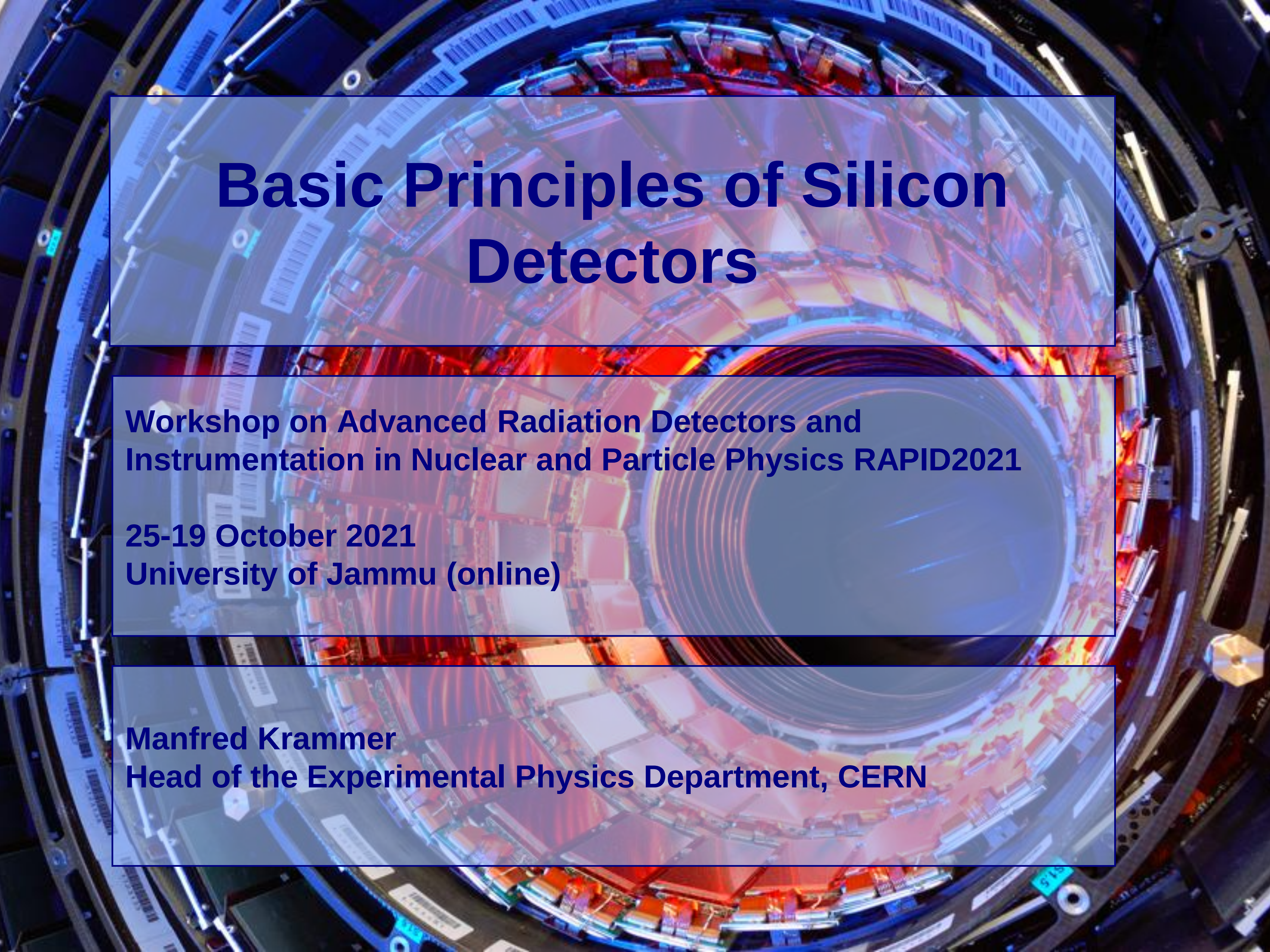

Basic Principles of Silicon Detectors

Workshop on Advanced Radiation Detectors and Instrumentation in Nuclear and Particle Physics RAPID2021

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University of Jammu (online)

Manfred Krammer
Head of the Experimental Physics Department, CERN

Content

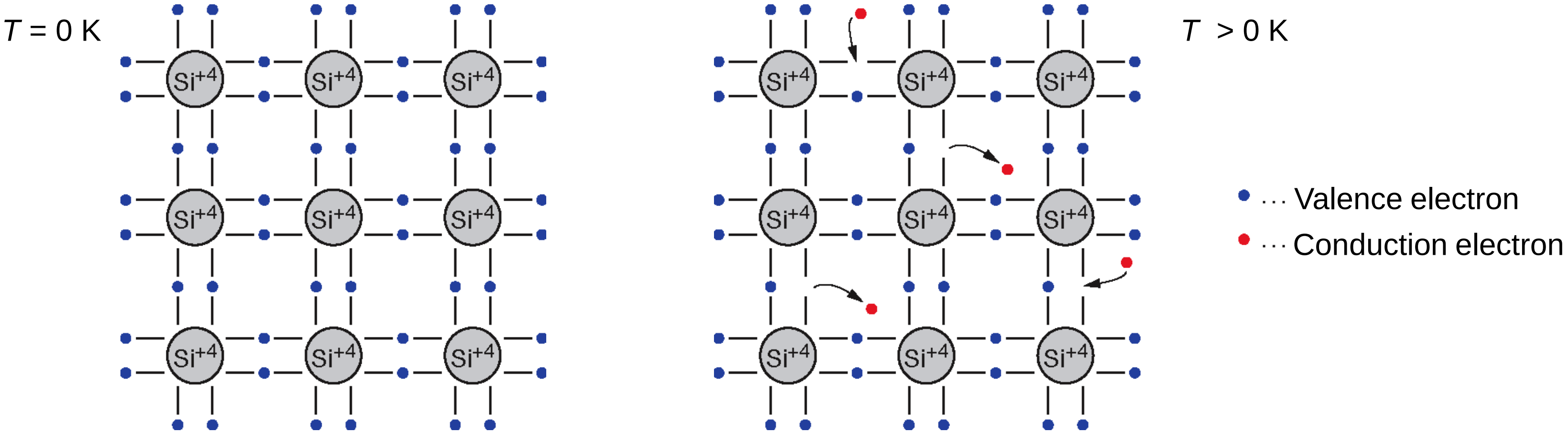
- Silicon as Sensor Material
- Radiation Effects
- Detector Structures

Silicon as Sensor Material

Material Properties

Bond model of semiconductors

Si is a column IV elemental semiconductor (2dim projection) :

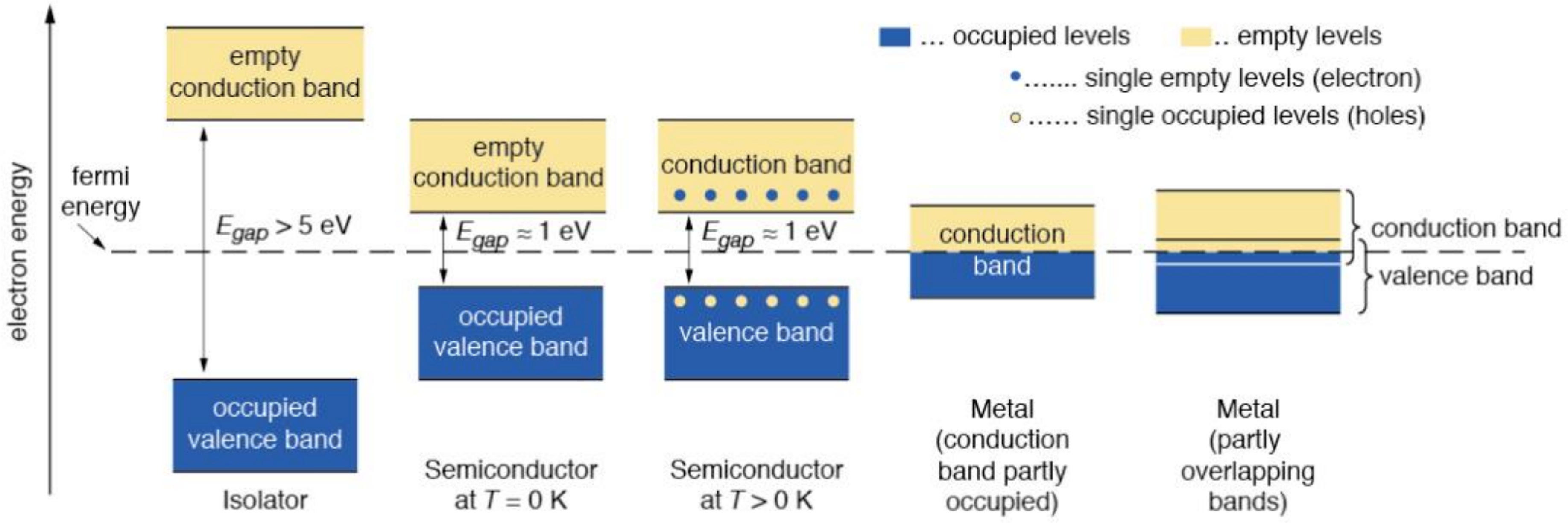


- Each atom has 4 closest neighbors, the 4 electrons in the outer shell are shared and form covalent bonds.
- At low temperature all electrons are bound
- At higher temperature thermal vibrations break some of the bonds → free e^- cause conductivity (electron conduction)
- The remaining open bonds attract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

Material Properties

Energy bands: isolator–semiconductor–metal

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).



Material Properties

Intrinsic carrier concentration

- ★ Due to the small band gap in semiconductors electrons already occupy the conduction band at room temperature. Silicon E_g=1.11 eV (T=300 K)

- ★ Electrons from the conduction band may recombine with holes.

- ★ A thermal equilibrium is reached between excitation and recombination
  Charged carrier concentartion $n_e = n_h = n_i$
  This is called intrinsic carrier concentration:

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

In ultrapure silicon at room temperature the intrinsic carrier concentration is $1.45 \cdot 10^{10}$ cm^{-3}.

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

Material Properties
Drift velocity and mobility

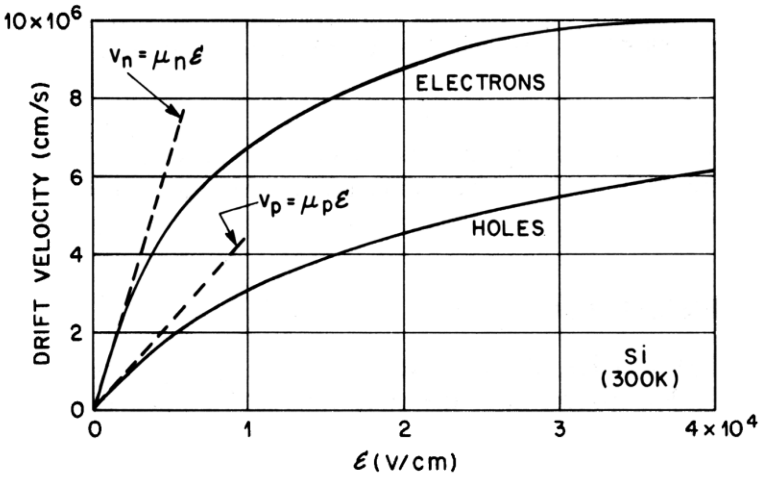
Drift velocity

For electrons: $\vec{v}_n = -\mu_n \cdot \vec{\mathrm{E}}$ and for holes: $\vec{v}_p = \mu_p \cdot \vec{\mathrm{E}}$

Mobility

For electrons: $\mu_n = \frac{e\,\tau_n}{m_n}$ and 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



e … electron charge

E … external electric field

m_n, m_p … effective mass of e$^-$ and holes

τ_n, τ_p … mean free time between collisions for e$^-$ and holes

Source: S.M. Sze, *Semiconductor Devices* , J. Wiley & Sons, 1985

Constructing a Detector

The ideal semiconductor detector

★ Charged particles penetrating or traversing the detector create electron-hole pairs. The electron-hole pairs are separated by an electric field and drift to the electrodes. This is the signal we are looking for.

★ 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

  → particles should produce many electron-holes → low ionization energy → small band gap

- Low noise

  → very few intrinsic charge carriers → large band gap

Constructing a Detector

Estimate SNR in an intrinsic silicon detector

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 (minimum ionizing particle) ***dE/dx* = 3.87 MeV/cm**

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

→ Signal of a mip in such a detector:

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

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

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

→ Number of thermal created e$^-$h$^+$-pairs is four orders of magnitude larger than signal!!!

Need to reduce noise, remove intrinsic charge carrier!

→ Depletion zone in reverse biased **pn junction**

Doping

pn junction needs doped materials

A pn junction consists of n and p doped substrates:

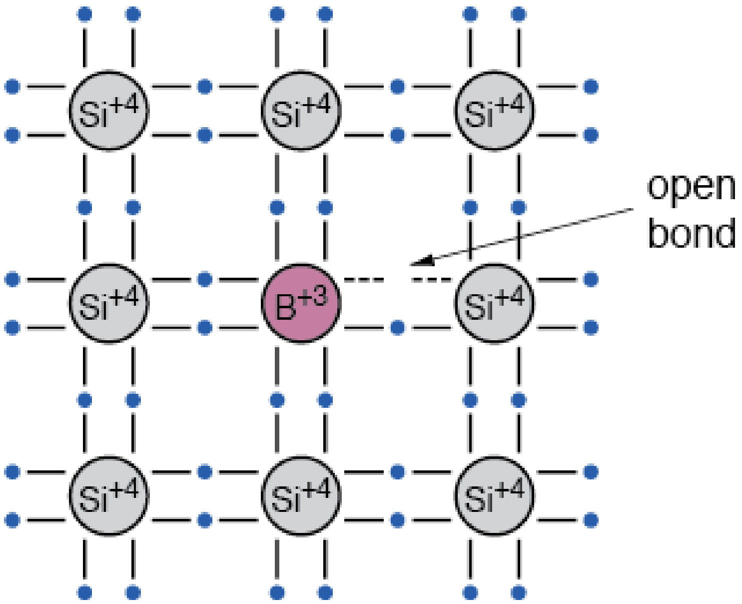
- Doping is the replacement of a small number of atoms in the lattice by atoms of neighboring columns from the atomic table (with one valence electron more or less compared to the basic material). Typical doping concentrations for Si detectors are ≈10^{12} atoms/cm^3 (10^{14} und 10^{18} atoms/cm^3 for CMOS elements).
- These doping atoms create energy levels within the band gap and therefore alter the conductivity.
- An undoped semiconductor is called an intrinsic semiconductor
- A doped semiconductor is called an extrinsic semiconductor.
- In an intrinsic semiconductor for each conduction electron there exists the corresponding hole. In extrinsic semiconductors there is a surplus of electrons or holes.

Doping

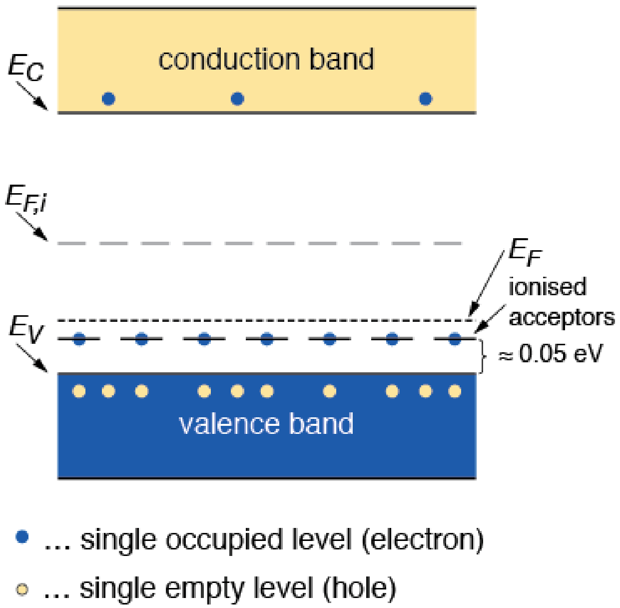
Bond model: p-doping in Si

Doping with an element 3 atom (e.g. B, Al, Ga, In). One valence bond remains open. This open bond attracts electrons from the neighbor atoms.

The doping atom is called acceptor.



- The energy level of the acceptor is 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.

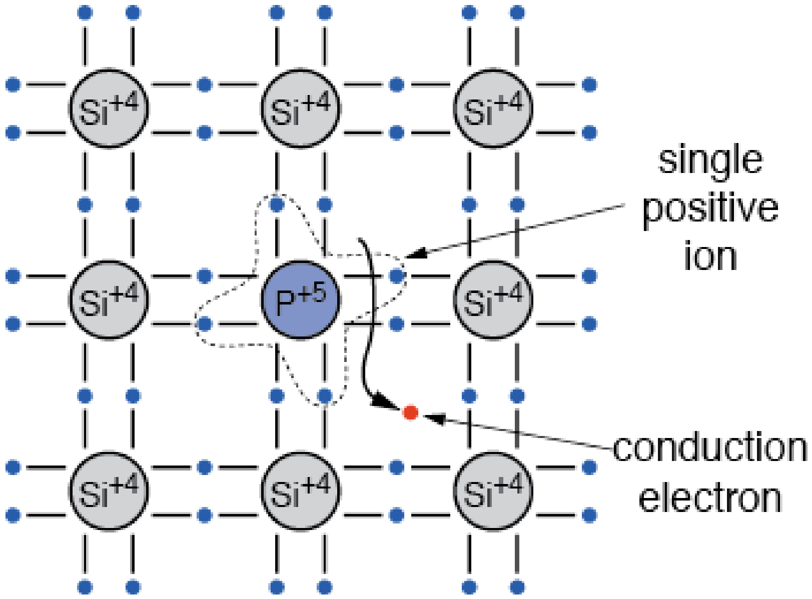


Doping

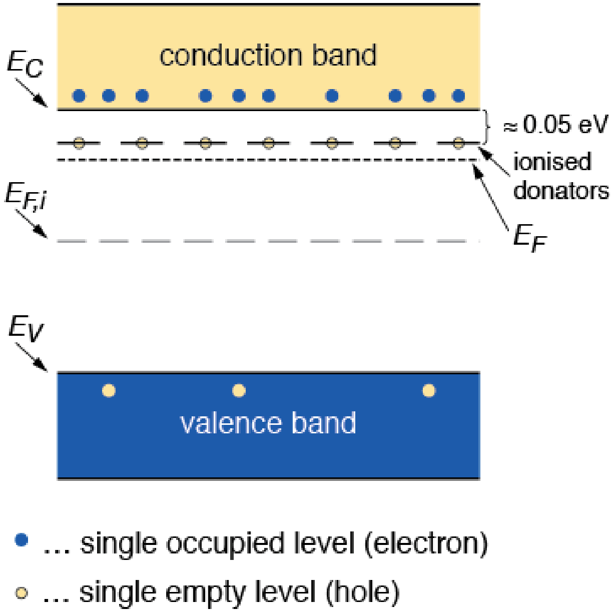
Bond model: n-doping in Si

Doping with an element 5 atom (e.g. P, As, Sb)
The 5th valence electrons is weakly bound.

The doping atom is called donor



- The energy level of the donor is 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.

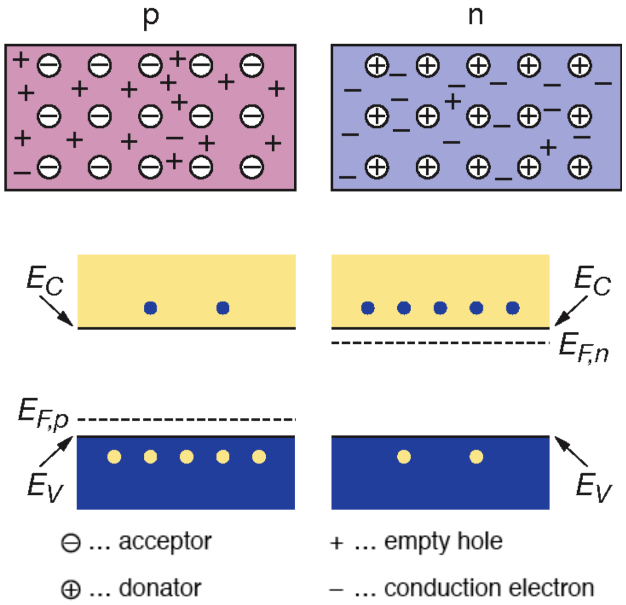


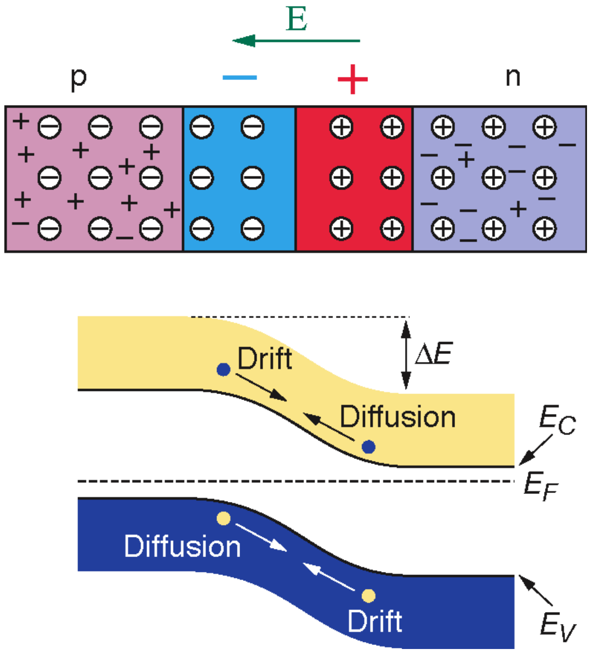
The p-n Junction

Creating a p-n junction

At the interface of an n-type and p-type semiconductor the difference in the fermi levels cause diffusion of surplus 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 and an electric field stopping further diffusion.

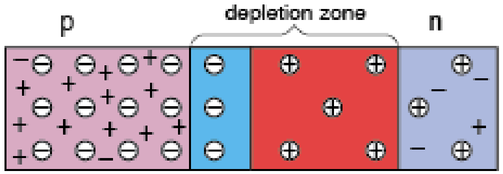
The stable space charge region is free of charge carries and is called the depletion zone.



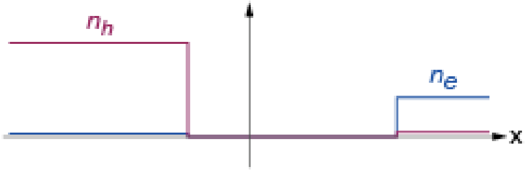


The p-n Junction
Electrical characteristics

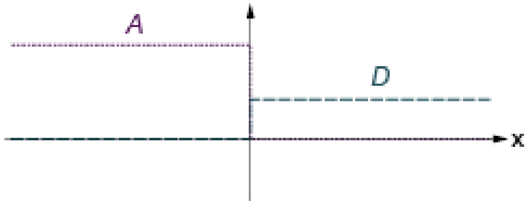
pn junction scheme



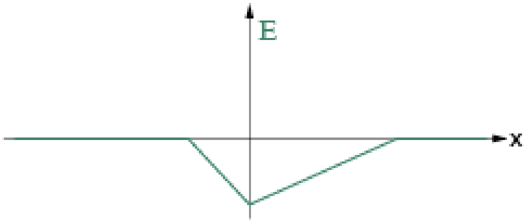
concentration of free charge carriers



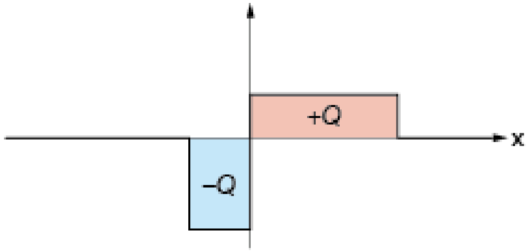
acceptor and donator concentration



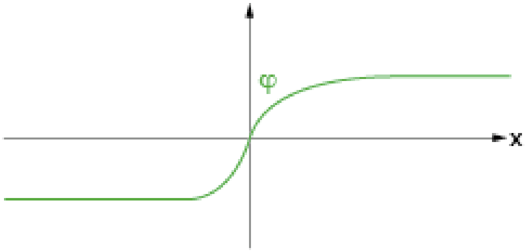
electric field



space charge density



electric potential



⊖ … acceptor

+ … empty hole

⊕ … donator

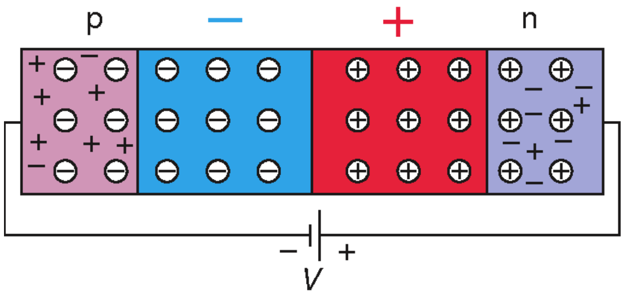
− … conduction electron

The p-n Junction

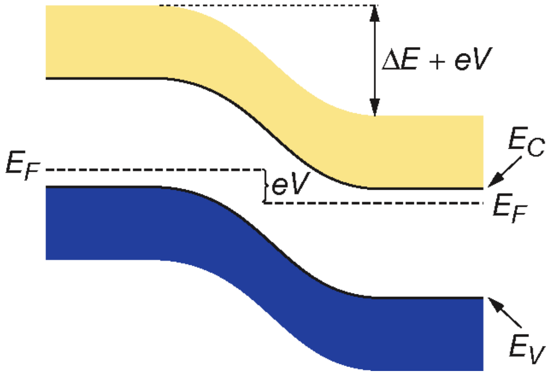
Operation with reverse bias

Applying an external voltage V with the cathode to p and the anode to n e- and holes are pulled out of the depletion zone. The depletion zone becomes larger.

p-n junction with reverse bias



The potential barrier becomes higher by *eV* and diffusion across the junction is suppressed. The current across the junction is very small "leakage current".



→ That's the way we operate our semiconductor detector!

The p-n Junction

Width of the depletion zone

Example of a typical p$^+$-n junction in a silicon detector:

Effective doping concentration $N_a = 10^{15}$ cm^{-3} in p+ region and $N_d = 10^{12}$ cm^{-3} in n bulk.

Without external voltage:

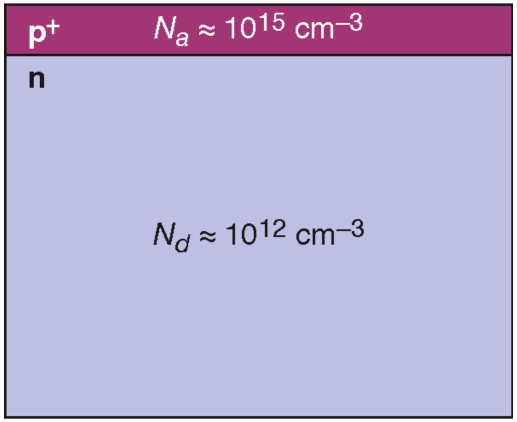
$$W_p = 0.02\ \mu\text{m}$$

$$W_n = 23\ \mu\text{m}$$

Applying a reverse bias voltage of 100 V:

$$W_p = 0.4\ \mu\text{m}$$

$$W_n = 363\ \mu\text{m}$$



p$^+$n junction

Width of depletion zone in n bulk:

$$\boxed{W \approx \sqrt{2\varepsilon_0\varepsilon_r\mu\rho|V|}} \quad \text{with} \quad \rho = \frac{1}{e\mu N_{eff}}$$

V … External voltage
ρ … specific resistivity
μ … mobility of majority charge carriers
N_{eff} … effective doping concentration

n-type and p-type Detectors

Note:

The previous slide explains an n-type detector (detector bulk is n-type silicon)

Using p-type silicon and exchanging p^+ and n^+ gives a perfectly working p-type detector.

For tradition and production reasons most detectors used in the past are n-type detectors. Future detectors, e.g. for LHC upgrades will employ p-type detectors due to advantages in high radiation environment.

For simplicity I will continue discussing n-type detectors only.

Detector Characteristics

Capacitance and Depletion Voltage of a detector

The depletion voltage is the minimum voltage at which the bulk of the sensor is fully depleted. The operating voltage is usually chosen to be slightly higher (overdepletion).

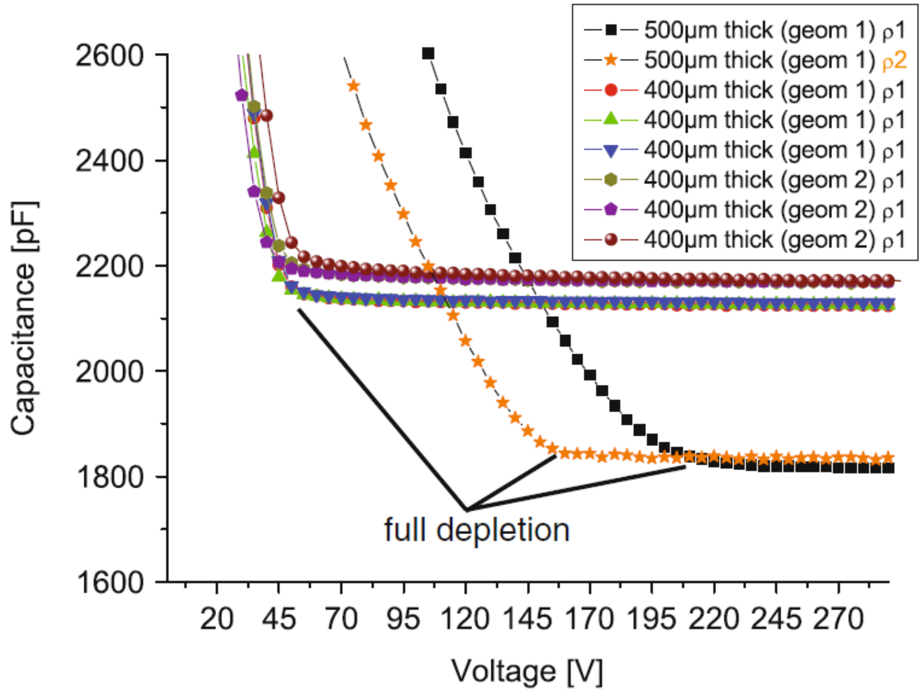
High resistivity material (i.e. low doping) requires low depletion voltage.

$$V_{FD} = \frac{D^2}{2\varepsilon\mu\rho}$$

For a typical Si p-n junction ($N_a >> N_d >> n_i$) the detector capacitance is given as:

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

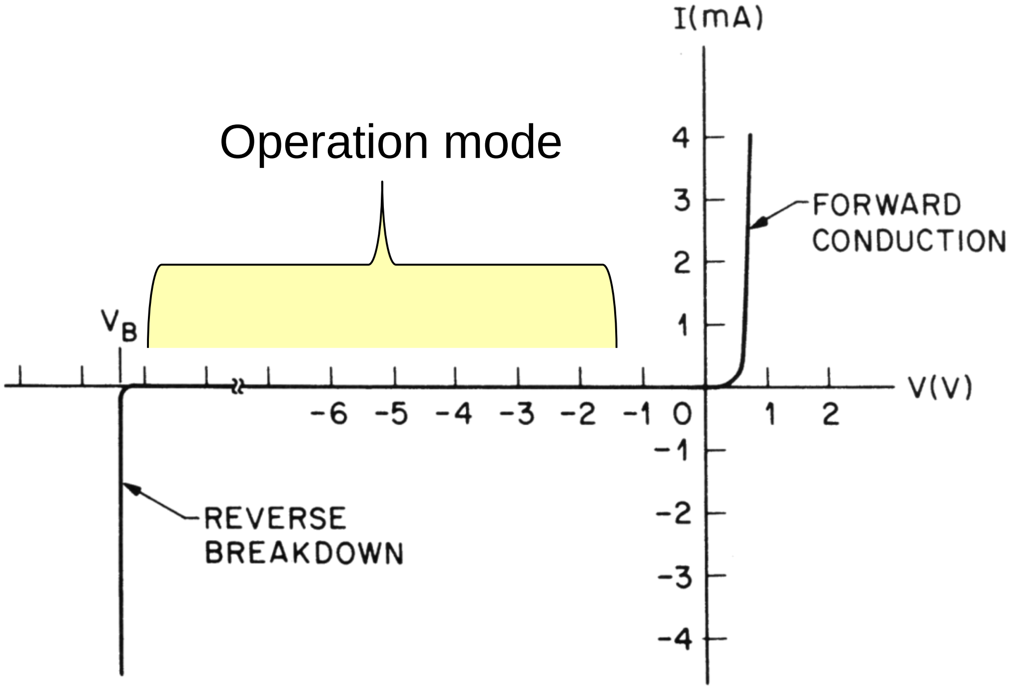
ρ … specific resistivity of the bulk
μ … mobility of majority charge carrier
V … bias voltage
A … detector surface
D … detector thickness



The p-n Junction

Current-voltage characteristics

Typical current-voltage of a p-n junction (diode): exponential current increase in forward bias, small saturation in reverse bias.



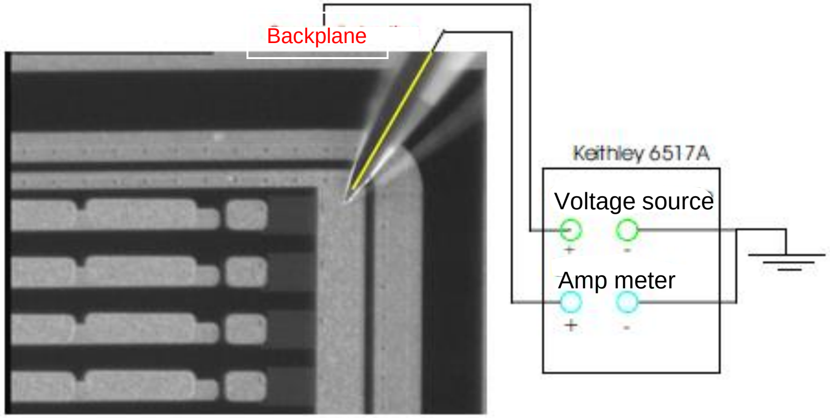
Operation mode

S.M. Sze, *Semiconductor Devices* , J. Wiley & Sons, 1985

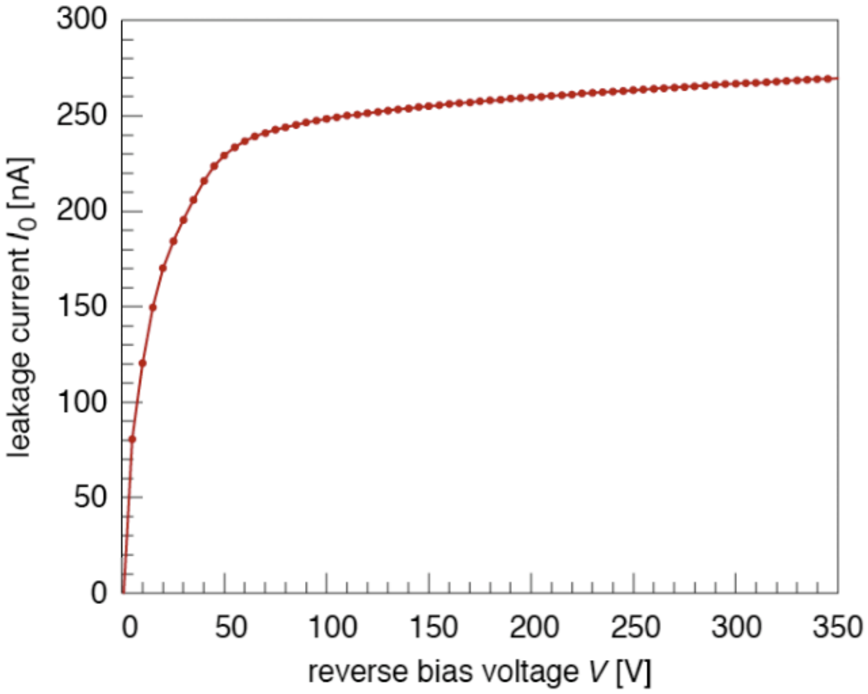
Detector Characteristics

Leakage Current

A silicon detector is operated with reverse bias, hence reverse saturation current is relevant (leakage current). This current is dominated by thermally generated e^-h^+ pair. Due to the applied electric field they cannot recombine and are separated. The drift of the e^- and h^+ to the electrodes causes the leakage current.



Measured detector leakage current, CMS strip detector (measurement at room temperature):



Radiation Effects

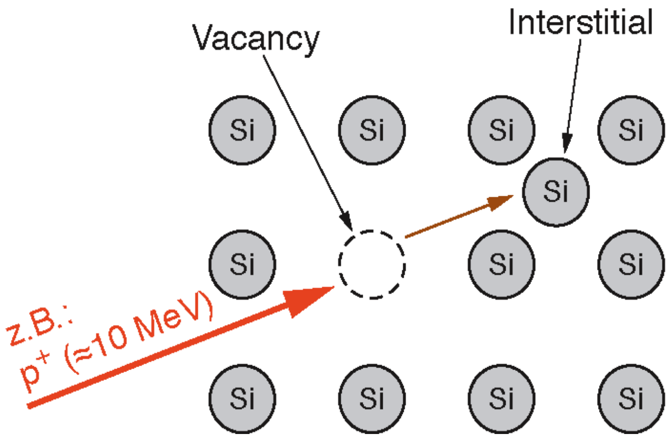
Radiation damage

Point defects

Simplest defects introduced by radiation: Point defects

- A displaced silicon atom produces an empty space in the lattice (Vacancy, V) and in another place an atom in an inter lattice space (Interstitial, I).

  A vacancy-interstitial pair is called a Frenkel-defect.



Frenkel-defect

- At room temperature these defects are mobile within the lattice.
  An interstitial atom may drop into a vacancy and both defects disappear → the defects anneal.
  Other defects form stabile secondary defects.

Many other types of defects possible, including those involving dopants, etc.

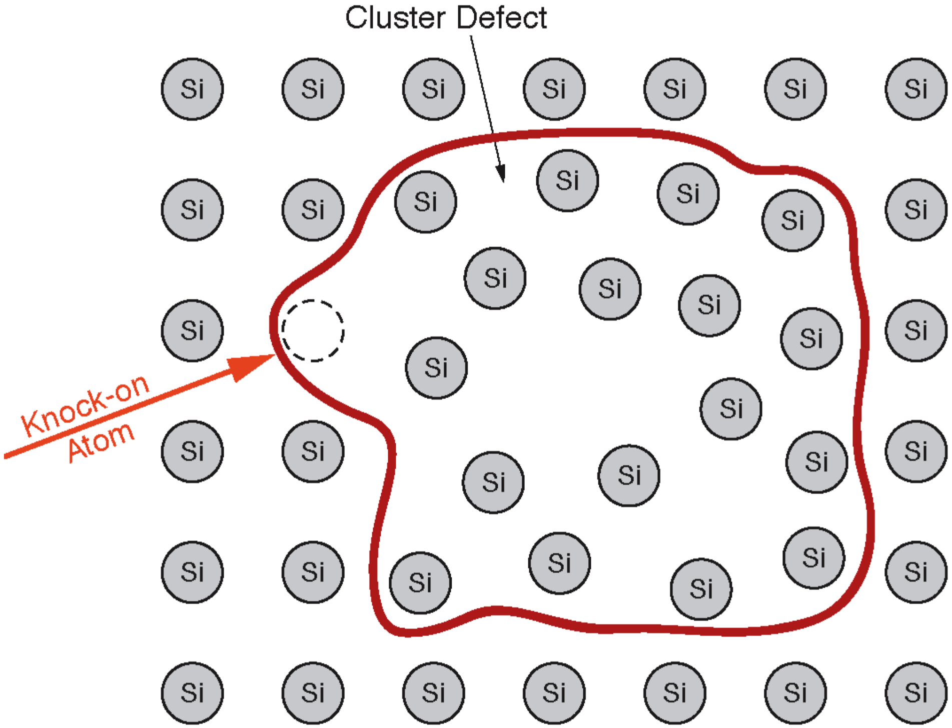
Radiation damage

Cluster defects

- In hard impacts the primary knock-on atom displaces additional atoms. These defects are called cluster defects.

- The size of a cluster defect is approximately 5 nm and consists of about 100 dislocated atoms.

- For high energy PKA cluster defects appear at the end of the track when the atom looses the kinetic energy and the elastic cross section increases.



Cluster defect

Radiation damage

Consequences for the detector

- Defects in the semiconductor lattice create energy levels in the band gap between valence and conduction band (see section on doping).
- Depending on the position of these energy levels the following effects will occur:

1. Modification of the effective doping concentration

   → shift of the value of the depletion voltage.

   This effect is caused by shallow energy levels (close to the band edges).

2. Trapping of charge carriers

   → reduced lifetime of charge carriers

   Mainly caused by deep energy levels.

3. Easier thermal excitement of e^- and h^+

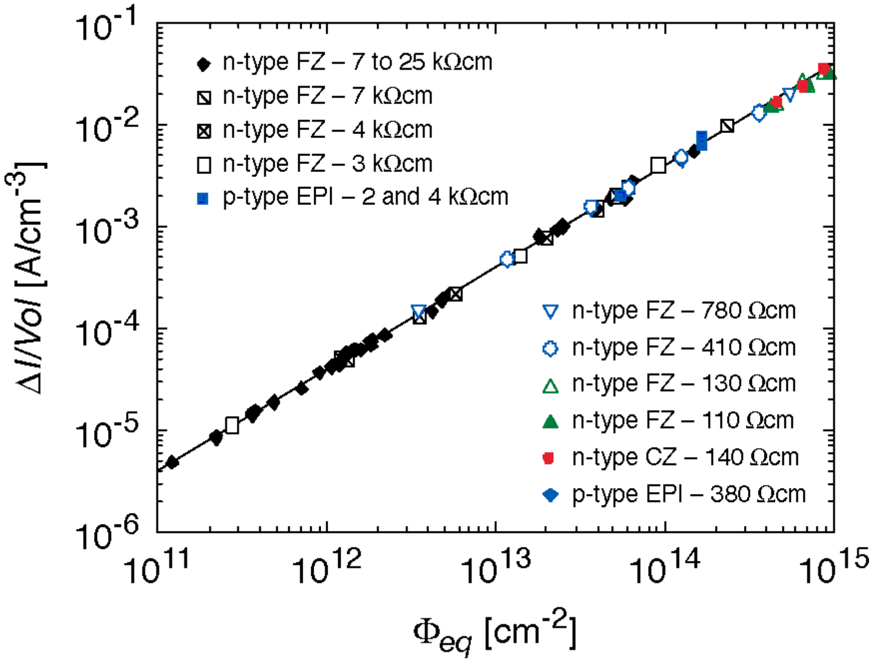
   → increase of the leakage current

   Responsible are mainly levels in the middle of the band gap.

Radiation damage

Leakage current – measurements

Increase of leakage current as function of irradiation fluence (different materials). Measurement after 80 minute annealing time at 60° C. The linear increase equals to $\alpha \approx 4\cdot10^{-17}$ A/cm.



M. Moll, *Radiation Damage in Silicon Particle Detectors*, PhD-Thesis (1999)

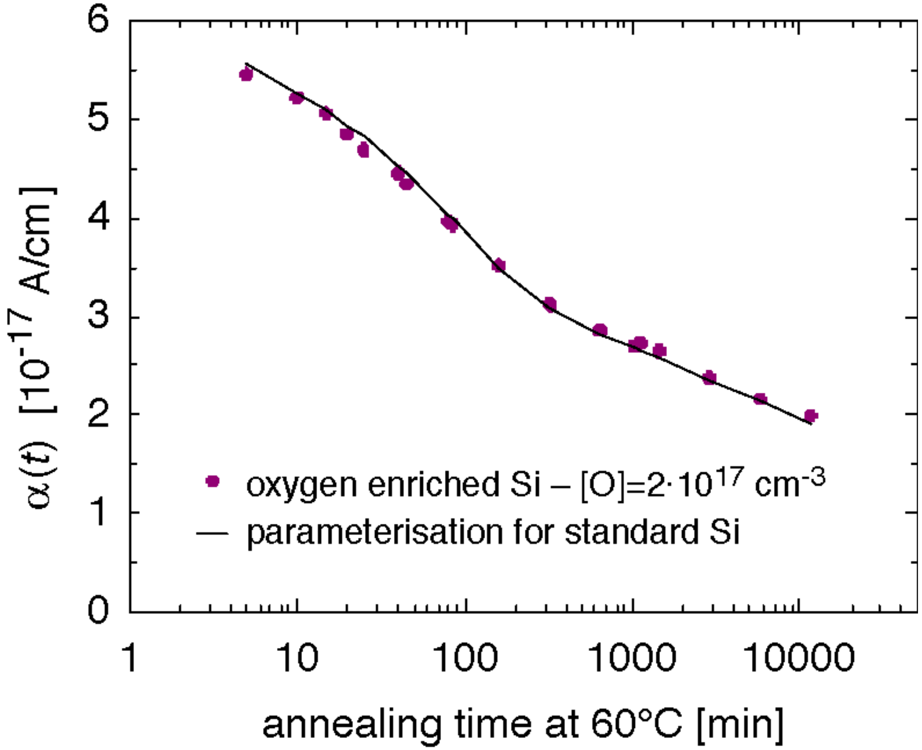
In ten years of LHC operation the currents of the innermost layers increase by 3 orders of magnitude!

Radiation damage

Leakage current – annealing

The damage rate α is time dependent.

The plot shows the development of α for a detector stored at T = 60° C after irradiation:



G. Lindström, *Radiation Damage in Silicon Detectors*, Nucl. Instr. Meth. A **512**, 30 (2003)

Radiation damage

Change of effective doping concentration - 1

- The irradiation produces mainly acceptor like defects and removes donor type defects. In a n type silicon the effective doping concentration N_{eff} decreases and after a point called type inversion (n type Si becomes p type Si) increases again.

- The voltage needed to fully deplete the detector V_{FD} is directly related to the effective doping concentration:

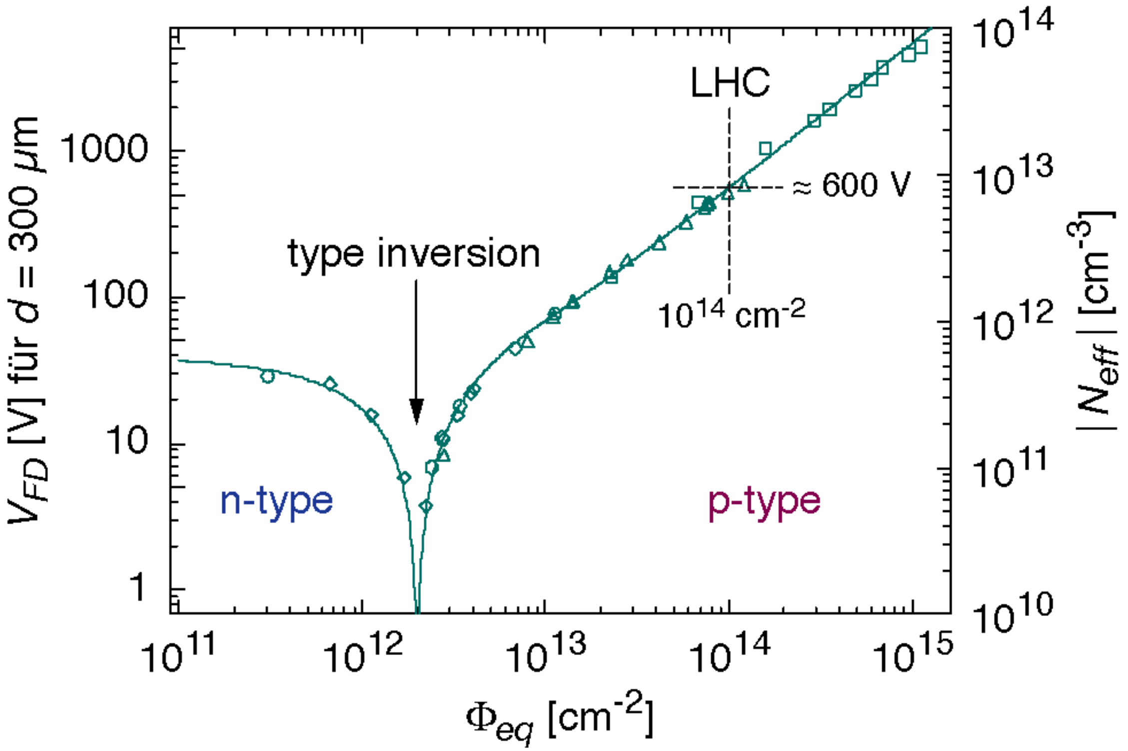
$$\boxed{V_{FD} \approx \frac{e}{2\varepsilon_0\varepsilon_r}\left|N_{eff}\right| d^2}$$

→ The depletion voltage and consequently the minimum operation voltage decreases, and after the inversion point increases again.

Radiation damage

Change of effective doping concentration - 2

Full depletion voltage and effective doping concentration) of an originally n type silicon detector as a function of the fluence Φ_{eq}:

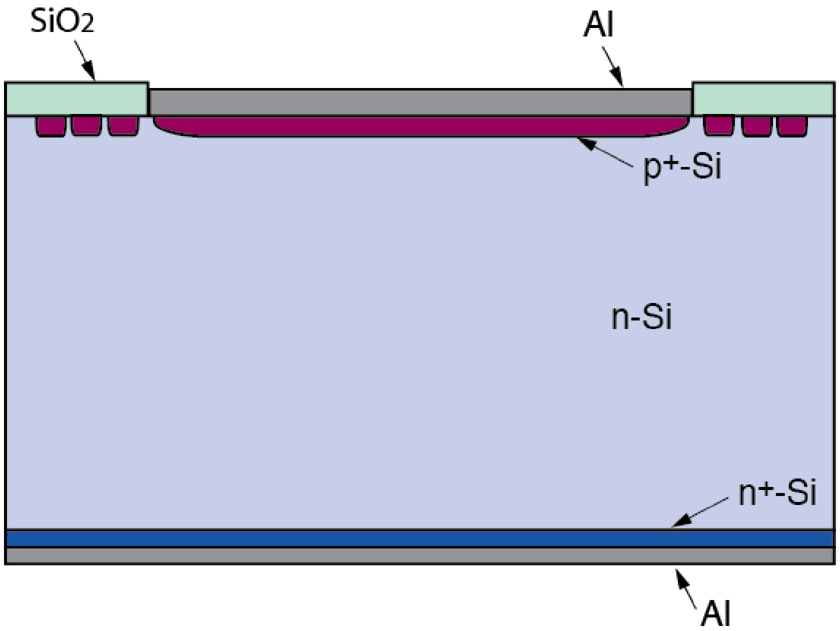


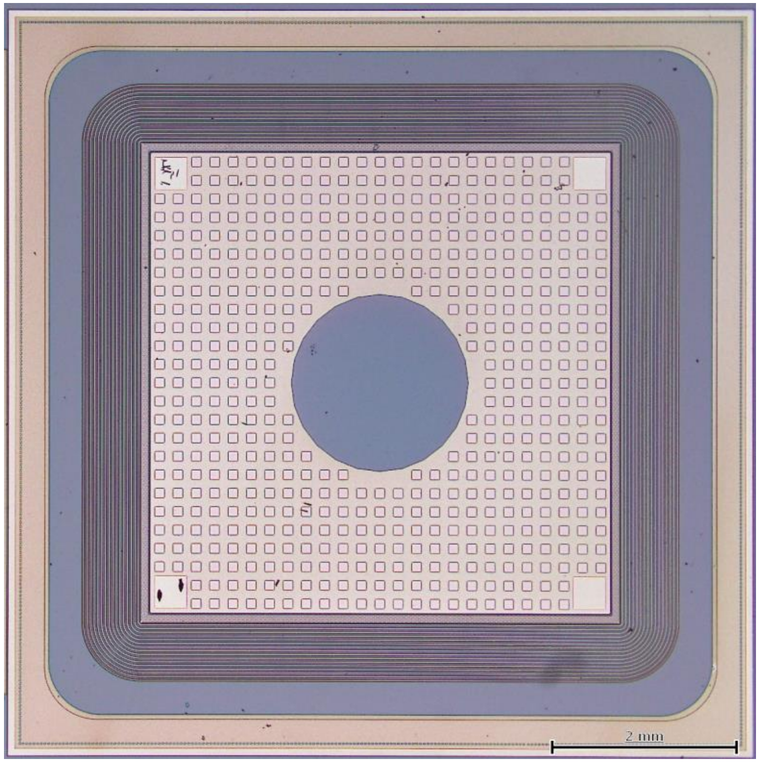
G. Lindström, *Radiation Damage in Silicon Detectors*, Nucl. Instr. Meth. A **512**, 30 (2003)

Detector Structures

Pad Detector

The most simple detector is a large surface diode with guard ring(s).





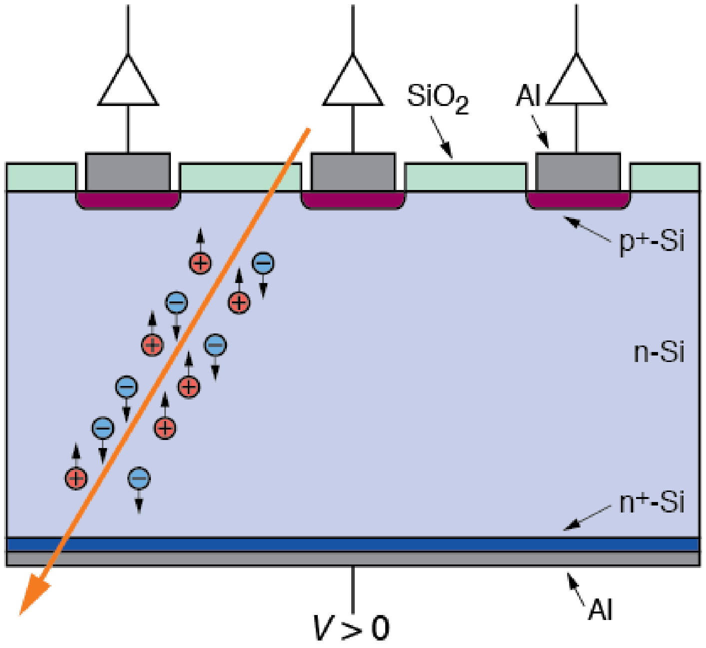
Microstrip Detector

DC coupled strip detector

Traversing charged particles create e^-h^+ pairs in the depletion zone (about 30.000 pairs in standard detector thickness). These charges drift to the electrodes. The drift (current) creates the signal which is amplified by an amplifier connected to each strip. From the signals on the individual strips the position of the through going particle is deduced.

A typical n-type Si strip detector:

- p^+n junction:
  $N_a \approx 10^{15}\ \text{cm}^{-3}$, $N_d \approx 1\text{–}5\cdot10^{12}\ \text{cm}^{-3}$
- n-type bulk: $\rho > 2\ \text{k}\Omega\text{cm}$
  → thickness 300 µm
- Operating voltage < 200 V.
- n^+ layer on backplane to improve ohmic contact
- Aluminum metallization



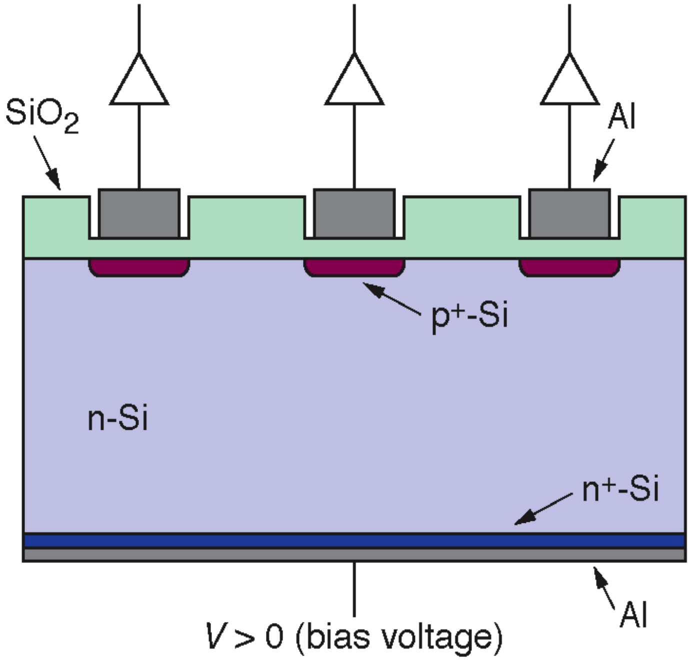
Microstrip Detector

AC coupled strip detector

AC coupling blocks leakage current from the amplifier.

- Integration of coupling capacitances in standard planar process.
- Deposition of SiO_2 with a thickness of 100–200 nm between p+ and aluminum strip
- Depending on oxide thickness and strip width the capacitances are in the range of 8–32 pF/cm.
- Problems are shorts through the dielectric (pinholes). Usually avoided by a second layer of Si_3N_4.

AC coupled strip detector:

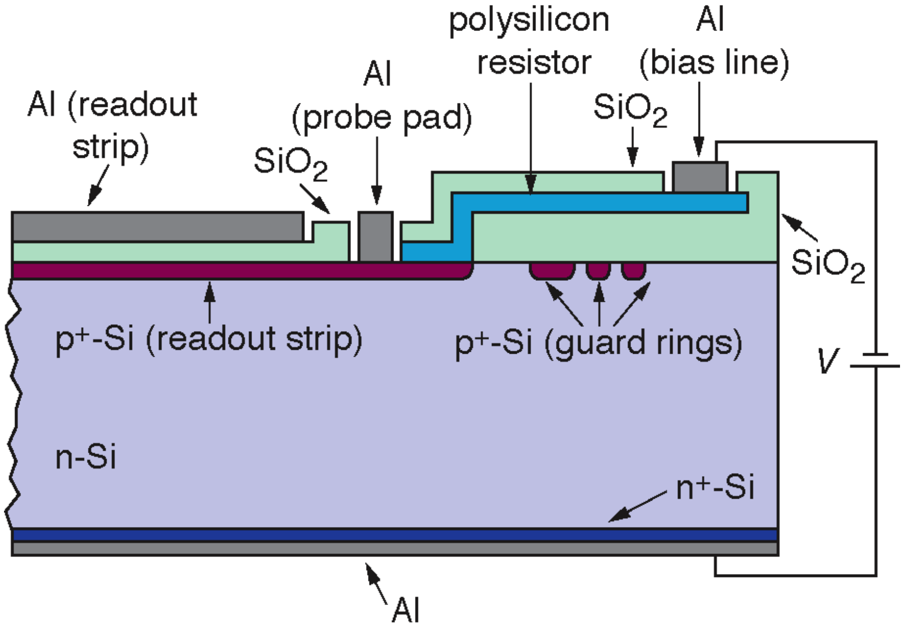


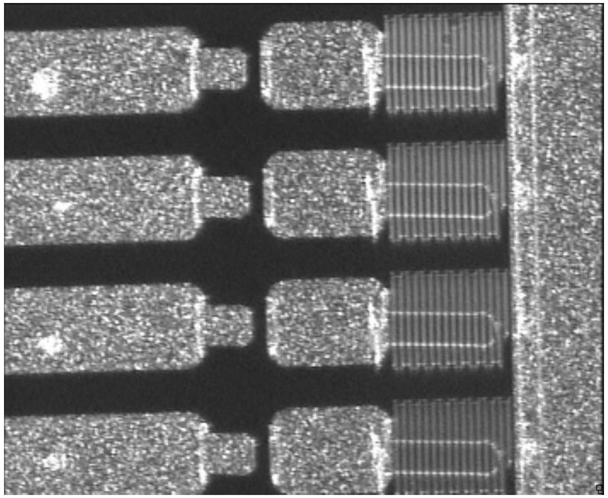
Several methods to connect the bias voltage: polysilicon resistor, punch through bias, FOXFET bias.

Microstrip Detector

Polysilicon bias resistor

- Deposition of polycristalline silicon between p^+ implants and a common bias line.
- Sheet resistance of up to $R_s \approx 250\ \mathrm{k\Omega}/\square$. Depending on width and length a resistor of up to $R \approx 20\ \mathrm{M\Omega}$ is achieved ($R = R_s \cdot length/width$).
- To achieve high resistor values winding poly structures are deposited.





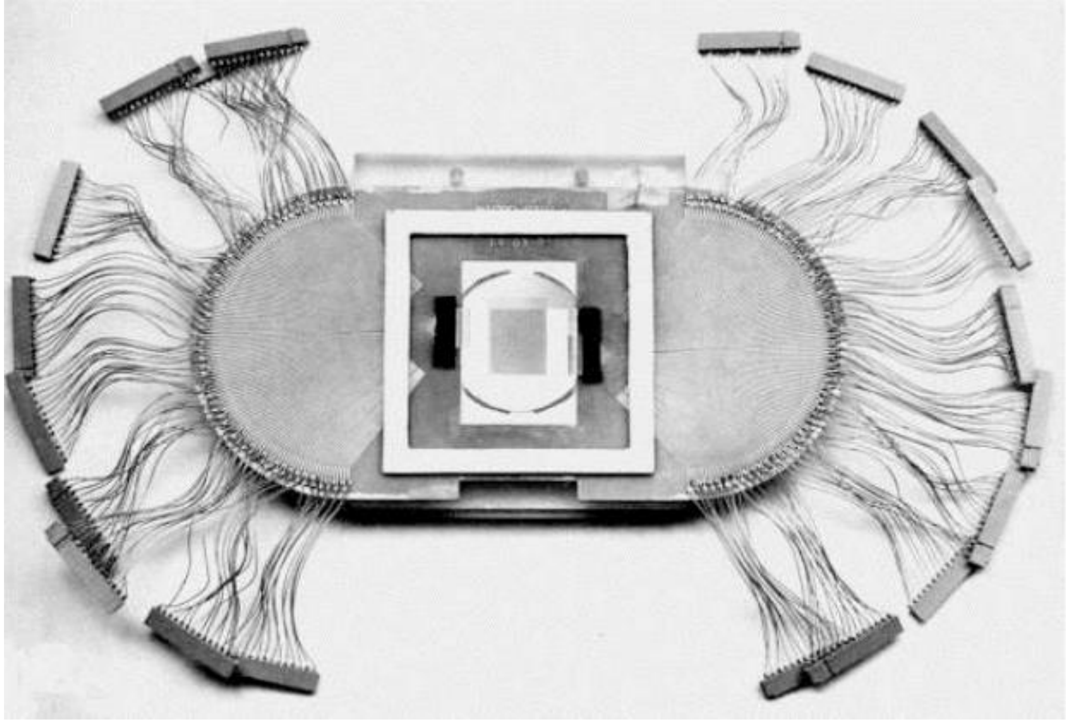
Cut through an AC coupled strip detector with integrated poly resistors:

First Silicon Strip Detector in HEP

The NA11 silicon detector 1983

Experiments NA11/NA32 at CERN

Goal: Measure lifetime and mass of the charm mesons D^0, D^-, D^+, D^+_s, D^-_s



NIM205 (1983) 99

Surface 24 cm^2 (2” wafer)
1200 strip, 20 µm pitch
Ever $3^{rd}/6^{th}$ strip connected.
Precision 4,5 µm !

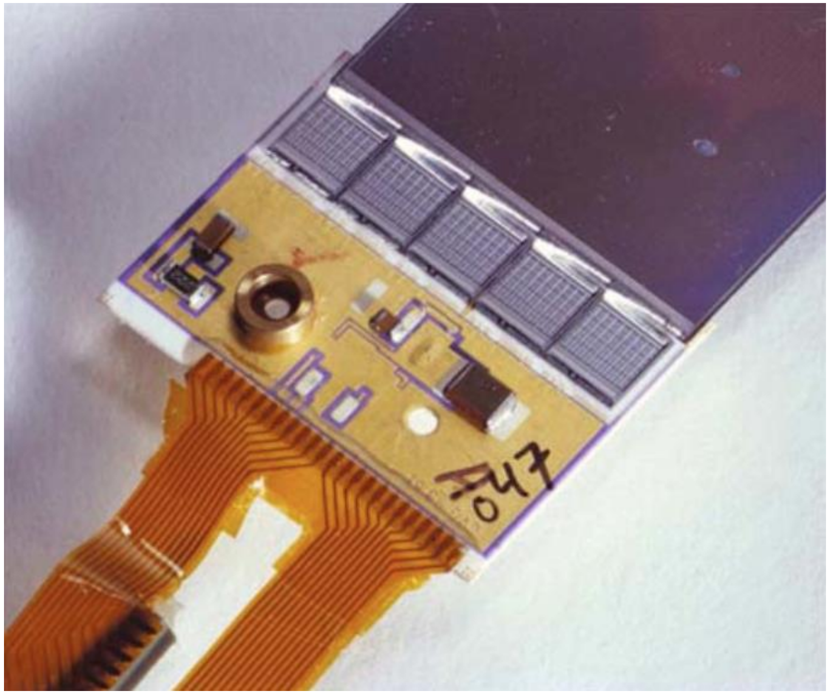
8 silicon detectors
(2 in front, 6 behind the Target)

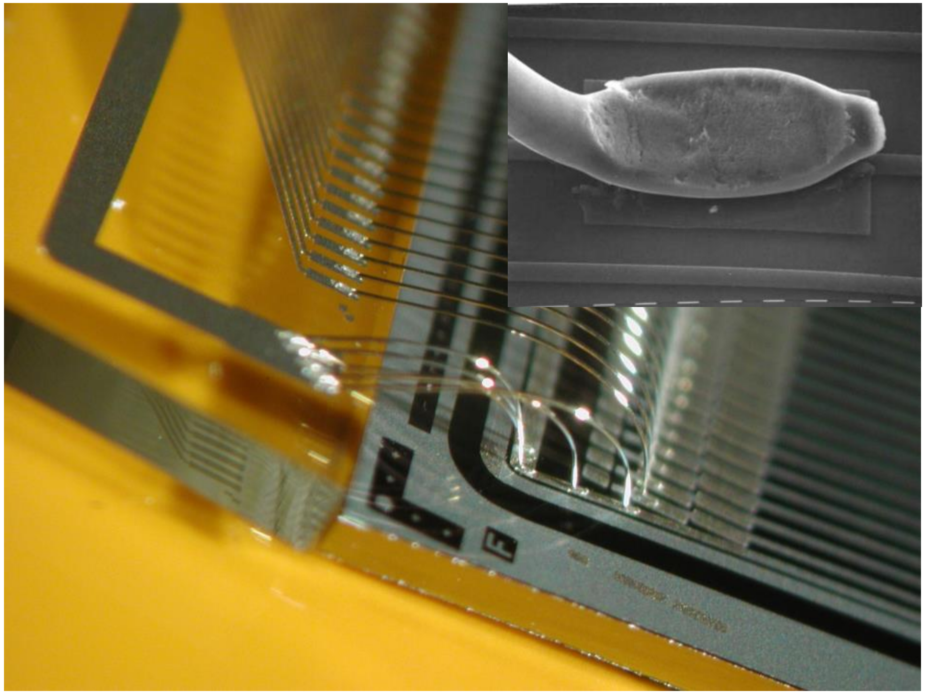
Ratio detector surface to nearby electronics surface 1:300 !

Towards Complex Detectors

Progress in electronics integration

- Development of costume designed VLSI chips with up to 128 readout channels. Chips containing preamplifier, shaper, pipeline, multiplexer, etc.
- Connection to the strips on the sensors using thin pitch wire bonding

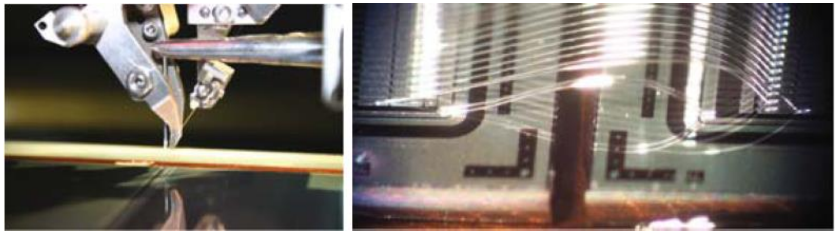


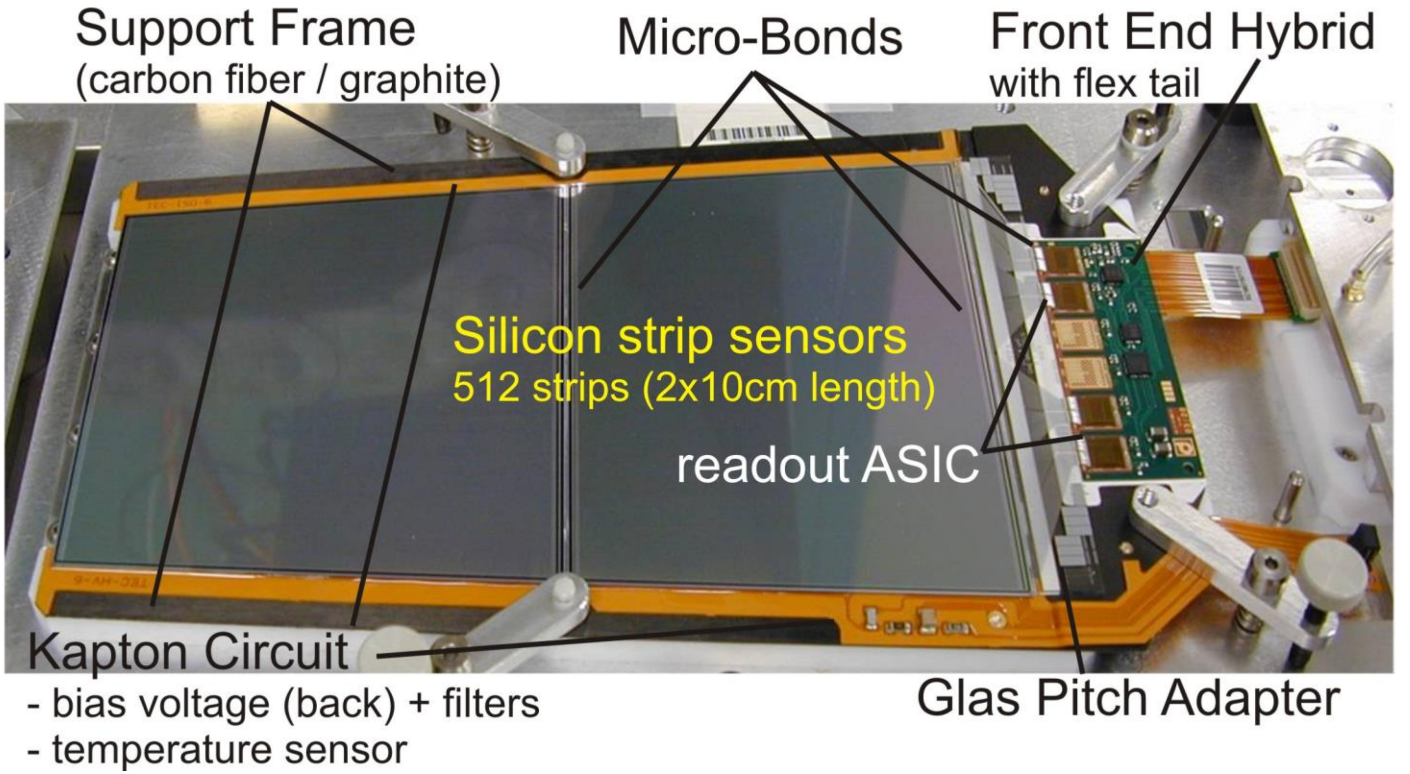


Detail from the DELPHI Vertex detector

Strip Sensor to Detectors Module

Details from a CMS Si Module:

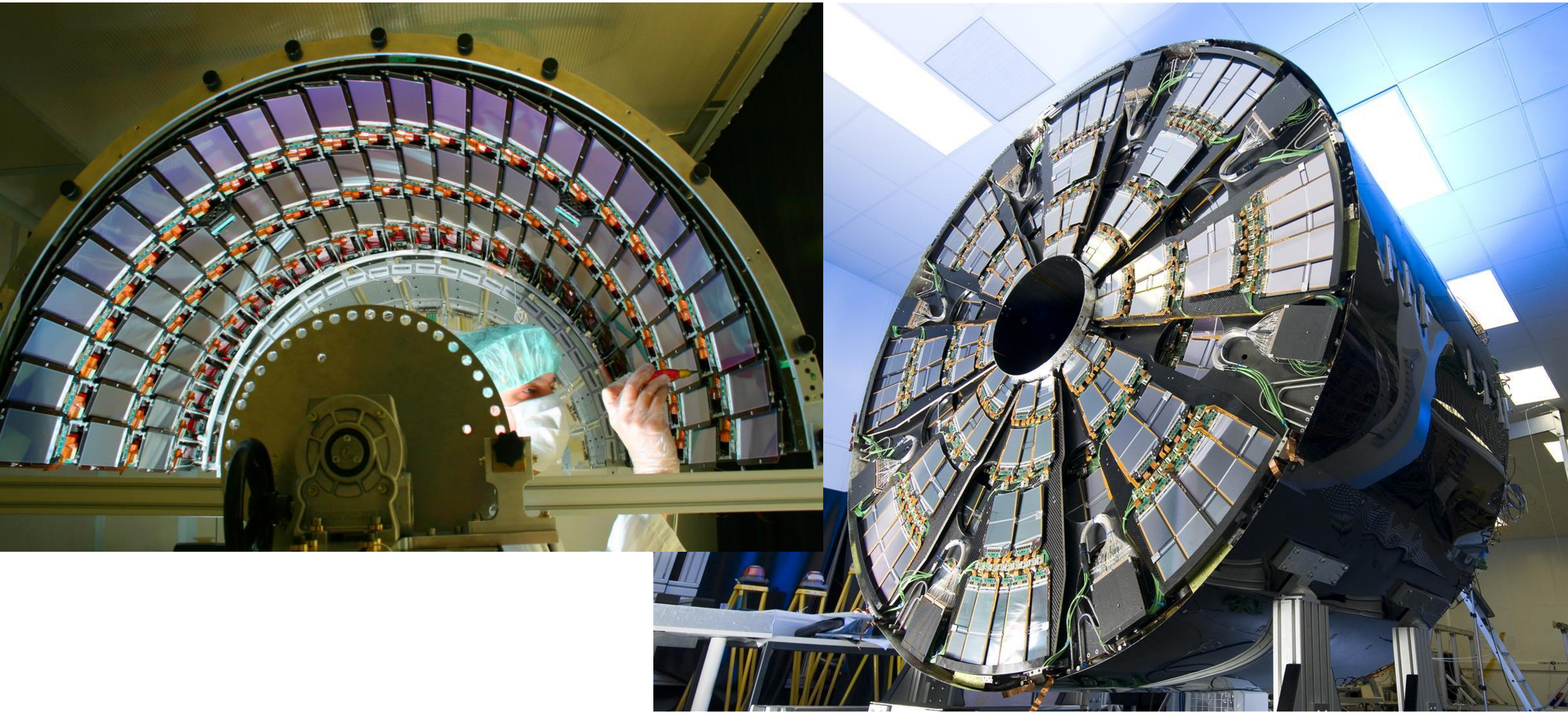




CMS

The CMS Full Silicon Tracker

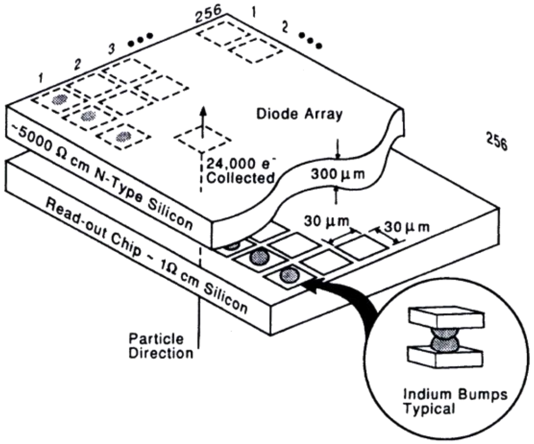
The largest Silicon Device, 200 m^2, >70 million channels



Hybrid Pixel Detectors

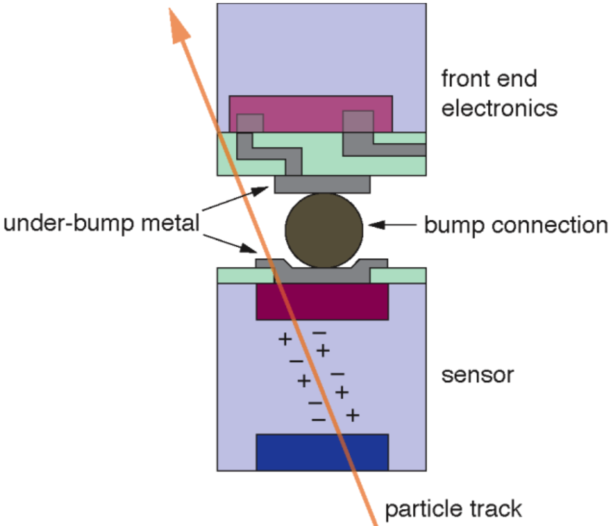
Principle

“Flip-Chip” pixel detector:
On top the Si detector, below the readout chip, bump bonds make the electrical connection for each pixel.



S.L. Shapiro et al., *Si PIN Diode Array Hybrids for Charged Particle Detection*, Nucl. Instr. Meth. A **275**, 580 (1989)

Detail of bump bond connection. Bottom is the detector, on top the readout chip:



L. Rossi, *Pixel Detectors Hybridisation*, Nucl. Instr. Meth. A **501**, 239 (2003)

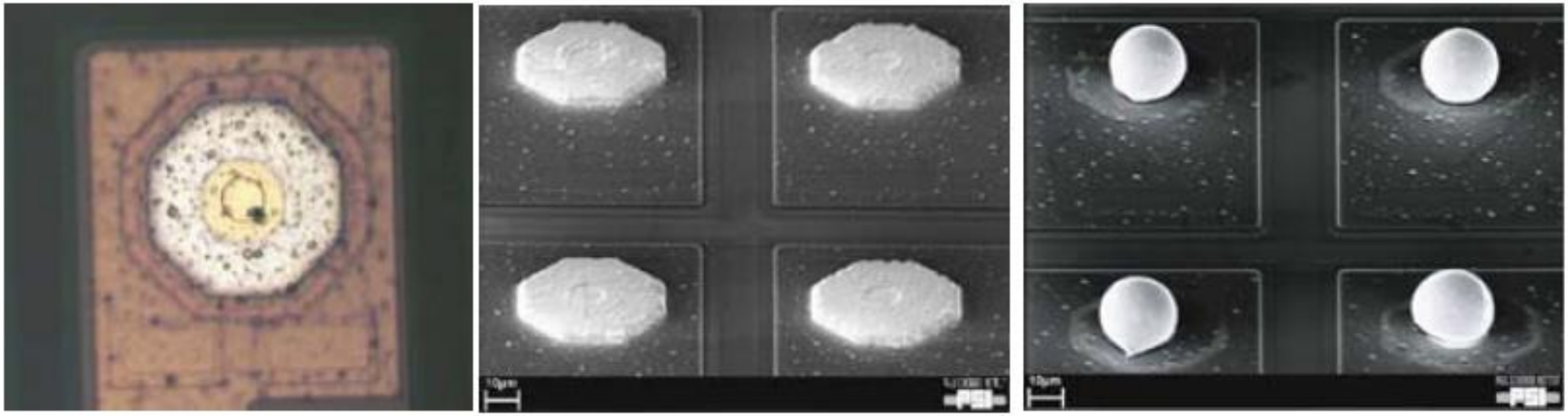
Drawback of hybrid pixel detectors: Large number of readout channels

→ Large number of electrical connections and large power consumption.

Hybrid Pixel Detectors

Bump bonding process

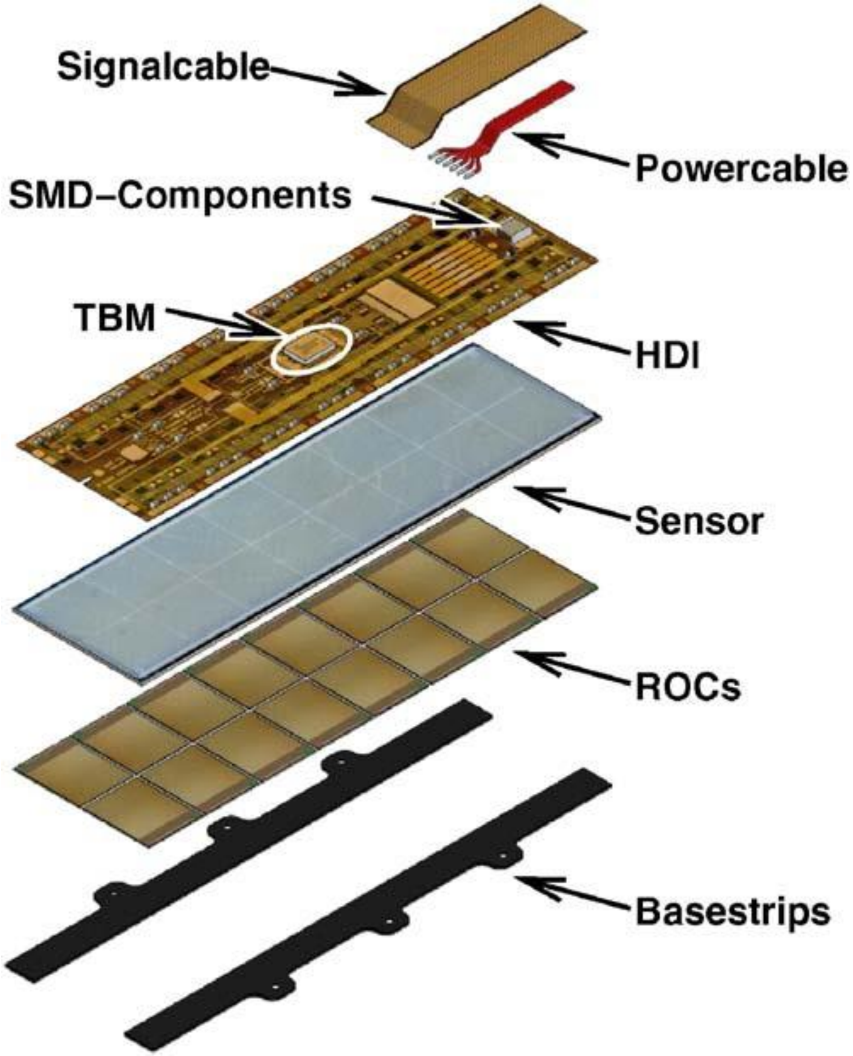
Electron microscope pictures before and after the reflow production step.
In bump, The distance between bumps is 100 µm, the deposited indium is 50 µm wide while the reflowed bump is only 20 µm wide.



C. Broennimann, F. Glaus, J. Gobrecht, S. Heising, M. Horisberger, R. Horisberger, H. Kästli,J. Lehmann, T. Rohe, and S. Streuli, *Development of an Indium bump bond process for silicon pixel detectors at PSI, Nucl. Inst. Met. Phys, Res. A565(1) (2006) 303–308 82*

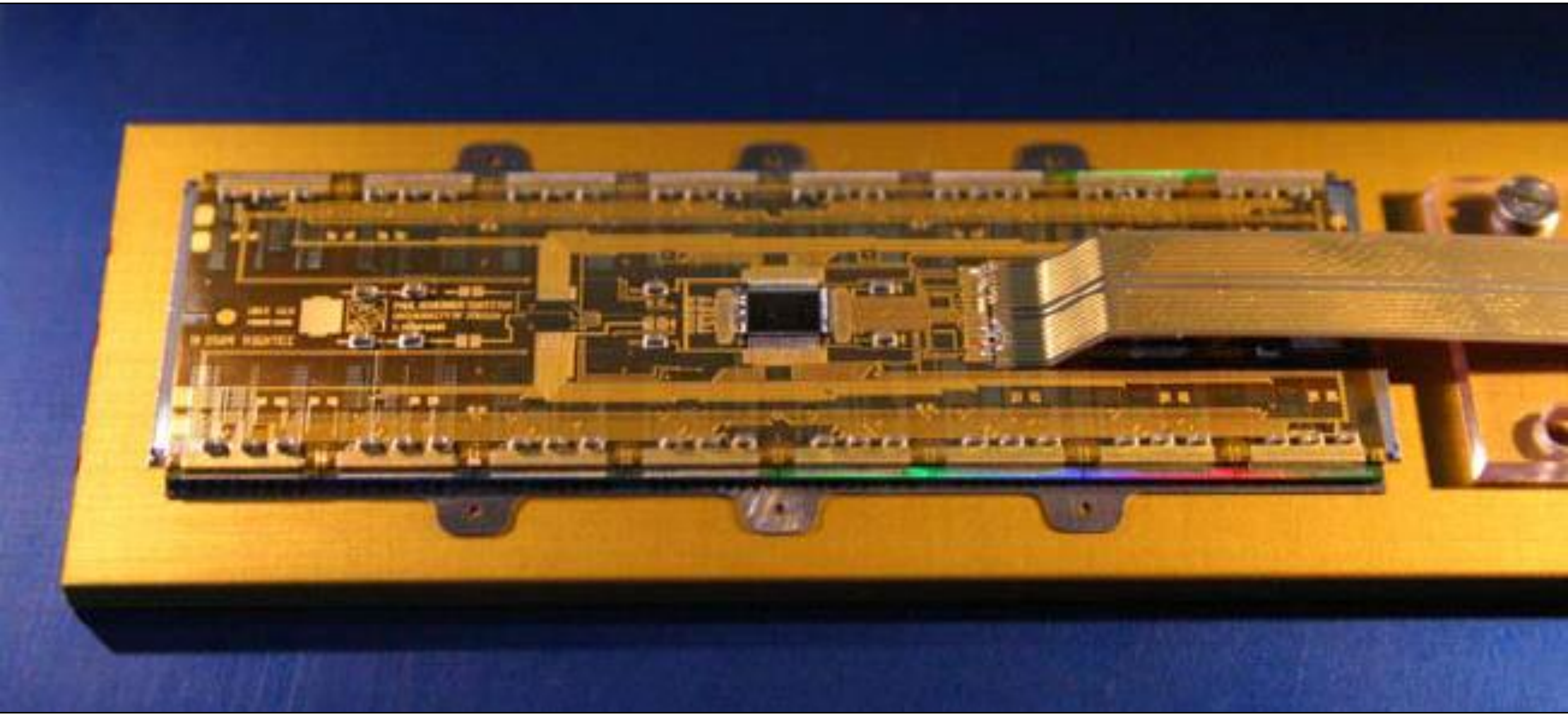
The CMS Inner Tracker

Barrel pixel: module design



The CMS Inner Tracker

A barrel pixel module



The barrel pixel consists of about 800 modules

The CMS Inner Tracker

A half disc of the forward pixel detector

Forward Pixel: consists of 672 plaquettes

Other Silicon Detector Structures

Strip and hybrid pixel detectors are employed in almost every experiment in HEP

Additional interesting silicon detector structures are:

- Double Sided Strip Detectors (DSS)
- Charged Coupled Devices (CCD)
- Silicon Drift Detectors (SDD)
- Avalanche Photo Diode (APD)
- Silicon Photo Multiplier (SiPM)
- Monolithic Active Pixels (MAPS)
- Low Gain Avalanche Detectors (LGAD)
- Depleted Field Effect detectors (DEPFET)
- Silicon On Oxide (SOI)
- 3D detectors

Other Silicon Detector Structures

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- 3D detectors

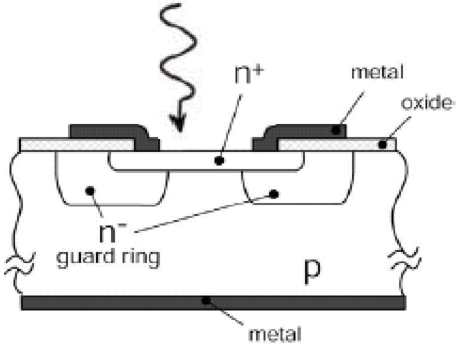
For time reasons I will discuss these only.

APDs and SiPMs have replaced classical photomultipliers in many places. MAPS and LGADs are new, but are already used or considered in HEP experiments.

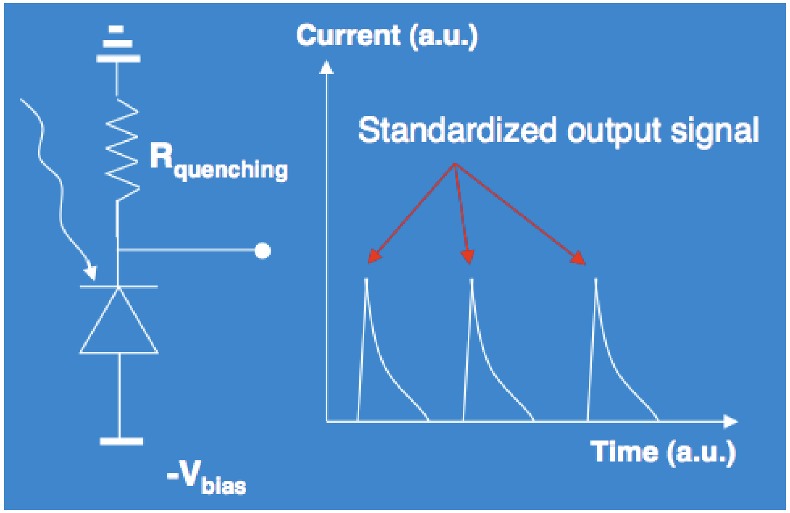
The other structures you will find in the back up.

Avalanche Photo Diode (APD)

APD are operated in reverse bias mode in the breakdown regime. A photon is able to trigger an avalanche breakdown. The current increase has to be limted by a quenching resistor.



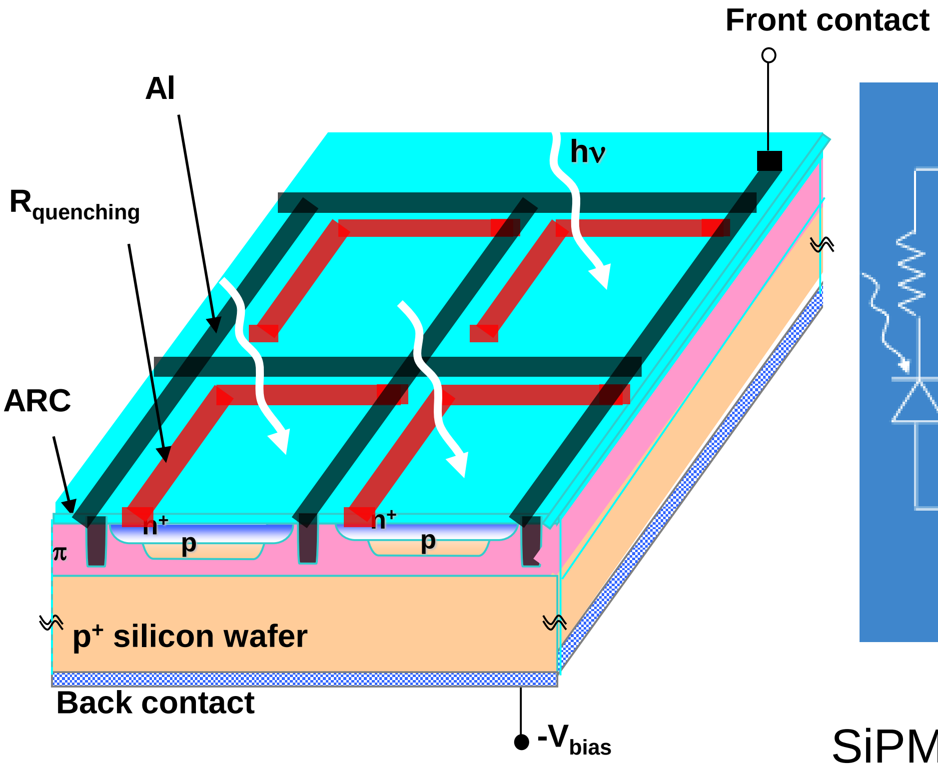
R. H. Haitz, J. App.Phys. Vol. 36, No. 10 (1965) 3123

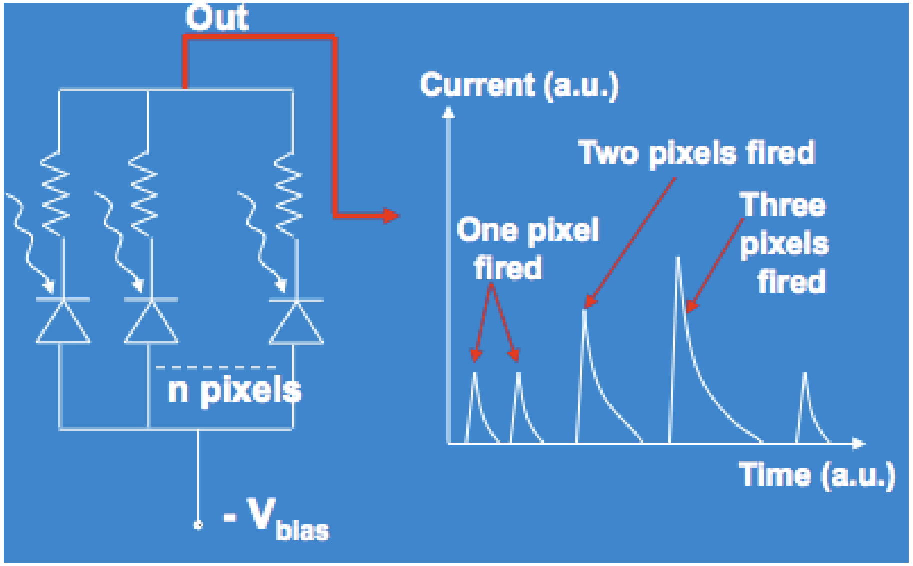


Used for photon detection in calorimeters (e.g the electromagnetic calorimeter of CMS), in cherenkov counters, etc.

Silicon Photo Multiplier (SiPM)

SiPM are matrices of APDs:



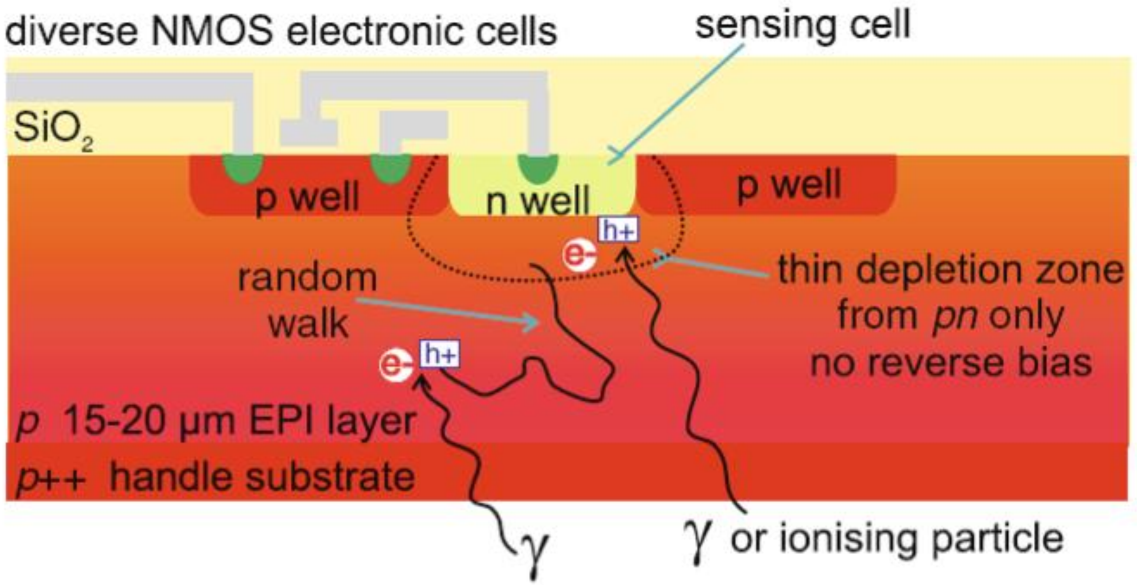


SiPM become more and more popular as replacement for standard photo multiplier.

Monolithic Active Pixels

CMOS

Scheme of a CMOS monolithic active pixel cell with an NMOS transistor. The N-well collects electrons from both ionization and photo-effect.

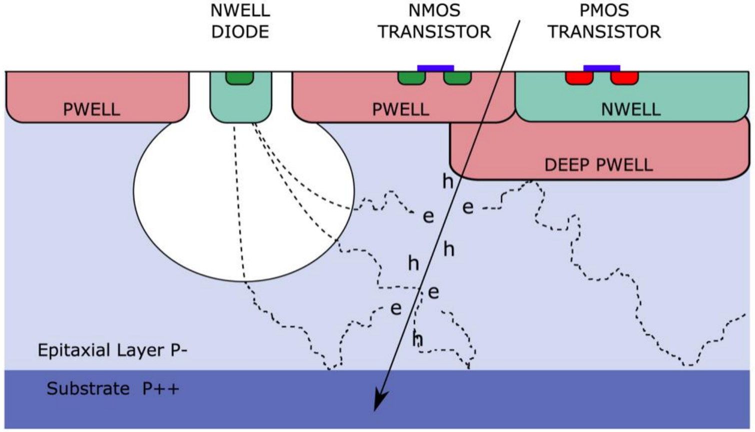


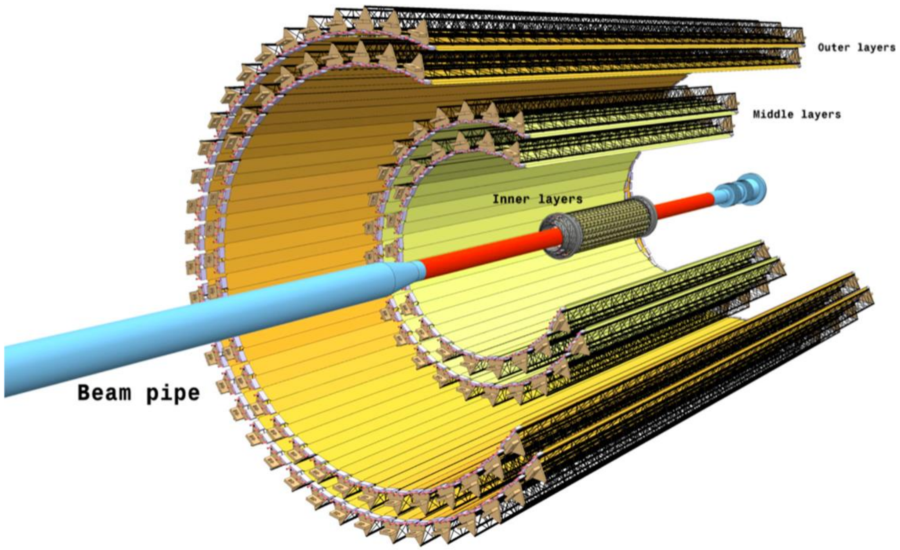
Evolution of Silicon Sensor Technology in Particle Physics,
F. Hartmann, Springer Volume 231, 2009

Monolithic Active Pixels

The ALICE ITK – the ALPIDE chip

ALPIDE chip: 180 nm CMOS Imaging Sensor process of TowerJazz

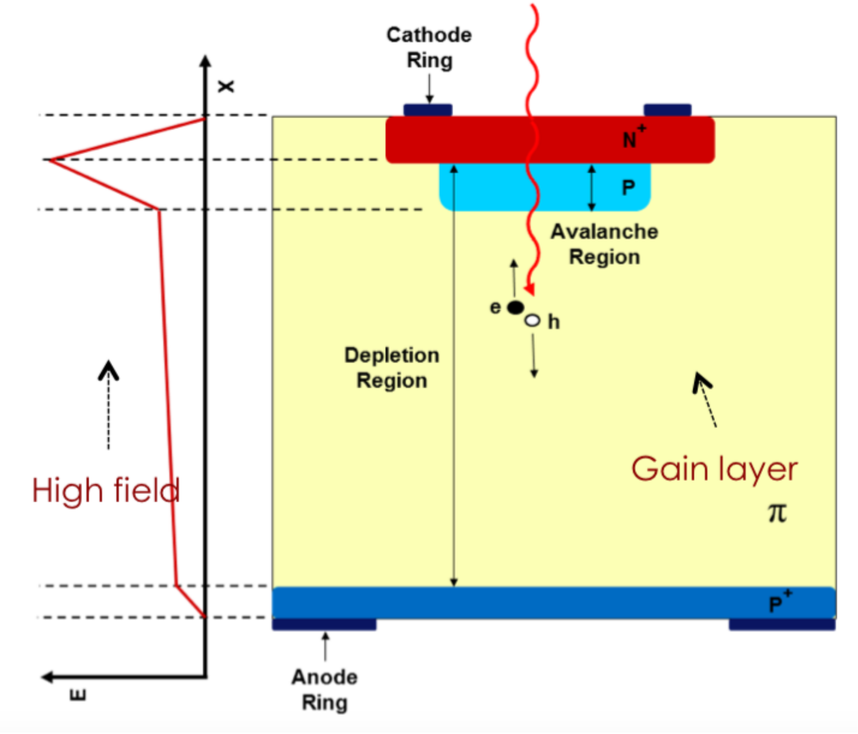




ALPIDE, the Monolithic Active Pixel Sensor for the ALICE ITS upgrade,
M. Mager, NIM A824 (2016) 434

Low Gain Avalanche (LGAD) detector

LGADs consists of an extra doping layer which creates a field close to the breakdown voltage (E~300 kV/cm)
Detectors with precision spatial and timing resolution



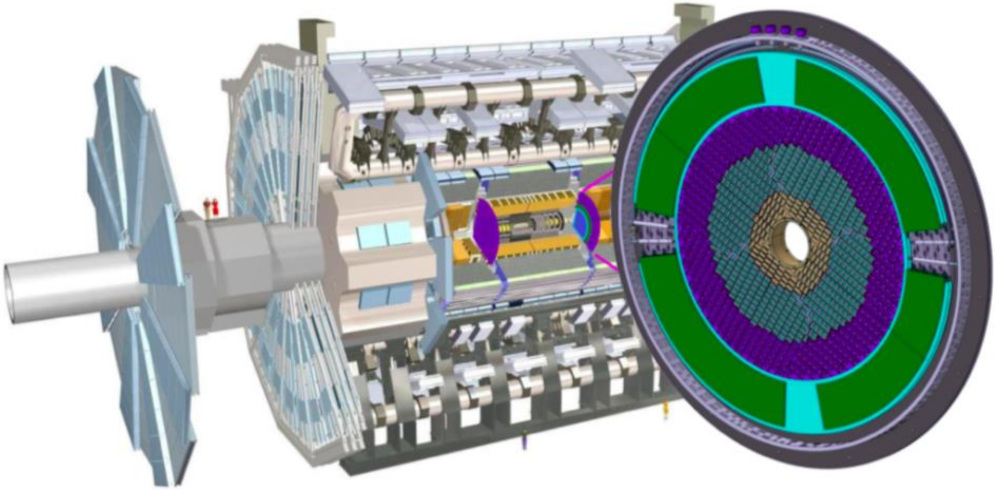
Internal Gain 10-30

Very fast detector, timing resolution possible 10..30 ps

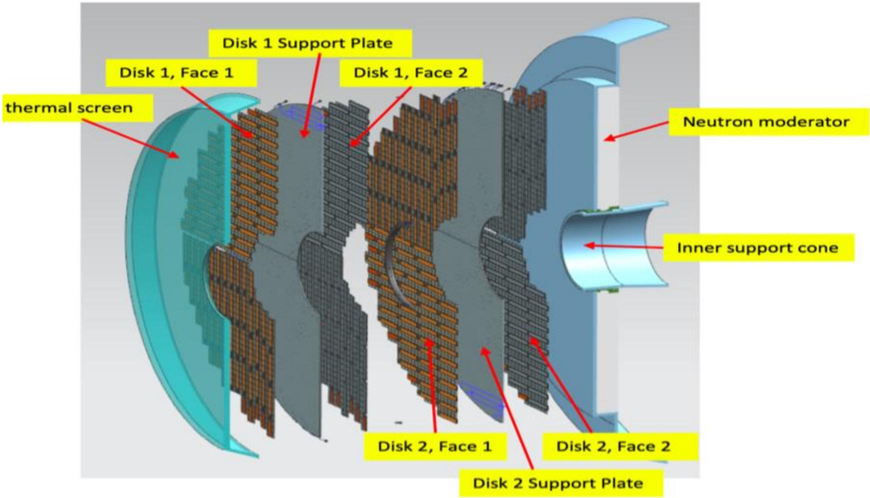
LGAD Detectors for HL-LHC

Both ATLAS and CMS foresee an upgrade with LGAD sensors
Timing layers to for precision timing to reduce pile up effect at HL-LHC

High Granularity Timing Detector (HGDT) for ATLAS:



Endcap Timing Layer (ETL) for CMS



Final Remarks

- Silicon detectors used by every Particle Physics Experiment since more than 30 years

- Silicon position sensors opened new physics opportunities, e.g. heavy flavour physics through detection of secondary vertex

- Many new innovative structure developed in recent years, also with internal amplification
  - SiPMs replacing photomultipliers
  - LGADs for fast 4D detectors

- More to come, stay tuned.

Thank you for your attention.

I hope to meet you soon in real live!

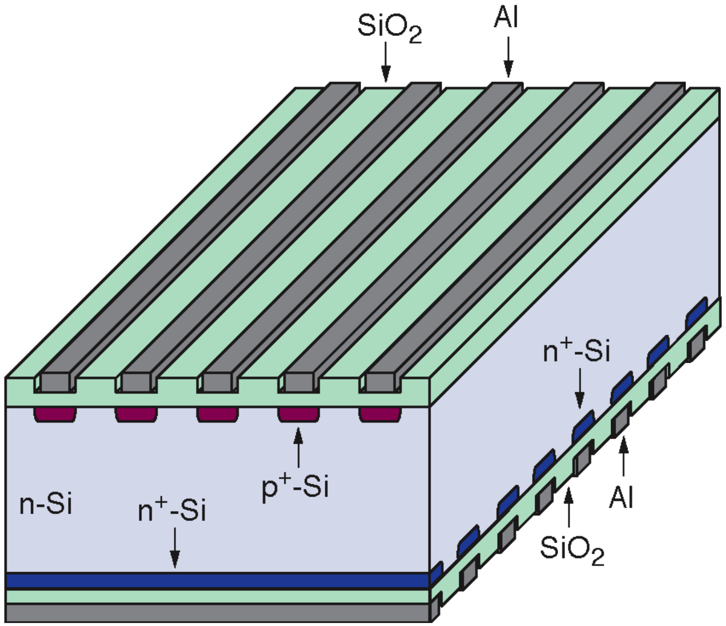
Back Up

Double Sided Strip Detectors

Principle

- Single sided strip detector measures only one coordinate. To measure second coordinate requires second detector layer.
- Double sided strip detector measures two coordinates in one detector layer (minimizes material).
- In n-type detector the n^+ backside becomes segmented, e.g. strips orthogonal to p^+ strips.
- Drawback: Production, handling, tests are more complicated and hence double sided detector are expensive.

Scheme of a double sided strip detector (biasing structures not shown):



Double Sided Strip Detectors

n-side separation

- Problem with n$^+$ segmentation: Static, positive oxide charges in the Si-SiO$_2$ interface.

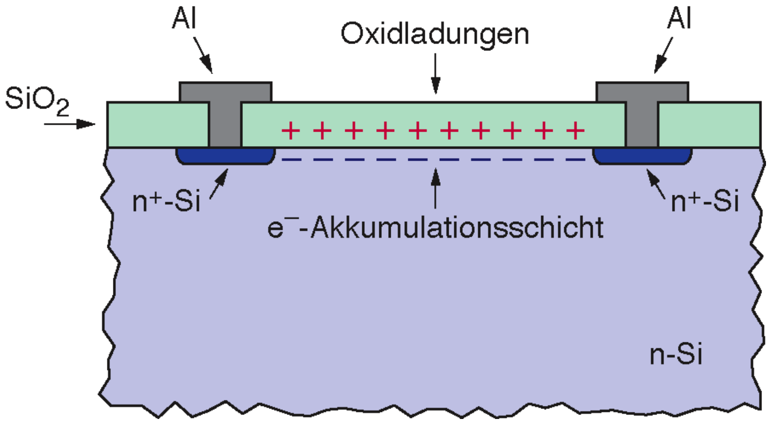
→ These positive charges attract electrons. The electrons form an accumulation layer underneath the oxide.

→ n+ strips are no longer isolated from each other (resistance ≈ kΩ).

→ Charges generated by through going particle spread over many strips.

→ No position measurement possible.

- Solution: Interrupt accumulation layer using p$^+$-stops, p$^+$-spray or field plates.



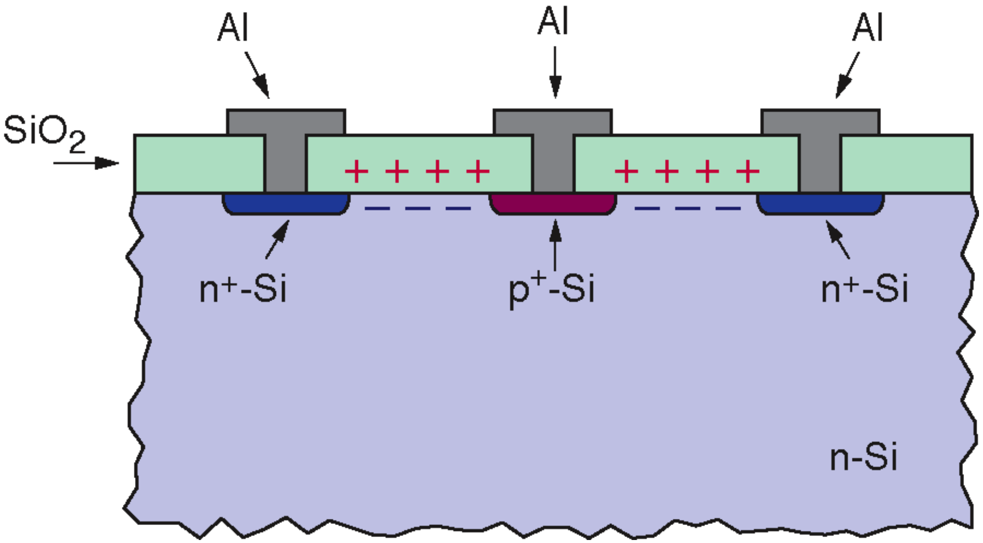
Positive oxide charges cause electron accumulation layer.

Double Sided Strip Detectors

p^+-stops

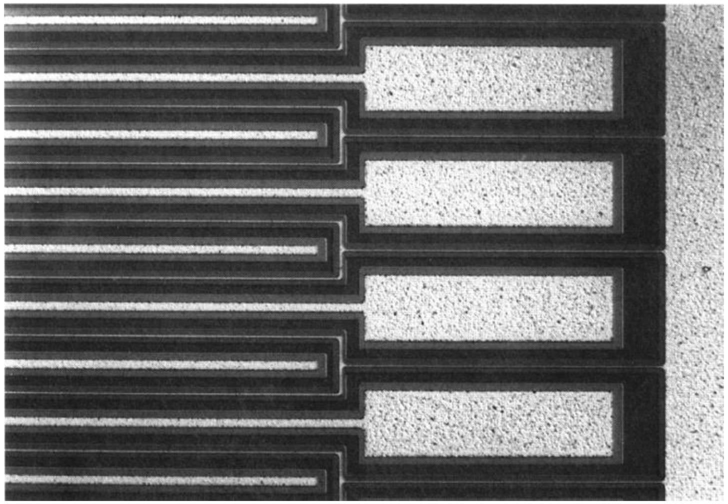
- p^+-implants (p^+-stops, blocking electrodes) between n^+-strips interrupt the electron accumulation layer.

→ Interstrip resistance reach again GΩ.



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

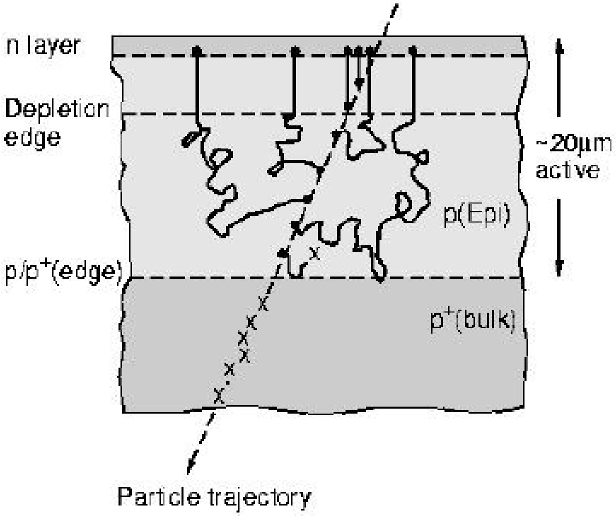
Picture showing the n^+-strips and the p^+-stop structure:

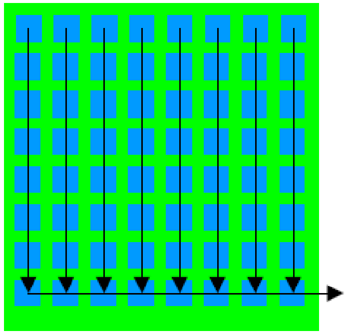


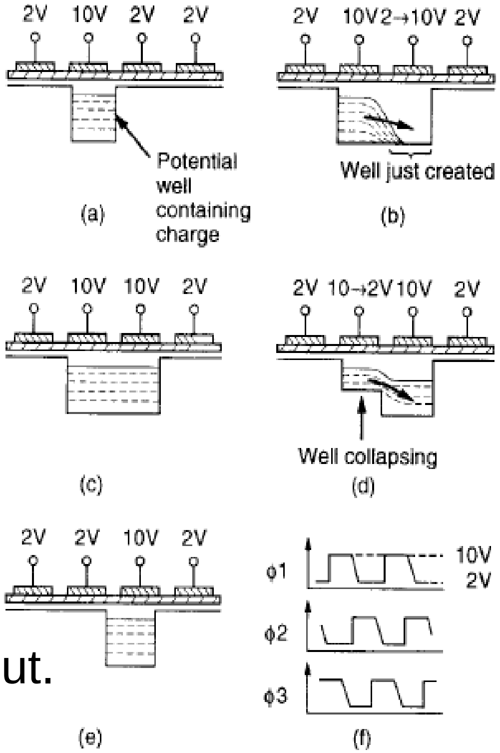
J. Kemmer and G. Lutz, *New Structures for Position Sensitive Semiconductor Detectors*, Nucl. Instr. Meth. A **273**, 588 (1988)

Charge Coupled Devices (CCD)

Shallow depletion layer (typically 15 μm), relatively small signal, the charge is kept in the pixel and during readout shifted through the columns and through final row to a single signal readout channel:





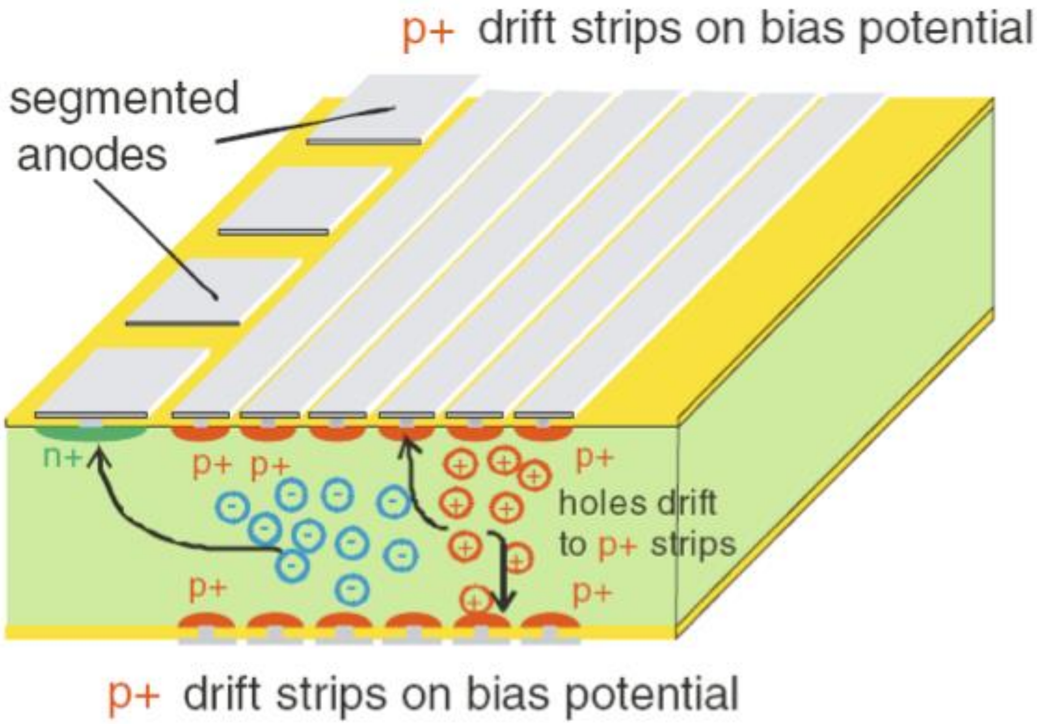


Slow device, hence not suitable for fast detectors.
Improvement are developed, e.g. parralel column readout.

Used as vertex detector for SLD (SLAC, USA) 1992-1998

Silicon Drift Detectors

In silicon drift detectors p$^+$ strips and the backplane p$^+$ implantation are used to fully deplete the bulk. A drift field transports the generated electrodes to the readout electrodes (n$^+$). One coordinate is measured by signals on strips, the second by the drift time.



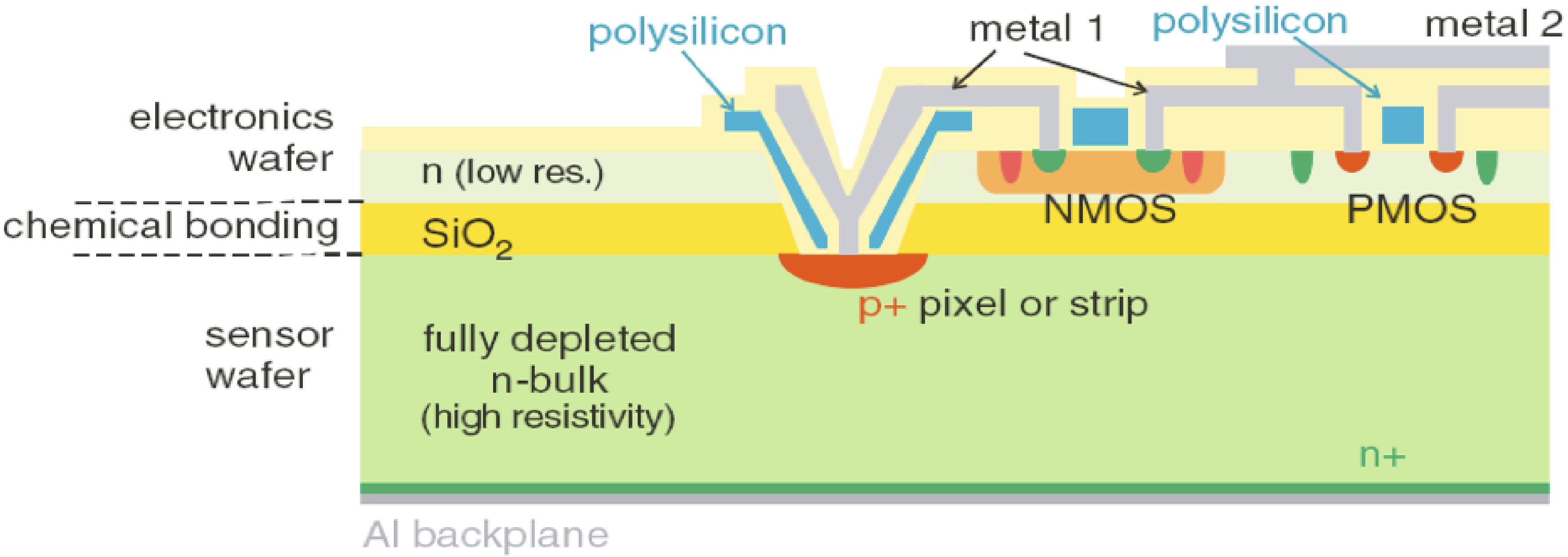
Evolution of Silicon Sensor Technology in Particle Physics, F. Hartmann, Springer Volume 231, 2009

Used for example in the experiment ALICE (CERN)

Monolithic Active Pixels

Silicon on Insulator (SOI)

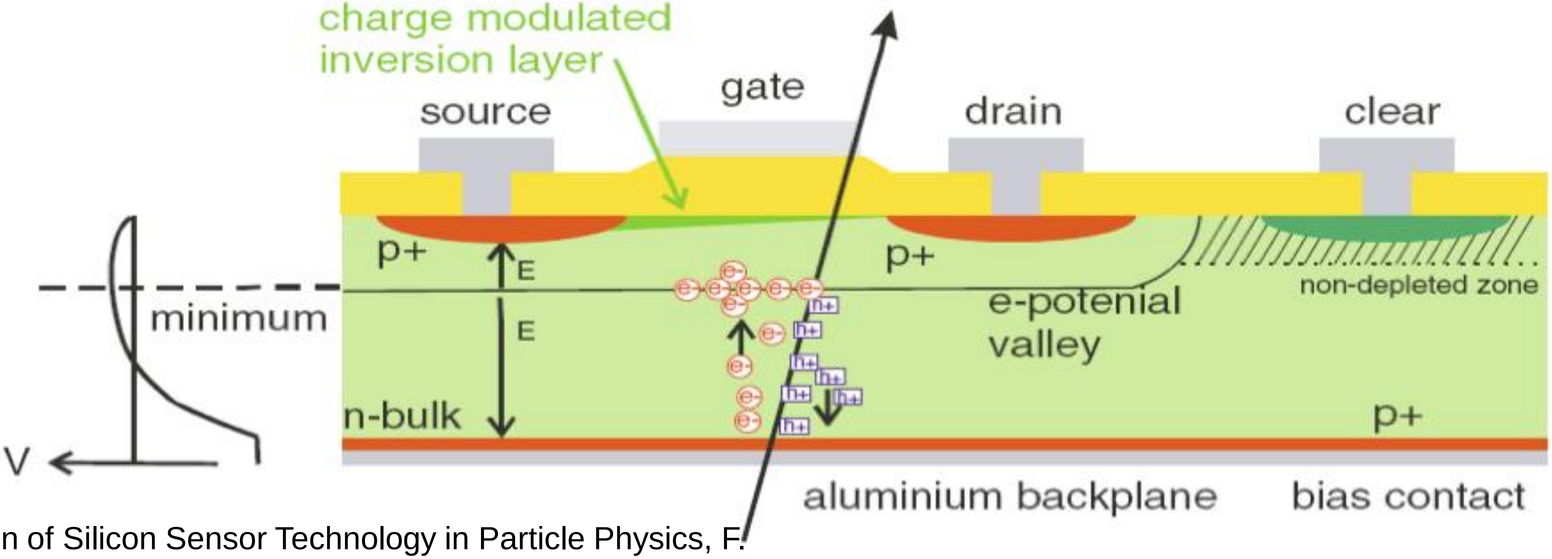
A SOI detector consists of a thick full depleted high resitivity bulk and seperated by a layer of SiO_2 a low resistivity n-type material. NMOS and PMOs transistors are implemented in the low resitivity material using standard IC methods.



Evolution of Silicon Sensor Technology in Particle Physics, F. Hartmann, Springer Volume 231, 2009

DEPFET Detectors

The DEPFET detector is a detector with an internal amplification structure. The n-bulk is fully depleted with a potential minimum below the strips and the structure of a field effect transistor. The electrons created by a charged particle accumulate in the potential minimum. The field configuration is such that the electrons drift underneath the gate of the transistor modifying the source drain curreny. An active clear is necessary to remove the electrons.

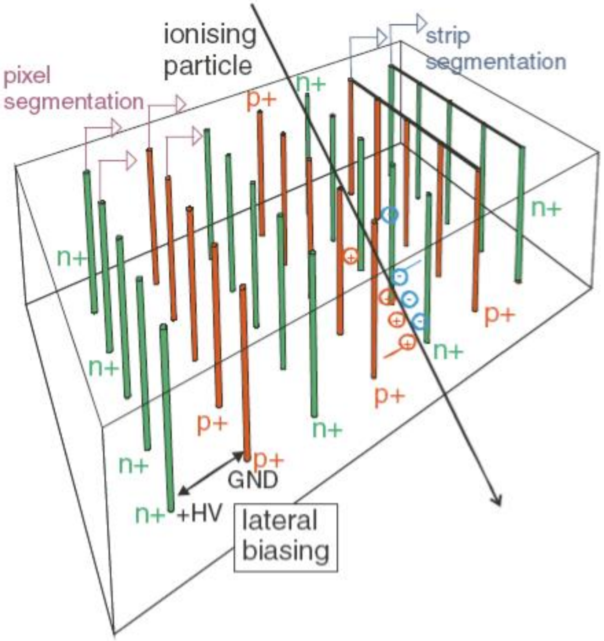


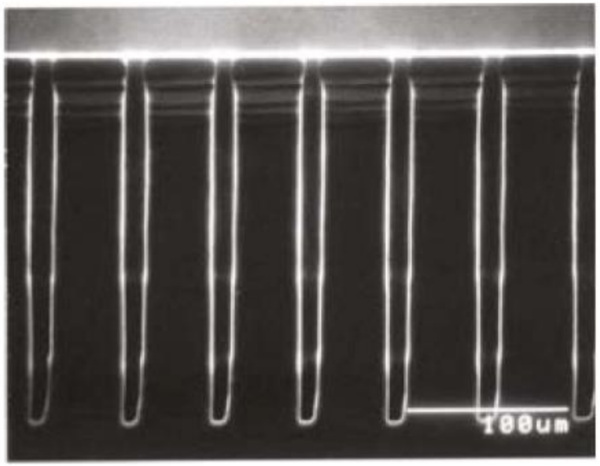
Evolution of Silicon Sensor Technology in Particle Physics, F. Hartmann, Springer Volume 231, 2009; J. Kemmer and G. Lutz, NIM A253 (1987) 365

Detector used in Belle II

3D Detectors

3D detecors are non planar detectors. Deep holes are etched into the silicon and filled with n$^+$ and p$^+$ material. Depletion is sideways. The distances between the electrodes are small, hence depletion voltage can be much smaller and charge carries travel much short distances.





Picture from CNM-IMB (CSIC), Barcelona

Very radiation tolerant detectors.