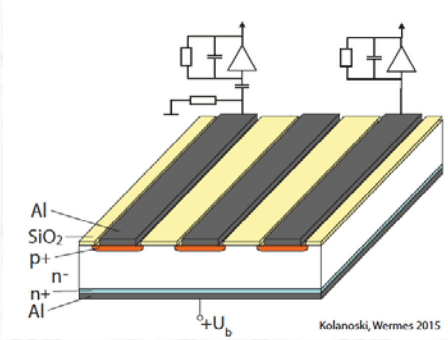
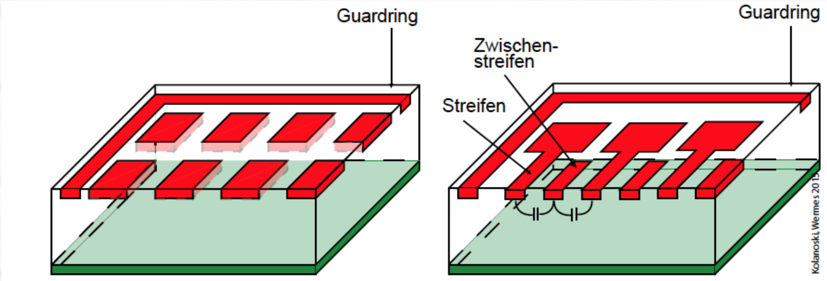
6. Silicon Strip and Pixel Detectors



6.1 Introduction

6.2 Basic properties of silicon

6.3 Silicon strip detectors



6.4 Silicon pixel detectors

6.5 Radiation damage of silicon detectors

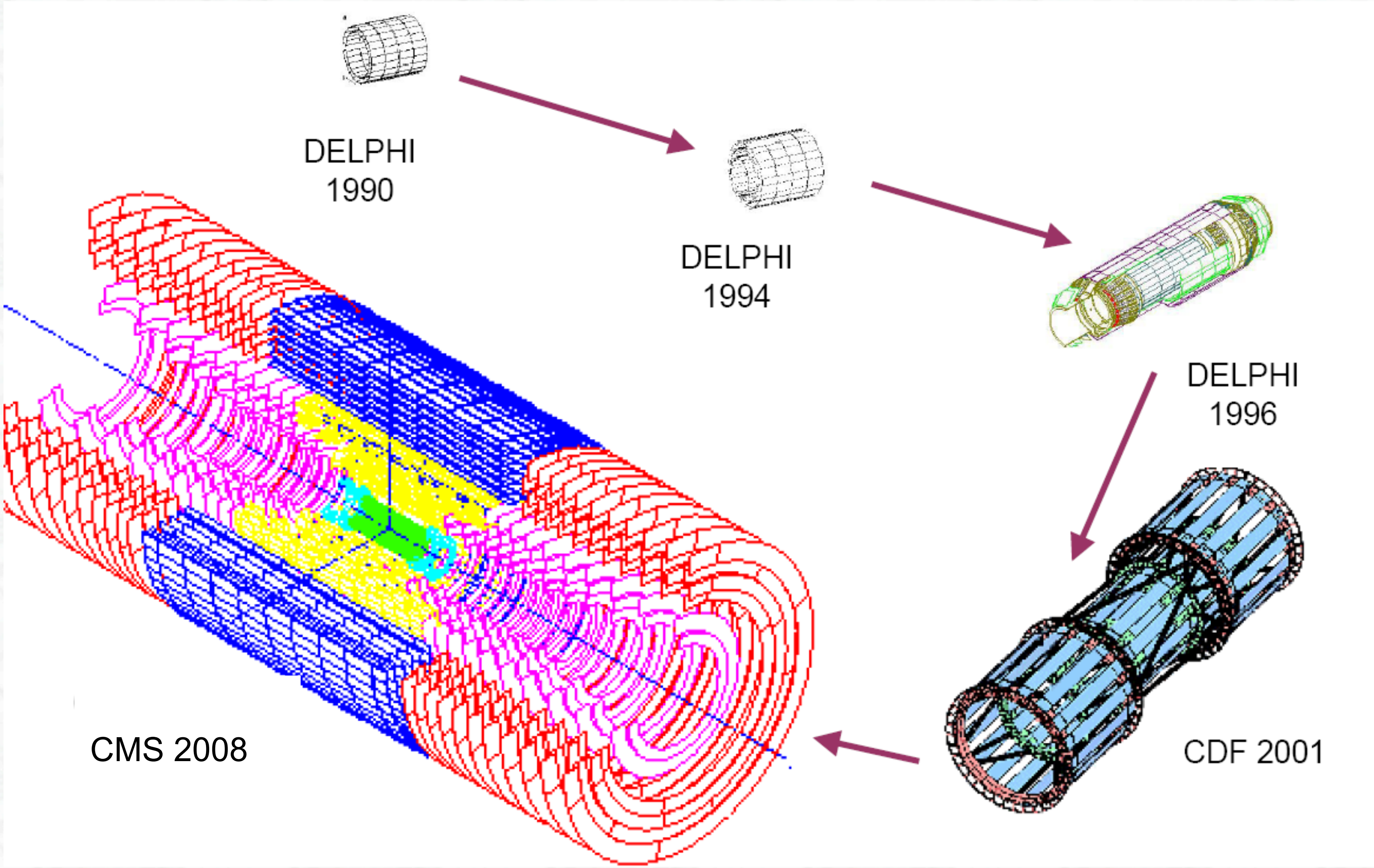
6.6 Vertexing and impact parameter measurements

6.7 The ATLAS and CMS Central Tracking Detectors

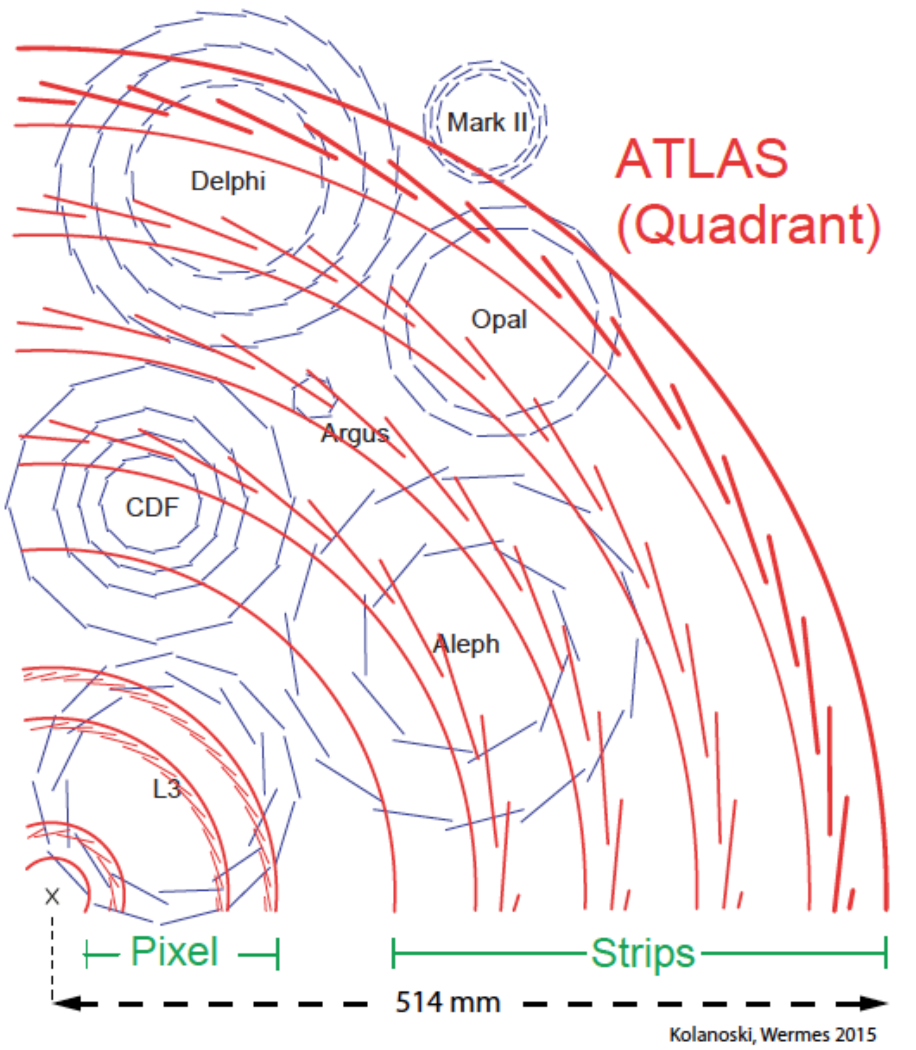
6.1 Introduction, the use of silicon detectors for tracking

- Silicon detectors can be viewed as solid-state ionisation chambers
- The application as highly segmented tracking detectors emerged in the 1980s, however, expensive and difficult at first
  (before: applications in energy measurement, germanium and silicon detectors)
- Increased commercial use of Si-photolithography and availability of VLSI electronics lead to a boom for Si-detectors in the 1990s – and it still goes on, although we need R&D on Si radiation hardness…
- Nearly all high energy physics experiments use Silicon Detectors as innermost high-precision tracking devices
- High energy physics experiments are now exporting Si-technology back to the commercial world (Medical Imaging)

Evolution in Si-Detector Area

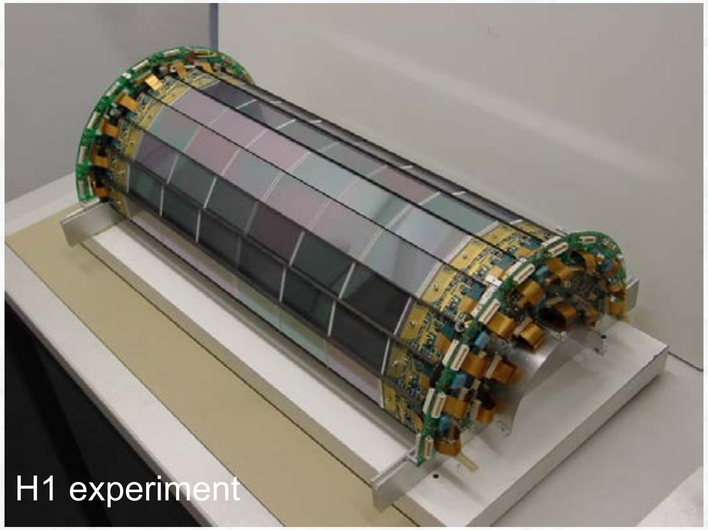


Evolution in Si-Detector Area

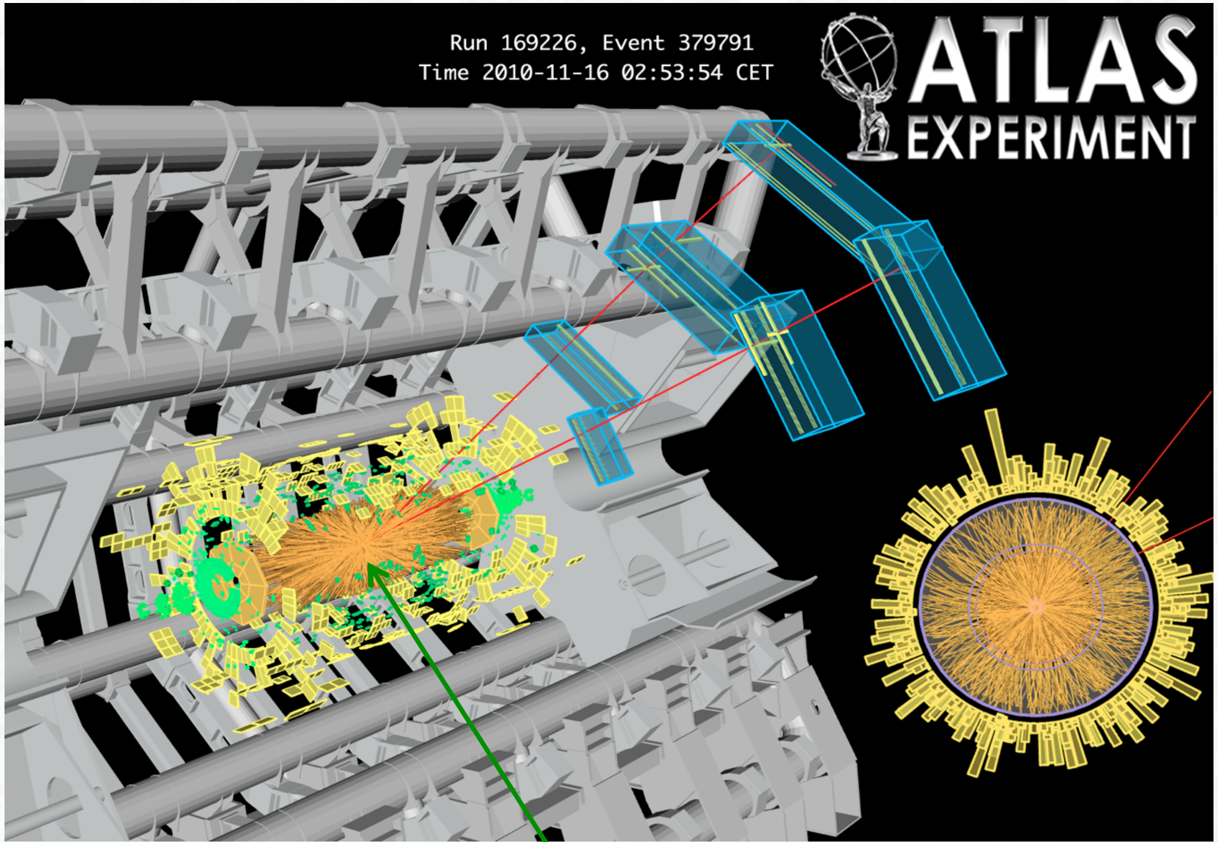


All e^+e^- and pp collider experiments have / had high precision semiconductor detectors close to the interaction region

CMS: full silicon tracking detector



Tracking in pp Collisions at the LHC



1200 tracks every 25 ns

or 10^{11} per second

→ high track density, but in addition high radiation dose for detectors

10^{15} (1 MeV) n_{eq} /cm^2 / 10 y

or 600 kGy through the ionization of mips in 250 μm silicon detectors

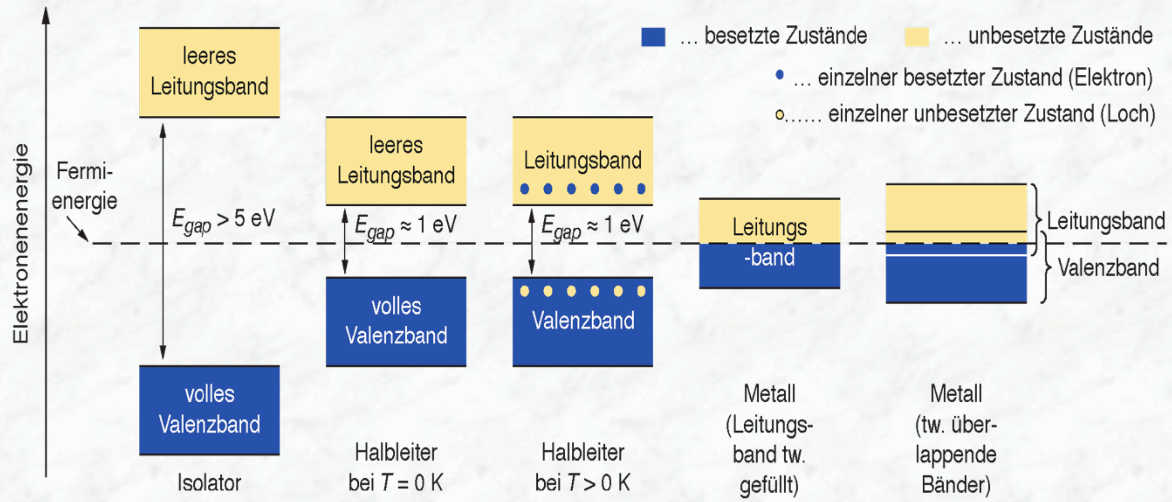
position of tracking detectors
(silicon pixel, silicon strips and straw tubes)

LHC: 10^6 times the track rate from LEP
HL-LHC (High Luminosity LHC, after 2026): another factor of 10 compared to LHC

6.2 Basic properties of silicon

- Silicon is a semi-conductor element in the 4th group of the periodic system

  Band gap of 1.1 eV

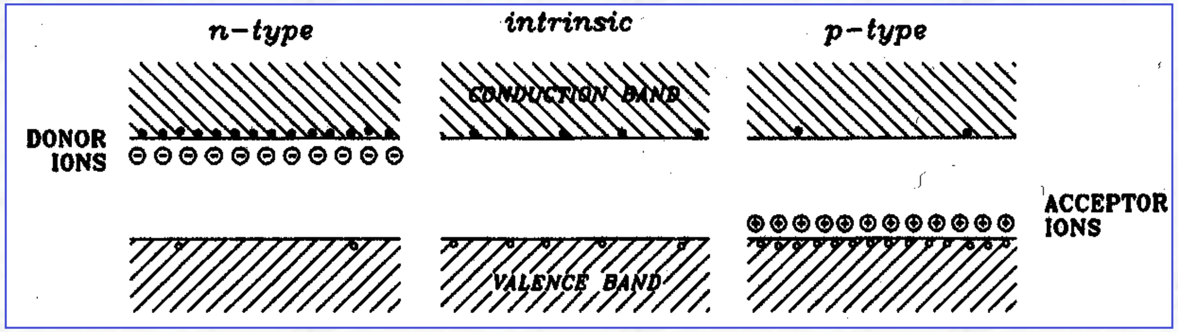


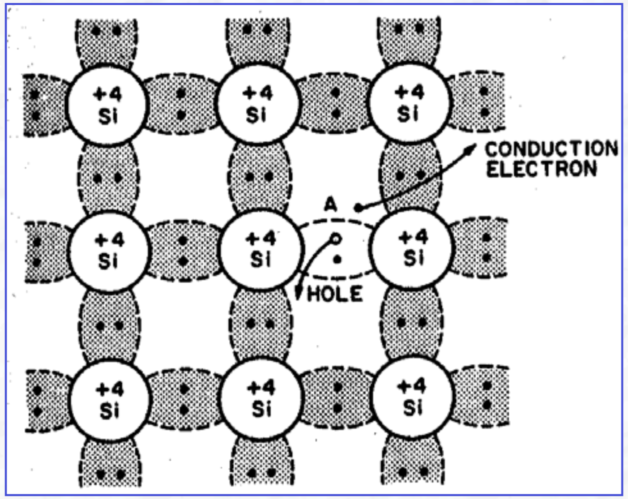
- The intrinsic conductivity is very low:

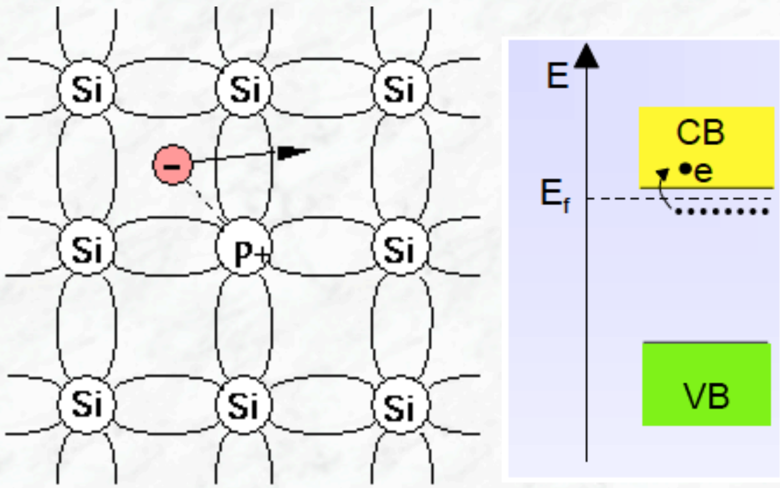
  $$\sigma_i = e \cdot N_i \, (\mu_e + \mu_h)$$

- Carrier density at 300 K:
  - $1.5 \cdot 10^{10}$ cm^{-3} compared to $5 \cdot 10^{22}$ Si atoms per cm^{-3}
  - often dominated by impurities

- “Doping“: Small admixtures of type III or type V elements increase conductivity
  - Donors like Phosphorous give extra electron → n-type Si
  - Acceptors (e.g. Boron) supply extra hole → p-type Si
  - Contact between p- and n-Si forms p-n-junction
  - Doping dominates conductivity as $N_i \ll N_D$
  - for n-type Si: $\sigma_D = e \cdot N_D \cdot \mu_e$

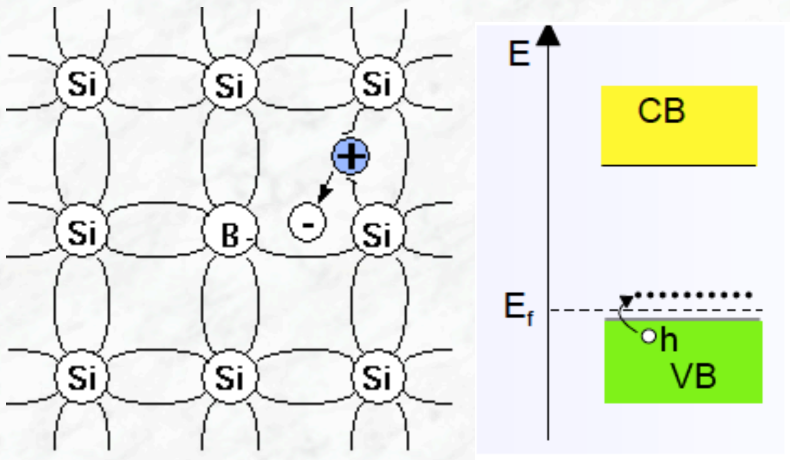






n-type silicon

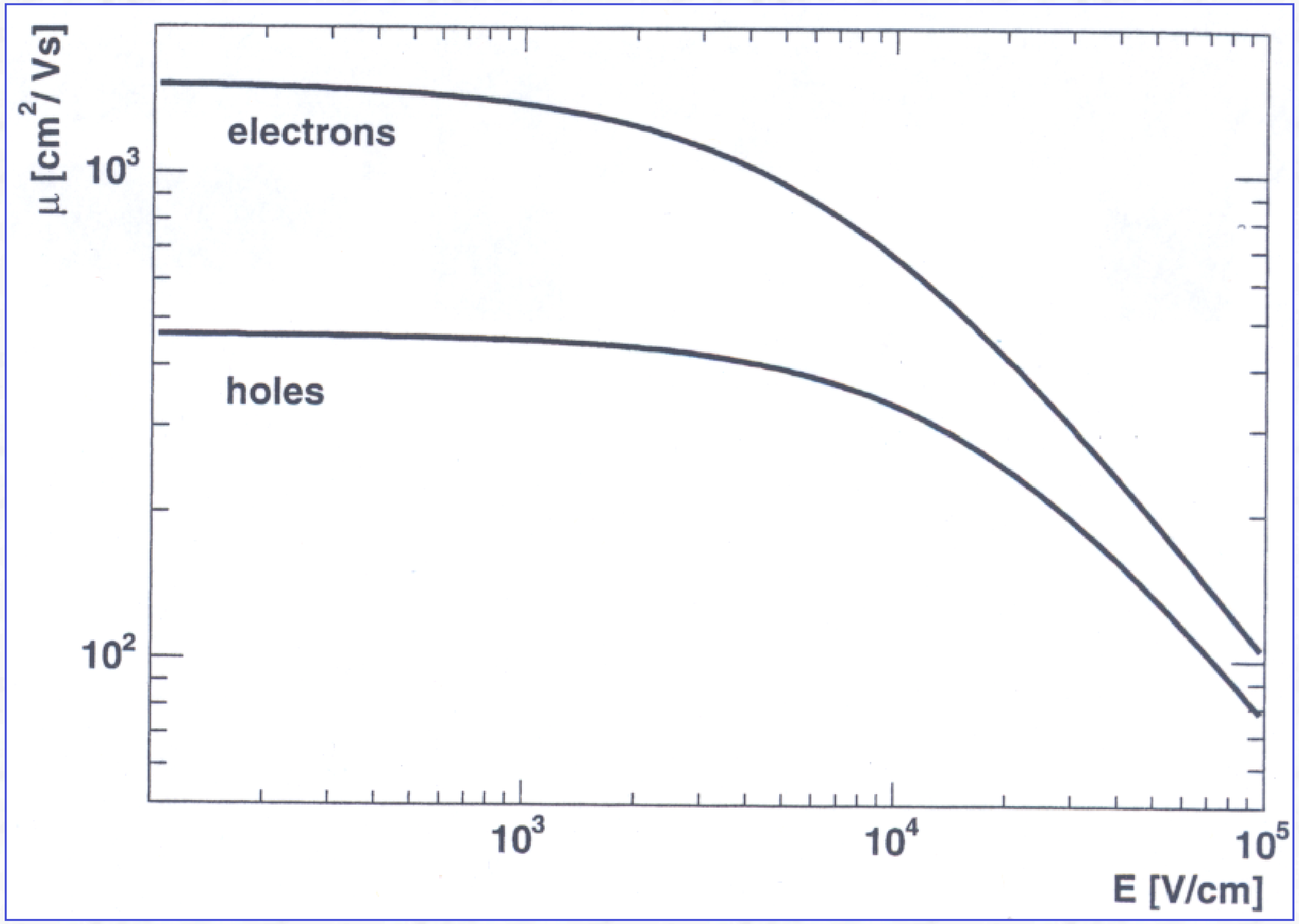
- Si: 4 valence electrons
- Add elements from Vth group: 5 valence electrons
- Donors give away one electron
- n-type: electron concentration n larger than hole concentration p
  - $n \cong N_D$
    (N_D = donor concentration)



p-type silicon

- Si: 4 valence electrons
- Add elements from III-rd group: 3 valence electrons
- Acceptors miss one electron
- p-type: holes are majority carriers
  - $p \cong N_A$
    (N_A = acceptor concentration)

Mobility of electrons and holes as a function of the electric field



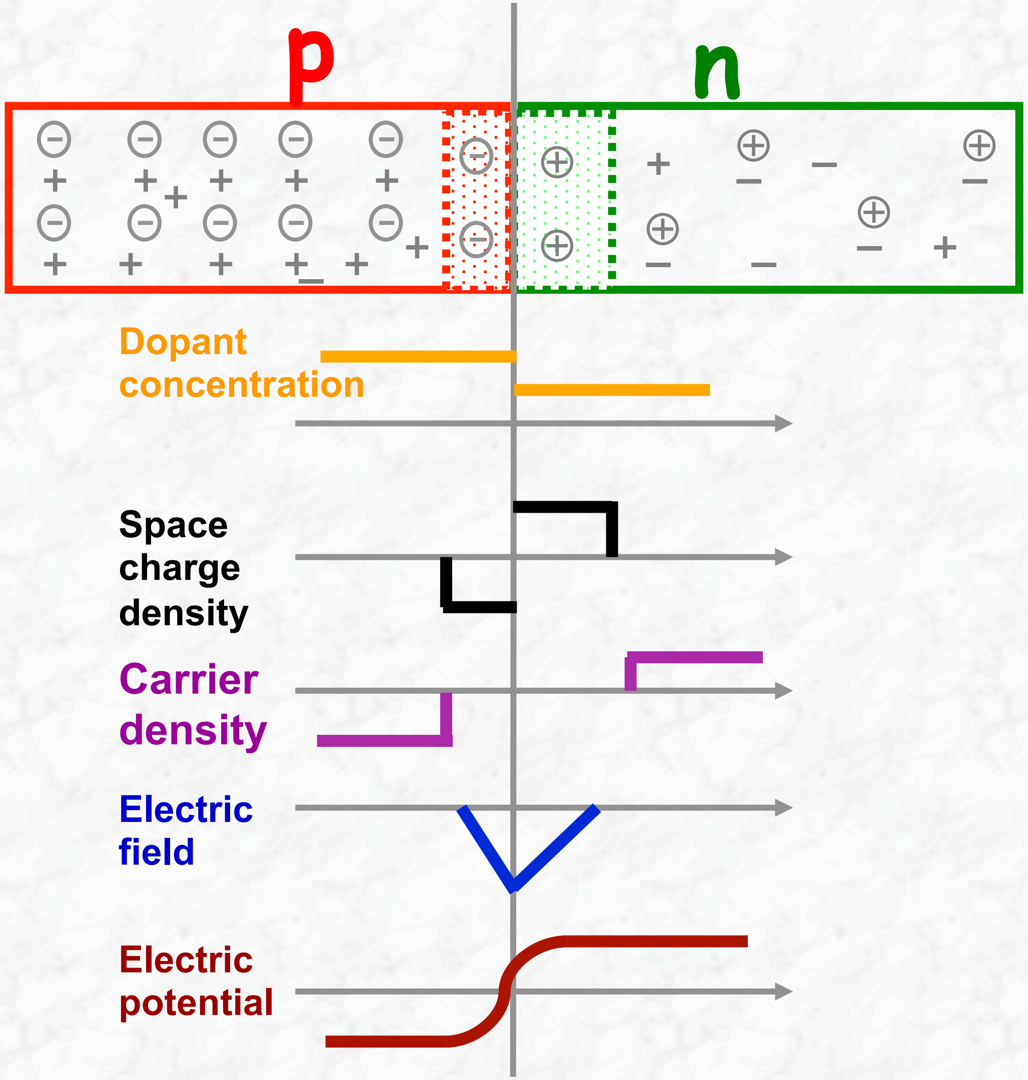
Semiconductor materials suited for particle detectors

Semiconductor	band gap (eV)	intrinsic carrier conc. (cm^{-3})	average Z	w_{eh} (eV)	mobility cm^2/Vs e	h	carrier life time
Si	1.12	$1.45 \cdot 10^{10}$	14	3.61	1450	505	100μs
Ge	0.66	$2.4 \cdot 10^{13}$	32	2.96	3900	1800	
GaAs	1.42	$1.8 \cdot 10^{6}$	32	4.35	8800	320	1-10 ns
CdTe	1.44	10^7	50	4.43	1050	100	0.1-2 μs
CdZnTe	~1.6		49.1	4.6	~1000	50-80	~ μs
CdS	2.42		48 + 16	6.3	340	50	
HgI_2	2.13		62	4.2	100	4	~ μs
InAs	0.36		49 + 33		33000	460	
InP	1.35		49 + 15		4600	150	
ZnS	3.68		30 + 16	8.23	165	5	
PbS	0.41		82 + 16		6000	4000	
Diamond	5.48	$<10^3$	6	13.1	1800	1400	~1 ns

Materials favoured with: low Z (minimize material, in terms of radiation length)
fast, i.e. high mobility or charge carriers
high charge carrier lifetime
affordable prize / availability

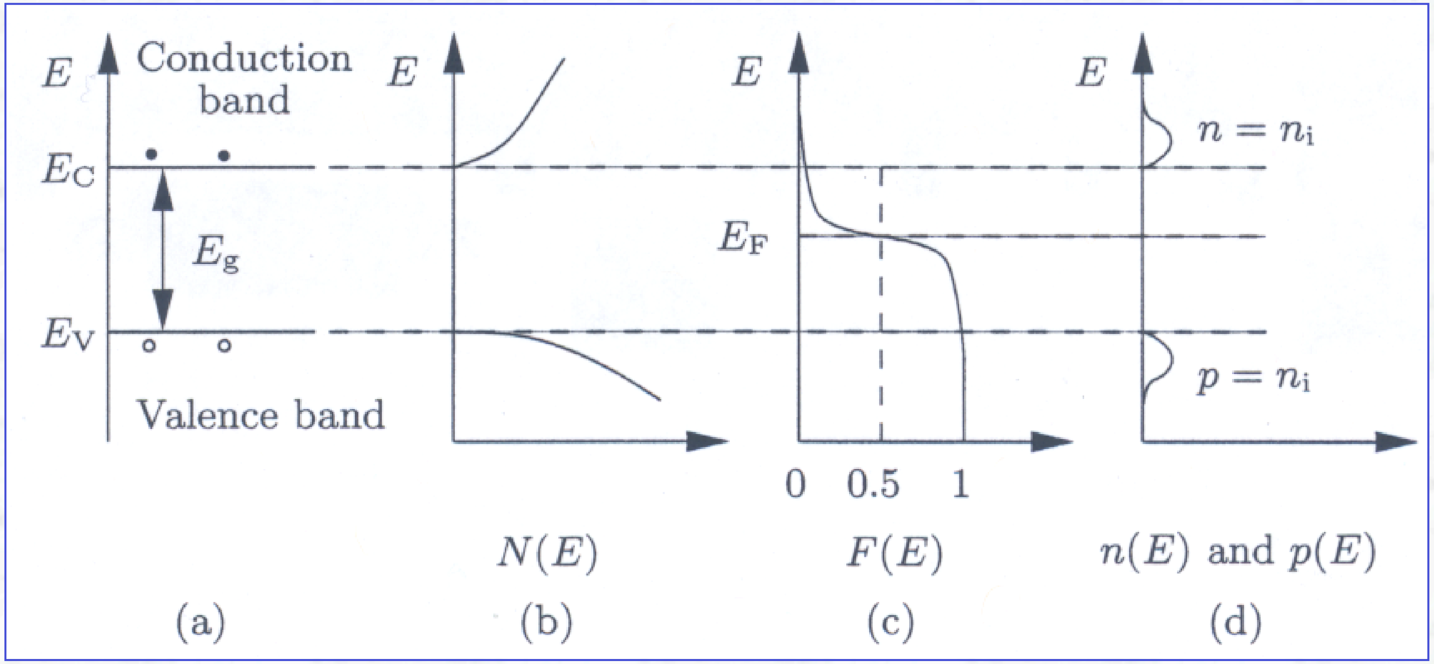
Medical applications (γ ray absorption) → high Z-materials favoured

p-n-Junction



- Diffusion of e^- from n-side and h^+ from p-side
- Recombination on other side, free charges disappear around junction ("depletion")
- Neutral p- or n-Si becomes charged → E-Field
- External field can increase or decrease depletion zone
- Depletion is what we want for detectors!

Charge carrier density:

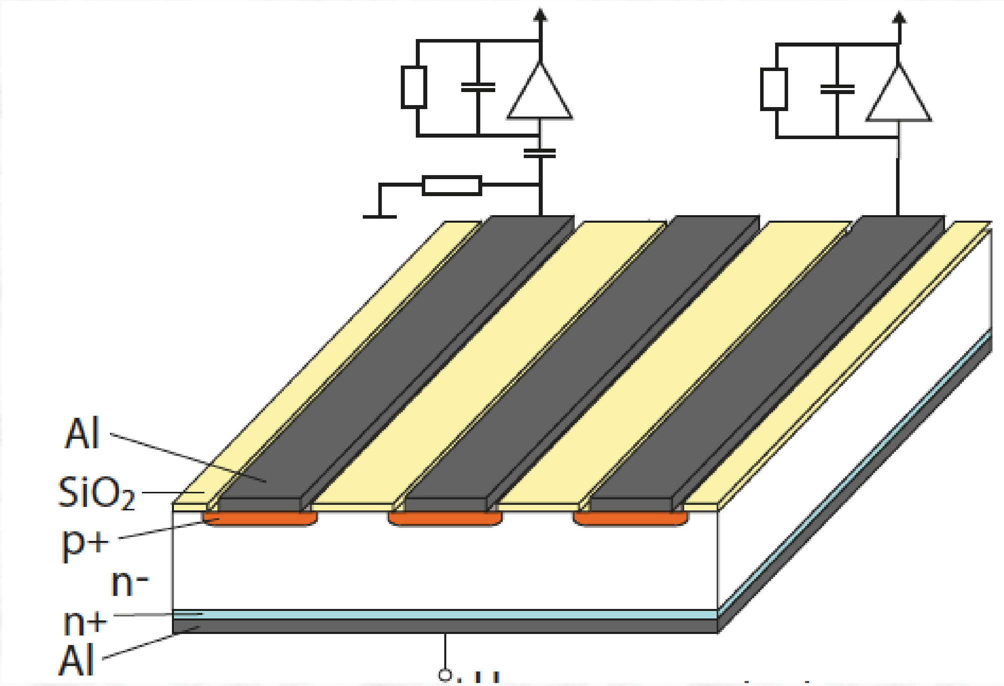


Quelle: L.Rossi, P.Fischer, T.Rohe, N.Wermes, *Pixel Detectors*, Springer 2006, S. 27

$$n_{free,e-} = \int_{E_C=0}^{\infty} N(E) \cdot F(E) dE$$

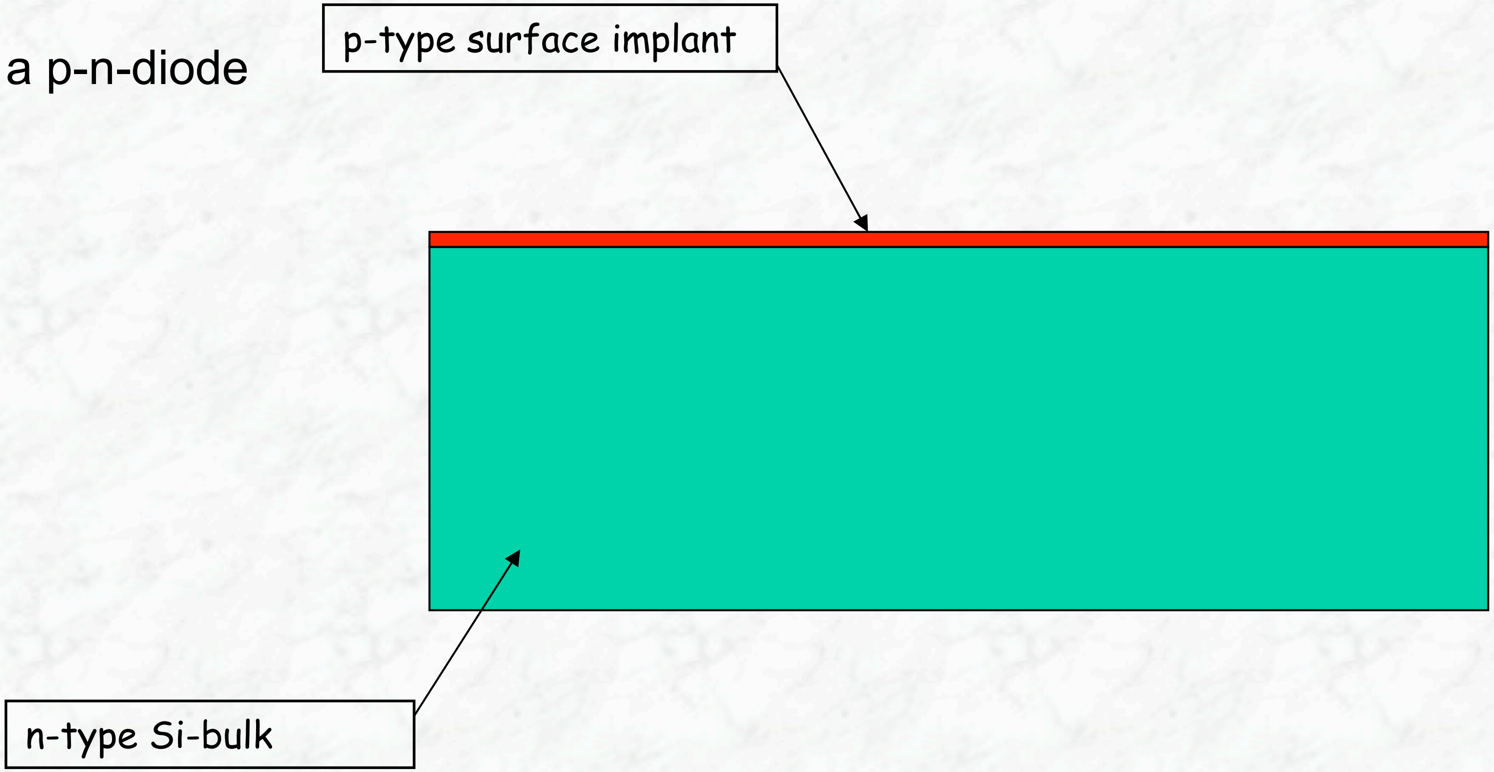
$$np = n_i^2 = N_C N_V \cdot \exp(-E_g / kT)$$

6.3 Silicon Strip detectors



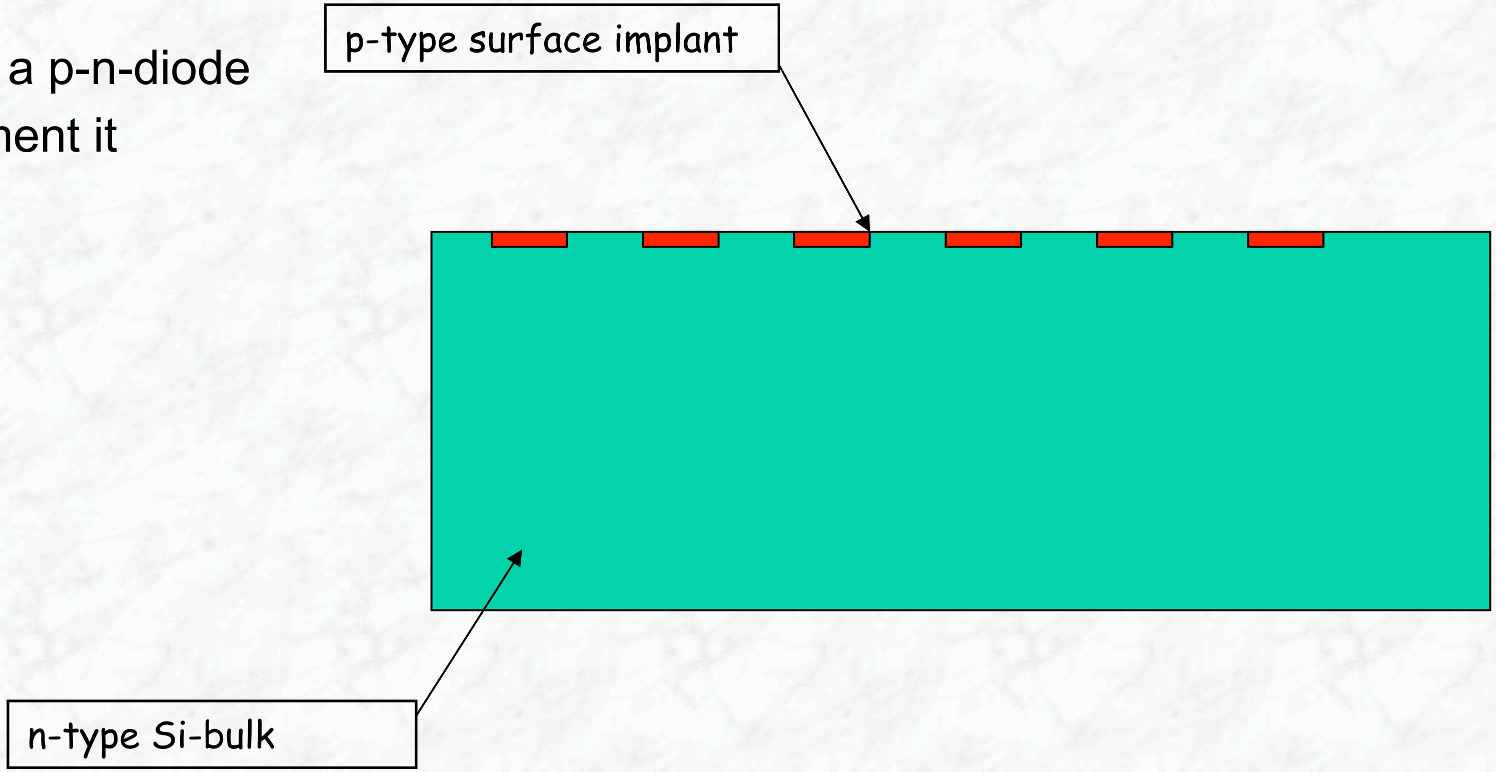
A Basic Silicon Detector

- Take a p-n-diode



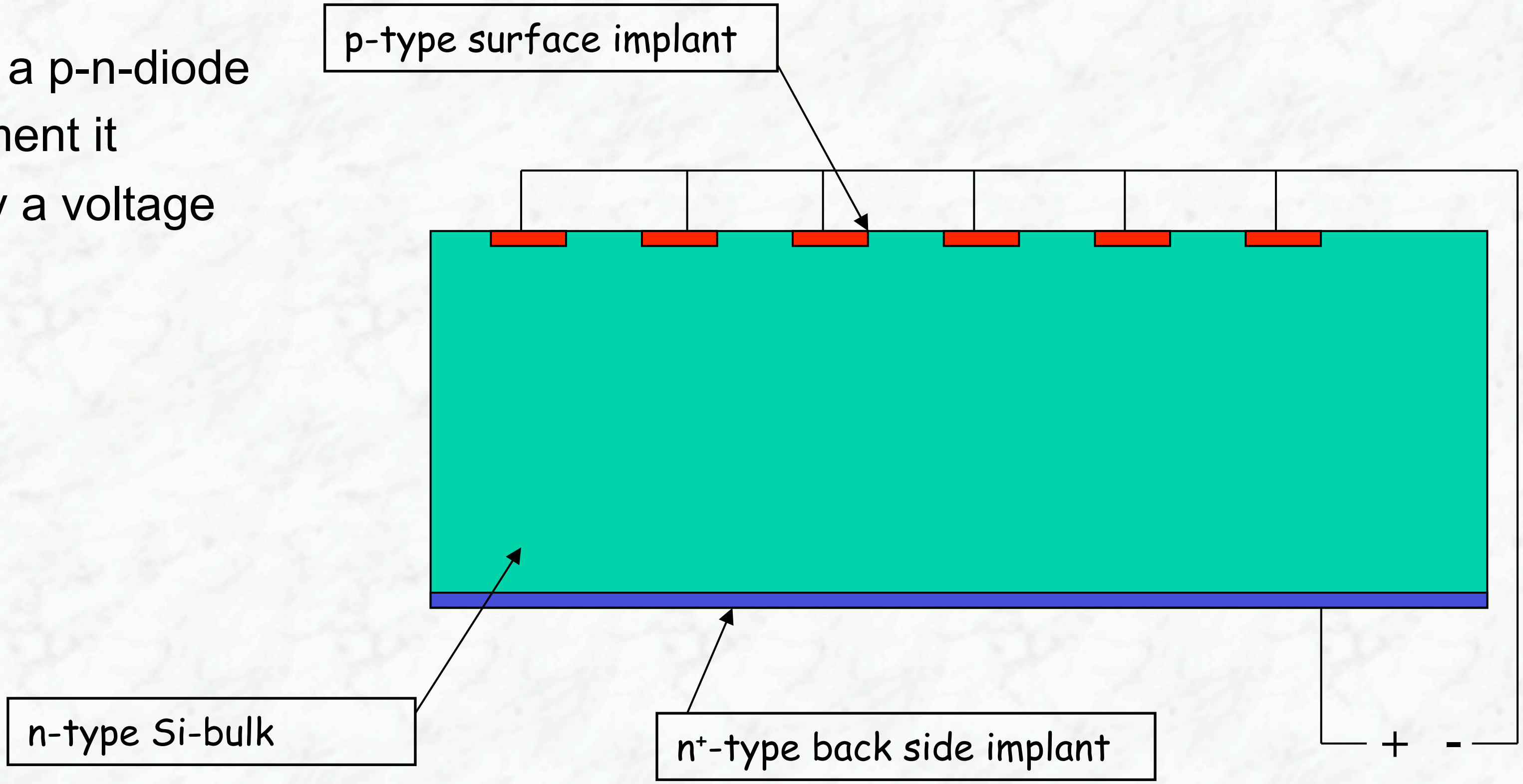
A Basic Silicon Detector

- Take a p-n-diode
- Segment it



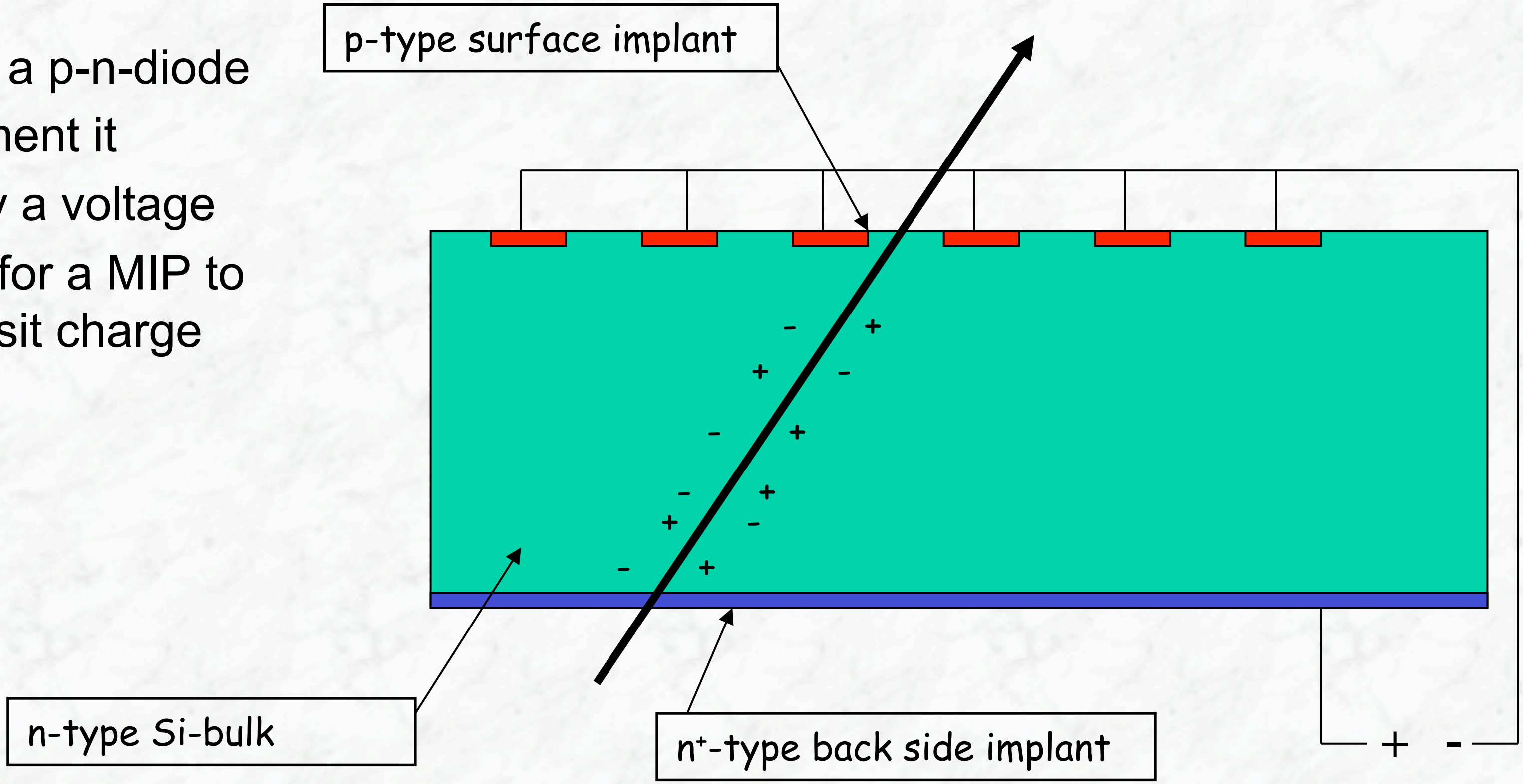
A Basic Silicon Detector

- Take a p-n-diode
- Segment it
- Apply a voltage



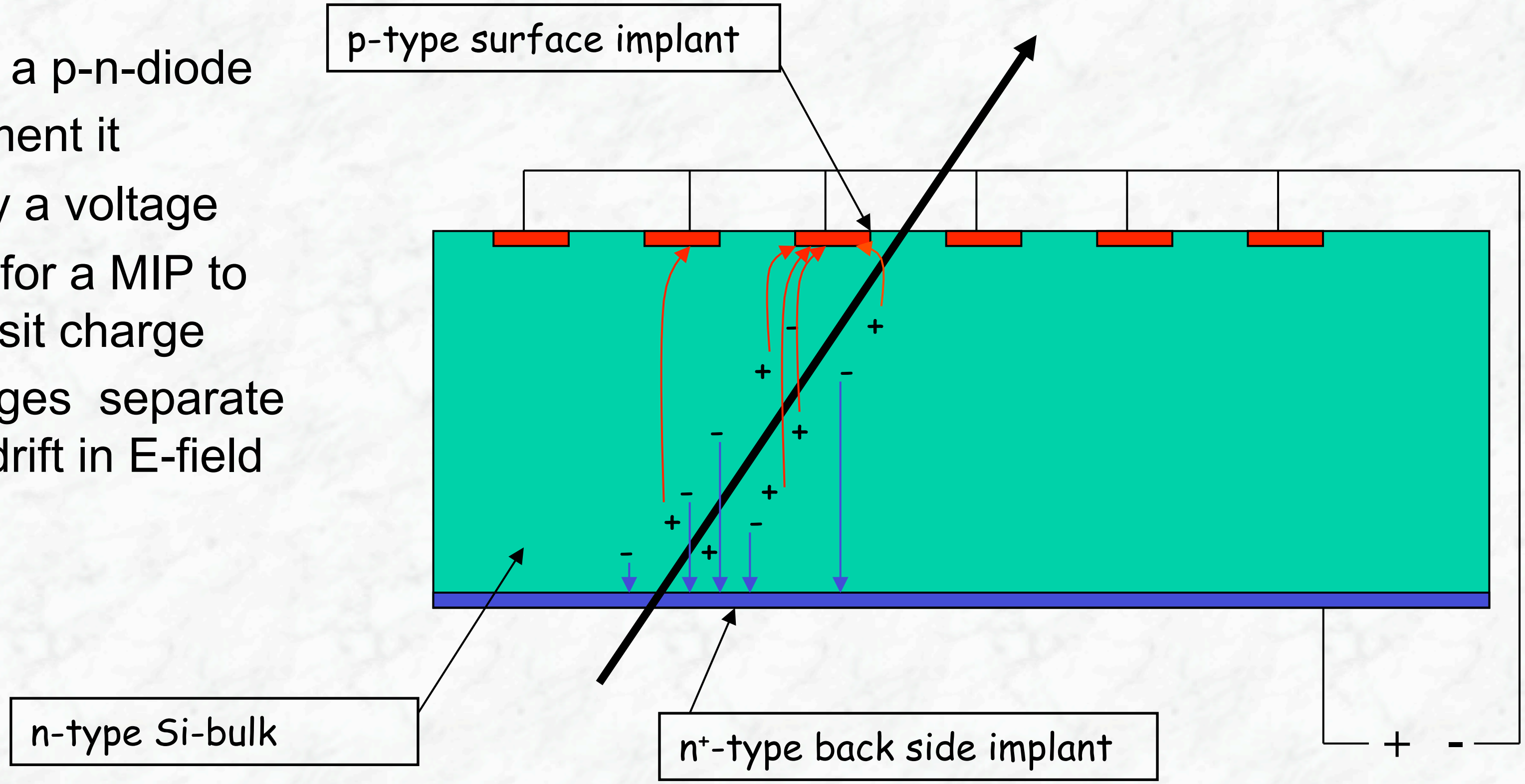
A Basic Silicon Detector

- Take a p-n-diode
- Segment it
- Apply a voltage
- Wait for a MIP to deposit charge



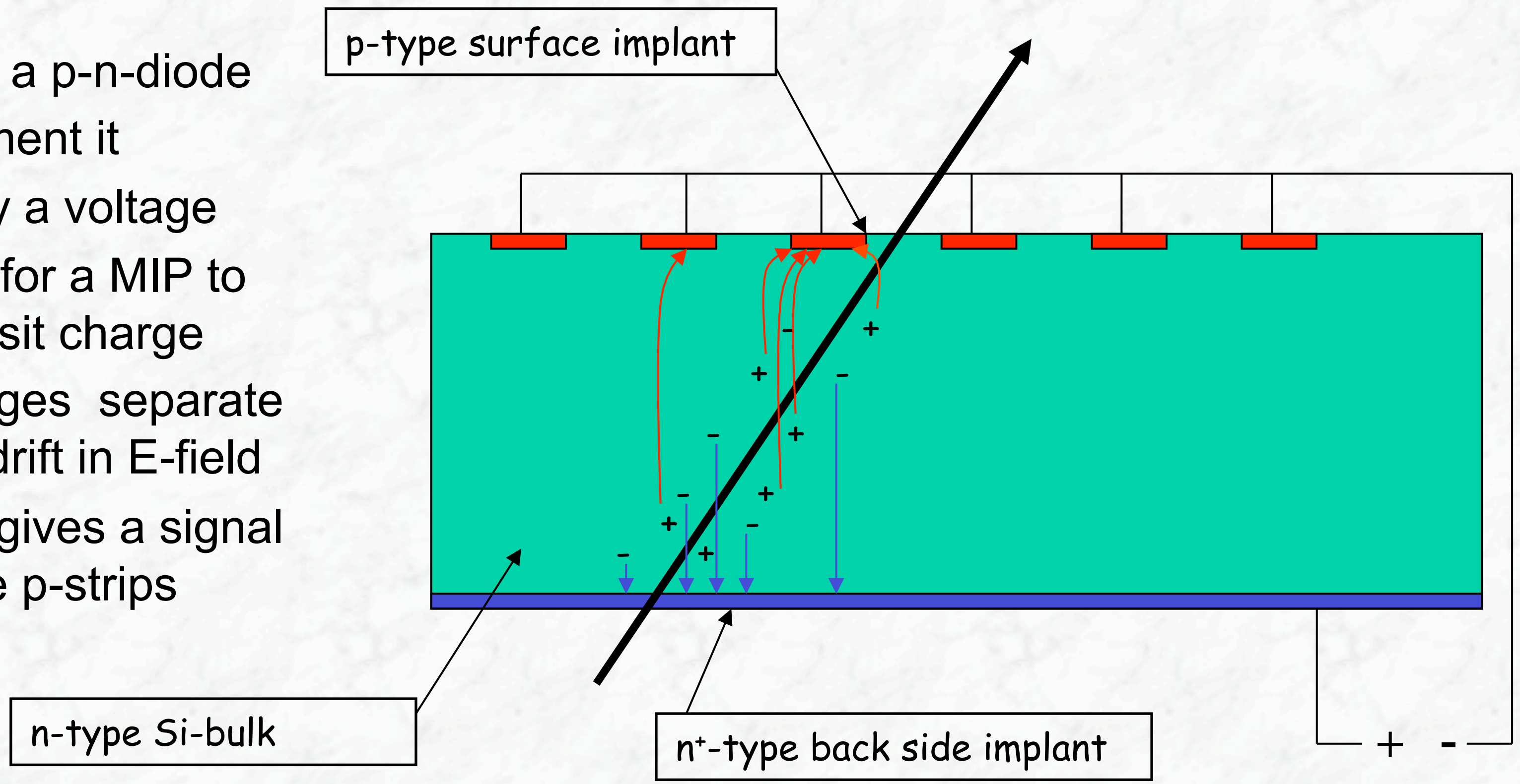
A Basic Silicon Detector

- Take a p-n-diode
- Segment it
- Apply a voltage
- Wait for a MIP to deposit charge
- Charges separate and drift in E-field



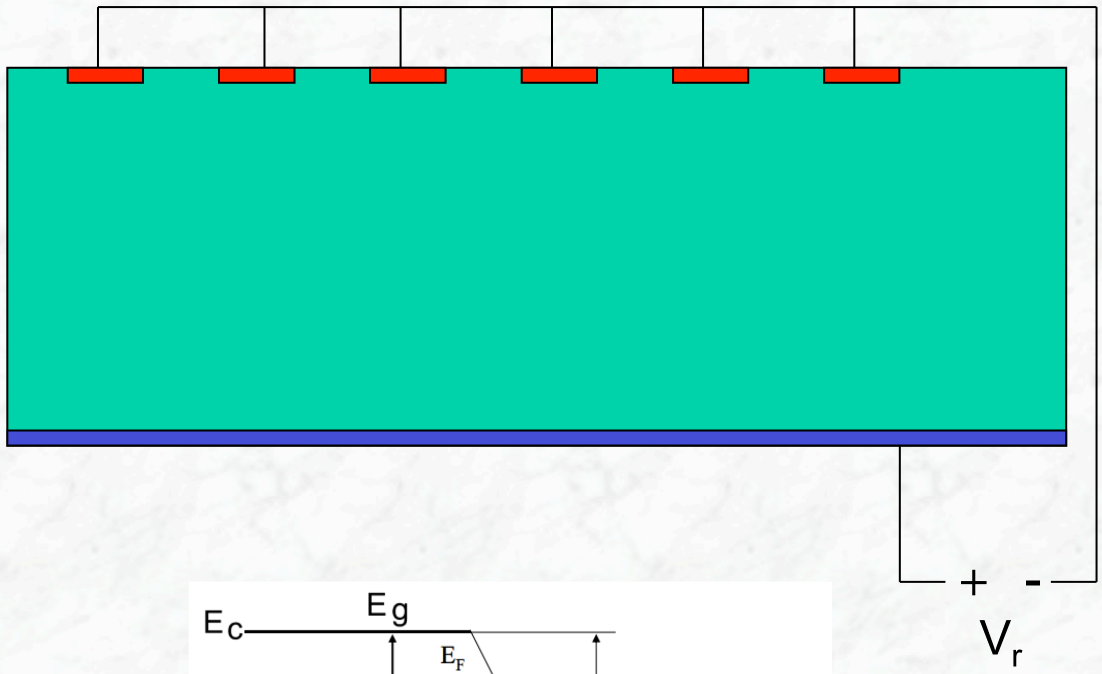
A Basic Silicon Detector

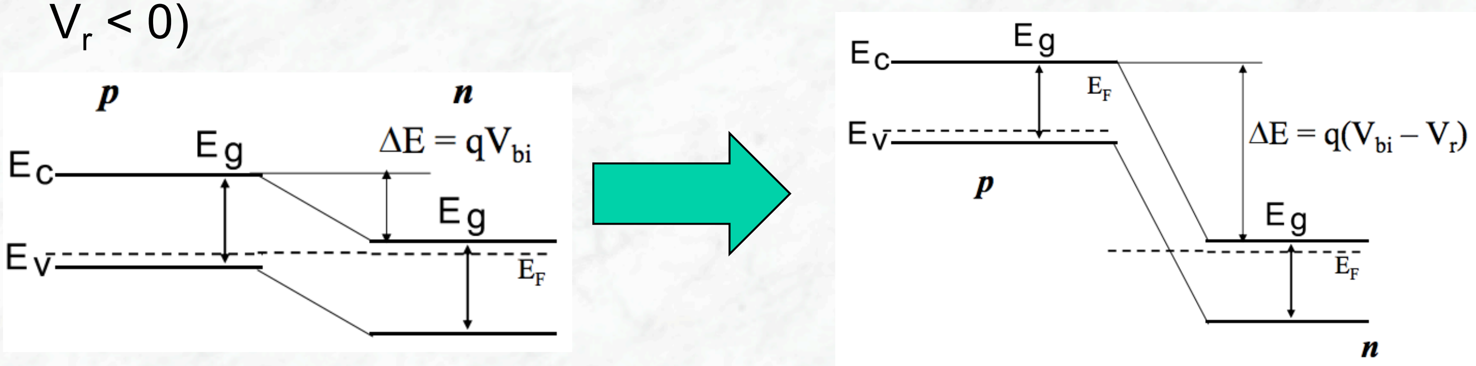
- Take a p-n-diode
- Segment it
- Apply a voltage
- Wait for a MIP to deposit charge
- Charges separate and drift in E-field
- This gives a signal in the p-strips



Depletion

- MIP charge in 300 µm Si is 4fC (22.000 e^-h^+-pairs)
- Free charge in 1 cm^2 Si-Detector 10^4 times larger (T=300K), so signal is invisible. Options:
  - Cryogenic operation
  - E-field to get rid of free charge
- Apply external Voltage V_r to deplete Si from charges (reverse bias, $V_r < 0$)





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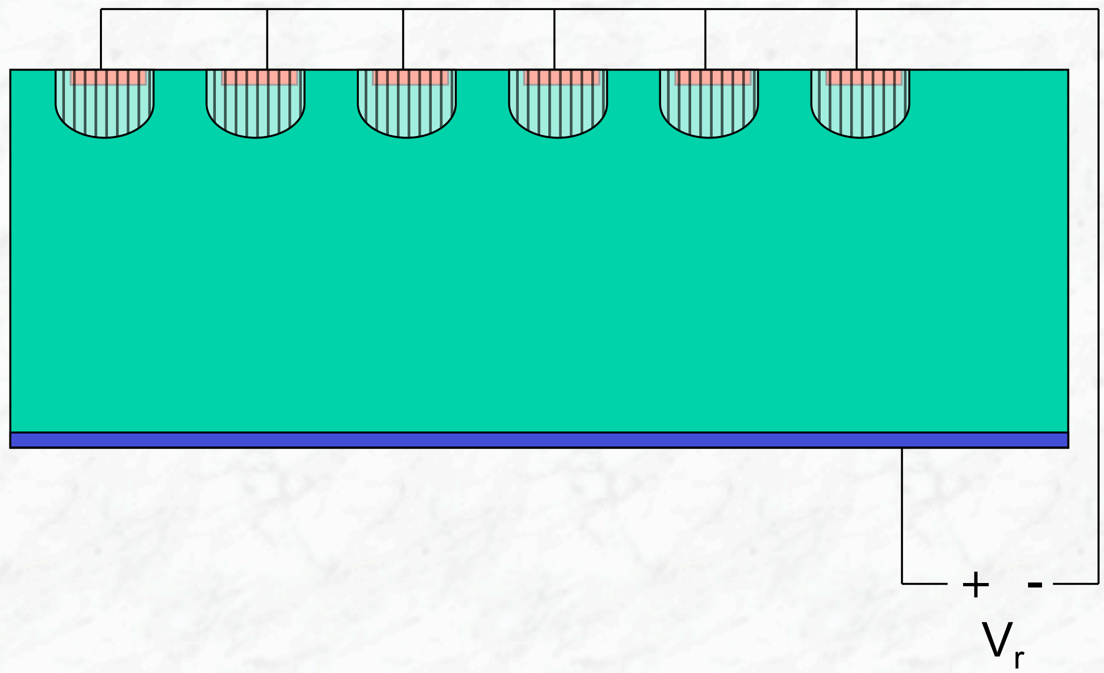
- Depletion zone grows from p-n-junction towards the back side



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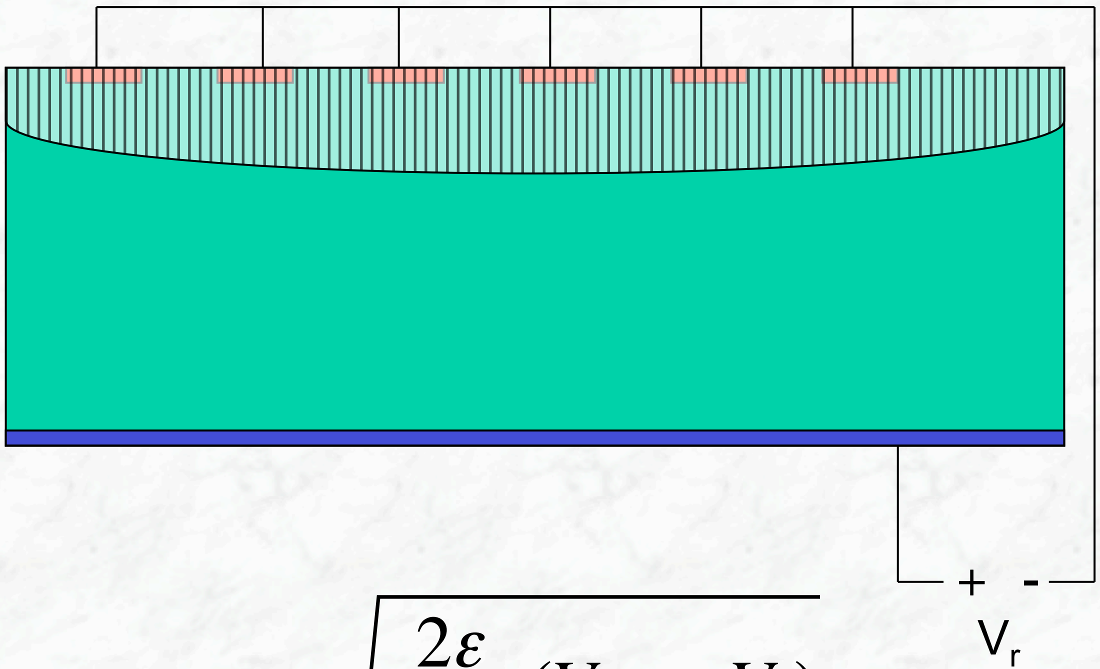

$$w_{depletion} = \sqrt{\frac{2\varepsilon}{qN_D}(V_{bias} - V_r)}$$

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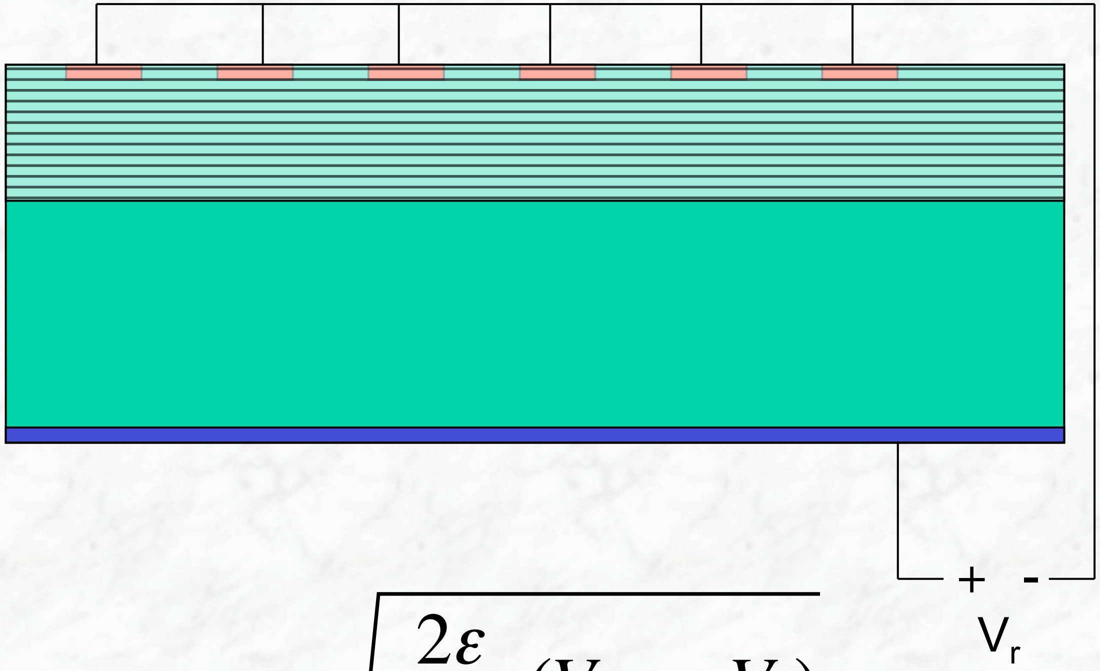

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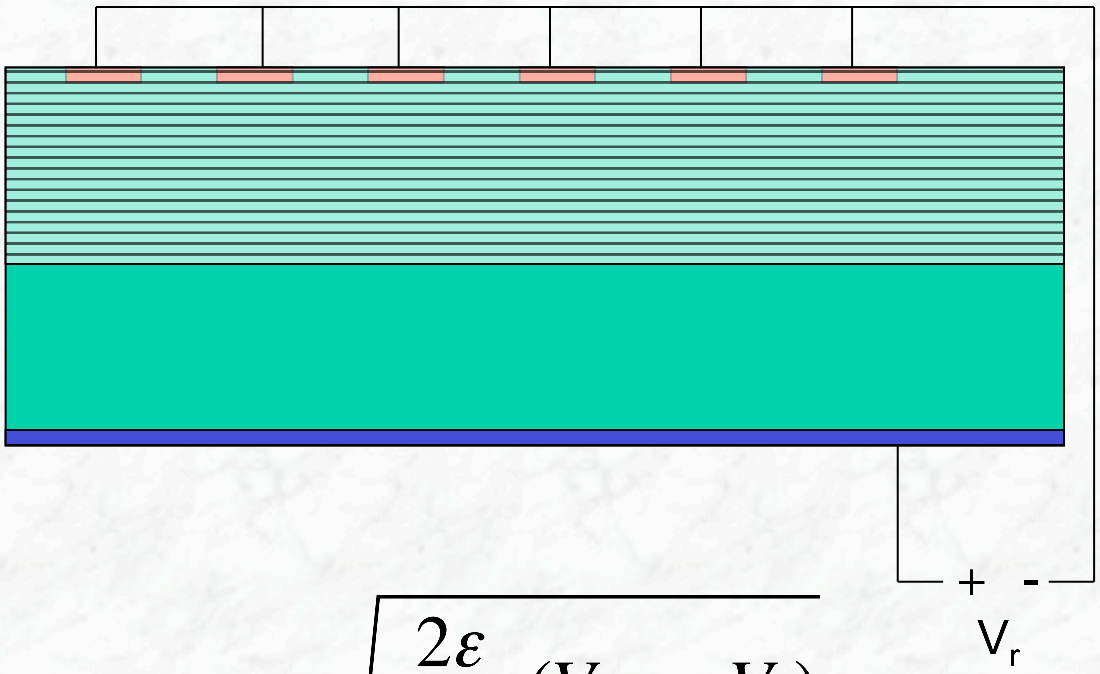

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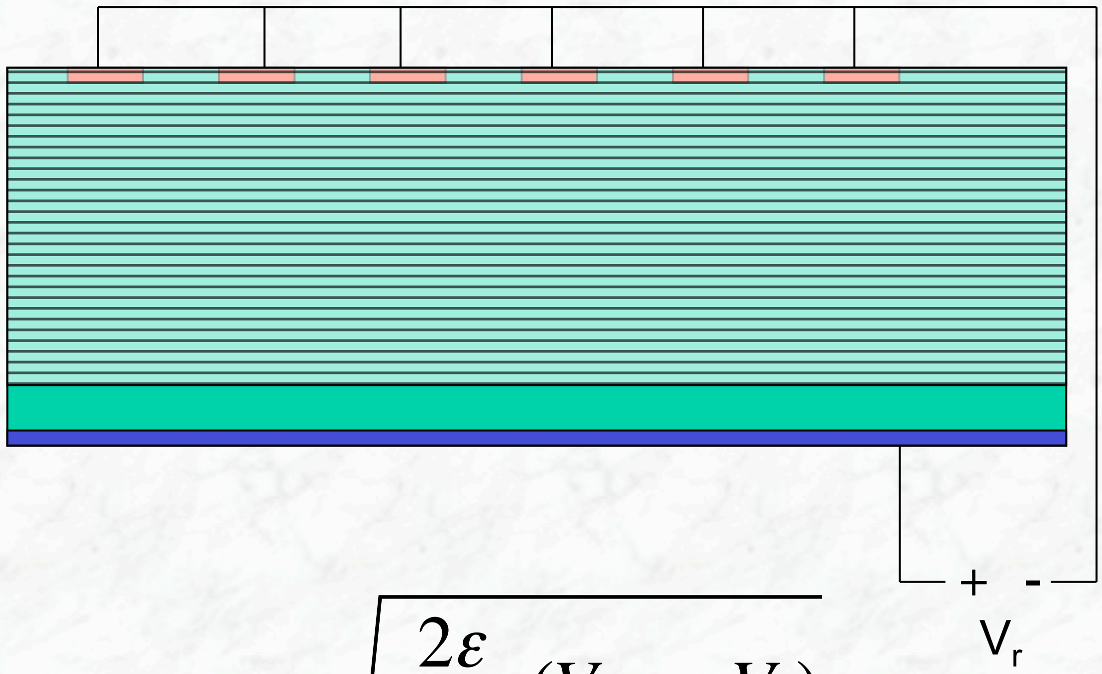

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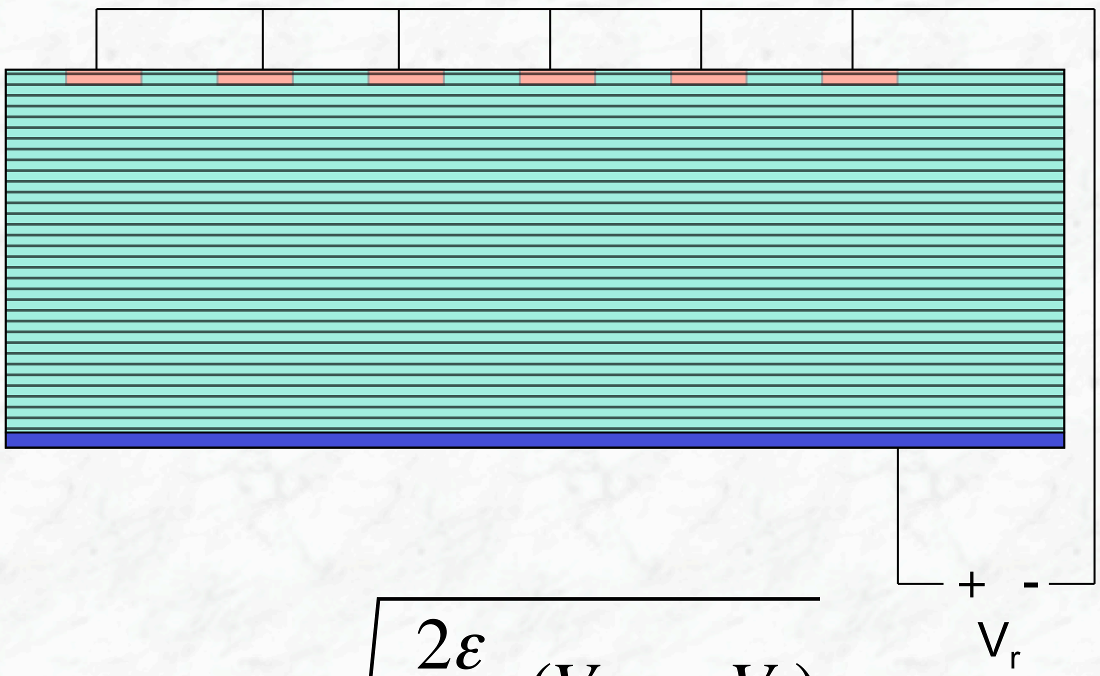
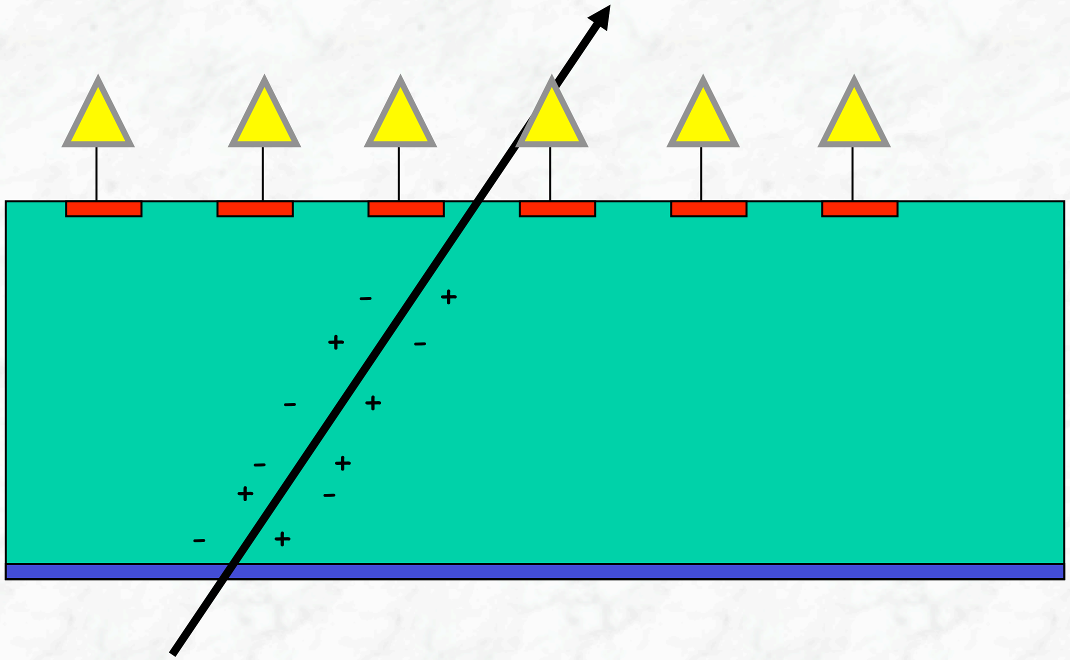


$$w_{depletion} = \sqrt{\frac{2\varepsilon}{qN_D}(V_{bias} - V_r)}$$

Signal

- Depleted piece of Si, a MIP generates $e^{-}h^{+}$-pairs…
- $e^{-}h^{+}$-pairs separate in E-field, and drift to electrodes
- Moving charges -> electric current pulse
- Small current signal is amplified, shaped and processed in ASICs ("chips") on read-out electronics



ASIC = application specific integrated circuit

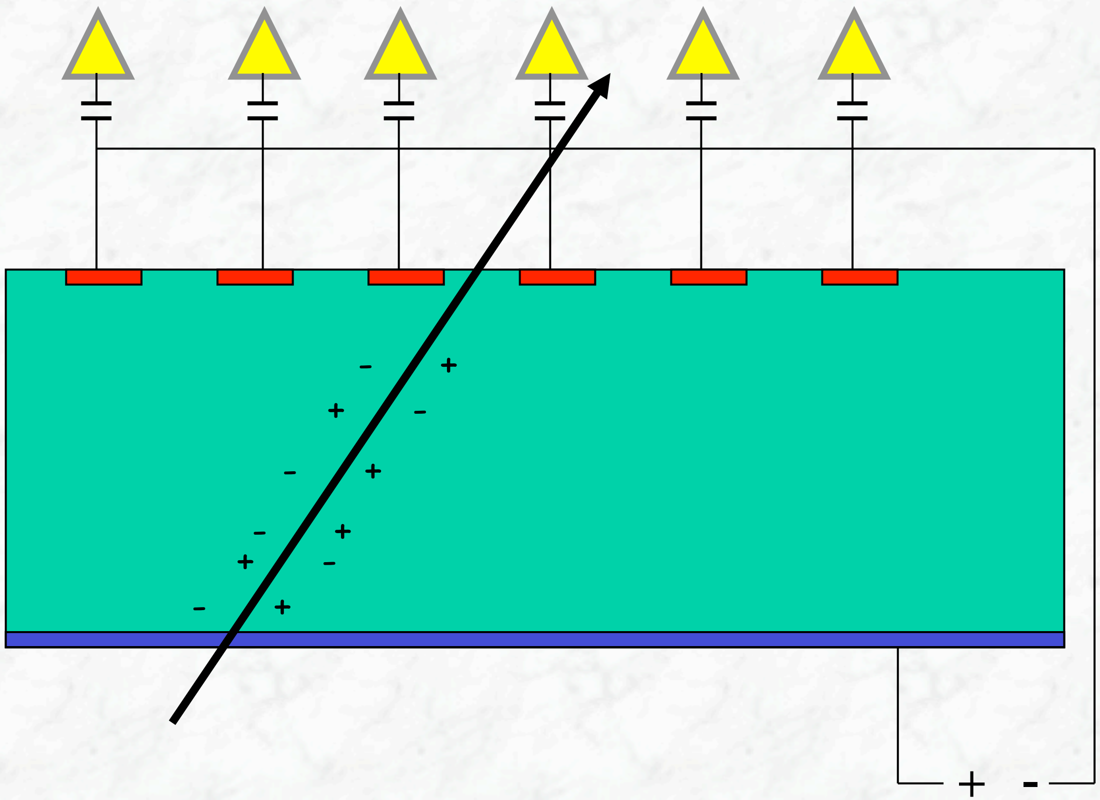
Some subtleties

- Even under reverse bias, there is a permanent thermal current going into the amplifiers

- Amplifying this current consumes power, generates heat and noise

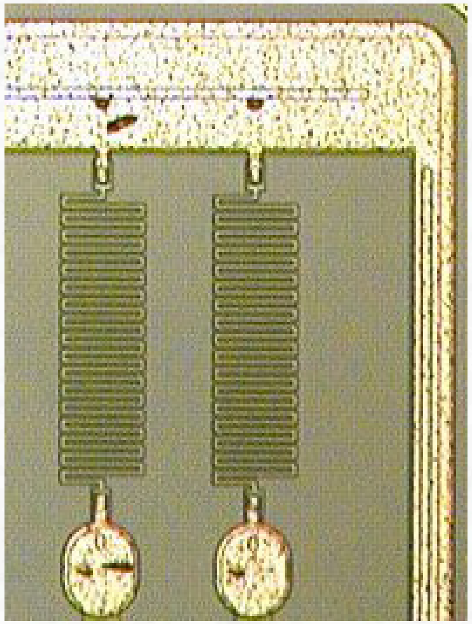
- Solution: decouple strips from amplifiers for DC signals only -> AC-coupling

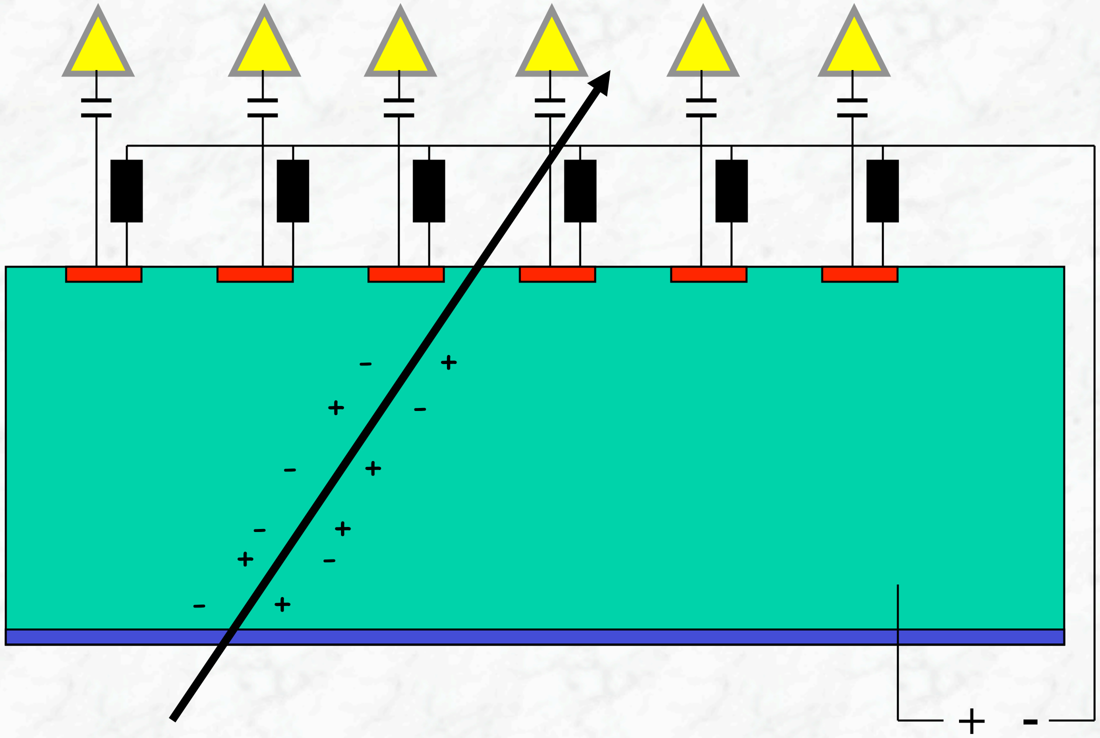
- Integration of capacitors into Si-detector possible (and common today)



More Subtleties

- Diodes need to be on same potential but electrically separated (to avoid shorting them)
- Solution: decouple strips with bias resistors
  - ~ 1 MΩ





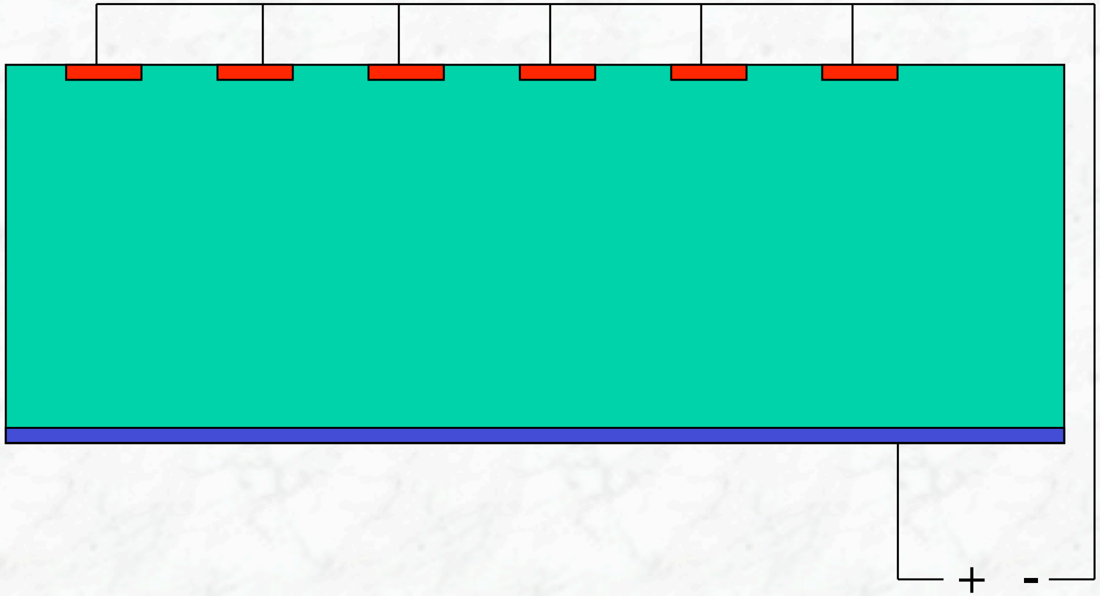
Schematic Si-Detector

- This detector will deliver 2D information – we need one more coordinate:

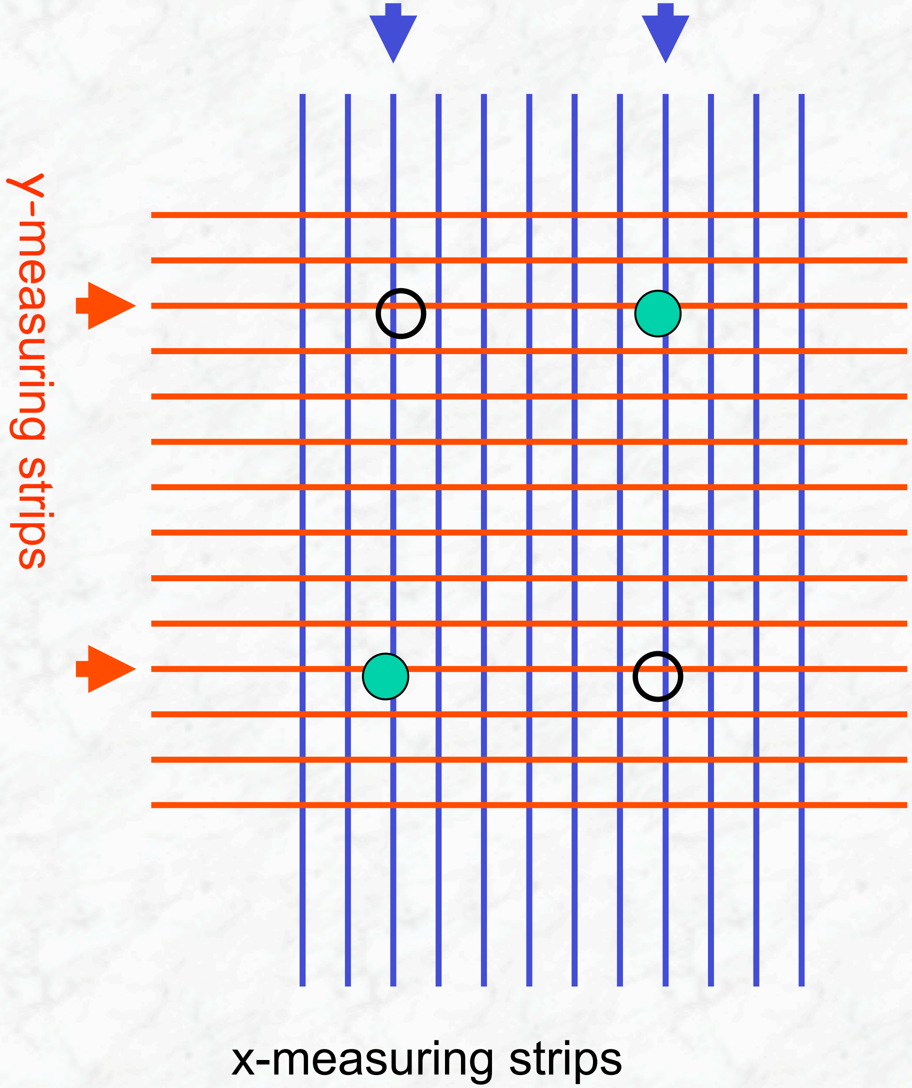
- Take another detector and place it on top with orthogonal strips

- Or segment the n-side (backside) as well -> double-sided detector

- Both will work – but one has to think about the angle of the two Si-planes



Angle between two Si-Detectors



- Charge from MIP
- Signal strips
- "Ghost" (combinatorial hit)

N hits per readout cycle generate N^2 ambiguities in hit position

Ambiguities are reduced by stereo angle < 90^o

ATLAS Reality: O(10) hits per detector module per 25 ns.

Stereo angle of few degrees.

Performance: Resolution

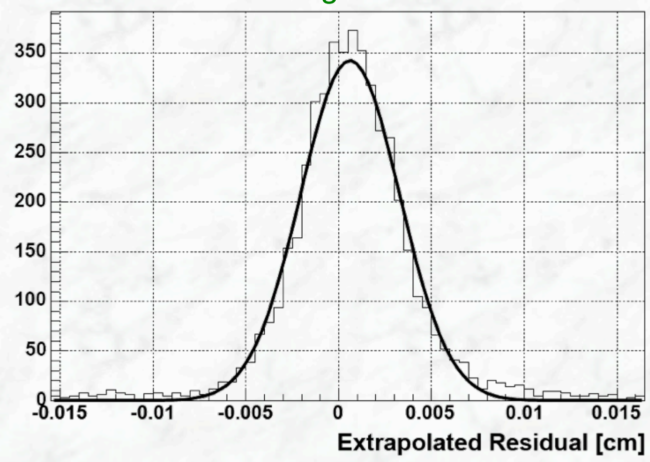
- Spatial resolution σ:
  - Dominated by strip pitch d
  - Single strip hits: **$\sigma = d/\sqrt{12}$**
  - Double strip hits improve resolution (weighted average)
  - Ratio single/double hits gets worse for larger pitches

Pitch	Typ. σ	σ_{naive} / σ
25 µm	2.6 µm	2.8
60 µm	9 µm	1.9
100 µm	29 µm	1

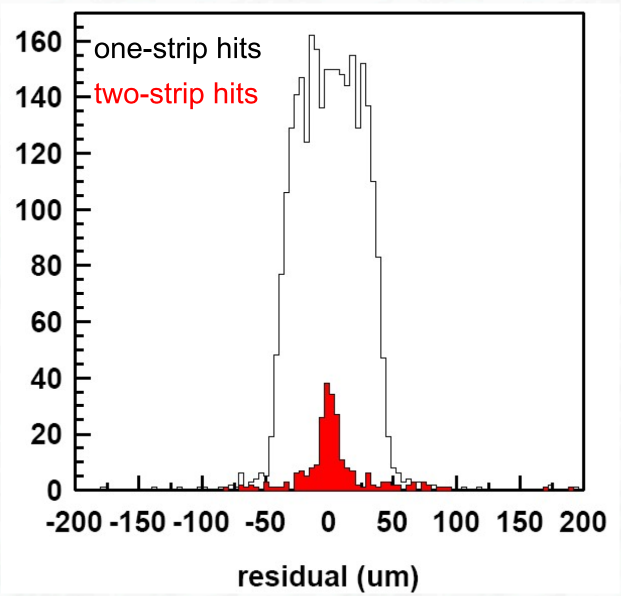
→ Resolution worsens rapidly with increasing pitch

  - Higher S/N → more two-strip hits
    → better resolution
  - An analogue readout has better space resolution than a binary one

Resolution for analogue readout



Resolution for binary readout



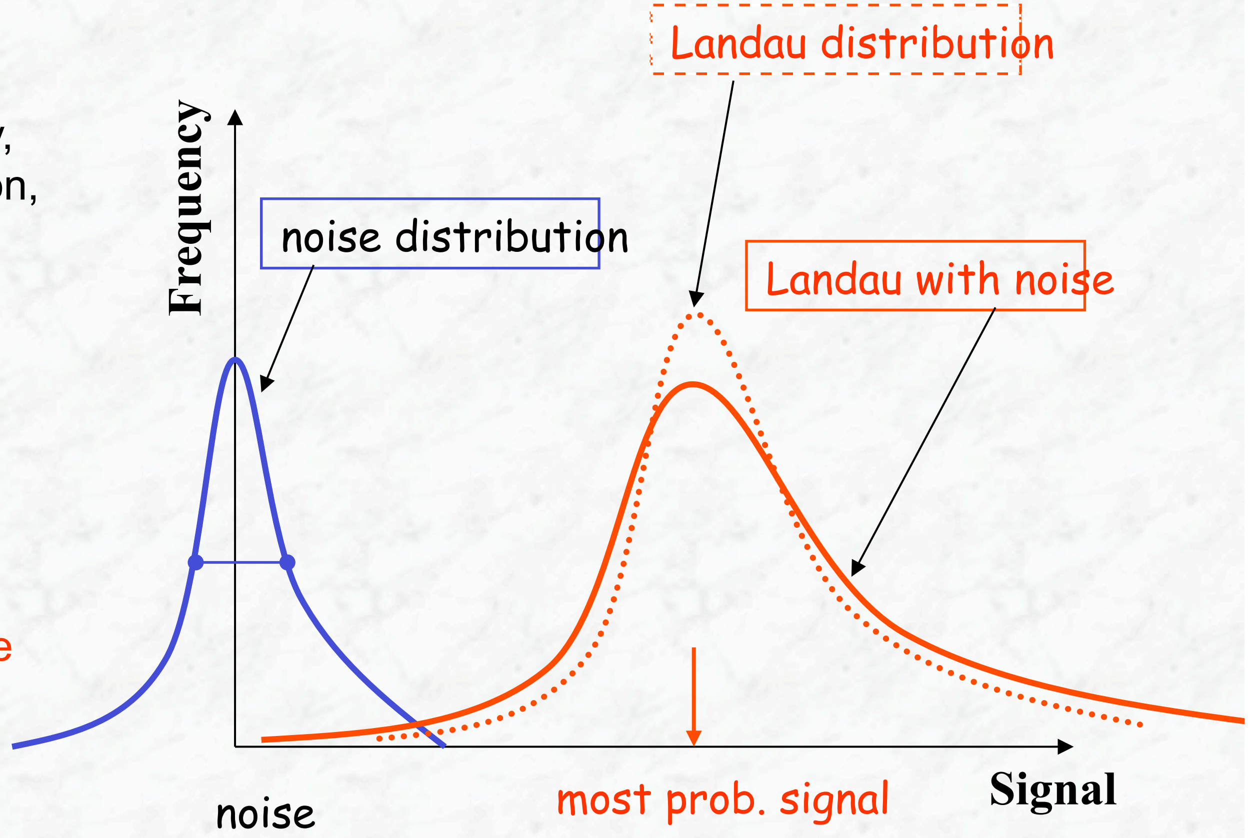
Performance: Rate

- Rate:
  - Signal collection $t_{collect}$ ~10ns
  - Signal shaping in front end electronics: $t_{shape} \geq t_{collect}$
  - A lot of Si-detectors operate successfully at LHC speed (25ns)

Signal and Noise

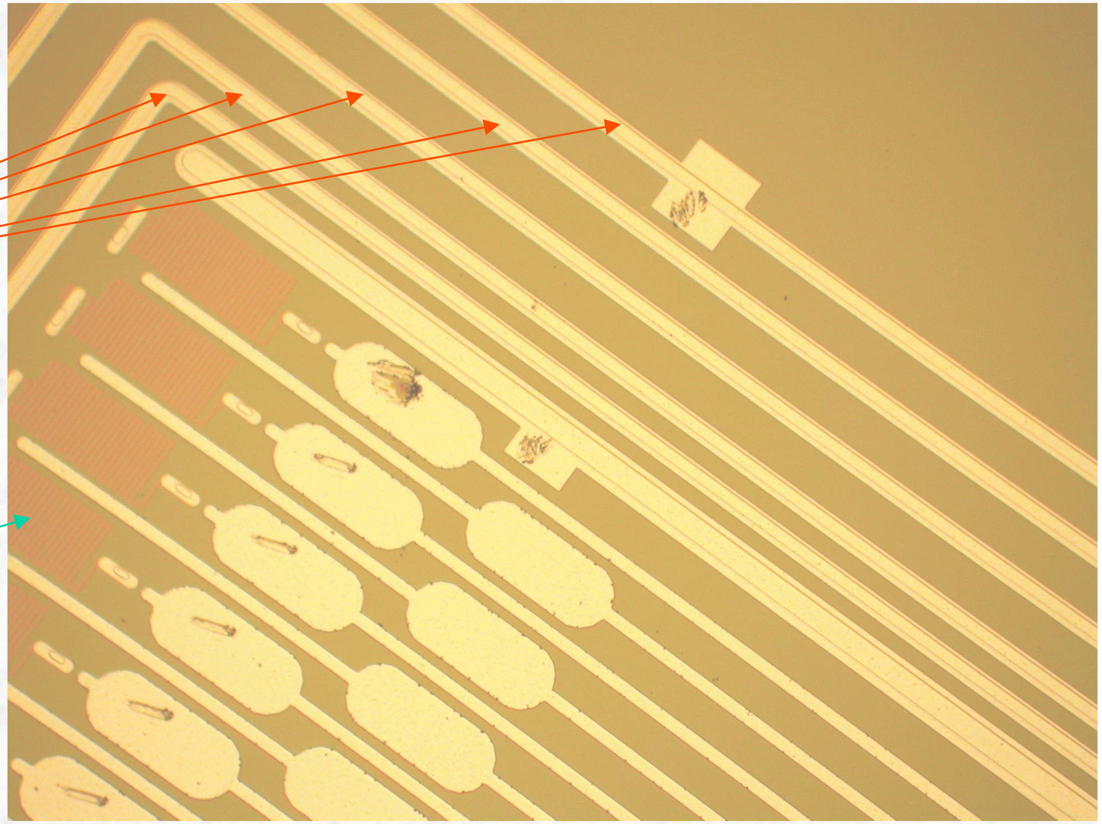
- Noise "Signal" from strips has a Gaussian shape
- MIPs deposit ~100 keV energy, according to Landau distribution, broadened by noise
- Need to separate signal and noise

  → threshold value
  → efficiency
- Figure of merit: Signal-to-Noise ratio or S/N
- S/N also affects resolution!

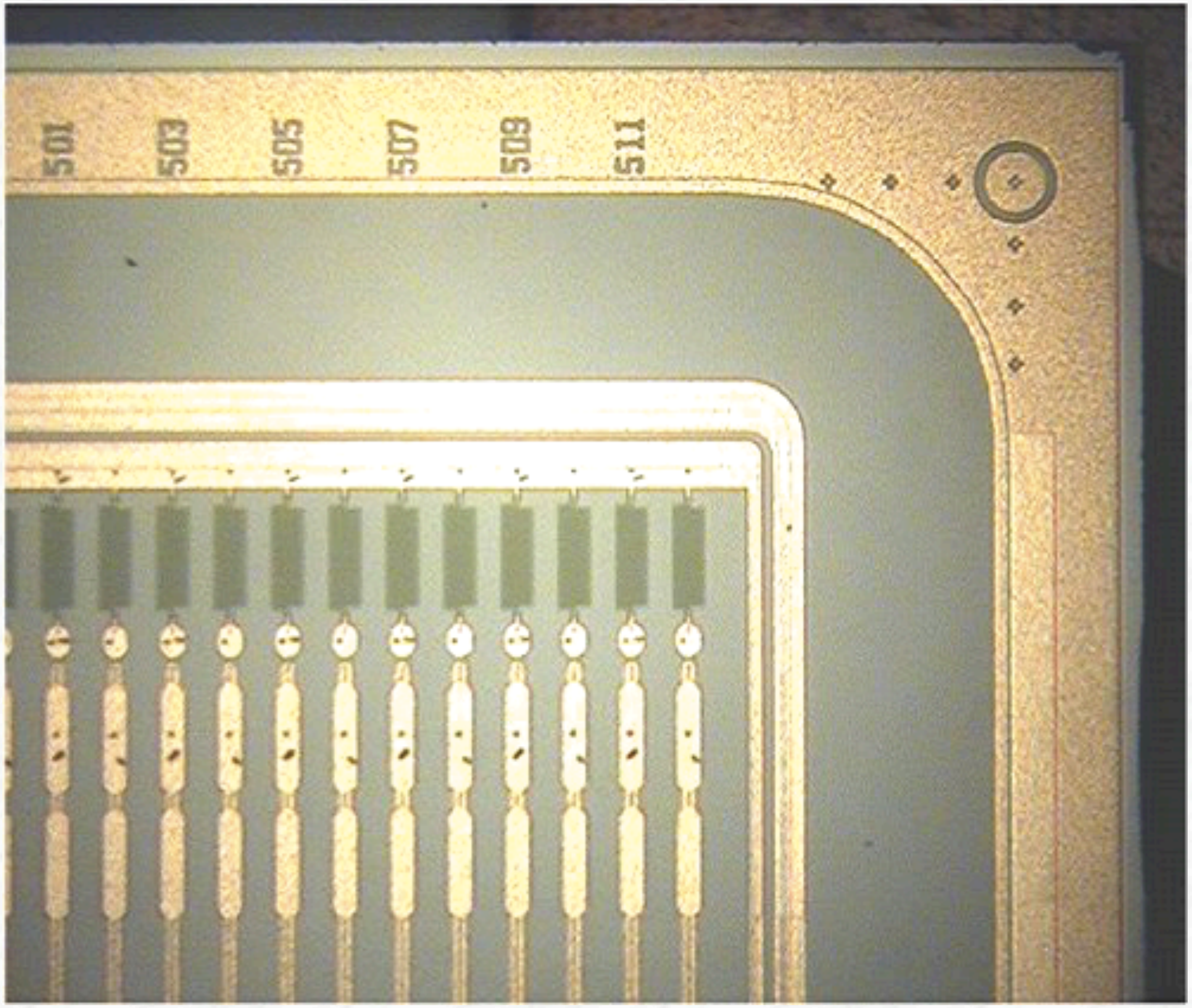


Some details on detector designs

- Detector has edges, which are cut Silicon with many defects -> generation of current
- Solution: add structures to avoid depleting edges, and grade down potential in steps: Guard rings
- Guard rings are p-implants that run around the active detector area
- Bias resistors

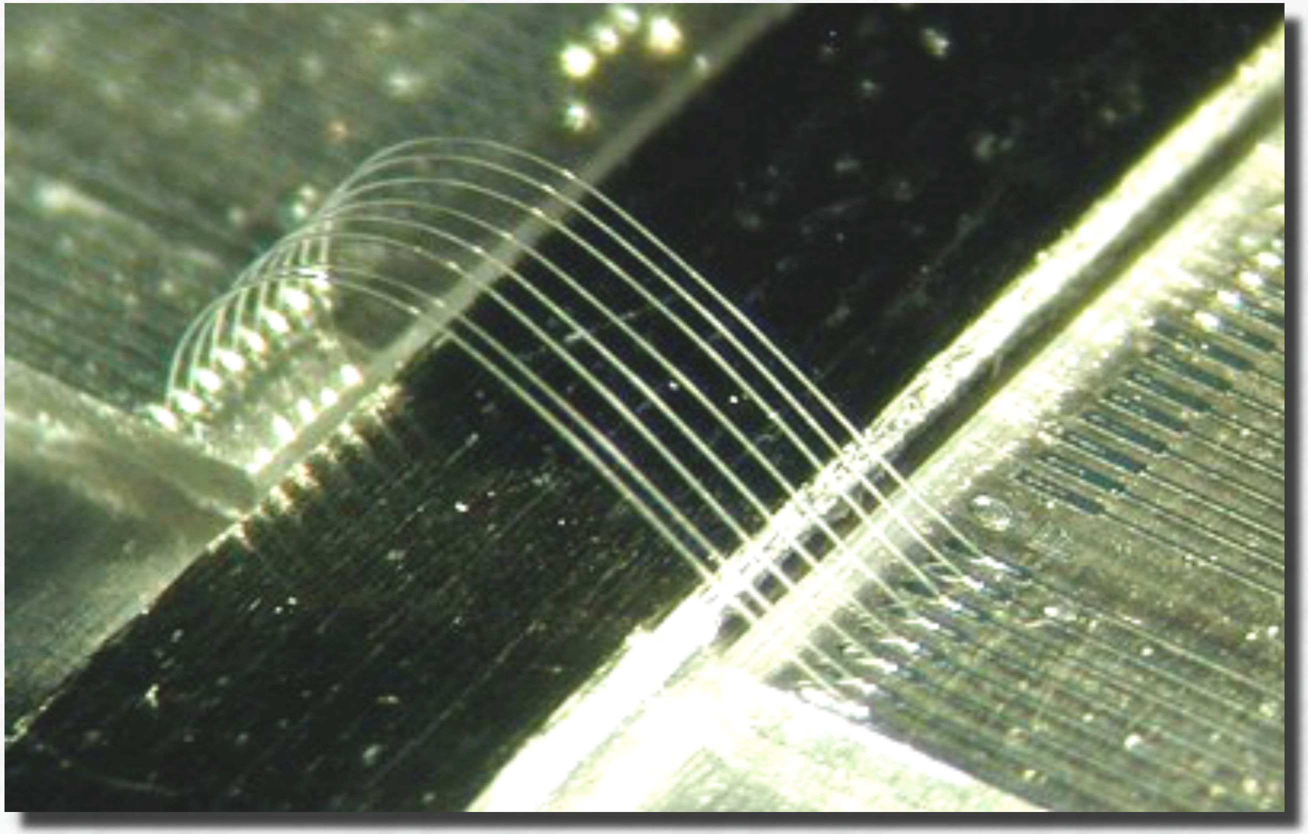


Example of a Si-detector with a single guard ring

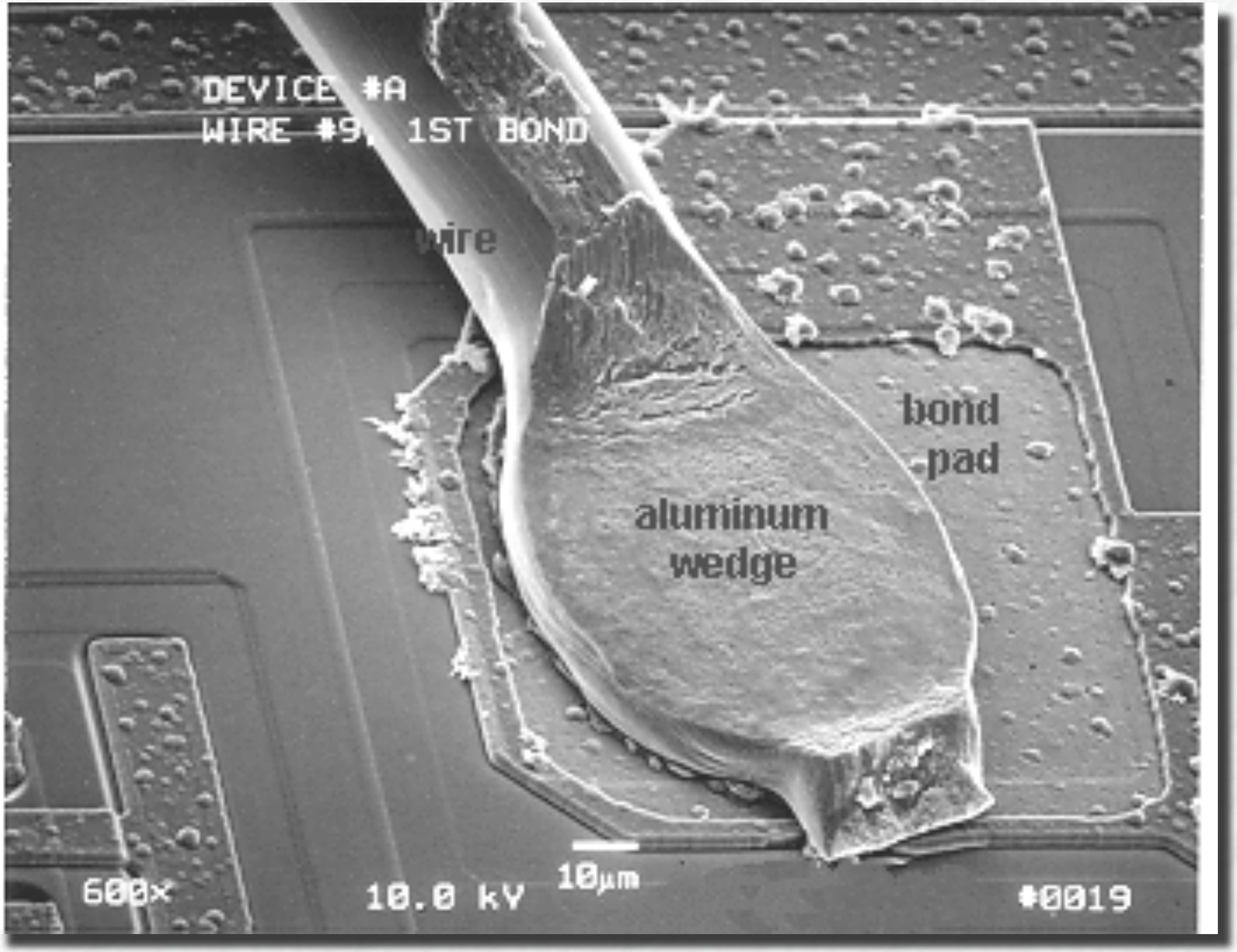


Wire Bonding

- Si detector needs connection to readout electronics
- High connection density with O(15) wires per mm
- Ultra-sonic bonding of ~20μm wires with semiautomatic system



Single Wire Bond Foot



Full Si-Detector System

- So far we only have a piece of Silicon with some electronics attached, which will give us a 3D space point…

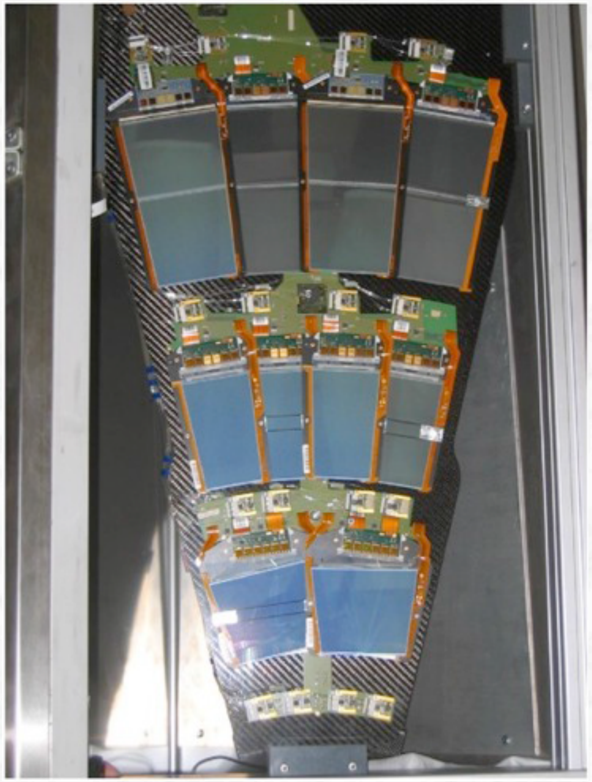
- Need to put many (thousands) of Si-Detectors together in a smart way

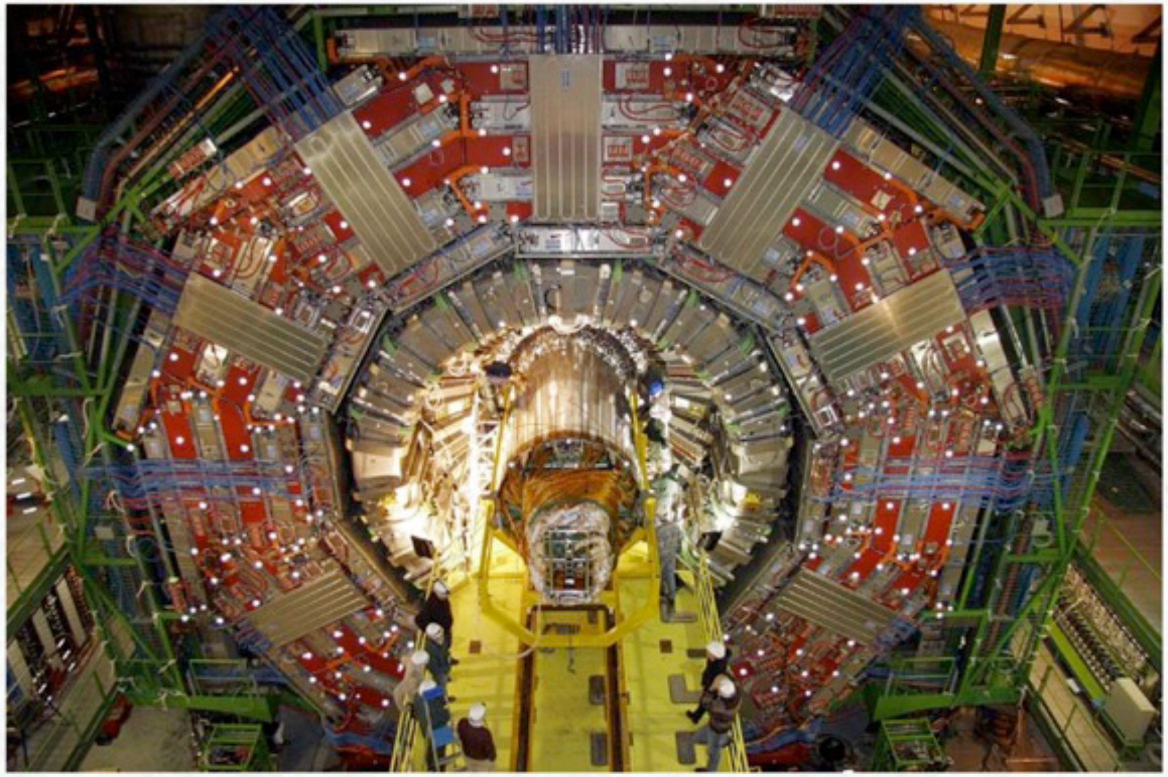
  - Require several space points → several layers
  - Need to see all charged tracks → hermetically closed
  - For collider experiments (e.g. ATLAS, CMS) this means

    a multilayer cylindrical structure

- Some examples will follow

CMS Silicon Tracker





Micro strip:

- 214 m^2 of silicon strip sensors
- 11.4 m strips
- Diameter: 2.4 m

Pixel:

- Inner three layers: silicon pixels, ~1m^2
- 66 million pixels
- Precision: $\sigma(r\phi) \sim \sigma(z) \sim 15\ \mu m$