Lecture 2b

Tracking with Solid State Detectors

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Production of a FZ silicon ingot..
... at this stage almost all detectors look still the same

CERN Academic Training Programme 2004/2005

IIb Tracking with Solid State Detectors

- **Lecture 1 - Introduction** C. Joram, L. Ropelewski
- **Lecture 2 - Tracking Detectors** L. Ropelewski, M. Moll
  - **2a) Tracking with Gas detectors**
  - **2b) Tracking with Solid State Detectors** **Michael Moll (CERN - PH/DT2)**
    - Why use Semiconductor Detectors ?
    - How are Silicon Detectors made and how do they work ?
    - Detector types: Microstrip and Pixel Detectors, CCDs
    - Examples: Detectors at LHC
    - Radiation Damage in Silicon Detectors
    - Outlook: Radiation tolerant detectors
    - References
- **Lecture 3 - Scintillation and Photodetection** C. D'Ambrosio, T. Gys
- **Lecture 4 - Calorimetry, Particle ID** C. Joram
- **Lecture 5 - Particle ID, Detector Systems** C. Joram, C. D'Ambrosio

Transparencies: http://cern.ch/ph-dep-dt2/lectures_PD_2005.htm

Solid State Detectors – Why silicon?

Some characteristics of Silicon crystals

- Small band gap E_g = 1.12 eV ⇒ E(e-h pair) = 3.6 eV (≈ 30 eV for gas detectors)
- High specific density 2.33 g/cm^3 ; dE/dx (M.I.P.) ≈ 3.8 MeV/cm ≈ 106 e-h/μm (average)
- High carrier mobility μ_e =1450 cm^2/Vs, μ_h = 450 cm^2/Vs ⇒ fast charge collection (<10 ns)
- Very pure < 1ppm impurities and < 0.1ppb electrical active impurities
- Rigidity of silicon allows thin self supporting structures
- Detector production by microelectronic techniques

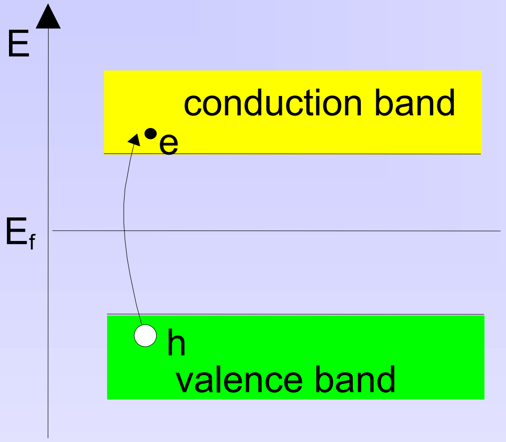
  ⇒ well known industrial technology, relatively low price, small structures easily possible

Alternative semiconductors

- Diamond
- GaAs
- Silicon Carbide
- Germanium

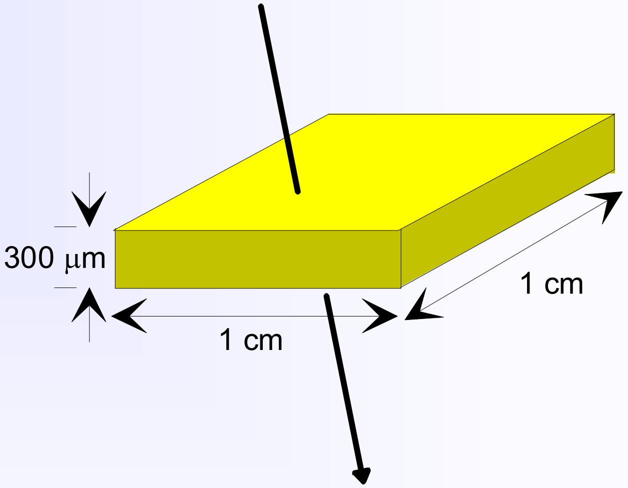
	Diamond	SiC (4H)	GaAs	Si	Ge
Atomic number Z	6	14/6	31/33	14	32
Bandgap E_g [eV]	5.5	3.3	1.42	1.12	0.66
E(e-h pair) [eV]	13	7.6-8.4	4.3	3.6	2.9
density [g/cm^3]	3.515	3.22	5.32	2.33	5.32
e-mobility μ_e [cm^2/Vs]	1800	800	8500	1450	3900
h-mobility μ_h [cm^2/Vs]	1200	115	400	450	1900

How to obtain a signal ?



In a pure intrinsic (undoped) semiconductor the electron density *n* and hole density *p* are equal.

$n = p = n_i$ For Silicon: $n_i \approx 1.45 \cdot 10^{10}$ cm^{-3}



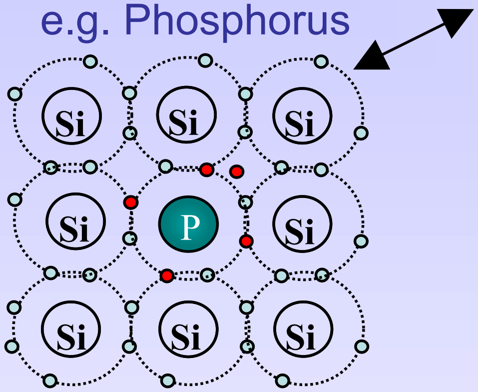
$4.5 \cdot 10^{8}$ free charge carriers in this volume,
but only $3.2 \cdot 10^{4}$ e-h pairs produced by a M.I.P.

⇒ Reduce number of free charge carriers, i.e. deplete the detector

⇒ **Most detectors make use of reverse biased p-n junctions**

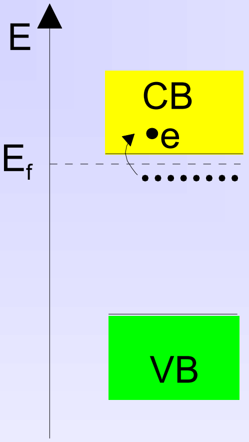
Doping, resistivity and p-n junction

e.g. Phosphorus



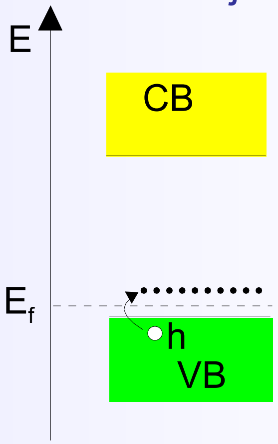
Doping: n-type Silicon

- add elements from V^{th} group
  ⇒ **donors** (P, As,..)
- electrons are majority carriers



Doping: p-type Silicon

- add elements from III^{rd} group
  ⇒ **acceptors** (B,..)
- holes are the majority carriers



Resistivity

- carrier concentrations *n*, *p*
- carrier mobility μ_n, μ_p

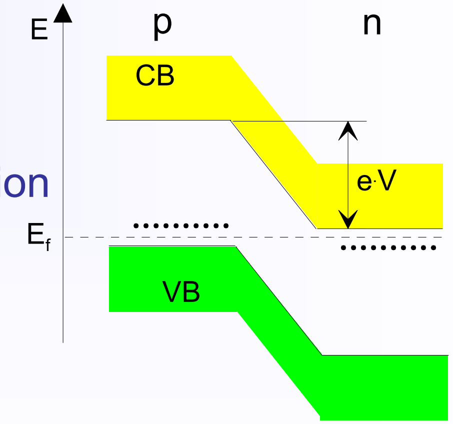
$$\rho = \frac{1}{q_0(\mu_n n + \mu_p p)}$$

	detector grade	electronics grade
doping	**≈ 10^{12} cm^{-3}**	**≈ 10^{17} cm^{-3}**
resistivity ρ	**≈ 5 kΩ·cm**	**≈1 Ω·cm**

p-n junction

There must be a single
Fermi level !

⇒ band structure deformation
⇒ potential difference
⇒ depleted zone

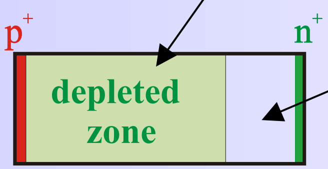


Reverse biased abrupt p^+ n junction

Poisson's equation

$$-\frac{d^2}{dx^2}\phi(x) = \frac{q_0}{\varepsilon\varepsilon_0}\cdot N_{eff}$$

Positive space charge, N_{eff} =[P]
(ionized Phosphorus atoms)

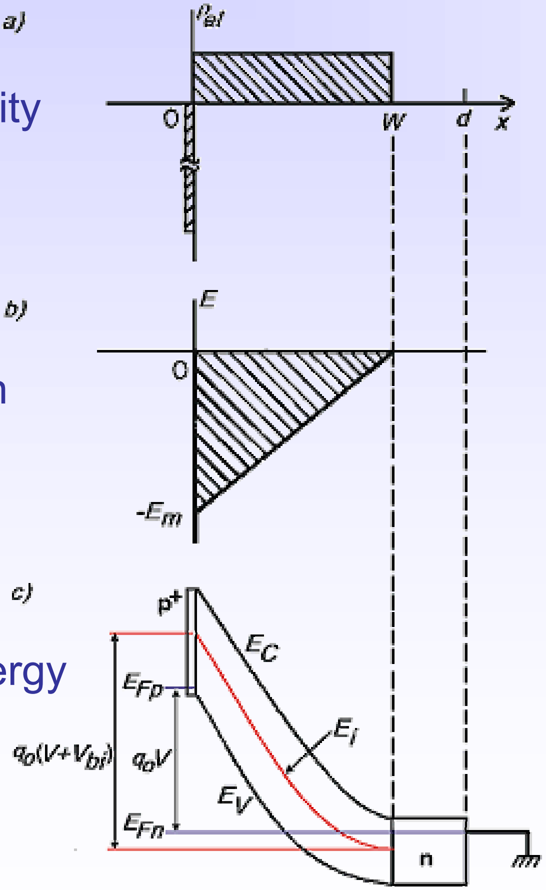


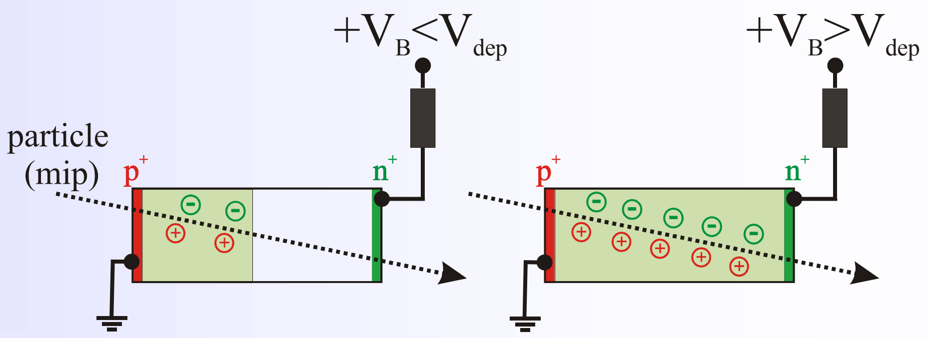
neutral bulk
(no electric field)

Electrical charge density

Electrical field strength

Electron potential energy





Full charge collection only for $V_B>V_{dep}$!

depletion voltage

$$\boxed{V_{dep} = \frac{q_0}{\varepsilon\varepsilon_0}\cdot\left|N_{eff}\right|\cdot d^2}$$

effective space charge density

Calculation of depletion voltage (diode)

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Poisson's equation

$$-\frac{d^2}{dx^2}\phi(x)=\frac{q_0}{\varepsilon\varepsilon_0}\cdot N_{eff}$$

with $$\frac{d}{dx}\phi(x=w)=0$$

$$\phi(x=w)=0$$

w = depletion depth
d = detector thickness
U = voltage

N_{eff} = effective doping concentration

$$-\frac{d}{dx}\phi(x)=\frac{q_0}{\varepsilon\varepsilon_0}\cdot N_{eff}\cdot(x-w)$$

$$\phi(x)=\frac{1}{2}\cdot\frac{q_0}{\varepsilon\varepsilon_0}\cdot N_{eff}\cdot(x-w)^2$$

$$\boxed{w(V)=\sqrt{\frac{2\varepsilon\varepsilon_0}{q_0\left|N_{eff}\right|}\cdot V}}$$

$$\boxed{C=\frac{dQ}{dU}=\frac{dQ\cdot dw}{dw\cdot dU}}$$

$$dQ=q_0\cdot\left|N_{eff}\right|\cdot A\cdot dw$$

$$dw=\sqrt{\frac{\varepsilon\varepsilon_0}{q_0\left|N_{eff}\right|2U}}\cdot dU$$

$$\boxed{C(U)=A\cdot\sqrt{\frac{\varepsilon\varepsilon_0 q_0\left|N_{eff}\right|}{2U}}}$$

$$\boxed{C(w)=\frac{\varepsilon\varepsilon_0 A}{w}}$$

depletion voltage

$$\boxed{V_{dep}=\frac{q_0}{2\varepsilon\varepsilon_0}\cdot\left|N_{eff}\right|\cdot d^2}$$

effective space charge density

How to make a Float Zone Silicon wafer?

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Produce a polysilicon rod

- Melt very pure sand (SiO_2) together with coke (~1800°C)

$$SiO_2 + 2C \rightarrow Si + 2CO$$

- Grind the “metallurgical grade silicon” (98% Si) and expose it to hydrochloric gas

$$Si + 3HCl\,(gas) \rightarrow \boxed{SiHCl_3} + H_2$$

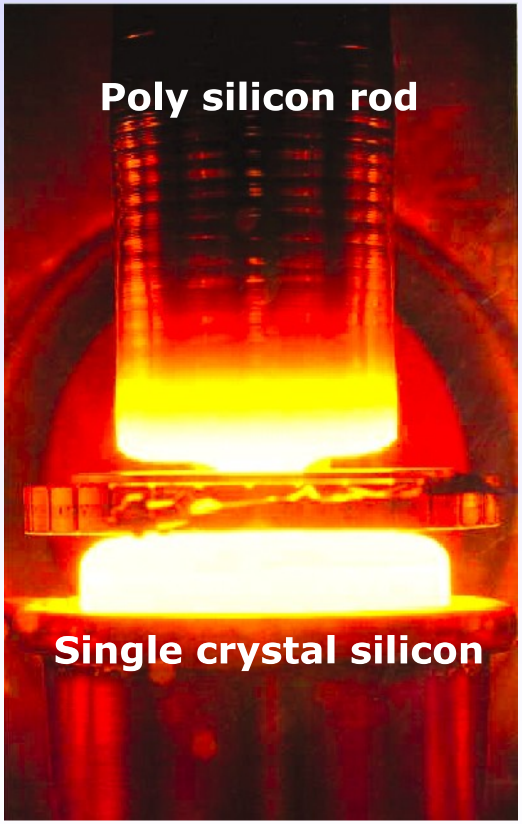
- Trichlorsilane boils at 31.7°C and can thus be distilled and purified
- Deposit silicon in a Chemical Vapour Deposition process

$$SiHCl_3 + H_2 \rightarrow Si + 3HCl$$

- Cast silicon into a polycrystalline silicon rod

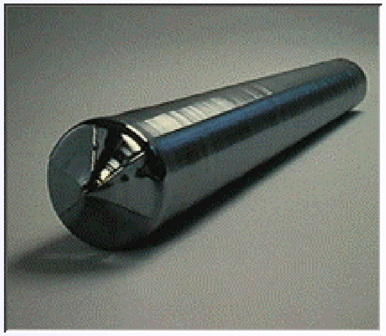
Float Zone process

- Using a single Si crystal seed, melt the vertically oriented rod onto the seed using RF power and “pull” the monocrystalline ingot



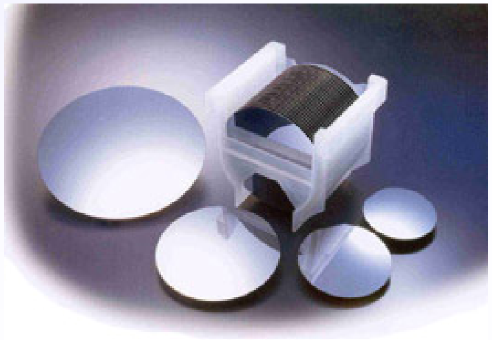
Monocrystalline Ingot

- grind into round shape
- make the flat or a notch



Wafer production

- Slice the ingot into wafers of 300-500 μm (diamond saw)
- lapping of wafers
- etching of wafers
- polishing of wafers

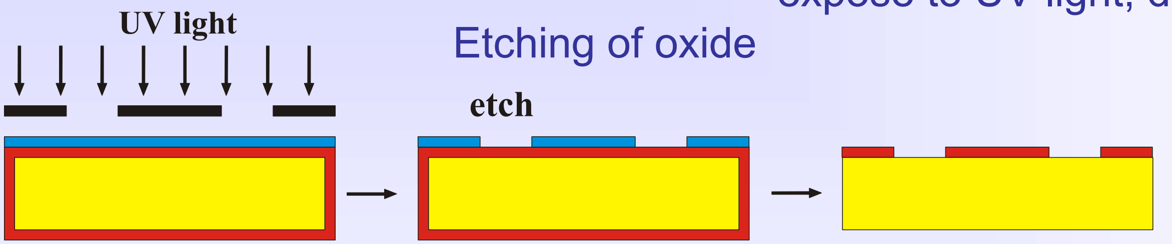


Silicon Sensor Production

A "simple“ production sequence (schematic)

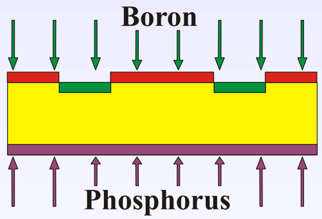
- Polished n-type silicon wafer (typical $\rho \sim 1\text{-}10\ \mathrm{K\Omega cm}$)

- Oxidation (800-1200°C)



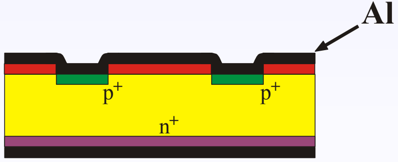
- Photolithograpy (coat with photo resist; align mask, expose to UV light, develop photoresist);

  Etching of oxide

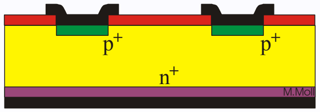


- Doping with boron and phosphorus by implantation (or by diffusion)

  Annealing to cure radiation damage and activate dopants
  - p^+ n junction on front side
  - n n^+ ohmic contact on back side



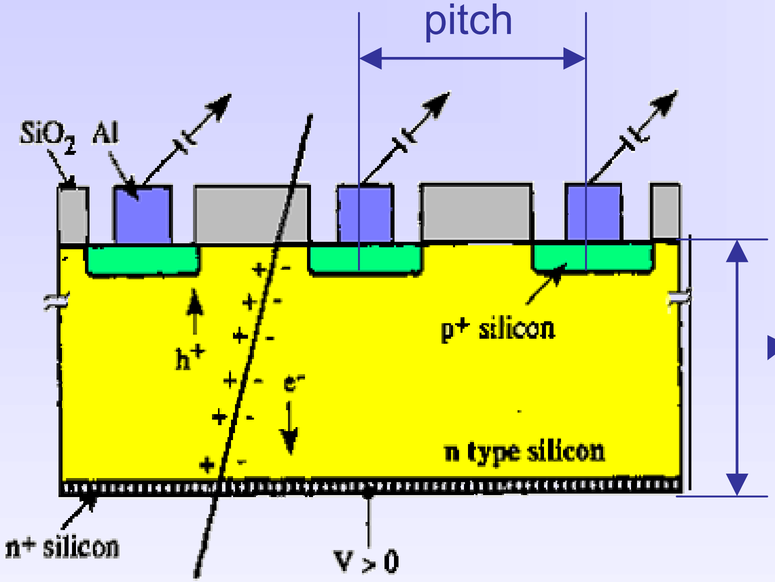
- Aluminize surface (e.g. by evaporation)



- Pattern metal for diode contacts

Single Sided Strip Detector

- Segmentation of the p⁺ layer into strips (Diode Strip Detector) and connection of strips to individual read-out channels gives spatial information



typical thickness: 300μm (150μm - 500μm used)

- using n-type silicon with a resistivity of

  ρ = 2 KΩcm (N_D ~$2.2 \cdot 10^{12}$cm^{-3})

  results in a depletion voltage ~ 150 V

- Resolution σ depends on the pitch p (distance from strip to strip)

  - e.g. detection of charge in binary way (threshold discrimination) and using center of strip as measured coordinate results in

$$\sigma = \frac{p}{\sqrt{12}}$$

typical pitch values are 20 μm– 150 μm ⇒ 50 μm pitch results in 14.4 μm resolution

Capacitive charge division

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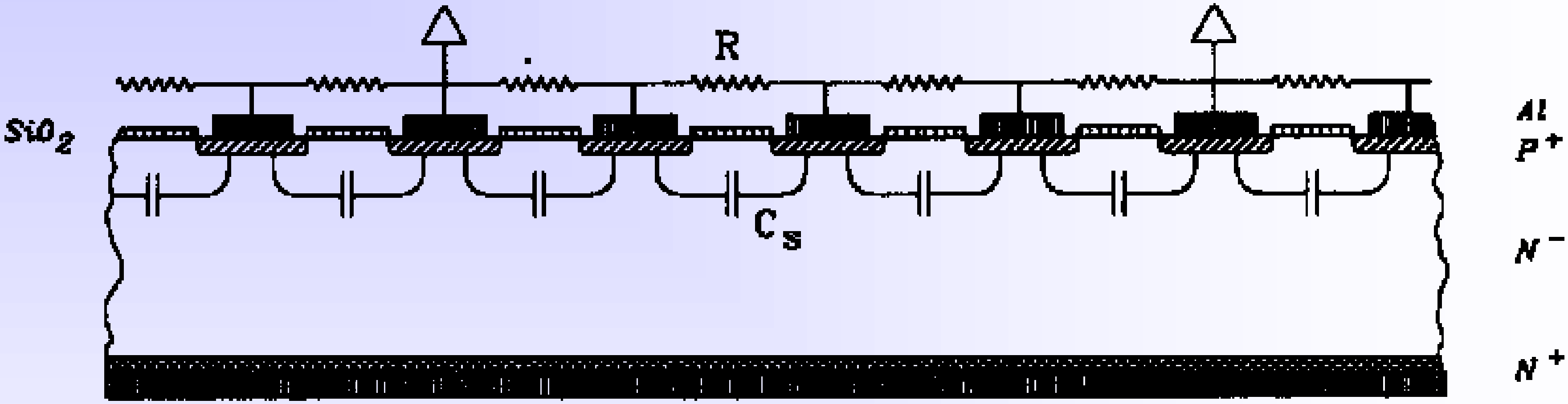
- Analog readout (measurement of signal height) of every strip leads to substantial improvement of position resolution, however not every strip has to be read:



- Charge division readout reduces the number of readout channels as only a fraction of the strips is connected to readout amplifier.

- Charge collected at the interpolation strips is divided between the two neighboring readout channels according to the relative position.

Bias resistor and AC Coupling

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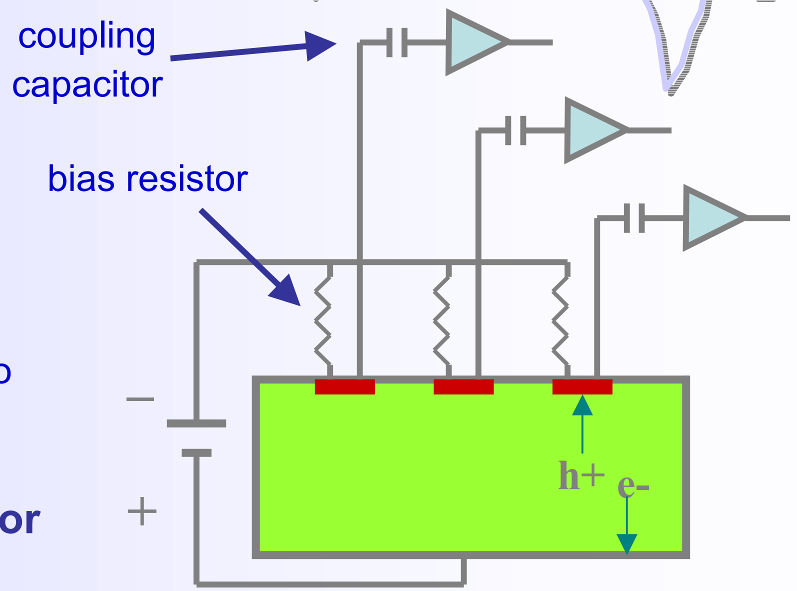


Bias resistor

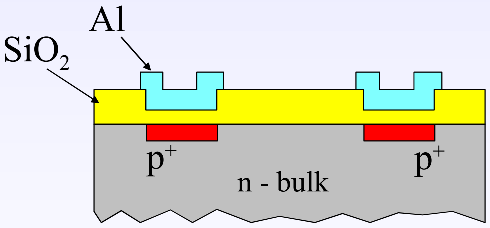
- Need to isolate strips from each other to collect/measure charge on each strip
  ⇒ high impedance bias connection (≈ 1MΩ resistor)

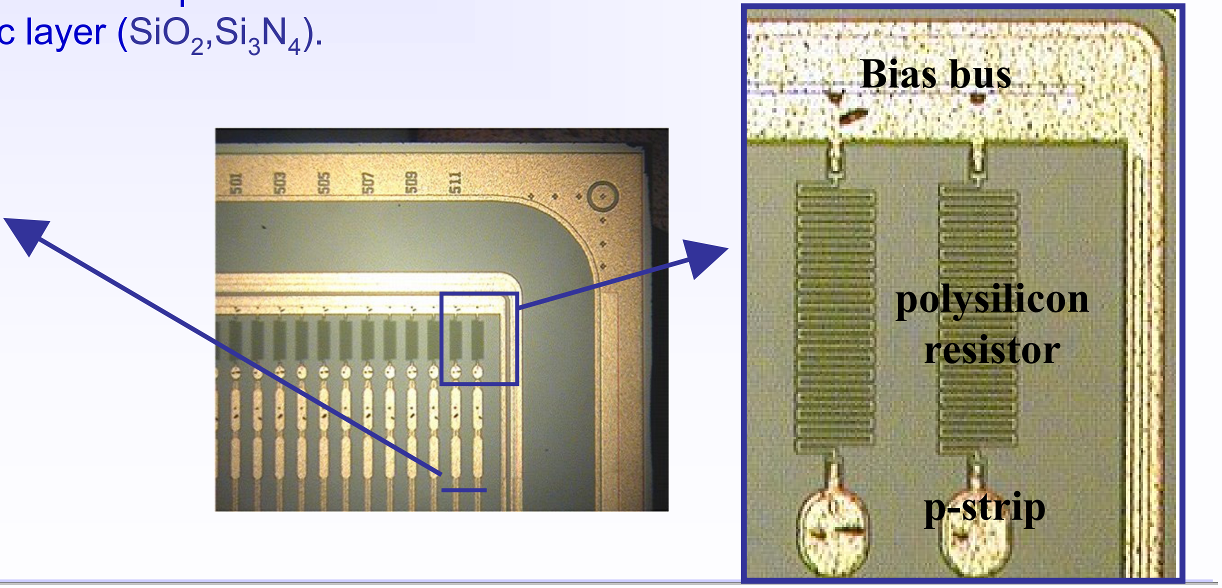
Coupling capacitor

- Couple input amplifier through a capacitor (AC coupling) to avoid large DC input from leakage current

Integration of capacitors and resistors on sensor

- Bias resistors via deposition of doped polysilicon
- Capacitors via metal readout lines over the implants but separated by an insulating dielectric layer (SiO_2,Si_3N_4).





⇒ nice integration
⇒ more masks, processing steps
⇒ pin holes

The Charge Signal

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Collected Charge for a Minimum Ionizing Particle (MIP)

- **Mean energy loss**
  dE/dx (Si) = 3.88 MeV/cm
  ⇒ 116 keV for 300μm thickness

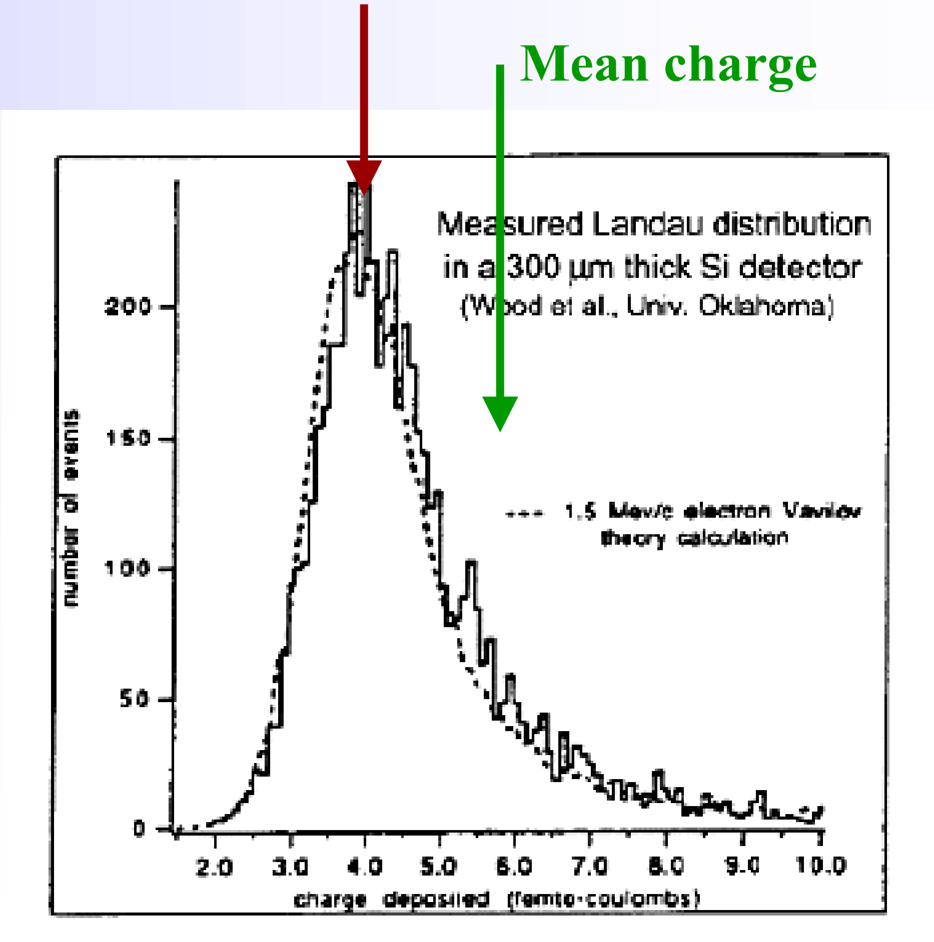
- **Most probable energy loss**
  ≈ 0.7 ×mean
  ⇒ 81 keV

- **3.6 eV to create an e-h pair**
  ⇒ 72 e-h / μm (mean)
  ⇒ 108 e-h / μm (most probable)

- **Most probable charge** (300 μm)

  ≈ 22500 e   ≈ 3.6 fC

Most probable charge ≈ 0.7× mean



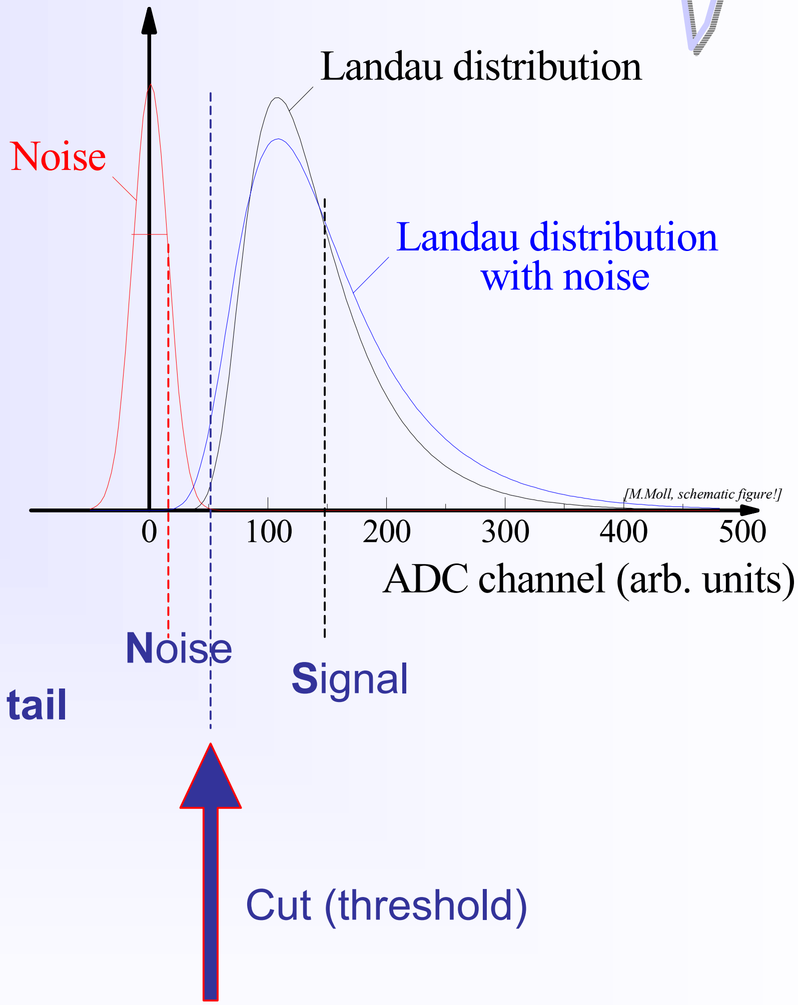
Mean charge

Signal to noise ratio (S/N)

- **Landau distribution** has a low energy tail
  - becomes even lower by noise broadening

Noise sources: (ENC = Equivalent Noise Charge)

- Capacitance $ENC \propto C_d$
- Leakage Current $ENC \propto \sqrt{I}$
- Thermal Noise $ENC \propto \sqrt{k_B T / R}$
  (bias resistor)



- **Good hits selected by requiring N_{ADC} > noise tail**
  If cut too high ⇒ efficiency loss
  If cut too low ⇒ noise occupancy
- **Figure of Merit: Signal-to-Noise Ratio S/N**
- **Typical values >10-15, people get nervous below 10.**
  Radiation damage severely degrades the S/N.

Charge Collection time and diffusion

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Charge Collection time

- Drift velocity of charge carriers v ≈ μE, so drift time, $t_d = d/v = d/\mu E$

Typical values: d=300 μm, E= 2.5 kV/cm,
with μ_e= 1350 cm^2 / V·s and μ_h= 450 cm^2 / V·s

$$\Rightarrow t_d(e) = 9\text{ns}\ ,\ t_d(h) = 27\text{ns}$$

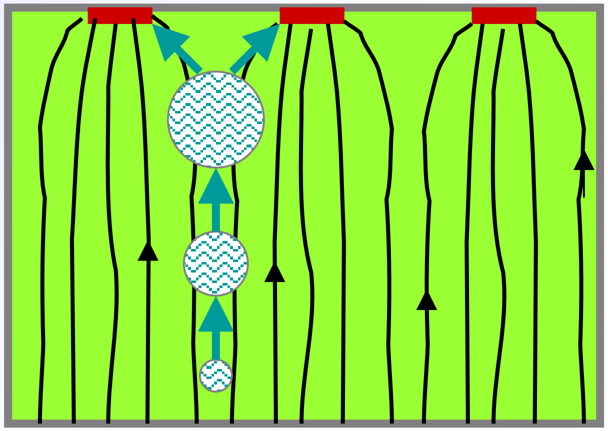
Diffusion

- Diffusion of charge "cloud" caused by scattering of drifting charge carriers, radius of distribution after time td:

$$\sigma = \sqrt{2Dt_d} \quad \text{with diffusion constant} \quad D = \mu \, {}^{kT}\!/_{q}$$

- Same radius for e and h since $t_d \propto 1/\mu$

Typical charge radius: $\sigma \approx 6\mu$m, could exploit this to get better position resolution due to charge sharing between adjacent strips (using centroid finding), but need to keep drift times long (low field).



Double sided silicon detectors

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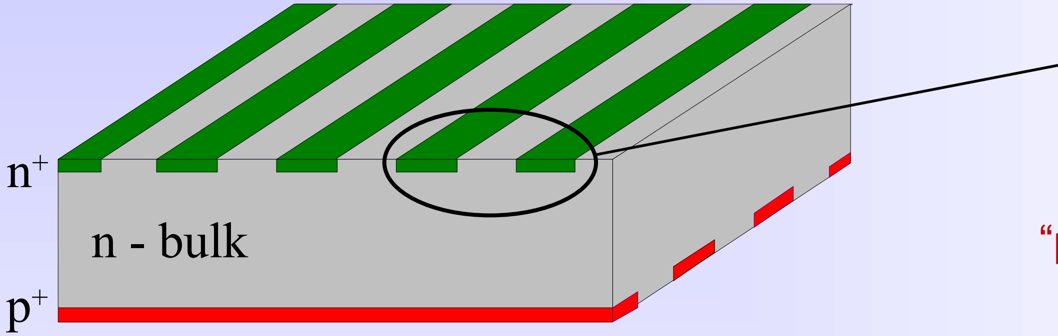
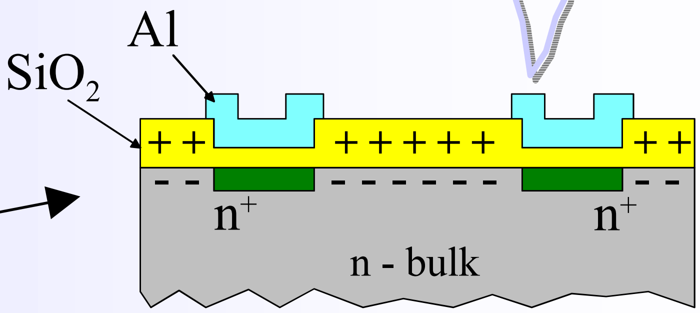
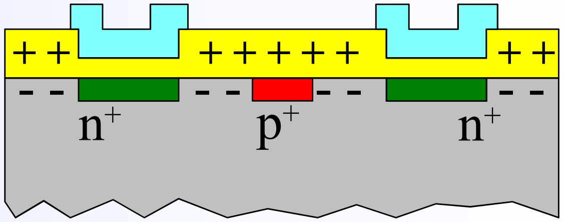
- **Get a 2nd coordinate**
  Put n^+ and p^+ strips on opposite sides and read them both



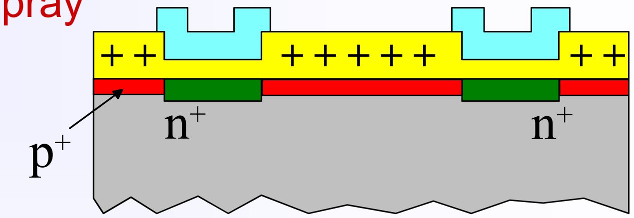


"p-stop"



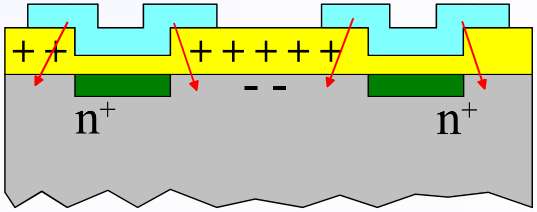
- **Problem: Electron accumulation layer**
  n^+-strips are not isolated because of an electron accumulation layer at the Si-SiO_2 interface. This effect is due to the presence of positive charge in SiO_2 layer which attracts electrons.

"p-spray"



- **Solution:** "Break" accumulation layer
  - p-strips in between the n-strips ("**p-stop**")
  - moderate p^+-implantation over all surface ("**p-spray**")
  - "**field plates**" (metal over oxide) over the n^+-strips and apply negative potential with respect to n^+-strips to repel electrons.

"field plates"

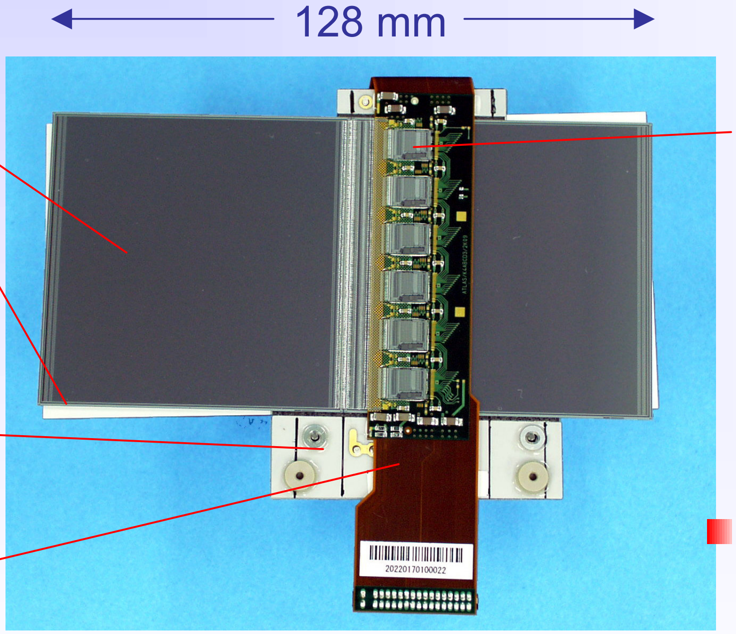


Detector Module

- **Detector Modules** - "Basic building block of tracking detectors"
  - Silicon Sensors
  - Mechanical support (cooling)
  - Front end electronics and signal routing (connectivity)

SCT = SemiConductor Tracker
ASICS = Application Specific Integrated CircuitS
TPG = Thermal Pyrolytic Graphite

- **Example: ATLAS SCT Barrel Module**



- **Silicon sensors (x4)**
  - 64 x 64 mm^2
  - p-in-n, single sided
  - AC-coupled
  - 768 strips
  - 80μm pitch/12μm width
- **Mechanical support**
  - TPG baseboard
  - BeO facings
- **Hybrid (x1)**
  - flexible 4 layer copper/kapton hybrid
  - mounted directly over two of the four silicon sensors
  - carrying front end electronics, pitch adapter, signal routing, connector

$\sigma(r\phi) \sim 16\ \mu\text{m}$, $\sigma(z) \sim 850\mu\text{m}$ [NIMA538 (2005) 384]

- **ASICS (x12)**
  - ABCD chip (binary readout)
  - DMILL technology
  - 128 channels
- **Wire bonds** (~3500)
  - 25 μm Al wires

- **ATLAS – SCT**
  - 15.552 microstrip sensors
  - 2.112 barrel modules
  - 1.976 forward modules
  - 61 m^2 silicon, 6.3$\cdot$10^{6}strips

Wire bonding

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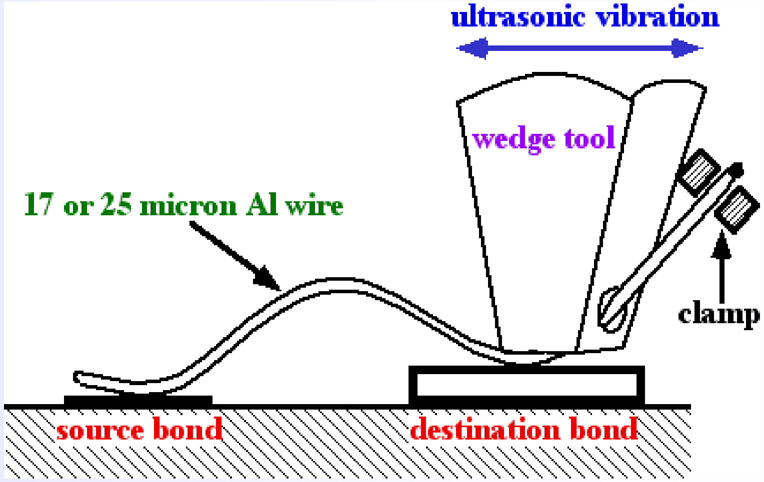
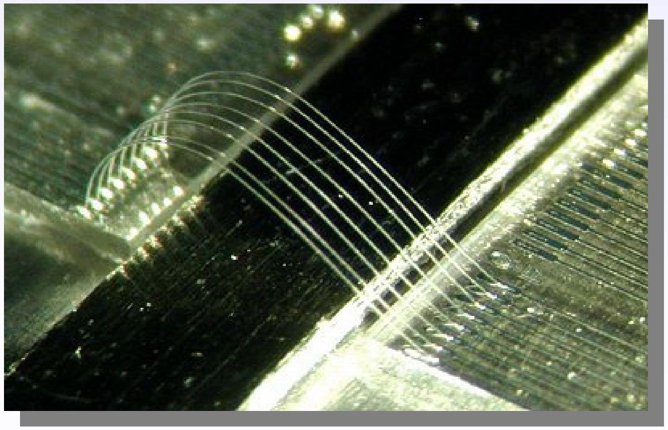
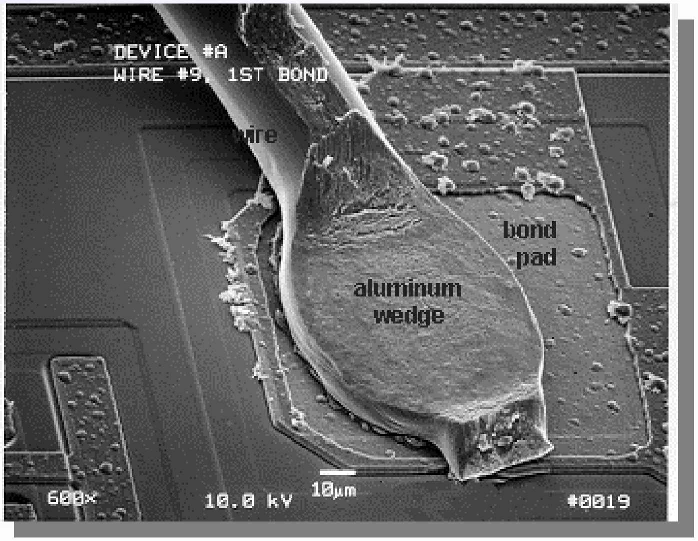
- Uses ultrasonic power to vibrate needle-like tool on top of wire. Friction welds wire to metallized substrate underneath.
- Can easily handle 80µm pitch in a single row and 40µm in two staggered rows (typical FE chip input pitch is 44µm).
- Generally use 25µm diameter aluminum wire and bond to aluminum pads (chips) or gold pads (hybrid substrates).
- Heavily used in industry (PC processors) but not with such thin wire or small pitch.





Microscope: connect sensor to fan-out circuit

Electron microscope: bond “foot”



Silicon Drift Detectors

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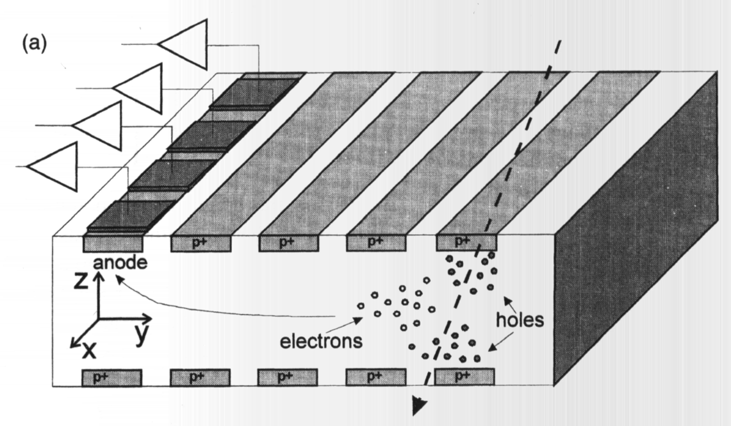
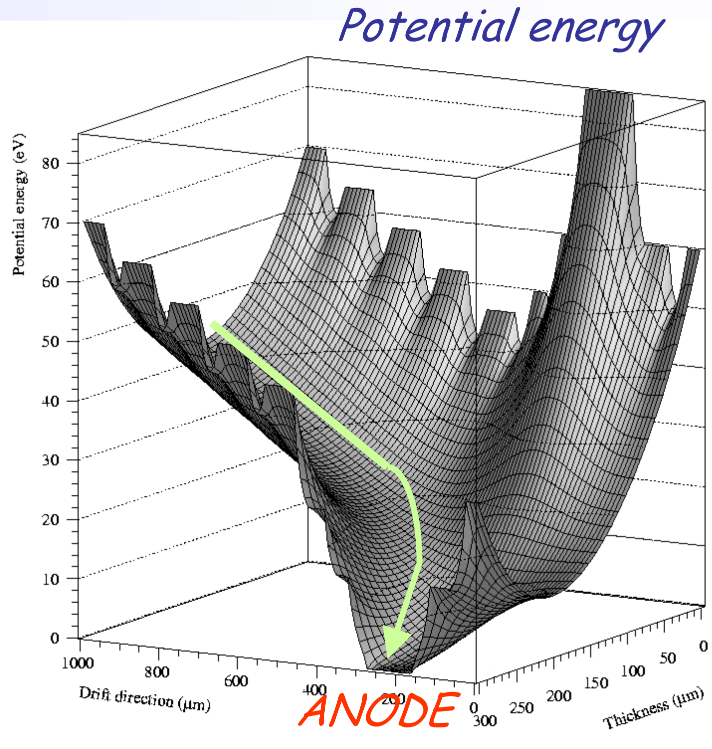
- Principle of sideways depletion (as for DEPFET sensors)
- p^+ segmentation on both sides of sensor
- complete depletion of wafer from segmented n^+ anodes located at one side of sensor
- electrons drift parallel to substrate surface to n^+ anodes
- voltage divider network (resistors) for p-strips to provide uniform drift field



Potential energy



- Need to ensure good material uniformity, low defect rates, good drift field homogeneity, precise voltage dividing on p-strips and good temperature control.
- HEP: Implemented for STAR at RHIC and for ALICE at LHC

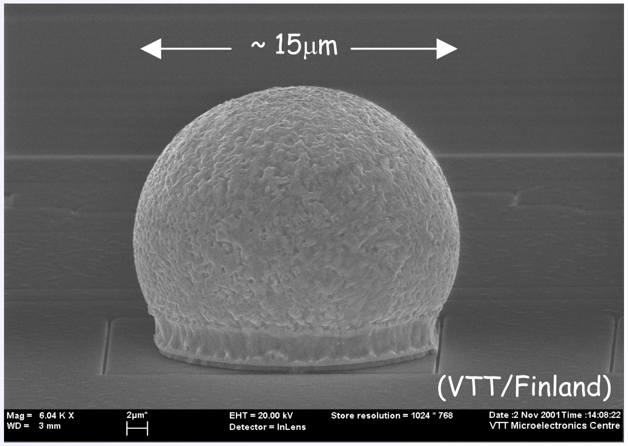
Hybrid Pixel Detectors

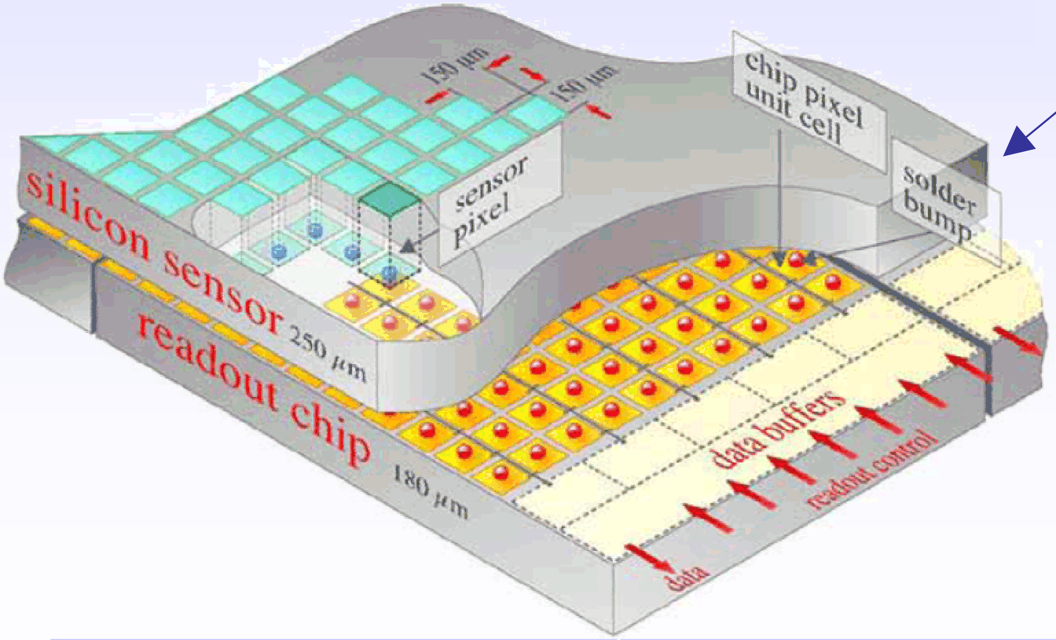
CERN Globe is a 3 million times bigger bump!

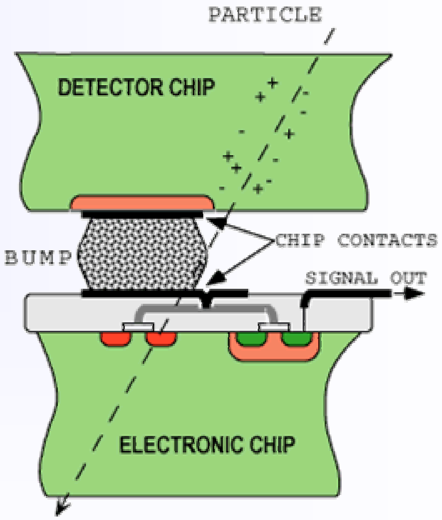
HAPS – Hybrid Active Pixel Sensors

- segment silicon to diode matrix with high granularity (⇒ true 2D, no reconstruction ambiguity)
- readout electronic with same geometry (every cell connected to its own processing electronics)
- connection by "bump bonding"
- requires sophisticated readout architecture
- Hybrid pixel detectors will be used in LHC experiments: ATLAS, ALICE, CMS and LHCb

Solder Bump: Pb-Sn



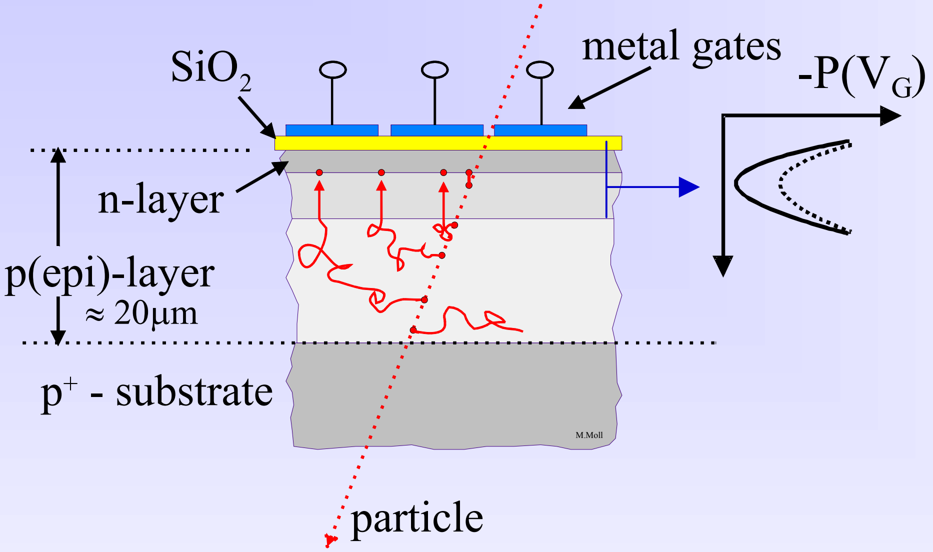


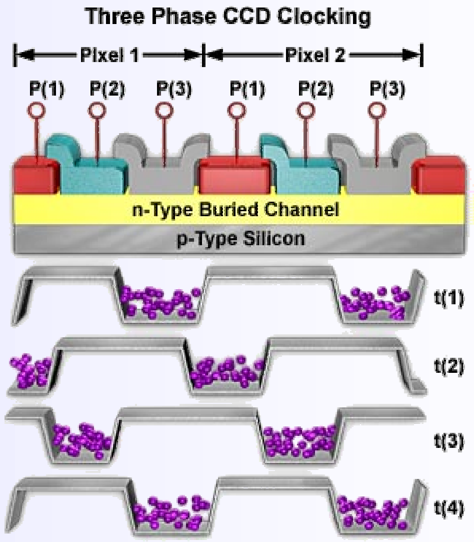


Flip-chip technique

CCD – Charged Coupled Devices

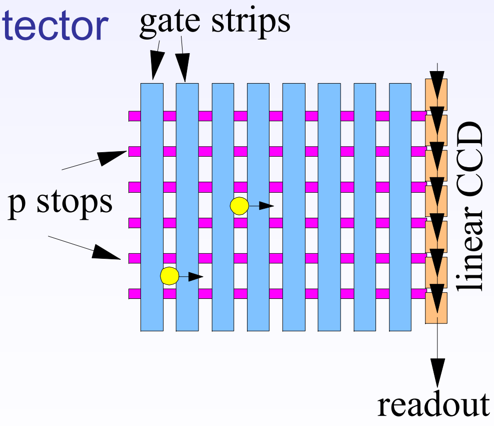
(1) MOS structure with segmented metal layer;
Charge is captured in a potential well.





(2) Readout: Shift electrons towards anode
by periodic variation of 3 potentials

(3) Create an array of pixel for
a 2D detector



Pixel CCD

- needs only few readout channels
- small charge (≈2000 e) ⇒ needs cooling
- long readout time, active during readout
- sensitive to radiation damage

⇒ applicable for low rate experiment
without high intensity radiation field

MAPS – Monolithic Active Pixel Sensors

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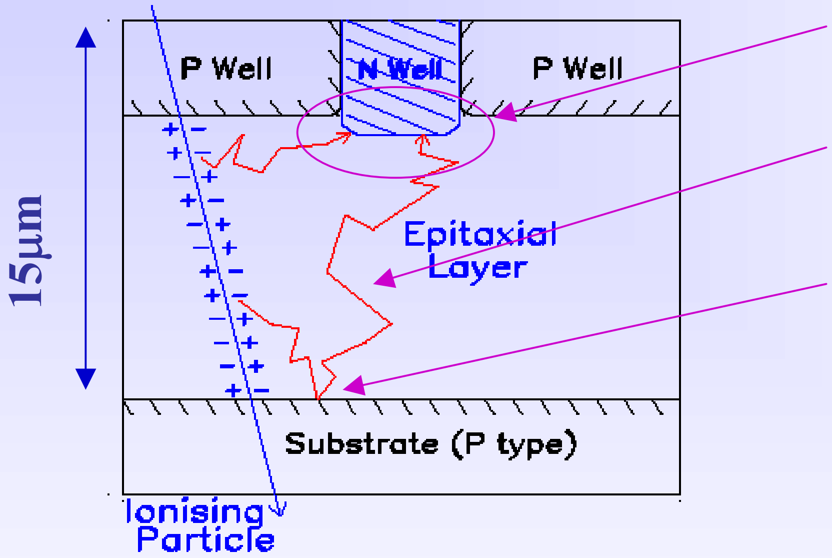
Monolithic detectors

- readout electronics directly within sensor material (same epi layer)



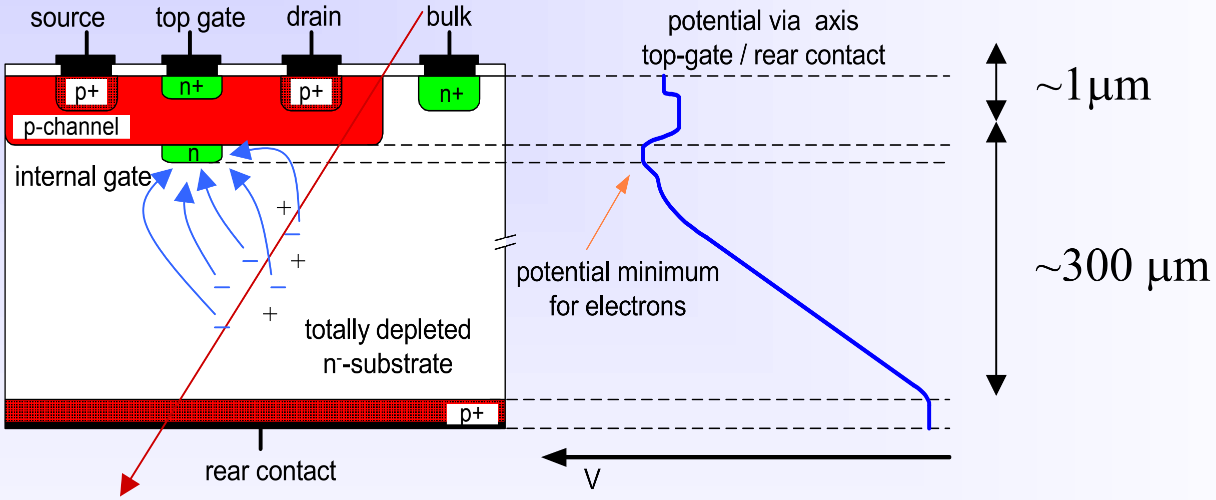
- charge collected at n-well / p-epi diode
- thermal diffusion of free charge
- reflection at potential barriers between areas with different doping concentration
- no depletion voltage applied
  ⇒ potential formed by different doping concentrations only

- no connections needed to electronics (e.g. no bumps)
- very small sizes achievable

extra slide
not shown

DEPFET - DEP(leted)F(ield)E(ffect)T(ransistor)

- FET integrated on high resistivity bulk, bulk sideward depleted
- electrons collected in potential minimum at internal gate
  - transistor current modulated by collected charge
  - charge removed by reset mechanism (clear)
- switch on/off by (external) top gate to read out



- amplification of charge at the position of collection ⇒ no transfer loss
- full bulk sensitivity, bulk can be thinned down to 50 μm if needed
- non structured entrance window (backside)
- very low imput capacitance ⇒ very low noise

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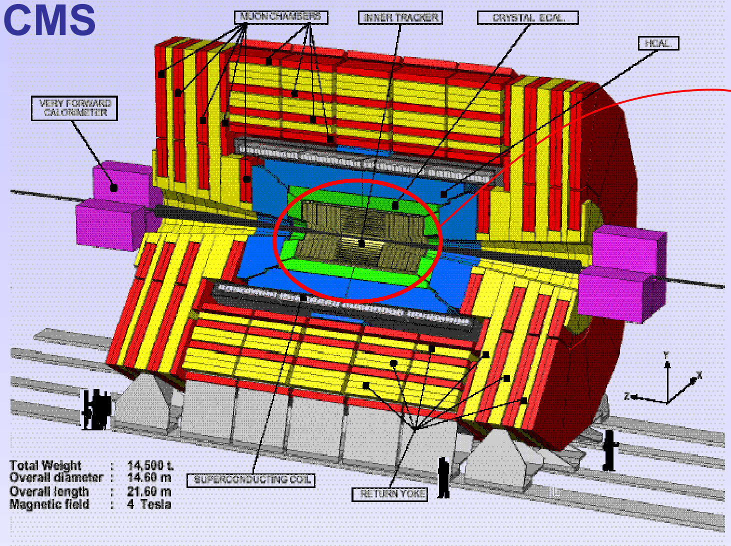
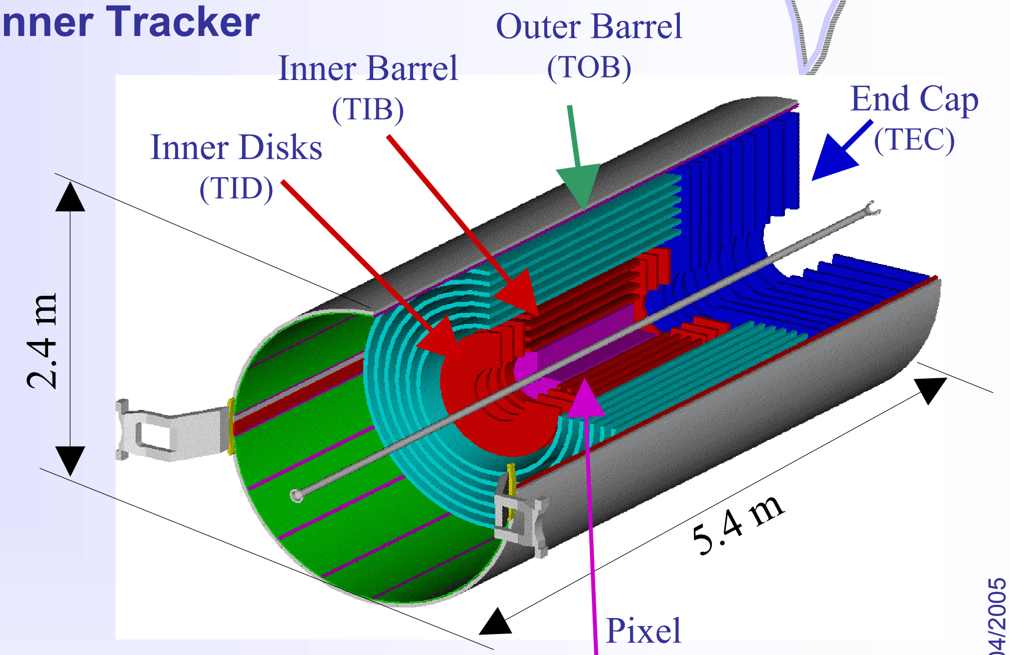
Example from LHC: The CMS tracker

- **CMS**



- **Inner Tracker**



- **CMS** - **C**urrently the **M**ost **S**ilicon

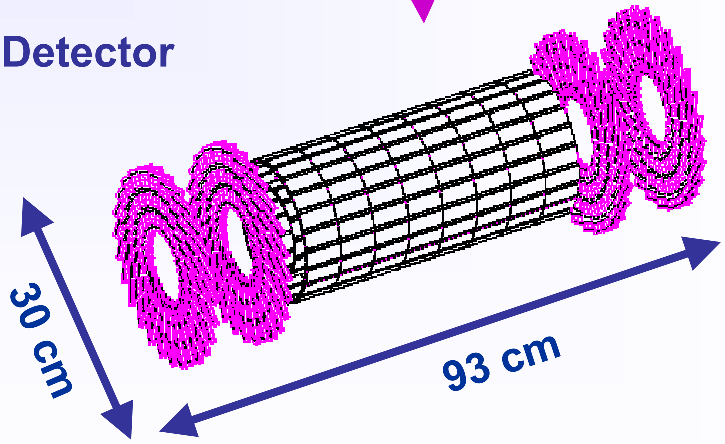
Micro Strip:

- ~ 214 m^2 of silicon strip sensors
- 11.4 million strips

Pixel:

- Inner 3 layers: silicon pixels (~ 1m^2)
- 66 million pixels (100x150μm)
- Precision: $\sigma(r\varphi) \sim \sigma(z) \sim 15\mu$m
- Most challenging operating environments (LHC)

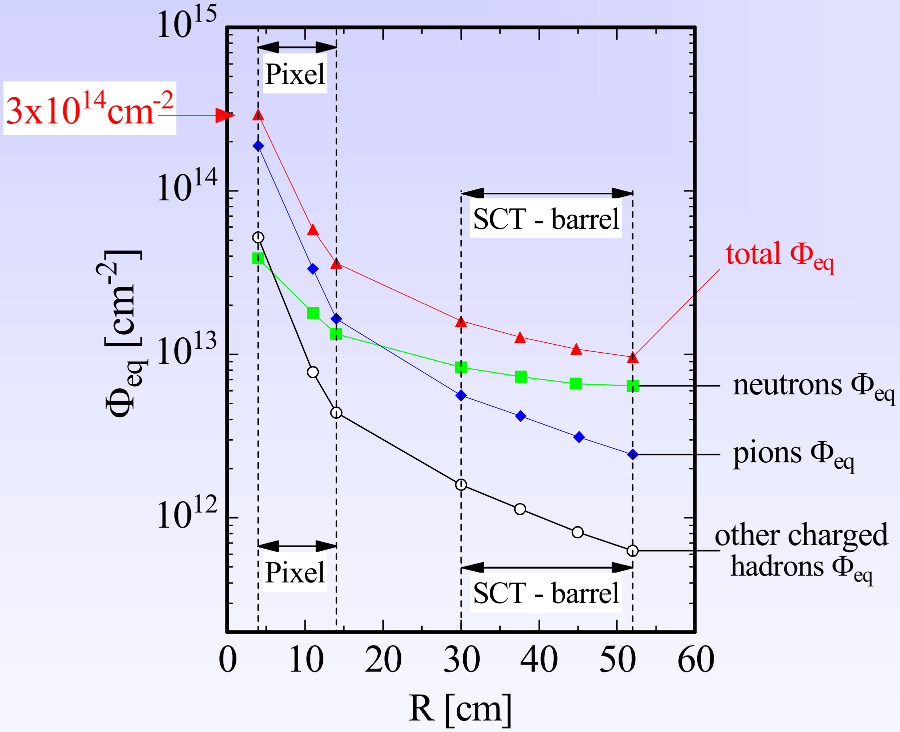
- **Pixel Detector**



Radiation Levels at LHC and SLHC

Example: ATLAS

- Fluences per year at full Luminosity



- Pixel detector: up to $\Phi_{eq} \approx 3.5 \cdot 10^{14}$ cm^{-2} /year
- Dominating type of particle is different for pixel (pions) and strip detectors (neutrons)

LHC silicon detectors:

- All detectors have been extensively tested and developed for radiation tolerance and are expected to survive the LHC radiation environment.

- Some experiments have already foreseen upgrades (e.g. LHCb Velo after 3 years).

Super LHC

- upgrade of LHC to 10 x higher Luminosity
  - ⇒ 10 x higher radiation levels
  - ⇒ Radiation damage will become a critical issue!

⇒ New, radiation tolerant detectors needed!

- What is radiation damage ?
- How to cope with it ?

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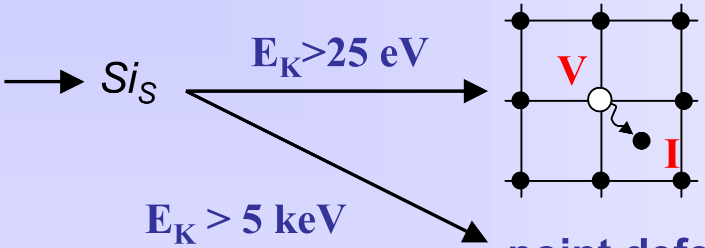
Radiation Damage: Microscopic defects

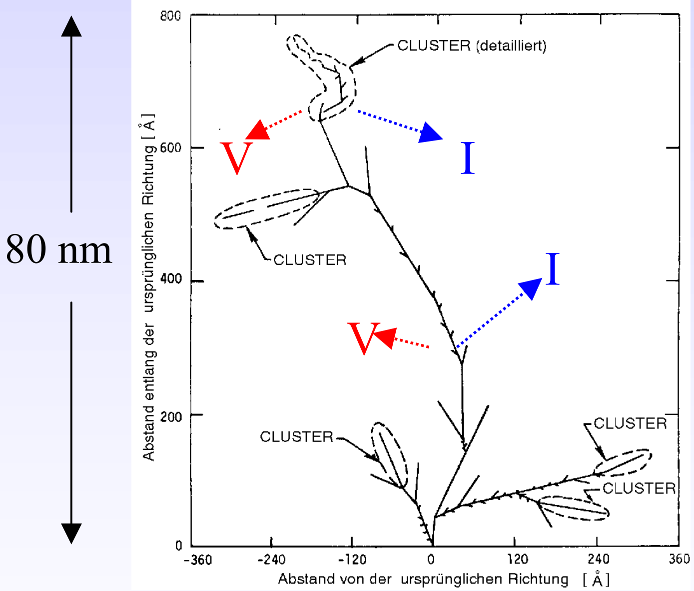
- **Damage to the silicon crystal:** Displacement of lattice atoms



particle → Si_S

$E_K > 25$ eV → **Vacancy + Interstitial** ⟺ **“point defects”, mobile in silicon, can react with impurities (O,C,..)**

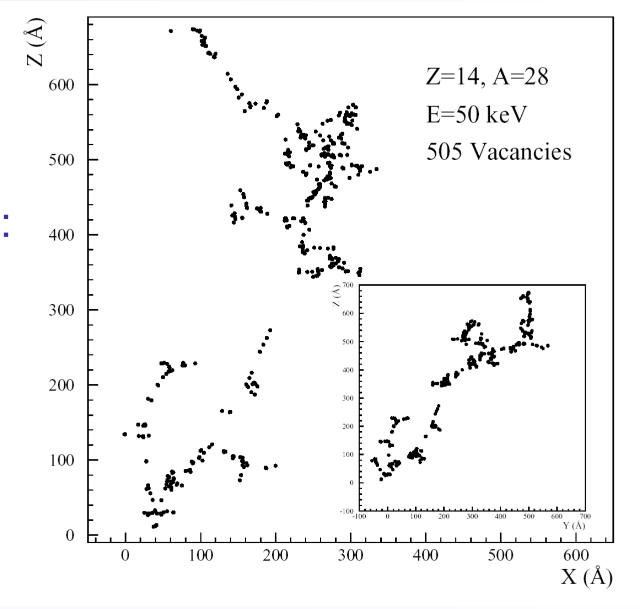
$E_K > 5$ keV → **point defects and clusters of defects**



Distribution of vacancies created by a 50 keV Si-ion in silicon (typical recoil energy for 1 MeV neutrons):

⬅ **Schematic**
[Van Lint 1980]

Simulation ➡
[M.Huhtinen 2001]



- **Defects can be electrically active (levels in the band gap)**
  - capture and release electrons and holes from conduction and valence band

  ⇒ can be charged - can be generation/recombination centers - can be trapping centers

Radiation Damage: Particle dependence

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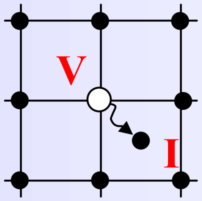
- particle ⟶ Si_S ⟶ $E_K > 25$ eV



Vacancy
+
Interstitial ⟶ **point defects**
(V-O, C-O, ..)

Si_S ⟶ $E_K > 5$ keV **point defects and clusters of defects**

---

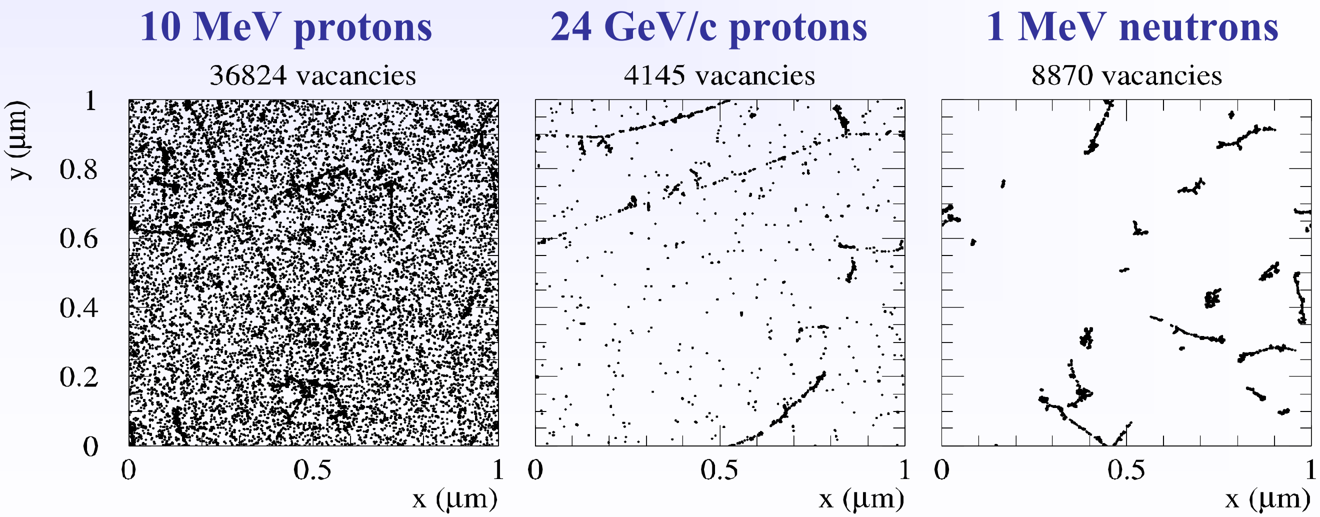
^{60}Co-gammas	**Electrons**	**Neutrons (elastic scattering)**
Compton Electrons with max. $E_\gamma \approx$ MeV	**$E_e > 255$ keV for displacement**	**$E_n > 185$ eV for displacement**
(<u>no cluster production</u>)	**$E_e > 8$ MeV for cluster**	**$E_n > 35$ keV for cluster**

only point defects ⟷ **point defects & clusters** ⟷ **mainly clusters**

- **Simulation:**

Initial distribution of vacancies in $(1\mu m)^3$ after 10^{14} particles/cm^2

[Mika Huhtinen NIMA 491(2002) 194]


10 MeV protons — 36824 vacancies

24 GeV/c protons — 4145 vacancies

1 MeV neutrons — 8870 vacancies

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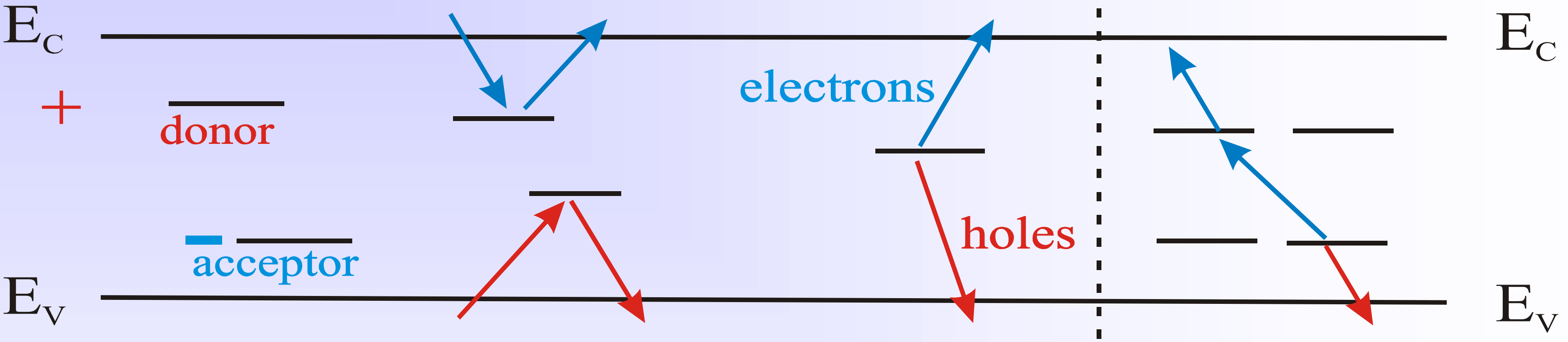
Impact of defects on detector properties

Shockley-Read-Hall statistics
(standard textbook theory)

Inter-center charge transfer model
(inside clusters only)



charged defects
⇒ N_{eff} , V_{dep}
e.g. donors in upper and acceptors in lower half of band gap

trapping (e and h)
⇒ CCE
shallow defects do not contribute at room temperature due to fast detrapping

generation
⇒ leakage current
Levels close to midgap are most effective

enhanced generation
⇒ leakage current
⇒ space charge

- **Impact on detector properties can be calculated if all defect parameters are known:**

$\sigma_{n,p}$: cross sections   **ΔE : ionization energy**   **N_t : concentration**

Radiation Damage in Silicon Sensors

- **Two general types of radiation damage:**

  - **Bulk (Crystal) damage** due to **Non Ionizing Energy Loss (NIEL)**
    - Displacement Damage –

    I. Change of **depletion voltage** (higher operation voltage, underdepletion)
    ⇒ constant cooling needed to avoid reverse annealing

    II. Increase of **leakage current** (increase of shot noise, thermal runaway)
    ⇒ needs cooling of sensors during operation

    III. Decrease of **charge collection efficiency**
    due to underdepletion and increased trapping

  - **Surface damage** due to **Ionizing Energy Loss (IEL)**
    - accumulation of positive in the oxide (SiO_2) and the Si/SiO_2 interface –

    affects: interstrip capacitance (noise factor), breakdown behavior
    and other structures depending on near-surface effects

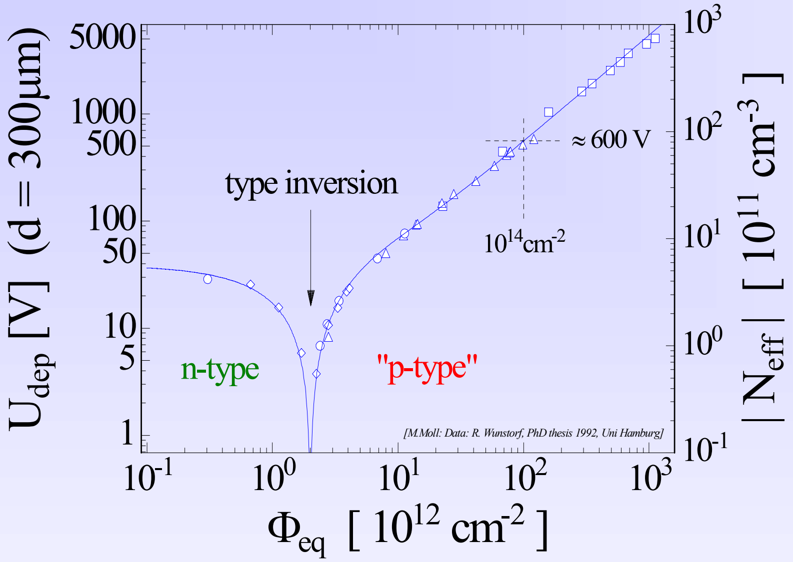
- **Signal/noise ratio is the quantity to watch**

  ⇒ **Sensors can fail from radiation damage !**

Radiation Damage – I. Depletion Voltage

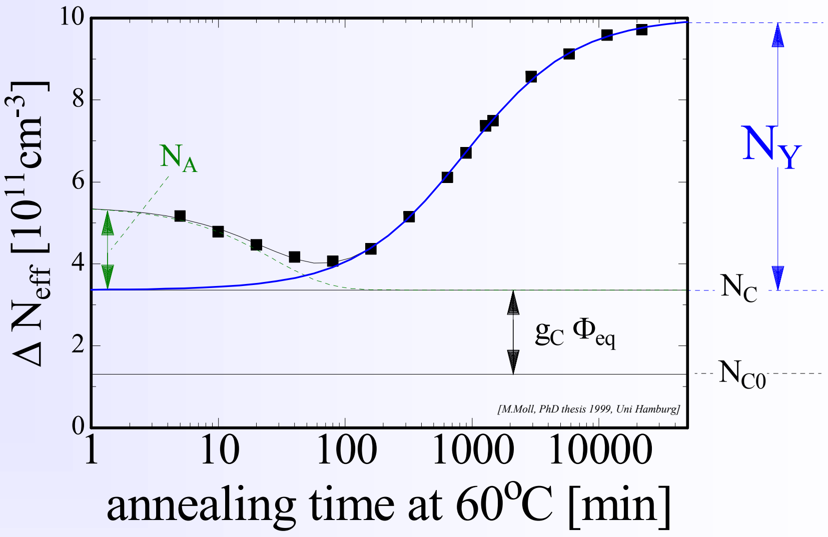
Change of Depletion Voltage V_{dep} (N_{eff})

…. with particle fluence:



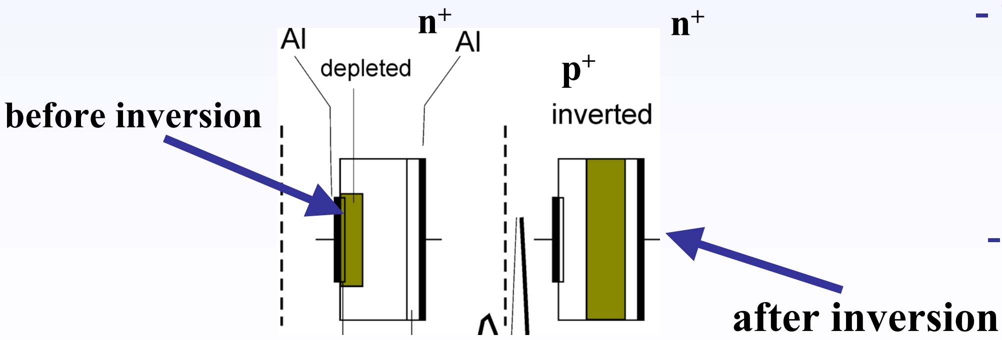
[M.Moll: Data: R. Wunstorf, PhD thesis 1992, Uni Hamburg]

…. with time (annealing):



[M.Moll, PhD thesis 1999, Uni Hamburg]

- "Type inversion": N_{eff} changes from positive to negative (Space Charge Sign Inversion)



- **Short term:** "Beneficial annealing"
- **Long term:** "Reverse annealing"
  - time constant depends on temperature:
    ~ 500 years (-10°C)
    ~ 500 days (20°C)
    ~ 21 hours (60°C)
  - **Consequence:** Detectors must be cooled even when the experiment is not running!

Radiation Damage – II. Leakage Current

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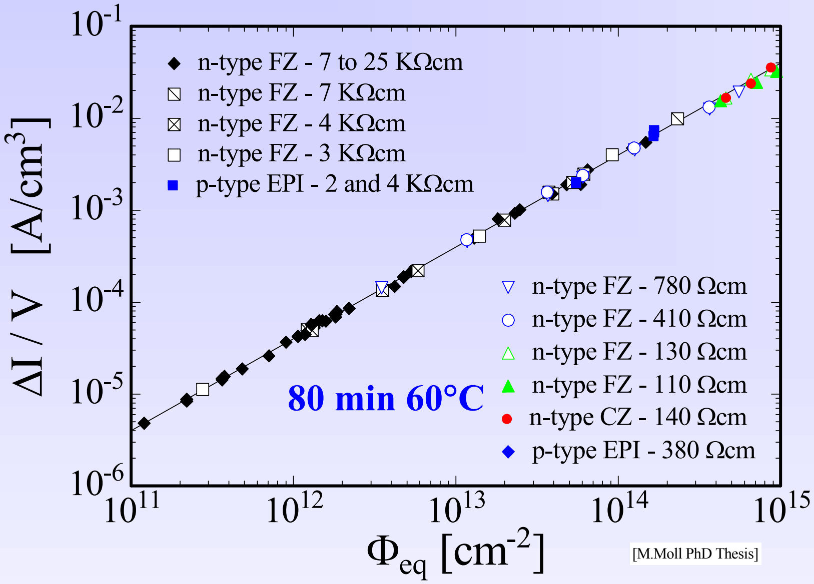
Change of Leakage Current (after hadron irradiation)

…. with particle fluence:



[M.Moll PhD Thesis]

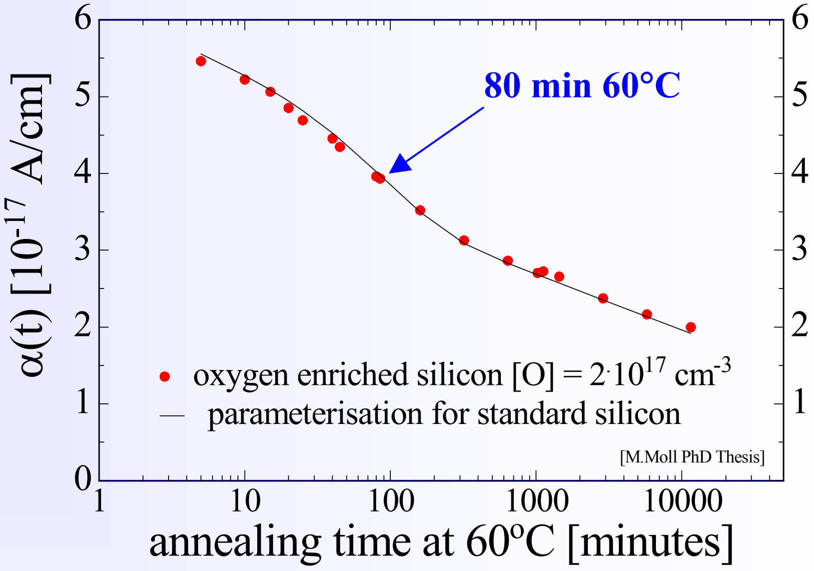
- Damage parameter α (slope in figure)

$$\alpha = \frac{\Delta I}{V \cdot \Phi_{eq}}$$

Leakage current
per unit volume
and particle fluence

- α is constant over several orders of fluence and independent of impurity concentration in Si
  ⇨ can be used for fluence measurement

…. with time (annealing):



[M.Moll PhD Thesis]

- Leakage current decreasing in time (depending on temperature)
- Strong temperature dependence

$$I \propto \exp\left(-\frac{E_g}{2k_BT}\right)$$

Consequence:

Cool detectors during operation!

Example: $I(-10°C) \sim 1/16\ I(20°C)$

Radiation Damage – III. CCE

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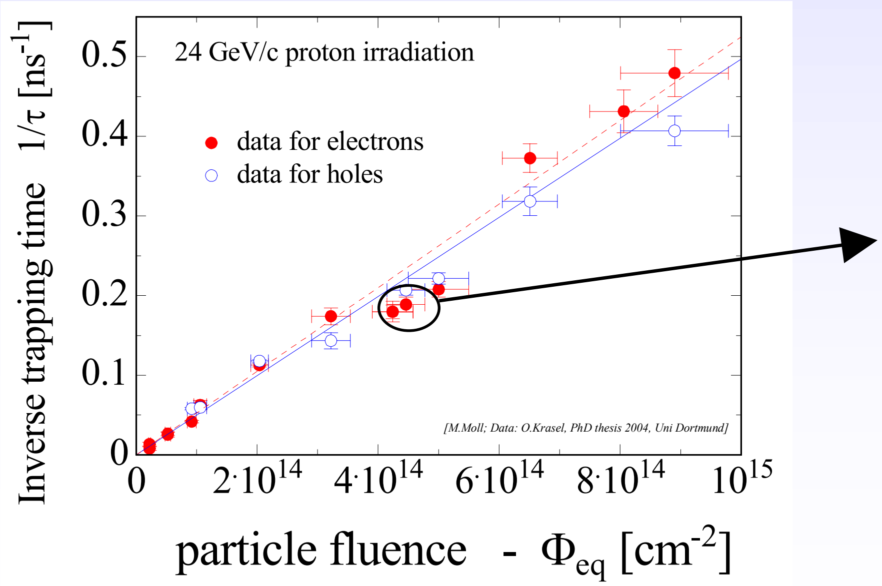
Deterioration of Charge Collection Efficiency (CCE)

2 mechanisms: - Trapping of electrons and holes
- Underdepletion (loss of active detector volume due to increase of V_{dep})

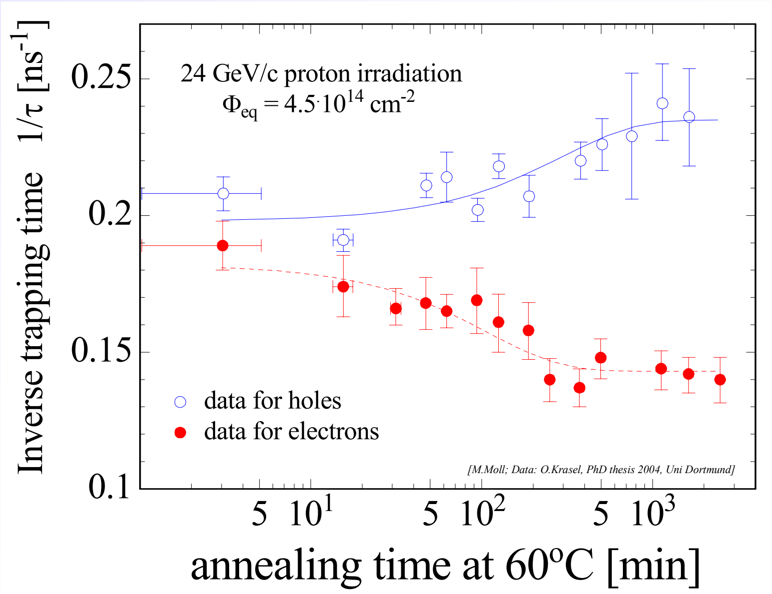
Trapping is characterized by an effective trapping time τ_{eff} for electrons and holes:

$$Q_{e,h}(t) = Q_{0e,h} \exp\left(-\frac{1}{\tau_{eff\ e,h}} \cdot t\right) \qquad \text{where} \qquad \frac{1}{\tau_{eff\ e,h}} \propto N_{defects}$$

Increase of inverse trapping time (1/τ) with fluence ….. and change with time (annealing):



[M.Moll; Data: O.Krasel, PhD thesis 2004, Uni Dortmund]



[M.Moll; Data: O.Krasel, PhD thesis 2004, Uni Dortmund]

R&D : Radiation tolerant tracking detectors

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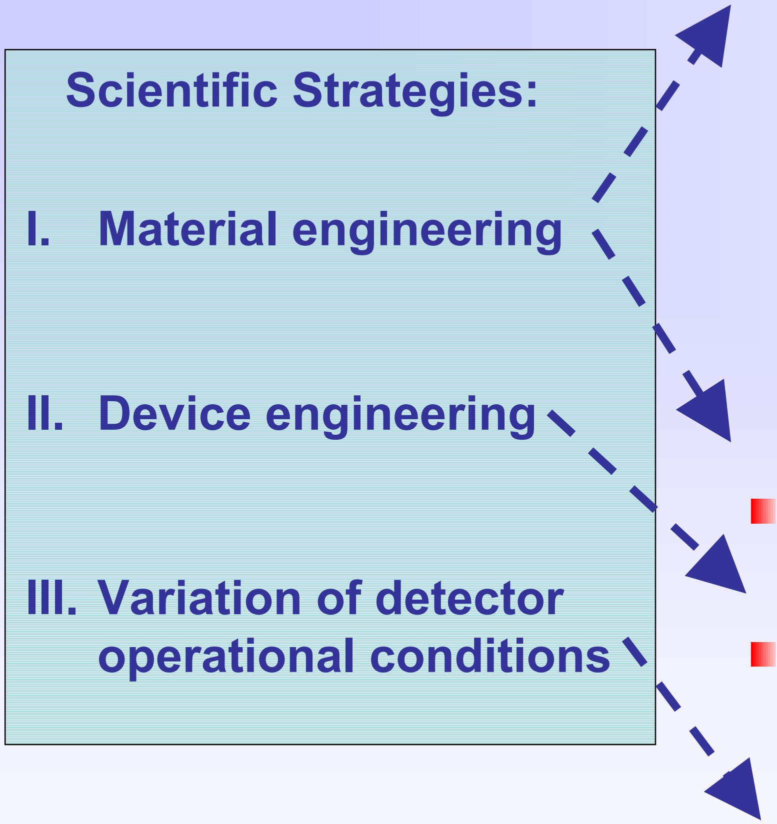


Scientific Strategies:

I. Material engineering

II. Device engineering

III. Variation of detector operational conditions

- **Defect Engineering of Silicon**

  Deliberate incorporation of impurities or defects into the silicon bulk to improve radiation tolerance of detectors

  – **Needs:** profound understanding of radiation damage
  (microscopic defects, macroscopic parameters,
  dependence on particles type and energy,
  defect formation kinetics and annealing processes)

  – **Examples:** - Oxygen enriched silicon
  - Hydrogen enriched silicon
  - Pre-irradiated silicon

- **New Materials** (other semiconductors than Si)

  – Diamond, Silicon Carbide (SiC), …

- **New detector designs**

  – **Examples:** - p-type silicon detectors (n-in-p)
  - thin detectors, epitaxial detectors
  - 3D and Semi 3D detectors

- **Cryogenic operation of detectors**

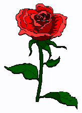
  Operate detectors at 100-200K to reduce the charge loss (“Lazarus effect”)

Active CERN R&D collaborations:

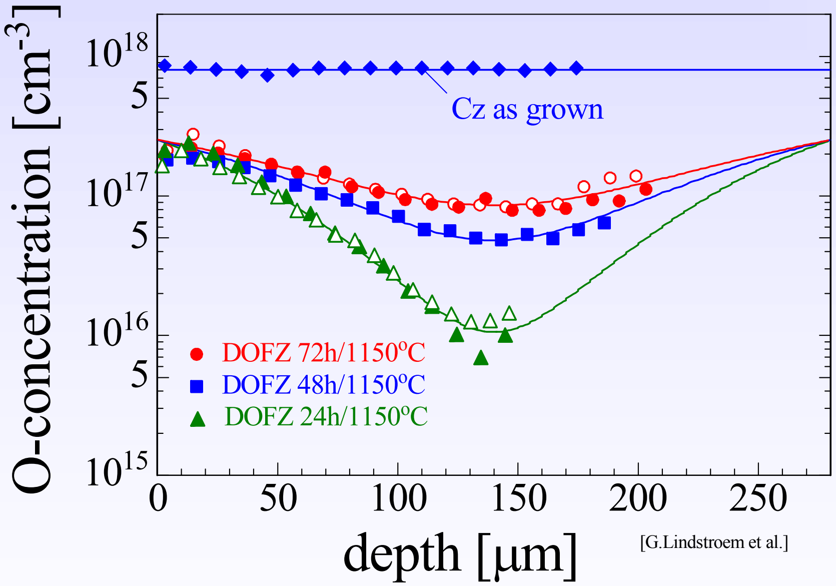
- *RD50 “Radiation hard semiconductor devices for very high luminosity colliders”*
- *RD42 “CVD Diamond Radiation Detectors”*
- *RD39 “Cryogenic Tracking Detectors”*

New Material: Oxygen enriched silicon – DOFZ

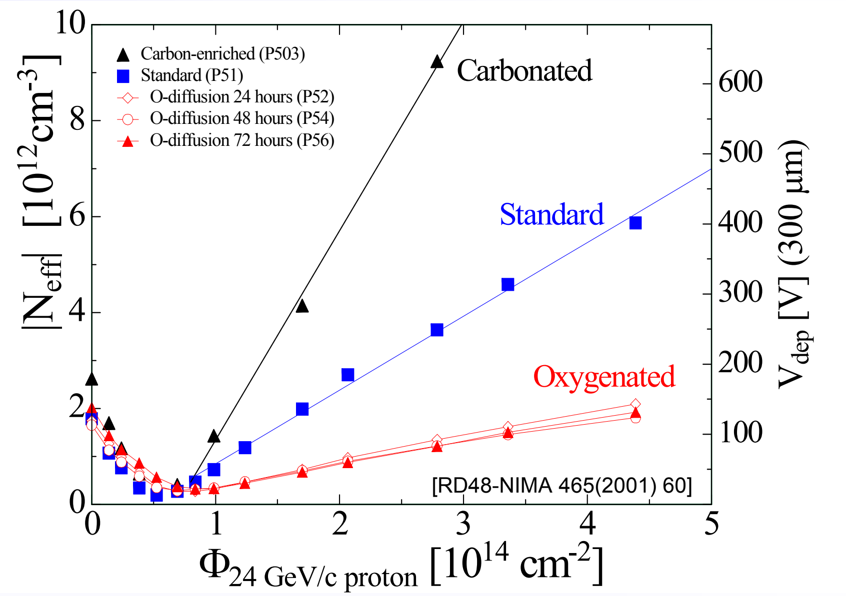
DOFZ (Diffusion Oxygenated Float Zone Silicon)

- 1982 First oxygen diffusion tests on FZ [Brotherton et al. J.Appl.Phys.,Vol.53, No.8.,5720]
- 1995 First tests on detector grade silicon [Z.Li et al. IEEE TNS Vol.42,No.4,219]
- 1999 Introduced to the HEP community by CERN - RD48 (ROSE-Collaboration )

Very long oxidation (e.g. 48h at 1150°C) increases the oxygen content in silicon → Strong improvement after charged hadron irradiation observed



[G.Lindstroem et al.]



[RD48-NIMA 465(2001) 60]

- 2005: DOFZ silicon used for the ATLAS and CMS Pixel detectors
- 2005: Other types of oxygen rich silicon under investigation: Czochralski Si, epitaxial Si

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n-in-n vs p-in-n

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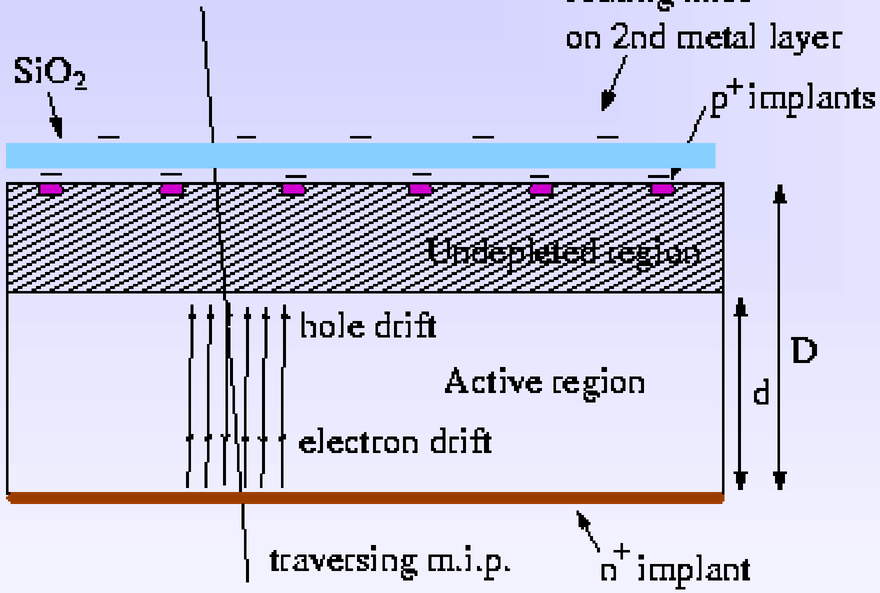
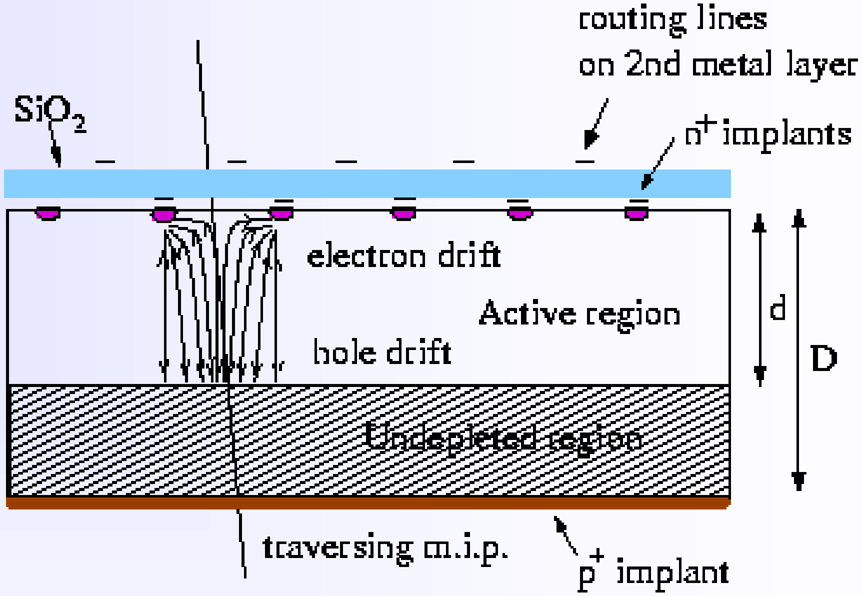
n-type silicon after type inversion:

p^+on-n



n^+on-n



p-on-n silicon, under-depleted:

- **Charge spread – degraded resolution**
- **Charge loss – reduced CCE**

n-on-n silicon, under-depleted:

- **Limited loss in CCE**
- **Less degradation with under-depletion**
- **Collect electrons (fast)**

New detector concepts: 3D detectors

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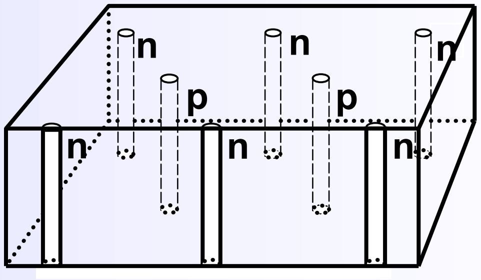
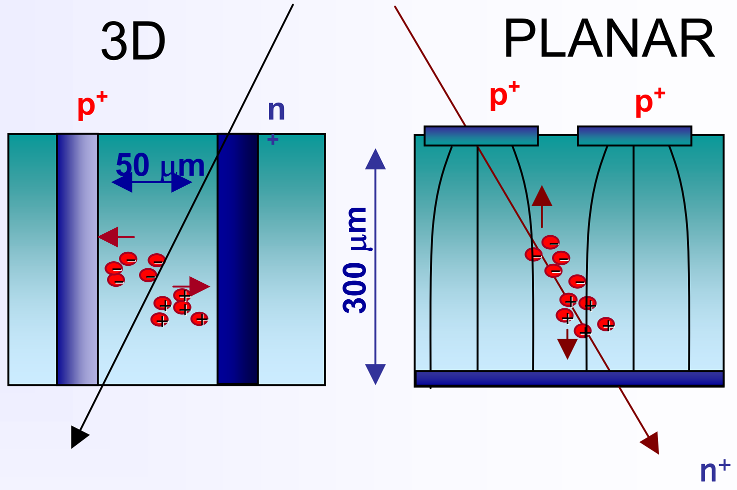
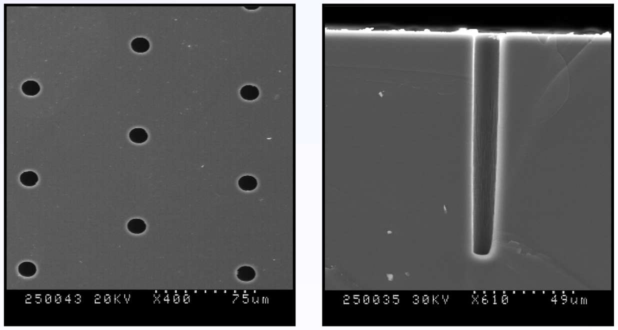
- **Electrodes:**
  - narrow columns along detector thickness-"3D"
  - diameter: ≈10µm; distance: 50 - 100µm
- **Lateral depletion:**
  - lower depletion voltage needed ($V_{dep} \sim d^2$)
  - radiation tolerant or thick detectors possible
  - fast signal (≈ 3.5 ns measured)
- **Processing of detectors:**
  - complex fabrication: Holes have to be made and filled with electrodes (DRIE etching, Laser drilling, Photo Electro Chemical etching); present aspect ratio (depth to diameter) ≈ 30:1
  - possibility to implement narrow dead regions at edges "edgeless detectors"
- **Application:**
  - detectors still under development!
  - option for LHC experiments upgrade ?



[Proposed: S.I. Parker et al., NIMA 395 (1997) 328]





References and Acknowledgements

Besides references given on the transparencies, the following sources have been used:

Books

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- Michael Moll, “Radiation Damage in Silicon Particle Detectors”, PhD thesis, DESY, December 1999
- Geoffrey Hall, “Semiconductor particle tracking detectors”, Rep.Prog.Phys. 57 (1994) 481-531

Lectures and Presentations

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- **Christian Joram, “Particle Detectors”, CERN, Summer Student Lectures June 2003**
- Paula Collins, “Recent Detector R&D and operational experience”, IWORID07, Riga, September 2003
- Gerhard Lutz, “Semiconductor Radiation Detectors”, Louvain, Seminar, June 2002
- Marcello Mannelli, “Tracking at the LHC: The CMS example”, CERN Academic Training, March 2005
- Pierre Jarron, “Microelectronics, Nanoelectronics, Monolithic Pixel Detectors” CERN Academic Training, Jan. 2004
- Hans Dijkstra, “Overview of Silicon Detectors”, Vienna conference, VCI 2001
- Volker Adler, “The TESLA Vertex Detector” ZEUS Student Seminar, Jan.2004
- Daniela Bortoletto, “An introduction to semiconductor detectors”, Vienna conference, VCI 2004
- A list of conferences about Solid State Detectors and Radiation Damage: http://cern.ch/mmoll/links/conferences.htm
- Vertex 2004 conference: http://sucimaweb.dipscfm.uninsubria.it/vertex04/