Fundamentals of Particle Detectors and Developments in Detector Technologies for Future Experiments

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Lecture 5/5

Abstract:

This lecture series will first review the elementary processes and techniques on which particle detectors are based. These must always be kept in mind when discussing the limits of existing technologies and motivations for novel developments. Using the examples of LHC detectors, the limits of state of the art detectors will be outlined and the current detector R&D trends for the LHC upgrade and other future experiments will be discussed. This discussion will include micro-pattern gas detectors, novel solid state detector technologies and trends in microelectronics.

4/27/2008

Outline

1) History of Instrumentation
Cloud Chambers/Bubble Chambers/Geiger Counters/Scintillators/Electronics/Wire Chambers

2) Electro-Magnetic Interaction of Charged Particles with Matter
Excitation/ Ionization/ Bethe Bloch Formula/ Range of Particles/ PAI model/ Ionization Fluctuation/ Bremsstrahlung/ Pair Production/ Showers/ Multiple Scattering

3) Signals/Gas Detectors
Detector Signals/ Signal Theorems/
Gaseous Detectors/ Wire Chambers/ Drift Chamber/ TPCs/ RPCs/ Limits of Gaseous Detectors/ Current Trends in Gaseous Detector Development

4) Solid State Detectors
→ Principles of Solid State Detectors/ Diamond Detectors/ Silicon Detectors/ Limits of Solid State Detectors/ Current Trends in Solid State Detectors

5) Calorimetry & Selected Topics
EM showers/ Hadronic Showers/ Crystal Calorimeters/ Noble Liquid Calirimeters/ Current Trends in Calorimetry

Solid State Detectors

Most material is taken from lectures by Michael Moll/CERN and Daniela Bortoletto/Purdue and the book 'Semiconductor Radiation Detectors' by Gerhard Lutz.

In gaseous detectors, a charged particle is liberating electrons from the atoms, which are freely bouncing between the gas atoms.

An applied electric field makes the electrons and ions move, which induces signals on the metal readout electrodes.

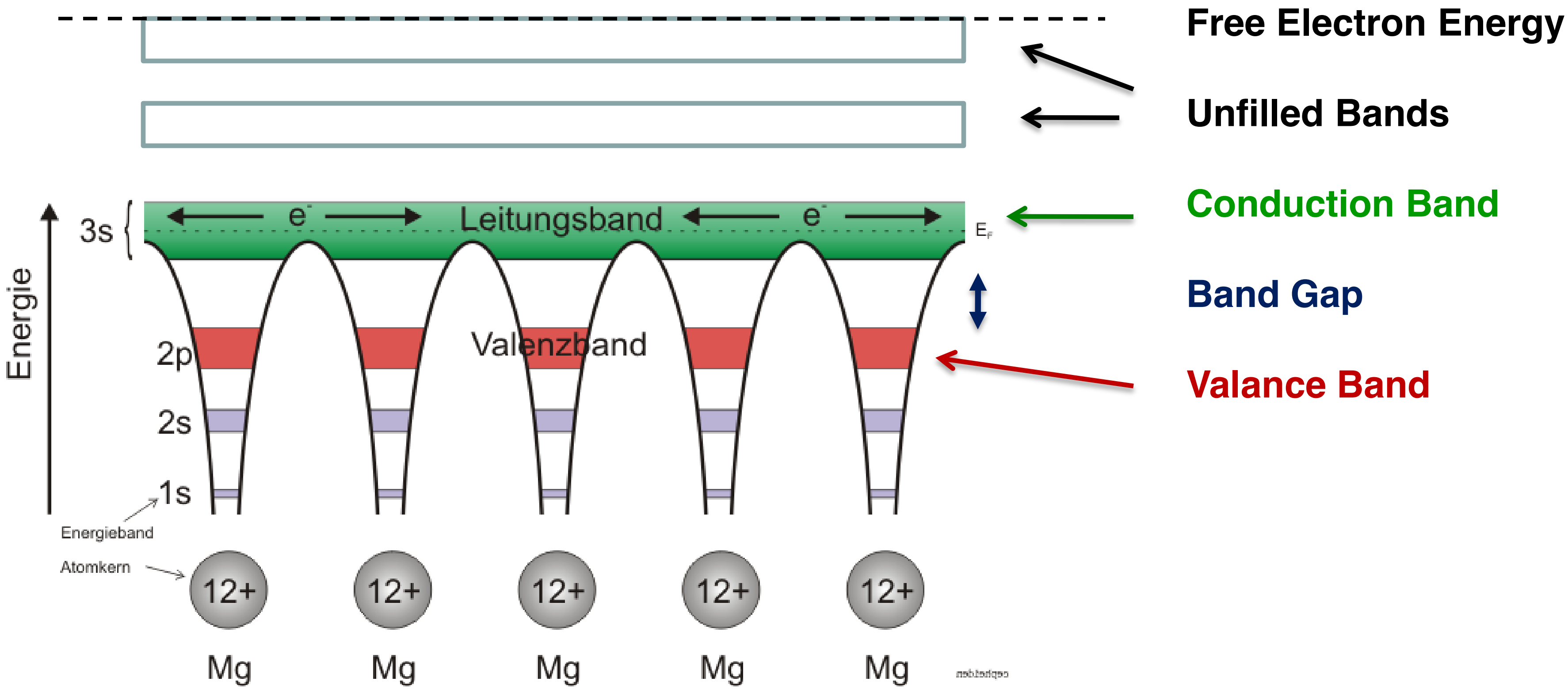
For individual gas atoms, the electron energy levels are discrete.

In solids (crystals), the electron energy levels are in 'bands'.

Inner shell electrons, in the lower energy bands, are closely bound to the individual atoms and always stay with 'their' atoms.

In a crystal there are however energy bands that are still bound states of the crystal, but they belong to the entire crystal. Electrons in this bands and the holes in the lower band can freely move around the crystal, if an electric field is applied.

Solid State Detectors



Solid State Detectors

In case the conduction band is filled the crystal is a conductor.

In case the conduction band is empty and ‘far away’ from the valence band, the crystal is an insulator.

In case the conduction band is empty but the distance to the valence band is small, the crystal is a semiconductor.

The energy gap between the last filled band – the valence band – and the conduction band is called band gap E_g.

The band gap of Diamond/Silicon/Germanium is 5.5, 1.12, 0.66 eV.

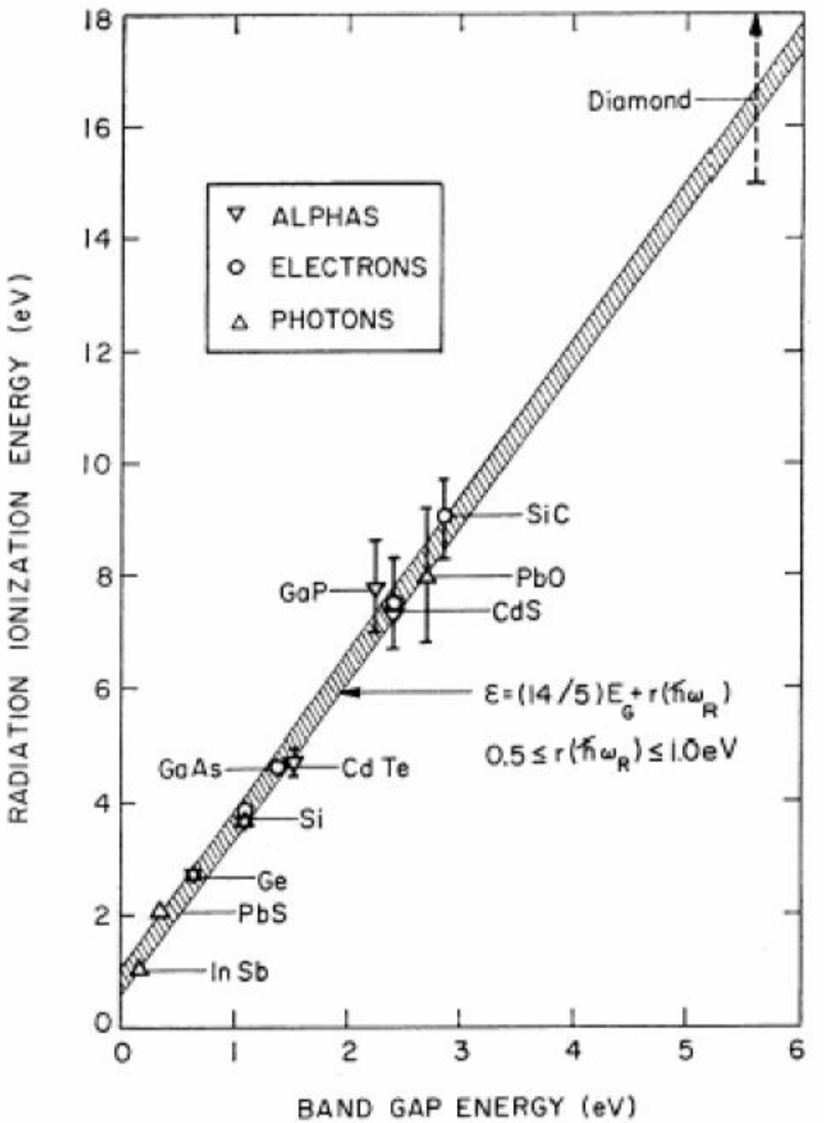
The average energy to produce an electron/hole pair for Diamond/Silicon/Germanium is 13, 3.6, 2.9eV.

In case an electron in the valence band gains energy by some process, it can be excited into the conduction band and a hole in the valence band is left behind.

Such a process can be the passage of a charged particle, but also thermal excitation → probability is proportional $Exp(-E_g/kT)$.

The number of electrons in the conduction band is therefore increasing with temperature i.e. the conductivity of a semiconductor increases with temperature.

Solid State Detectors



	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

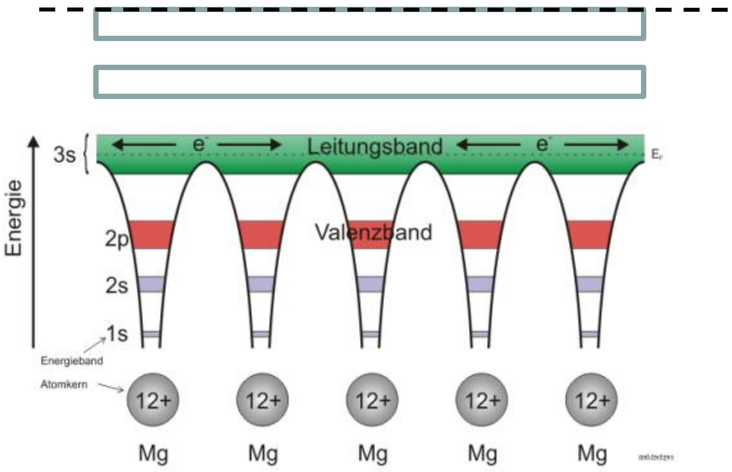
Solid State Detectors

It is possible to treat electrons in the conduction band and holes in the valence band similar to free particles, but with and effective mass different from elementary electrons not embedded in the lattice.

This mass is furthermore dependent on other parameters such as the direction of movement with respect to the crystal axis. All this follows from the QM treatment of the crystal.

If we want to use a semiconductor as a detector for charged particles, the number of charge carriers in the conduction band due to thermal excitation must be smaller than the number of charge carriers in the conduction band produced by the passage of a charged particle.

Diamond (E_g=5.5eV) can be used for particle detection at room temperature, Silicon (E_g=1.12 eV) and Germanium (E_g=0.66eV) must be cooled, or the free charge carriers must be eliminated by other tricks → doping → see later.



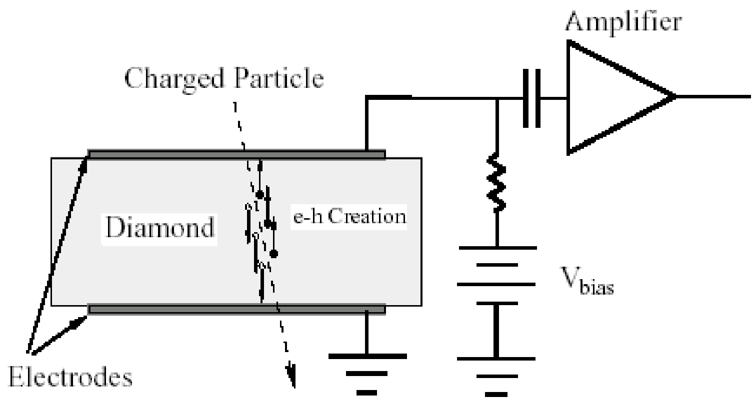
Solid State Detectors

The average energy to produce an electron/hole pair for Diamond/Silicon/Germanium is 13, 3.6, 2.9eV.

Comparing to gas detectors, the density of a solid is about a factor 1000 larger than that of a gas and the energy to produce and electron/hole pair e.g. for Si is a factor 7 smaller than the energy to produce an electron-ion pair in Argon.

The number of primary charges in a Si detector is therefore about 10^4 times larger than the one in gas → while gas detectors need internal charge amplification, solid state detectors don't need internal amplification.

While in gaseous detectors, the velocity of electrons and ions differs by a factor 1000, the velocity of electrons and holes in many semiconductor detectors is quite similar.

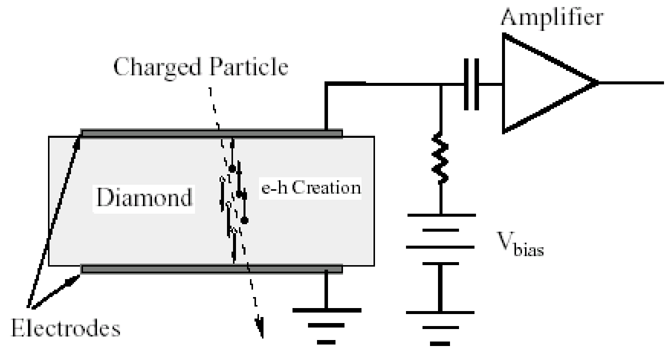


Diamond → A solid state ionization chamber

Diamond Detector

Typical thickness – a few 100µm.

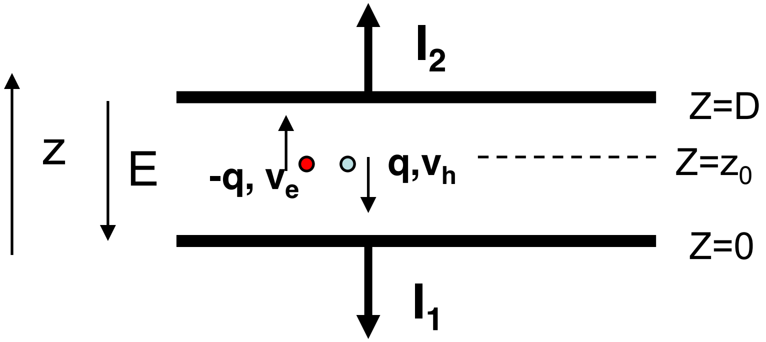
<1000 charge carriers/cm^3 at room temperature due to large band gap.



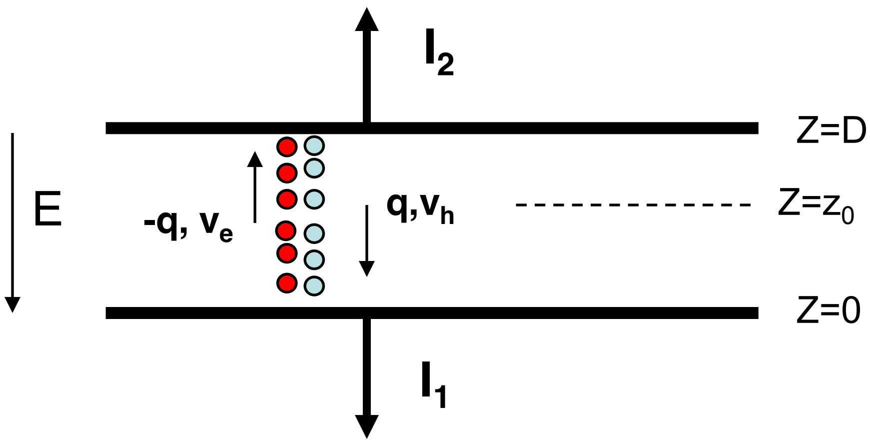
Velocity:

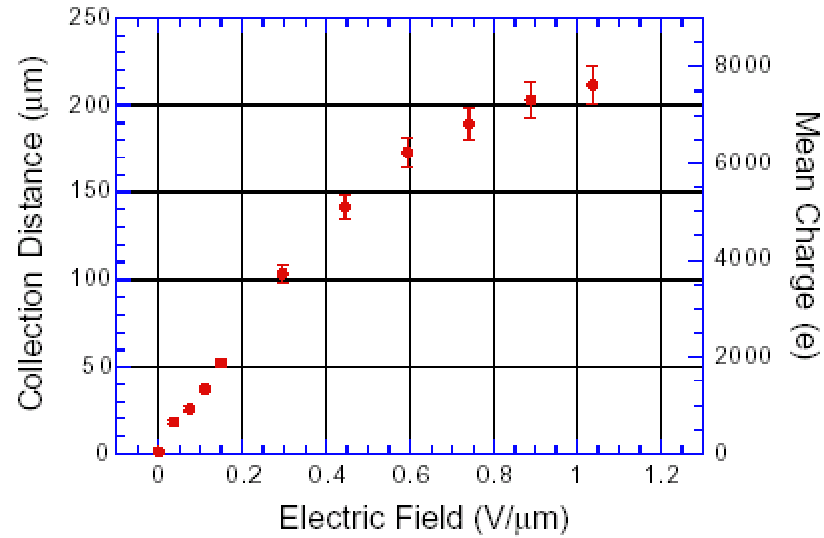
μ_e=1800 cm^2/Vs, μ_h=1600 cm^2/Vs

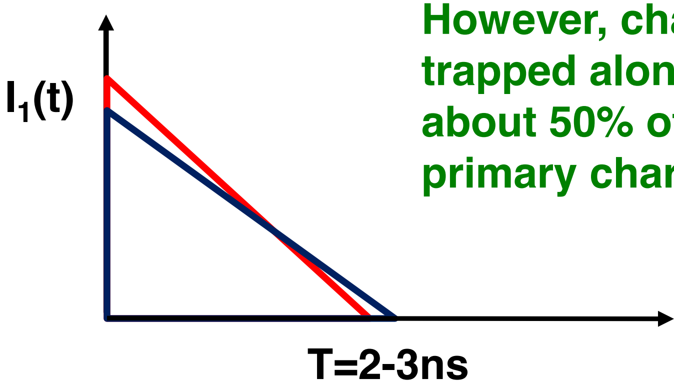
Velocity = µE, 10kV/cm → v=180 µm/ns → Very fast signals of only a few ns length !



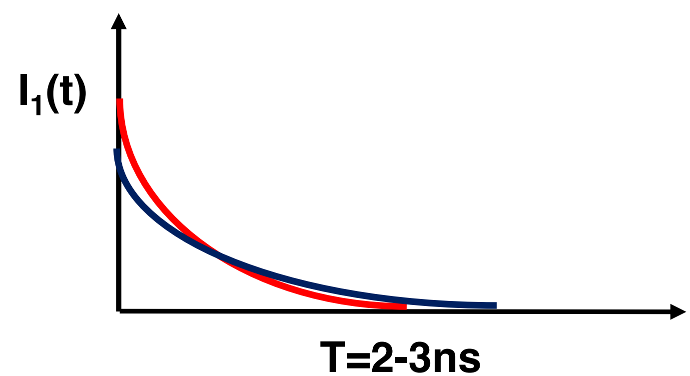
Diamond Detector







However, charges are trapped along the track, only about 50% of *produced* primary charge is *induced* →

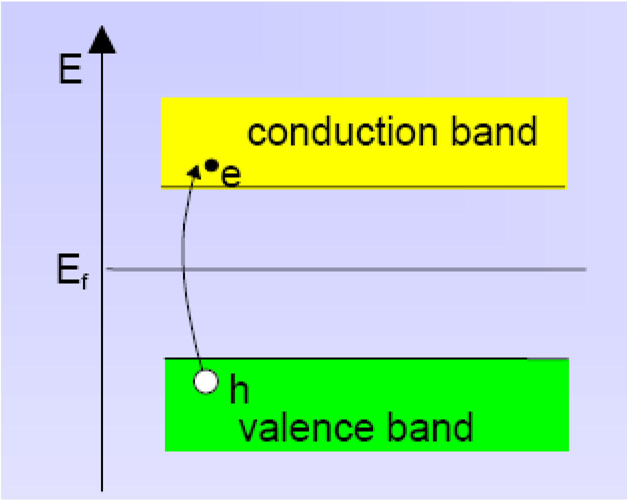


Silicon Detector

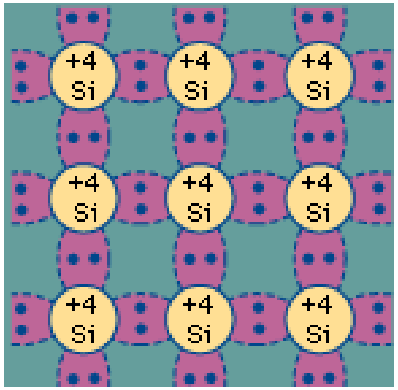
Velocity:
μ_e=1450 cm²/Vs, μ_h=505 cm²/Vs, 3.63eV per e-h pair.
~11000 e/h pairs in 100μm of silicon.

However: Free charge carriers in Si:
T=300 K: n/h = 1.45×10^{10} / cm³ but only 33000e-/h in 300μm produced by a high energy particle.

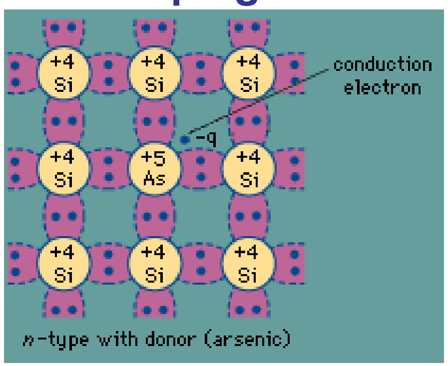
Why can we use Si as a solid state detector ???

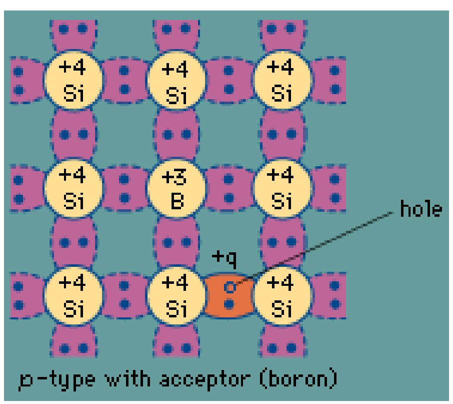


Doping of Silicon



doping



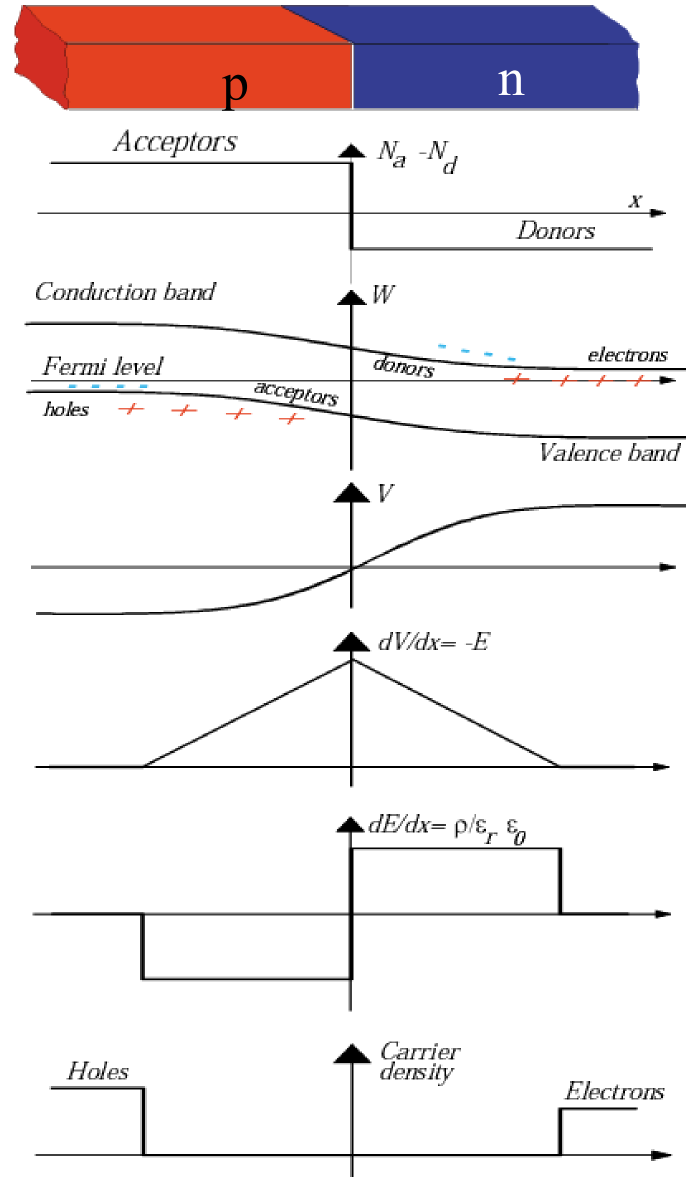


In a silicon crystal at a given temperature the number of electrons in the conduction band is equal to the number of holes in the valence band.

Doping Silicon with Arsen (+5) it becomes and n-type conductor (more electrons than holes).

Doping Silicon with Boron (+3) it becomes a p-type conductor (more holes than electrons).

Bringing p and n in contact makes a diode.



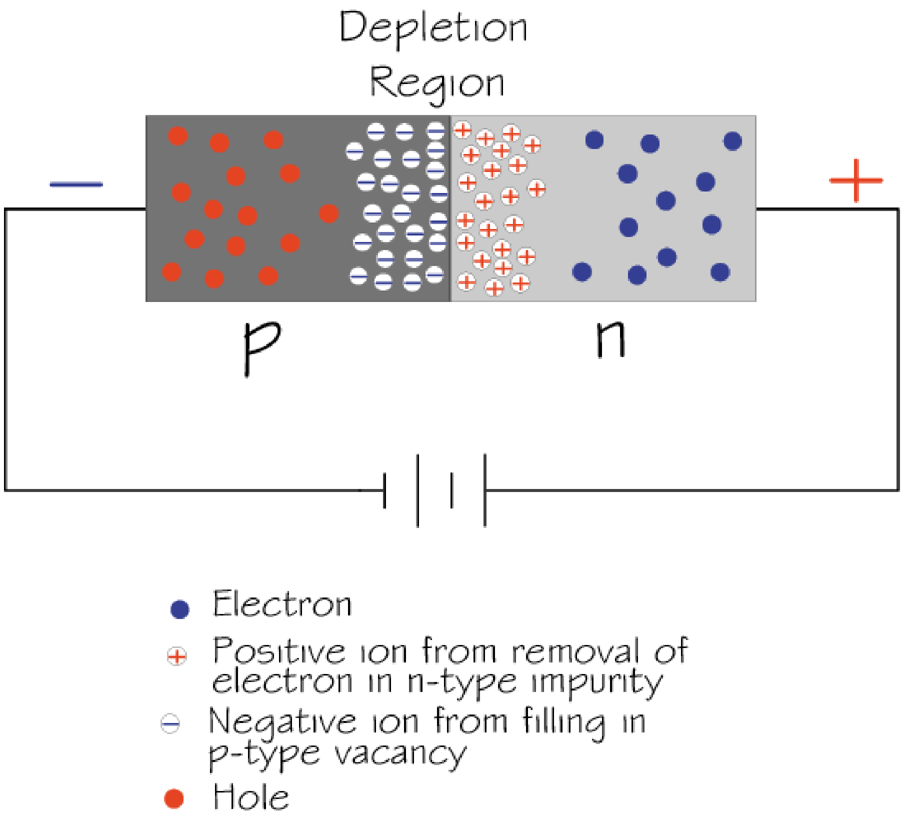
Si-Diode used as a Particle Detector !

At the p-n junction the charges are depleted and a zone free of charge carriers is established.

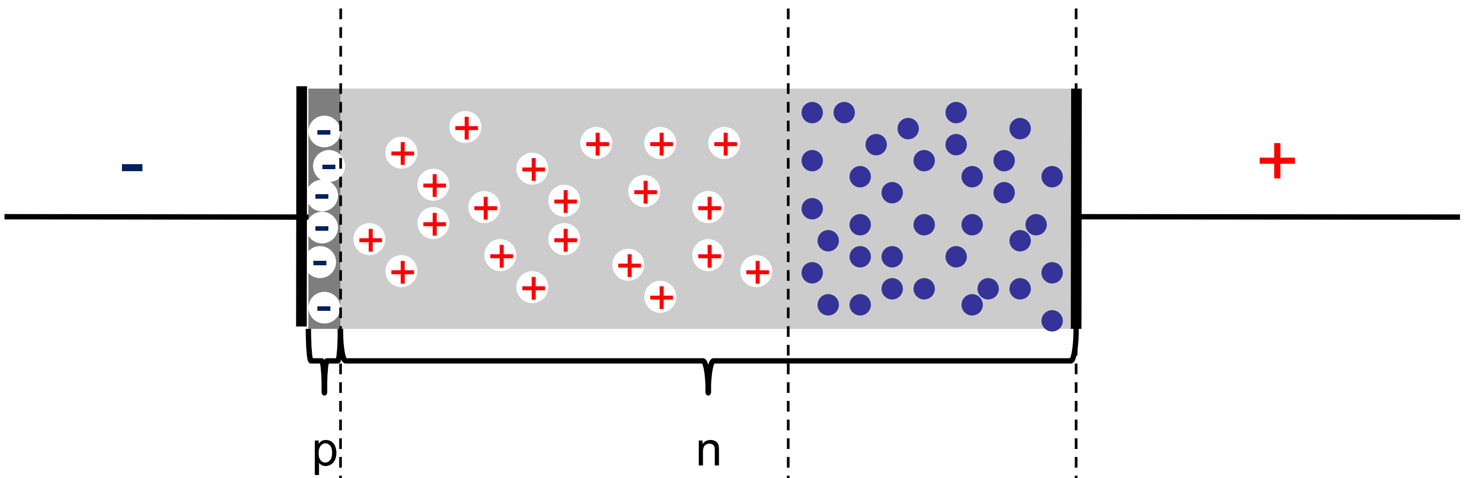
By applying a voltage, the depletion zone can be extended to the entire diode → highly insulating layer.

An ionizing particle produces free charge carriers in the diode, which drift in the electric field and induce an electrical signal on the metal electrodes.

As silicon is the most commonly used material in the electronics industry, it has one big advantage with respect to other materials, namely highly developed technology.

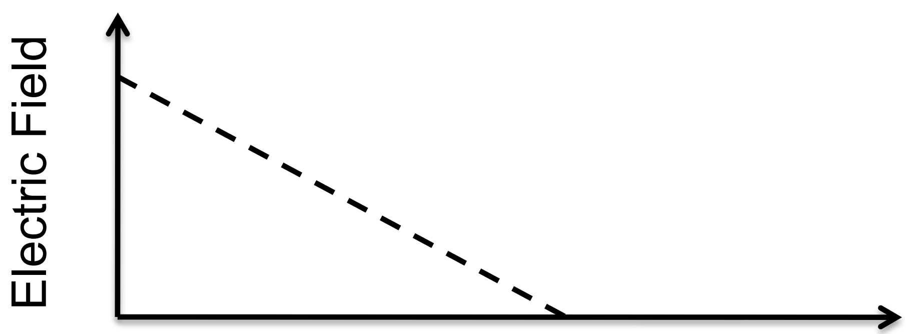


Under-Depleted Silicon Detector

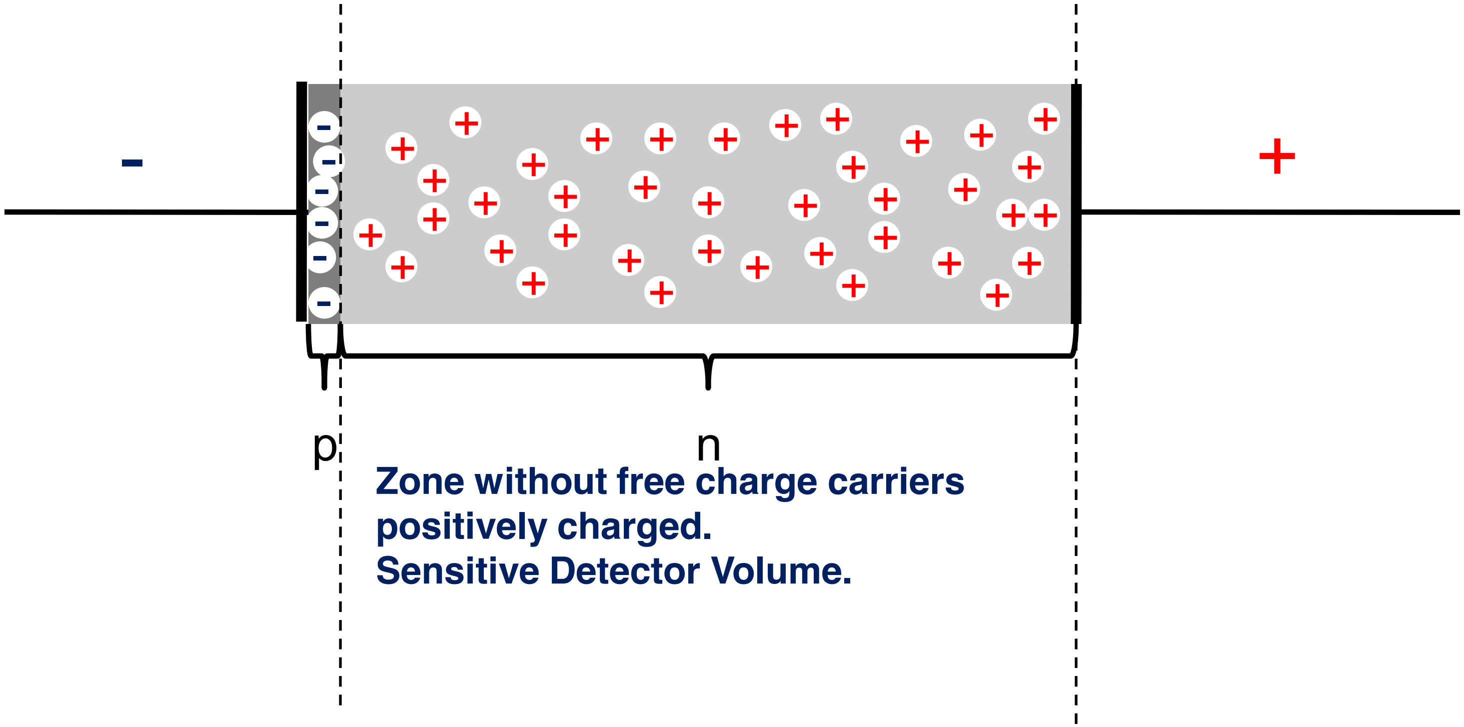


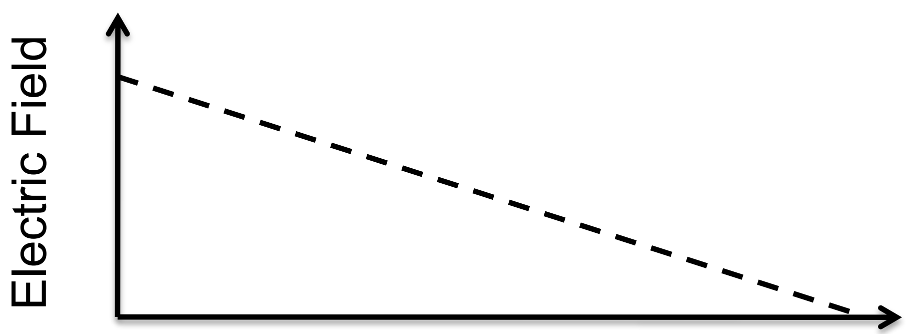
Zone without free charge carriers positively charged. Sensitive Detector Volume.

Zone with free electrons. Conductive. Insensitive to particles.

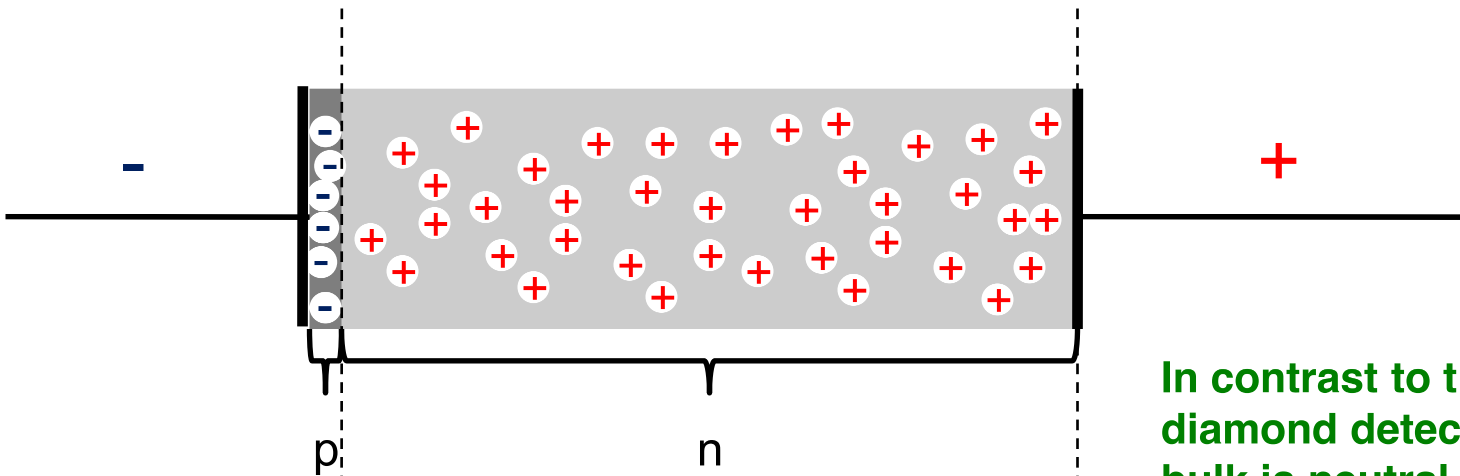


Fully-Depleted Silicon Detector

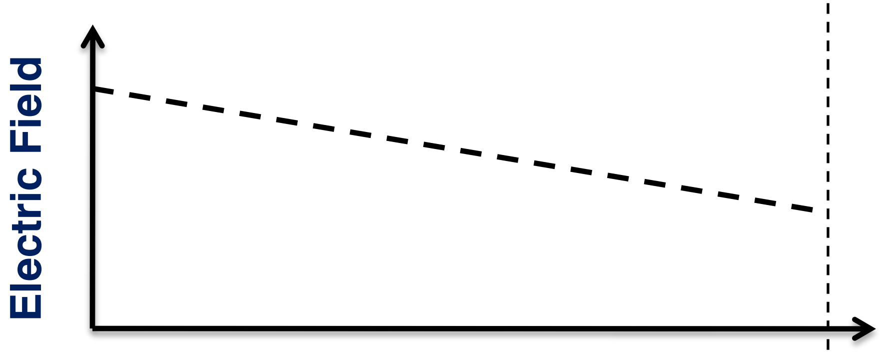




Over-Depleted Silicon Detector



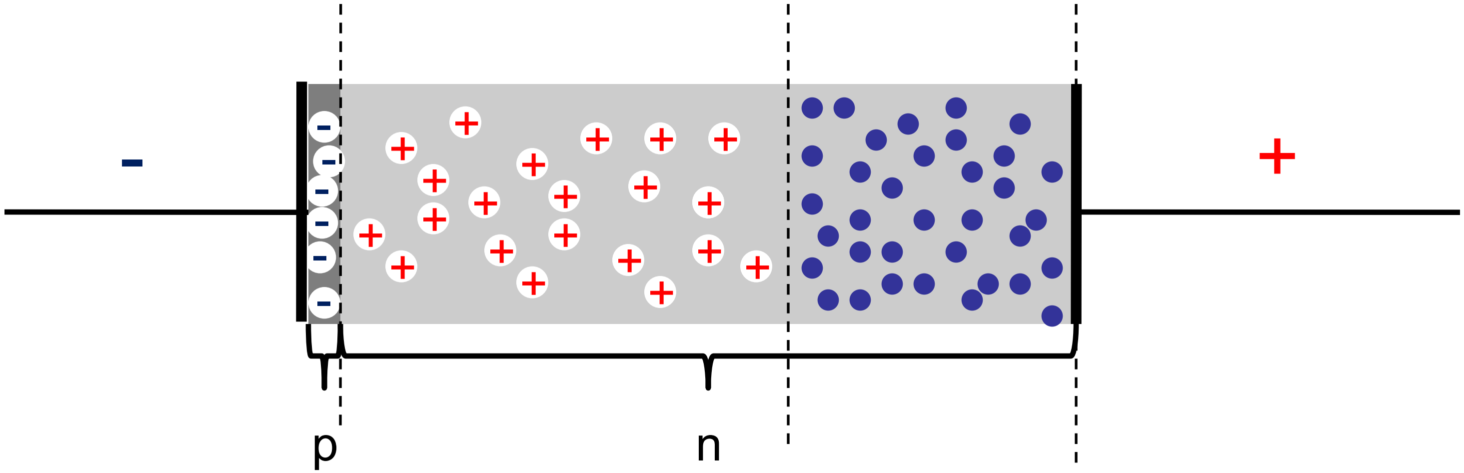
Zone without free charge carriers positively charged. Sensitive Detector Volume.



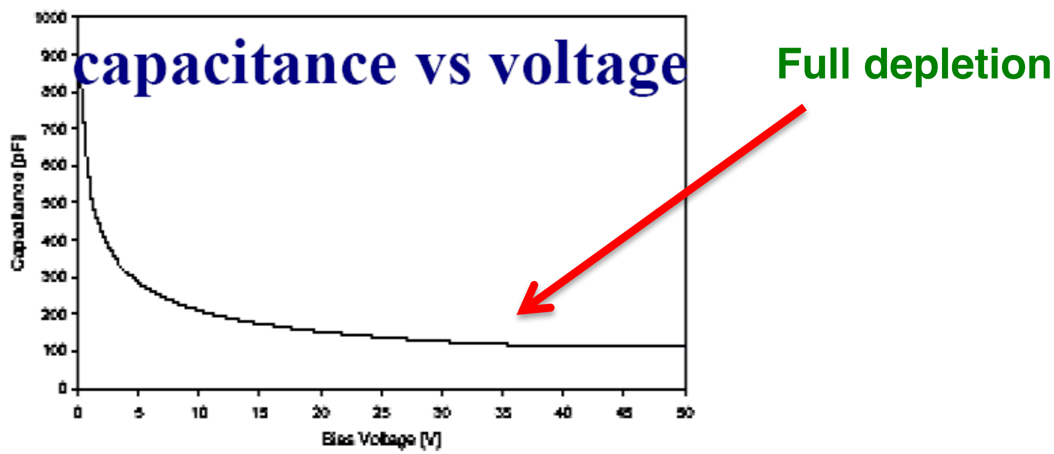
In contrast to the (un-doped) diamond detector where the bulk is neutral and the electric field is therefore constant, the sensitive volume of a doped silicon detector is charged (space charge region) and the field is therefore changing along the detector.

→ Velocity of electrons and holes is not constant along the detector.

Depletion Voltage

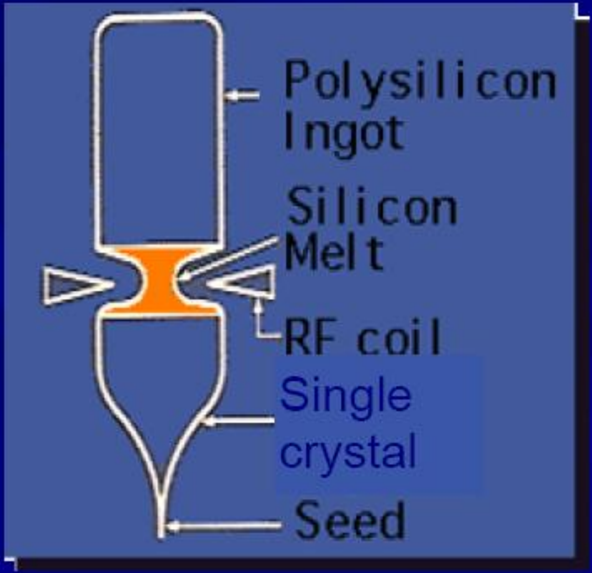


The capacitance of the detector decreases as the depletion zone increases.

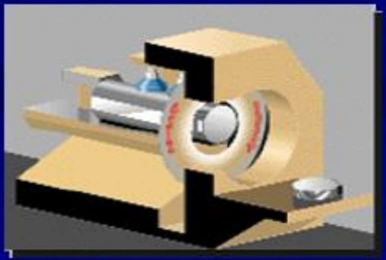


Wafer Fabrication

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'.



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

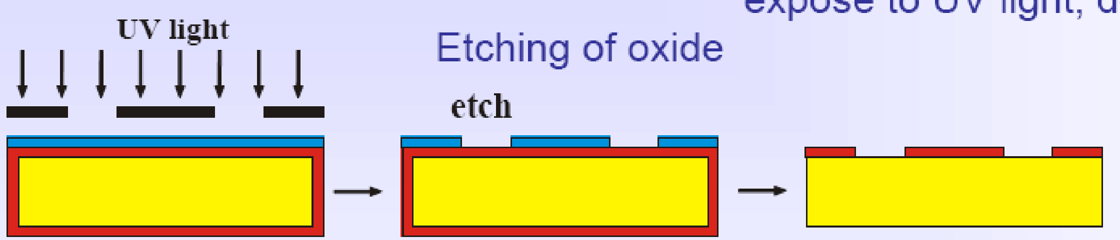
Silicon Sensor Production

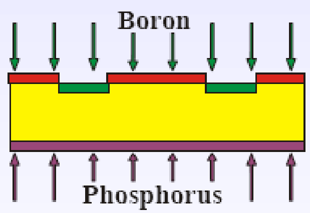
A "simple“ production sequence (schematic)

- Polished n-type silicon wafer (typical ρ ~ 1-10 KΩcm)

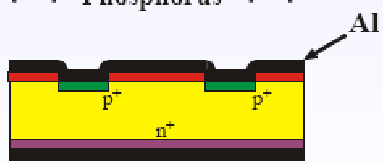
- Oxidation (800-1200°C)

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

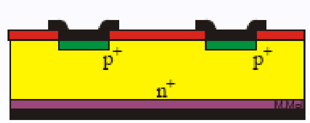




- Doping with boron and phosphorus by implantation (or by diffusion)
  Annealing to cure radiation damage and activate dopants
  - p^+ n junction on front side
  - n n^+ ohmic contact on back side

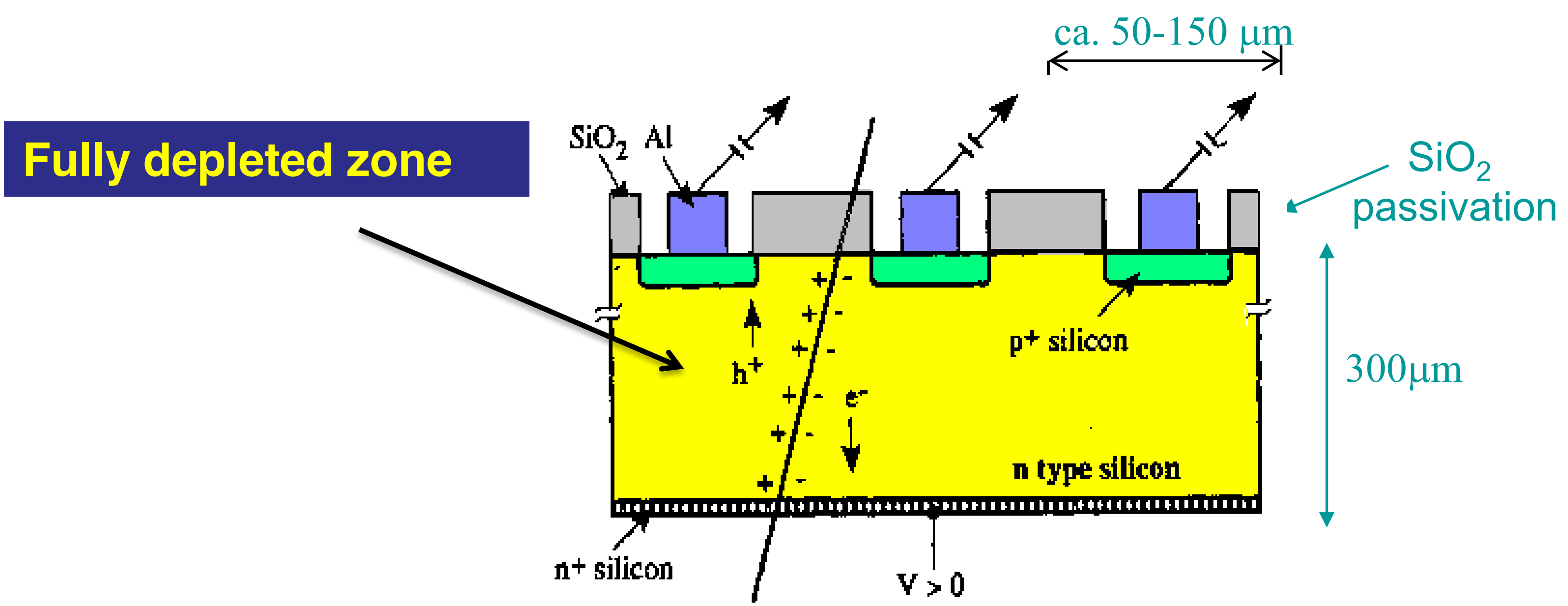


- Aluminize surface (e.g. by evaporation)



- Pattern metal for diode contacts

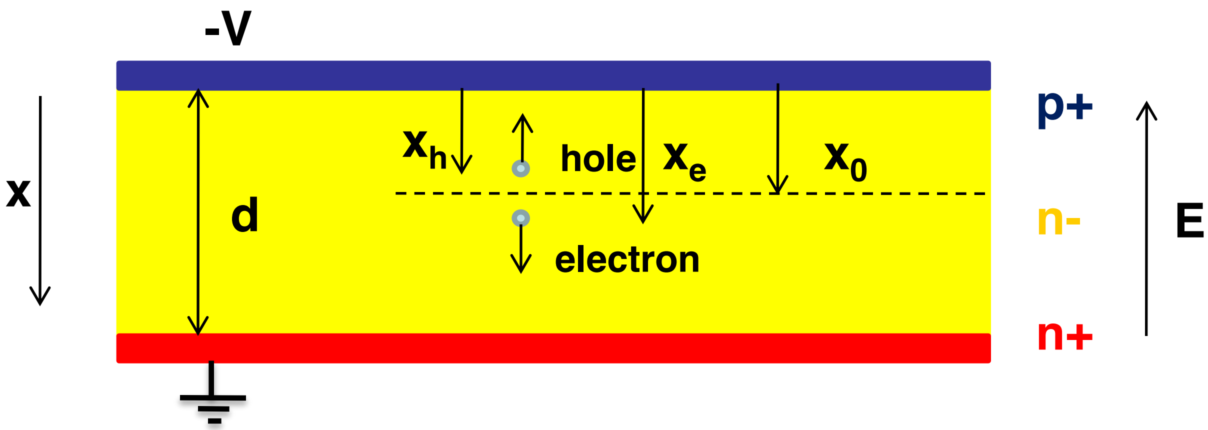
Silicon Detector



N (e-h) = 11 000/100μm

Position Resolution down to ~ 5μm !

What is the Signal induced on the p+ layer ?



What is the signal induced on the p+ 'electrode' for a single e/h pair created at x_0=d/2 for a 300um Si detector ?

$$E(x) = -\left[2\frac{d-x}{d^2}V_{dep} + \frac{V-V_{dep}}{d}\right] \qquad v_e(x) = \mu_e\, E(x) \qquad v_h(x) = \mu_h\, E(x)$$

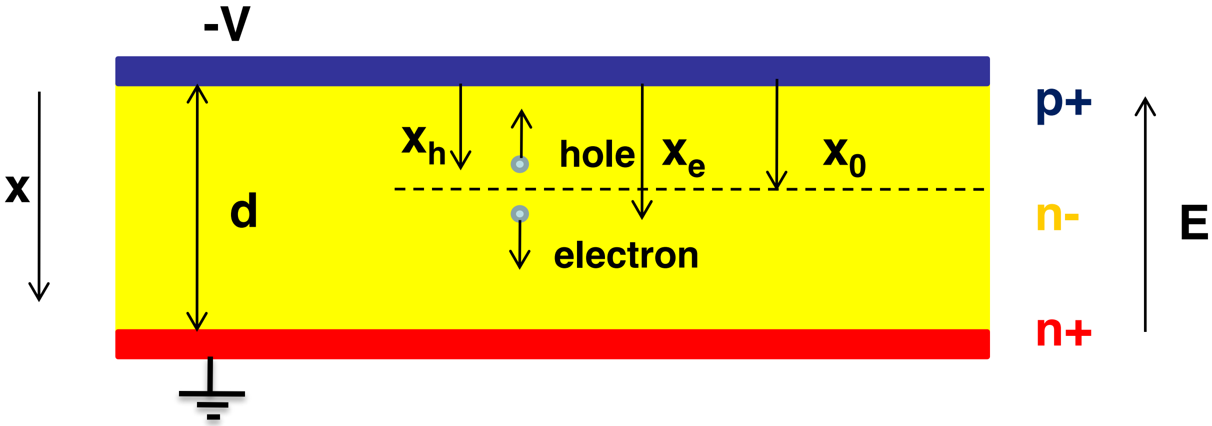
$$\frac{dx_e(t)}{dt} = \mu_e\, E(x(t)) \qquad x_e(t) = d\frac{V+V_{dep}}{2V_{dep}} + \left[x_0 - d\frac{V+V_{dep}}{2V_{dep}}\right] e^{-2\mu_e V_{dep} t/d^2}$$

$$\boxed{\frac{dx_e(t)}{dt} = \mu_e\left[\frac{2V_{dep}}{d^2}x_0 - \frac{V+V_{dep}}{d}e^{-2\mu_e V_{dep} t/d^2}\right]}$$

$$\frac{dx_h(t)}{dt} = -\mu_h\, E(x(t)) \qquad x_h(t) = d\frac{V+V_{dep}}{2V_{dep}} + \left[x_0 - d\frac{V+V_{dep}}{2V_{dep}}\right] e^{2\mu_h V_{dep} t/d^2}$$

$$\boxed{\frac{dx_h(t)}{dt} = \mu_h\left[\frac{2V_{dep}}{d^2}x_0 - \frac{V+V_{dep}}{d}e^{2\mu_h V_{dep} t/d^2}\right]}$$

What is the Signal induced on the p+ layer ?



$$x_e(t_e) = d \qquad t_e = \frac{d^2}{2\mu_e V_{dep}} \ln\left[\frac{V+V_{dep}}{V-V_{dep}}\left(1-\frac{x_0}{d}\frac{2V_{dep}}{V+V_{dep}}\right)\right]$$

$$x_h(t_h) = 0 \qquad t_h = -\frac{d^2}{2\mu_e V_{dep}} \ln\left(1-\frac{x_0}{d}\frac{2V_{dep}}{V+V_{dep}}\right)$$

$$E_w(x) = \frac{V_w}{d} \qquad i(t) = -\frac{q}{V_w}E_w(x(t))\frac{dx(t)}{dt}$$

$$i(t) = i_e(t) + i_h(t) = \frac{e_0}{d}\frac{dx_e(t)}{dt} - \frac{e_0}{d}\frac{dx_h(t)}{dt}$$

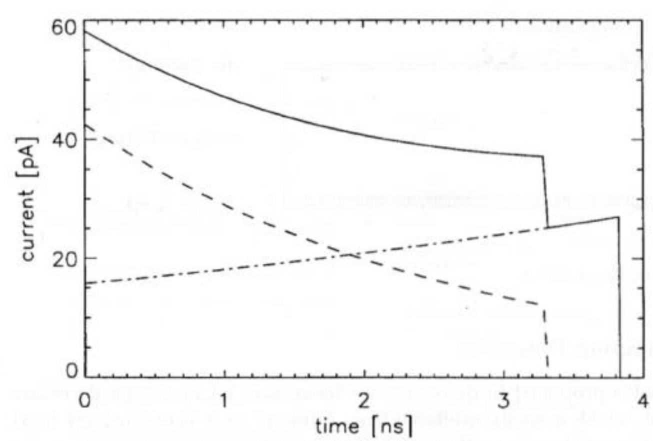
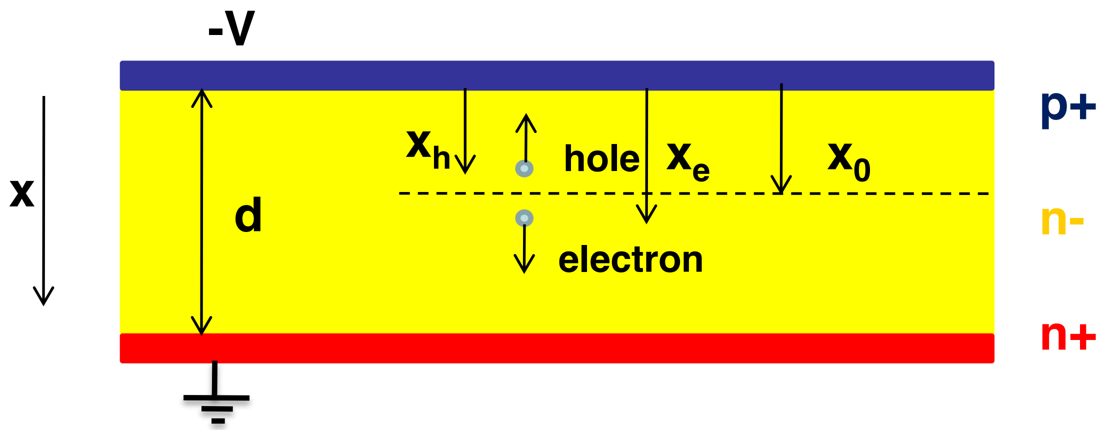


Fig. 5.4. Signal current formation induced by the separation of an electron–hole pair in the electric field of the space-charge region of the detector. The electron–hole pair is created in the center plane of a slightly (20%) overdepleted diode (see Example 5.2). Plotted are the electron-induced (*dashed line*), hole-induced (*dash-dot line*) and total (*continuous line*) currents

What is the Signal induced on the p+ layer ?



What is the signal induced on the p+ 'electrode' for a single e/h pair created at x_0=d/2 for a 300um Si detector ?

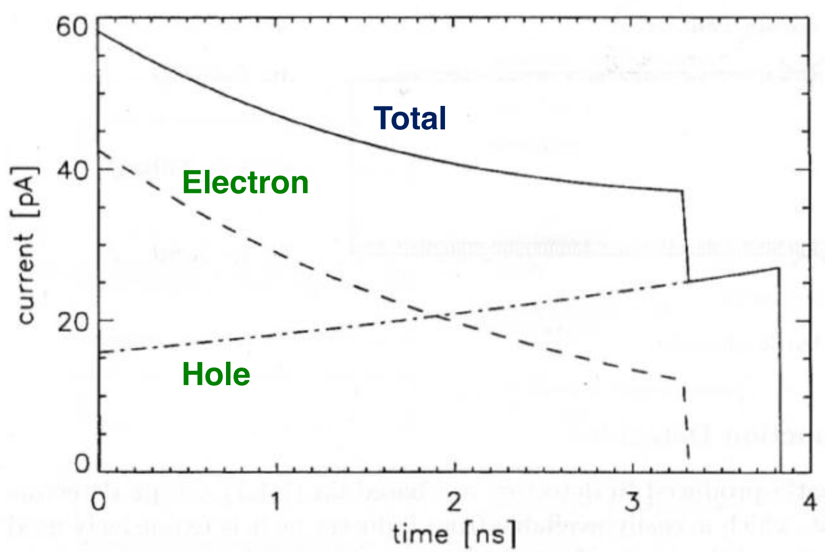


Fig. 5.4. Signal current formation induced by the separation of an electron–hole pair in the electric field of the space-charge region of the detector. The electron–hole pair is created in the center plane of a slightly (20%) overdepleted diode (see Example 5.2). Plotted are the electron-induced (*dashed line*), hole-induced (*dash-dot line*) and total (*continuous line*) currents

To calculate the signal from a track one has to sum up all the e/h pair signal for different positions x_0.

Si Signals are fast T<10-15ns. In case the amplifier peaking time is >20-30ns, the induced current signal shape doesn't matter at all.

The entire signal is integrated and the output of the electronics has always the same shape (delta response) with a pulse height proportional to the total deposited charge.

Biasing, AC coupling

Bias resistor and AC Coupling

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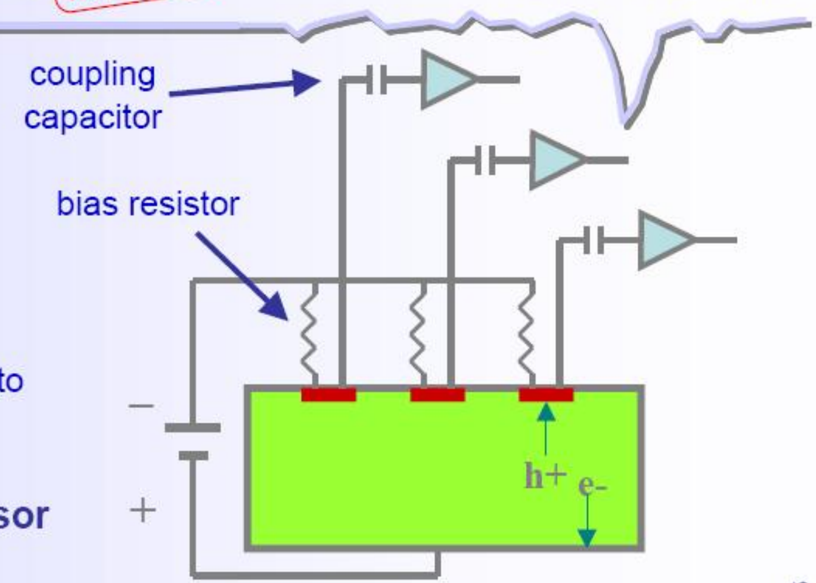


Bias resistor

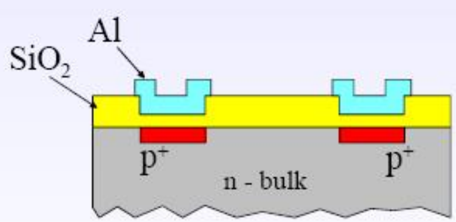
- Need to isolate strips from each other to collect/measure charge on each strip
  ⇒ high impedance bias connection (≈ 1MΩ resistor)

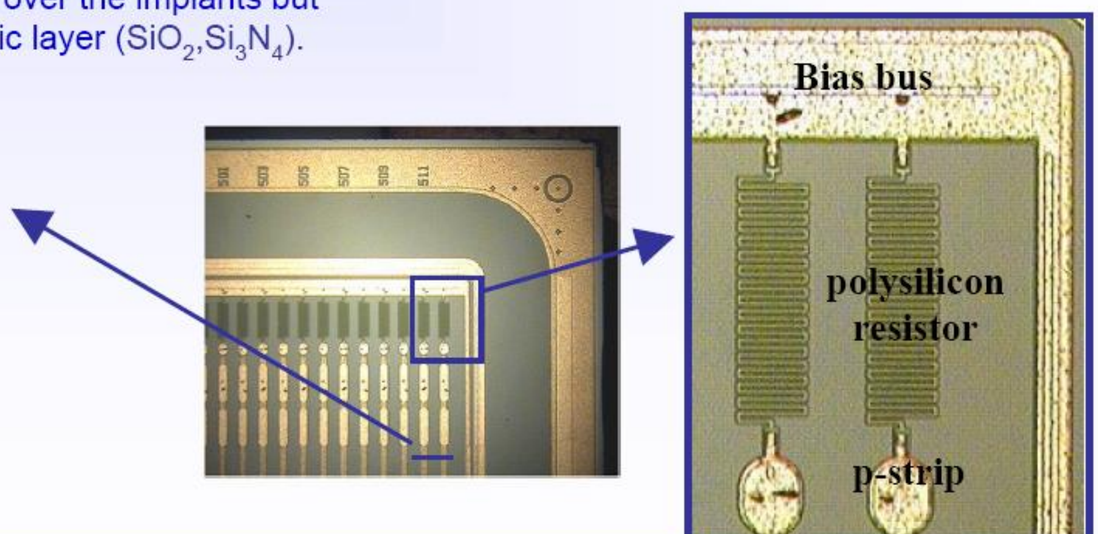
Coupling capacitor

- 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

CERN Academic Training Programme 2004/2005

The Charge Signal

extra slide not shown

Collected Charge for a Minimum Ionizing Particle (MIP)

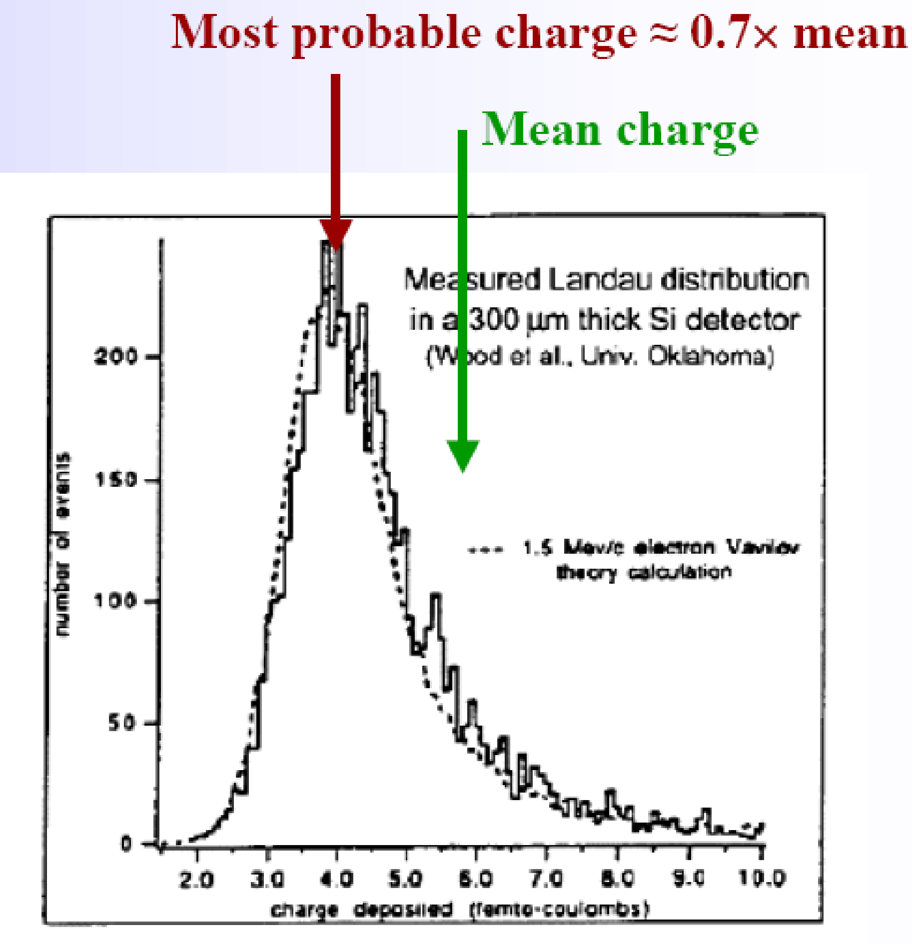
- **Mean energy loss**
  dE/dx (Si) = 3.88 MeV/cm
  ⇒ 116 keV for 300μm thickness

- **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)

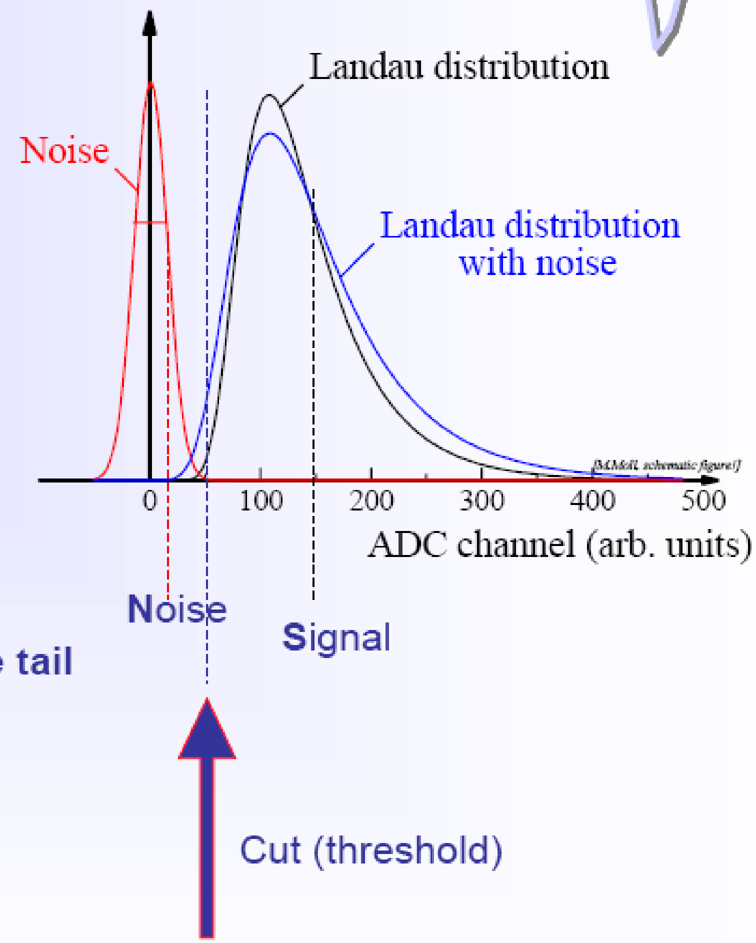
- **Most probable charge** (300 μm)

  ≈ 22500 e ≈ 3.6 fC



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 (bias resistor) $ENC \propto \sqrt{k_B T / R}$

- **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

extra slide not shown

Charge Collection time

- Drift velocity of charge carriers $v \approx \mu E$, 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)= 9ns , t_d(h)= 27ns**

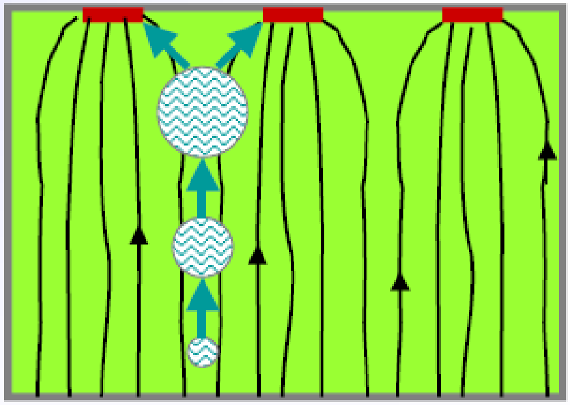
Diffusion

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

$$\sigma = \sqrt{2Dt_d} \quad \text{with diffusion constant} \quad D = \mu \frac{kT}{q}$$

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

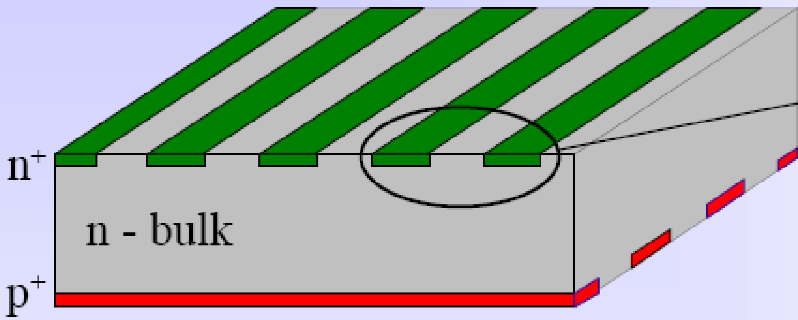
Typical charge radius: $\sigma \approx 6\mu m$, could exploit this to get better position resolution due to charge sharing between adjacent strips (using centroid finding), but need to keep drift times long (low field).

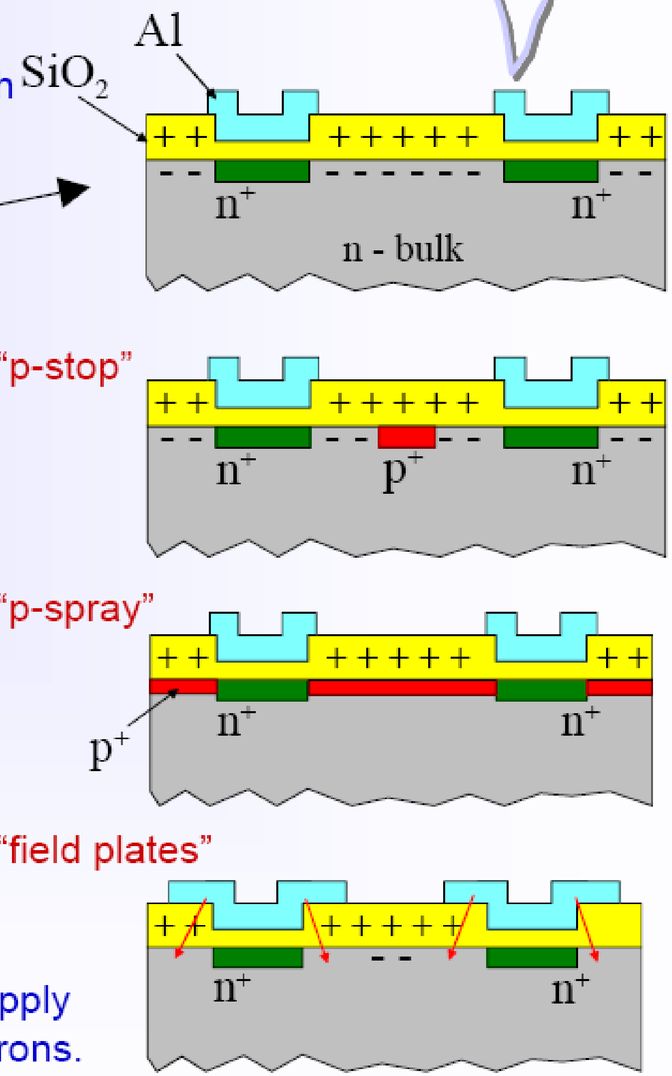


Double sided silicon detectors

extra slide not shown

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



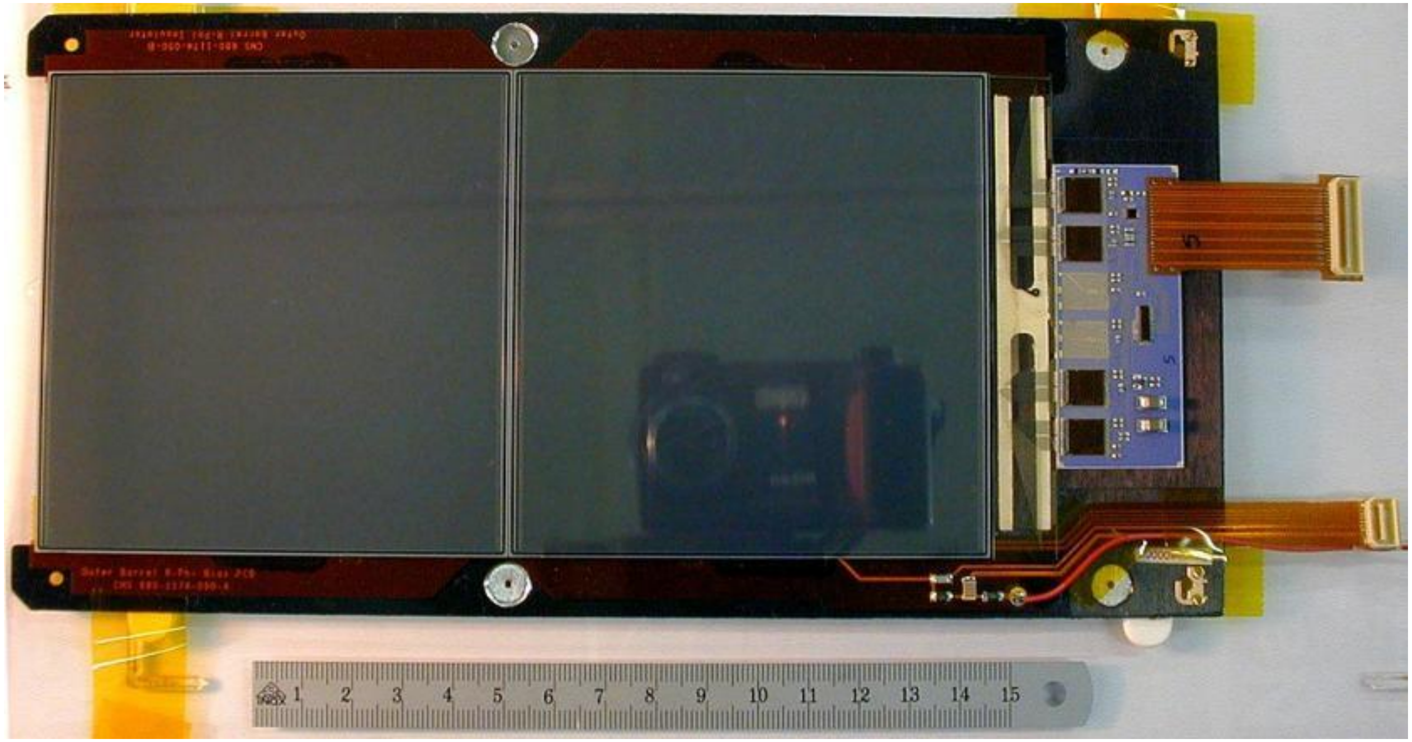


- **Problem: Electron accumulation layer**
  n^+-strips are not isolated because of an electron accumulation layer at the Si-SiO_2 interface. This effect is due to the presence of positive charge in SiO_2 layer which attracts electrons.

- **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.

Picture of an CMS Si-Tracker Module

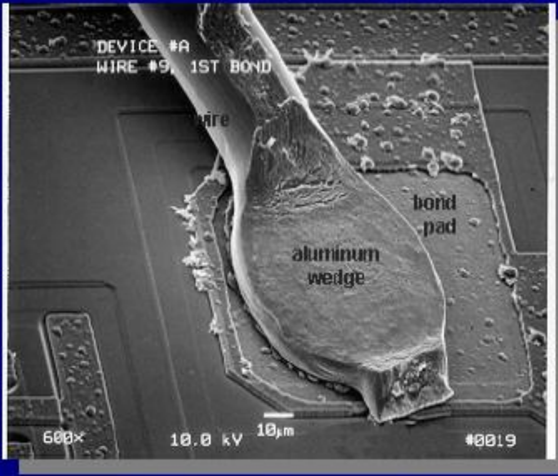
Outer Barrel Module



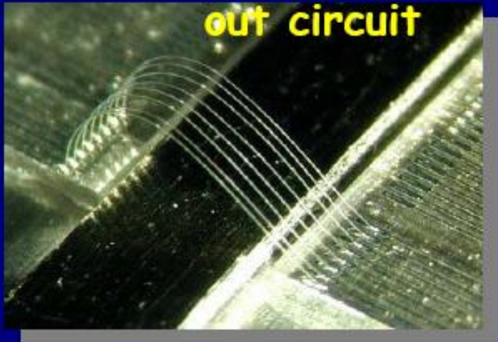
Wire Bonding

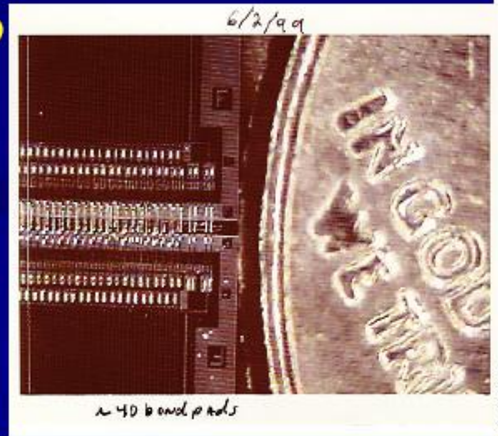
- Ultrasonic power is used to vibrate needle-like tool on top of Al wire. Friction welds wire to metallized substrate underneath.
- Pitch: 80μm pitch in a single row and 40μm in two staggered rows (typical FE chip pitch is ≈44μm).
- ≈25μm diameter aluminum wire and bond to aluminum pads (chips) or gold pads (hybrid substrates).
- Used in industry (PC processors) but not with such thin wire or small pitch.

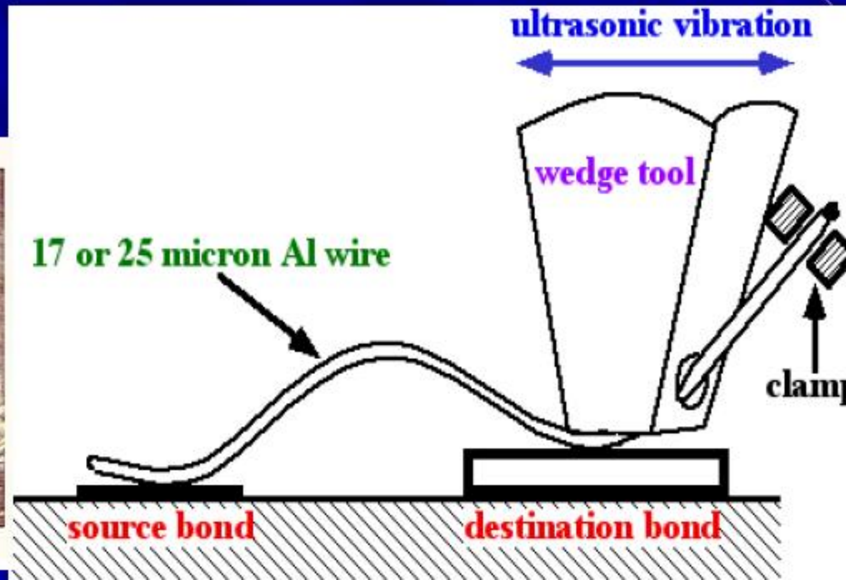
Electron micrograph of bond "foot"



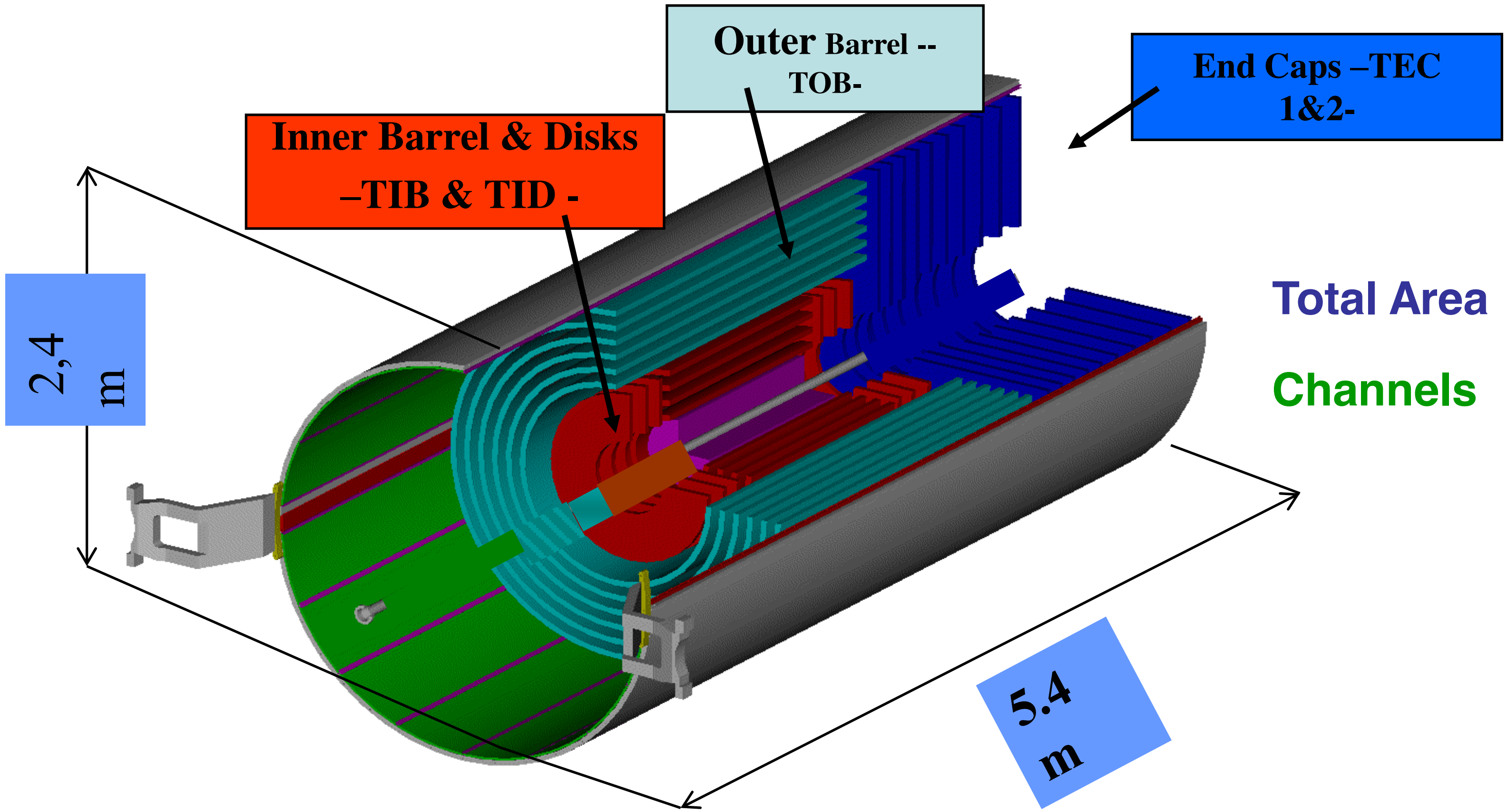
View through microscope of wire bonds connecting sensor to out circuit







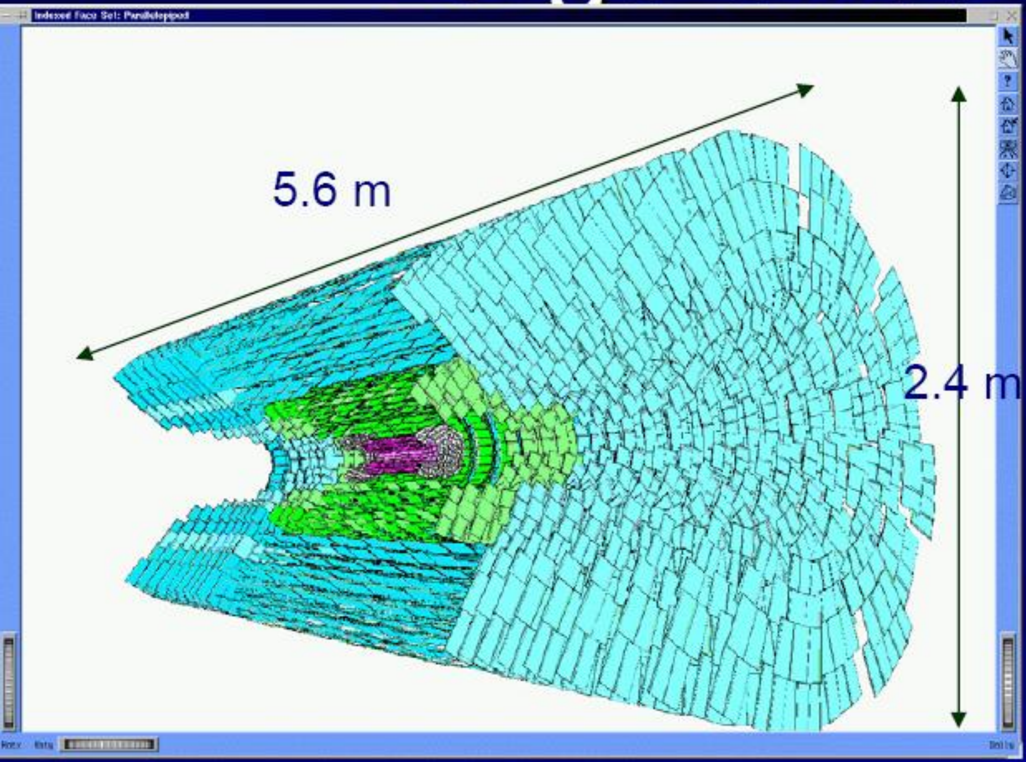
CMS Tracker Layout

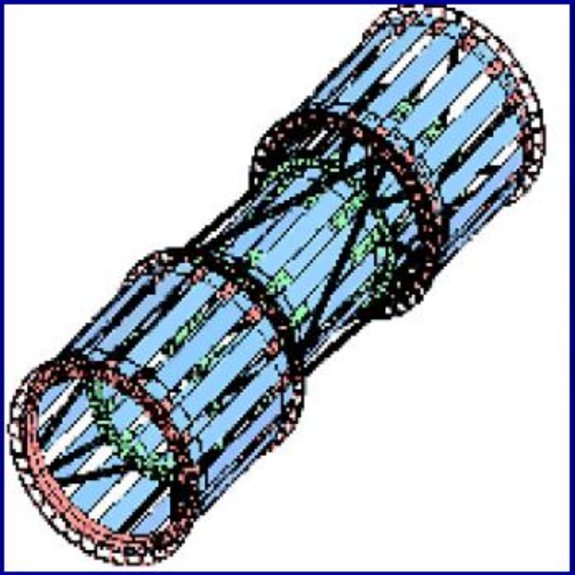


Total Area : 200m²

Channels : 9 300 000

Large Silicon Systems





CMS tracker (~2007)

12000 modules

~ 445 m^2 silicon area

~ 24,328 silicon wafers

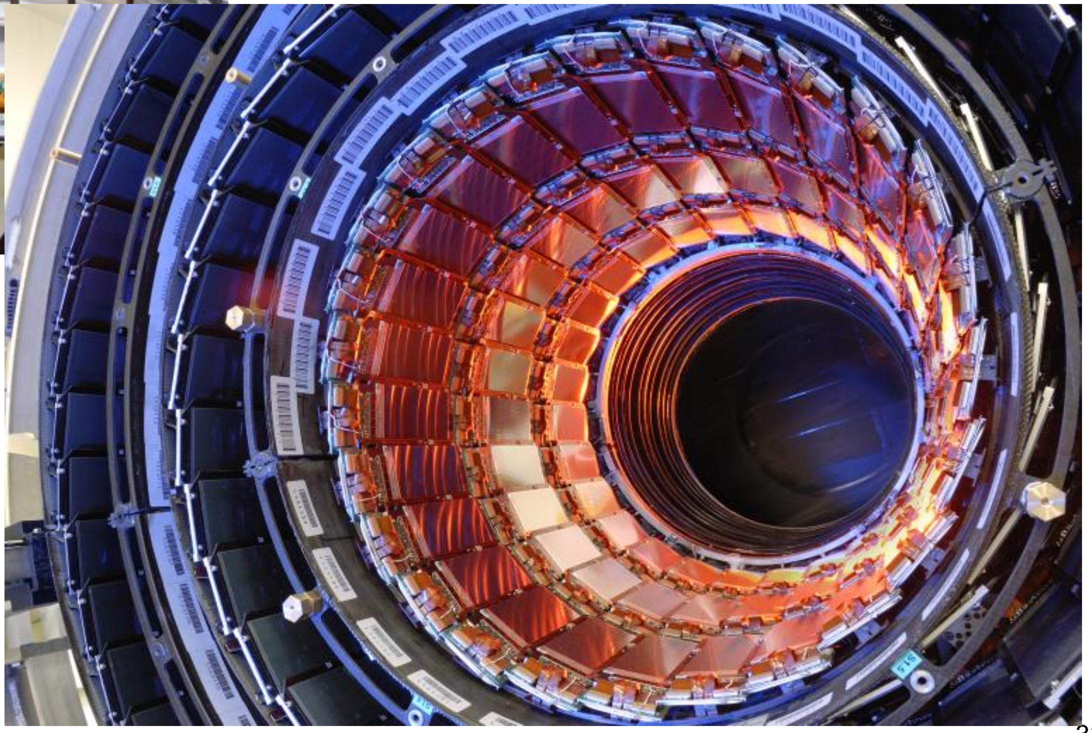
~ 60 M readout channels

CDF SVX IIa (2001-)

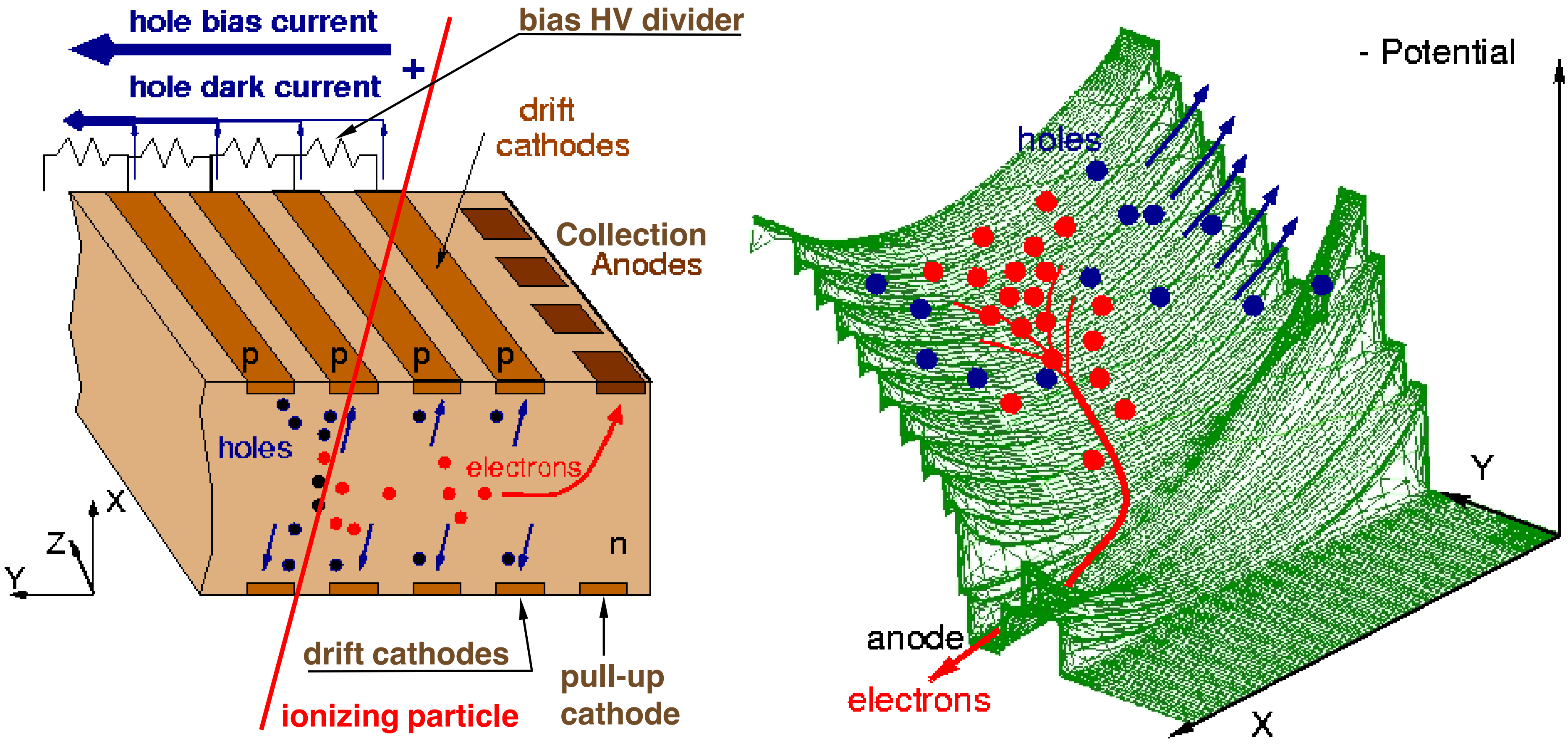
~ 11m^2 silicon area

~ 750 000 readout channels

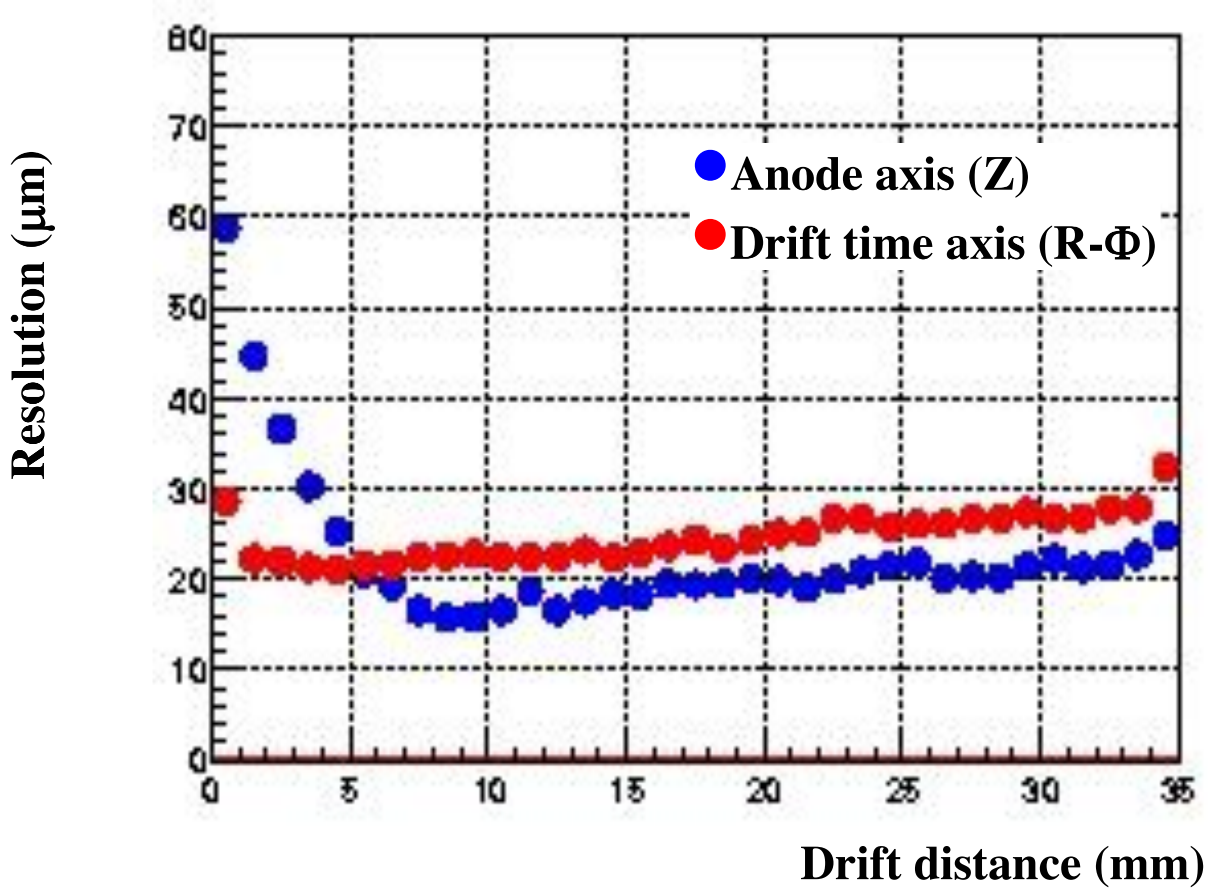
CMS Tracker



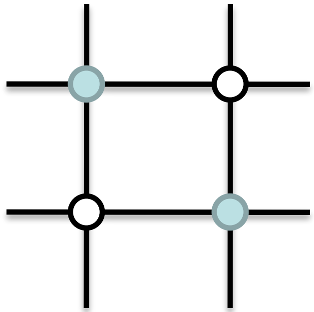
Silicon Drift Detector (like gas TPC !)



Silicon Drift Detector (like gas TPC !)



Pixel-Detectors



Problem:

2-dimensional readout of strip detectors results in 'Ghost Tracks' at high particle multiplicities i.e. many particles at the same time.

Solution:

Si detectors with 2 dimensional 'chessboard' readout. Typical size 50 x 200 μm.

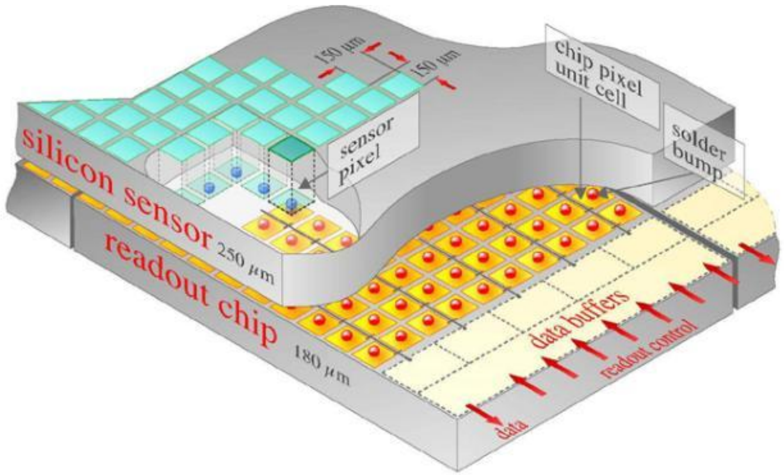
Problem:

Coupling of readout electronics to the detector.

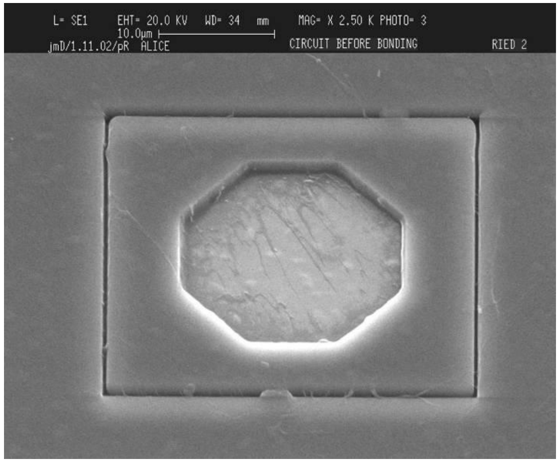
Solution:

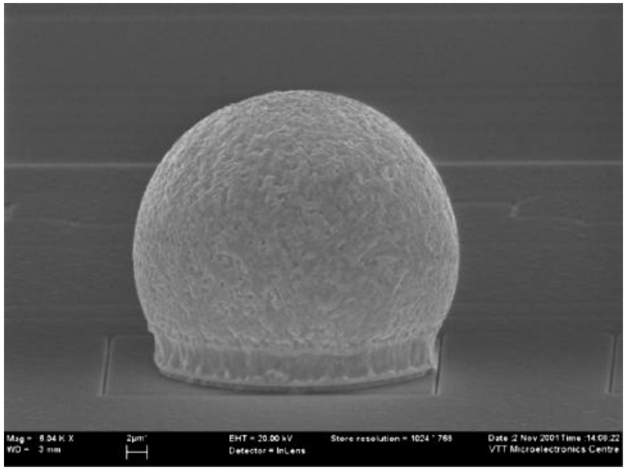
Bump bonding.

Bump Bonding of each Pixel Sensor to the Readout Electronics



ATLAS: 1.4x10^8 pixels





Radiation Effects 'Aging'

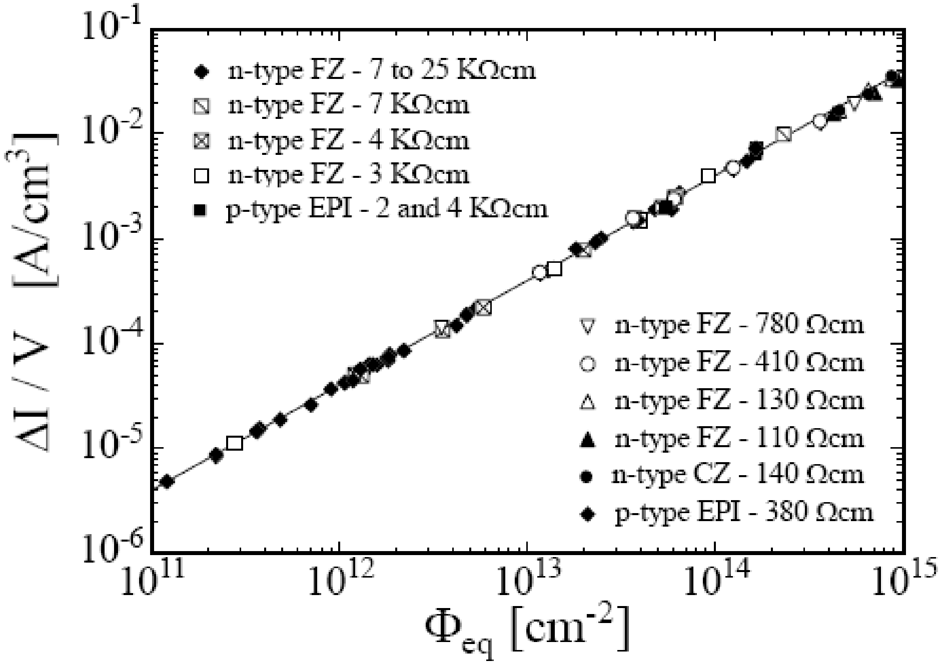
- Two general types of radiation damage
  - "Bulk" damage due to physical impact within the crystal
  - "Surface" damage in the oxide or Si/SiO_2 interface
- Cumulative effects
  - Increased leakage current (increased shot noise)
  - Silicon bulk type inversion (n-type to p-type)
  - Increased depletion 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

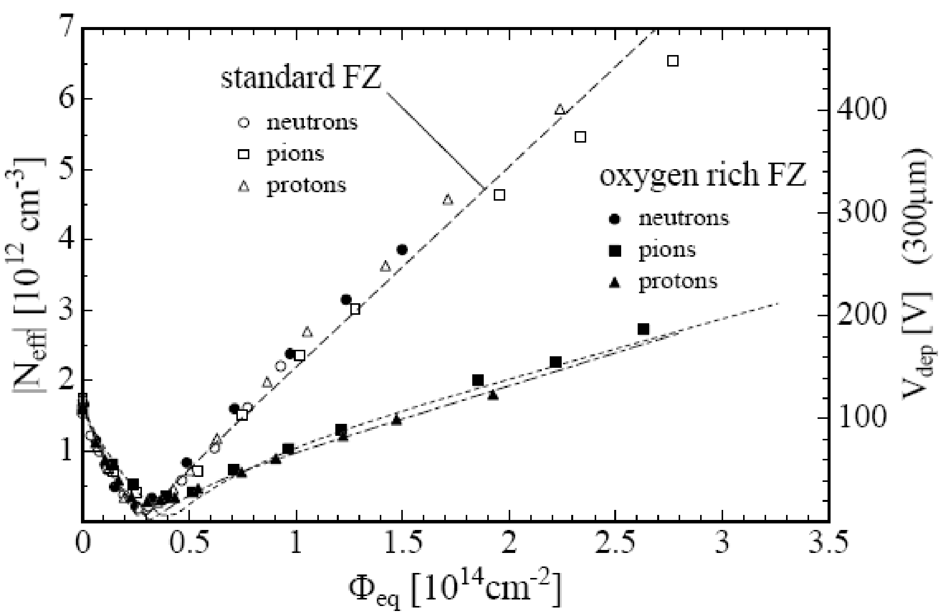
Radiation Effects 'Aging'

Increase in leakage current

Increase in depletion voltage

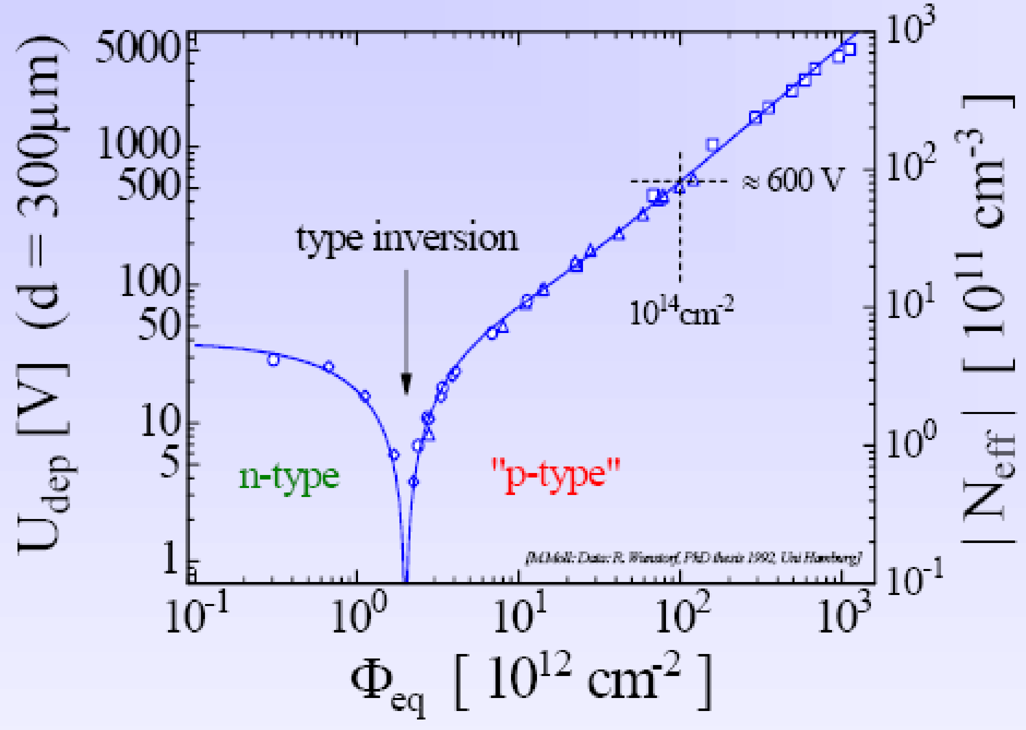
Decrease in charge collection efficiency due to underdepletion and charge trapping.





Radiation Effects ‘Aging’

Type inversion ! An n-tyle Si detector becomes a p-type Si detector !



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

Silicon Detectors: towards higher Radiation Resistance

Typical limits of Si Detectors are at 10^{14}-10^{15} Hadrons/cm^2

LHC

- We can identify 3 different regions to match radiation damage and occupancy in the current LHC detector

R	Φ	Technology
>50 cm	10^{13}	p-on-n strip 500 μm thick, high resistivity (≈5 KΩ·cm), pitch ~ 200 μm
20-50 cm	10^{14}	p-on-n strips 320 μm thick, low resistivity (≈2 KΩ·cm), pitch ~80 μm
<20 cm	10^{15}	n-on-n pixels 270 μm thick sensors low resistivity (≈2 KΩ·cm) oxygenated

SLHC

- Radiation fluence increases by about a factor of 10 from one region to the other and by a factor of 10 between LHC and SLHC.

R	Φ	CCE	Technology
>50 cm	10^{14}	20ke	Present rad-hard technology (or n-on-p)
20-50 cm	10^{15}	10ke	Present n+-n LHC pixel (or n-on-p)
<20 cm	10^{16}	>5Ke	RD needed

R&D Strategy:

Defect Engineering
- Oxygen enriched Si

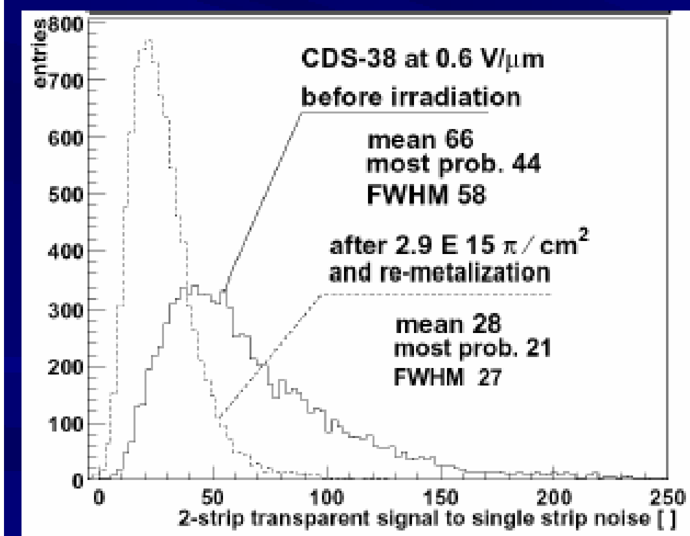
New Materials
- Diamonds
- Czochralski Si
- …

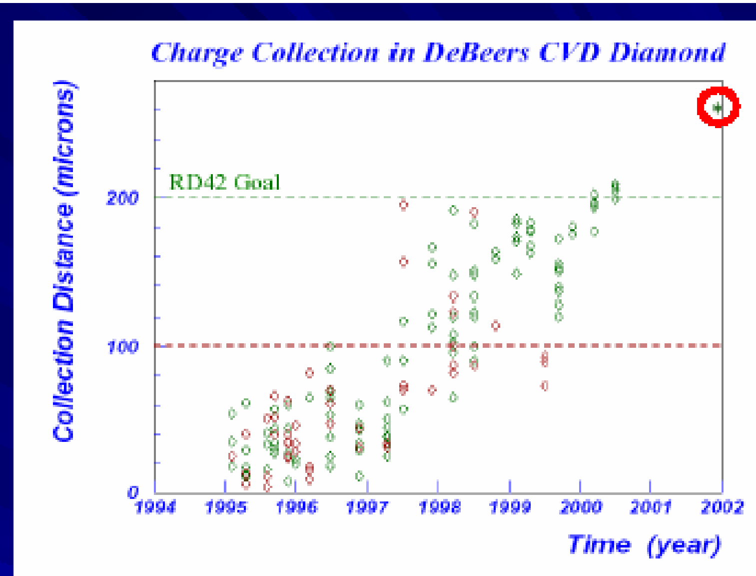
New Geometries

Low Temperature Operation

New Materials: Polycrystalline Diamond

- RD42 in collaboration with Element Six have achieved impressive improvements in collection distances
- pCVD structures show good radiation hardness





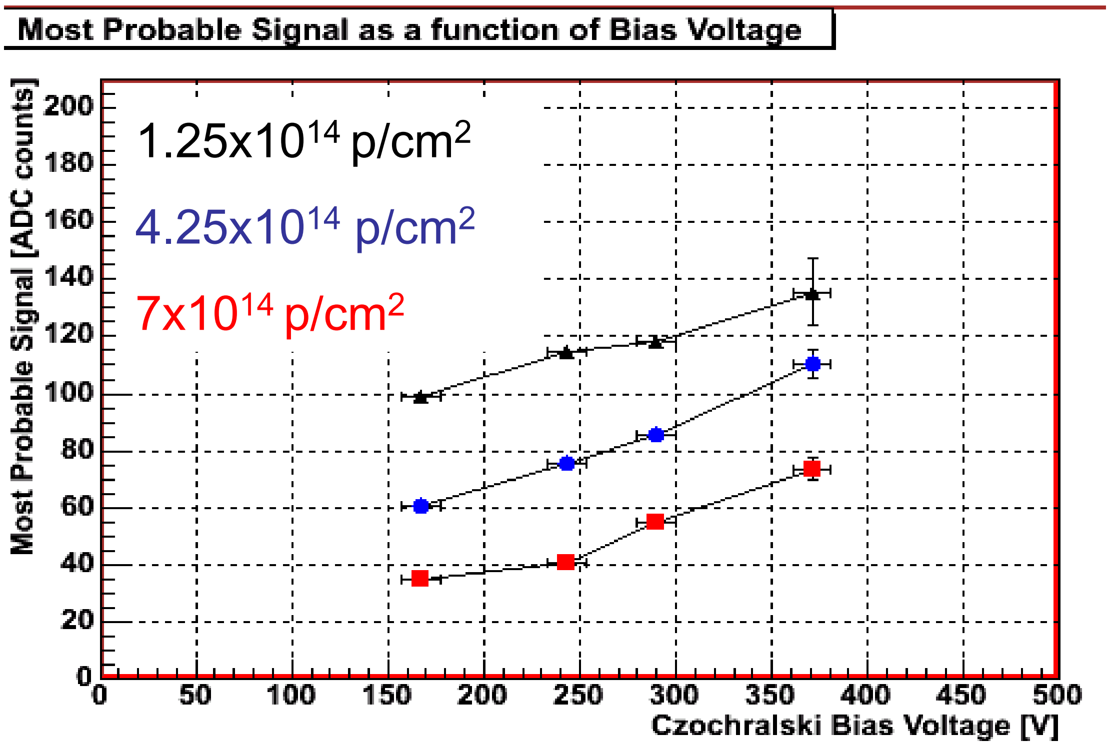
52% loss of S/N at 2.9 10^{15} π/cm^2

23% improvement in resolution

Application:

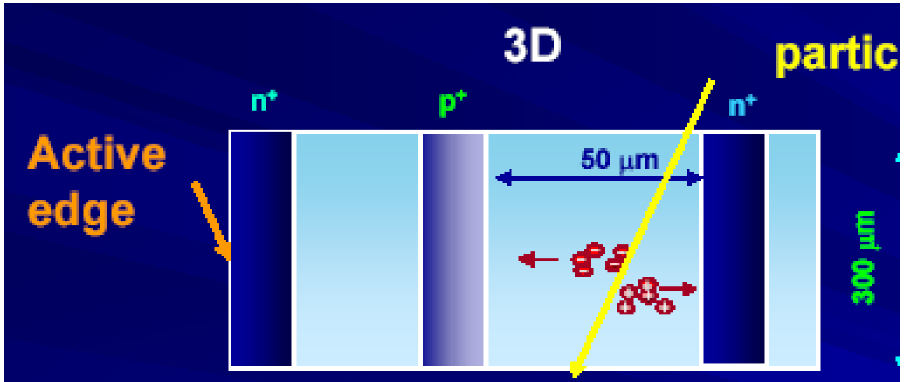
- Used in successfully for radiation monitoring for BaBar (see Kagan's talk at Vertex 2003)

New Material: Czochralski Silicon

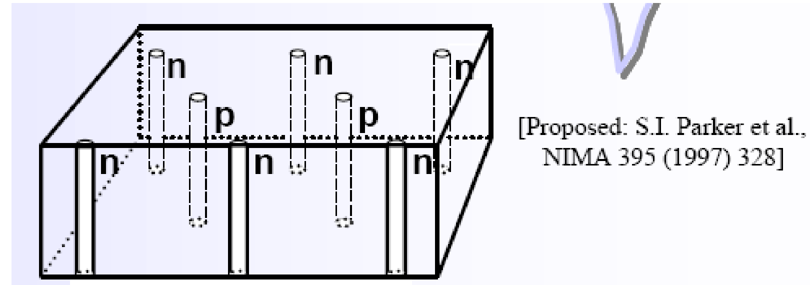


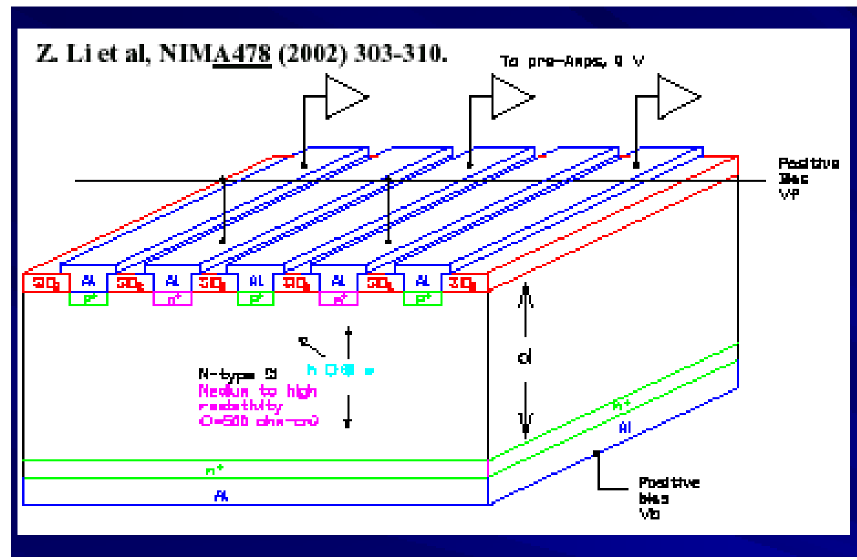
Due to 1000 times higher Oxygenation levels compared to standard Si: expect improved Radiation Resistance

New Geometries: ‘3D’ Si Detectors



	3D	Planar
Q collection path	50µm	300 µm
$V_{depletion}$	<10V	70 V
Edge sensitivity	10µm	500 µm
Q Collection time	1-2 ns	10-20 ns





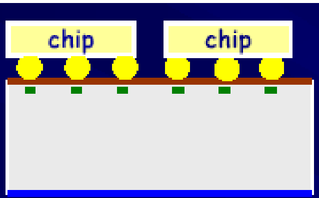
Good Performance after 10^{15} p/cm^2

High Resolution Low Mass Silicon Trackers, Monolithic Detectors

Linear Collider Physics requirement:

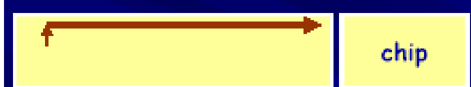
$\delta\,(IP) < 5\ \mu m \oplus 10\ \mu m/(p \sin^{3/2}\theta)$

(best SLD $8\ \mu m \oplus 33\ \mu m/(p \sin^{3/2}\theta)$)



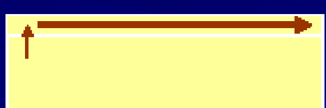
Hybrid Active Pixel: Chip bump bonded to sensor

RD: make it thinner (LHC sensors 2% X_0/layer), improve space point resolution with interleaved pixels



CCD: charge collected in thin layer and transferred through silicon

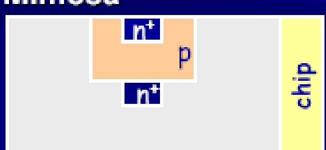
RD: readout speed, radiation hardness, material support



CMOS sensors (MAPS, FAPS): standard CMOS wafer integrates all functions.

RD: fast readout, non-standard technologies

Poster by Deptuch on Mimosa



DEPFET, CMOS on SOI (talk by Kucewiz) : Fully depleted sensor with integrated preamp

RD:pixel size, power, thinning, speed

Large variety of monolithic pixel Detectors explored, mostly adapted to low collision rates of LC.

Summary on Solid State Detectors

Solid state detectors provide very high precision tracking in particle physics experiments (down to 5um) for vertex measurement but also for momentum spectroscopy over large areas (CMS).

Technology is improving rapidly due to rapis Silicon development for electronics industry.

Typical number where detectors start to strongly degrade are 10^{14}-10^{15} hadron/cm^2.

Diamond, engineered Silicon and novel geometries provide higher radiation resistance.

Clearly, monolithic solid state detectors are the ultimate goal. Current developments along these lines are useful for low rate applications. ar

Thanks you your attention !

See you on Monday at 11:00 for calorimetry

or some time in the future around a particle detector.