# Detectors for Particle Physics
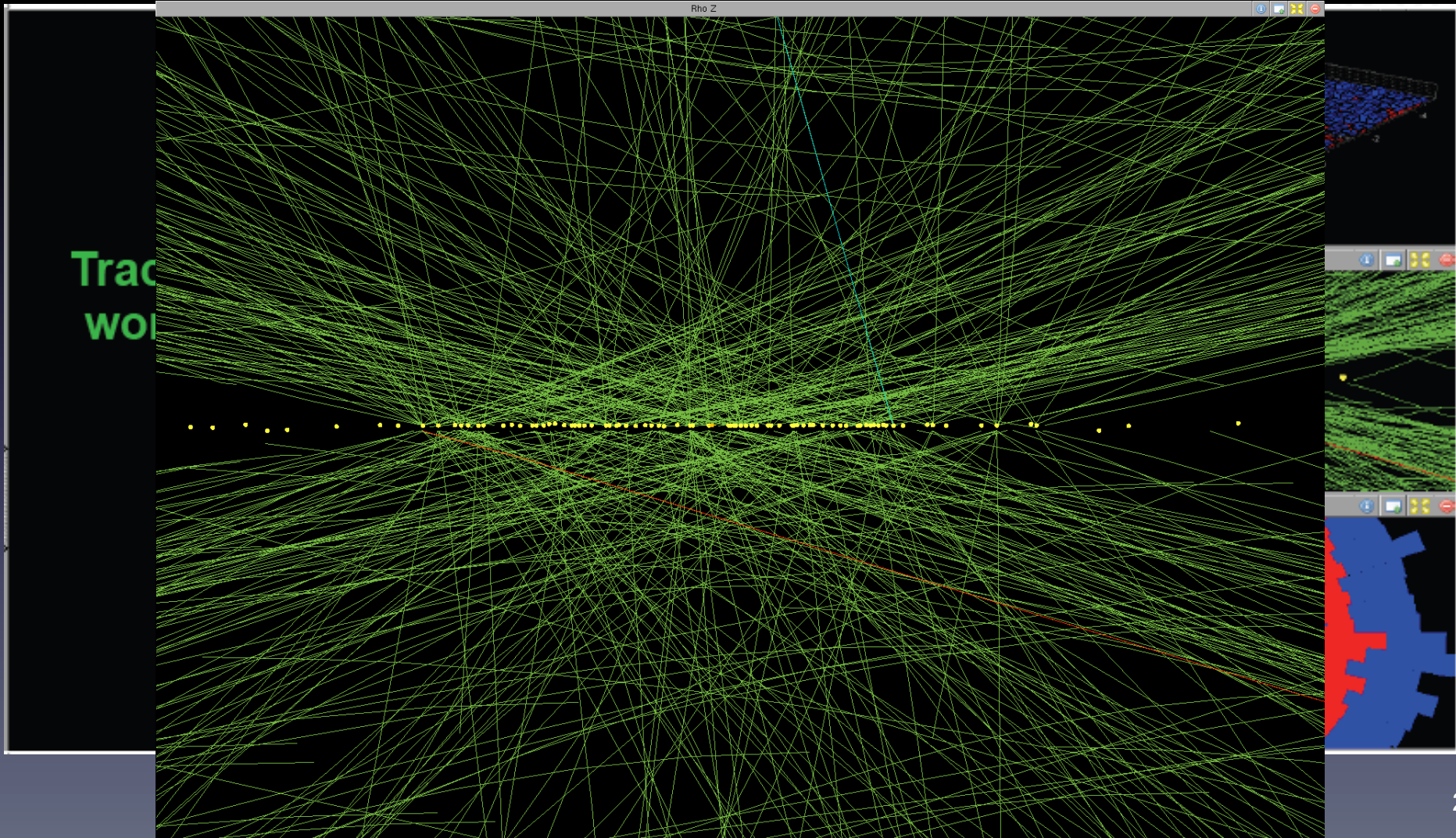
## Semiconductor  Detectors

**D. Bortoletto**
**University of Oxford &Purdue University**

# Tracking and Vertex Detector

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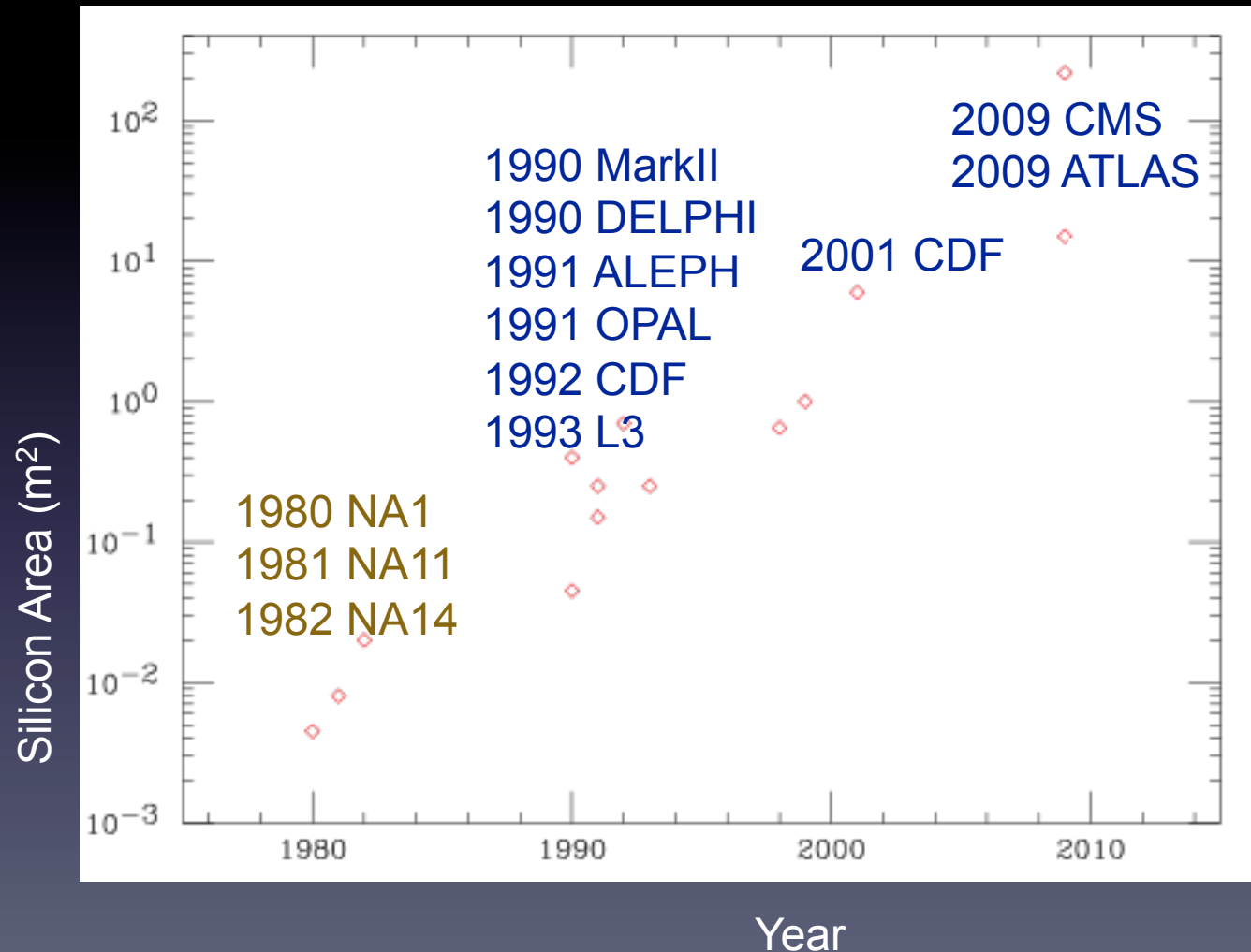- Determine position of primary interaction vertex and secondary decays

# Silicon Detectors in HEP

## (representative selection, approx. dates)

- Silicon detectors also continue to be improved
  - Size
  - Material
  - Radiation hardness

Silicon Area (m²)

Year

1990 MarkII
1990 DELPHI
1991 ALEPH
1991 OPAL
1992 CDF
1993 L3

2009 CMS
2009 ATLAS

2001 CDF

1980 NA1
1981 NA11
1982 NA14

# A brief history of solid state detectors

- J. Kemmer 1979

**FABRICATION OF LOW NOISE SILICON RADIATION DETECTORS BY THE PLANAR PROCESS**

J KEMMER

*Fachbereich Physik der Technischen Universitat Munchen, 8046 Garching, Germany*

Received 30 July 1979 and in revised form 22 October 1979

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

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

- NA11 at CERN
  - First use of a position-sensitive silicon detector in HEP experiment
  - Measurement of charm quark lifetimes
  - 1200 diode strips on 24x 36 mm$^2$
  - 250-500 µm thick bulk material
  - 4.5 µm resolution
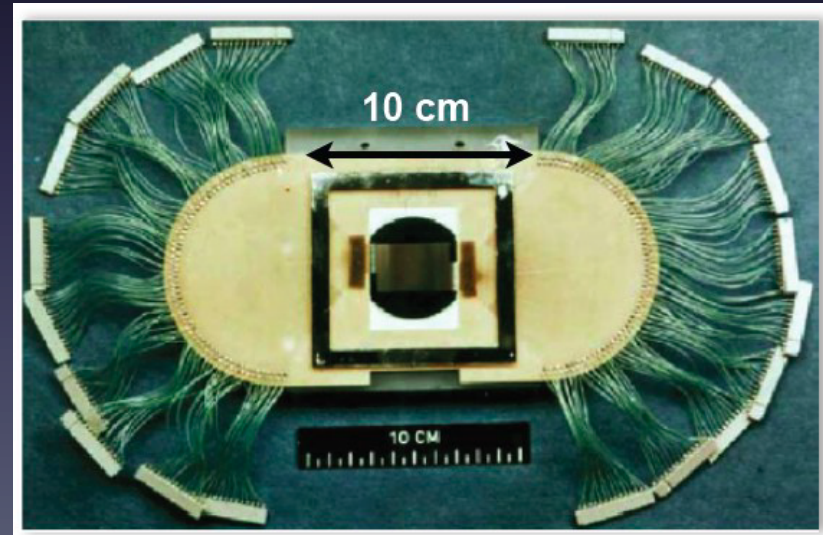
# LEP and SLAC SLC Experiments

- **LEP and SLC**
  - Readout ASICs at end of ladders
  - Minimize mass inside tracking volume
  - Minimize mass between interaction point and detectors
  - Minimize the distance between interaction point and the detectors
- Enabled measurement of b-quark lifetimes and b-tagging
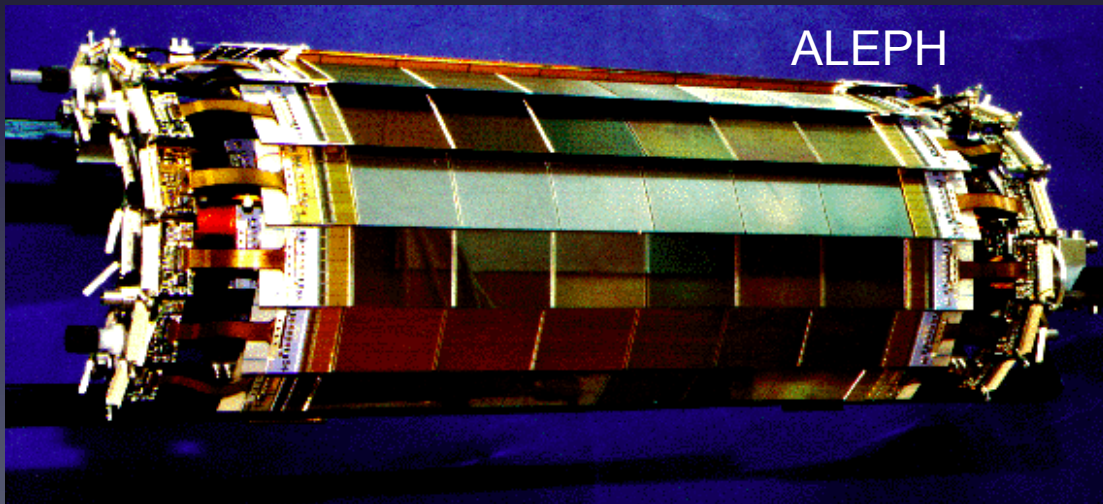


ALEPH

ALEPH
- 2 silicon layers, 40cm long, inner radius 6.3cm, outer radius 11cm
- 300 μm silicon wafers giving thickness of only $0.015X_0$
- S/N(r-φ) = 28:1
- S/N(z )= 17:1
- r-φ= 12 μm; z = 14μm

# CDF & D0 at the Tevatron

- CDF pioneered the silicon vertex detector in the hadron collider environment and pioneered the silicon vertex trigger separating *b*-hadrons

- Emphasis shifted to tracking and vertexing allowing precision measurements in very complex environment

- Cover large area with many silicon layers

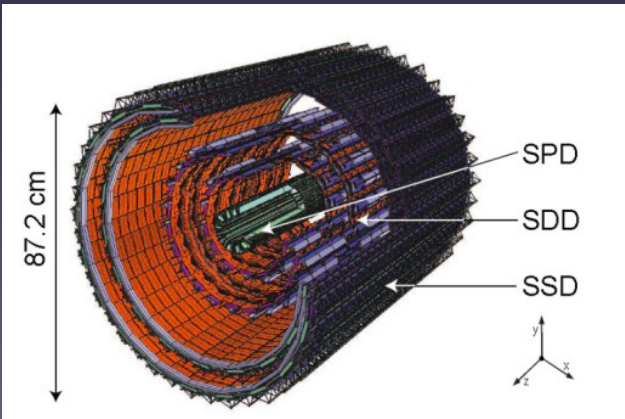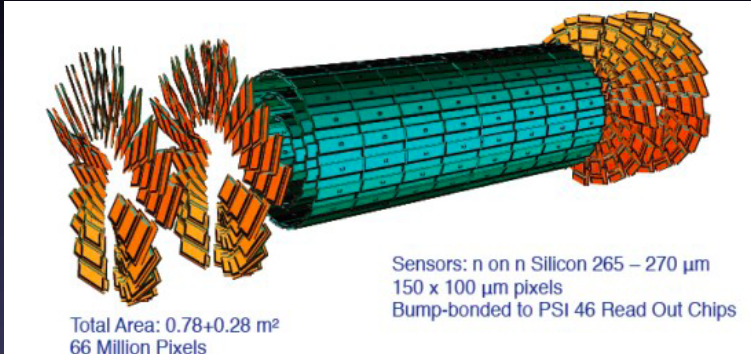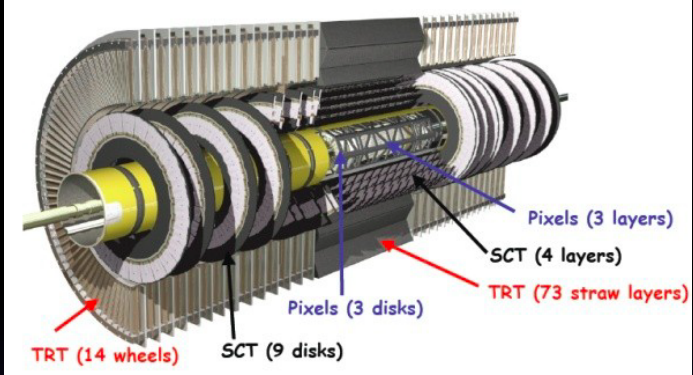- Detector modules including ASIC's and services INSIDE the tracking volume

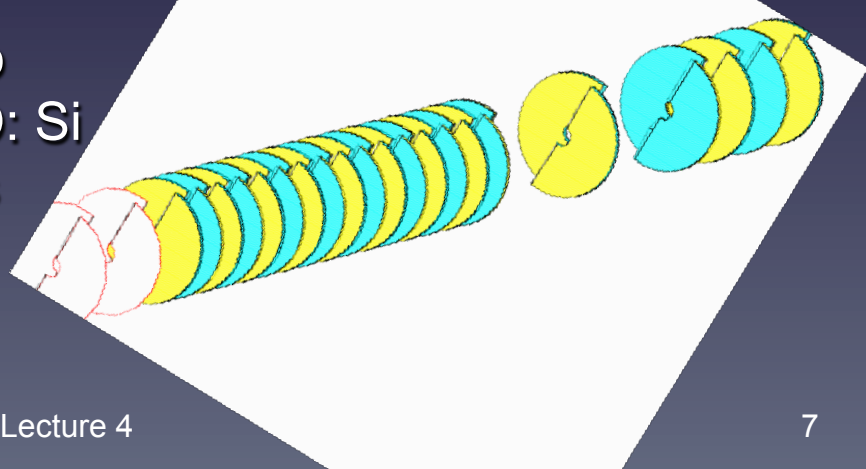CDF's first Silicon Vertex Detector at the Smithsonian Museum, Washington
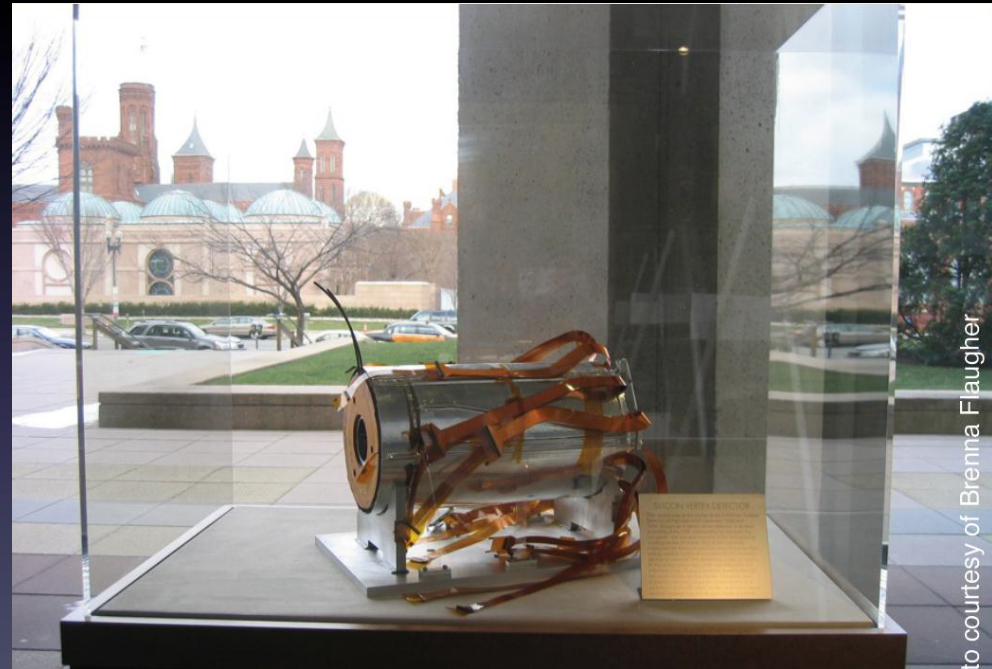


to courtesy of Brenna Flaugher

# The LHC silicon detectors

- **ATLAS** Strips: 61 m$^2$ of silicon, 4088 modules, 6x10$^6$ channels Pixels: 1744 modules, 80 x 10$^6$ channels

- **CMS** the world largest silicon tracker 200 m$^2$ of strip sensors (single sided) 11 x 10$^6$ readout channels ~1m$^2$ of pixel sensors, 60x10$^6$ channels

- **ALICE** Pixel sensors Drift detectors Double sided strip detectors

- **LHCb** VELO: Si Strips



Pixels (3 layers)
SCT (4 layers)
TRT (73 straw layers)
Pixels (3 disks)
TRT (14 wheels)
SCT (9 disks)



Sensors: n on n Silicon 265 – 270 μm
150 x 100 μm pixels
Bump-bonded to PSI 46 Read Out Chips
Total Area: 0.78+0.28 m²
66 Million Pixels
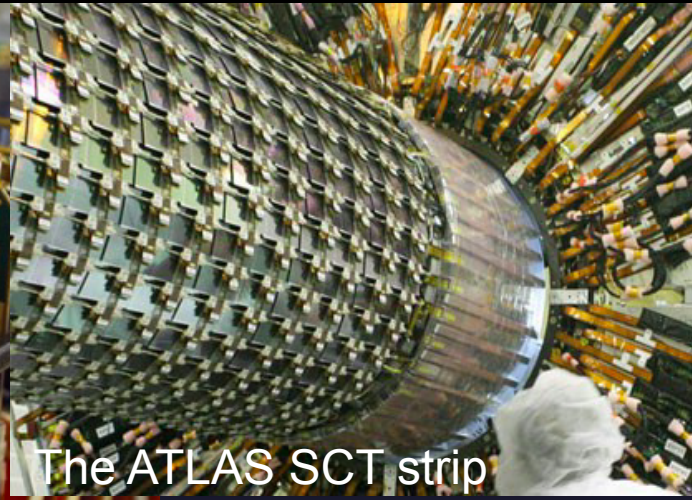


87.2 cm
SPD
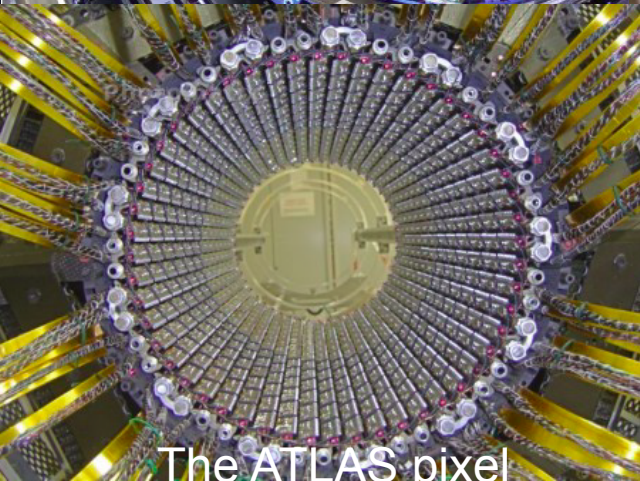SDD
SSD

# The LHC detectors

The CMS TIB strip

The LHCb- VELO strip \

The ATLAS SCT strip
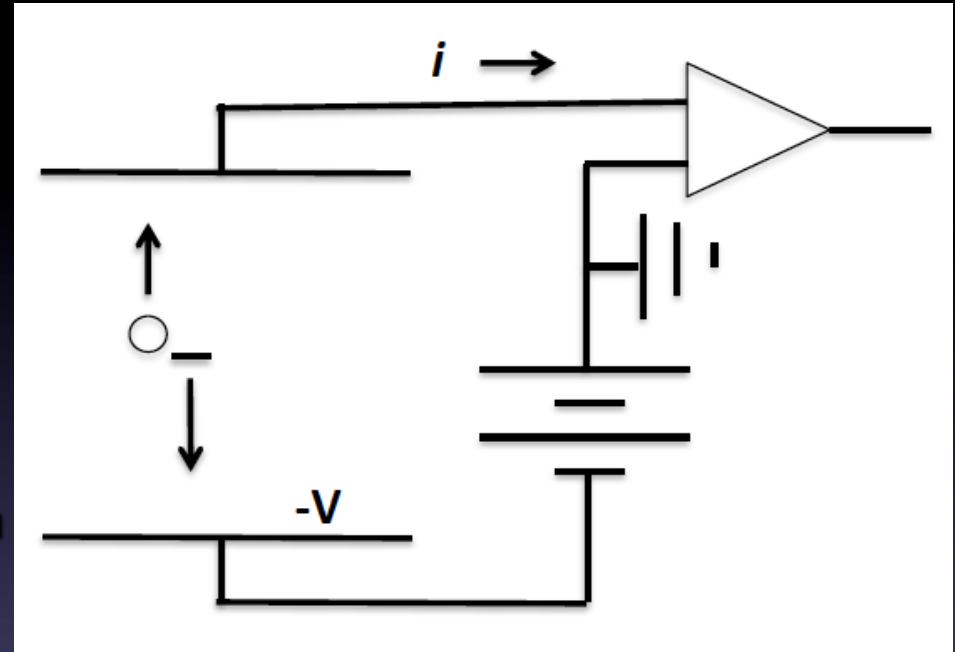
The ATLAS pixel

ALICE pixel

The CMS pixel

# From LEP to the LHC

# Solid State  Detector

- A solid state detector is an ionization chamber

  - Ionizing radiation creates electron/hole pairs
  - Charge carriers move in applied E field
  - Motion induces a current in an external circuit, which can be amplified and sensed.



- However, free carriers must first be removed so the applied voltage doesn't simply result in a (large) DC current – this is usually accomplished with a revers**e biased diode.**

# Comparison solid state versus gas

**Ionization chamber medium could be gas, liquid, or solid**

– **Gas $\Rightarrow$ electron and ion pairs; Semiconductor $\Rightarrow$ electron and hole pairs**

|  | Gas | Solid |
|---|---|---|
| **Density** | Low | High |
| **Atomic number (Z)** | Low | Moderate (Z=14) |
| **Ionization Energy ($\varepsilon_I$)** | Moderate ($\approx$ 30 eV) | Low ($\approx$3.6 eV) |
| **Signal Speed** | Moderate (10ns-10$\mu$s) | Fast (<20 ns) |

**Solid State Detectors**

- Energy (E) to create e-h pairs 10 times smaller than gas ionization $\Rightarrow$ increase charge$\Rightarrow$ good E resolution
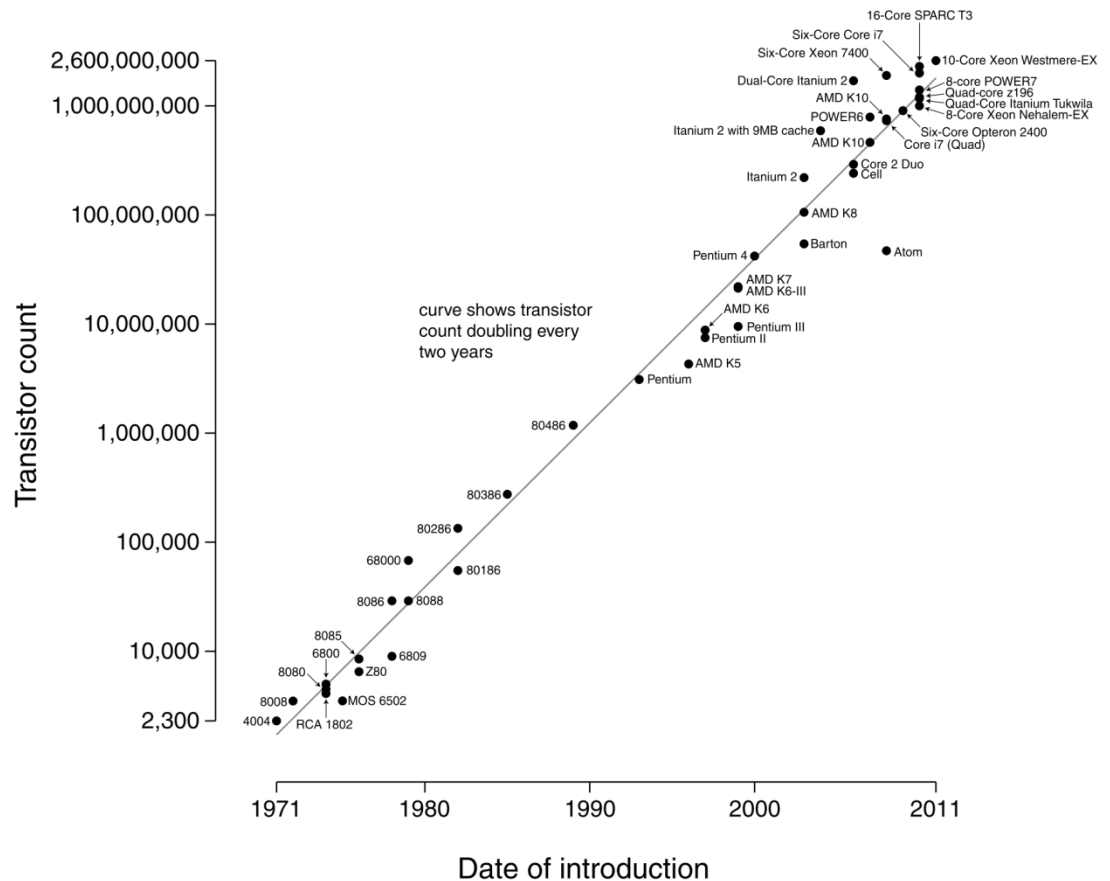
$$\frac{\Delta E}{E} \propto \frac{1}{\sqrt{N}} \propto \frac{1}{\sqrt{E/\varepsilon_I}} \propto \sqrt{\varepsilon_I}$$

- Greater density:
  - Reduced range of secondary electrons $\Rightarrow$ excellent spatial resolution
  - Average $E_{loss} \approx$390eV/ $\mu$m $\approx$108 e-h/ $\mu$m (charge collected is a function of thickness d. Up-to-now no multiplication)
- To minimize multiple scattering d is small
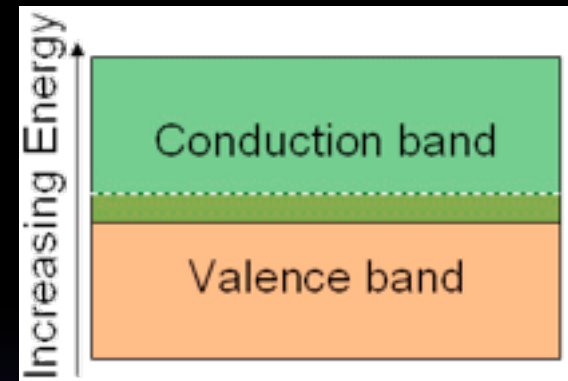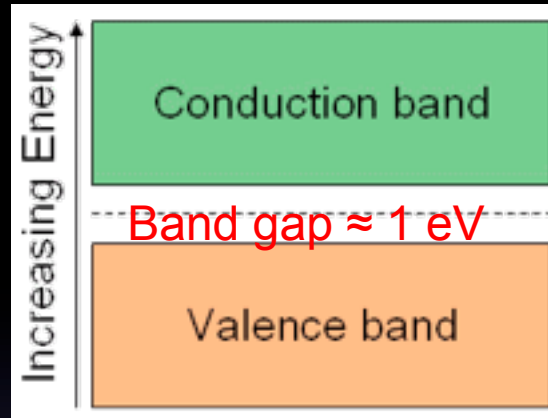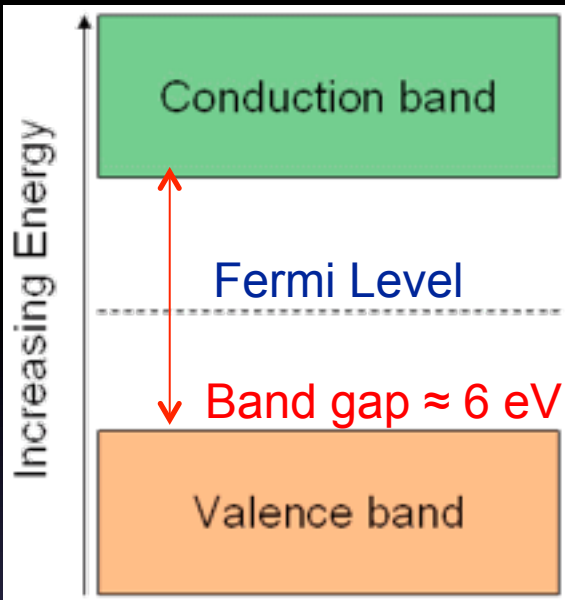  - 300 $\mu$m $\approx$32,000 e-h pairs ➔ good S/N

# Why silicon ?

- After Oxygen, Silicon is the 2 nd most abundant element in Earth's crust (>25% in mass)

- Leverages IC Technology

- Exponential improvements of silicon ICs

- WILL end someday… but when?



Microprocessor Transistor Counts 1971-2011 & Moore's Law

# Semiconductor



Conduction band

Fermi Level

Band gap ≈ 6 eV

Valence band

Conduction band

Band gap ≈ 1 eV

Valence band

Conduction band

Valence band

- Fermi level
  – Maximum electron energy at T = 0 K

- Semiconductor: at room temperature electrons can already occupy the conduction band and may recombine with holes.

- Thermal equilibrium is reached between excitation and recombination when the charge carrier concentration $n_e = n_h = n_i$ = intrinsic carrier concentration ≈ $1.5 \times 10^{10}$ cm$^{-3}$



$T = 0$ K

$T > 0$ K

- Valence electron
- Conduction electron
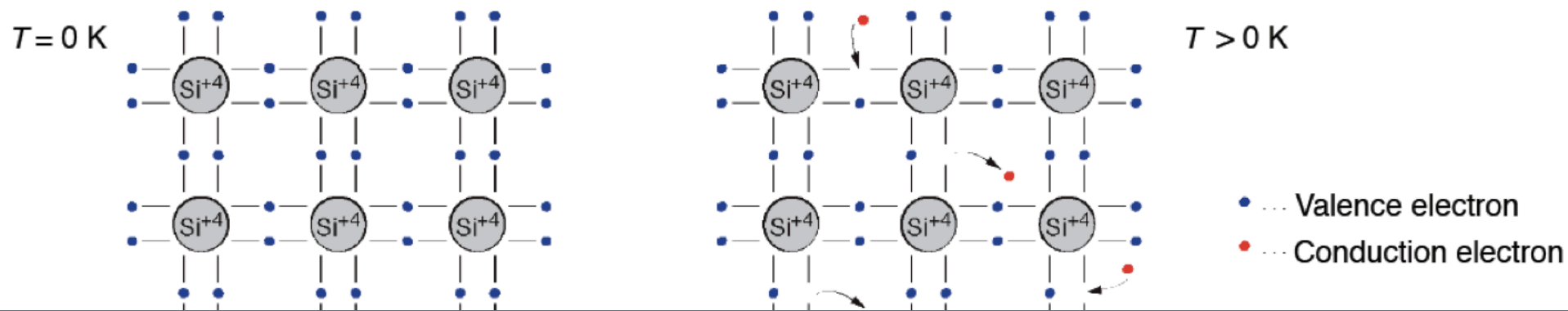
# Principle of operation

- Mean ionization energy $I_0$ = **3.62 eV**; Mean energy loss per flight path of a mip **$dE/dx$ = 3.87 MeV/cm**

- Consider a detector of thickness $d$ = 300 μm and area $A$ = 1 cm$^2$.
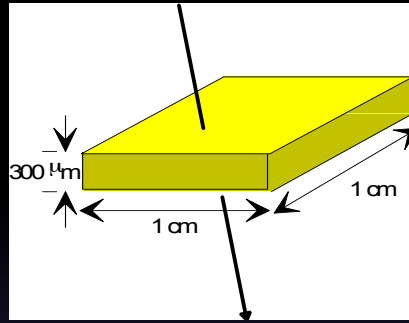
- **MIP signal is**

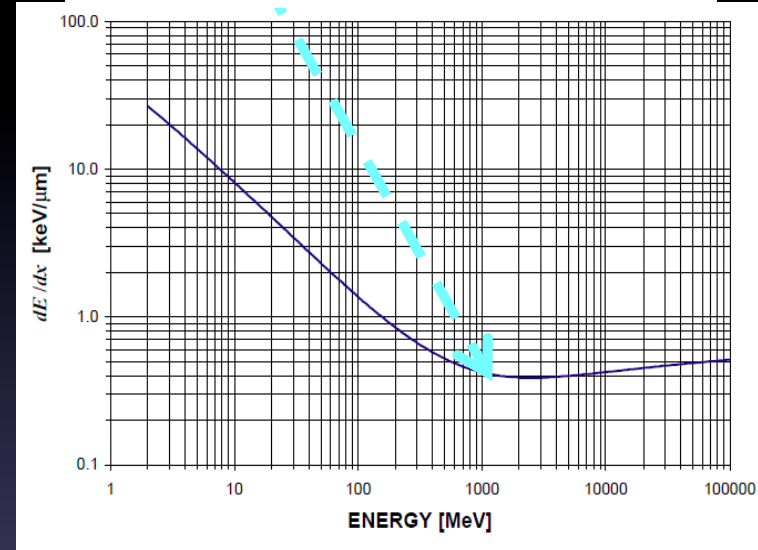$$\frac{(dE/dx)d}{I_0} = \frac{3.87 \cdot 10^6 \, eV/cm \cdot 0.03cm}{3.63eV}$$

$$\cong 3.2 \cdot 10^4 \, \text{e-h pairs}$$

dE/dx of Protons in Silicon

- **Intrinsic charge carriers in the same volume** ($T$ = 300 K):

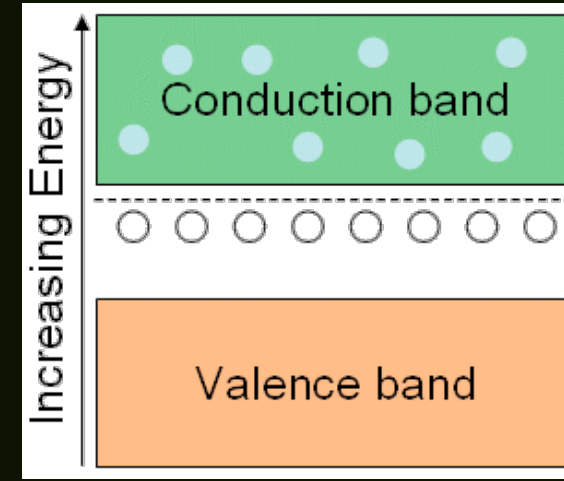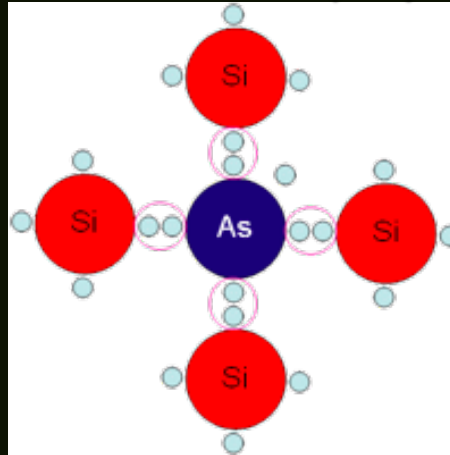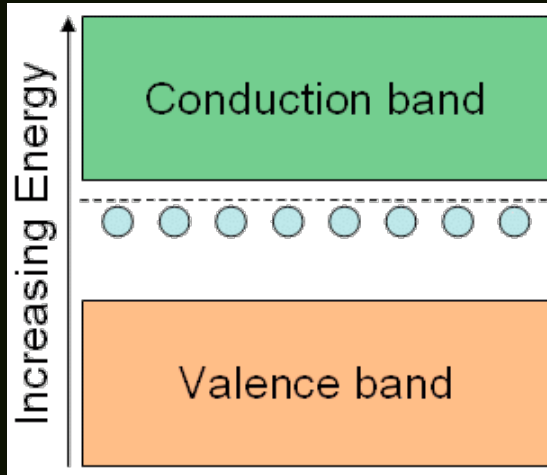$$n_i dA = 1.45 \cdot 10^{10} \, cm^{-3} \cdot 0.03cm \cdot 1cm^2 \cong 4.35 \cdot 10^8 \, \text{e-h pairs}$$

  - Number of thermal created e–h-pairs (noise) is four orders of magnitude larger than the signal
  - We need to deplete the free charge carriers

# Doped semiconductors
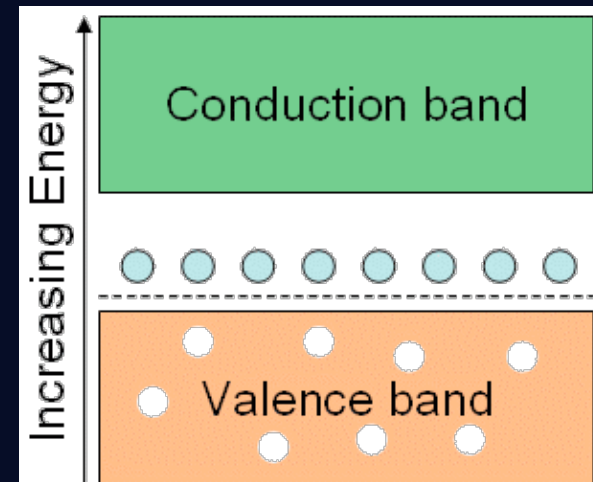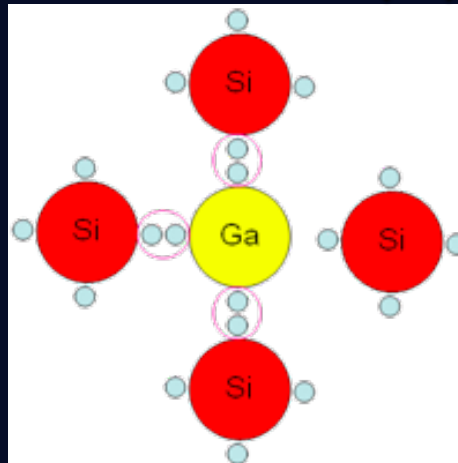
# PN Junction

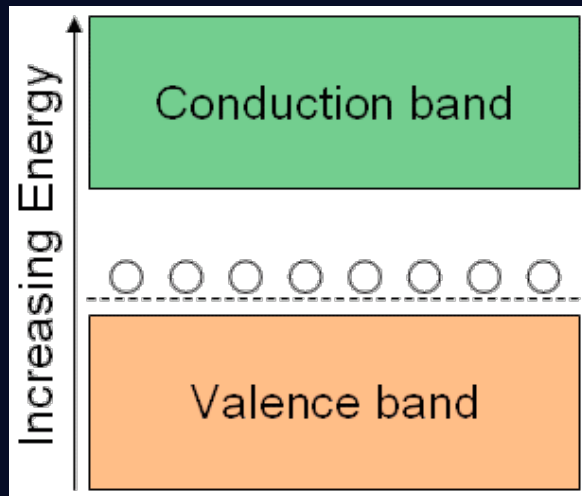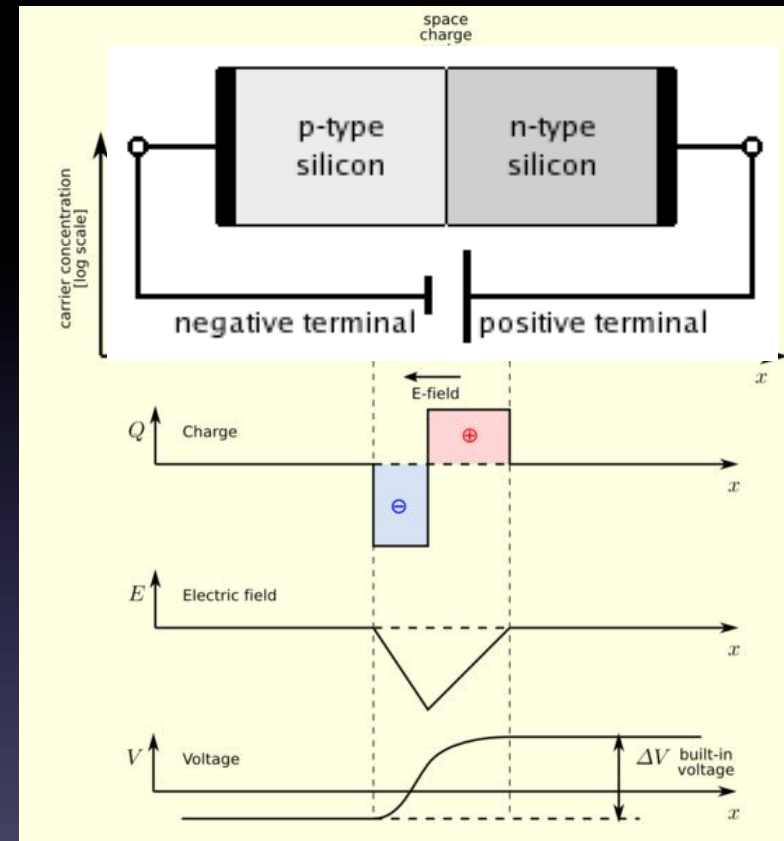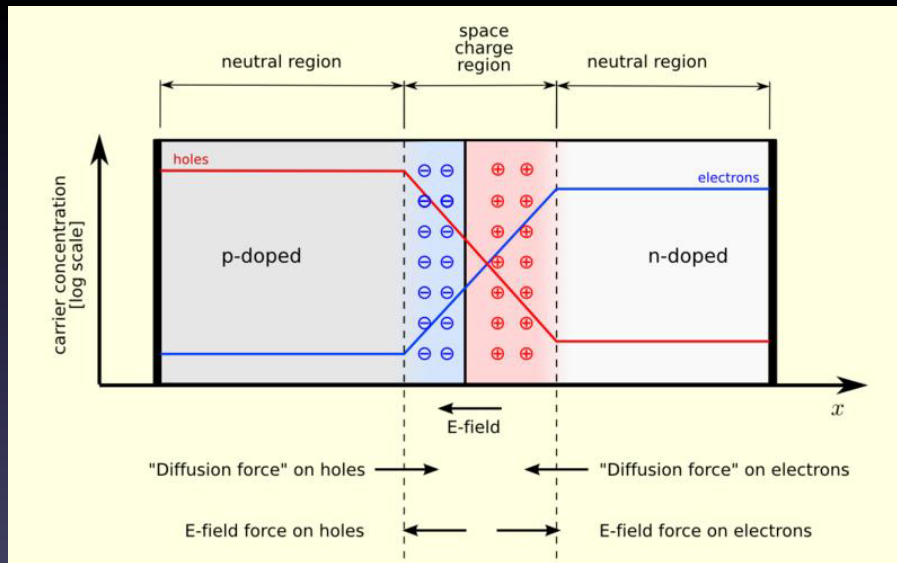- PN junction without external voltage
  - Free charges move until the chemical potential is balanced by an electrical potential called the built-in potential





- The space charge (depletion) region can be made bigger by applying a reverse bias voltage

# Width of the depletion zone

- Solve Poisson eq. using conservation of charge $N_A d_p = N_D d_n$
- Effective doping concentration in typical silicon detector with p$^+$-n junction
  - $N_A = 10^{15}$ cm$^{-3}$ in p$^+$ region
  - $N_D = 10^{12}$ cm$^{-3}$ in n bulk.
- Without external voltage:
  - $W_p = 0.02$ μm and $W_n = 23$ μm
- Applying a reverse bias voltage of 100 V:
  - $W_p = 0.4$ μm and $W_n = 363$ μm

$$W_p = \sqrt{\frac{2\varepsilon |V|}{e} \frac{1}{N_A(1 + N_A / N_D)}}$$

$$W_n = \sqrt{\frac{2\varepsilon |V|}{e} \frac{1}{N_D(1 + N_D / N_A)}}$$

| p$^+$ | $N_a \approx 10^{15}$ cm$^{-3}$ |
|---|---|
| n | |
| | $N_d \approx 10^{12}$ cm$^{-3}$ |
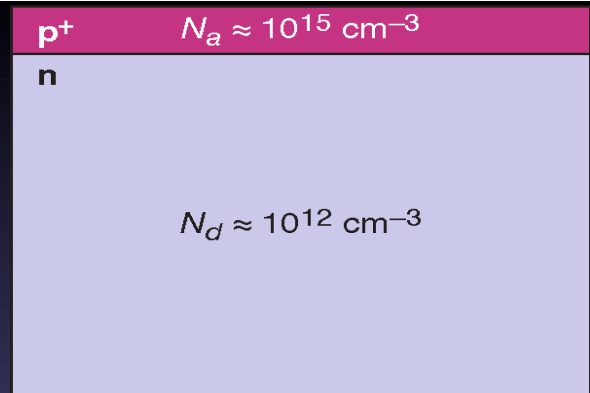
## Width of depletion zone

$$W = \sqrt{\frac{2\varepsilon V}{e} \frac{1}{N_D}} \quad if \quad N_A >> N_D$$

e=electron charge, ε=resistivity
μ= majority carriers mobility
N= dopant density

$$W \approx \sqrt{2\varepsilon \mu \rho V} \quad with \quad \rho = \frac{1}{e\mu N}$$

The voltage V needed to deplete a device of thickness d is called the depletion voltage $V_d$

# Depletion Zone & Capacitance

- The depletion voltage can be determined by measuring the capacitance versus reverse bias voltage. The capacitance is simply the parallel plate capacity of the depletion zone.

$$C = \frac{\varepsilon A}{d} = A\sqrt{\frac{\varepsilon}{2\rho\mu V_b}}$$



**V**

**Depletion zone**   **W**

**undepleted zone**   **d**



**capacitance vs voltage**



**1/C² vs voltage**

**V_d**

# Leakage current



REVERSE BIAS

Current

~0.7V

>>100V

Knee

On resistance

Leakage current

X scale

Voltage

Off resistance

Breakdown

FORWARD BIAS
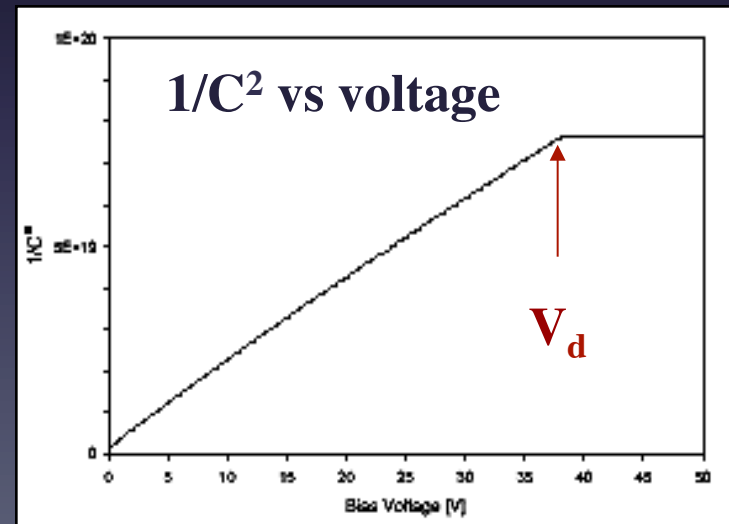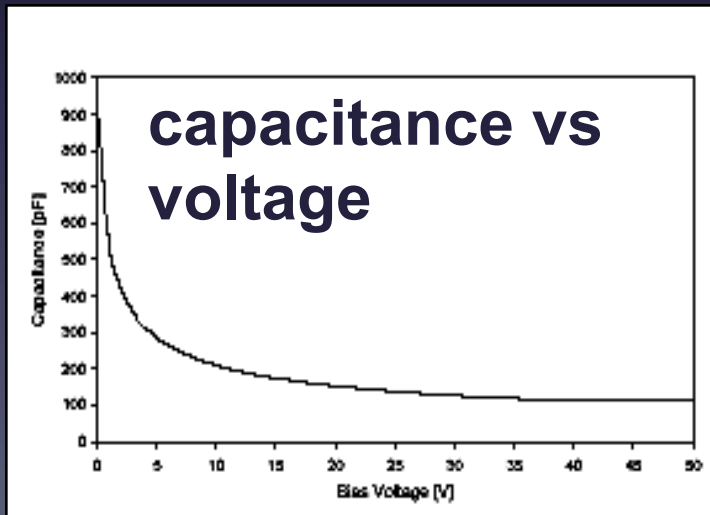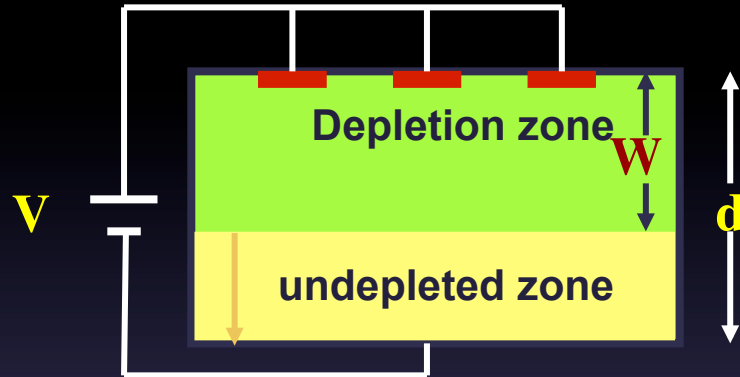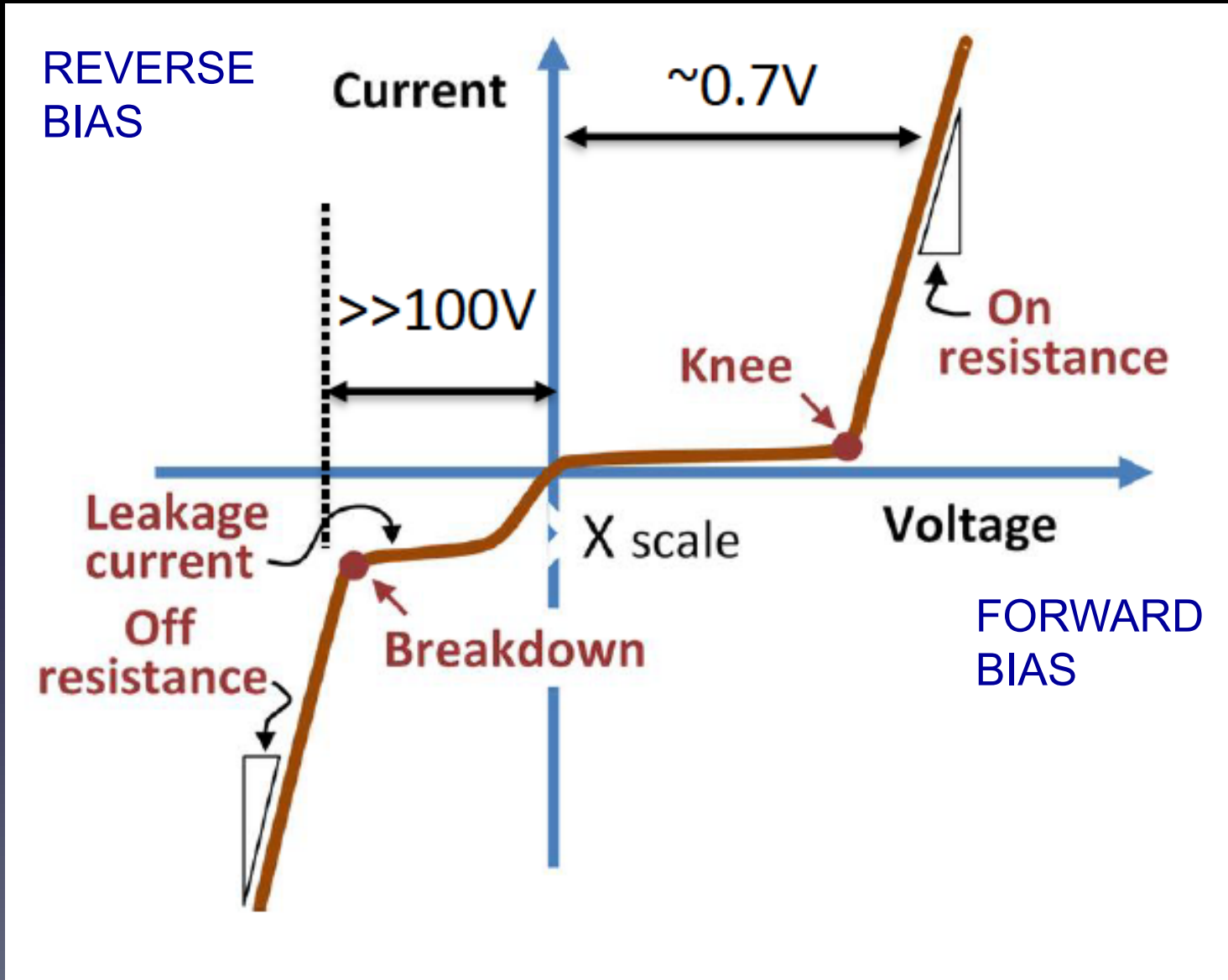
# Leakage current
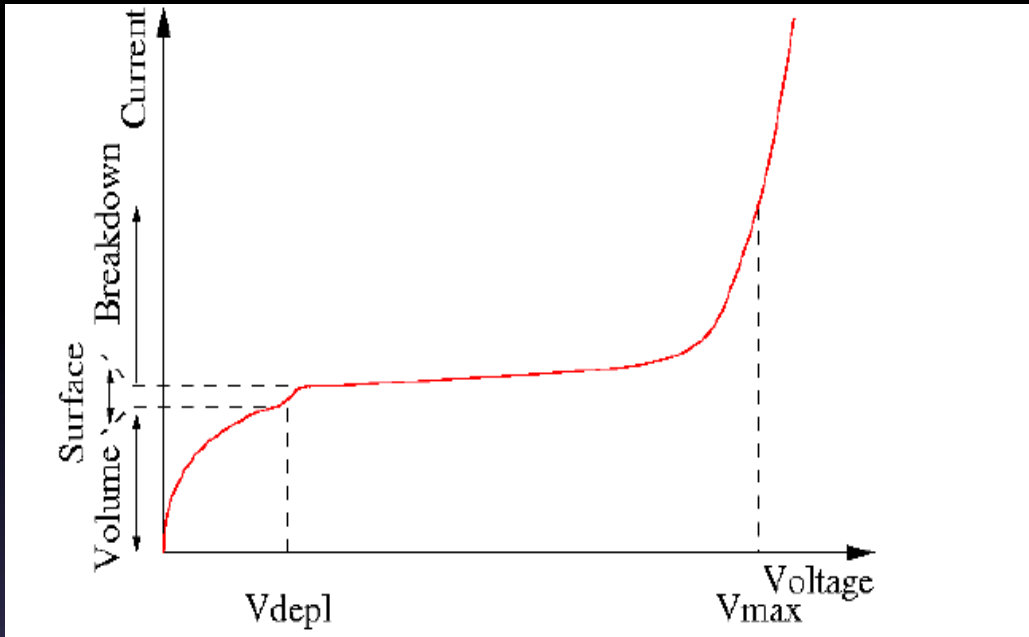
$I_{leak}$ sensitive to process quality

Diffusion current
- charge generated in the undepleted zone adjacent to the depletion zone which diffuse into the depletion zone



Leakage Current Vs Temperature

Factor 2 every 8 $^0$C

Generation current
- From thermal generation in the depletion region
- Reduced by using pure and defect free material with high carrier lifetime
- Keep temperature low & controlled

$$j_{gen} \propto T^{3/2} \exp\left(\frac{1}{2kT}\right)$$

D. Bortoletto Lecture 4
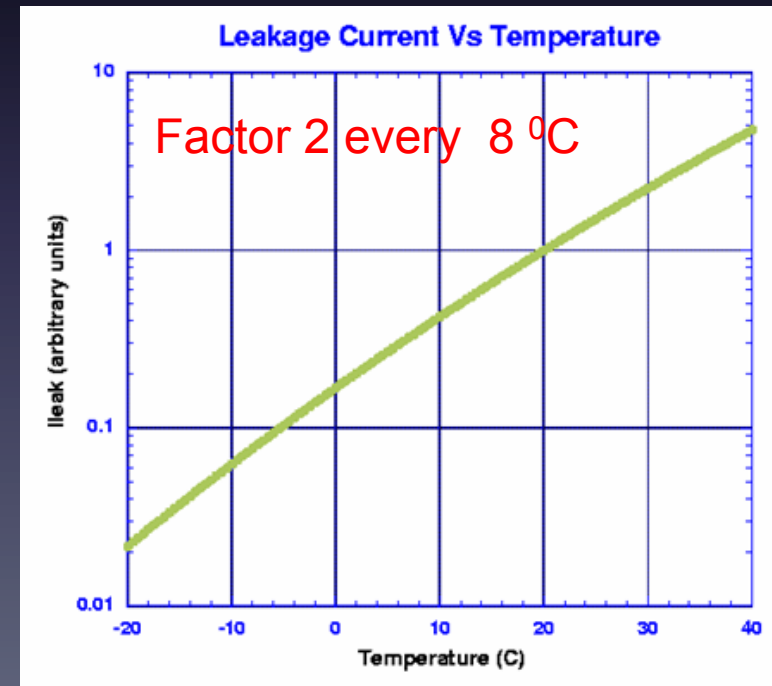
# Charge collection

- Electron and hole pairs created in the depletion region move under the E field

$$v_{e,h}(x) = \mu_{e,h}E(x)$$

$$\mu_e = 1500\,cm^2/Vs$$

$$\mu_h = 450\,cm^2/Vs$$



Charge Collection Time (Vd = 40 V)

Electrons
Holes

Time (ns)

Bias Voltage

**30 ns**

**10 ns**

- The time required for a carrier to traverse the sensitive volume is the collection time.
- The collection time can be reduced by over-biasing the sensor

D. Bortoletto Lecture 4                                21
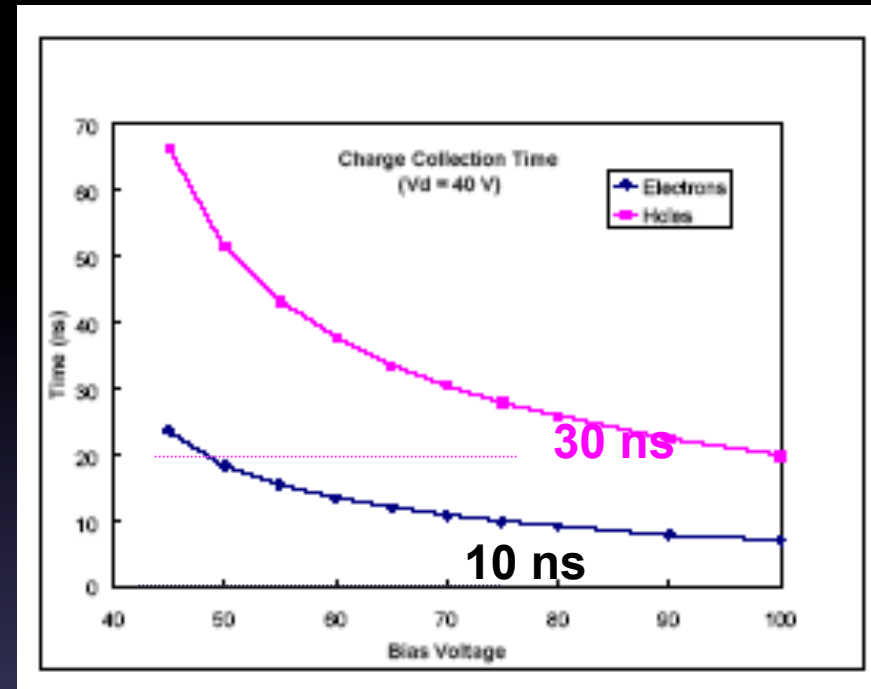
# Silicon Strip Detectors (SSD)

- By segmenting the implant we can reconstruct the position of the traversing particle in one dimension

- DC-coupled strip detector – simplest position sensitive Silicon detector

- Standard configuration:
  - Strips p implants
  - Substrate n doped (~2-10 kΩcm) and ~300µm thick
  - $V_{dep} <$ 200 V
  - Backside Phosphorous implant to establish ohmic contact and to prevent early breakdown

- Highest field close to the collecting electrodes (junction side) where most of the signal is induced
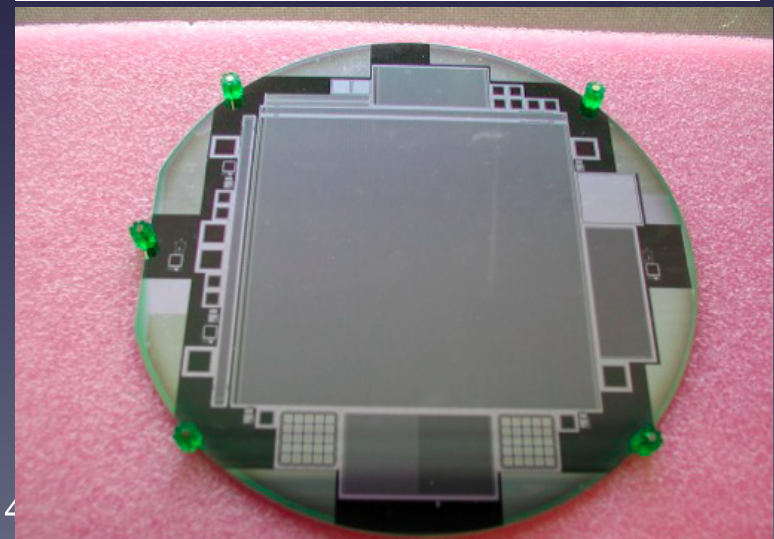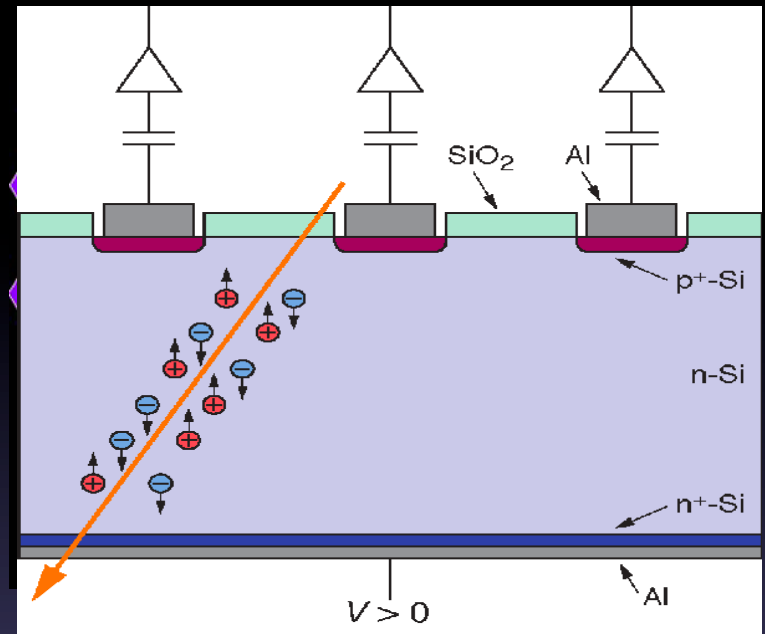
# Strip Detector

- AC coupling blocks DC leakage current
- Integration of coupling capacitances in standard planar process.
  - Deposition of $SiO_2$ with a thickness of 100–200 nm between p+ and aluminum strip
  - Increase quality of dielectric by a second layer of $Si_3N_4$.
- Long poly silicon resistor with R>1MΩ to connect the bias voltage to the strips:
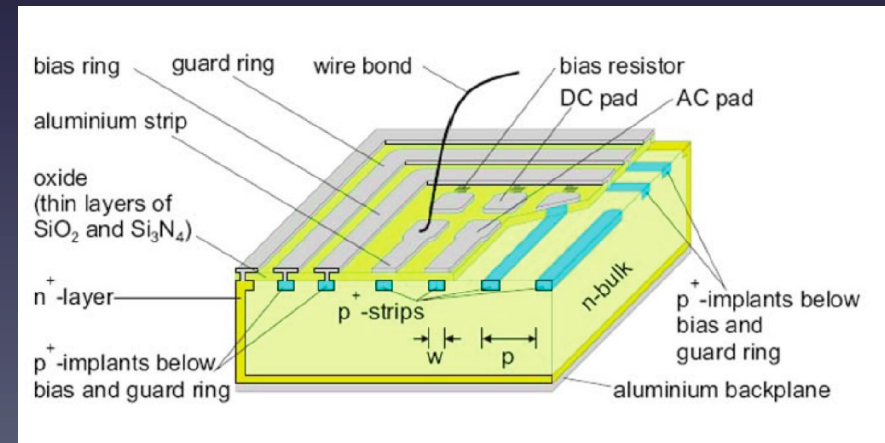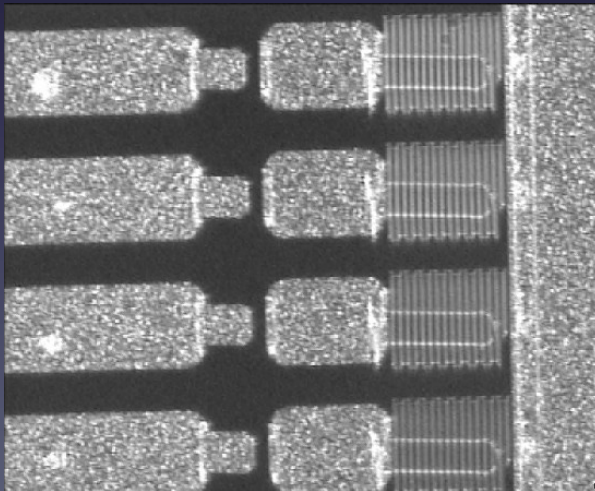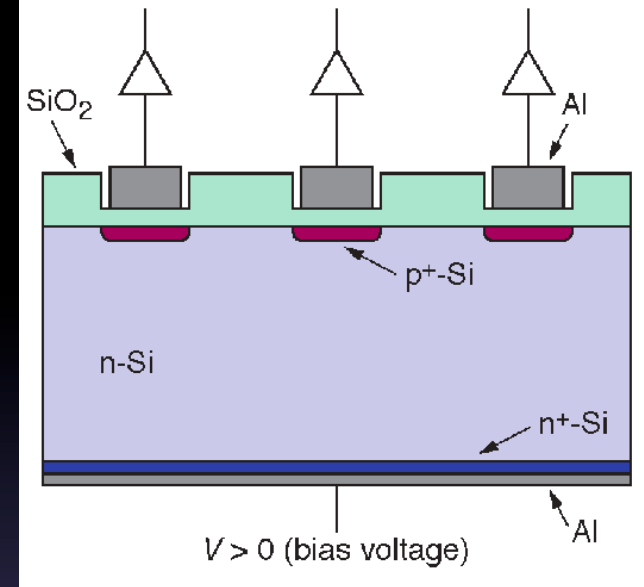
# A typical strip module (CMS)



silicon sensors
~20 cm strip length

carbon fibre
support

pitch adapter

hybrid
front-end electronics
with read-out chips

kapton flat cables
for power and data

DEVICE #A
WIRE #9, 1ST BOND

bond
pad

aluminum
wedge

600x    10.0 kV    10µm    #0019
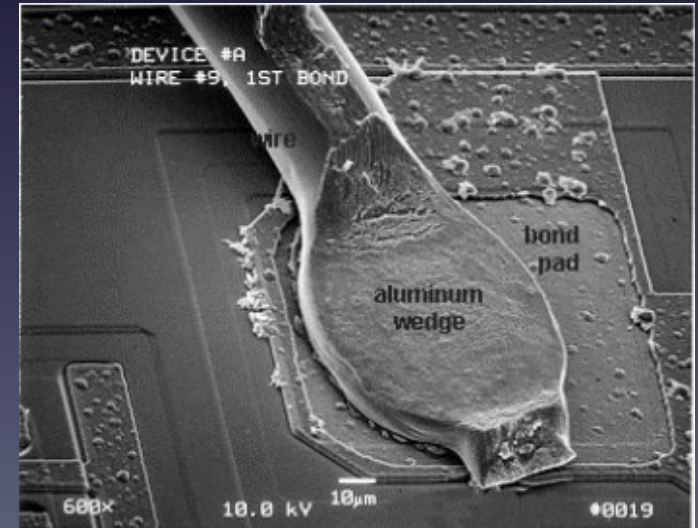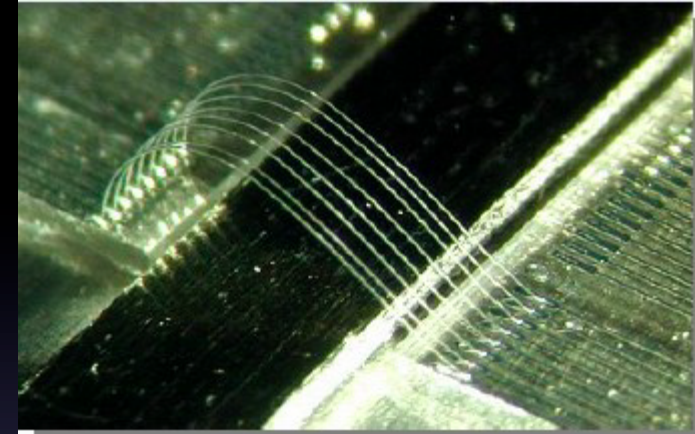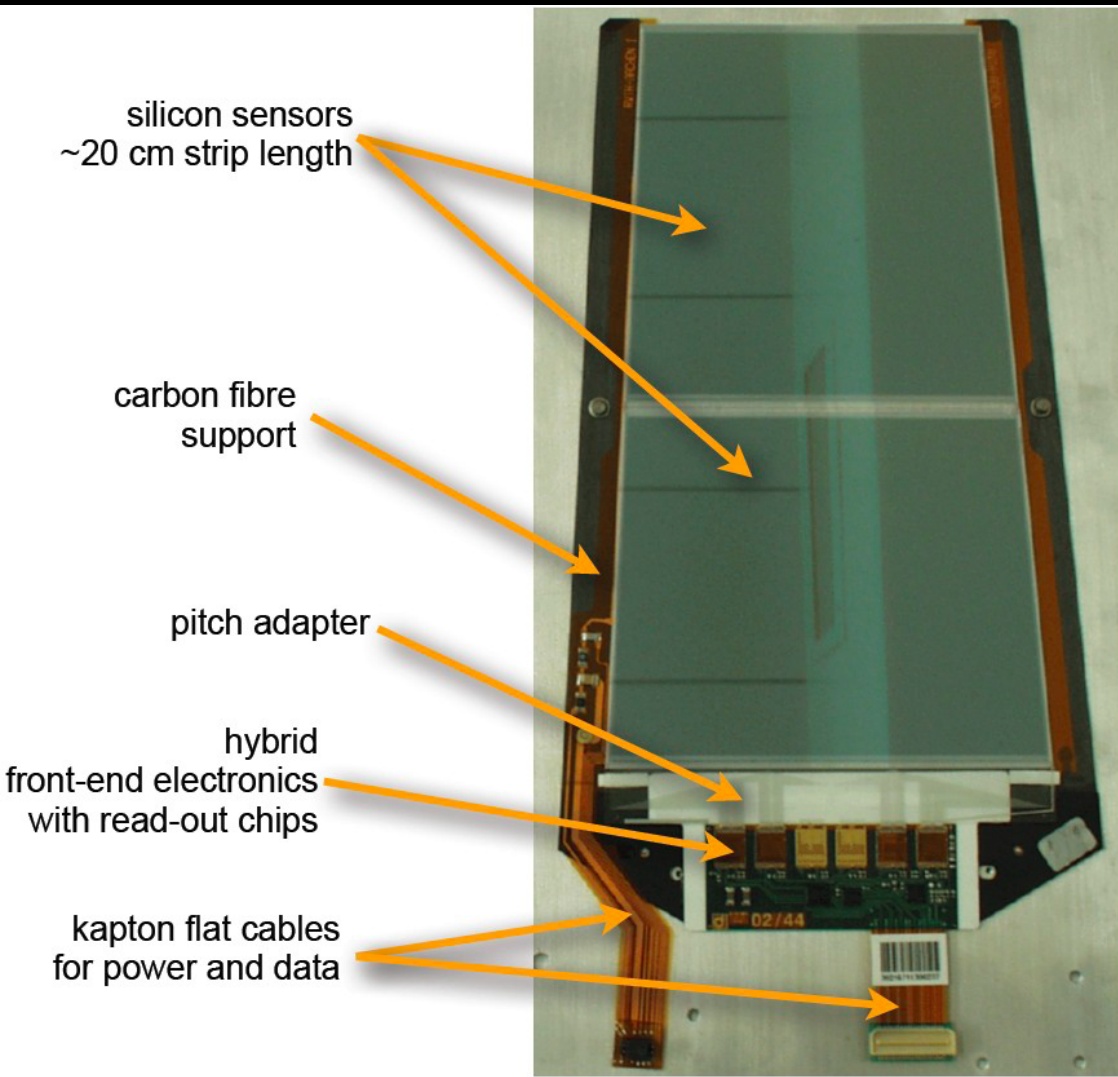
# Double Sided Silicon Detectors

- **Advantages:**
  - More elegant for measuring 2 coordinates than using stereo modules
  - Saves material

- **Disadvantages:**
  - Needs special strip insulation of n-side (p-stop, p-spray techniques)
  - Complicated manufacturing and handling procedures

- Expensive

- Ghost hits possible



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



Positive oxide charges cause electron accumulation layer.



✗ real hits
○ "Ghosts"
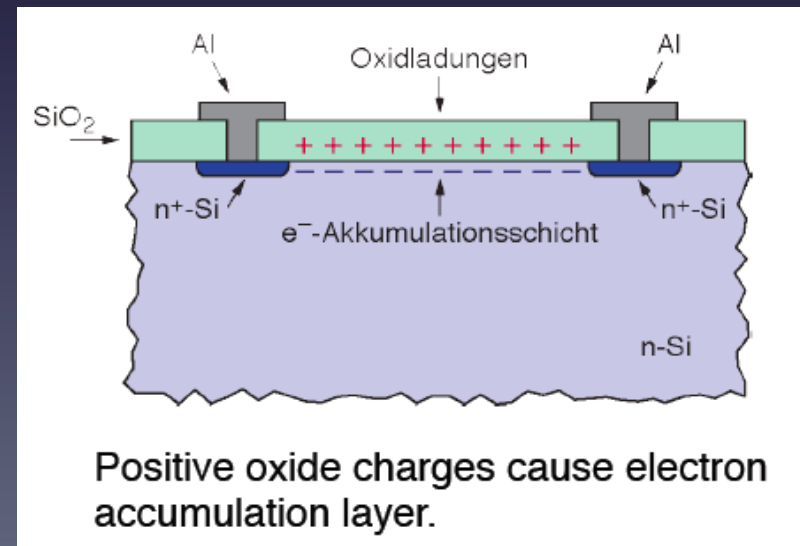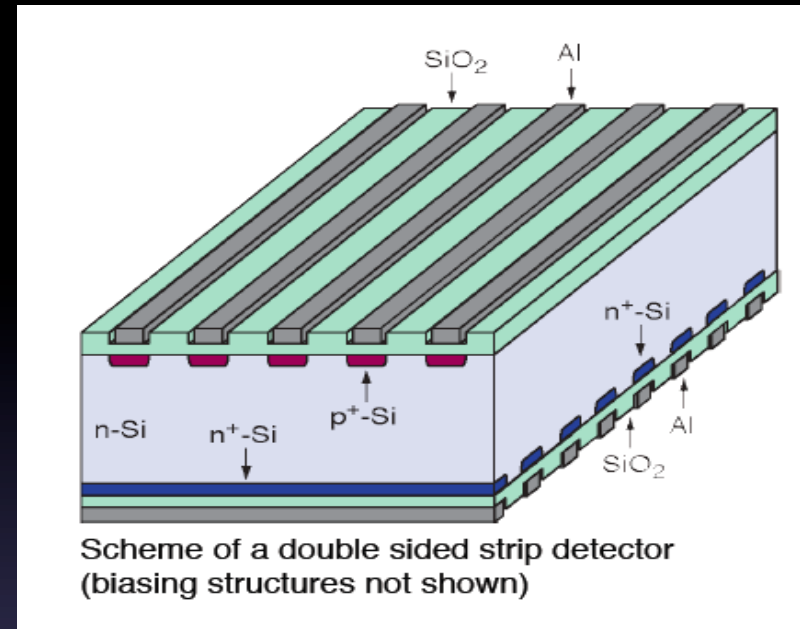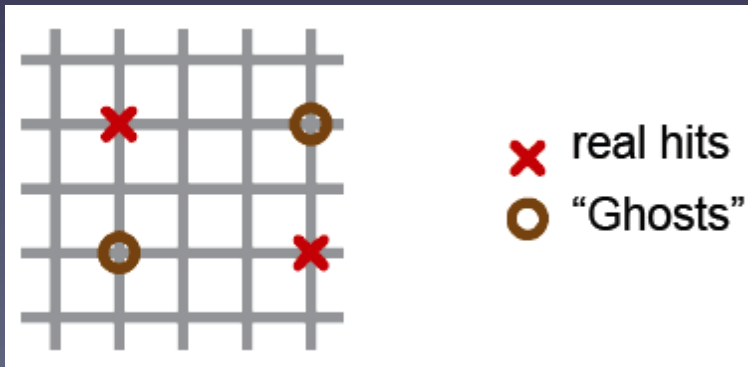
# Pixel detector

- Advantages
  - Pixel detectors provides space-point information
- Small pixel area
  - low detector capacitance (≈1 fF/Pixel)
  - large signal-to-noise ratio (e.g. 150:1).
- Small pixel volume
  - low leakage current (≈1 pA/Pixel)
- n+-on n for the LHC
  - Electron have faster collection time
- **Disadvantages:**
  - Large number of readout channels
  - Large bandwidth
  - Large power consumption
  - Bump bonding is costly





fine pitch (50 μm) bump placements solder

chip indium

https://www.youtube.com/watch?v=ojeVwQxOrGo&feature=youtu.be
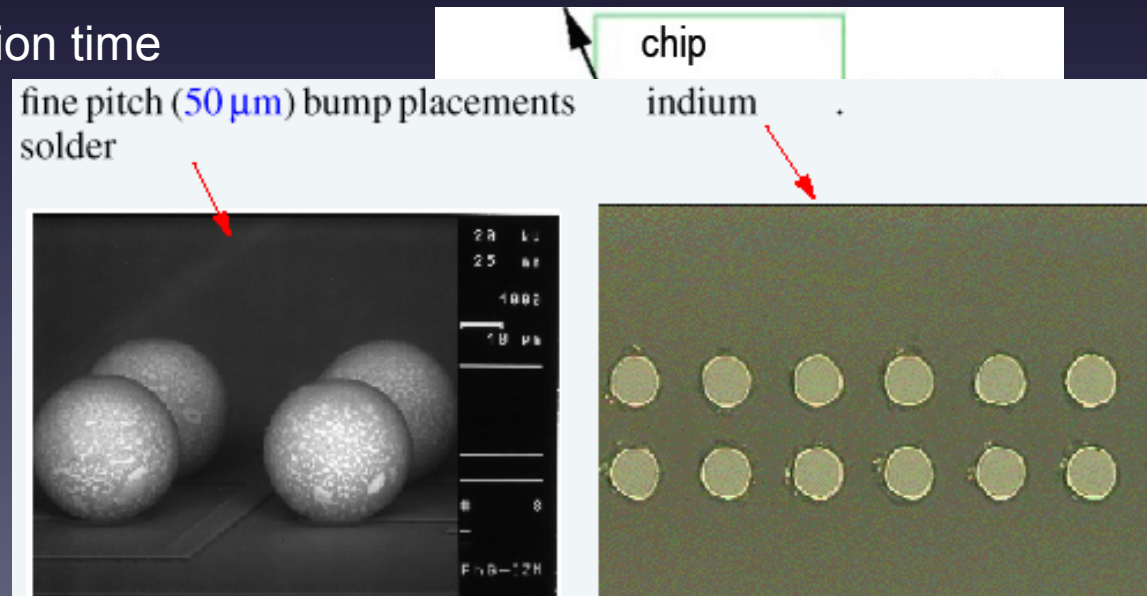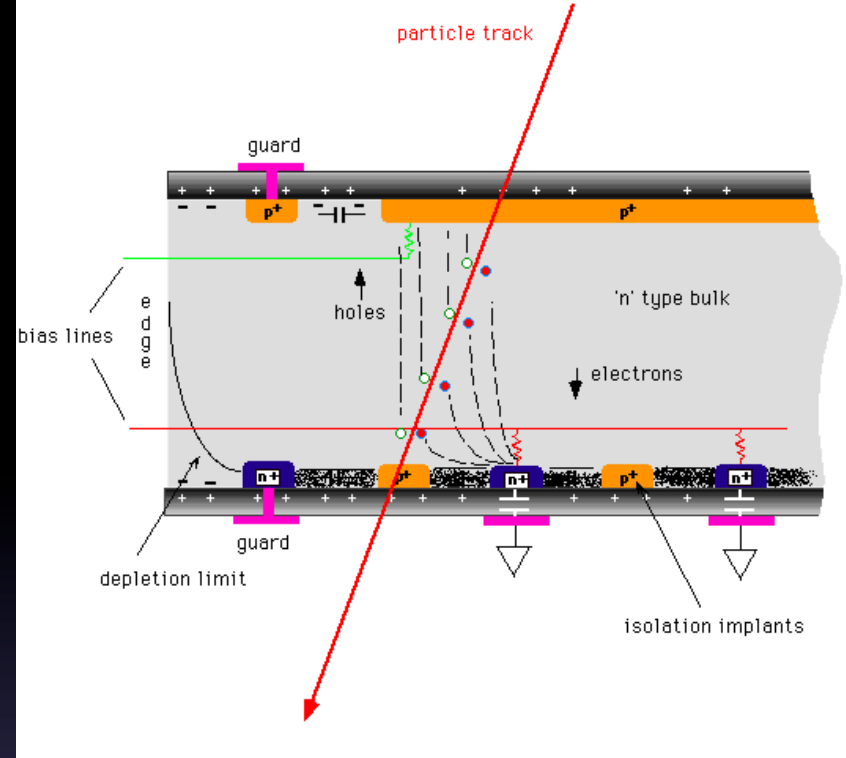
# Signal

- The signal generated in a silicon detector depends essentially only on the thickness of the depletion zone and on the dE/dx of the particle.
  - The distribution is given by the Landau distribution
  - Since the mean energy loss per cm is 3.87 MeV/cm
  - For 300 μm silicon the most probable charge is ≈ 23400 e-/h pairs
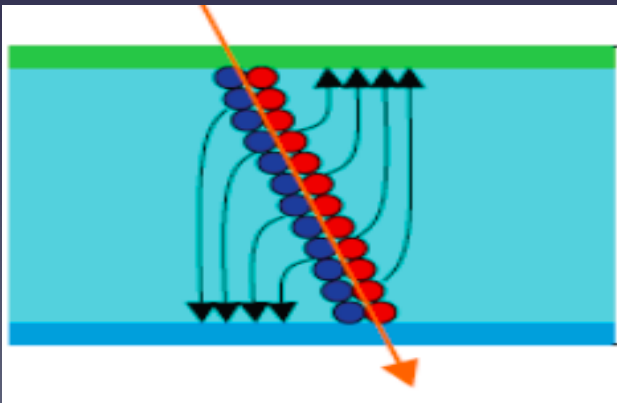
Most probable charge ≈ 0.7× mean

Mean charge



Measured Landau distribution in a 300 μm thick Si detector (Wood et al., Univ. Oklahoma)

--- 1.5 Mev/c electron Vaviov theory calculation

number of events

charge deposited (femto-coulombs)
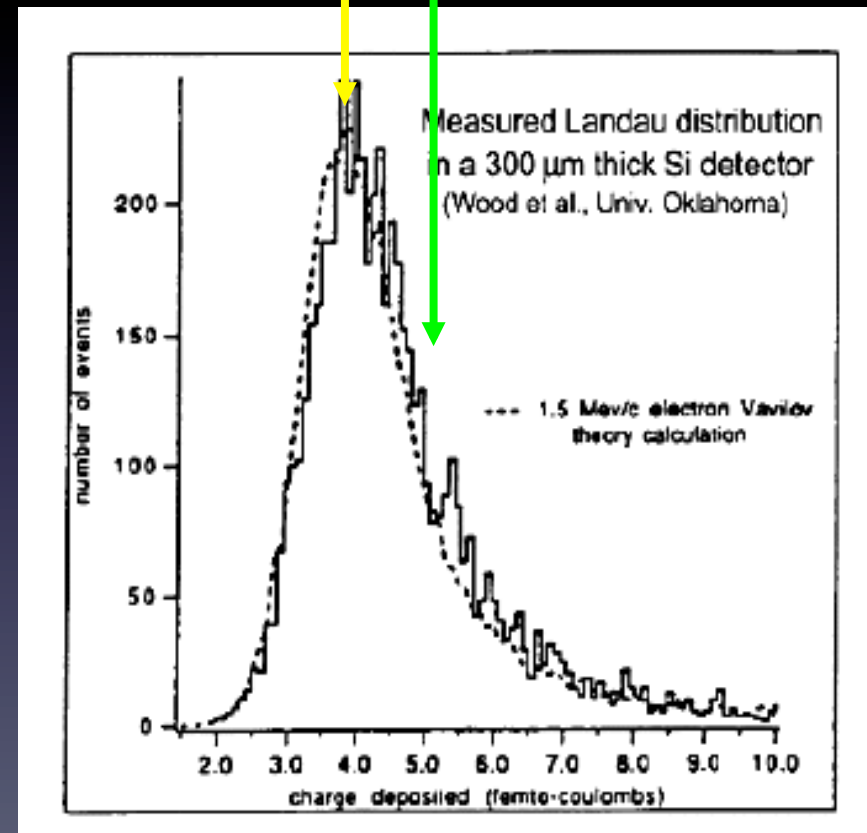
# Noise

- **The noise depends on**: geometry of the detector, the biasing scheme, the readout electronics..

- Noise is given as "equivalent noise charge" ENC. This is the noise at the input of the amplifier in elementary charges.

- The most important noise contributions are:
  - Leakage current
  - Detector capacitance
  - Detector parallel resistor
  - Detector series resistor

- The overall noise is the quadratic



noise distribution Landau distribution

with noise
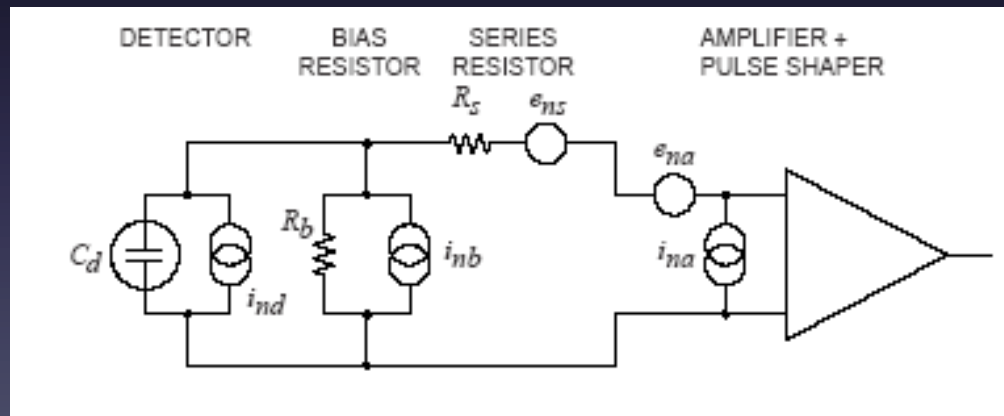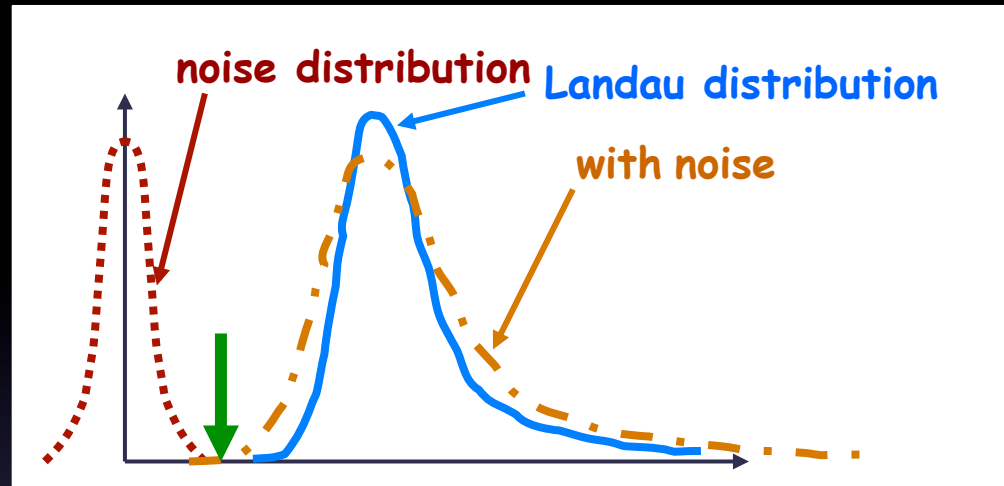


$$ENC = \sqrt{ENC_C^2 + ENC_I^2 + ENC_{Rp}^2 + ENC_{Rs}^2}$$

28

# S/N optimization

- Silicon sensors have low occupancy $\Rightarrow$ most channels have no signal. Good hits are select by requiring $N_{ADC}>$ noise tail. If cut is too high $\Rightarrow$ efficiency loss

- Typical Values for strip detectors is N/S> 10-15. Radiation damage severely degrades the S/N. Thus S/N determines lifetime of the detector in a harsh radiation environment

- To achieve a high signal to noise ratio:
  - Low detector capacitance (i.e. small pixel size or short strips)
  - Low leakage current
  - Large bias resistor
  - Short and low resistance connection to the amplifier
  - Long integration time

- The optimal design depends on the application

- For pixel detectors the important parameter is the S/Threshold. The threshold in current detectors is of the order of 2500 e$^-$.

# Diffusion



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

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



- Drift time for: d=300 $\mu$m, E=2.5KV/cm:

    **$t_d$(e) = 9 ns, $t_d$(h)=27 ns**

- Diffusion: Typical value: 8 $\mu$m for 300 $\mu$m drift.
- Can be exploited to improve position resolution

Charge density distribution for 5 equidistant time intervalls:



$\sigma_D$=width "root-mean-square" of the charge carrier distribution
t=drift time
K=Boltzman constant
e=electron charge
D=diffusion coefficient
T=temperature
$\mu$=mobility $\mu_e$= 1350 cm$^2$ / V·s, $\mu_h$= 450 cm$^2$ / V·s
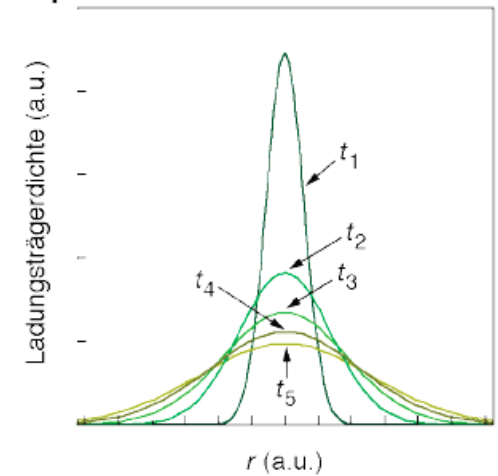
# Position resolution

- Resolution is the spread of the reconstructed position minus the true position



One strip clusters
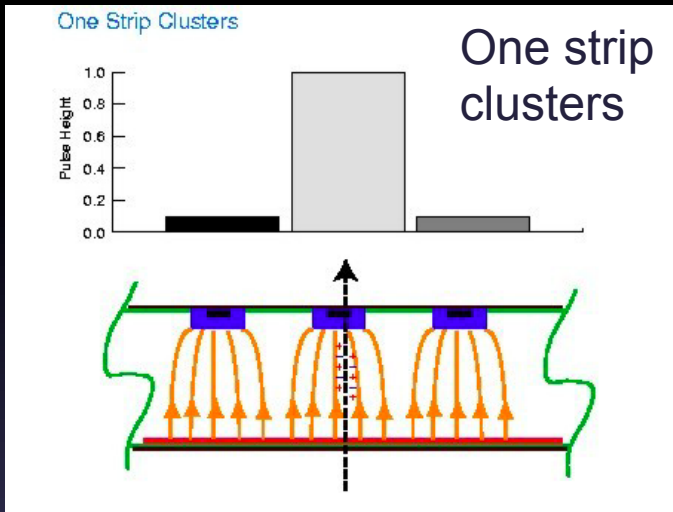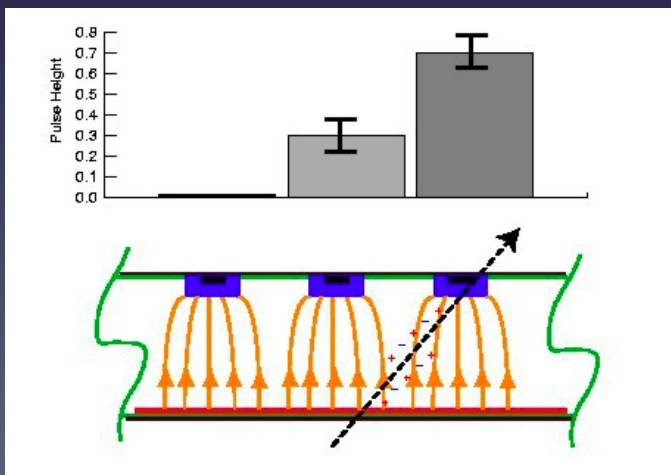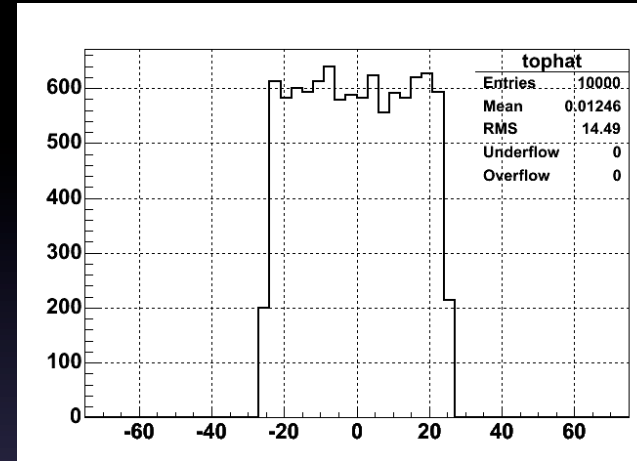
$$\sigma = \frac{pitch}{\sqrt{12}}$$



$$\sigma \approx \frac{pitch}{1.5 \cdot \sqrt{12}}$$

$$\eta = \frac{PH_R}{PH_L + PH_R}$$

Charge sharing
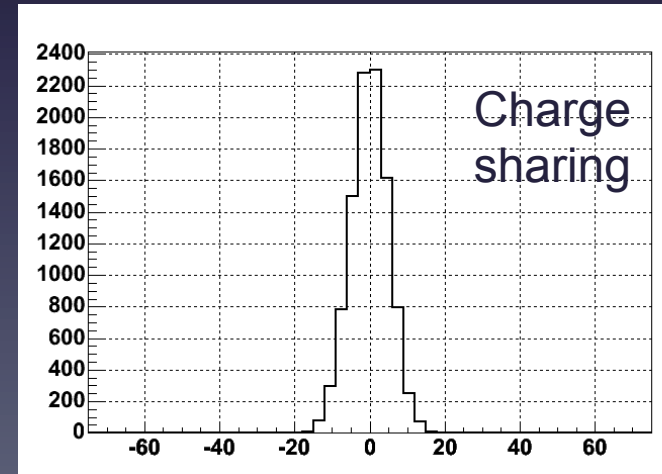
# Position resolution

- Position resolution is degraded by many factors
- Relationship of strip pitch and diffusion width  (typically 25-150 $\mu$m and 5-10 $\mu$m)
- Statistical fluctuations on the energy deposition
- Typical  position resolution s for a 300$\mu$m thick sensor with S/N=20

Single strip resolution dominates

Charge sharing

Pitch [$\mu$m]
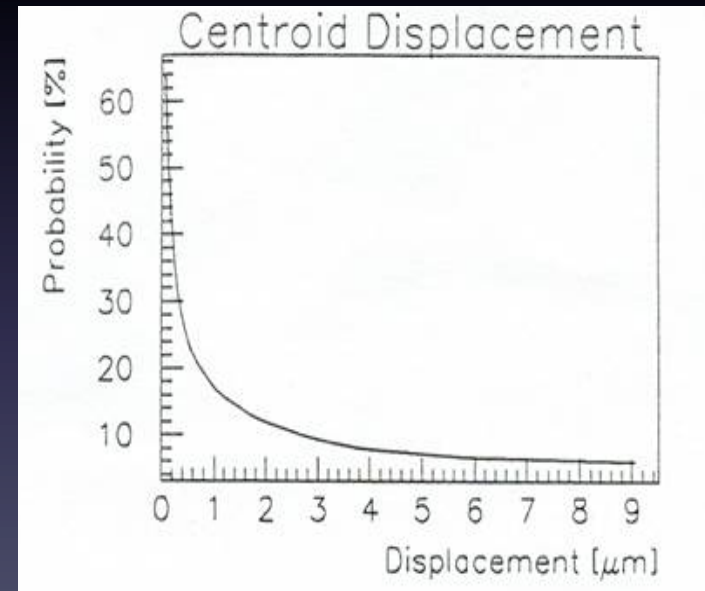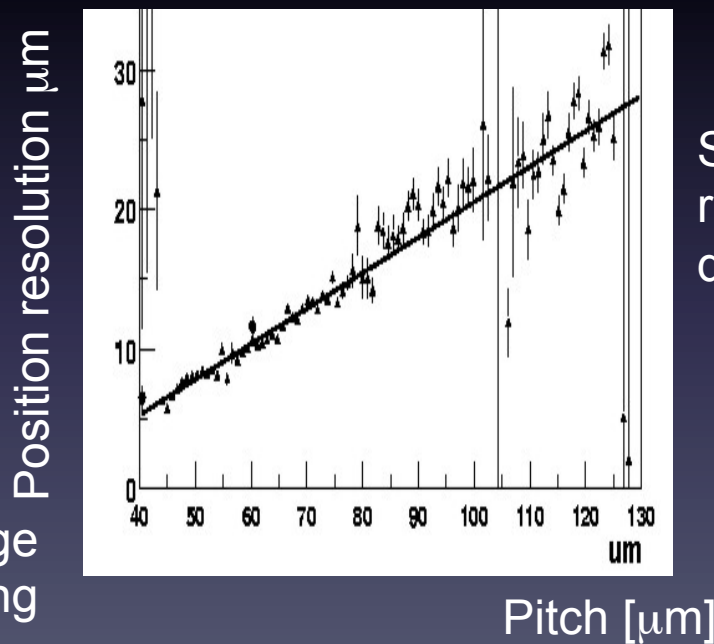
**Low probability $\delta$(E) release additional electrons drifting perpendicularly to the track and spoiling position resolution**

# Material

- Reconstruction of photon conversions ($\gamma \rightarrow e^+e^-$) can provide precise map of the material
    - The number of photon conversion in a volume ≈ amount of material x reconstruction efficiency
    - The reconstructed vertices can be used to build detailed maps of the Tracker material

## DATA
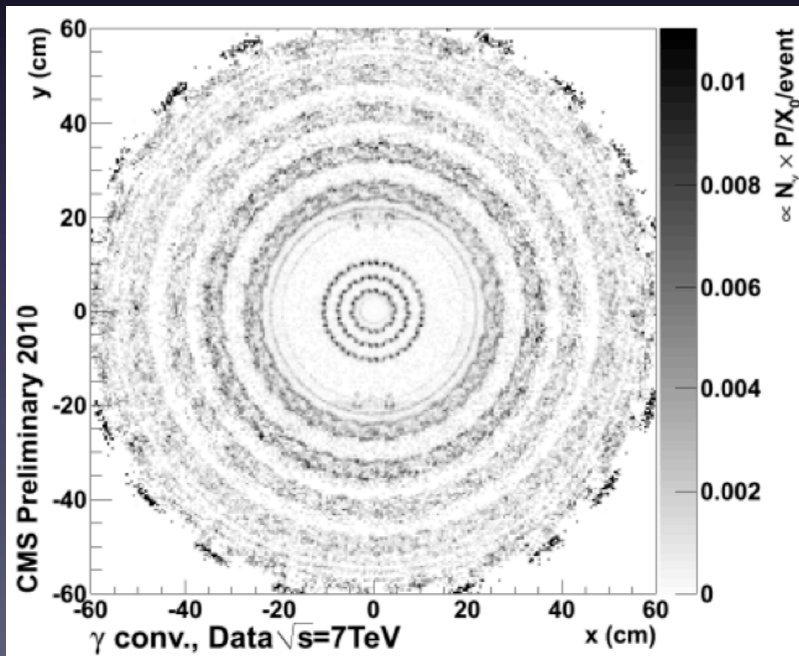
## MC
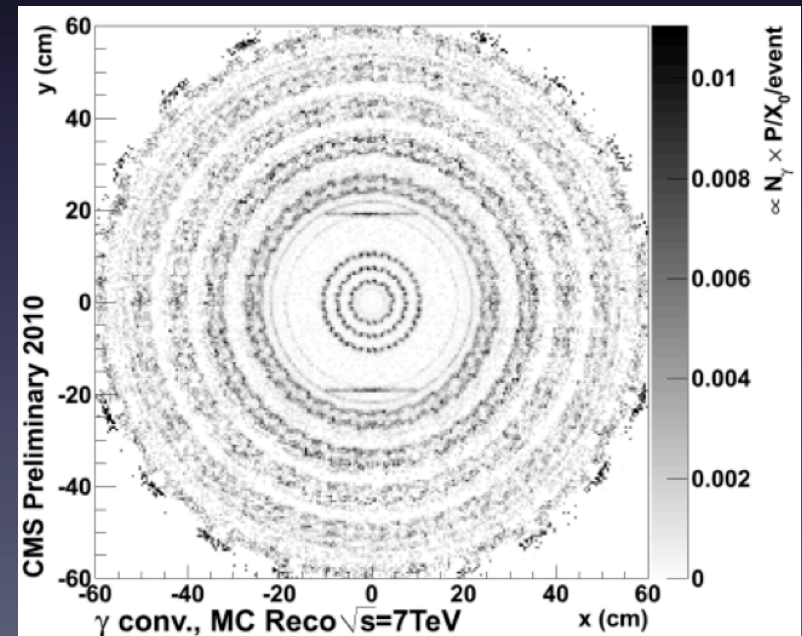
# Radiation damage

- Damage due to non ionizing energy loss (NIEL)

    – Atomic displacement caused by massive particles (p,n,$\pi$)
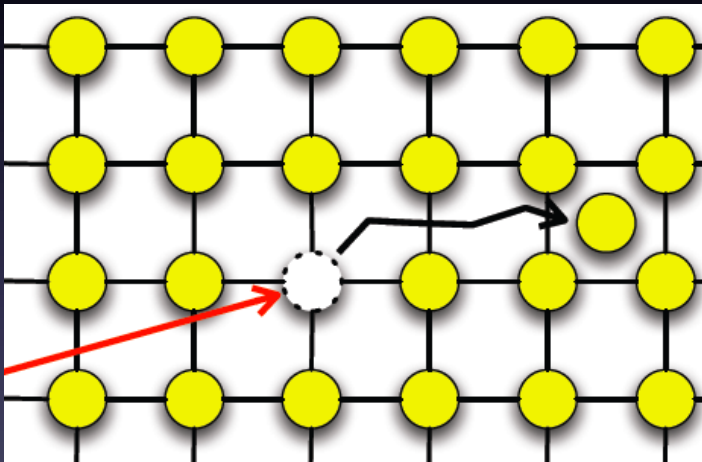


- Affects mainly the sensors

- Damage due to ionizing energy loss

    – Proportional to absorbed radiation dose

    – 1 Gy = 1 J/kg = 100 rad = $10^4$ erg/g (energy loss per unit mass)

    – Trap of ionization induced holes by "dangling bond" at Si-SiO2 interface
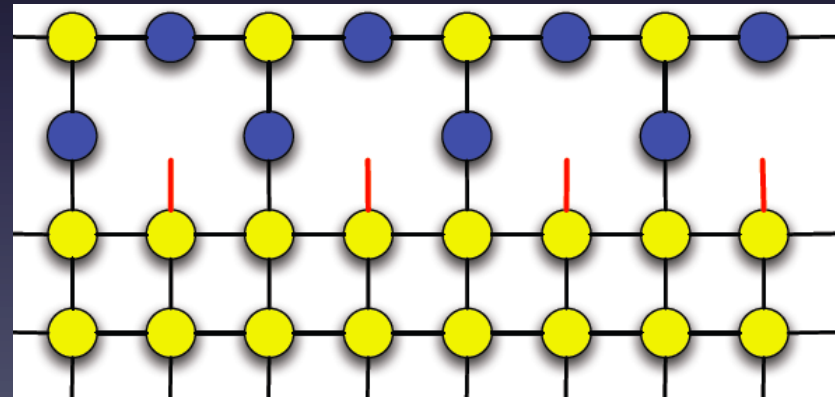


- Affects both detector and electronics

# Radiation damage due to NIEL

- Atomic displacement caused by massive particles (p,n,π)
  - Charged defects create donors and acceptors
  - Increase $N_{eff}$ (= $N_D$ − $N_A$) and depletion voltage ($V_{dep} \propto |N_{eff}|$)
  - Type Inversion
- Shallow defects trap and detrap electrons and holes
  - Degrade charge collection efficiency
- Midgap defects effectively reduces $E_g$
  - Increase dark current
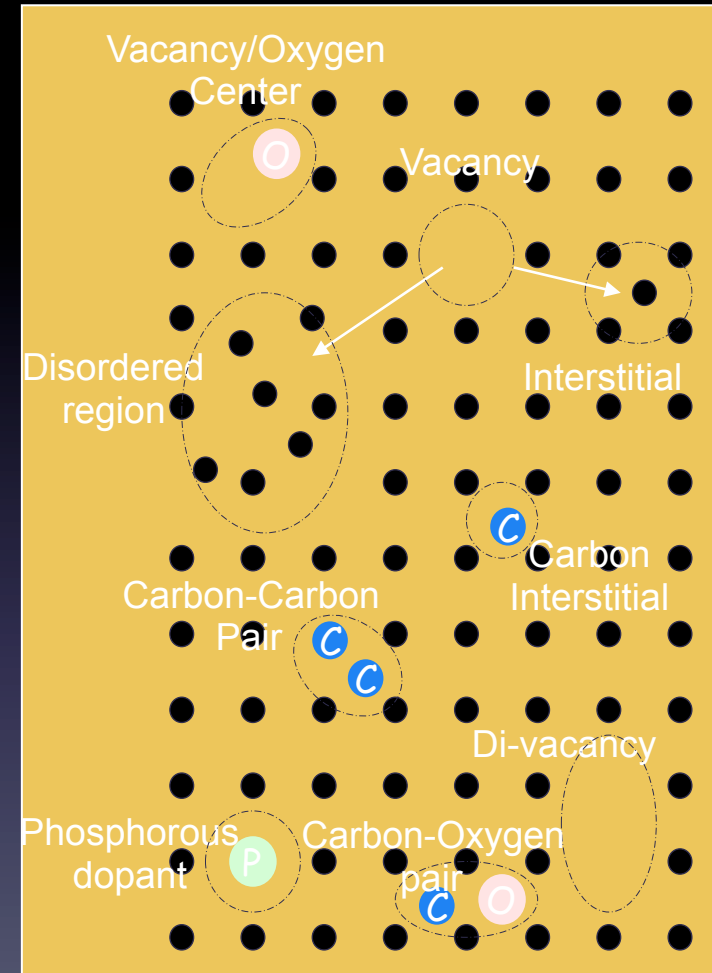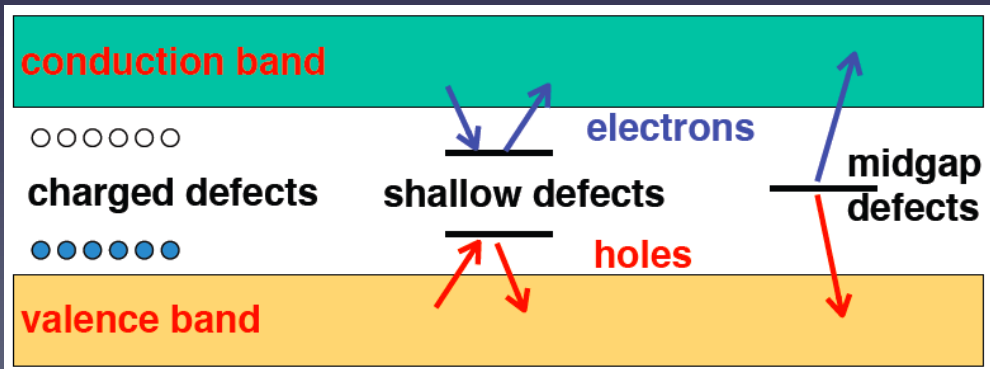
# Radiation damage due to NIEL

- **INCREASE IN DARK CURRENT**
  - It can saturate a charge integrating amplifier
  - It can lead to thermal runaway

- **TYPE INVERSION**
  - Increase of depletion voltage
  - Attention must be taken to avoid breakdown

$$\alpha = \frac{\Delta I}{V \cdot \Phi_{eq}} \approx 4 \times 10^{-17} \ A/cm$$

n-type FZ
n-type FZ - 7 KΩcm
n-type FZ - 4 KΩcm
n-type FZ - 3 KΩcm
p-type EPI - 2 and 4 KΩcm

n-type FZ - 780 Ωcm
n-type FZ - 410 Ωcm
n-type FZ - 130 Ωcm
n-type FZ - 110 Ωcm
n-type CZ - 140 Ωcm
p-type EPI - 380 Ωcm

[M.Moll PhD Thesis]

type inversion

≈ 600 V

$10^{14} cm^{-2}$

n-type

"p-type"

[M.Moll: Data: R. Wunstorf, PhD thesis 1992, Uni Hamburg]
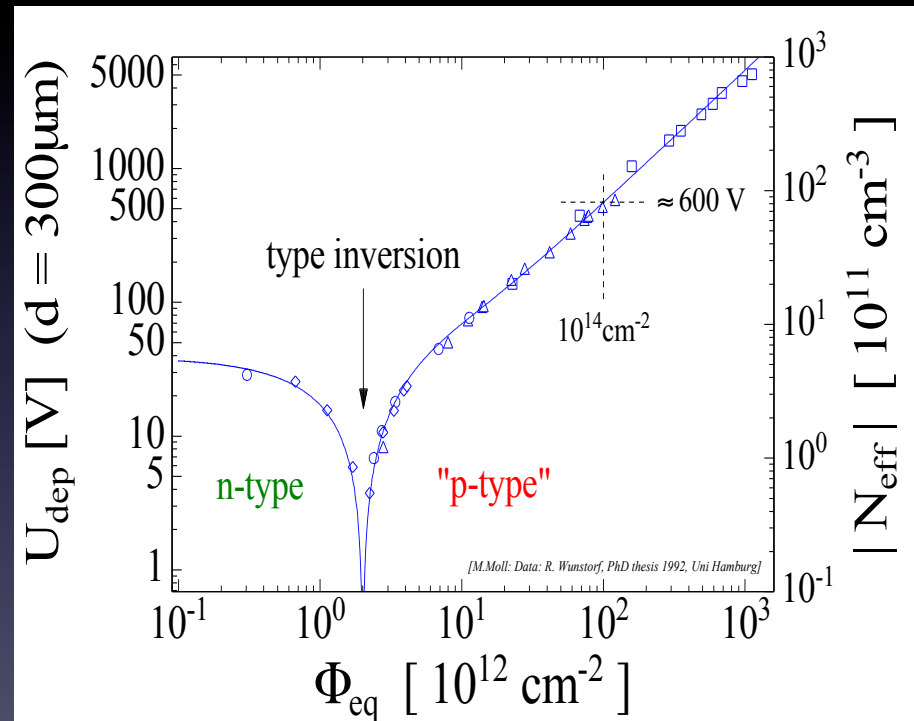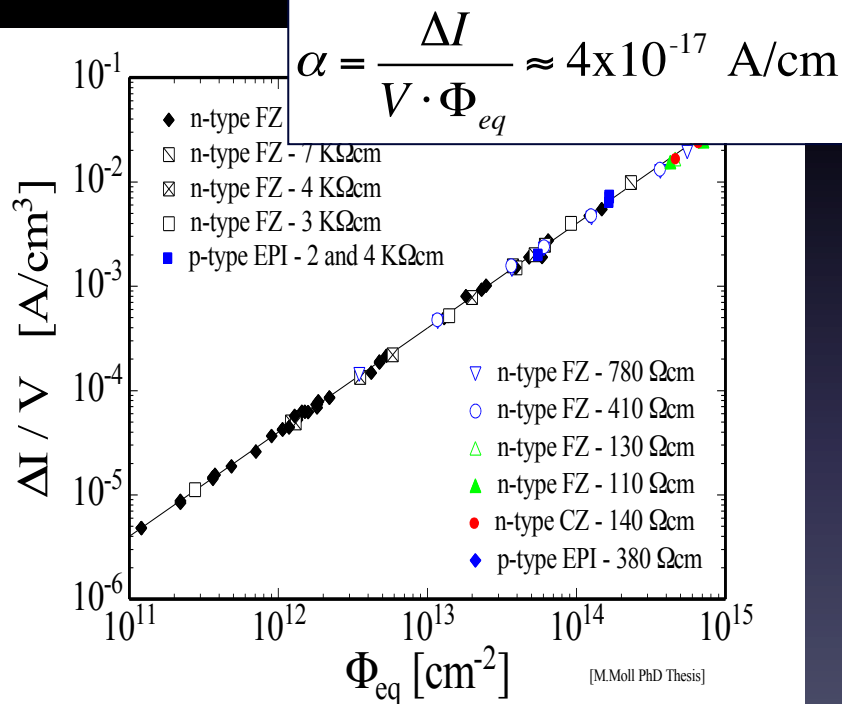
- Even after heavy irradiation **both** p and n sides work at low voltage (under depleted) and sensors act as if there were 2 diode junctions!

# Radiation damage due to NIEL

- Deterioration of Charge Collection Efficiency (CCE) by trapping
- Trapping is characterized by an effective trapping time $\tau_{eff}$ for electrons and holes:

$$Q_{e,h}(t) = Q_{0e,h} \exp\left(-\frac{1}{\tau_{eff\ e,h}} \cdot t\right)$$

where

$$\frac{1}{\tau_{eff\ e,h}} \propto N_{defects}$$



24 GeV/c proton irradiation

● data for electrons
○ data for holes

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

Inverse trapping time $1/\tau$ [ns$^{-1}$]

particle fluence - $\Phi_{eq}$ [cm$^{-2}$]

# Charge collection

Pixel sensors:

max. cumulated fluence for  LHC   and    HL-LHC

Note: Measured partly under different conditions! Lines to guide the eye

signal [electrons]

25000

20000

15000

10000

5000

p-in-n-FZ (500V) strip sensors

n-in-n FZ (600V) pixel sensors

FZ Silicon
Strip and Pixel Sensors

● n-in-n (FZ), 285μm, 600V, 23 GeV p

▲ p-in-n (FZ), 300μm, 500V, 23GeV p

△ p-in-n (FZ), 300μm, 500V, neutrons

References:

[1] p/n-FZ, 300μm, (-30ºC, 25ns), strip [Casse 2008]
[2] n/n-FZ, 285μm, (-10ºC, 40ns), pixel [Rohe et al. 2005]

$10^{13}$    $5 \ 10^{14}$    $5 \ 10^{15}$    $5 \ 10^{16}$

M.Moll - 08/2008

$\Phi_{eq}$ [cm$^{-2}$]

LHC-LHC will need more radiation tolerant tracking detector concepts

Strip sensors:

 max. cumulated fluence for LHC  and  HL-LHC

Arrows indicate fluences at 4 cm after 1 year at $10^{34}$, $4\times10^{34}$, $10 \times 10^{34}$ cm$^{-2}$ s$^{-1}$

# Challenges for the future

- High Luminosity LHC
  - Radiation tolerance (~$10^{16}$/cm$^2$ for pixels, $10^{15}$/cm$^2$ for strips; ~20 x current)
  - High hit rate (up to 1.5 GHz/cm$^2$ in pixels)
  - High track density (200 or more spectator events)

- e$^+$e$^-$ colliders
  - Extremely low material (minimize multiple scattering)
  - Requires very low average power
  - Extremely good position resolution (ILC goal is ~3 microns)

# Ultra radiation hard detectors: 3D



- P-N junction in the bulk by "drilling" electrodes using Deep Reactive Ion Etching (DRIE)
  - Maximum drift and depletion distance governed by electrode spacing
  - Lower depletion voltages
  - Radiation hardness
  - Fast response



PLANAR

p+

500 µm

n+



d

t

d
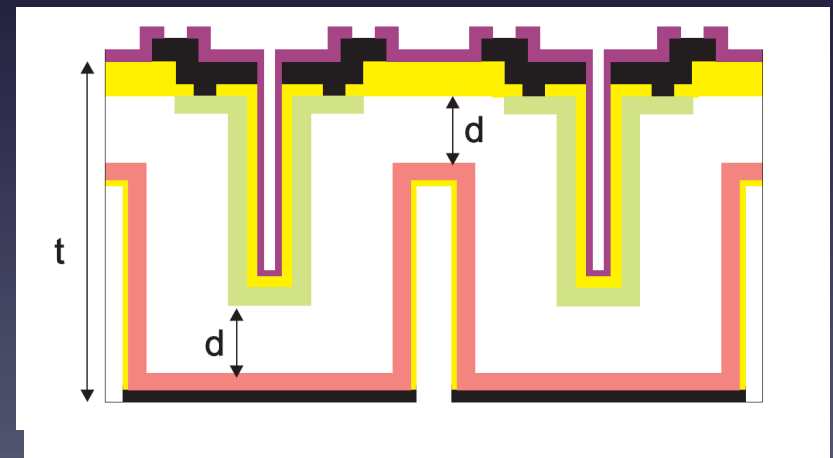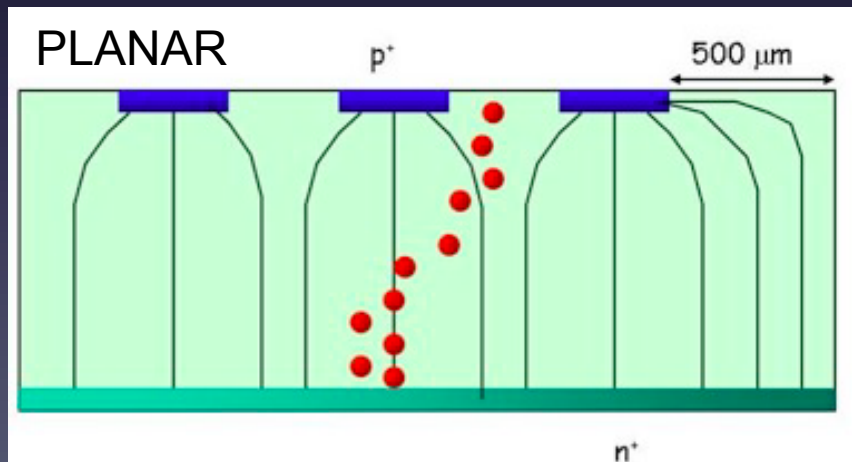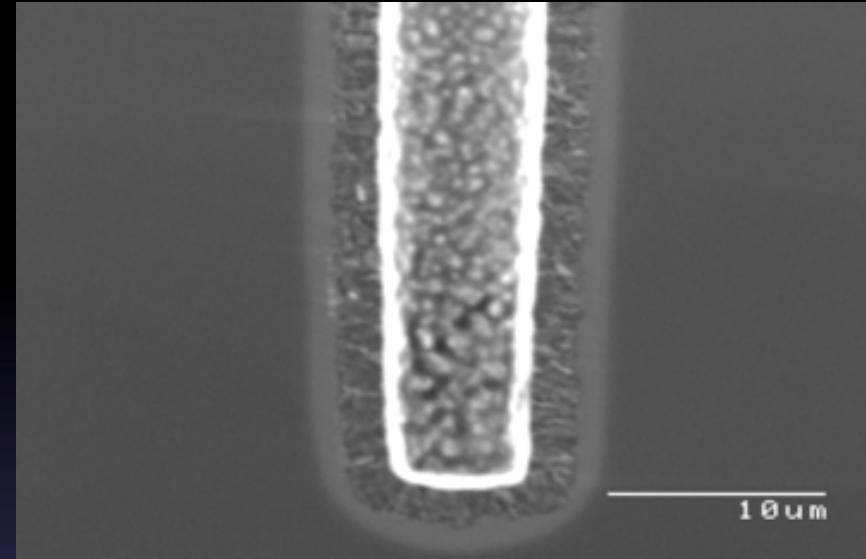
Industrialization has been successful and 3D technology is used ATLAS IBL

# Thin sensors

- **Thin sensors**
    - Reduced material budget
    - Reduced leakage current
    - At high bias voltage charge multiplication effects in n-in-p sensors observed
    - Long term behaviour under study
    - Increased leakage current and noise
    - Efforts to exploit effect by design engineering (e.g. trenches or modified implants)



Strip sensors
n-in-p

G. Casse, NIM A, 624(2011), 401–404
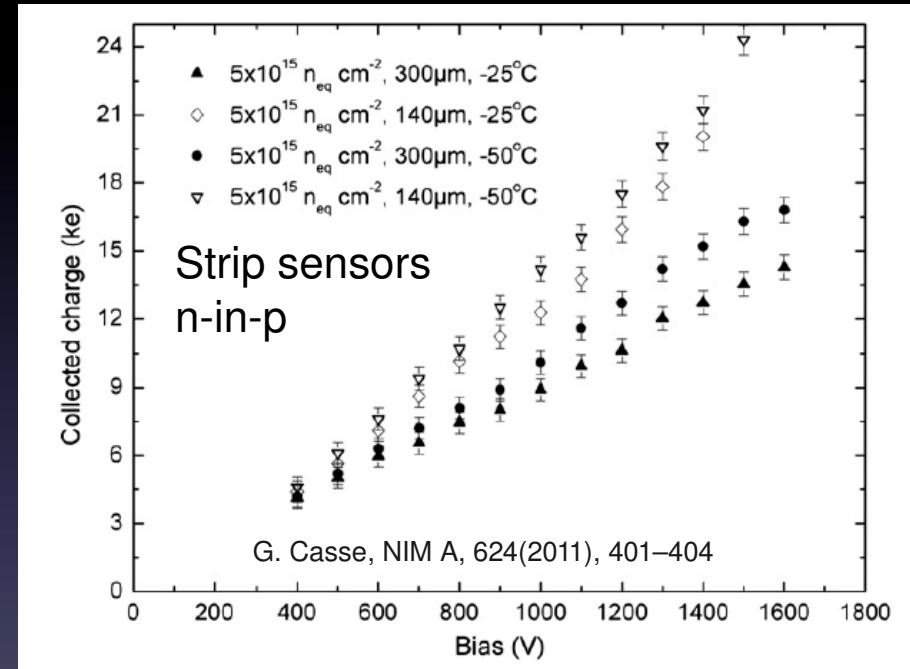
# Monolithic Pixels



- Sensors and ROC in the same wafer
- Signal is created in epitaxial layer (10-15 μm e.g. AMS 0.35 μm)
  - Q~ 80 e-h / μm → signal <1000 e−
- Q collection (thermally) to diode with help of reflection on boundaries with p-well and substrate (high doping)
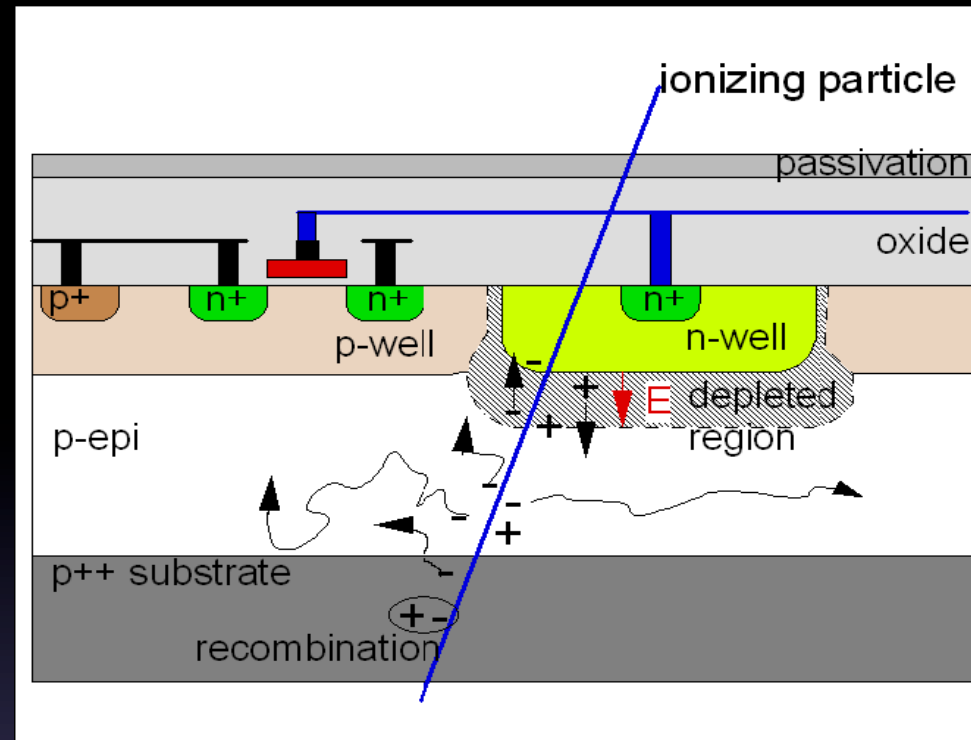
- Advantages of CMOS sensors:
  - Signal processing circuits integrated on sensor substrate (system-on-chip)
  - Sensitive volume ( epitaxial layer) is  10–15 μm thick
  - Standard production, fabrication technology → cheap, fast turn-around
  - small pixel sizes(pitch 20 –30 μm)→few μm resolution!
- BUT :
  - Very thin sensitive volume impact on signal magnitude
  - Sensitive volume almost un-depleted impact on radiation tolerance & speed

# Silicon-on-Insulator

- Chemical bonding of low resistivity wafer electronics with high resistivity sensor wafer
  - Full CMOS capability
    - In-pixel processing, low power, high speed
  - Fully depleted sensor wafer
  - Back gating effect
    - $V_{bias}$ affects analog transistor functionality
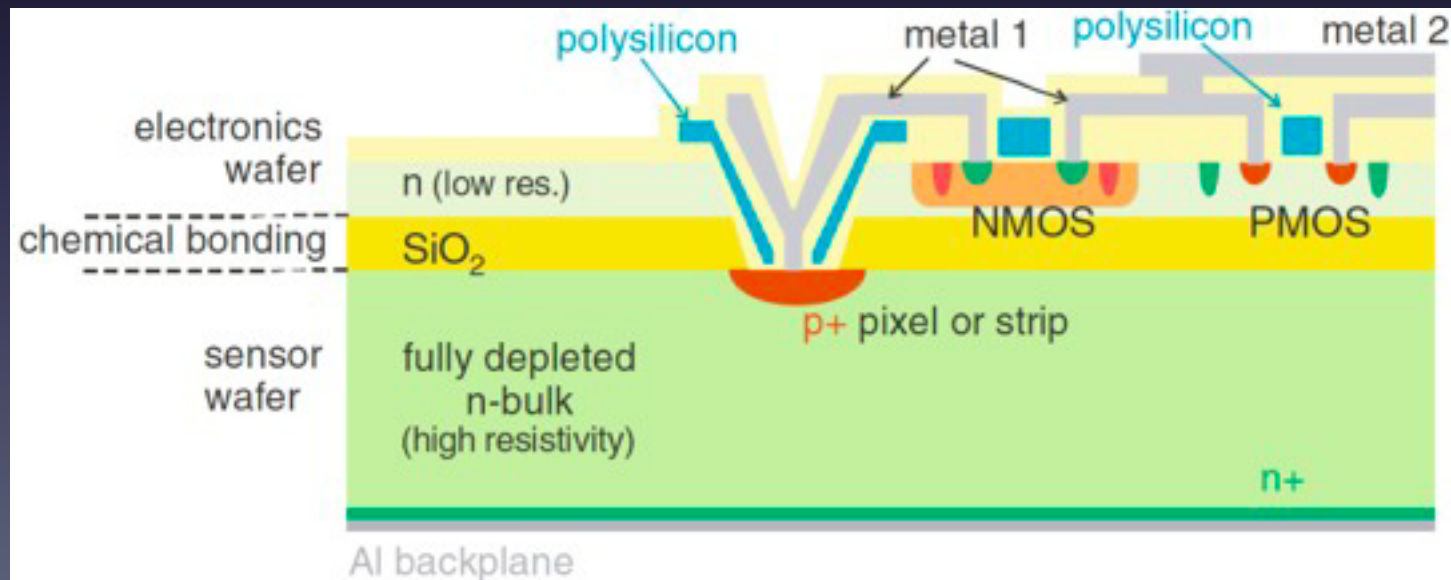
# Different pixel technologies



MONOLITHIC

VIP-3D

DEPFETs

SOI-3D

GAPD

Planar

3D-Si

Diamond

HYBRID

Hybrid-3D

Pixel technologies

chronopixels

MAPS

N-well MAPS

CCD

FPCCD

CPCCD

ISIS
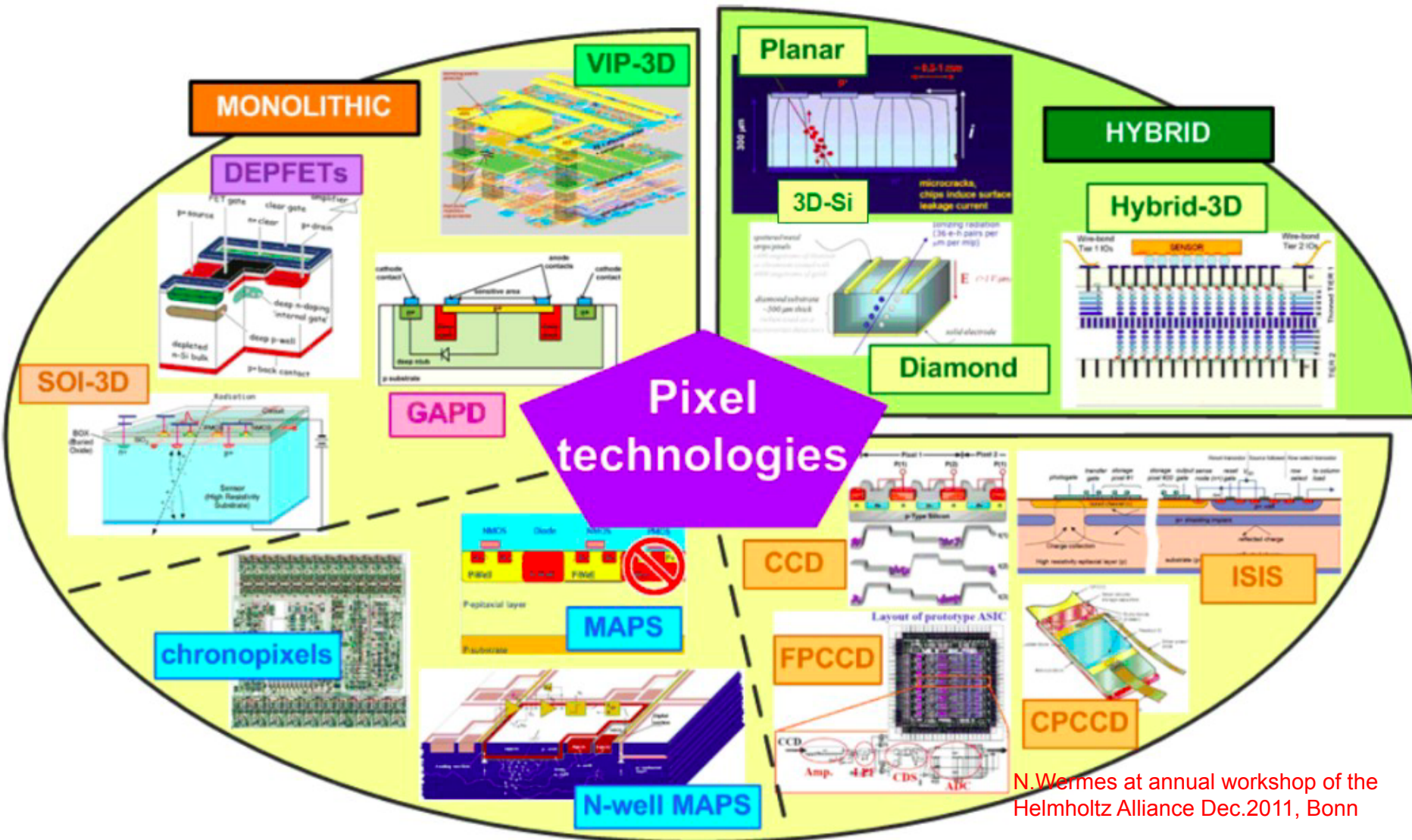
N.Wermes at annual workshop of the Helmholtz Alliance Dec.2011, Bonn

# References

- Sze, Physics of semiconductor devices
- Helmuth Speiler lecture notes (www-physics.kbl.gov/~spieler)
- G. Lutz, Semiconductor radiation detectors : Device Physics, Springer (2007)
- Doris Eckstein (DESY lectures)
- Gino Bolla UTEV seminar: http://www.fnal.gov/orgs/utev/past_speakers.html
- R. Lipton Academic lectures: http://www-ppd.fnal.gov/eppoffice-w/Academic_Lectures/Past_Lectures.htm
- Steve Worm notes on Radiation Damage
- Silicon Microstrip Detectors , A. Peisert, in " Instrumentation in High Energy Physics ", F .Sauli (ed), World Scientific, (1992).
- Pixel Detectors, Rossi, Fisher, Rohe, Wermes, Springer
- M. Moll thesis on Radiation Damage

- BACKUP

# Radiation damage due to NIEL

- The conjecture that bulk damage is proportional to the total KE imparted to displaced silicon atoms is called "the NIEL hypothesis."

- It is conventional to use 1 MeV neutrons as the benchmark

KERMA = Kinetic Energy Released in Matter

$$KERMA(MeV) = D(MeVmb) \times \phi(\frac{\#}{cm^2}) \times (\#Si) \times (\frac{10^{-27}\ cm^2}{mb})$$

# Simulation



Ionizing particle with 45$^0$ angle t=7ns

All charge is collected

Simulation Thomas.Eichhorn@kit.edu

Simulation Thomas.Eichhorn@kit.edu

rentDensity) [A*cm^-2]
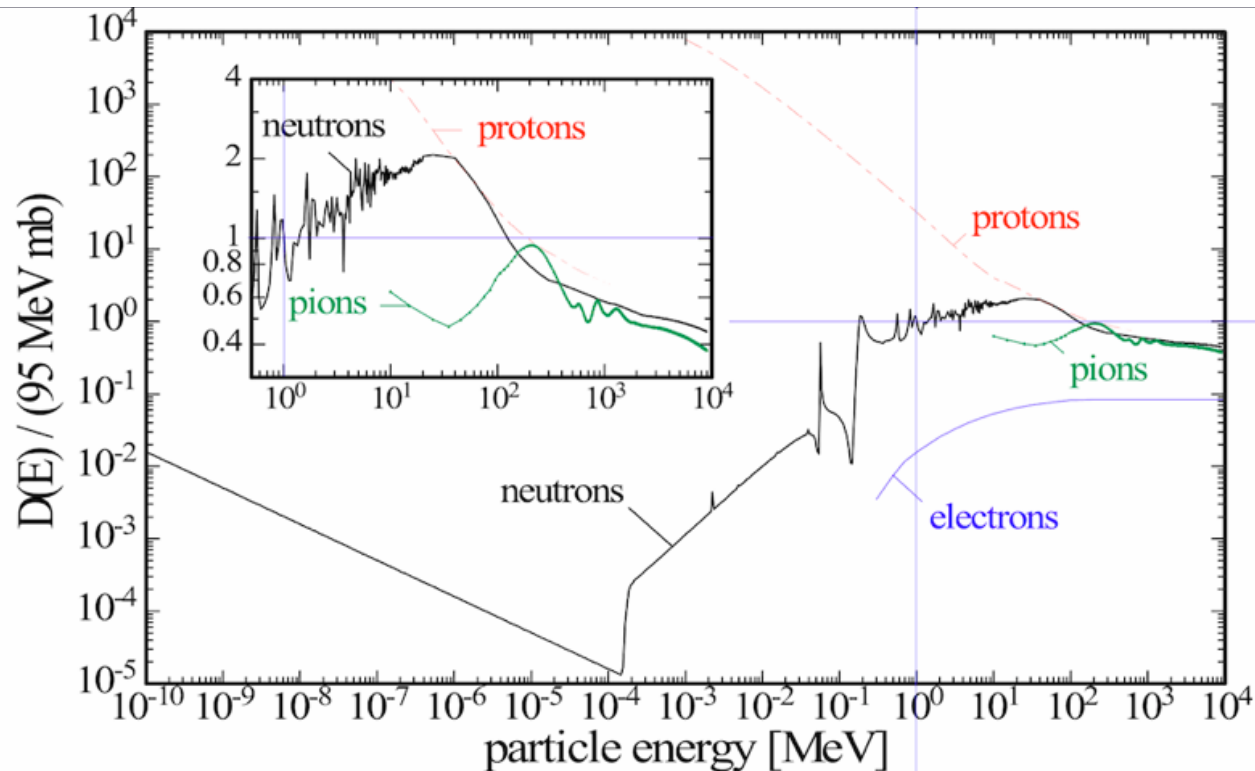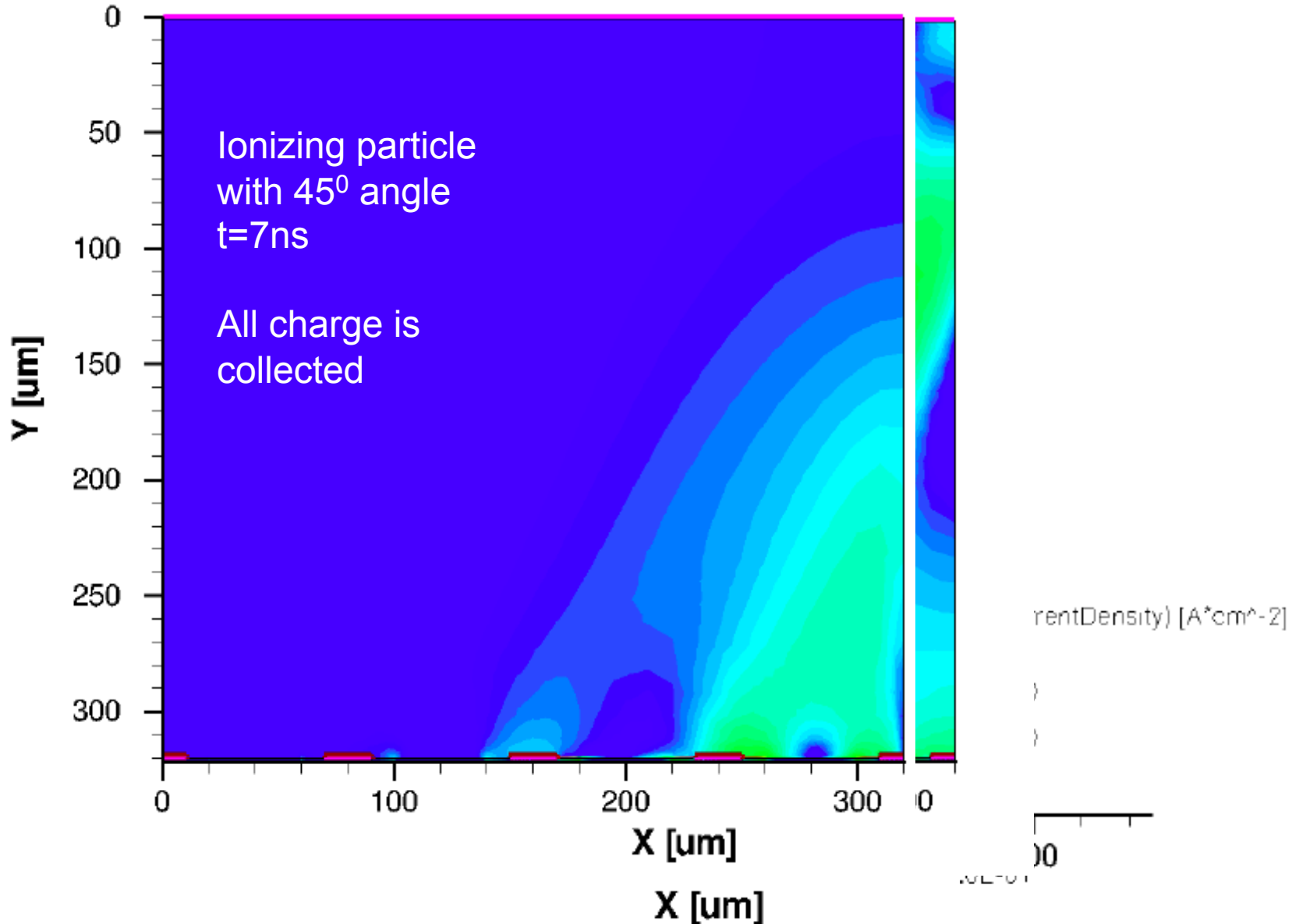
# Silicon Properties

- Excellent detector material
  - Low ionization energy (good signal). The band gap is 1.12 eV, but it takes 3.6 eV to ionize an atom. The remaining energy goes to phonon excitations (heat).
  - Long mean free path (good charge collection efficiency)
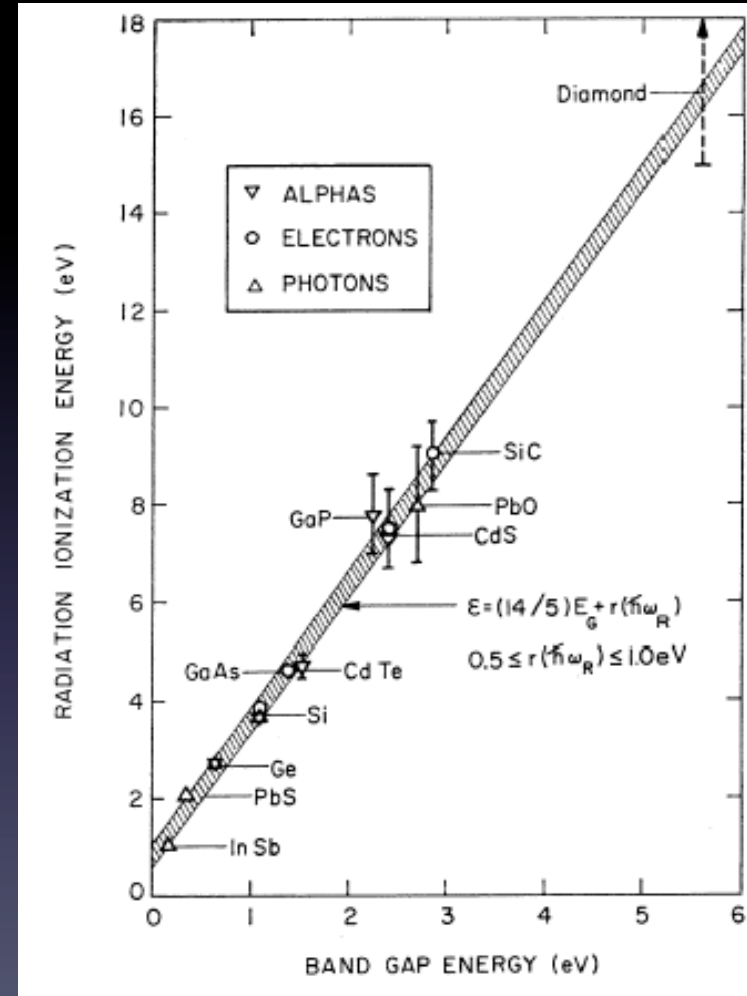  - High mobility (fast charge collection)
  - Low Z (Z=14 low multiple scattering)
- Oxide ($SiO_2$) has excellent electrical properties
- Good mechanical properties
  - Easily patterned to small dimensions
  - Can be operated in air and at room temperature (many SSD require cooling)
- Industrial experience and commercial applications
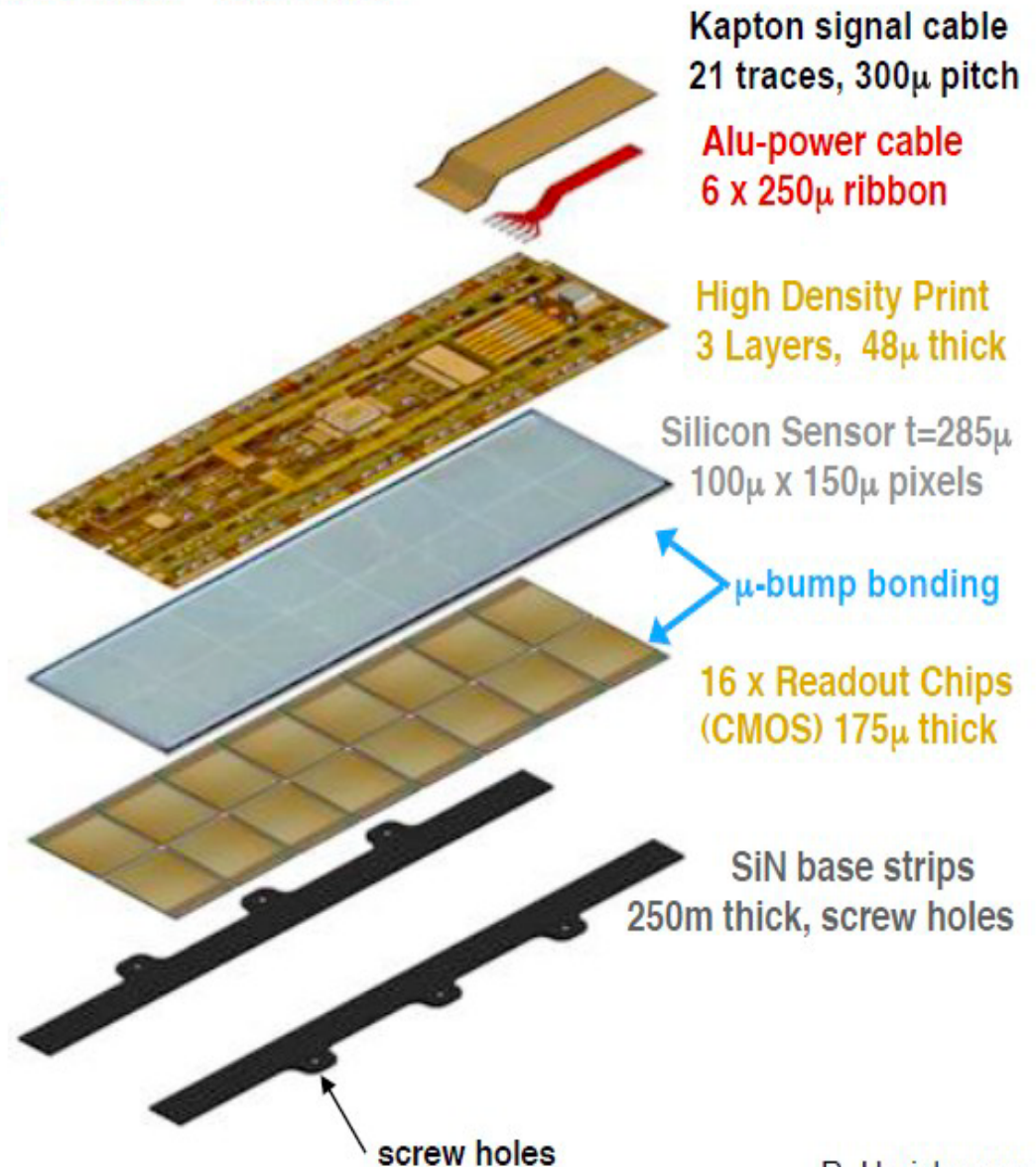- Crystalline $\Rightarrow$ radiation damage

# Hybrid Pixel Module for CMS

## Sensor:

- Pixel Size: 150mm x 100mm
  - Resolution $\sigma_{r-\varphi} \sim 15\mu m$
  - Resolution $\sigma_z \sim 20\mu m$

- n+-pixel on n-silicon design
  - Moderated p-spray → HV robustness

## Readout Chip:

- Thinned to 175μm
- 250nm CMOS IBM Process
- 8" Wafer

Kapton signal cable
21 traces, 300μ pitch

Alu-power cable
6 x 250μ ribbon

High Density Print
3 Layers, 48μ thick

Silicon Sensor t=285μ
100μ x 150μ pixels

μ-bump bonding

16 x Readout Chips
(CMOS) 175μ thick

SiN base strips
250m thick, screw holes

screw holes

R. Horisberger

# CMS Pixel Sensors

- Baseline CMS design: $n^+$-n pixels for partial depletion operation and increased Lorentz angle in high B field.
  - 78 $\mu$m $n^+$-implants.
  - P-spay or open p-stops rings provide isolation
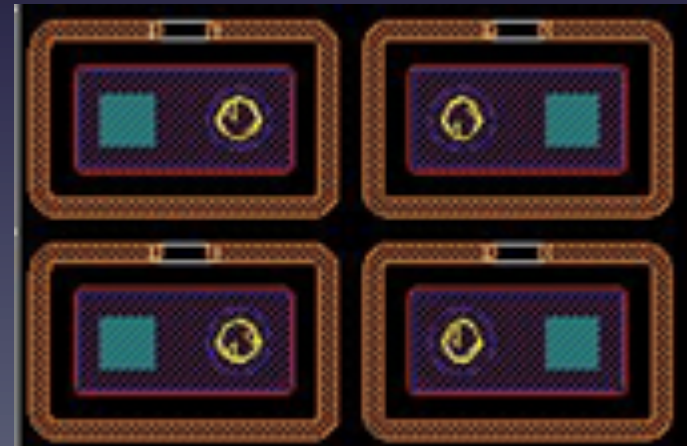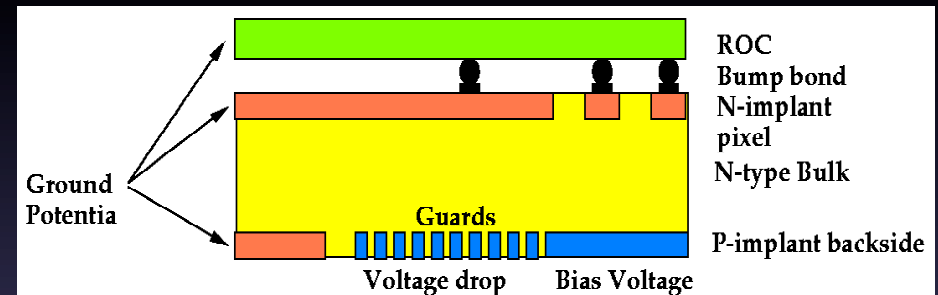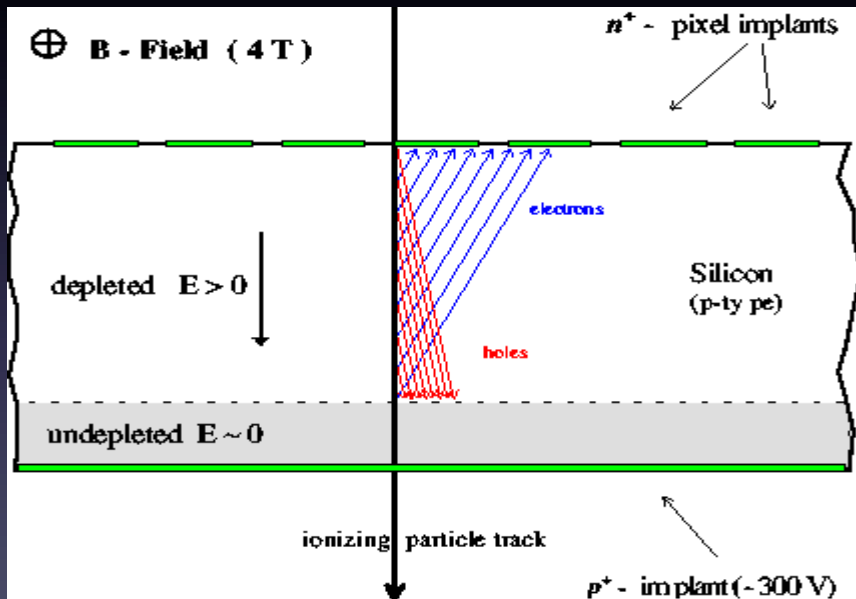
# Ultra-radiation hard: Diamond

- Poly crystalline and single crystal
- Competitive (to Si), used in several radiation monitor detectors
- Large band gap (x5 Si)
  - no leakage current
  - no shot noise
- Smaller $\varepsilon_r$ (x 0.5 Si)
  - lower input capacitance
  - lower thermal and 1/f noise
- Small Z=6 →large radiation length (x2 in g/cm$^2$)
- Narrower Landau distribution (by 10%)
- Excellent thermal conductivity (x15)
- Large $w_i$ (x 3.6) →smaller signal charge

- poly-CVD diamond wafers can be grown >12 cm diameter, >2 mm thickness.
- Wafer collection distance now typically 250μm (edge) to 310μm (center).
- 16 chip diamond ATLAS modules



- sc-CVD sensors of few cm$^2$ size used as pixel detectors
- High quality scCVD diamond can collect full charge for thickness 880μm
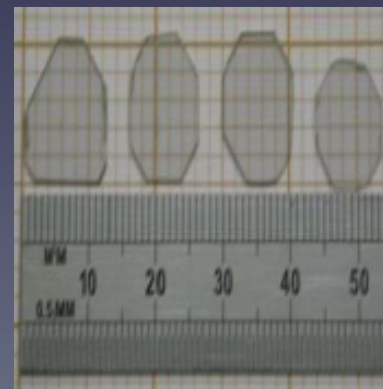
# Summary of material properties

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

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

**Mobility** for electrons: $\mu_n = \dfrac{e\tau_n}{m_n}$

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



$\mu_p$(Si, 300K)≈450 cm$^2$/Vs
$\mu_n$(Si, 300K)≈1450 cm$^2$/Vs

Ρεσιστιϖιτψ:

$$\rho = \dfrac{1}{e\left(\mu_n n_e + \mu_p n_h\right)}$$
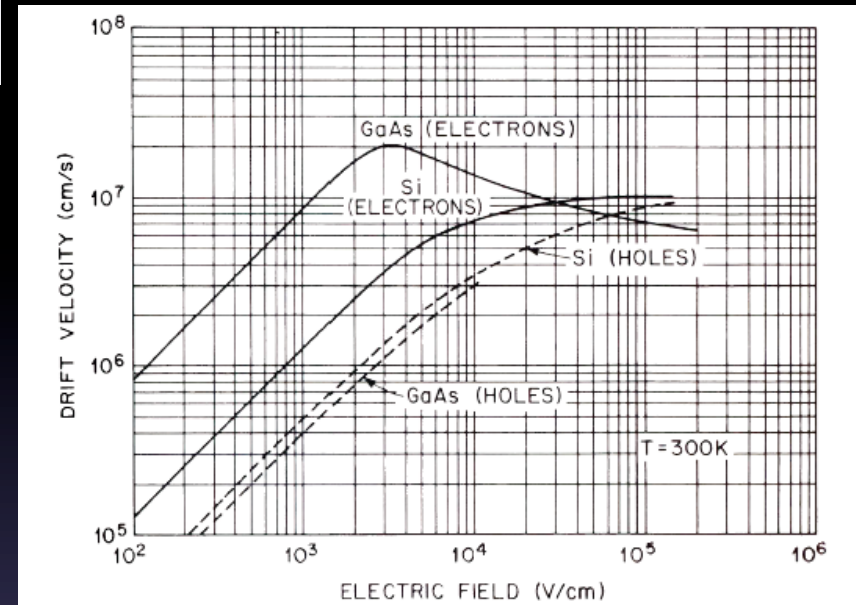
- e= electric charge
- E= external field
- $m_n$ and $m_p$= effective mass of electrons and holes
- $\tau_n$ and $\tau_p$= mean free path of electrons and holes
- $n_n$ and $n_p$=  density of electrons and holes

# Wafer Fabrication

1) Start with very pure quartzite sand. Clean it and further purify by chemical processes. Melt it and add the tiny concentration of phosphorus (boron) dopant to make n(p) type silicon. Pour it in a mold to make a polycrystalline silicon cylinder
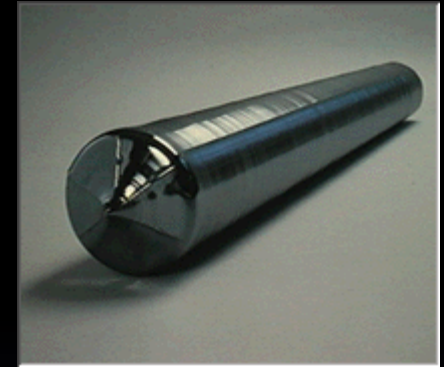


2) Using a single silicon crystal seed, melt the vertically oriented polysilicon cylinder onto the seed using RF power to obtain single crystal 'ingot'.



Polysilicon Ingot

Silicon Melt

RF coil

Single crystal

Seed
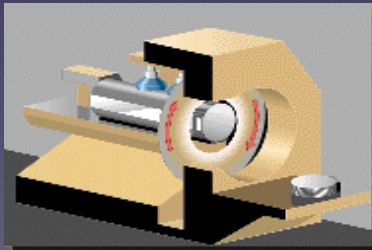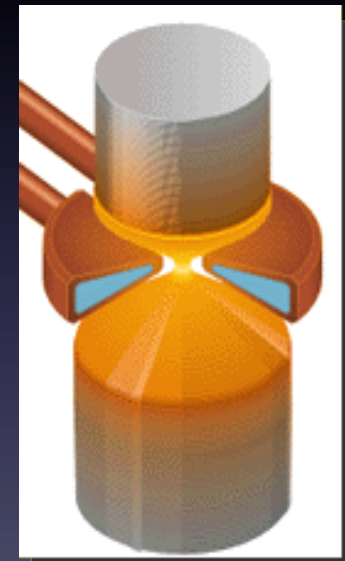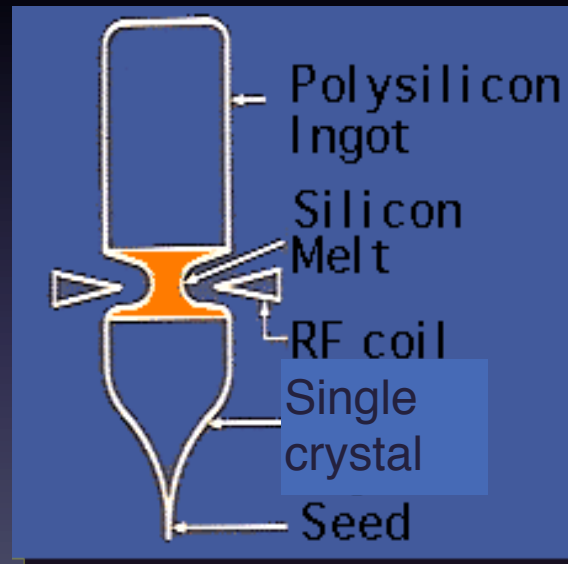




3) Slice ingot into wafers of thickness 300- 500μm with diamond encrusted wire or disc saws.

# Diode Processing

1) n-Si

Start with n-doped silicon wafer,
$\rho \approx$ 1-10 k$\Omega$cm. Silicon can be turned into n-type by
neutron doping ($^{30}$Si+n $\rightarrow$ $^{31}$Si,     $^{31}$Si $\rightarrow$$^{31}$P+$\beta^-$+$\nu$)

SiO$_2$

2) Oxidation at 800 - 1200°C

3) Photolithography (= mask align + photo-resist layer + developing) followed by etching to make windows in oxide



UV light     etch

mask

Photo-resist

# Diode Processing



4) Doping by ion implantation (or by diffusion)

5) Annealing (healing of crystal lattice) at 600 °C

6) Photolithography followed by Al metallization over implanted strips and over backplane usually by evaporation.

⇒Simple DC-coupled silicon strip detector

# Oxide Charge

- Many defects can appear at the interface between Si and $SiO_2$.
  - Some of the interface atoms will miss oxygen atoms and create Si-O bonds
  - Impurities (H, OH,N)
- These will create levels that can trap mobile electrons and holes (Interface traps)
- The charge due to the trapped electrons and holes onto the oxide defects is the "oxide charge"
- The oxide charge is usually positive $\Rightarrow$ electron accumulation layer
- It can affect device characteristics: breakdown voltage, strip isolation, interstrip capacitance



(a)

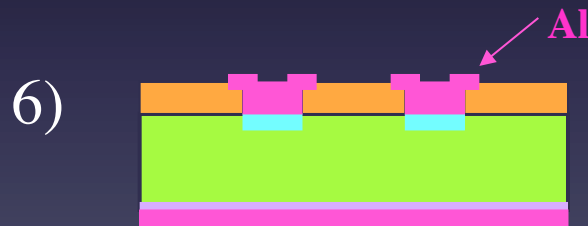Silicon Dioxide        Silicon

- ● Si atom
- ○ O atom
- ◇ Impurity atom/group
- · Unsaturated bond

(b)

vacuum level        conduction band

Energy (eV)

valence band

- ☒ donor type
- ⊠ acceptor type

1 Trivalent Silicon
2 Nonbridging Oxygen
3 Oxygen Vacancy
4 Interstitial Silicon
5 Silicon Vacancy
6 Interstitial Oxygen

A Interfacial Trivalent Silicon
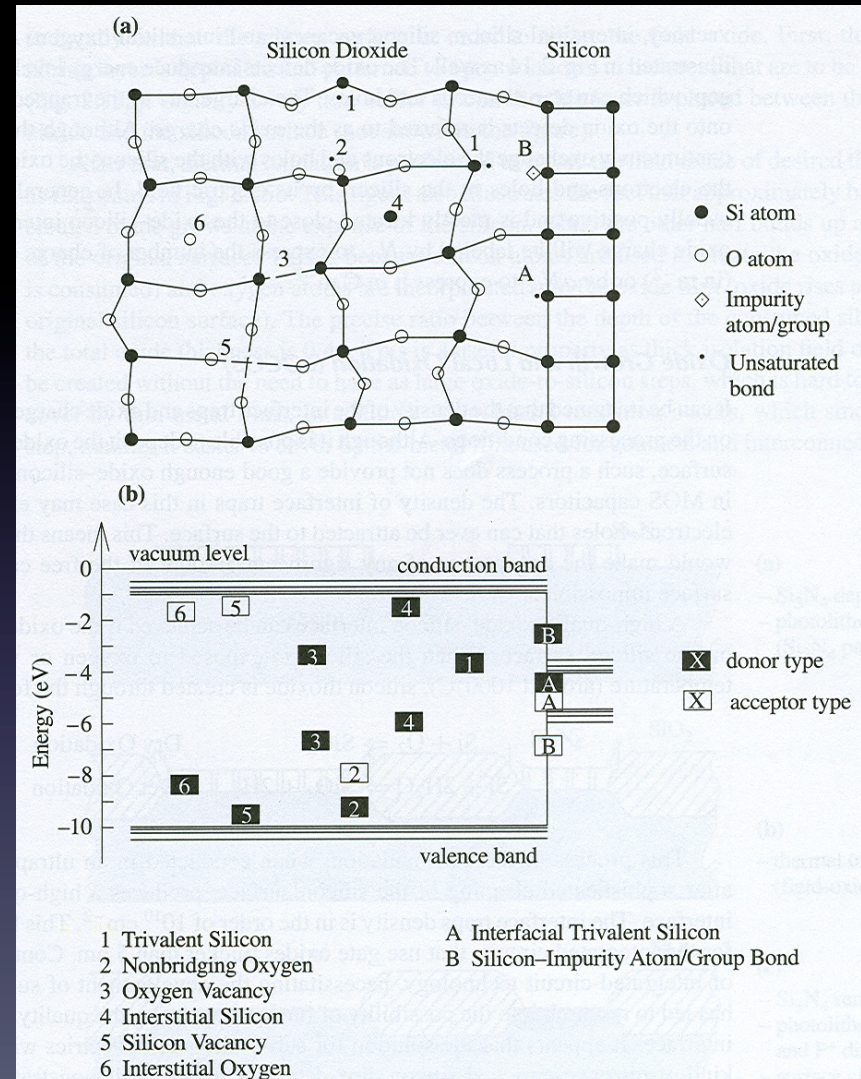B Silicon–Impurity Atom/Group Bond

**Figure 2.14** Illustration of the oxide–silicon interface and the associated defects: (a) a two-dimensional chemical-bond model and (b) the energy-band model.

Dimitrijev

# Radiation Damage in Silicon

- Two general types of radiation damage
  - "Bulk" damage due to physical impact within the crystal
  - "Surface" damage in the oxide or $Si/SiO_2$ interface
- Cumulative effects
  - Increased leakage current (increased shot noise)
  - Silicon bulk type inversion (n-type to p-type)
  - Increased depletion voltage
  - Increased capacitance
- Sensors can fail from radiation damage
  - Noise too high to effectively operate
  - Depletion voltage too high to deplete
  - Loss of inter-strip isolation (charge spreading)
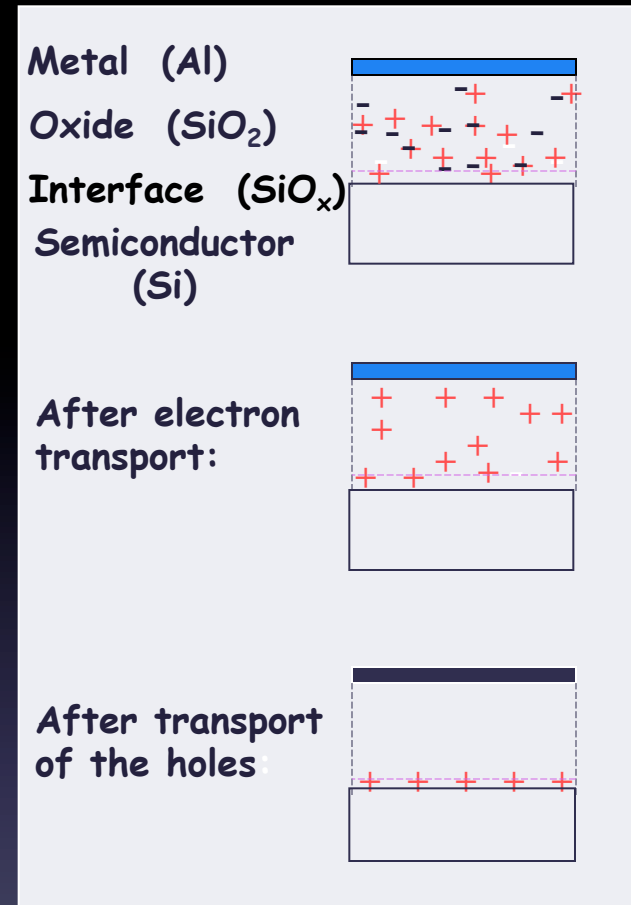- Signal/noise ratio is the quantity to watch

# Surface Damage

- Surface damage generation:
  - Ionizing radiation creates electron-hole pairs in the $SiO_2$
  - Many recombine, electrons migrate quickly
  - Holes slowly migrate to $Si/SiO_2$ interface since hole mobility is much lower than for electrons (20 $cm^2/Vs$ vs. $2x10^5$ $cm^2/Vs$)
  - Some holes 'stick' in the boundary layer
- Surface damage results in
  - Increased interface trapped charge
  - Increased fixed oxide charges
  - Surface generation centers

■ **MOS devices are sensitive to surface damage**

  - Electron accumulation under the oxide interface can alter the depletion voltage (depends on oxide quality and sensor geometry)
  - In silicon strip sensors, surface damage effects (oxide charge) saturate at a few hundred kRad



Metal (Al)
Oxide ($SiO_2$)
Interface ($SiO_x$)
Semiconductor (Si)

After electron transport:

After transport of the holes:
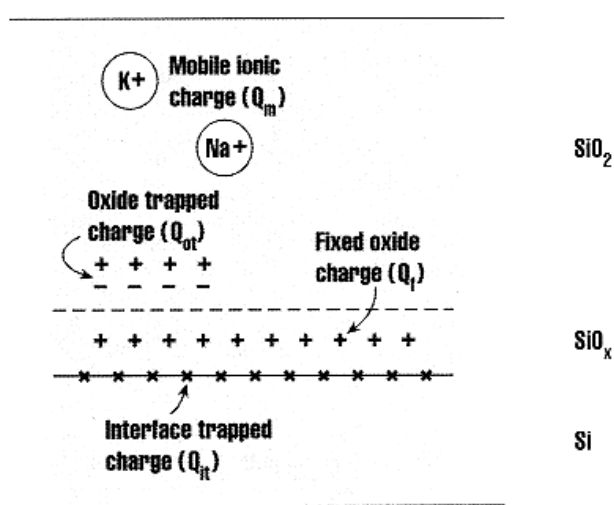
# Surface Damage Effects



**Figure 4-14** Silicon/silicon dioxide structure with mobile, fixed charge, and interface states (©1980,
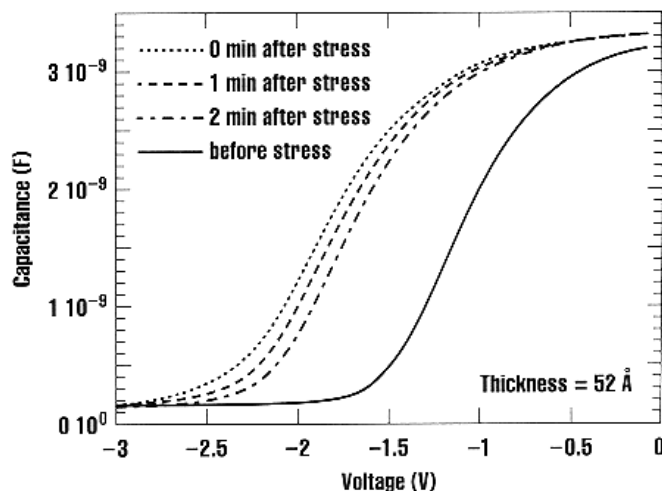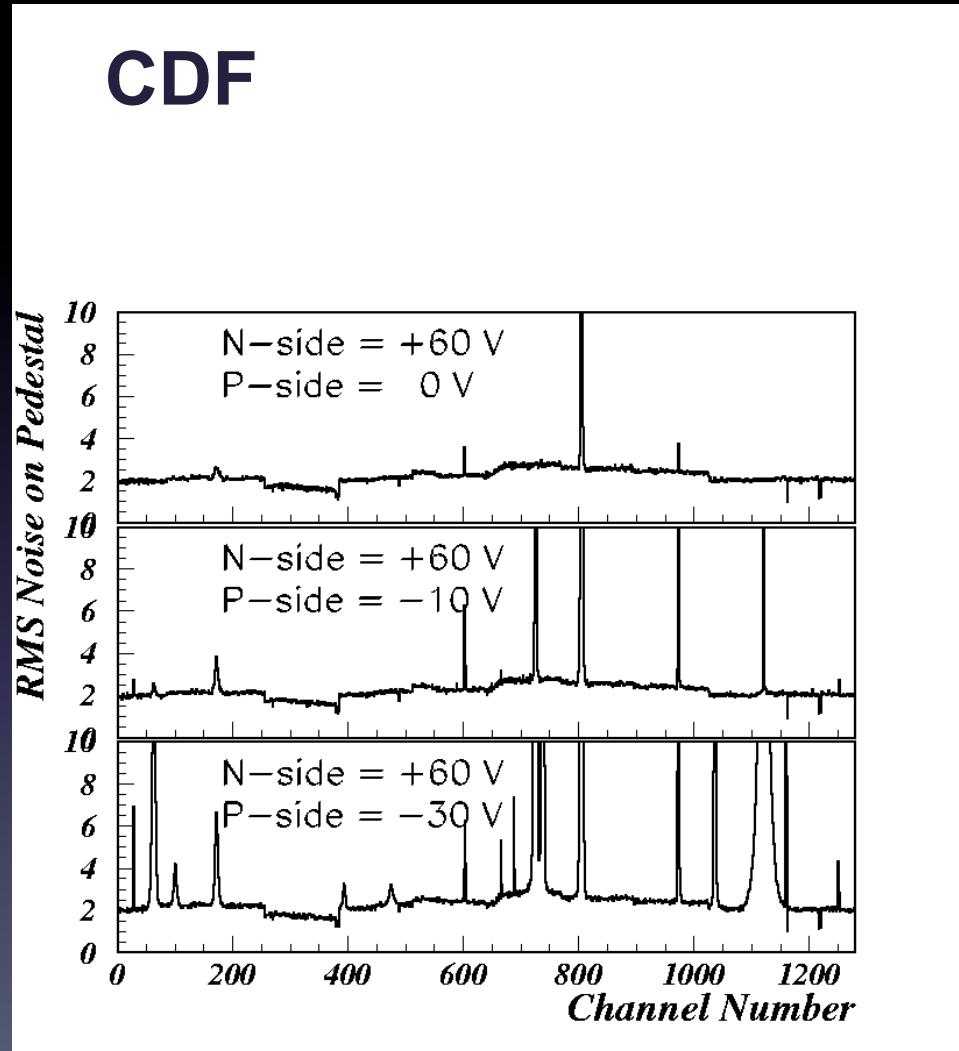


**Figure 4-15** High frequency C-V traces showing the effects of interface states and fixed charge.

- Charges in the oxide layer can cause:
  - Risk to readout electronics
    - threshold shifts
    - noise and gain deterioration
  - Increase in the sensors capacitances
  - Single event upset in small feature size devices
- Problems can be minimized by:
  - Silicon crystal orientation (<100> rather than <111>) can minimize interface traps at boundary
  - Reducing oxide thickness
    - Voltage shifts are proportional to the square of the thickness (0.25 µm CMOS more rad hard)
  - Processing

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# Surface Damage

- Oxide charges in the silicon strip sensors depend on vendor
  - Oxide charge starts out high before irradiation
  - Adversely influences operation in certain biasing configurations
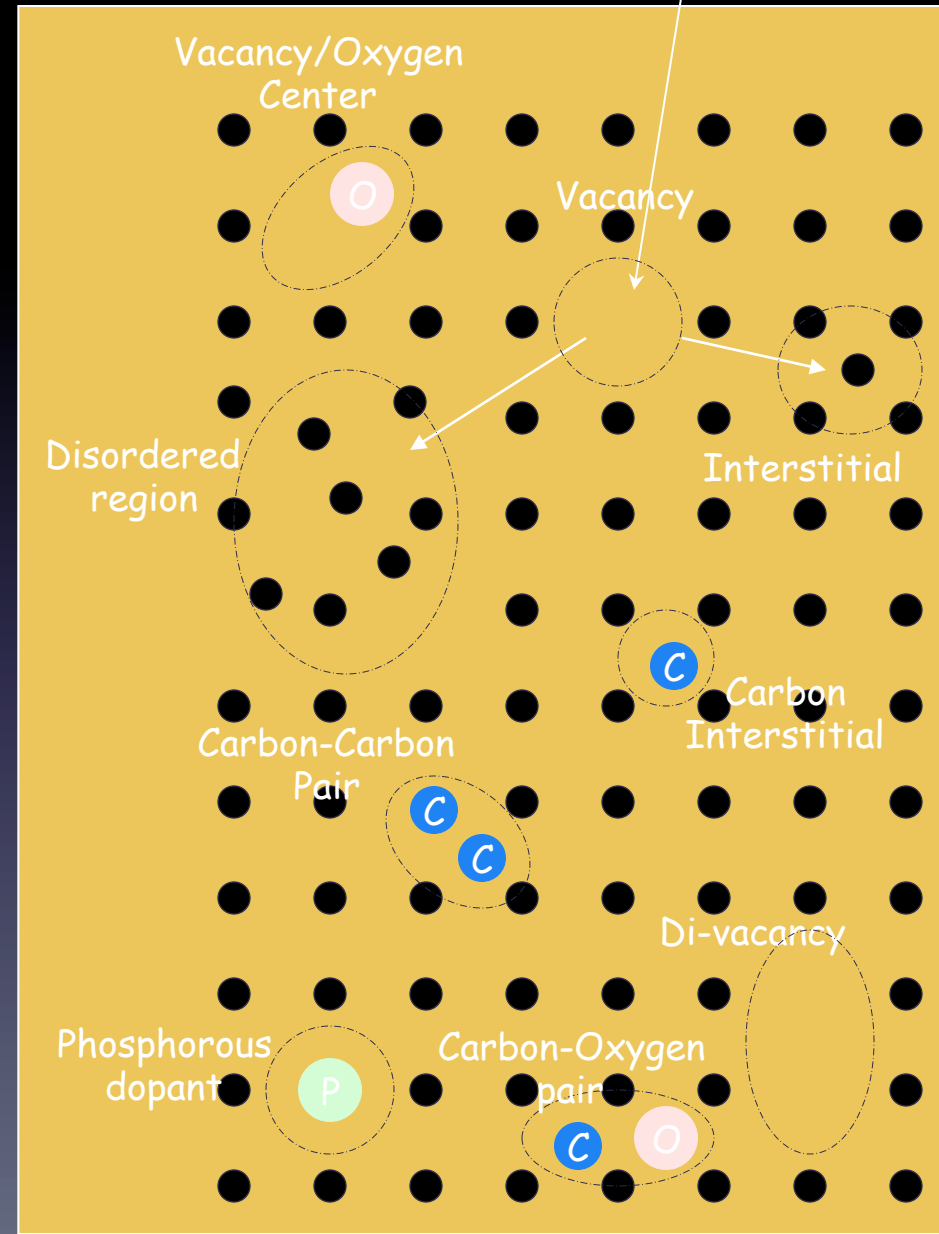  - Could set a limit to max bias voltage

**CDF**

# Process Defects and Scratches

# Bulk Damage

- Bulk damage is mainly from hadrons displacing primary lattice atoms (for E > 25 eV)
  - Results in silicon interstitial, vacancy, and large disordered region
  - 1 MeV neutron transfers 60-70 keV to recoiling silicon atom, which in turn displaces ~1000 additional atoms
- Defects can recombine or migrate through the lattice to form more complex and stable defects
  - Annealing can be beneficial
  - Defects can be stable or unstable
  - Displacement damage is directly related to the non-ionizing energy loss (NIEL) of the interaction
  - Varies by incident particle type and energy



Vacancy/Oxygen Center
Vacancy
Disordered region
Interstitial
Carbon Interstitial
Carbon-Carbon Pair
Di-vacancy
Phosphorous dopant
Carbon-Oxygen pair

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# Bulk Damage



$$\Phi = \Phi_0/r^{1.7}$$
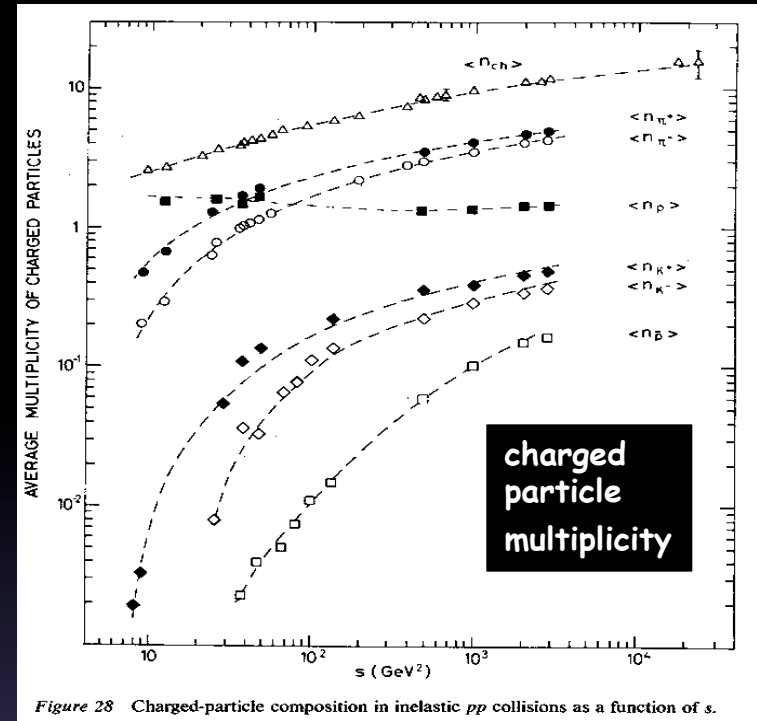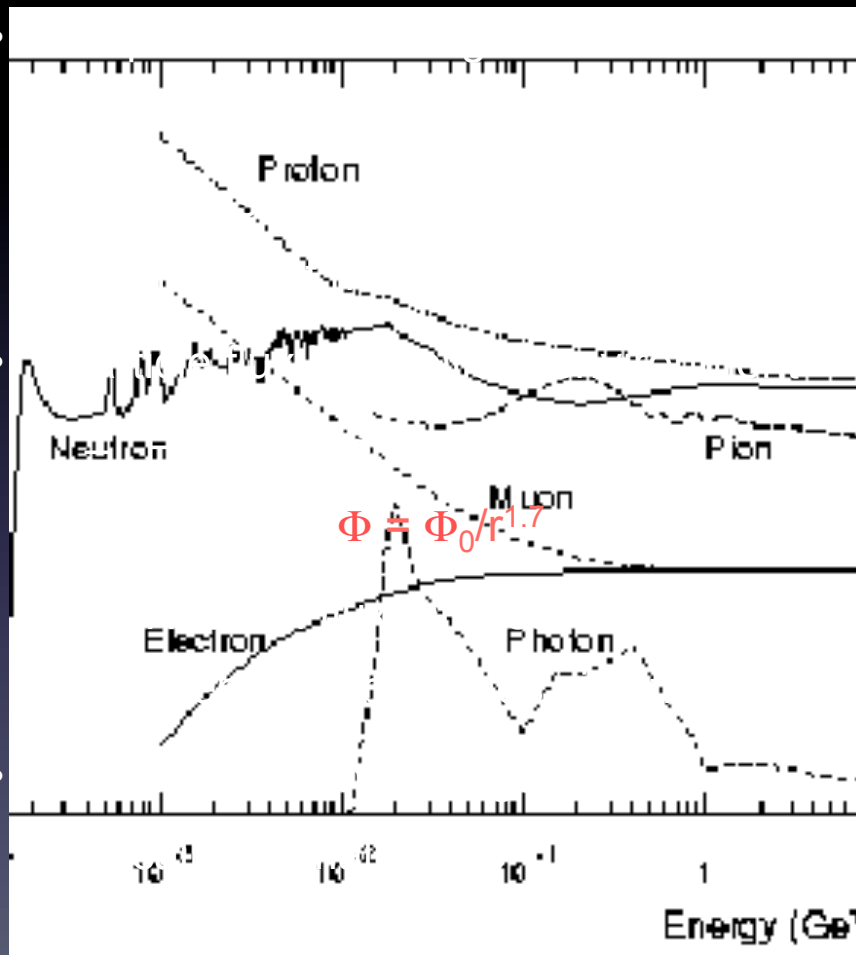


**charged particle multiplicity**

Figure 28 Charged-particle composition in inelastic *pp* collisions as a function of *s*.

# Bulk Damage Effects

- Leakage Current:

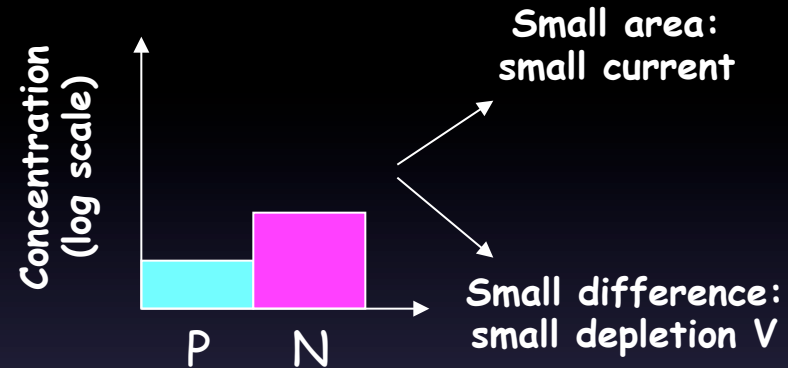$$\Delta I = \alpha(t)\Phi V$$

  - $\alpha(t)$ (damage constant), V (volume), and $\Phi$ (fluence).
  - Annealing reduces the current
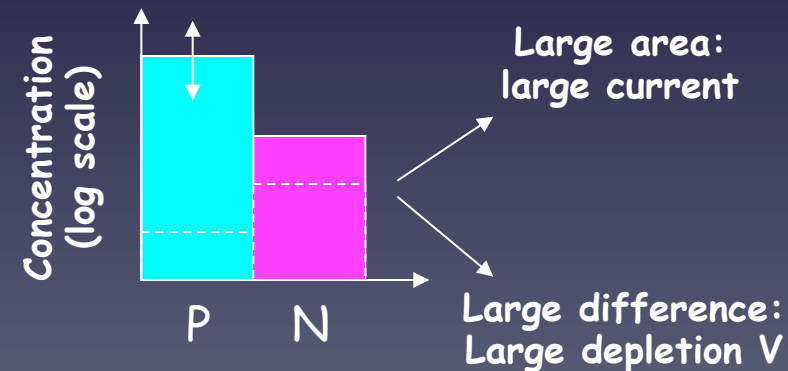  - Independent of particle type

- Depletion Voltage:

$$V_{dep} = q|N_{eff}|d^2/2\varepsilon\varepsilon_0$$

  - Effective dopant concentration ($N_{eff} = N_{donors} - N_{acceptors}$), sensor thickness (d), permitivity ($\varepsilon\varepsilon_0$).
  - Depletion voltage is parameterized in three parts:
    - **Short term annealing ($N_a$)**
    - **A stable component ($N_c$)**
    - **Long term reverse annealing ($N_\gamma$)**

**Before Irradiation:**

**Small area: small current**

**Small difference: small depletion V**

Concentration (log scale)

P    N

**After Irradiation:**

**Large area: large current**

**Large difference: Large depletion V**

Concentration (log scale)

P    N

# Leakage Current

- Defects create intermediate states within the band gap
  - intermediate states act as 'stepping stones' of thermal generation of electron/hole pairs
  - Some of these states anneal away; the bulk current reduces with time (and temperature after irradiation

- Annealing function $\alpha(t)$
  - Parameterized by the sum of several exponentials $\alpha_i exp(-t/\tau_i)$
  - Full annealing (for the example below) reached after ~1 year at 20°C
  - At low temperatures, annealing effectively stops
  - Dependant on incident particle type (?)



Fig. 3.24 Classification of levels in the forbidden gap.

A: shallow acceptor, e.g. B,
B: deep donor, e.g. $C_i O_i$
C: deep acceptor, e.g. $V O_i$
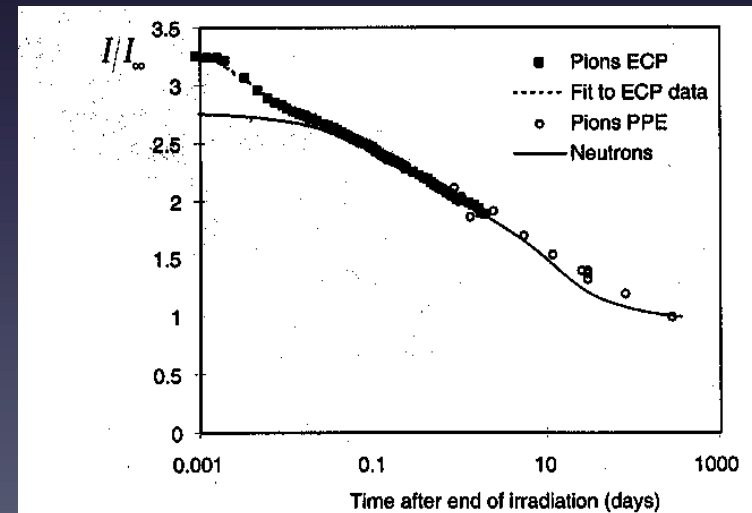D: shallow donor, e.g. P,
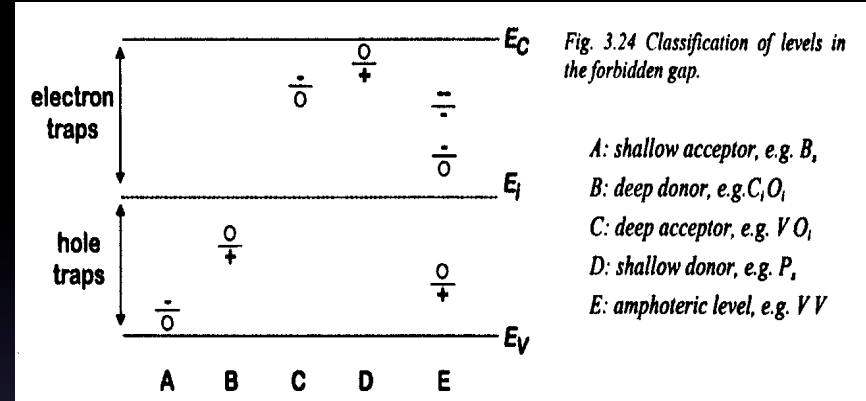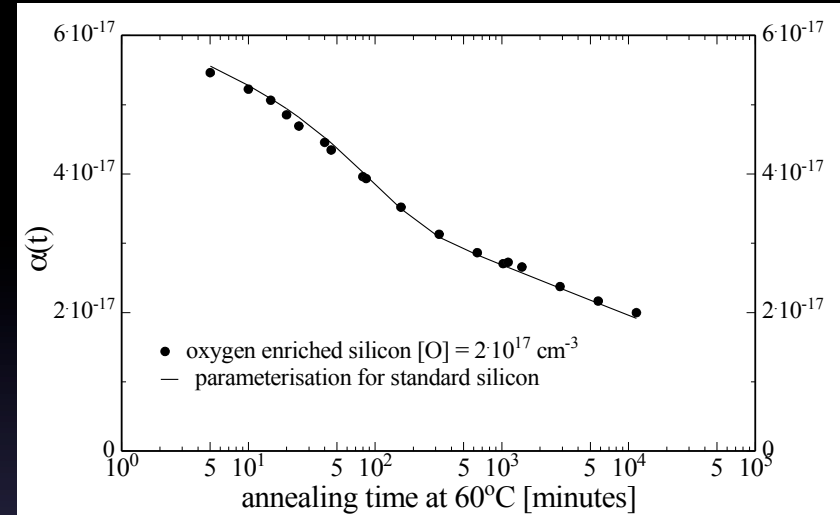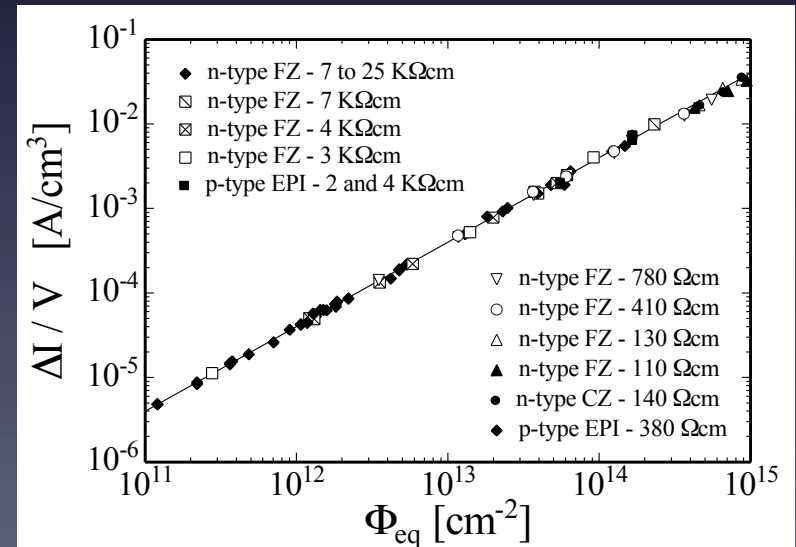E: amphoteric level, e.g. V V



Fig. 2: Short-term current annealing for pions and neutrons following a short (26 min) irradiation. Pion data taken from measurements, neutron curve taken from Ref. [6], (data for detectors before inversion) and recalculated for 26 min irradiation time.
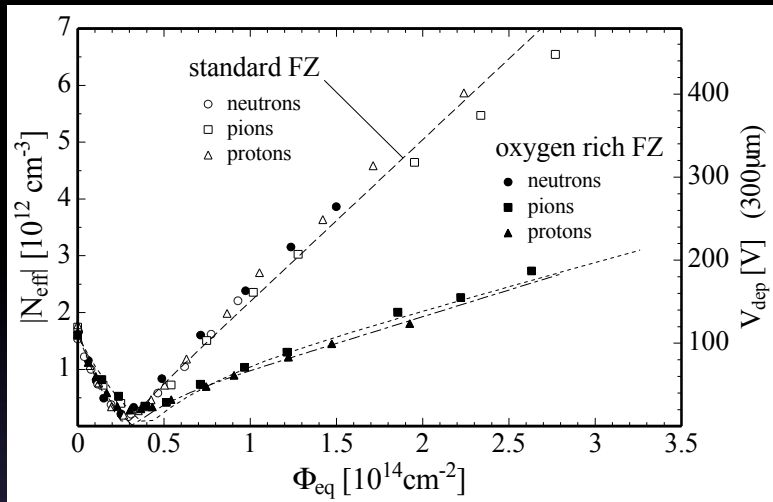
# Leakage Current

- Measured values of $\alpha(t)$
  - One quotes measured values of $\alpha(t)$ after complete annealing at T=20ºC: $\alpha_\infty = \alpha(t=\infty)$
  - 'World averages' for $a_\infty$ are :
    - $2.2 \times 10^{-17}$ A/cm$^3$ for protons, pions
    - $2.9 \times 10^{-17}$ A/cm$^3$ for neutrons
  - Measurment show $\alpha(t=80min,T=60ºC)= 4.0 \times 10^{-17}$ A/cm$^3$ for all types of silicon, levels of impurities, and incident particle types (NIM A426, 86, 1999).



oxygen diffused silicon and parameterisation given in Ref. [14].

# Depletion Voltage





Depletion voltage is often parameterized in three parts (Hamburg model):

$$\Delta N_{eff}(T,t,\Phi) = N_A + N_C + N_Y$$
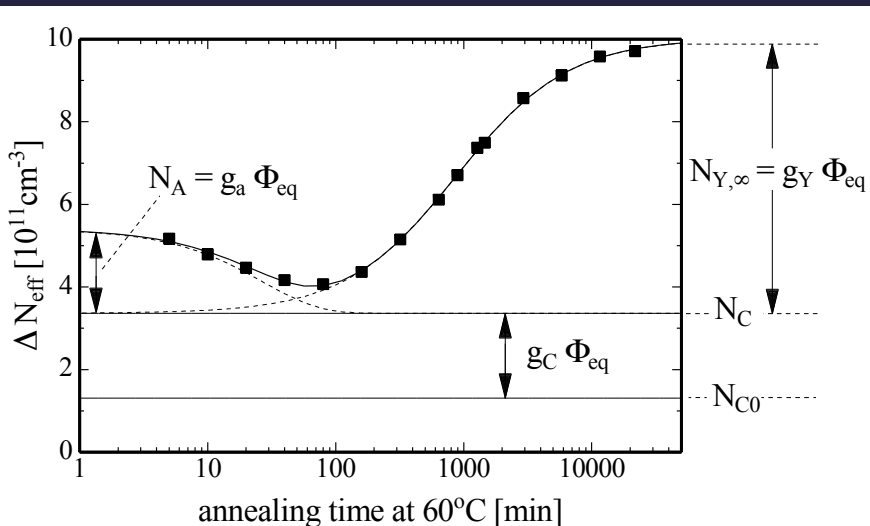
- Short term annealing ($N_A$)

  $$N_A = \Phi_{eq}\sum_i g_{a,i}\exp(-k_{a,i}(T)t)$$

  – Reduces $N_Y$ (beneficial)
  – Time constant is a few days at 20 C

- Stable component ($N_c$)

  $$N_c = N_{c0}(1-\exp(-c\Phi_{eq}))+g_c\Phi_{eq}$$

  – Does not anneal
  – Partial donor removal (exponential)
  – Creation of acceptor sites (linear)

- Long term reverse annealing ($N_Y$)

  $$N_Y = N_{Y,\infty}[1-1/(1+ N_{Y,\infty}k_Y(T)t)], \quad N_{Y,\infty}= g_Y\Phi_{eq}$$

  – Strong temperature dependence
  – 1 year at T=20 C or ~100 years at    T= -7 C (LHC)
  – Must cool Si at the LHC

# Most common semiconductors

- **Germanium:**
  - Used in nuclear physics
  - Needs cooling due to small band gap of 0.66 eV (usually done with liquid nitrogen at 77 K)
- **Silicon:**
  - Can be operated at room temperature (but electronics requires cooling)
  - Synergies with micro electronics industry
  - Standard material for vertex and tracking detectors in high energy physics
- **Diamond (CVD or single crystal):**
  - Large band gap (requires no depletion zone)
  - very radiation hard
  - Disadvantages: low signal and high cost

# Compound semiconductors

- **Compound semiconductors consist of**
  - two (binary semiconductors) or
  - more than two atomic elements of the periodic table.
    - IV-IV- (e.g. *SiGe*, *SiC*),
    - II-V- (e.g. *GaAs*)
    - II-VI compounds (*CdTe, ZnSe*)
- **Important III-V compounds:**
  - *GaAs*: Faster and probably more radiation resistant than Si. Drawback is less experience in industry and higher costs.
  - GaP, GaSb, InP, InAs, InSb, InAlP
- **important II-VI compounds:**
  - *CdTe*: High atomic numbers (48+52) hence very efficient to detect photons.
  - ZnS, ZnSe, ZnTe, CdS, CdSe, Cd1-xZnxTe, Cd1-xZnxSe