Semiconductor Detectors
basic structures

OUTLINE Part I:

1. Semiconductors
2. Basic semiconductor structures

   (a) the pn diode

   (b) the MOS structure

3. Semiconductor fabrication: detectors and electronis
4. Simple pn-diode type detectors
5. Applications in high energy physics

Semiconductors as detector and electronics material

1. **Semiconductors: $E_{Gap} \approx 1 - 3$ eV**
   → small leakage currents
   → low noise, operation @ r.t.

2. **Pair creation energy: w = 2 – 5 eV**
   → large number of signal charges per energy deposit in detector

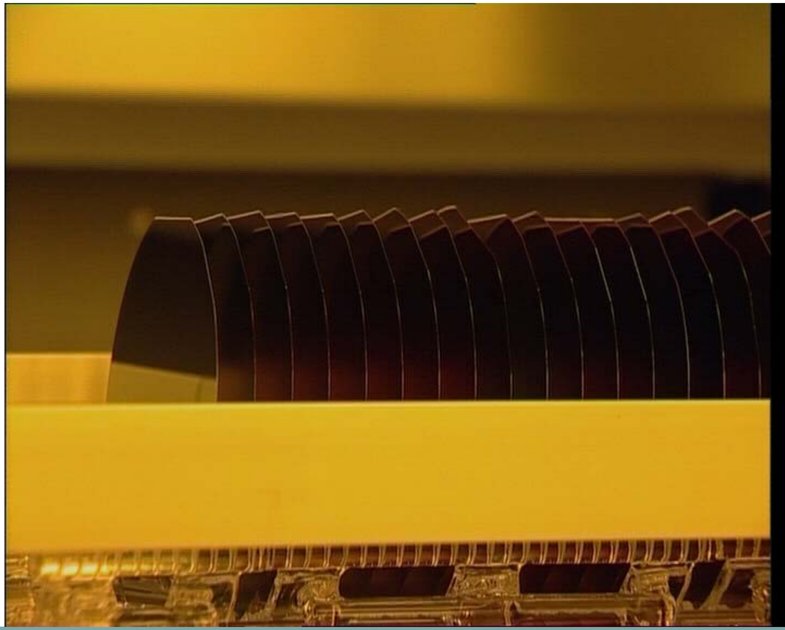
3. **Density: $\rho = 2 - 10\ \mathrm{g\ cm^{-3}}$**
   → high energy loss per unit length
   → low range of δ - electrons

This leads to:

good energy resolution
high spatial resolution
high quantum and detection efficieny
good mechanical regidity and thermal conductivity

Semiconductors equally offer:

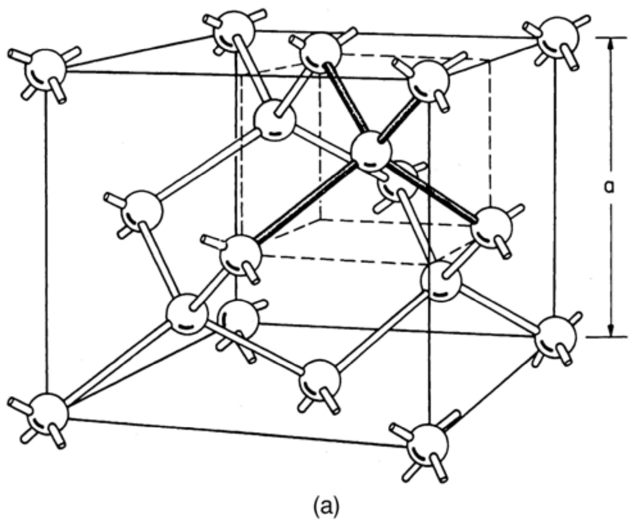
fixed space charges
high mobility of charge carriers



Semiconductor Physics,crystal stucture

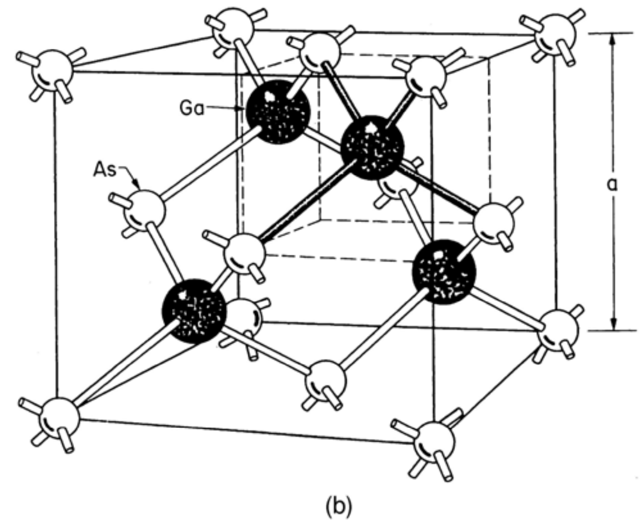
Crystal structure of most commonly used semiconductors:

Si ; Ge



Diamond lattice

GaAs

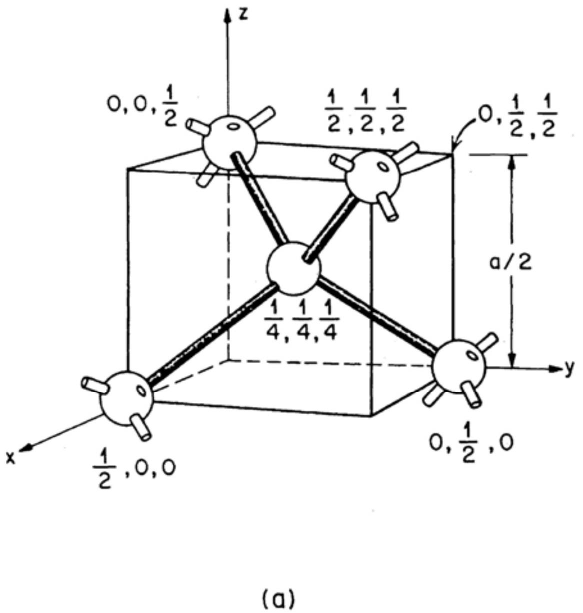


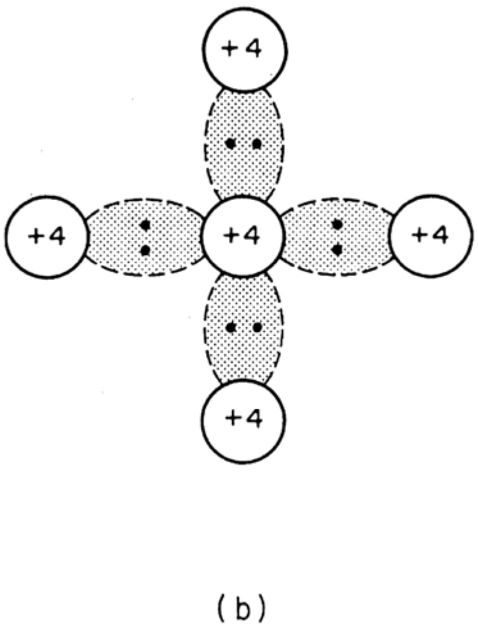
Zinc blende lattice

Can be considered as two interpenetrating face centered cubic sublattices displaced by one quarter of the diagonal of the cube

Lattice structure

Tetahedron bond to closest neighbors



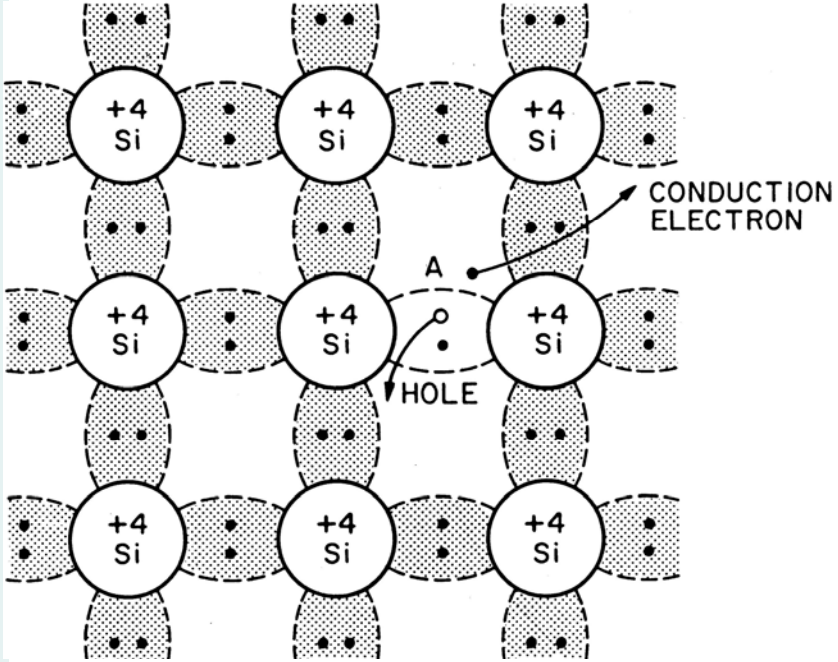


Three dimensional arrangement and symbolic two dimensional representation

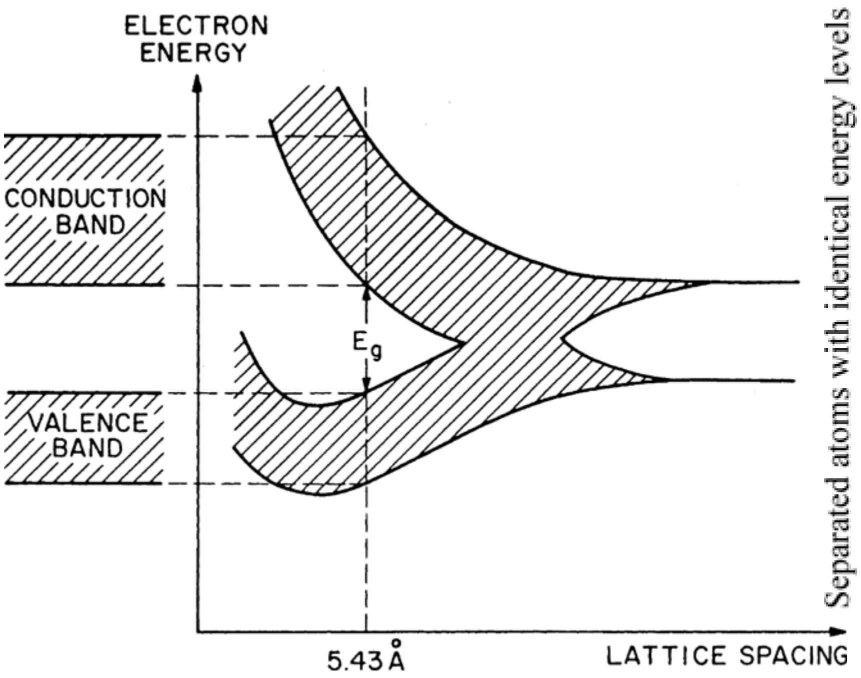
The silicon lattice

Reduce lattice spacing from infinity to lowest potential energy value

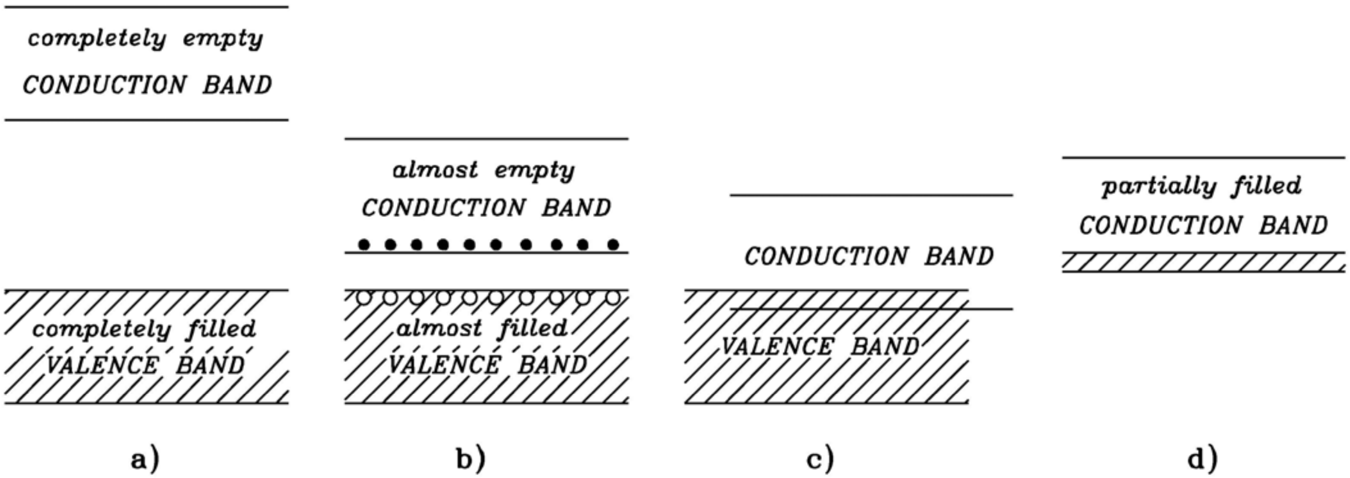
Bond representation



Band representation



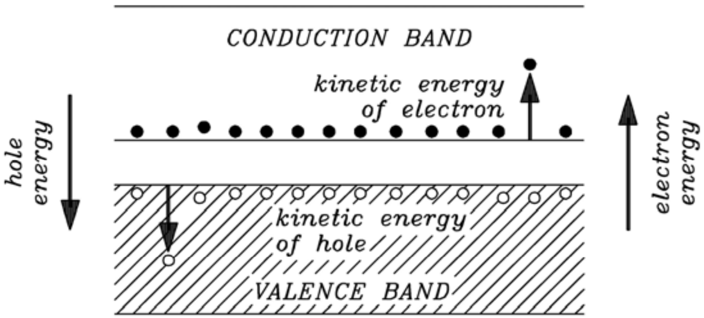
Isolators, conductors and in between



isolator
$E_{gap} \approx 5$ eV

semiconductor
$E_{gap} \approx 1$ eV

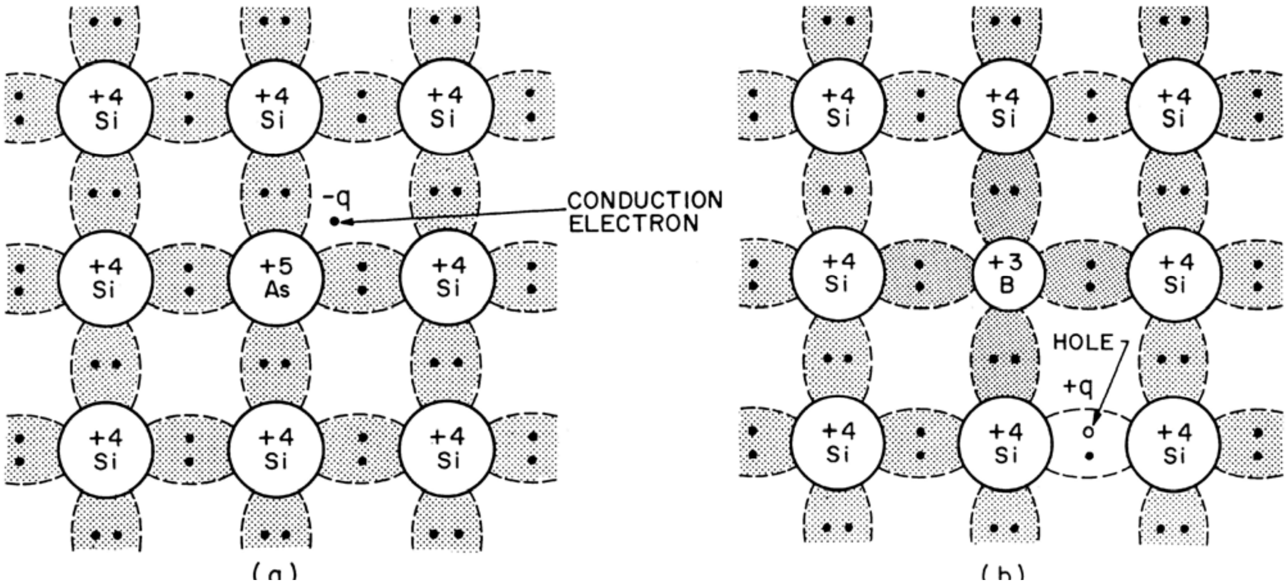
metal



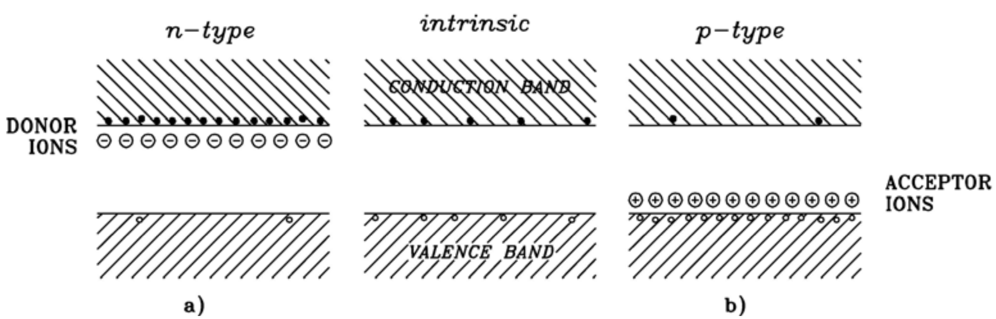
The silicon lattice

n-type **p-type**

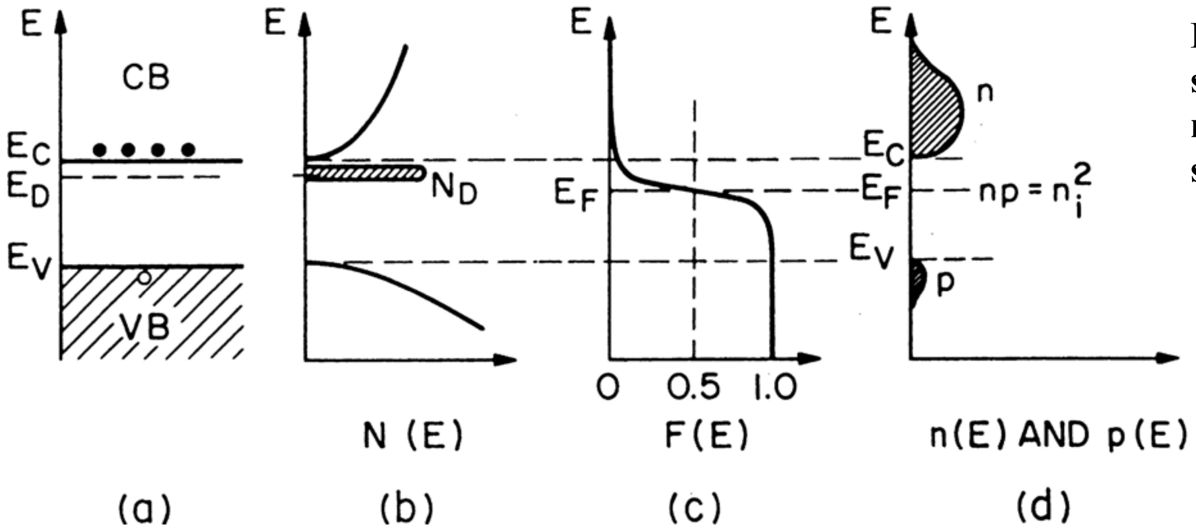
Bond picture



Band representation



Intrinsic and extrinsic semiconductors
Band structure



Localized energy levels shown in this figure not present in intrinsic semiconductors

Energy Band | **Density of States** | **Occupation probability** | **Carrier concentration**

$$F(E) = \frac{1}{1 + \exp\left(\frac{E - E_F}{k \cdot T}\right)}$$

$$N(E_{kin})\, dE_{kin} = 4\pi \cdot \left(\frac{2m}{h^2}\right)^{\frac{3}{2}} E_{kin}^{\frac{1}{2}}\, dE_{kin}$$

$$n = 2\left(\frac{2\pi m_n kT}{h^2}\right)^{\frac{3}{2}} e^{-\frac{E_C - E_F}{kT}} = N_C e^{-\frac{E_C - E_F}{kT}}$$

$$p = 2\left(\frac{2\pi m_p kT}{h^2}\right)^{\frac{3}{2}} e^{-\frac{E_F - E_V}{kT}} = N_V e^{-\frac{E_F - E_V}{kT}}$$

Carrier transport

Drift (acceleration between random collisions)

$$\vec{v}_n = -\frac{q \cdot \tau_c}{m_n}\mathcal{E} = -\mu_n \mathcal{E}$$

$$\vec{v}_p = \frac{q \cdot \tau_c}{m_n}\mathcal{E} = \mu_p \mathcal{E}$$

Diffusion

$$\vec{F}_n = -D_n \nabla n$$

$$\vec{F}_p = -D_p \nabla p$$

Current density (drift and diffusion)

$$\vec{J}_n = q\mu_n n\mathcal{E} + qD_n \nabla n$$

$$\vec{J}_p = q\mu_p p\mathcal{E} - qD_p \nabla p$$

Einstein equation

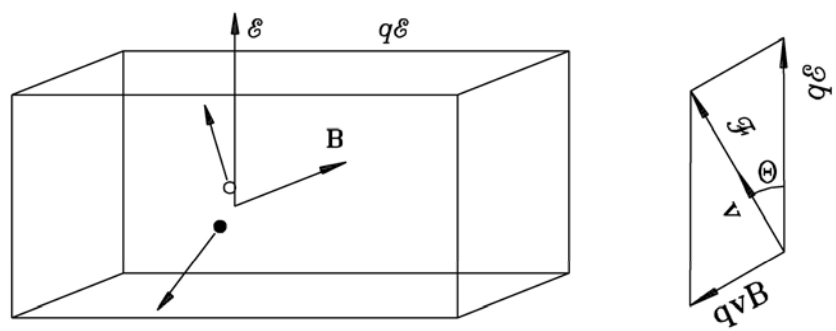
$$D_n = \frac{kT}{q}\mu_n$$

$$D_p = \frac{kT}{q}\mu_p$$

Inside magnetic field

$$\tan\theta_p = \mu_p^{\mathrm{H}}\mathcal{B}$$

$$\tan\theta_n = \mu_n^{\mathrm{H}}\mathcal{B}$$



Continuity equations

Simultaneous consideration of

Generation

Recombination

Drift

Diffusion

$$\frac{\partial n}{\partial t} = \mu_n n \nabla \mathcal{E} + D_n \nabla^2 n + G_n - R_n$$

$$\frac{\partial p}{\partial t} = -\mu_p p \nabla \mathcal{E} + D_p \nabla^2 p + G_p - R_p$$

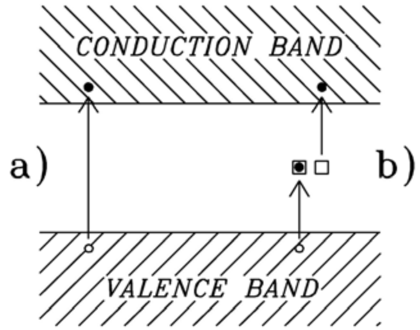
Drift due to electric field derived from Poisson Equation

$$\nabla \mathcal{E} = \frac{\rho}{\epsilon \epsilon_0} \quad , \quad \text{with } \rho = q(p - n + N_\mathrm{D} - N_\mathrm{A})$$

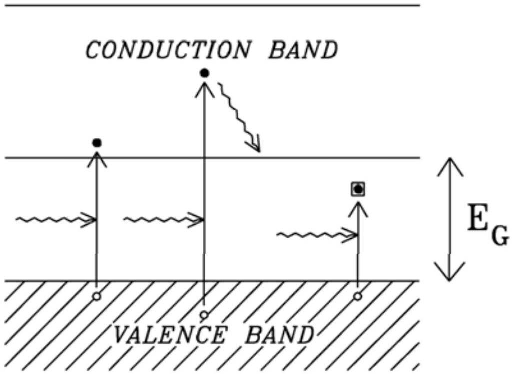
Numerical simulation: simultaneous solution of diffusion and Poisson equation with boundary conditions

Charge carrier generation

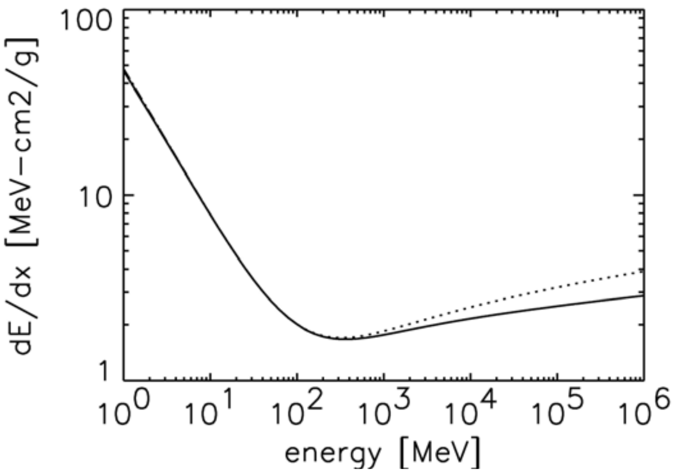
Thermal generation



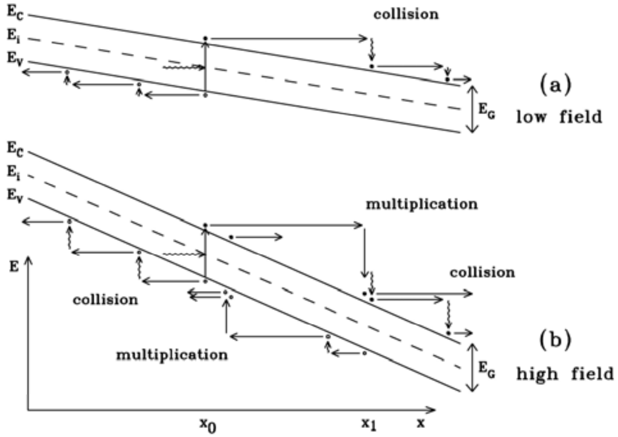
By photons



By charged particles (Bethe-Bloch)



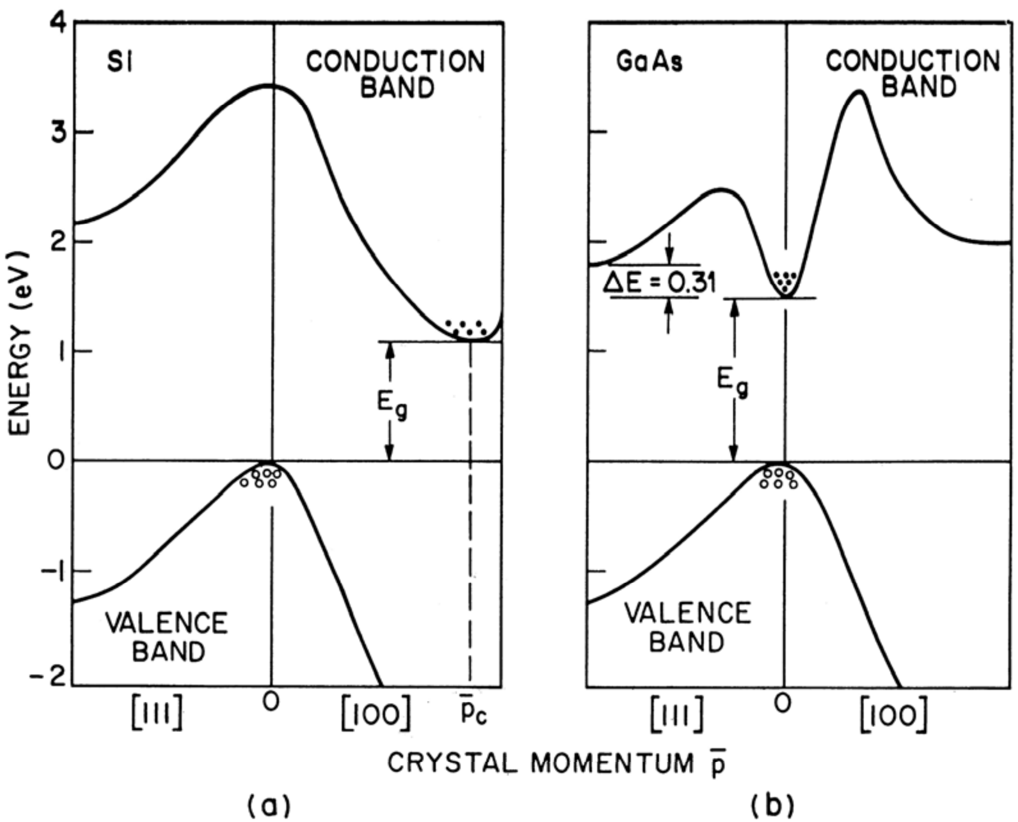
Charge multiplication



Recombination

♦ Direct and indirect semiconductors

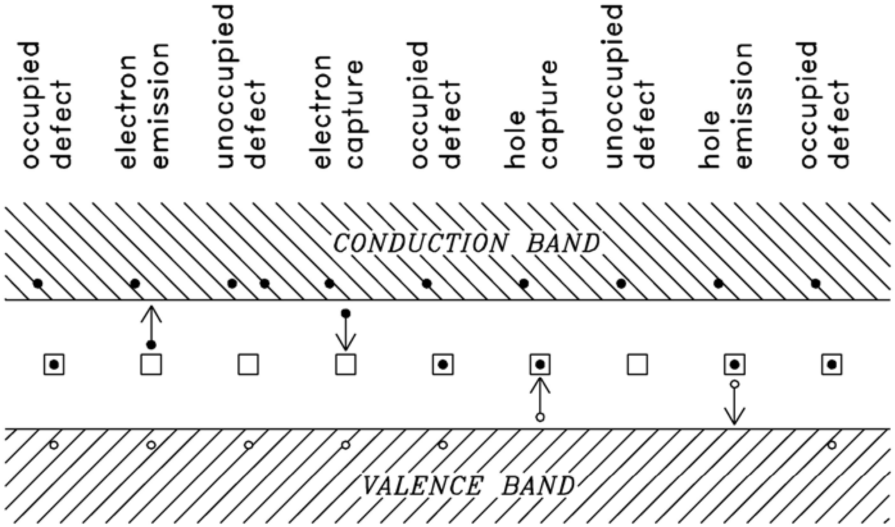
Si
indirect



GaAs
direct

Charge carrier lifetimes

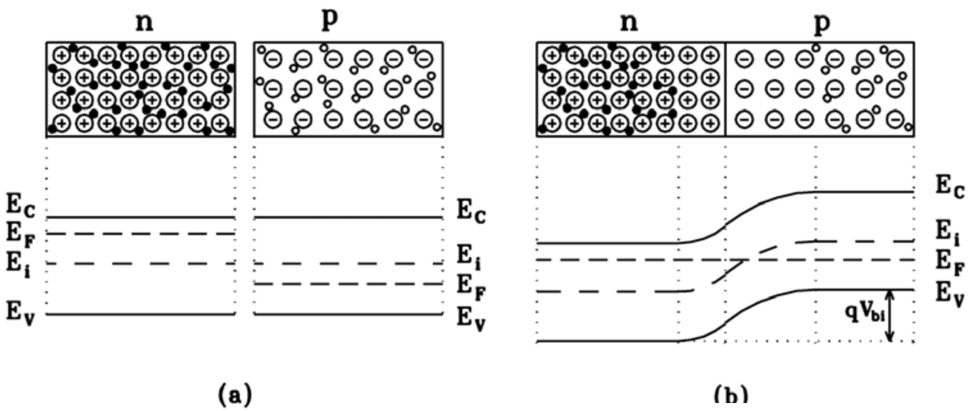
- Generation and recombination through two step processes



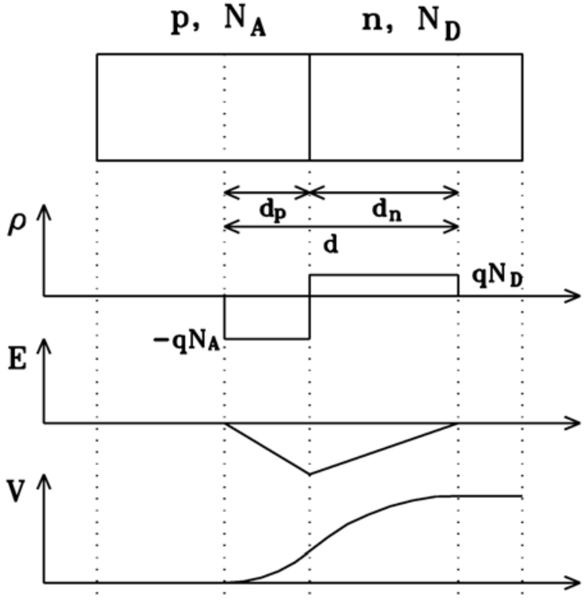
- Characterized by lifetimes
- Generation and recombination lifetimes are differently defined:
  - Recombination: return to equilibrium in neutral semiconductor (emission and capture processes)
  - Generation: approach to intrinsic carrier density in fully depleted semiconductor (emission processes only)

BASIC STRUCTURES
p-n junction

- **Connection between n-type and p-type semiconductor:**

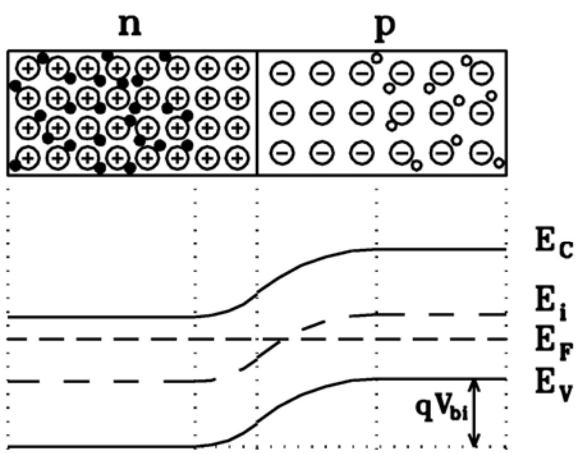


Approximation: abrupt change from neutral semiconductor to space charge region



p-n junction

- Thermal equilibrium
  - Constant Fermi level
  - Drift current equal diffusion current
  - Built in voltage



Shallow dopands majority carriers

$$n_n = N_D = n_i \, e^{\frac{E_F - E_i^n}{kT}}$$

$$p_p = N_A = n_i \, e^{\frac{E_i^p - E_F}{kT}}$$

$$N_A \cdot N_D = n_i^2 \, e^{\frac{E_i^p - E_i^n}{kT}}$$

Built in voltage

$$V_{bi} = \frac{1}{q}(E_i^p - E_i^n) = \frac{kT}{q} \ln \frac{N_A N_D}{n_i^2}$$

$$= 0.0259 \; \ln \frac{10^{16} \cdot 10^{12}}{(1.45 \times 10^{10})^2} = 0.458 \, \mathrm{V}$$

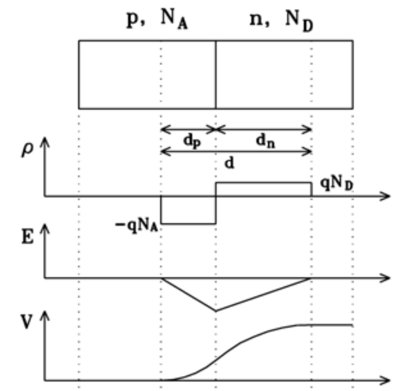
Example: high doped n (1e16) on low doped p(1e12)

p-n junction

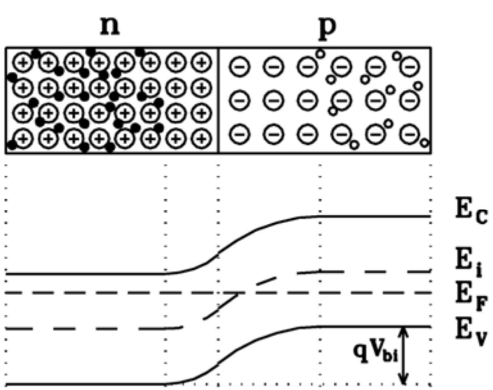
Application of an exteral voltage

- Change extent of space charge region

$$d = \sqrt{\frac{2\epsilon\epsilon_0(N_\mathrm{A}+N_\mathrm{D})}{qN_\mathrm{A}N_\mathrm{D}}(V_\mathrm{bi}-V)}$$



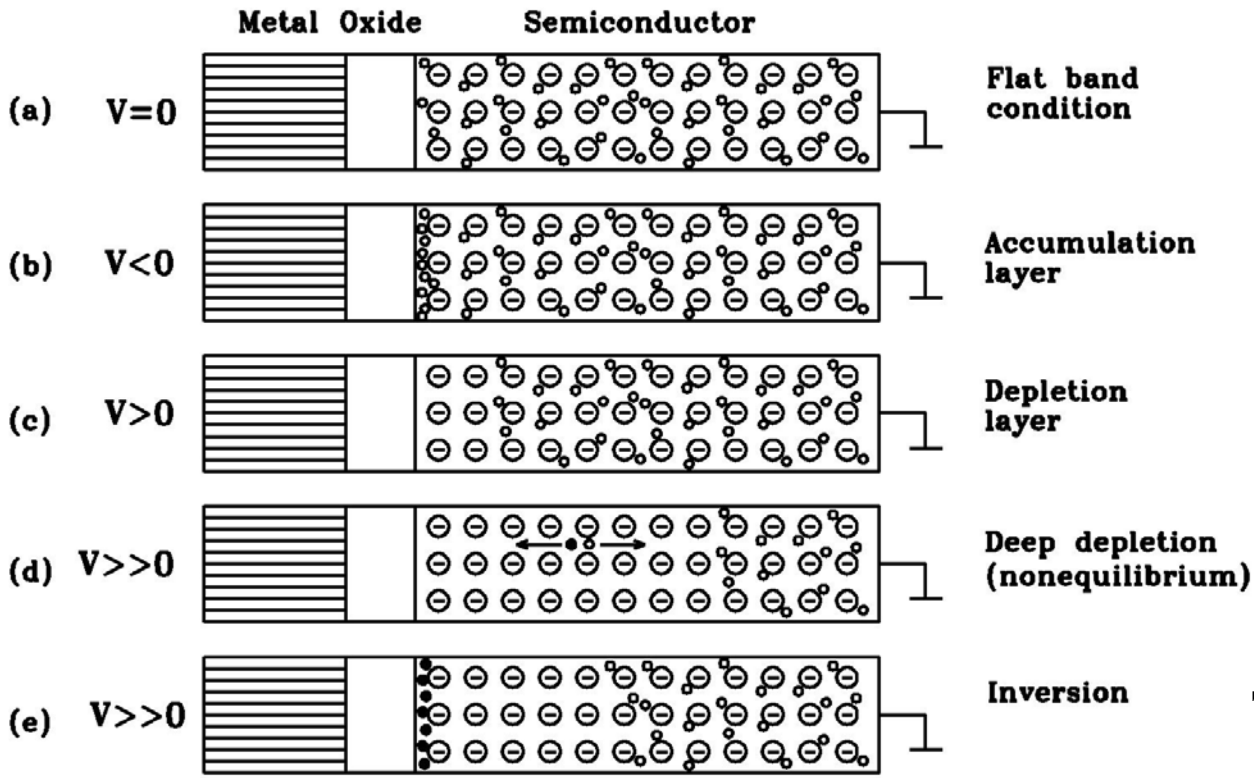
- Non-equilibrium: Fermi level not defined
- Drift current not equal diffusion current
- Diffusion of minority carriers into (out of) space charge region



$$J = (J_{\mathrm{s}_n} + J_{\mathrm{s}_p})\left(\mathrm{e}^{\frac{qV}{kT}} - 1\right) = J_\mathrm{s}\left(\mathrm{e}^{\frac{qV}{kT}} - 1\right)$$

$$J_\mathrm{s} = q\left(\frac{n_{p_0}D_n}{\sqrt{D_n\tau_{\mathrm{r}_n}}} + \frac{p_{n_0}D_p}{\sqrt{D_p\tau_{\mathrm{r}_p}}}\right)$$

MOS (Metal-Insulator-Semiconductor) Structure



CCD

Transistor

or)

Basic structure in MOS transistor and in MOS CCDs

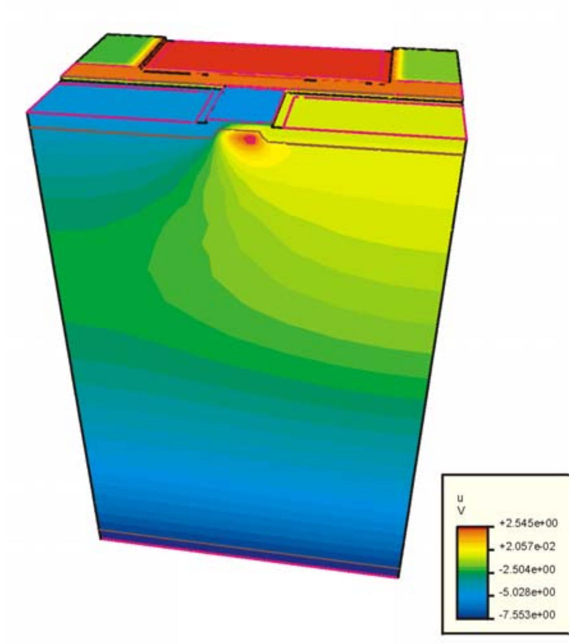
Semiconductors as Nuclear Radiation Detectors

Outstanding Material Properties

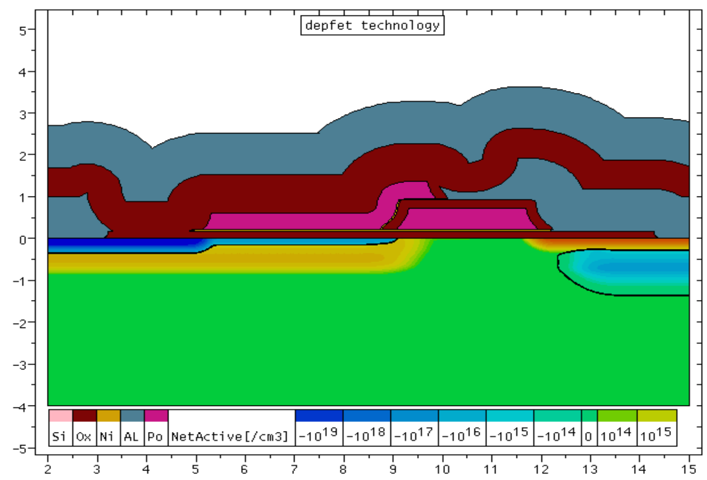
- small band gap (Si 1.12eV) ⇒ low e-h pair generation energy (Si 3.6 eV) (ionisation energy for gases ≈ 30 eV)
- High density (Si 2.33 g/cm²) ⇒ large energy loss/length for ionising particles ⇒ thin detectors; small range δ-electrons; precise position measurement
- Almost free movement of electrons and holes
- Mechanical rigidity; self supporting structure
- Doping creates fixed space charges; building of sophisticated field structures
- integration of detector and electronics in single device

Detector and electronics simulation and layout

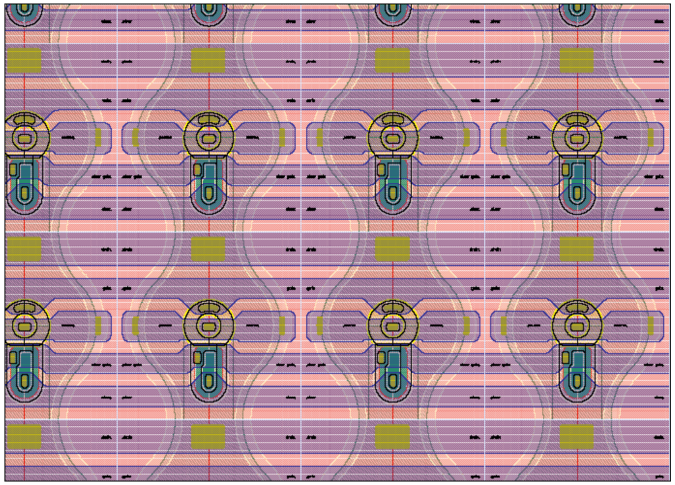
1. The detector idea: simulation of electrical properties



2. Simulationof the production process



3. Design and layout of the entire detetor system, including signal processing and DAQ



Detector and electronics fabrication

4. **Fabrication facility at the MPI - HLL**

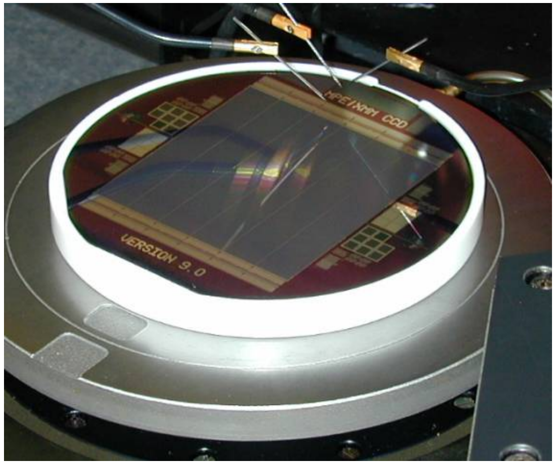
from outside

and from inside

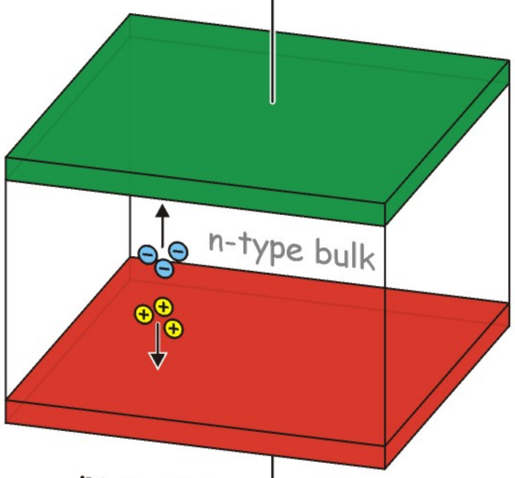
5. **Quality assurance and control**

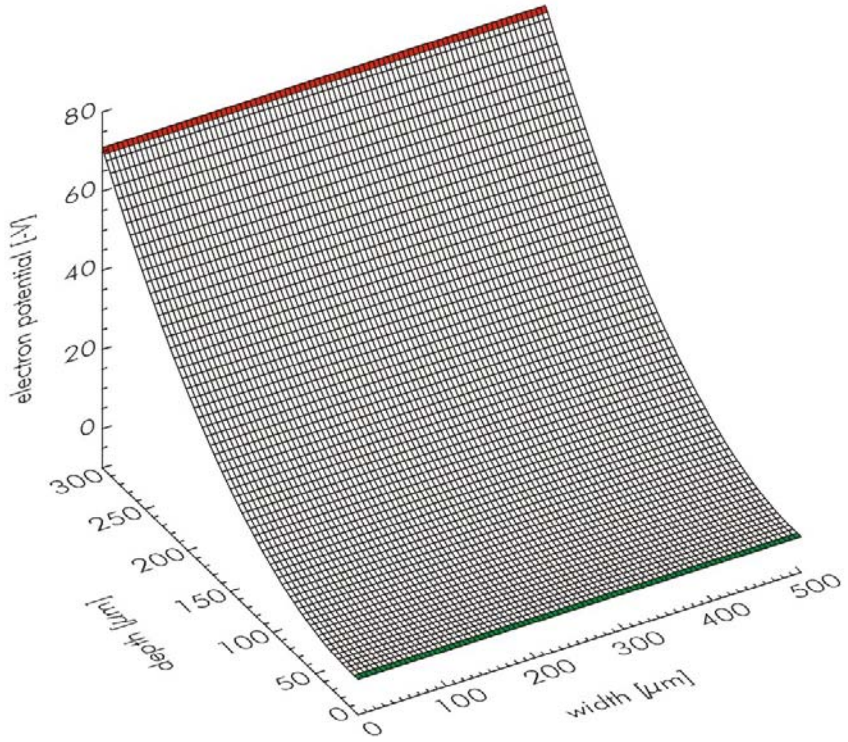
6. **Separation, mounting, bonding**

7. **System test, field test, data analysis and modelling**



Diode type detectors

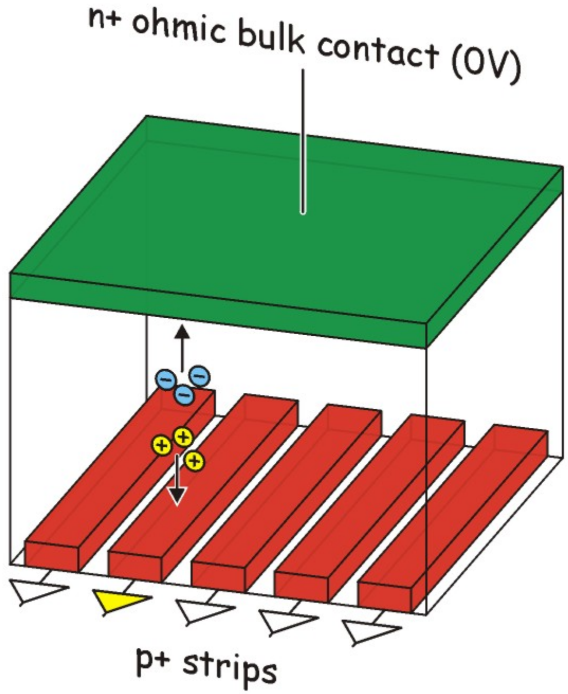


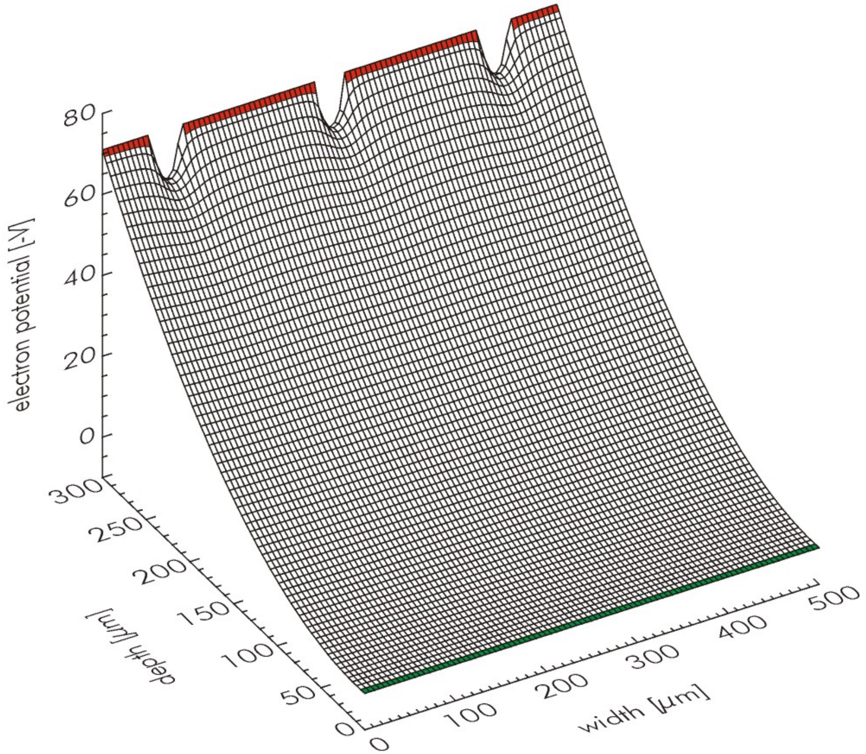


$$C = \frac{A\varepsilon_r \varepsilon_0}{d}$$

$$d = \sqrt{\frac{2\epsilon\epsilon_0(N_{\mathrm{A}} + N_{\mathrm{D}})}{qN_{\mathrm{A}}N_{\mathrm{D}}}(V_{\mathrm{bi}} - V)}$$

Structured Diode – Strip Detector

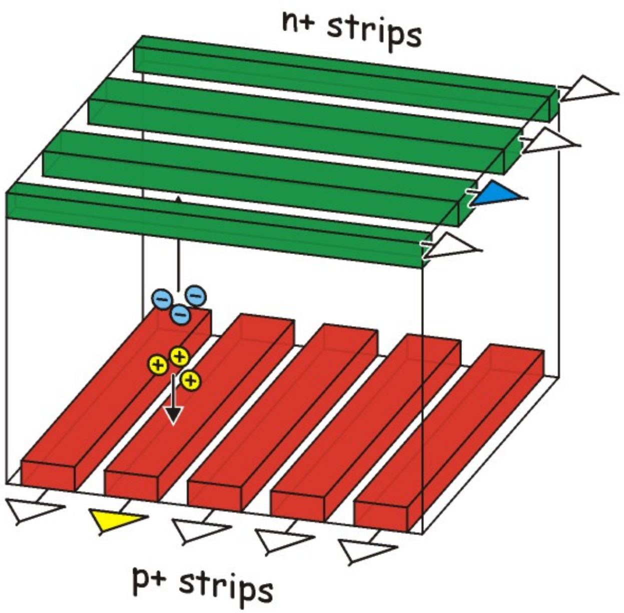


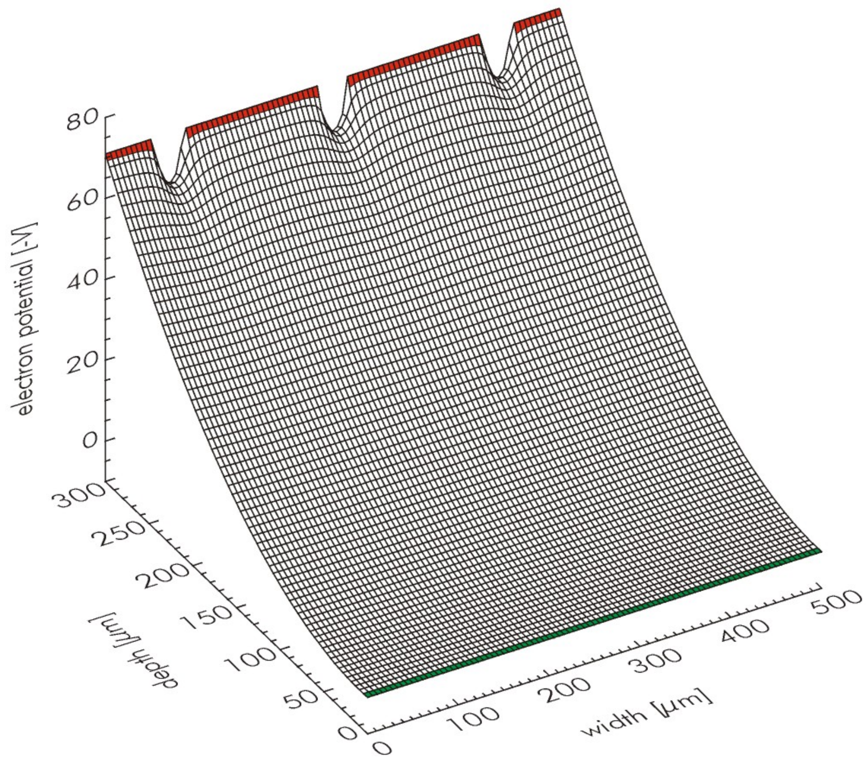


particle tracking = detection of individual charged particles

1D resolution

Structured Diode – Strip Detector





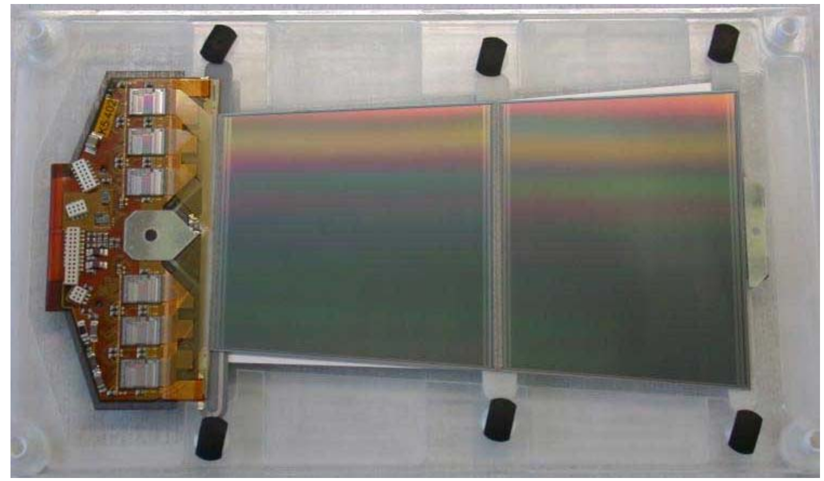
particle tracking

2D resolution

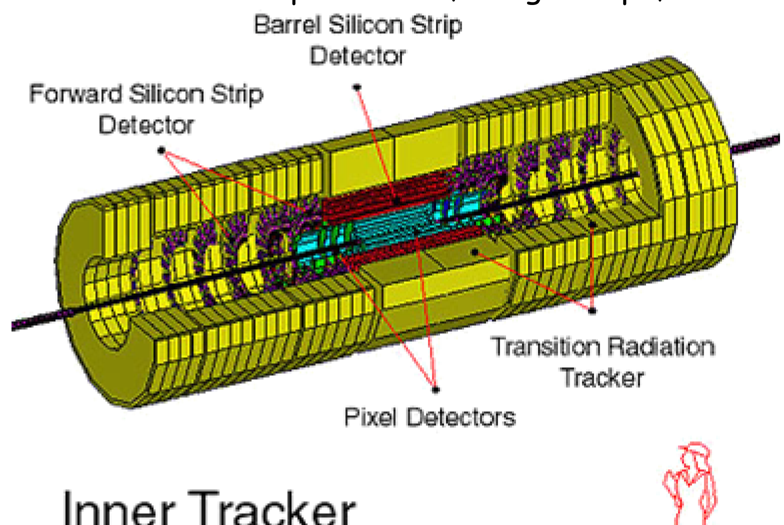
Strip Detector example

ATLAS Silicon Tracker @ CERN LHC

application	
particle tracking	
strip detector	
format	6 x 6 cm² x 280 µm
	single-sided
	p-strips on n-substrate
strips	768
strip pitch	80 µm
strip width	20 µm
resolution	23 µm rms
readout	ac-coupled, binary
strip capacitance	20 pF/cm coupling
	1 pF/cm interstrip
ATLAS silicon tracker	
55 m² of silicon strip and pixel detectors!	



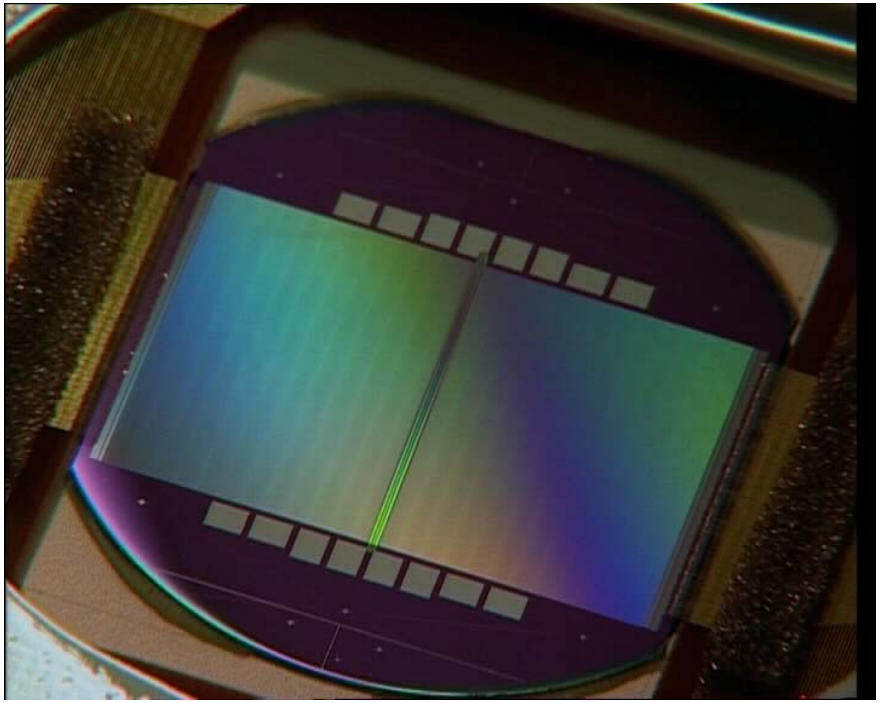
ATLAS strip detector, wedge shape, forward

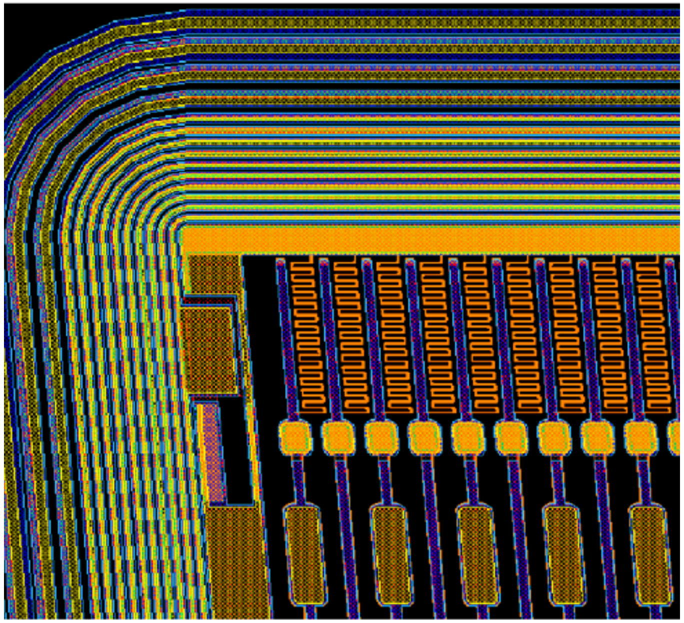


Silicon strip detectors for position resolution

First strip detector: NA11 experiment at CERN (1980):

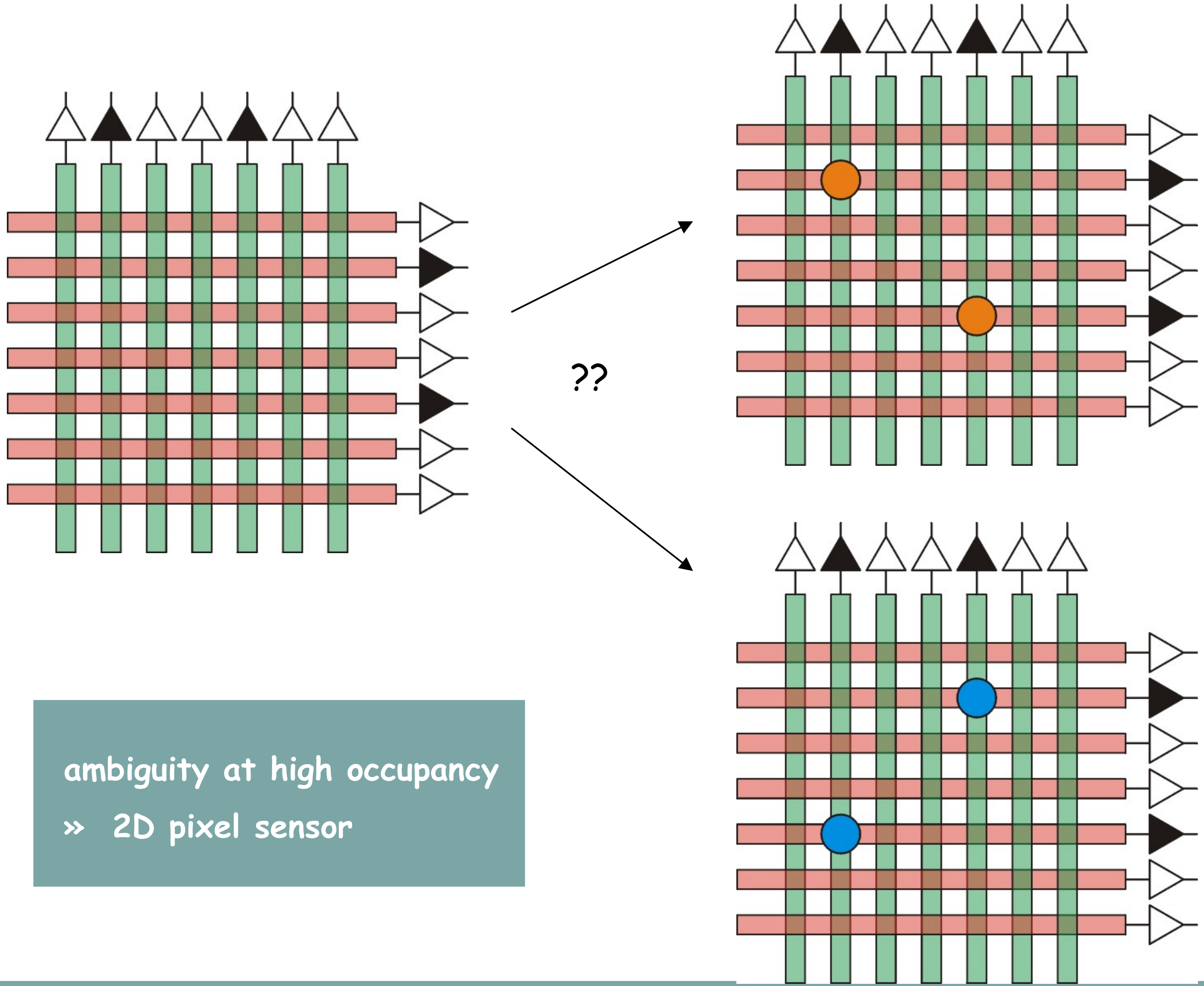
Hadronic charm production





Detector detail for the ATLAS SSD (2004)

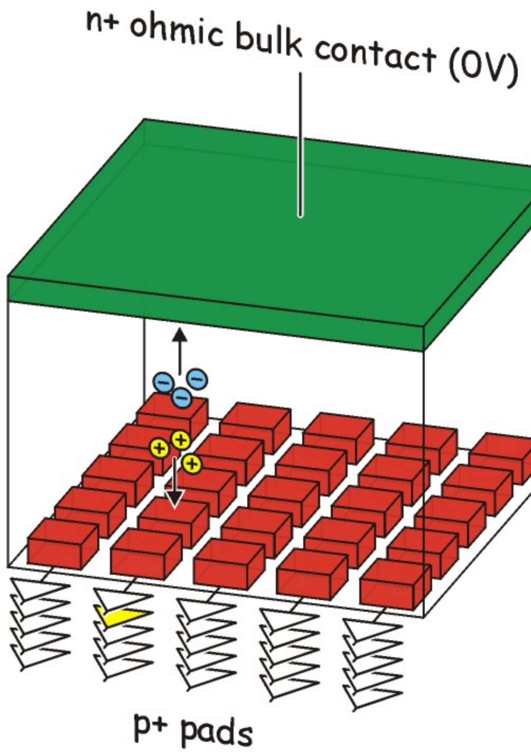
Strip Detector - Limitation



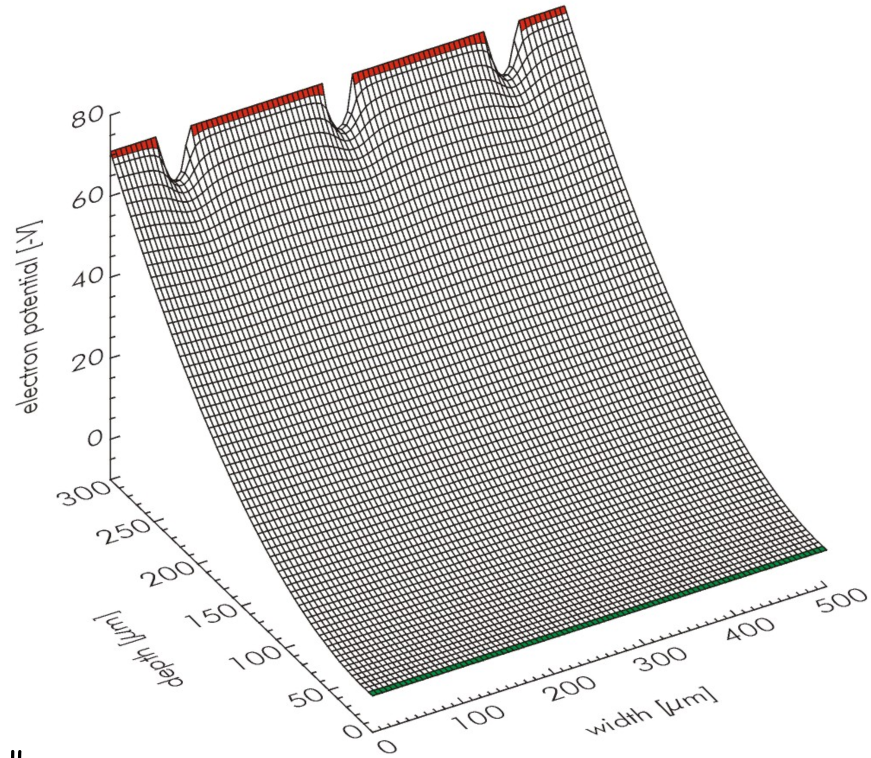
ambiguity at high occupancy

» 2D pixel sensor

Structured Diode – Pad Detector / Pixel Sensor



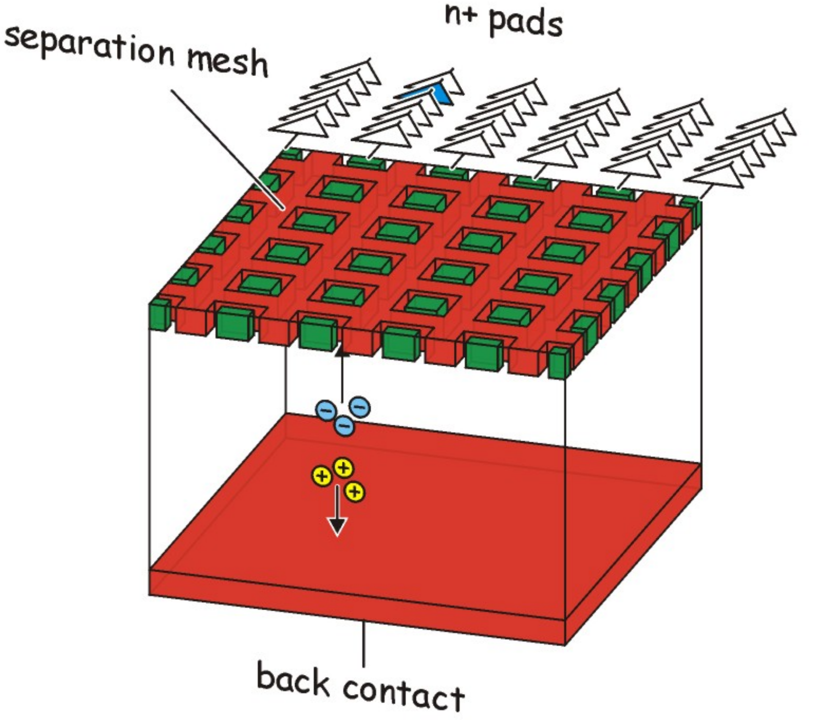
"p on n"

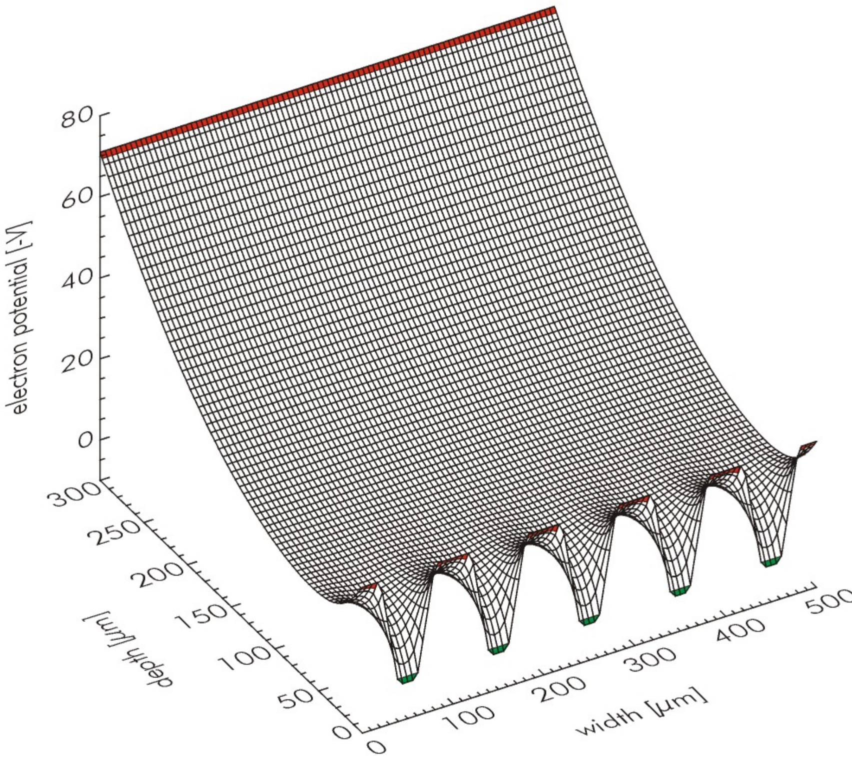


2D resolution

- particle tracking = detection of individual charged particles
- imaging = count / integrate particles or photons

Structured Diode – Pad Detector / Pixel Sensor



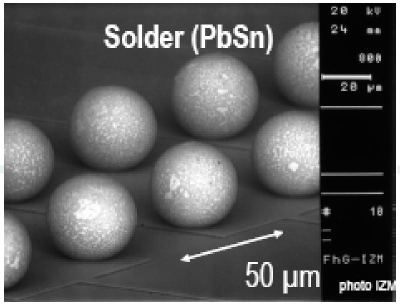


"n on n"

2D resolution

- particle tracking = detection of individual charged particles
- imaging = count / integrate particles or photons

Hybrid Pixel Sensor

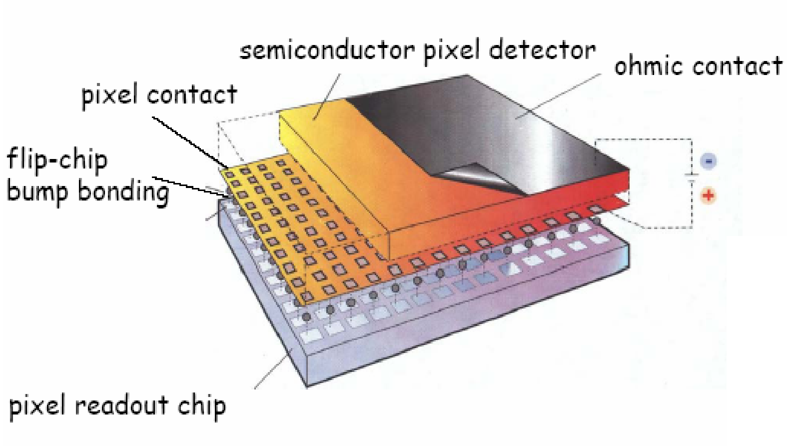


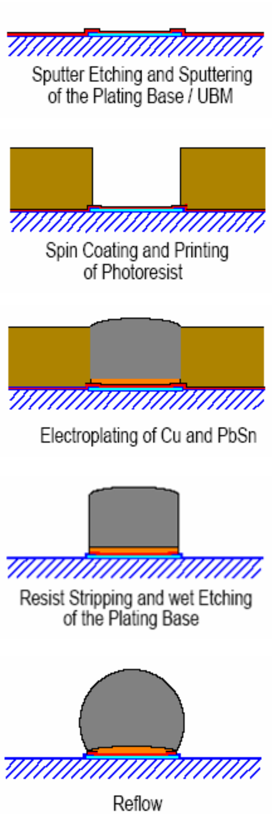
1 preamp per pixel!

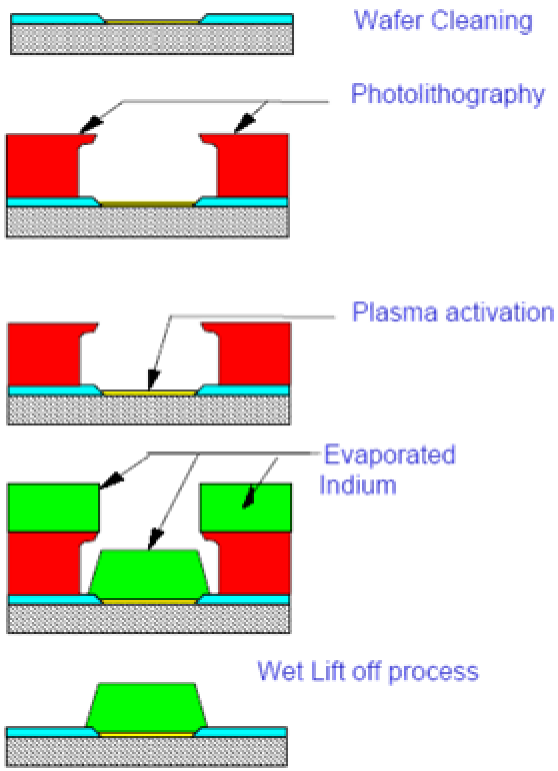
» front-to-front mounting of detector and readout chip ("bump bonding")

electroplating / reflow solder (PbSn) bumps

"lift-off" Indium bumps







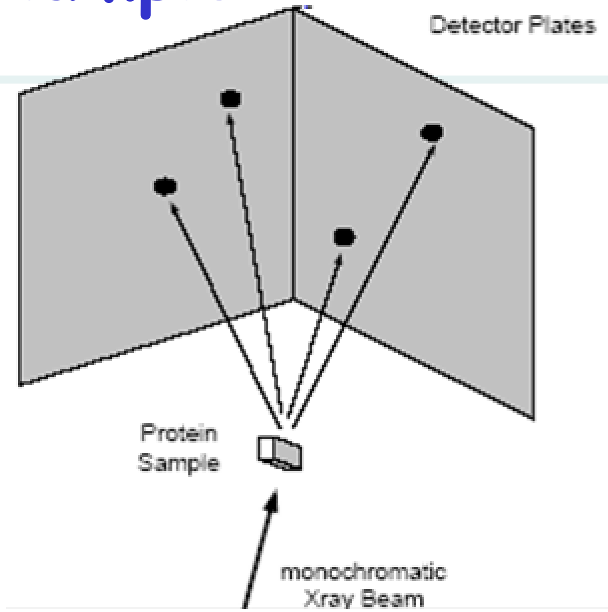
Hybrid Pixel Sensor example 1

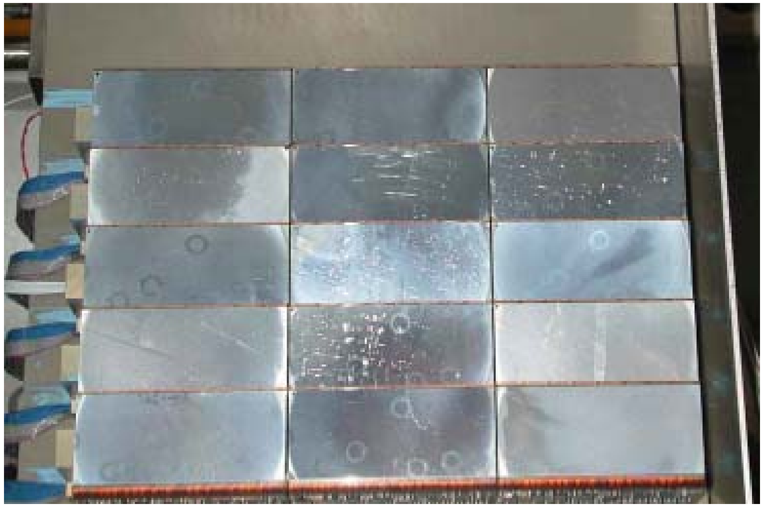
PILATUS @ SLS / PSI

application:

- imaging, protein crystallography

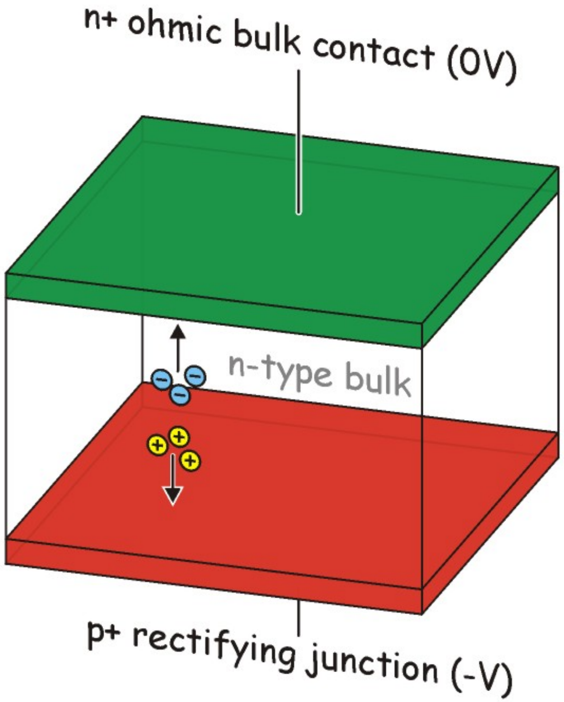
pixel sensor	
format	36 x 80 mm ^{2} x 300 μm
	157 x 366 pixels
	n-pixels on n-substrate
pixel size	217 x 217 μm^2
count rate	max. 10^6 sec^{-1}
dynamic range	> 10^4
PILATUS detector	
modules	3 x 5
total area	20 x 24 cm^2
pixels	0.85 M





PILATUS plate

Diode



electronic noise

$$C = \sqrt{a \frac{2kT}{g_m} C_{tot}^2 A_1 \frac{1}{\tau} + 2\pi a_f C_{tot}^2 A_2 + q I_L A_3 \tau}$$

thermal noise — 1/f noise — leakage

optimum shaping time

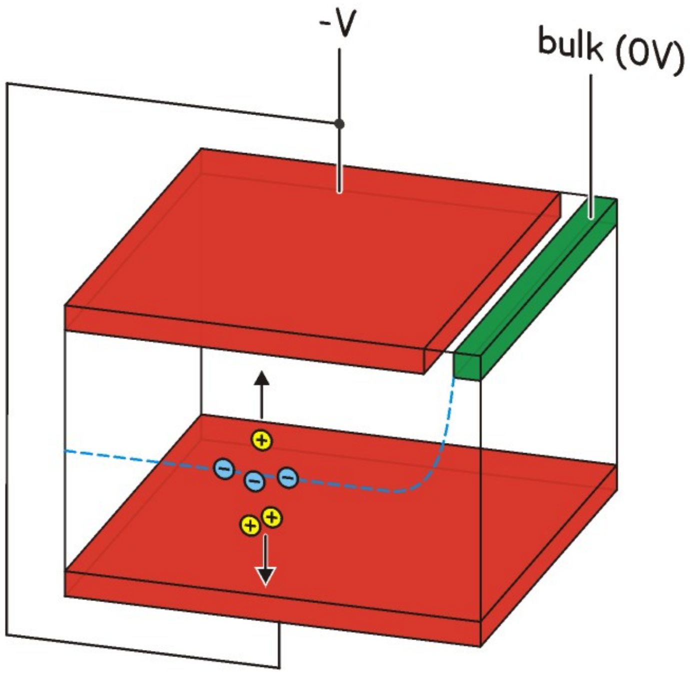
$$\mathrm{pt} = \sqrt{\frac{2A_3}{A_1} \frac{kT}{q} \frac{C_{tot}^2}{I_L} \frac{2}{3g_m}}$$

» For

- **good resolution**
- **high count rate capability**

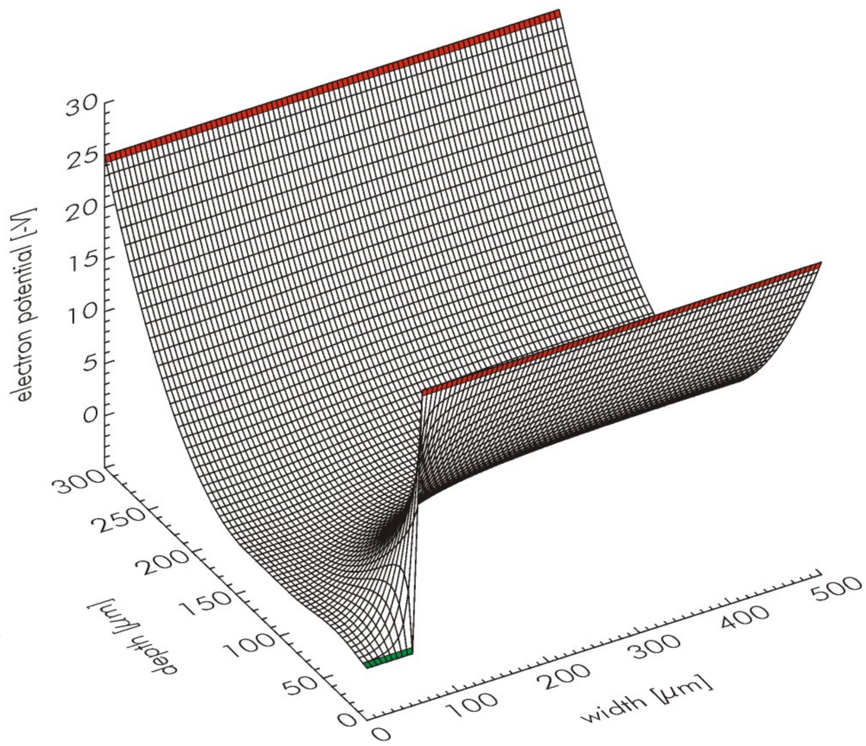
the total capacitance must be minimised!!

Sideward Depletion Structure



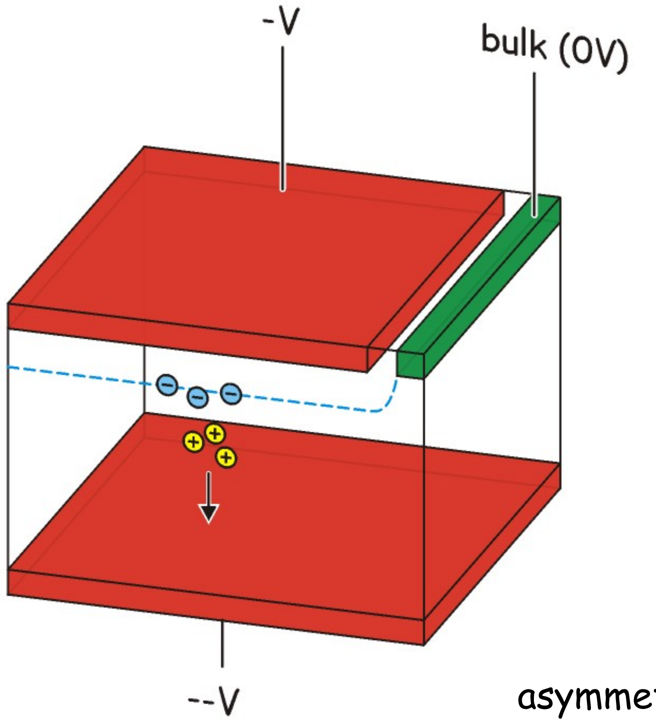
symmetric bias

Emilio Gatti & Pavel Rehak, 1983



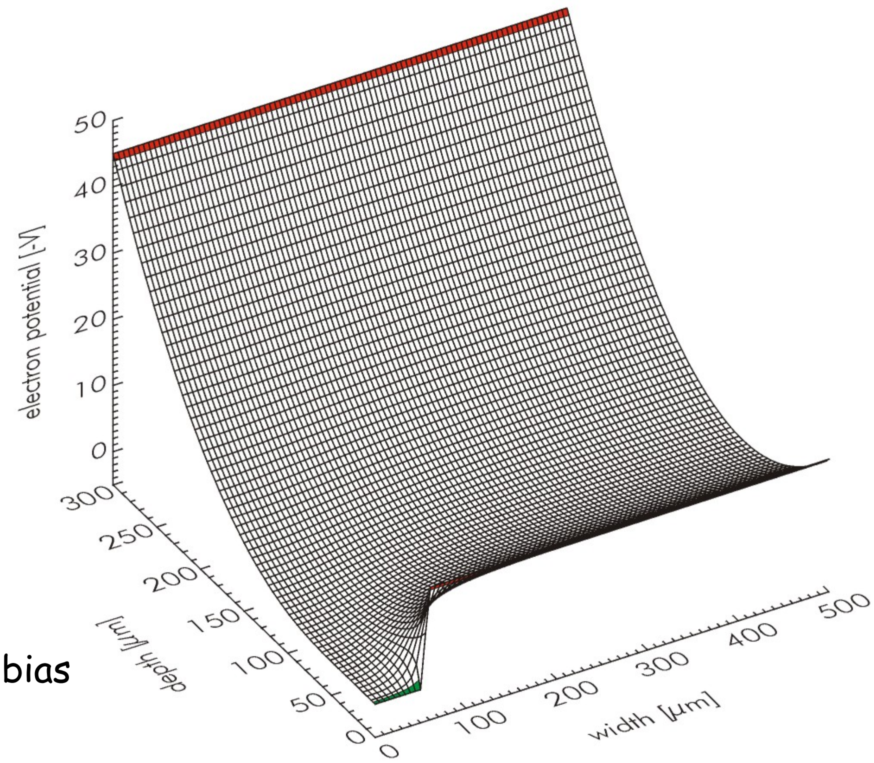
- fully depleted volume
- minimum capacitance of bulk contact (independent of sensitive area)

Sideward Depletion Structure



asymmetric bias

Emilio Gatti & Pavel Rehak, 1983

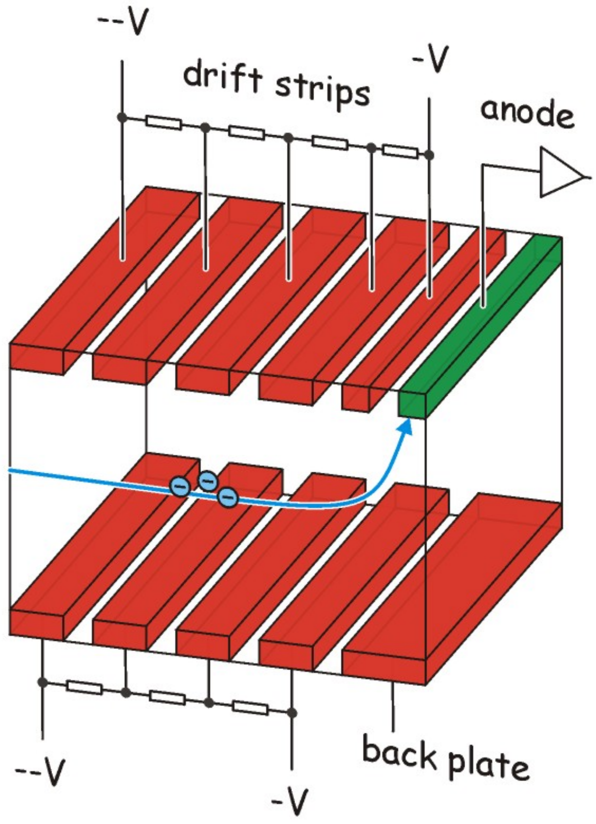


- fully depleted volume
- minimum capacitance of bulk contact (independent of sensitive area)

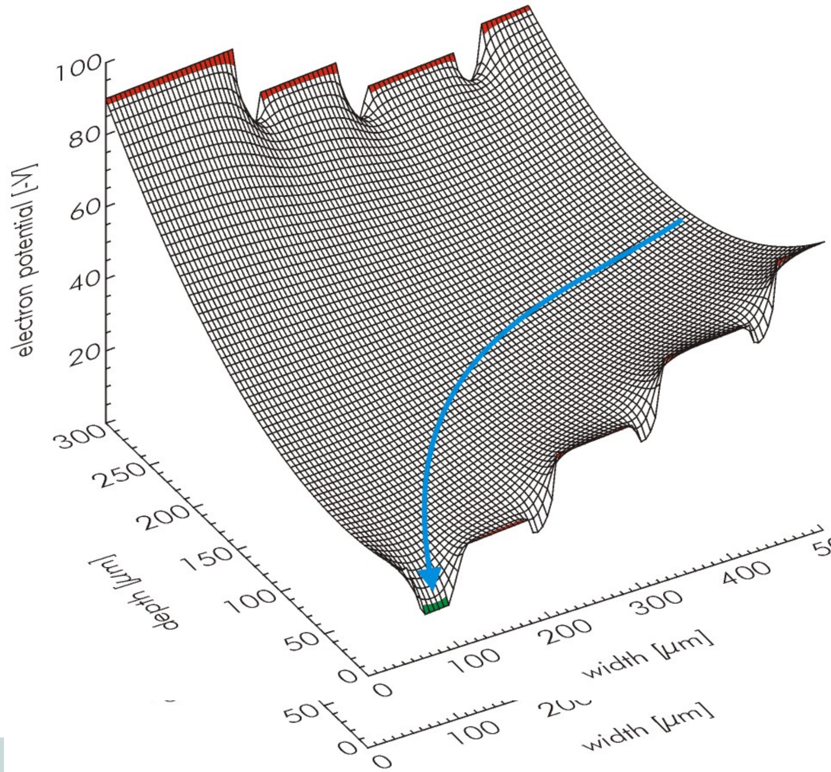
?? signal extraction ??

» advanced detector concepts

Silicon Drift Detector (SDD)



Emilio Gatti & Pavel Rehak, 1984



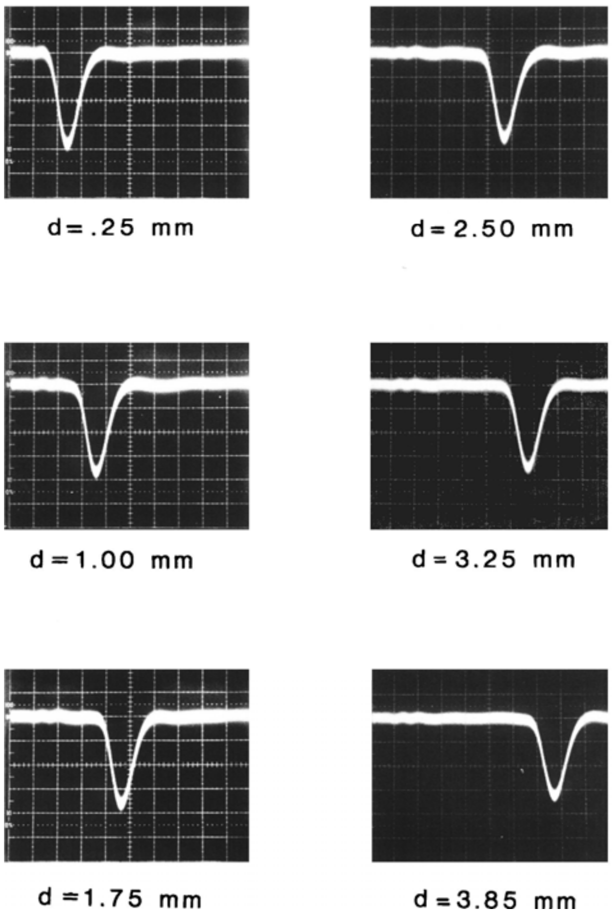
- drift field || surface
- 1D position resolution by drift time measurement

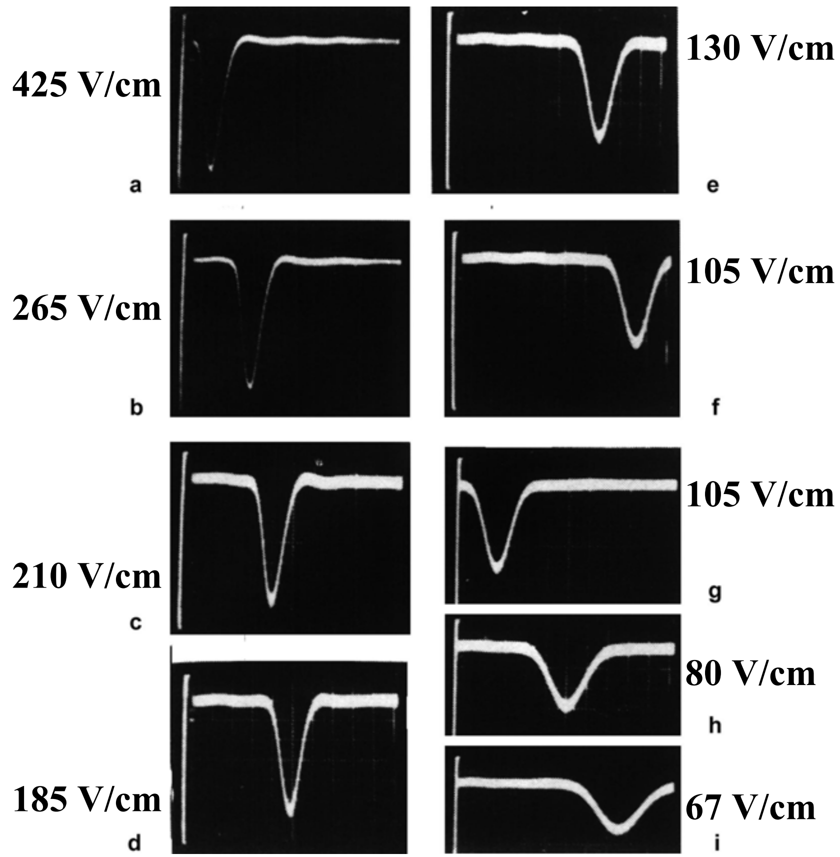
start trigger!!

Drift detector: signal shape
(first measurements by Rehak and Holl, 1985)

PNSensor

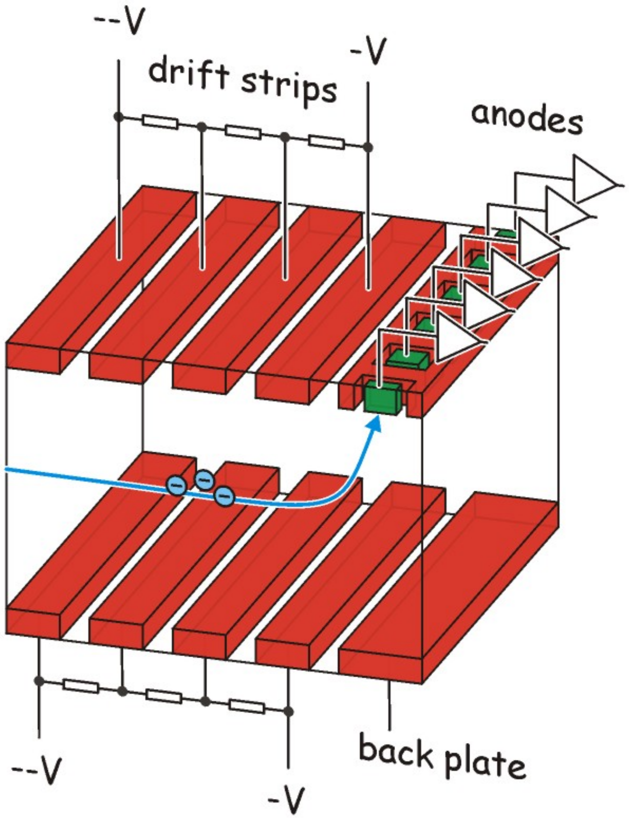
Signal for varying distance — **for varying drift field**



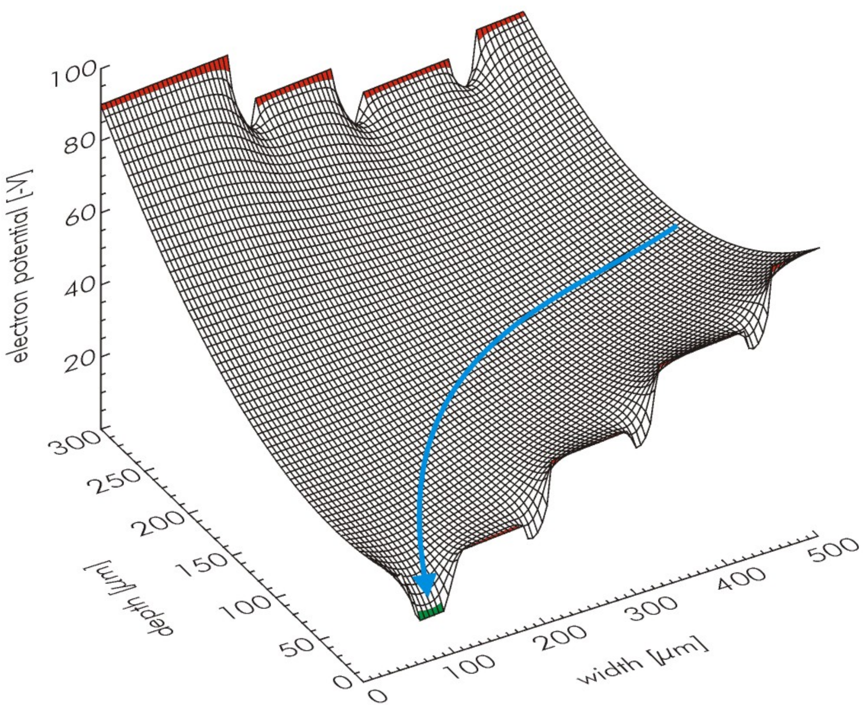


Light pulser 22000e 200 ns/div Light pulser 22000e

Silicon Drift Detector (SDD)



Emilio Gatti & Pavel Rehak, 1984



2D position resolution by

- drift time measurement
- segmentation of the anode

SDD example 1

STAR [1] experiment @ RHIC [2] / BNL [3]

application

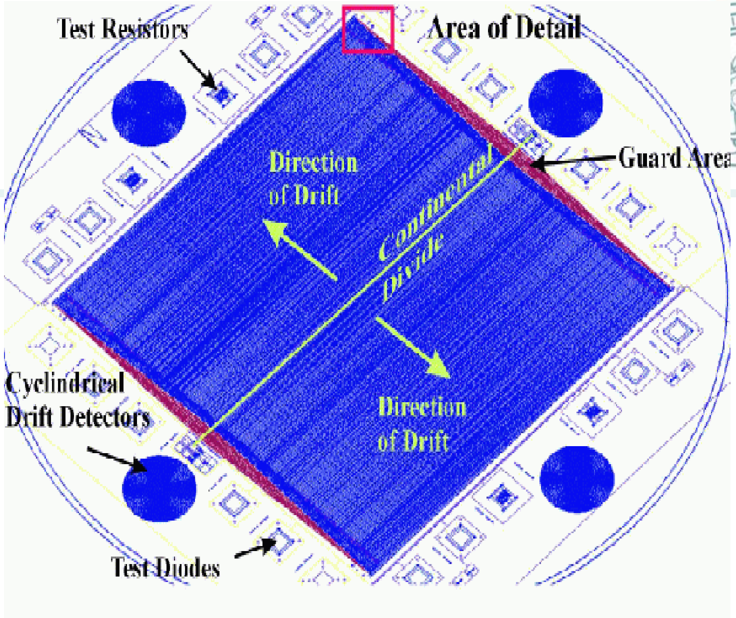
- particle tracking

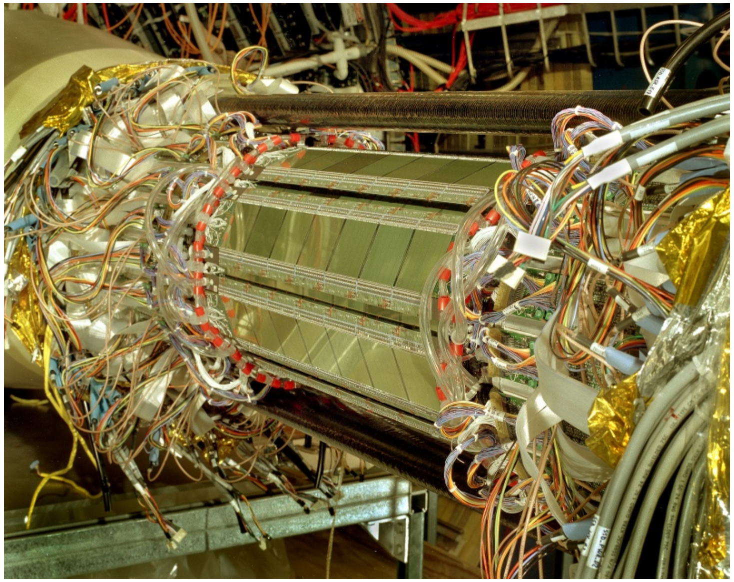
SDD parameters

• format	6 x 6 cm² x 280 µm
	bidirectional drift
• anodes	2 x 240
• anode pitch	250 µm
• drift voltage	1.500 V
• drift time	max. 5 µsec
• resolution	17 µm rms drift
	8 µm rms anode

STAR detector

• 3 barrels	r = 5, 10, 15 cm
• SDDs	216
• readout channels	103.680
• pixels	13.271.040

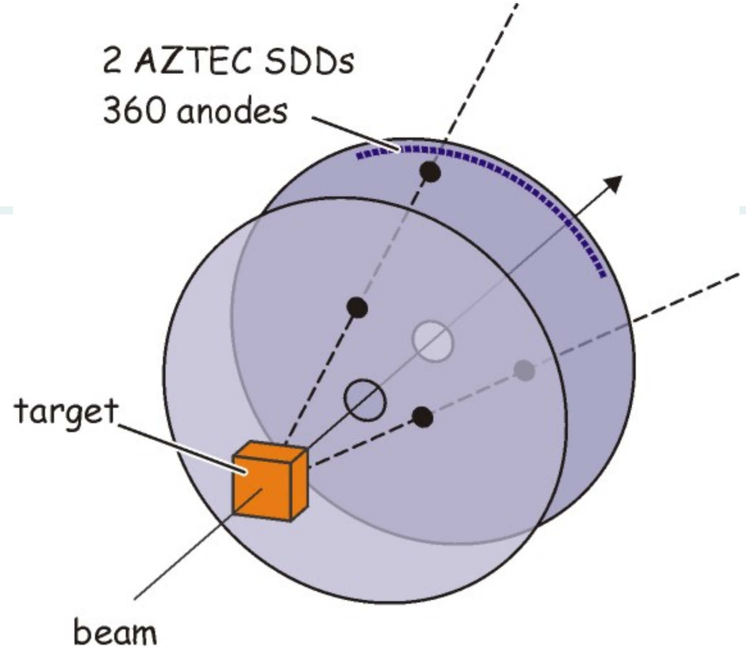




1) Solenoidal Tracker At RHIC
2) Relativistic Heavy Ion Collider
3) Brookhaven National Laboratory

SDD example 2

CERES experiment @ CERN SPS



application

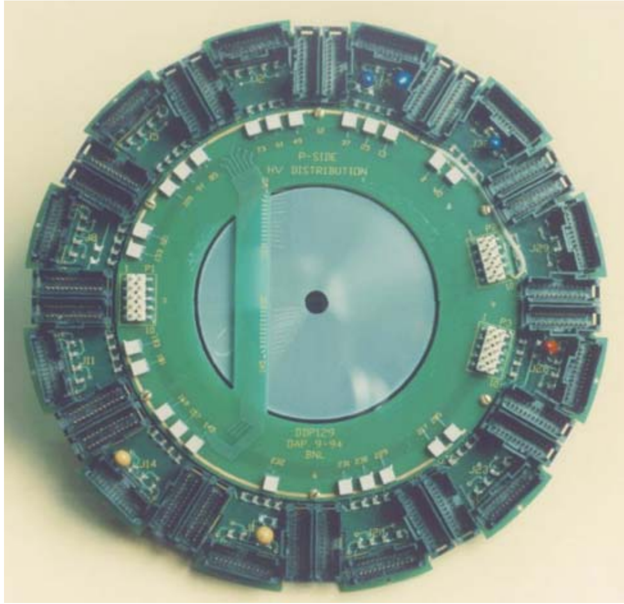
- particle tracking

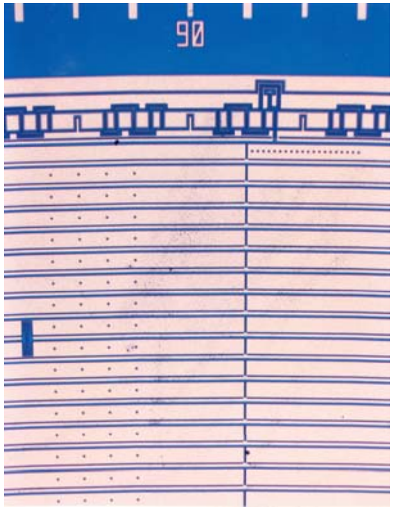
AZTEC SDD parameters

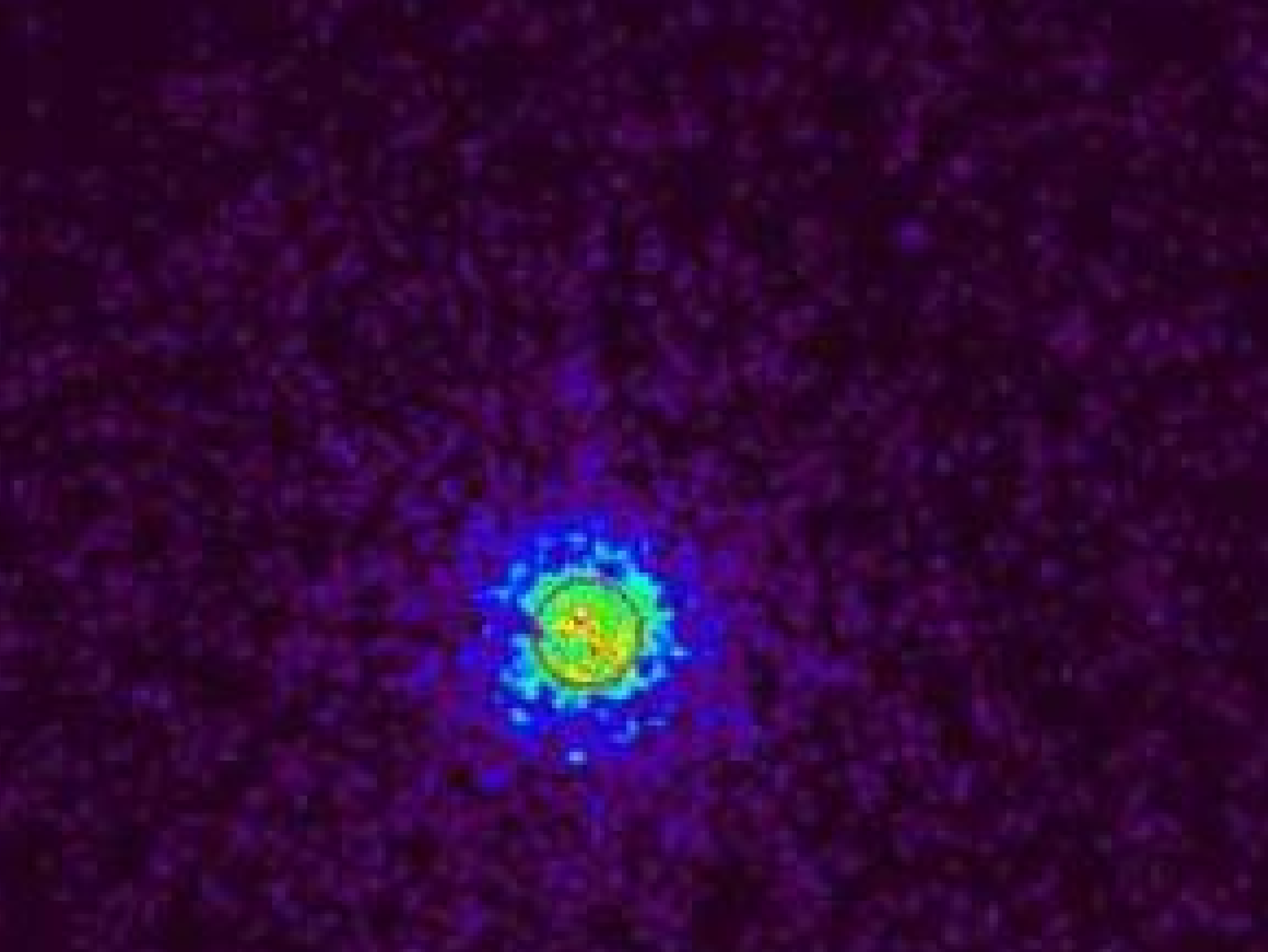
- format — Ø = 10 cm x 280 μm
  - central 6 mm hole
  - radial drift field
- anodes — 360
- anode pitch — 1°
- drift voltage — 2.000 V
- drift time — max. 6 μsec
- resolution — 16 mrad rms angular
  - < 25 μm rms radial

CERES detector

- 2 SDDs
- distance to target 10 cm, 13.8 cm







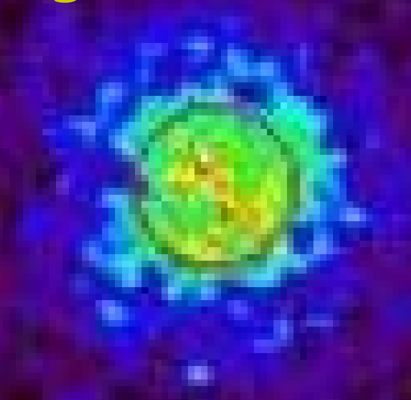
Semiconductor Detectors
applications in basic science and industry

OUTLINE Part II:

1. Semiconductors based on sideward depletion

   (a) the SDD with integrated FET

   (b) the pnCCD

   (c) the CDD

   (d) the DEPFET (active pixel sensor)

2. Avalanche amplifiers
3. Summary and Conclusion