# Concepts for Experiments at Future Colliders I

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25.11.2024

# Recapitulation of the previous lecture

## Instrumentation of the inner detector

### Requirements

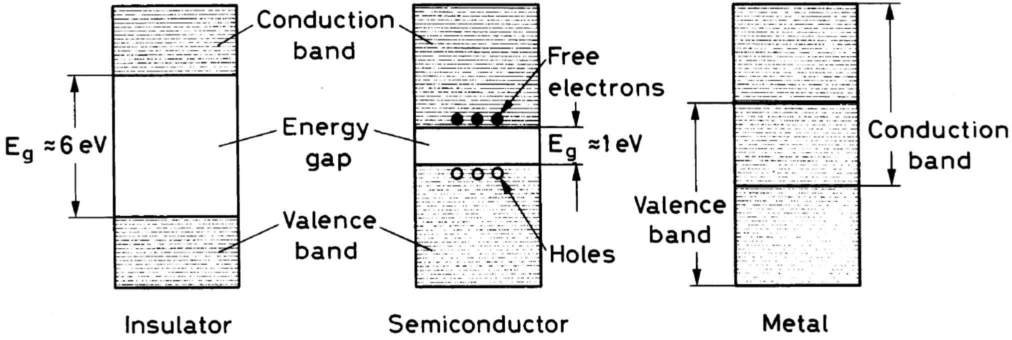
- General requirements
  - As little detector material as possible to minimize the multiple scattering contribution to the momentum resolution.
  - High spatial resolution to maximize the momentum resolution for highly energetic particles.
- Additional requirements at a hadron collider
  - High granularity to be able to separate particle trajectories even in the presence of high charged particle densities.
  - Radiation hardness.

### Detector types in modern inner detectors

- Experiments at $e^+e^-$ colliders
  - Highly granular semiconductor detectors close to the beam line for secondary vertex reconstruction.
  - Low-$X_0$ semiconductor or gaseous ionization detectors at larger distance from the beam line.
- Experiments at hadron colliders
  - Entire inner detector with highly granular and radiation hard semiconductor detectors.

# Recapitulation of the previous lecture

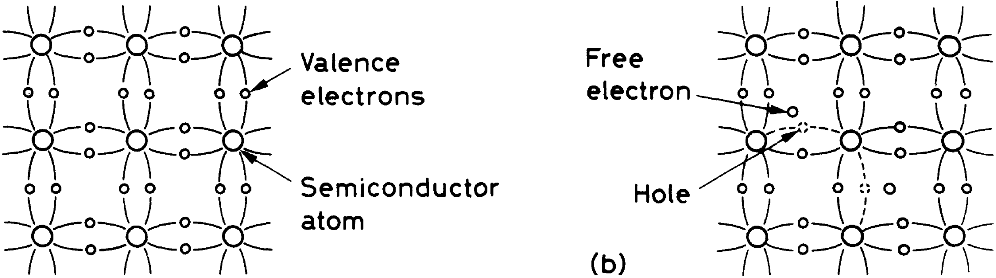
Energy bands in solid-state bodies



# Recapitulation of the previous lecture

## Charge carriers in semiconductors

Example: Covalent bonds between silicon atoms.



Two source of electrical conductivity in semiconductors:

- Motion of free electrons in the conduction band

and

- Motion of holes in the valence band.

(Only motion of electrons in the conduction bands in conductors.)

# Recapitulation of the previous lecture

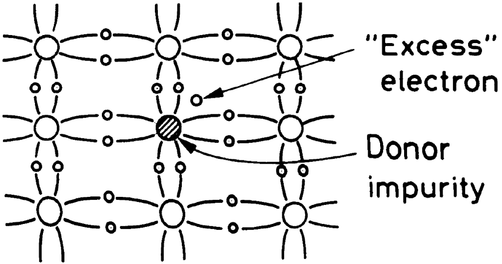
Doped semiconductors

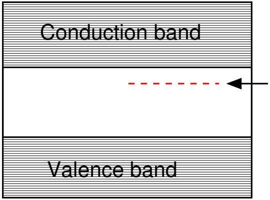
- The number of free electrons and holes is the same in pure semiconductors.
- There can be more free electrons than holes and vice versa in doped semiconductors.

# Recapitulation of the previous lecture

## Doping of silicon with pentavalent atoms

Pentavalent atoms: arsene, phosphor, antimony.





Donor level
a little bit below the
edge of the conduction
band (~0,01 eV)

⇒ Increased conductivity due to the excess electrons which can be very easily excited thermally into the conduction band.

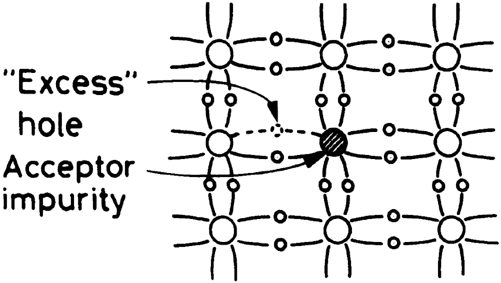
Nomenclature: n-type semiconductor.

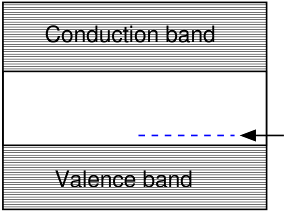
Main charge carriers in an n-type semiconductor: electrons.

# Recapitulation of the previous lecture

Doping of silicon with trivalent atoms

Trivalent atoms: gallium, boron, indium.





Acceptor level slightly above the edge of the valence band

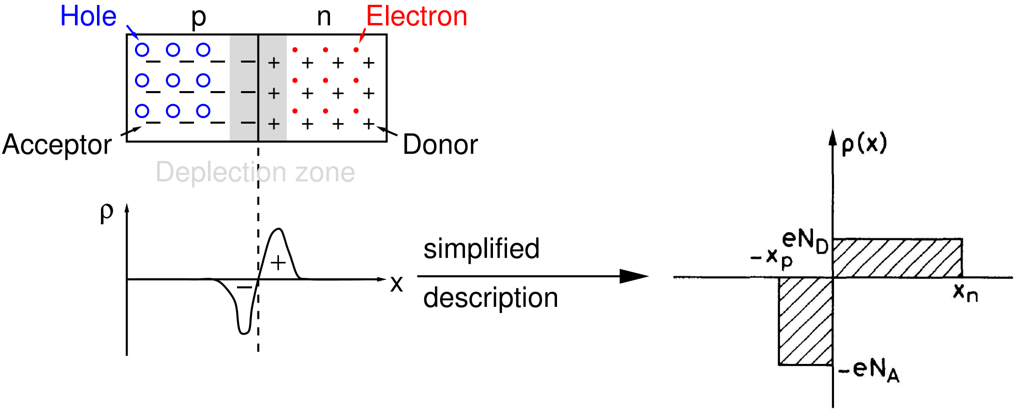
⇒ Increased conductivity due to excess holes into which valence electrons can be easily excited thermally.

Nomenklatur: p-type semiconductor.

Main charge carriers in an p-type semiconductor: holes.

# Recapitulation of the previous lecture

The pn junction



$N_{A/D}$: Acceptor-/Donor concentration

# Recapitulation of the previous lecture

## Size of the depletion zone

$$\rho(x) = \begin{cases} -eN_A \ (x \in [-x_p, 0[) \\ +eN_D \ (x \in [0, x_n]) \\ 0, \ \text{else} \end{cases}$$

$div\vec{E} = \frac{\rho}{\epsilon}$ leads to $\frac{dE}{dx} = \frac{\rho(x)}{\epsilon}$, such that

$$\begin{aligned} E(x) &= 0 \ (x < -x_p, x > x_n), \\ E(x) &= -\frac{e}{\epsilon} N_A(x + x_p) \ (x \in [-x_p, 0[), \\ E(x) &= +\frac{e}{\epsilon} N_D(x - x_n) \ (x \in [0, x_n]). \end{aligned}$$

Continuity at $x = 0$ leads to

$$N_A x_p = N_D x_n \Leftrightarrow \frac{x_p}{x_n} = \frac{N_D}{N_A} \ (*)$$

$\Rightarrow$ The deplection zone extends further into the region of lower doping concentration.

# Recapitulation of the previous lecture

## Contact potential

Potential difference (so-called "contact potential")

$$\begin{aligned} U_0 &= -\int_{-x_p}^{x_n} E(x)\,dx = +\frac{eN_A}{2\epsilon}(x+x_p)^2\bigg|_{-x_p}^{0} - \frac{eN_D}{2\epsilon}(x-x_n)^2\bigg|_{0}^{x_n} \\ &= \frac{e}{2\epsilon}(N_D x_n^2 + N_A x_p^2) \end{aligned}$$

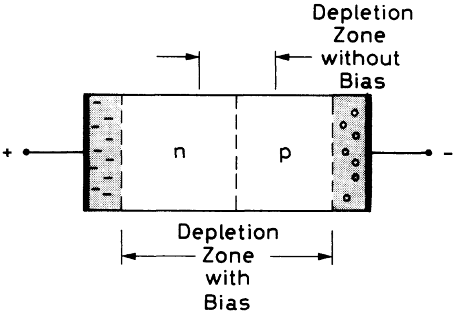
## Size of the depletion zone

$$x_n = \sqrt{\frac{2\epsilon U_0}{eN_D(1+\frac{N_D}{N_A})}},\quad x_p = \sqrt{\frac{2\epsilon U_0}{eN_A(1+\frac{N_A}{N_D})}}.$$

# Recapitulation of the previous lecture

## Increasing the depletion zone

The deplection zone can be increased by applying a so-called "bias voltage" $U_B$:



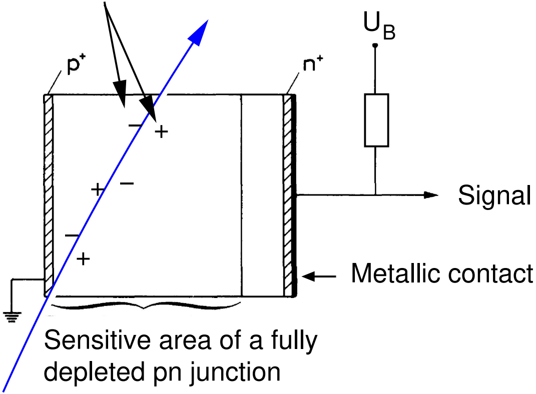
$$x_n = \sqrt{\frac{2\epsilon(U_0+U_B)}{eN_D(1+\frac{N_D}{N_A})}}, \quad x_p = \sqrt{\frac{2\epsilon(U_0+U_B)}{eN_A(1+\frac{N_A}{N_D})}}.$$

$U_B \sim 300$ V for complete depletion of the pn junction.

# Recapitulation of the previous lecture

## Basic principle of a semiconductor detector

Liberated charge carriers which are pulled by the electric field towards the contact



Metallic contact

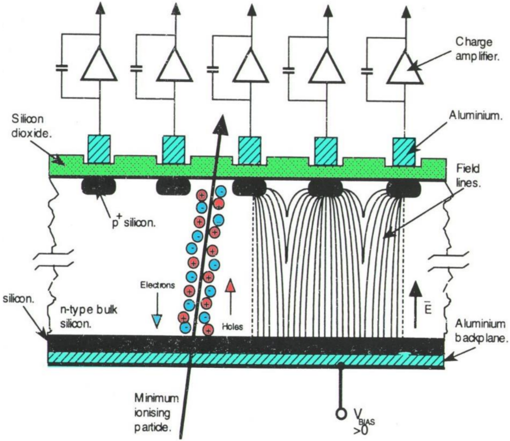
Sensitive area of a fully depleted pn junction

Ionizing particle

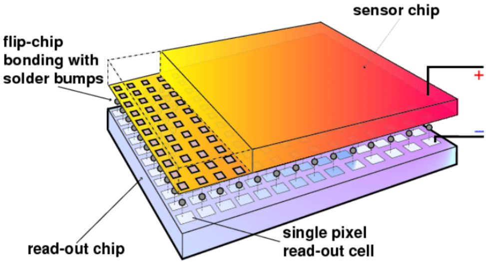
In order to prevent the creation of an ohmic contact with a deplection zone extending far into the semiconductor, contact surfaces with highly doped layers are used.

# Strip and pixel sensors

## Silicon strip sensors

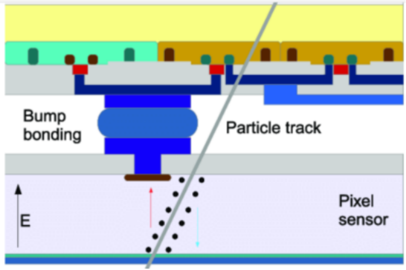


## Silicon pixel sensors



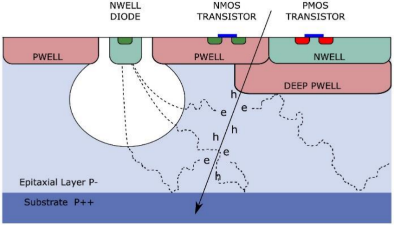
# Monolithic sensors

## Hybrid sensor



- Sensor and amplifier chip are two separate devices.
- Concept successfully used at the (HL)-LHC: required resolution, speed, granularity, radiation hardness.
- Disadvantage for the FCC-ee where radiation hardness is not an issue: a lot of extra material due to the amplifier chip

## Monolithic sensor



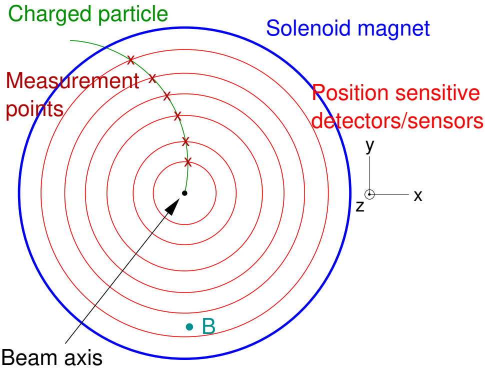
- Sensor and amplifier combined in one device.
- Main advantage: reduction of material.

# Functions of an inner detector

## Tasks

- Measurement of the charge $q$ and the momentum $\vec{p}$ of a charge particle.
- Measurement of the particle's origin/vertex.

## Basic structure of an inner detector



## Parameters of the reconstructed track

- Sign of the curvature → sgn$(q)$.
- Size of the curvature → $p$.
- Direction close to the beam axis → $\vec{p}/p$.
- Distance of the track from the beam axis → Vertex of the particle.

# Momentum resolution of an inner detector

- Recapitulation:

$$\frac{\delta\left(\frac{q}{p}\right)}{q/p} = \left.\frac{\delta\left(\frac{q}{p}\right)}{q/p}\right|_{Multiple\ \ scattering} \oplus \left.\frac{\delta\left(\frac{q}{p}\right)}{q/p}\right|_{Spatial\ \ resolution}.$$

  - $\left.\frac{\delta\left(\frac{q}{p}\right)}{q/p}\right|_{Multiple\ \ scattering}$ independent of $\frac{q}{p}$.
  - $\left.\frac{\delta\left(\frac{q}{p}\right)}{q/p}\right|_{Spatial\ \ resolution} \propto \frac{p}{|q|}$.

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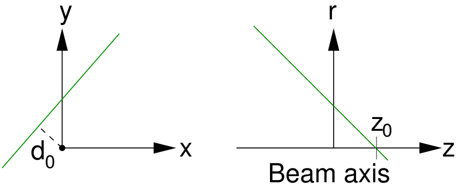
  - $\left.\frac{\delta\left(\frac{q}{p}\right)}{q/p}\right|_{Spatial\ resolution} \propto \frac{p}{|q|}$.

- Estimation of $\left.\frac{\delta\left(\frac{q}{p}\right)}{q/p}\right|_{Spatial\ resolution}$:

$$\left.\frac{\delta\left(\frac{q}{p}\right)}{q/p}\right|_{Spatial\ resolution} \approx \frac{\sigma 2\sqrt{5}}{BL^2\sqrt{n}} \cdot \frac{p}{|q|};$$

$\sigma$: Spatial resolution of a single measurement plane.
$B$: Magnetic field strenght in the inner detector.
$L$: Radius of the inner detector.
$n$: Number of (equidistant) measurement planes.

# Impact parameter



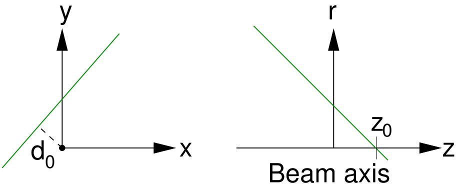
## Nomenclature

- $d_0$: Transverse impact parameter.
- $z_0$: Longitudinal impact parameter.

## Conventions

$d_0$ and $z_0$ are expressed either relative to the average collision point or relative to the primary vertex.

# Impact parameter



## Nomenclature

- $d_0$: Transverse impact parameter.
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## Conventions

$d_0$ and $z_0$ are expressed either relative to the average collision point or relative to the primary vertex.

## Requirements for the innermost detector plane for the $d_0$- and $z_0$ measurements

- Simplifying assumptions
  - Consider $z_0$ measurement.
  - Tracks are straight close to (0,0,0).
  - Two detector planes at $r_1$ and $r_2$ with spatial resolutions $\sigma_1$ and $\sigma_2$.
- $z_0$ resolution

$$\sigma_{z_0} = \frac{\sqrt{r_2^2\sigma_1^2 + r_1^2\sigma_2^2}}{|r_2 - r_1|} \oplus \sigma_{Multiple\ scattering}.$$

⇒ Thin layers close to the beam axis with high momentum resolution to maximize $\sigma_{z_0}$.

# Basic parameters of the HL-LHC and the FCC

## Centre-of-mass energy and luminosity

| Collider | $\sqrt{s}$ [TeV] | $\mathcal{L}_{max}$ [cm$^{-2}$s$^{-1}$] | $\int \mathcal{L}dt$ [ab$^{-1}$] |
|---|---|---|---|
| HL-LHC | $14$ | $7,5 \cdot 10^{34}$ | 3 |
| FCC, phase 1 | $100$ | $5 \cdot 10^{34}$ | 2,5 |
| FCC, phase 2 | $100$ | $30 \cdot 10^{34}$ | 15 |

## Scenarios

- HL-LHC: 2026 bis 2036.
- FCC, phase 1: 10 years of operation.
- FCC, phase 2: 15 years of operation.

## Number $N_{pile-up}$ of inelastic $pp$ collisions per bunch crossing

- HL-LHC: 140 (bunch crossings every 25 ns).
- FCC, phase 1:
  - 170 (bunch crossings every 25 ns).
- FCC, phase 2, 2 scenarios:
  - 1020 (bunch crossings every 25 ns).
  - 204 (bunch crossings every 5 ns).

# Minimum-bias events at the FCC and the HL-LHC

Radiation levels in the detectors depend on the structure of minimimum-bias events (simplified: "inelastice $pp$ collisions without a hard scatter).

Cross section of inelastice $pp$ collisions

- ≈80 mb at $\sqrt{s}$=14 TeV.
- ≈100 mb at $\sqrt{s}$=100 TeV, hence 25% larger than at the HL-LHC.

Charged particle multiplicity per rapidity unit

- ≈5,4 at $\sqrt{s}$=14 TeV.
- ≈8 at $\sqrt{s}$=100 TeV, hence 1.5 times larger than at the HL-LHC.

Average partiple momentum

- ≈0.6 GeV at $\sqrt{s}$=14 TeV.
- ≈0.8 GeV at $\sqrt{s}$=100 TeV, hance 1.3 times larger than at the HL-LHC.

Minimum-bias events at the FCC are very similar to those at the LHC.

⇒ Operation conditions in phase 1 of the FCC very similar to the operation conditions at the HL-LHC.

# Radiation levels in the inner detector

Inner detector: Radiation levels in the first pixel detector layer ($r = 3.7$ cm)

| | HL-LHC (3 ab$^{-1}$) | FCC, phase 1 | FCC, phase II |
|---|---|---|---|
| 1 MeV-neq flux [cm$^{-2}$] | $1.5 \cdot 10^{16}$ | $3 \cdot 10^{16}$ | $3 \cdot 10^{17}$ |
| Dose [MGy] | 4.8 | 9 | 90 |

⇒ Semiconductor detector for the HL-LHC are also suitable for the first phase of the FCC. Development of more radiation hard detector neccessary for the second phase of the FCC.

# Radiation damage of silicon detectors

The huge fluxes of charged and neutral particles in the inner detector cause damages of the semiconductor detectors.

## Two mechanisms

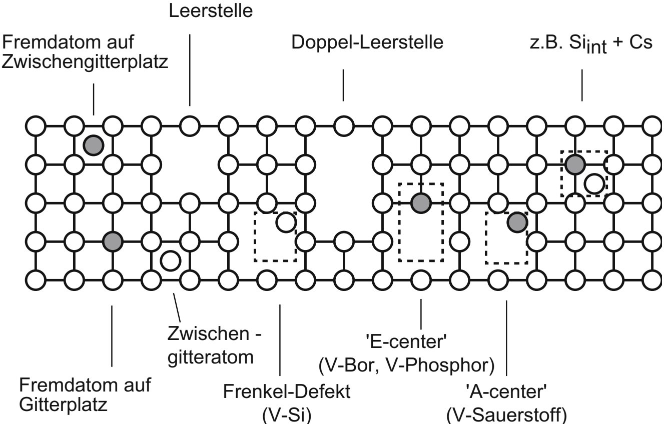
- Damage of the surface and boundary surfaces of semiconductor detectors and of the read-out chips by ionizing radiation.
  As the ionization is a resersible process in a semiconductor, no permant damages of the crystal.
- Scattering off the atoms of the crystal lattice can cause atom displacements and other damages of the crystal lattice.

## Convention

The damage of the substrate by scattering off the atoms is expressed as the damage of neutrons with 1 MeV energy.

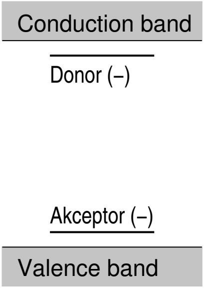
# Damages of the substrate

- Lattice atoms can be displaced by collisions with the radiation background leading to empty places and atoms on inter-lattice points as primary point defects.



- Most of the primary defects are instable and disappear by recombination.
- Due to their mobility primary point defects can build stable defect complexes with impurity atoms.

# Consequences of substrate damages



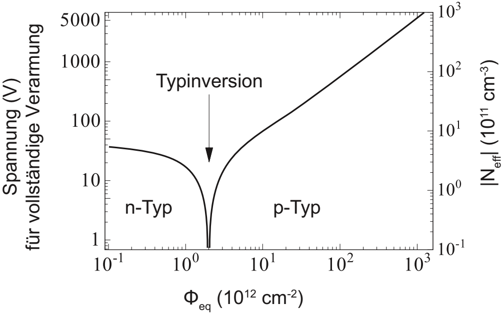
## Creation of acceptor and donor centres

- Charged defects which act as acceptor or Donor centres.

⇒ Modification of the effective doping concentration.

⇒ Modification of the depletion region and the depletion voltage. Type inversion is possible.

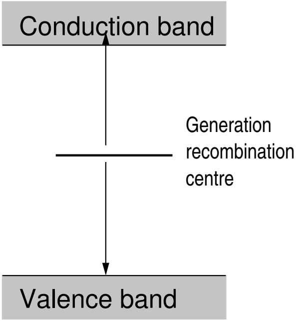
# Type inversion by acceptor and donor centres



Type inversion already after few years of operation at the LHC.

⇒ The value of the depletion voltage changes with time. After a long operation of the detectors, only partial depletion possible leading to loss of signal.

# Consequences of substrate damages



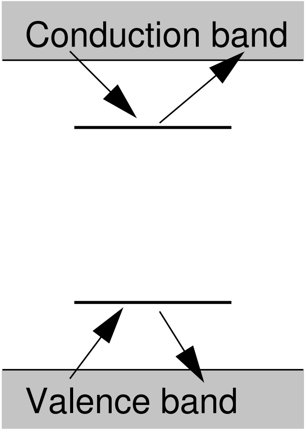
## Creation of generation recombination centres

- Impurity levels in the middle of the band gap act as generation and recombination centres.
- generation centres increase the leakage current.

⇒ Increased detector noise and detector temperature.

- Danger of destroying the detector by a chain reaction of a leakage current induced temperature increase and a temperature induced increase of the leakage current.

# Consequences of substrate damages



Creation of trapping centres

- Trapping of electrons and hole in impurity levels.

⇒ Reduced life time and mean free path of the charge carriers.

⇒ Signal loss if the trapping takes longer than the creation of the signal.

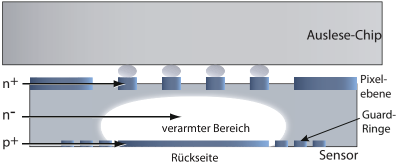
# Measures to increase the radiation hardness

## Cooling of the sensors

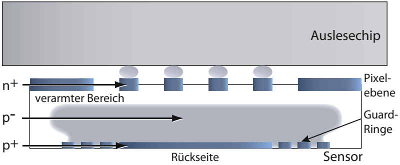
- Damages of the substrate are temperature dependent.

⇒ Damages can be cured by heating up the crystal. But too long heating can convert harmless impurities to harmful impurities.

⇒ Second process can be suppressed by operating the sensors at low temperatures ~-10$^o$C.



(a) n$^-$-Substratdotierung vor der Bestrahlung.



(b) p$^-$-Subatratdotierung nach der Bestrahlung.

## $n^+$-on-n- or $n^+$-on-p sensors

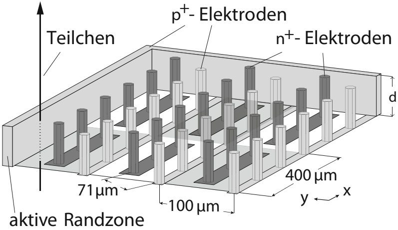
- After type inversion complete depletion no longer possible.

⇒ $n^+$-on-n or $n^+$-on-p sensoren to have the $n^+p$ layer on the side of the read-out electrode.

# Measures to increase the radiation hardness

## Enrichment of the silicon substrate with oxygen

- Suppression or prevention of type inversion by enrichment of the silicon substrate with oxygen.



## Thin sensors or 3-D pixel sensors

- Goal: Reduction of drift paths and acceleration of the charge collection to oppose trapping effects.
- Two possibilities: Thin planar sensors or 3D pixel sensors with column electrodes.

# Lecture on December 2

No lecture on December 2 because of conflicts with MPP internal meetings