Silicon detectors in HEP

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ACCTR Meeting

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Introduction to silicon

- Semiconductor material
  - Used for radiation detection/imaging in
    - Particle and nuclear physics experiments
    - Space and ground-based telescopes
    - Medical applications
    - Industrial applications
    - …
- Interacts with radiation
  - Radiation creates charge carriers
  - Electric field drifts carriers toward readout electronics
  - Signal integrated in frond-end electronics
  - Digitize integrated signal
  - Readout and store digital signal

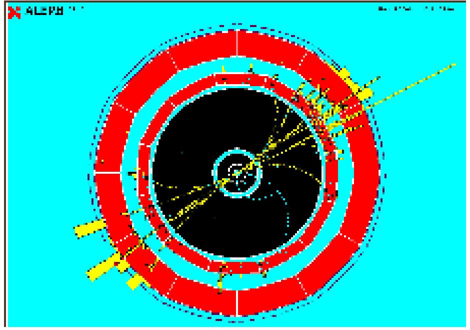
Particle reconstruction in time

- Why detectors change
  - Interested in rare events
    - in very high energies
    - with very small uncertainties
    - with very high background
- Need high precision
  - Very high granularity
  - low material budget
- High particle collision rates
  - High speed electronics
  - Good background tolerance
  - Long term reliability
  - Radiation hardness

Pre-silicon era

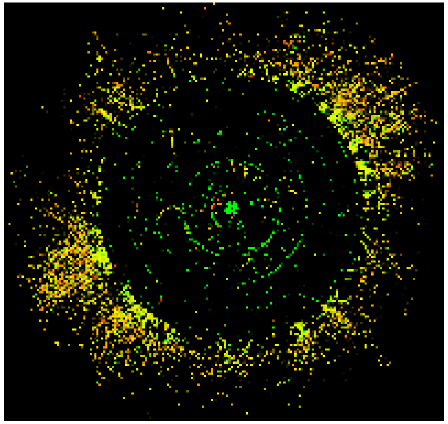
1970s

Si + gaseous tracking



1990s

Si tracking+vertex+calorimetry



2010s

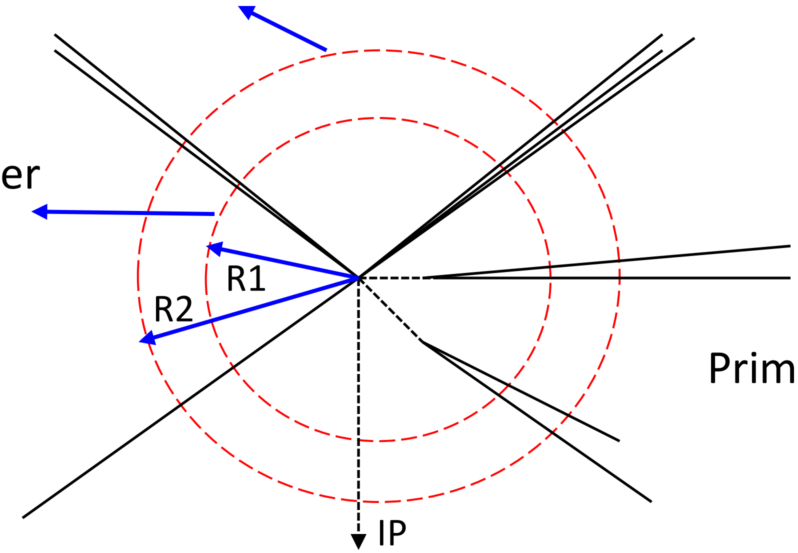
time

Gaseous vs silicon detectors

- In silicon detector
  - No multiplication → signal amplification needed
  - Optimum thickness to minimize multiple scattering

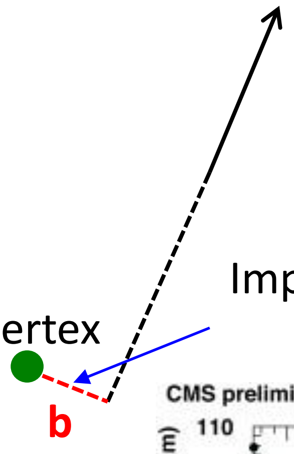
Property	Gas	Silicon	Importance
Density	Low	2.33 g/cm^3	Denser -> better spatial resolution
Charge	electrons and ions	electrons and holes	
Ionization energy	30eV per e- ion pair	3.6 eV per e- hole pair	Lower -> better energy resolution
Mobility	10 ns to 10 µs	few ns to 20 ns	Faster -> no dead time
Signal-to-noise	Low	High	Reliable signal

Vertex reconstruction



Outer Si layer

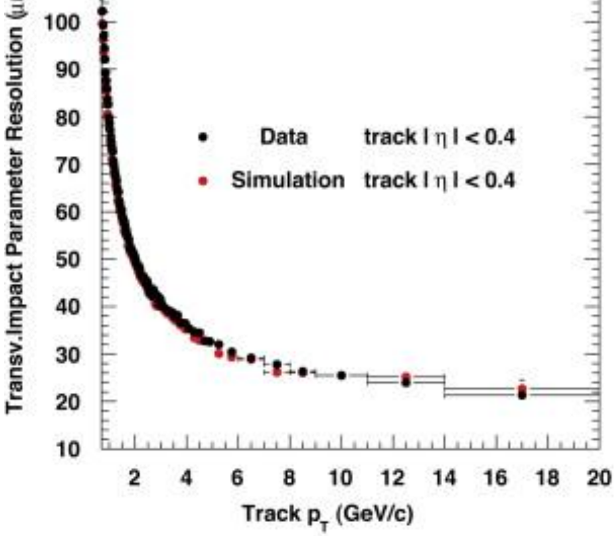
Inner Si layer



Outgoing particle

Impact parameter

Primary vertex

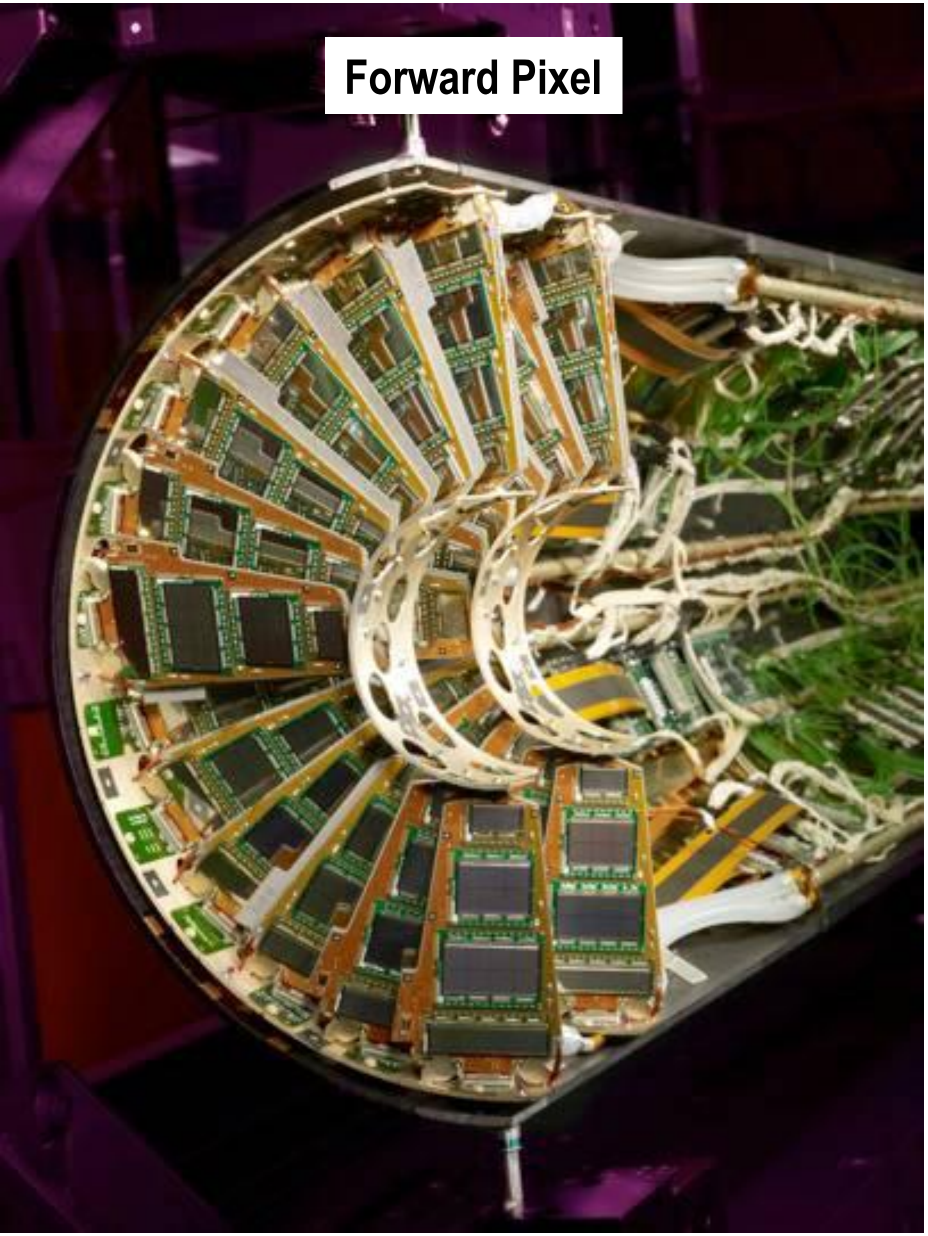


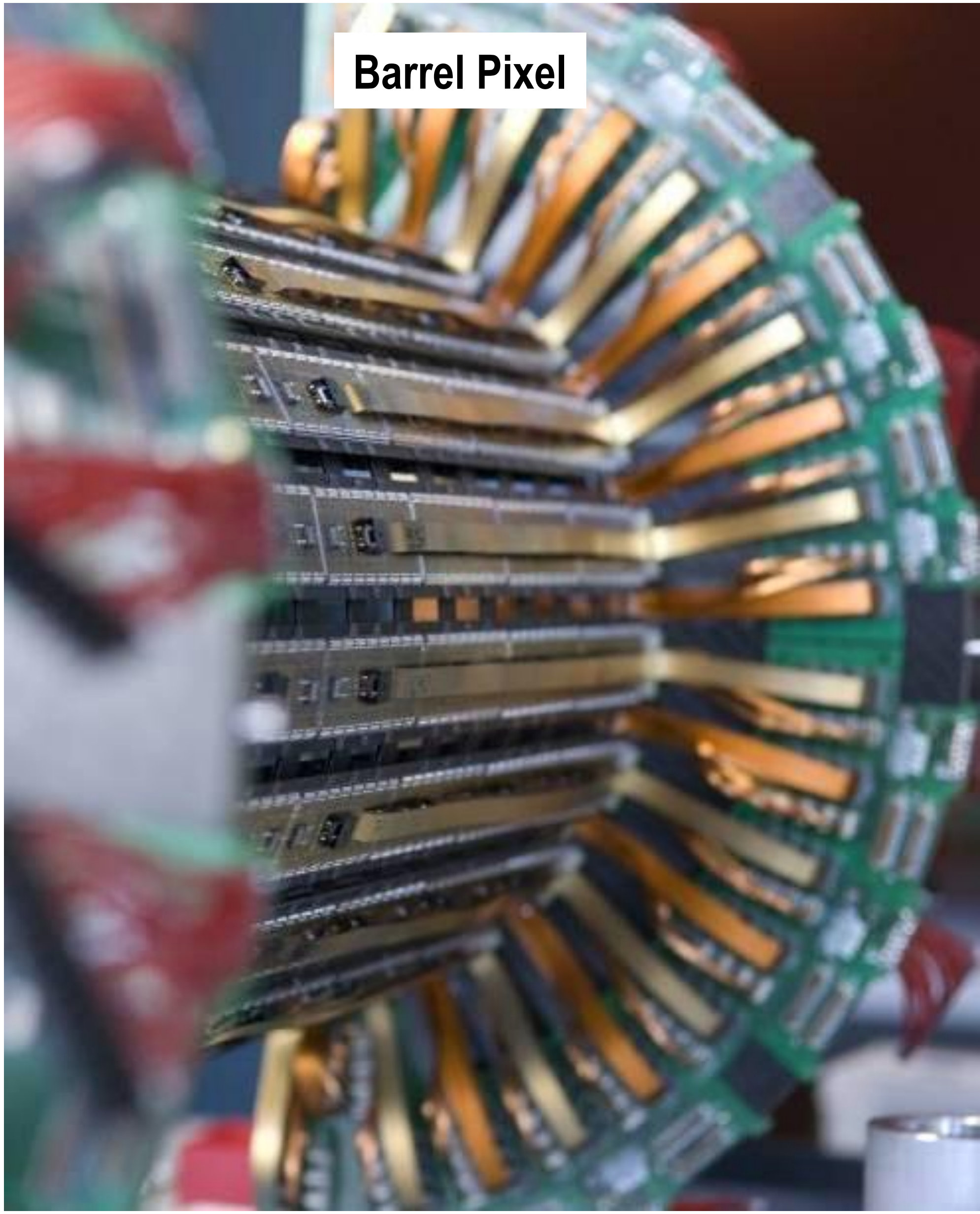
$$\sigma_b^2 \approx \frac{1}{(R_2-R_1)^2}\left[(\sigma_1 R_2)^2+(\sigma_2 R_1)^2\right]$$

If both layers have same spatial resolution (σ)

$$\left(\frac{\sigma_b}{\sigma}\right)^2 \approx \left(\frac{1}{1-R_1/R_2}\right)^2+\left(\frac{1}{R_2/R_1-1}\right)^2$$

CMS pixel detector

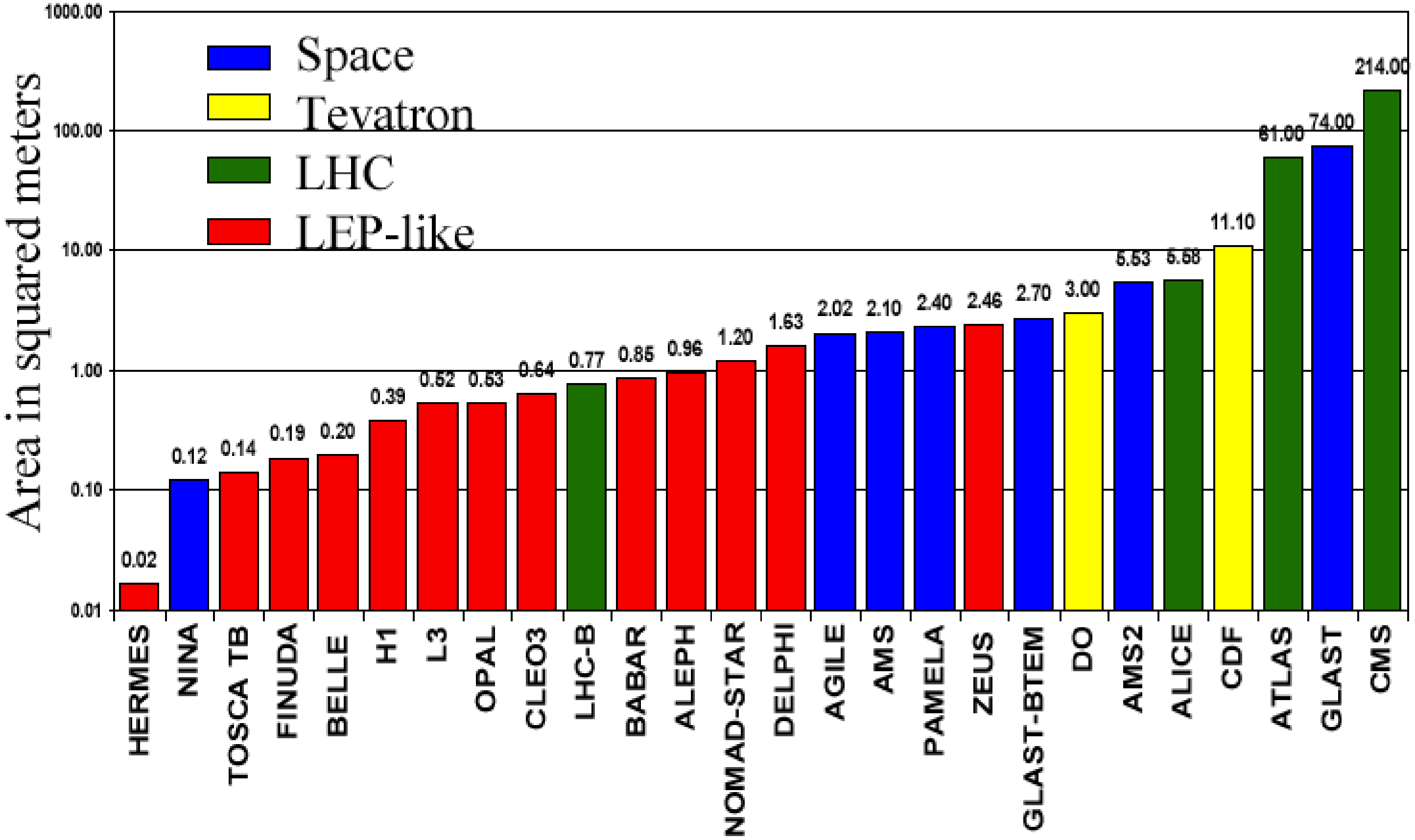




Silicon detectors in HEP

- In HEP experiment
  - Vertex reconstruction
  - Fast detection and position resolution

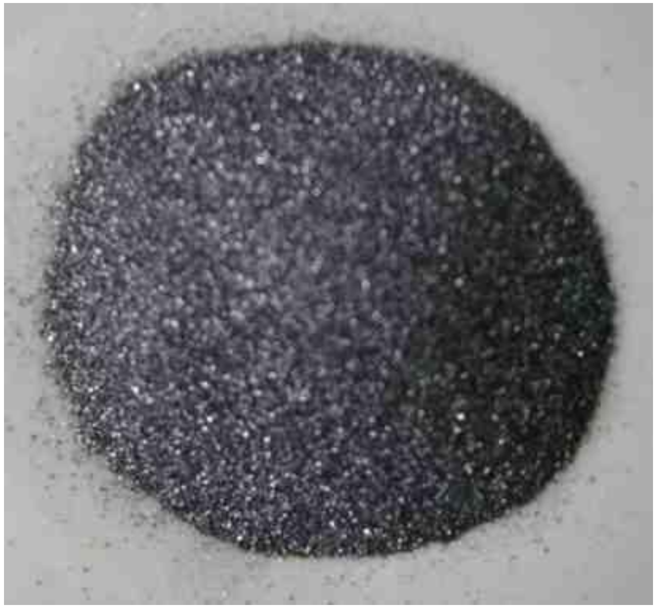
Experiments with silicon detector



E. Do Couto e Silva, Vertex 2000, Sept 10-15, National Lakeshore, MI, USA

Why silicon?

- 2nd most abundant element in Earth (28% by mass)
- Easy to process and purify to 0.001 ppb
- Natural SiO_2 as insulation during fabrication
- Found in form of silicate minerals and SO_2 (silica – sand)
- Discovered in 1824 by Swedish chemist J.J. Berzelius
- Commercially utilized since 1824

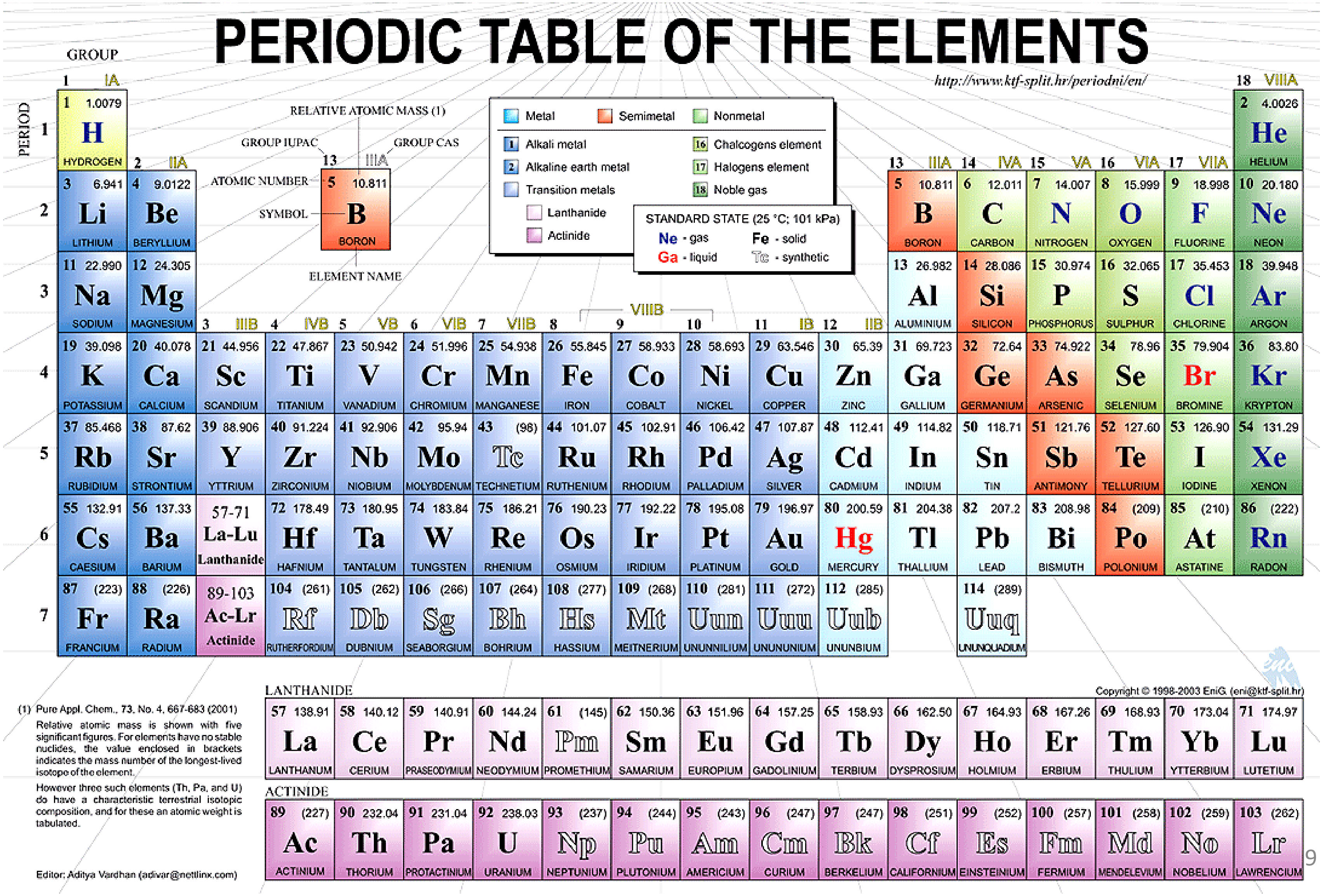


Silicon powder

Silicon crystal

Spectral lines of Silicon

Silicon - $_{14}Si^{28}$



PERIODIC TABLE OF THE ELEMENTS

http://www.ktf-split.hr/periodni/en/

PERIOD	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
GROUP	IA	IIA	IIIB	IVB	VB	VIB	VIIB	VIIIB			IB	IIB	IIIA	IVA	VA	VIA	VIIA	VIIIA
1	1 1.0079 H HYDROGEN																	2 4.0026 He HELIUM
2	3 6.941 Li LITHIUM	4 9.0122 Be BERYLLIUM											5 10.811 B BORON	6 12.011 C CARBON	7 14.007 N NITROGEN	8 15.999 O OXYGEN	9 18.998 F FLUORINE	10 20.180 Ne NEON
3	11 22.990 Na SODIUM	12 24.305 Mg MAGNESIUM											13 26.982 Al ALUMINIUM	14 28.086 Si SILICON	15 30.974 P PHOSPHORUS	16 32.065 S SULPHUR	17 35.453 Cl CHLORINE	18 39.948 Ar ARGON
4	19 39.098 K POTASSIUM	20 40.078 Ca CALCIUM	21 44.956 Sc SCANDIUM	22 47.867 Ti TITANIUM	23 50.942 V VANADIUM	24 51.996 Cr CHROMIUM	25 54.938 Mn MANGANESE	26 55.845 Fe IRON	27 58.933 Co COBALT	28 58.693 Ni NICKEL	29 63.546 Cu COPPER	30 65.39 Zn ZINC	31 69.723 Ga GALLIUM	32 72.64 Ge GERMANIUM	33 74.922 As ARSENIC	34 78.96 Se SELENIUM	35 79.904 Br BROMINE	36 83.80 Kr KRYPTON
5	37 85.468 Rb RUBIDIUM	38 87.62 Sr STRONTIUM	39 88.906 Y YTTRIUM	40 91.224 Zr ZIRCONIUM	41 92.906 Nb NIOBIUM	42 95.94 Mo MOLYBDENUM	43 (98) Tc TECHNETIUM	44 101.07 Ru RUTHENIUM	45 102.91 Rh RHODIUM	46 106.42 Pd PALLADIUM	47 107.87 Ag SILVER	48 112.41 Cd CADMIUM	49 114.82 In INDIUM	50 118.71 Sn TIN	51 121.76 Sb ANTIMONY	52 127.60 Te TELLURIUM	53 126.90 I IODINE	54 131.29 Xe XENON
6	55 132.91 Cs CAESIUM	56 137.33 Ba BARIUM	57-71 La-Lu Lanthanide	72 178.49 Hf HAFNIUM	73 180.95 Ta TANTALUM	74 183.84 W TUNGSTEN	75 186.21 Re RHENIUM	76 190.23 Os OSMIUM	77 192.22 Ir IRIDIUM	78 195.08 Pt PLATINUM	79 196.97 Au GOLD	80 200.59 Hg MERCURY	81 204.38 Tl THALLIUM	82 207.2 Pb LEAD	83 208.98 Bi BISMUTH	84 (209) Po POLONIUM	85 (210) At ASTATINE	86 (222) Rn RADON
7	87 (223) Fr FRANCIUM	88 (226) Ra RADIUM	89-103 Ac-Lr Actinide	104 (261) Rf RUTHERFORDIUM	105 (262) Db DUBNIUM	106 (266) Sg SEABORGIUM	107 (264) Bh BOHRIUM	108 (277) Hs HASSIUM	109 (268) Mt MEITNERIUM	110 (281) Uun UNUNNILIUM	111 (272) Uuu UNUNUNIUM	112 (285) Uub UNUNBIUM		114 (289) Uuq UNUNQUADIUM				

GROUP IUPAC — 13; GROUP CAS — IIIA

RELATIVE ATOMIC MASS (1) — 10.811

ATOMIC NUMBER — 5

SYMBOL — B

ELEMENT NAME — BORON

🟦 Metal 🟥 Semimetal 🟩 Nonmetal

1 Alkali metal

2 Alkaline earth metal

Transition metals

Lanthanide

Actinide

16 Chalcogens element

17 Halogens element

18 Noble gas

STANDARD STATE (25 °C; 101 kPa)

Ne - gas Fe - solid

Ga - liquid Tc - synthetic

LANTHANIDE

57 138.91 La LANTHANUM	58 140.12 Ce CERIUM	59 140.91 Pr PRASEODYMIUM	60 144.24 Nd NEODYMIUM	61 (145) Pm PROMETHIUM	62 150.36 Sm SAMARIUM	63 151.96 Eu EUROPIUM	64 157.25 Gd GADOLINIUM	65 158.93 Tb TERBIUM	66 162.50 Dy DYSPROSIUM	67 164.93 Ho HOLMIUM	68 167.26 Er ERBIUM	69 168.93 Tm THULIUM	70 173.04 Yb YTTERBIUM	71 174.97 Lu LUTETIUM

ACTINIDE

89 (227) Ac ACTINIUM	90 232.04 Th THORIUM	91 231.04 Pa PROTACTINIUM	92 238.03 U URANIUM	93 (237) Np NEPTUNIUM	94 (244) Pu PLUTONIUM	95 (243) Am AMERICIUM	96 (247) Cm CURIUM	97 (247) Bk BERKELIUM	98 (251) Cf CALIFORNIUM	99 (252) Es EINSTEINIUM	100 (257) Fm FERMIUM	101 (258) Md MENDELEVIUM	102 (259) No NOBELIUM	103 (262) Lr LAWRENCIUM

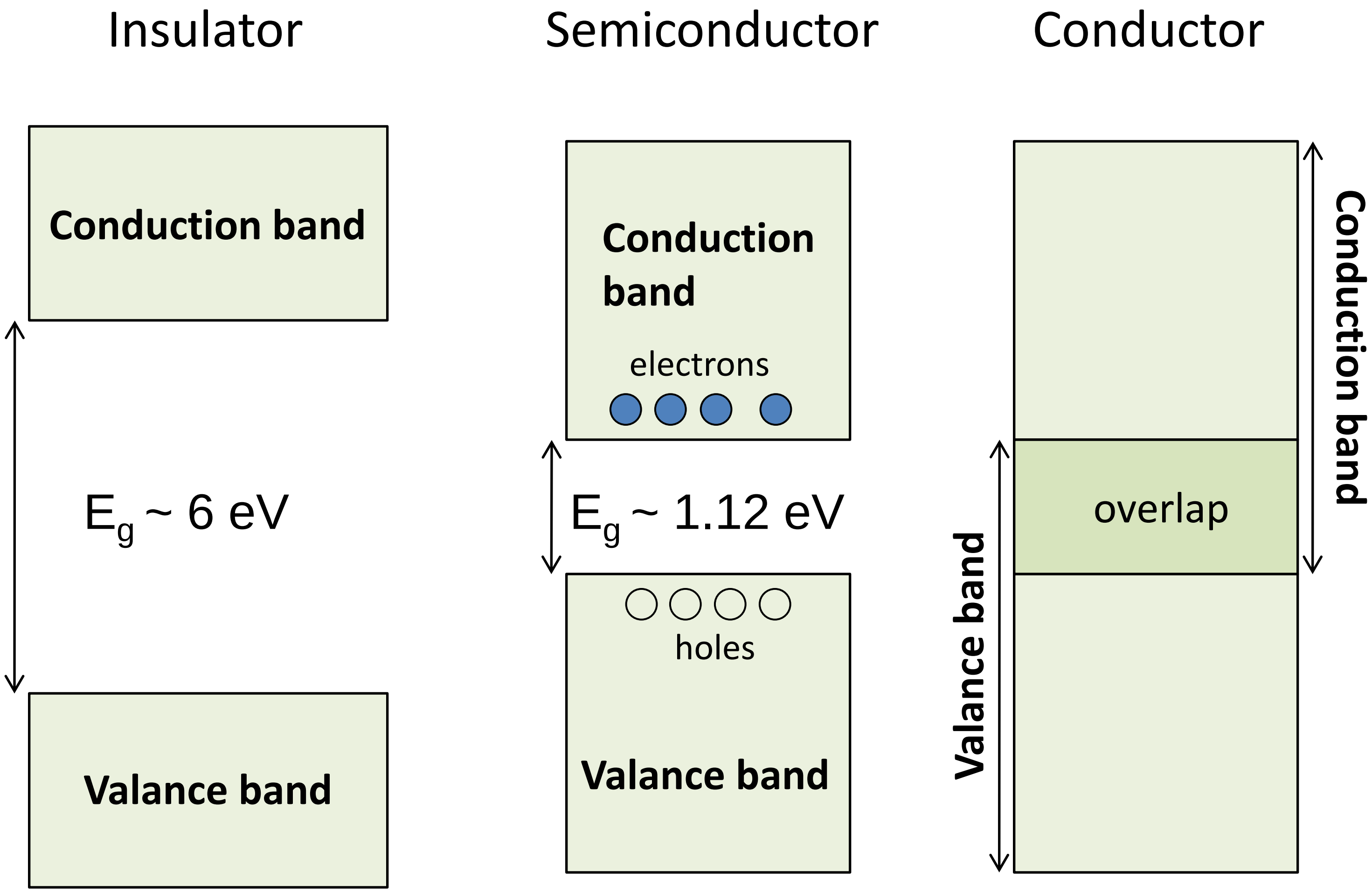
(1) Pure Appl. Chem., 73, No. 4, 667-683 (2001)

Relative atomic mass is shown with five significant figures. For elements have no stable nuclides, the value enclosed in brackets indicates the mass number of the longest-lived isotope of the element.

However three such elements (Th, Pa, and U) do have a characteristic terrestrial isotopic composition, and for these an atomic weight is tabulated.

Editor: Aditya Vardhan (adivar@nettlinx.com)

Basic properties – Band gap

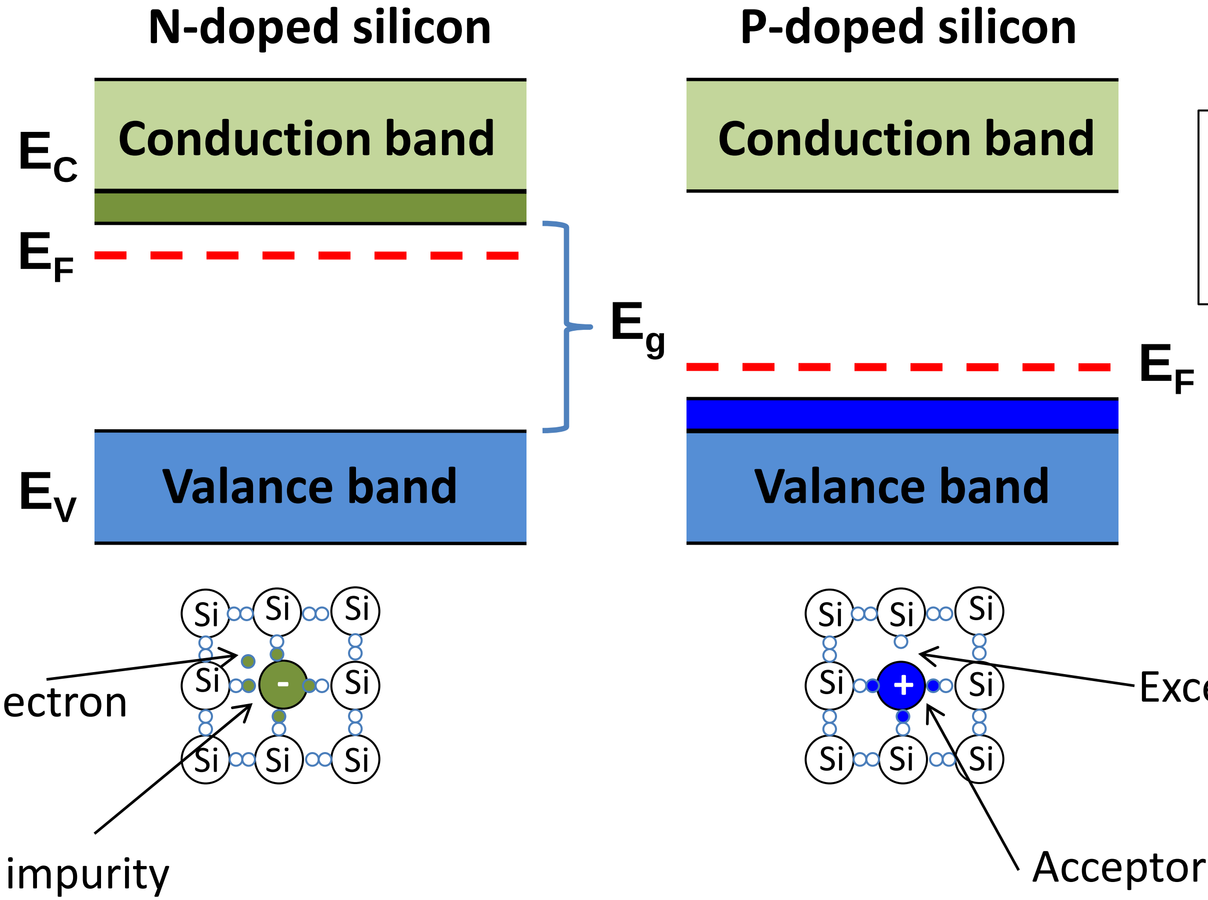


Basic properties

- Very pure material
- Charge carriers are created by
  - thermal, optical, and other excitations or ionization
- Four valance electrons (covalent bonds)
- Silicon (Si) and Germanium (Ge) are common
- Doped with extrinsic semiconductors
  - N-type: excess electrons (e- donor), i.e. P, As etc.
  - P-type: excess holes (e- acceptor), i.e. Al, B, Ga, etc.

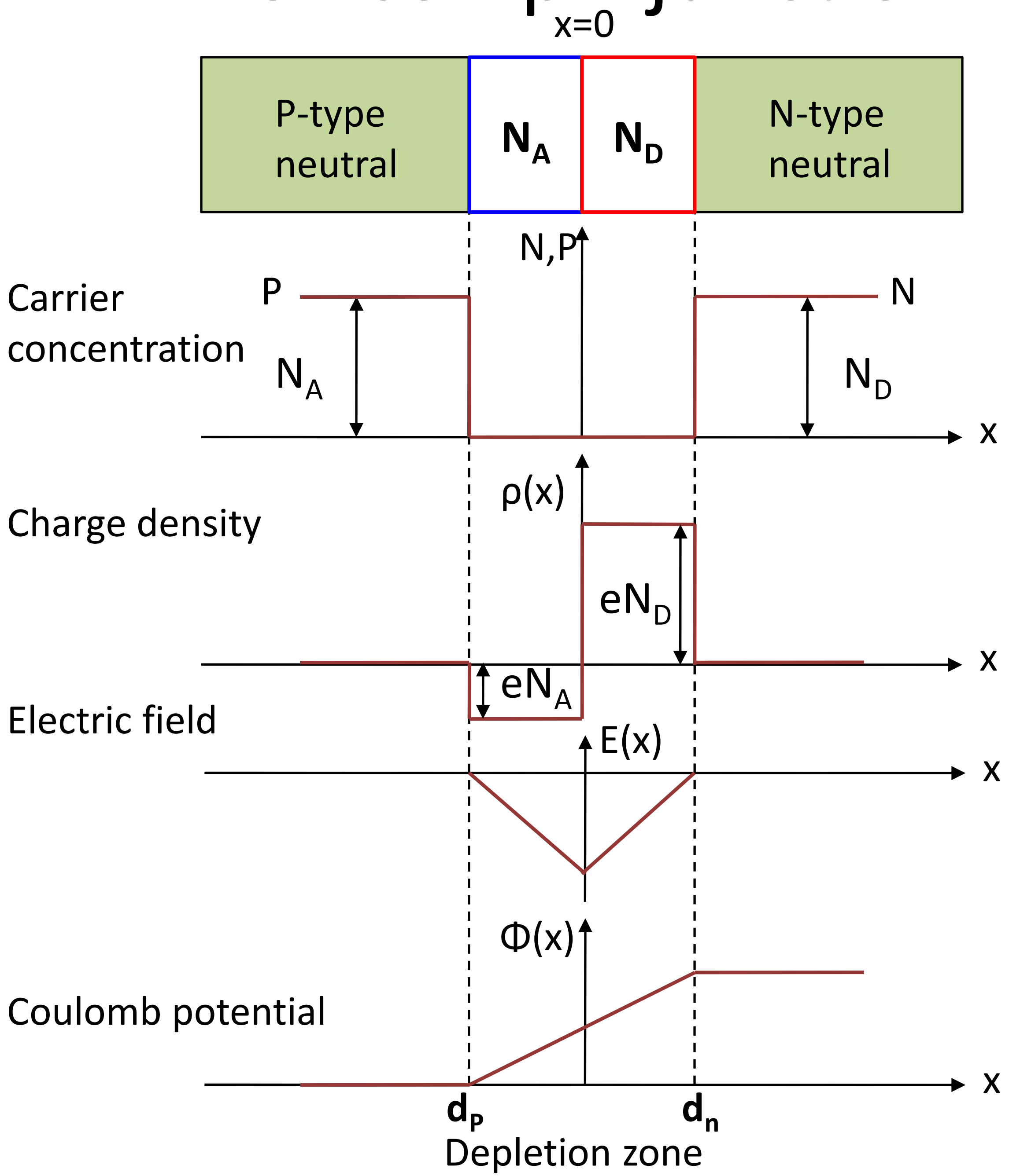
Silicon PN-junction

- Silicon detector are in basic form of PN-junction



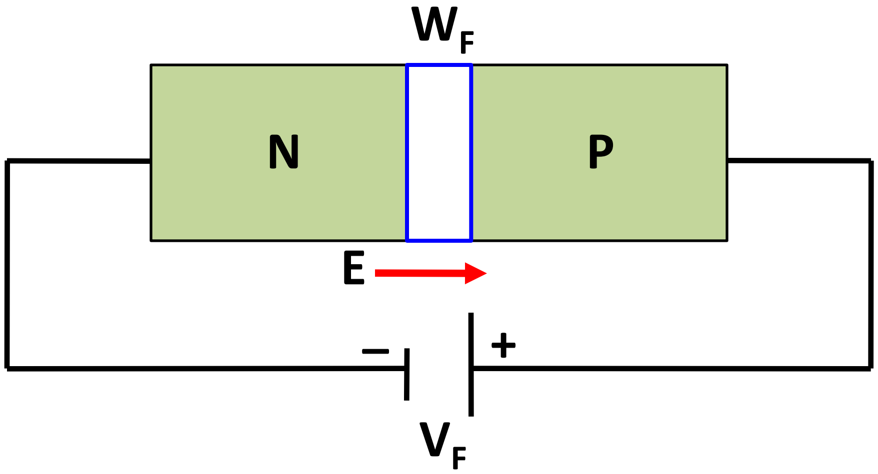
N-type: Phosphorus
P-type: Boron
E_g : Band gap (1.12 eV)

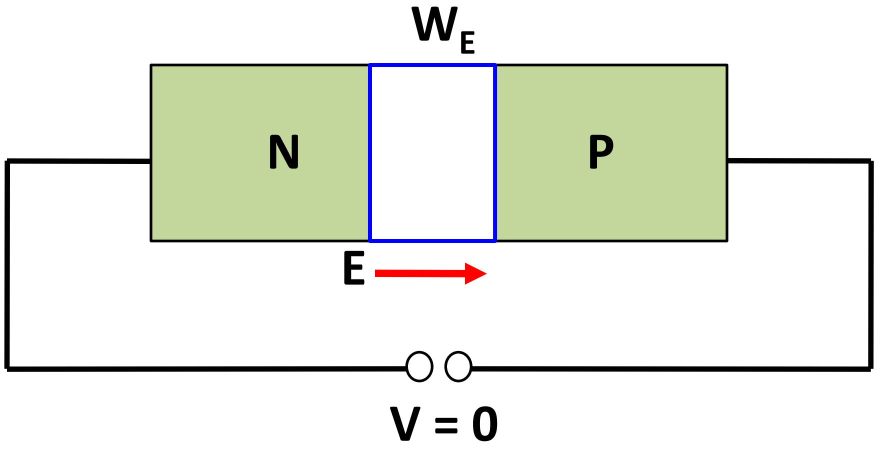
Silicon pn-junction formation

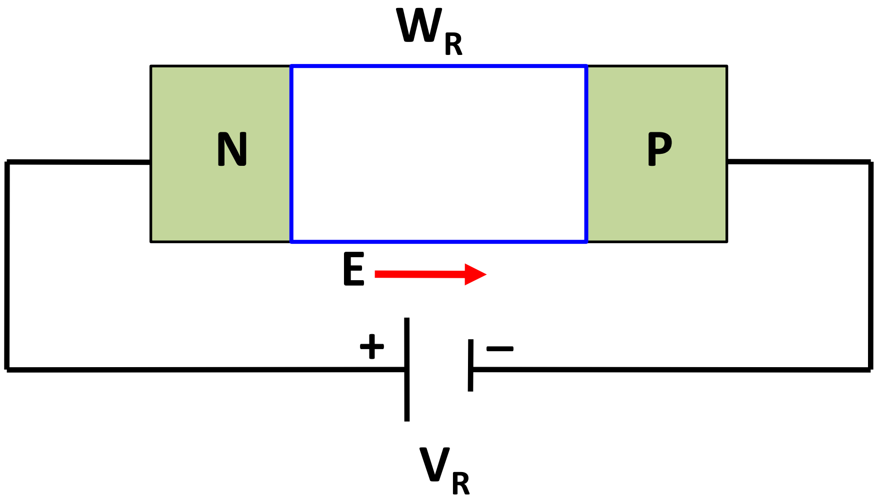


N_A: # of acceptor impurities
N_D: # of donor impurities

PN-junction bias schemes







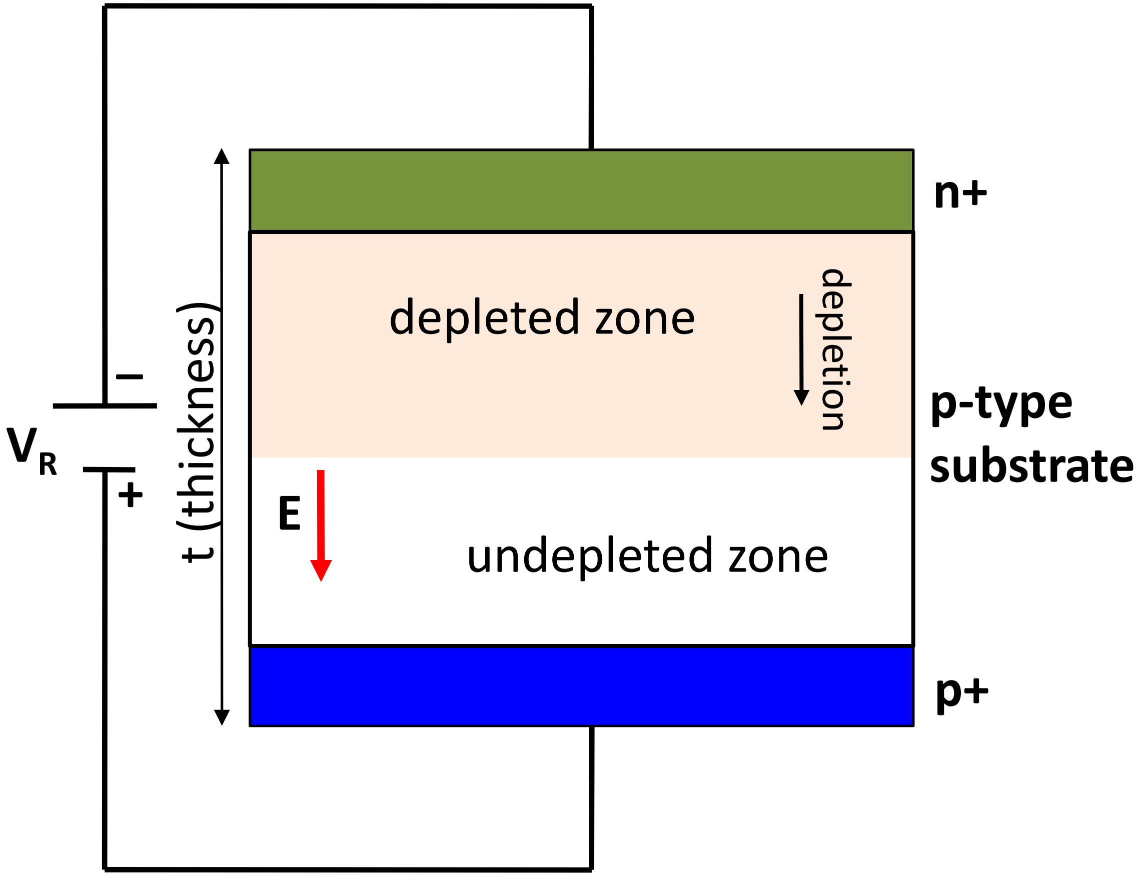
W_F : depletion width at forward bias
W_R : depletion width at reverse bias
W_E : depletion width in equilibrium

$W_F < W_E < W_R$

Reverse bias scheme is used for silicon detectors in HEP

A real life case

- Larger active area provided by n(p)-type subtstrate



Depletion with

$$W = \sqrt{2\epsilon\rho\mu V_R}$$

Resistivity

$$\rho = \frac{1}{q\mu N_{eff}}$$

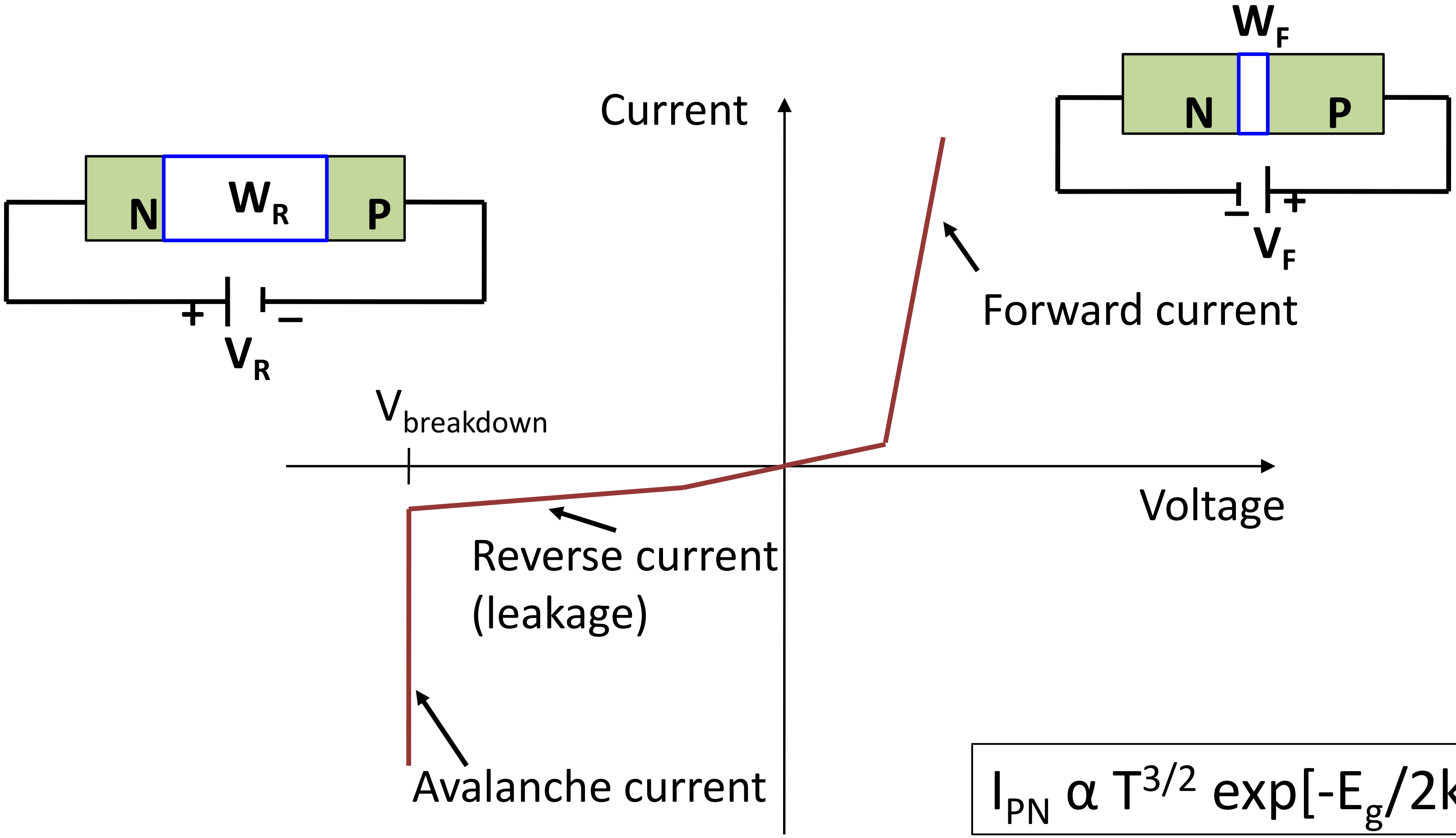
Depletion voltage

$$V_d = \frac{t^2}{2\epsilon\rho\mu}$$

Effective doping concentration

$$N_{eff} = |N_D - N_A|$$

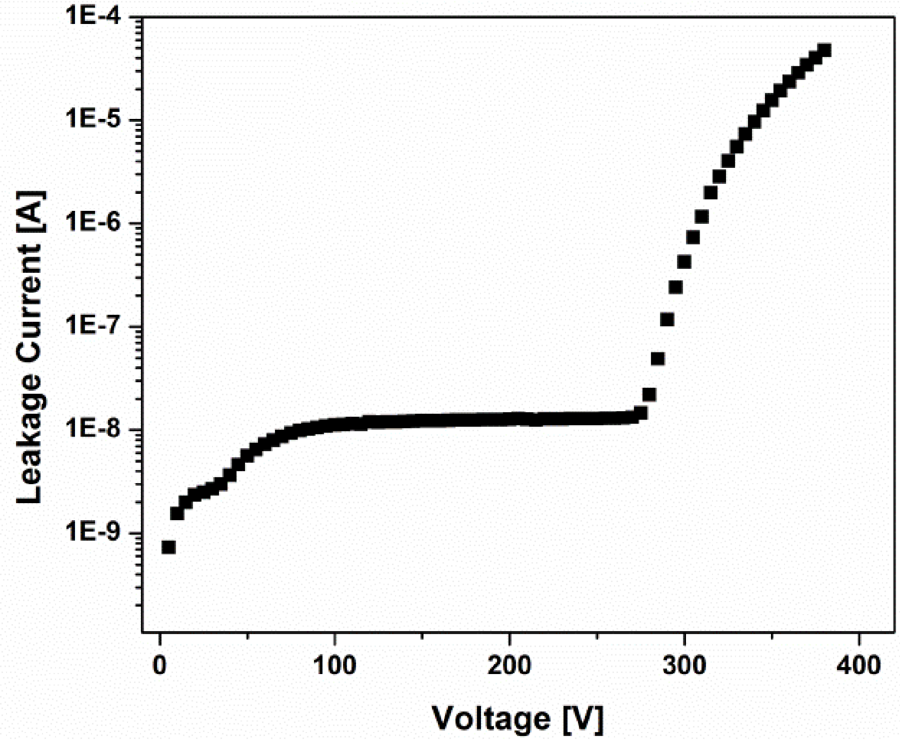
PN-junction current

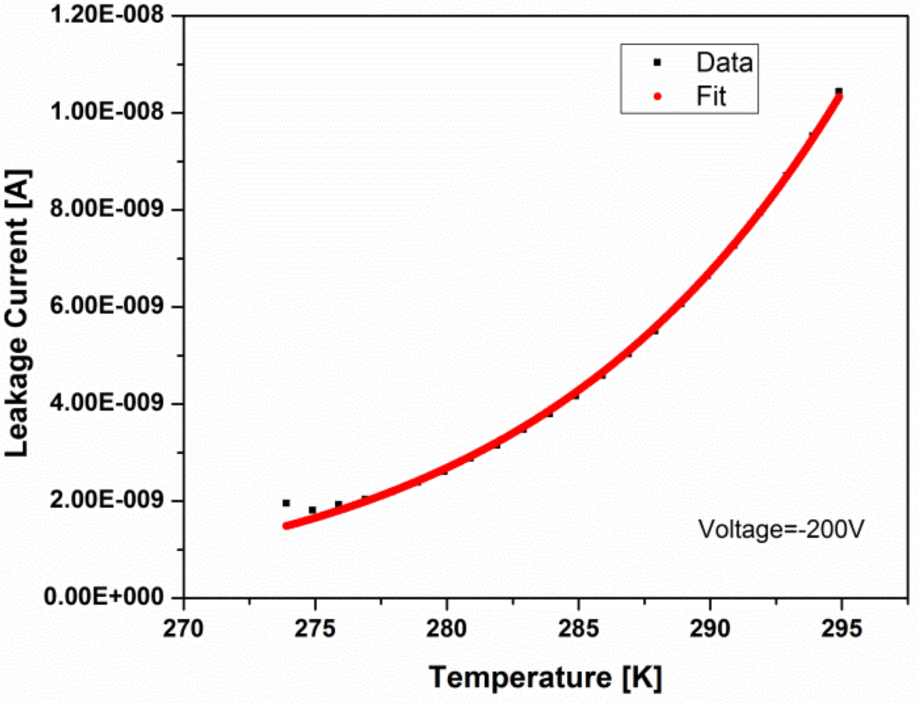


$I_{PN}\ \alpha\ T^{3/2} \exp[-E_g/2k_BT]$

Leakage current

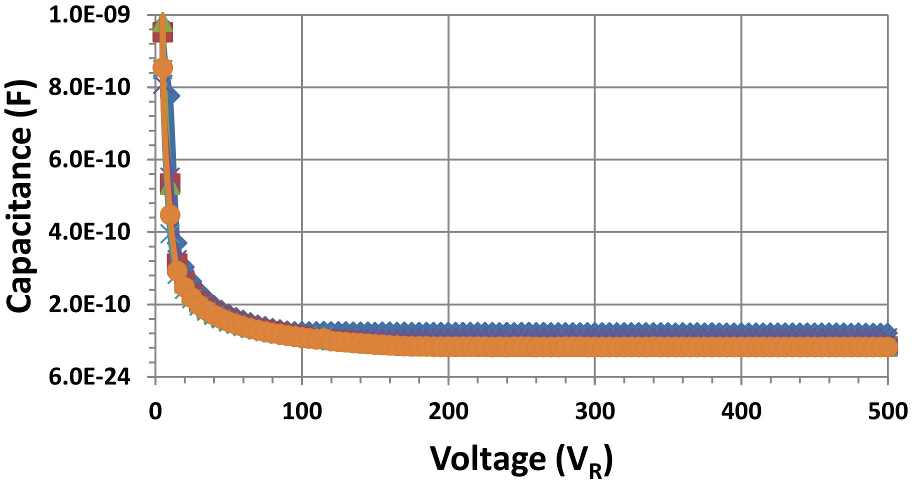
Current α $T^{3/2}\exp[-E_g/2k_BT]$



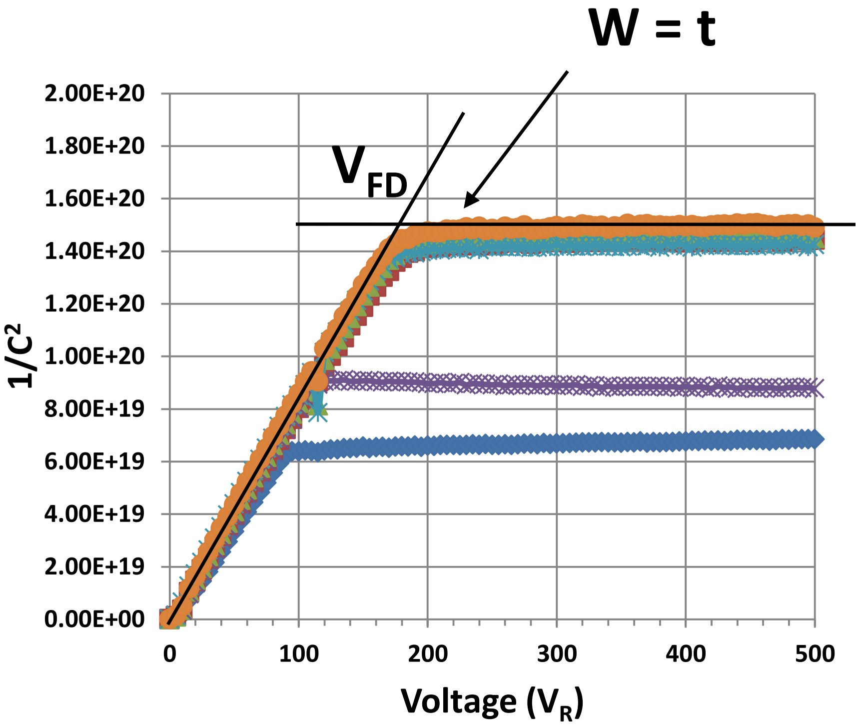


Breakdown voltage

- Extracted from capacitance measurements



$$C = A\sqrt{\frac{\epsilon}{2\rho\mu V_R}}$$



Charge collection

- Carriers are drifted under the electric field

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

μ_{e-} = 1500 cm^2/Vs μ_h = 450 cm^2/Vs

- Total drift time for a carrier created at depth x

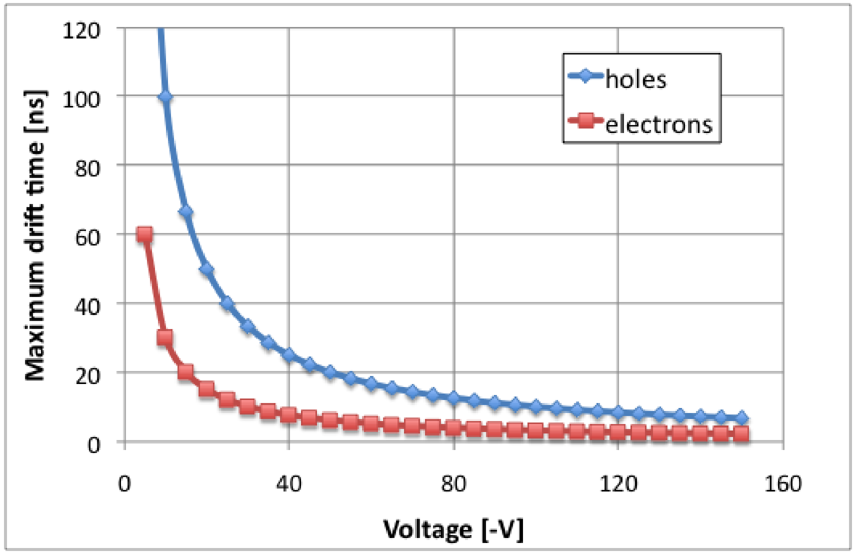
$$\mathrm{t(x) = \frac{d^2}{2\mu V_{FD}} \ln\left(\frac{V_B - V_{FD}}{V_B - V_{FD} + 2V_{FD}(1 - x/d)}\right)}$$

V_B = applied voltage
V_{FD} = full depletion voltage
d = detector thickness

- Maximum drift time (V_B >> V_{FD})

$$\mathrm{t_{max} = t(x=0) = \frac{d^2}{2\mu V_B}}$$

For d = 300 µm ➔

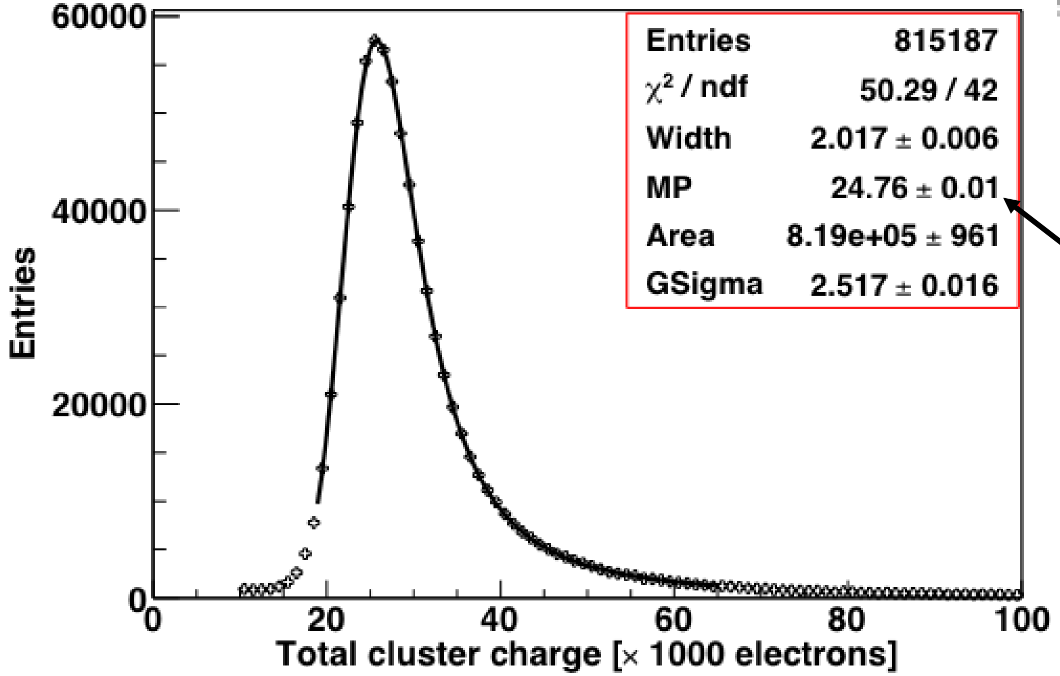


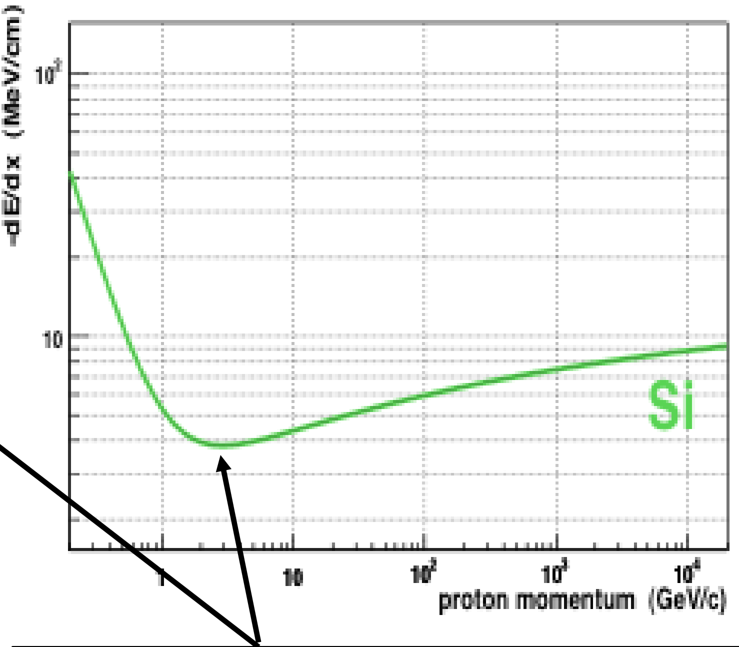
Radiation detection

Ionization energy loss:

$$-\frac{\mathrm{dE}}{\mathrm{dx}}[\mathrm{MeV/cm}] = 2\pi \mathrm{N_A} \mathrm{r_e^2} \mathrm{m_e} \mathrm{c}^2 \rho \frac{\mathrm{Z}}{\mathrm{A}} \frac{\mathrm{z}^2}{\beta^2} \left[\ln \left(\frac{2\mathrm{m_e} \mathrm{c}^2 \beta^2 \gamma^2 \mathrm{E_{kin}^{max}}}{\mathrm{I}^2} - 2\beta^2 - \delta \right) \right]$$

- Ionization loss follows Landau statistics
- Average energy loss is 390 eV/µm of Si
- Average charge is 108 e-h/µm of Si
- Most probable charge 80 e-h/µm of Si
    - 24 ke in 300 µm thick Si



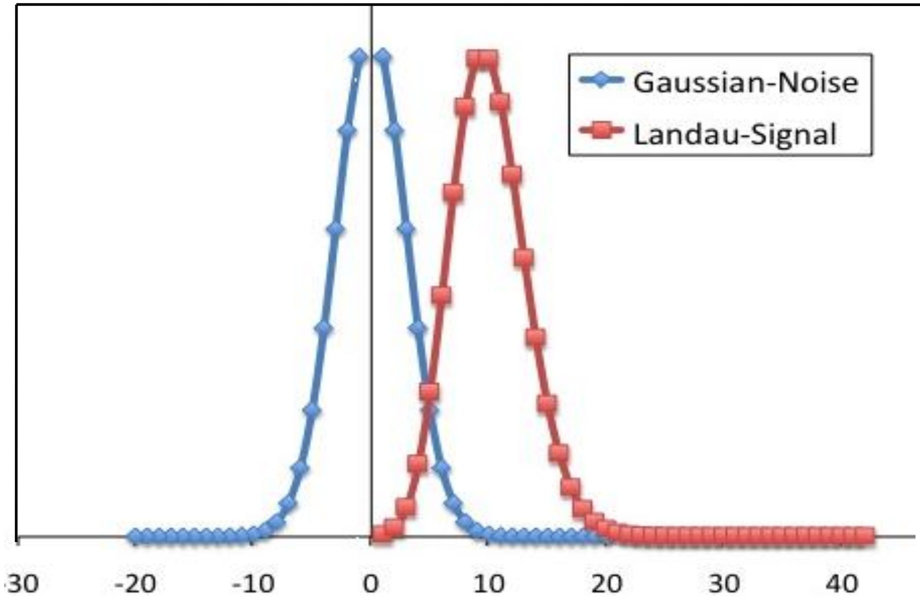


Most ionizing particle = Landau MP

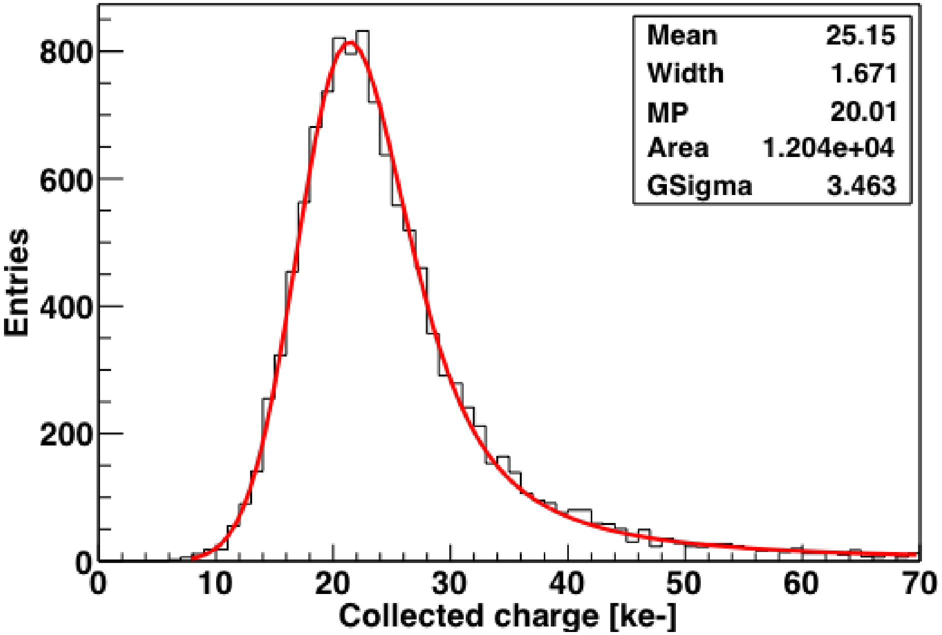
Signal-to-Noise (S/N)

- Signal is Landau, noise is Gaussian

$$S/N = \frac{\text{Most probable signal}}{\text{Noise}}$$



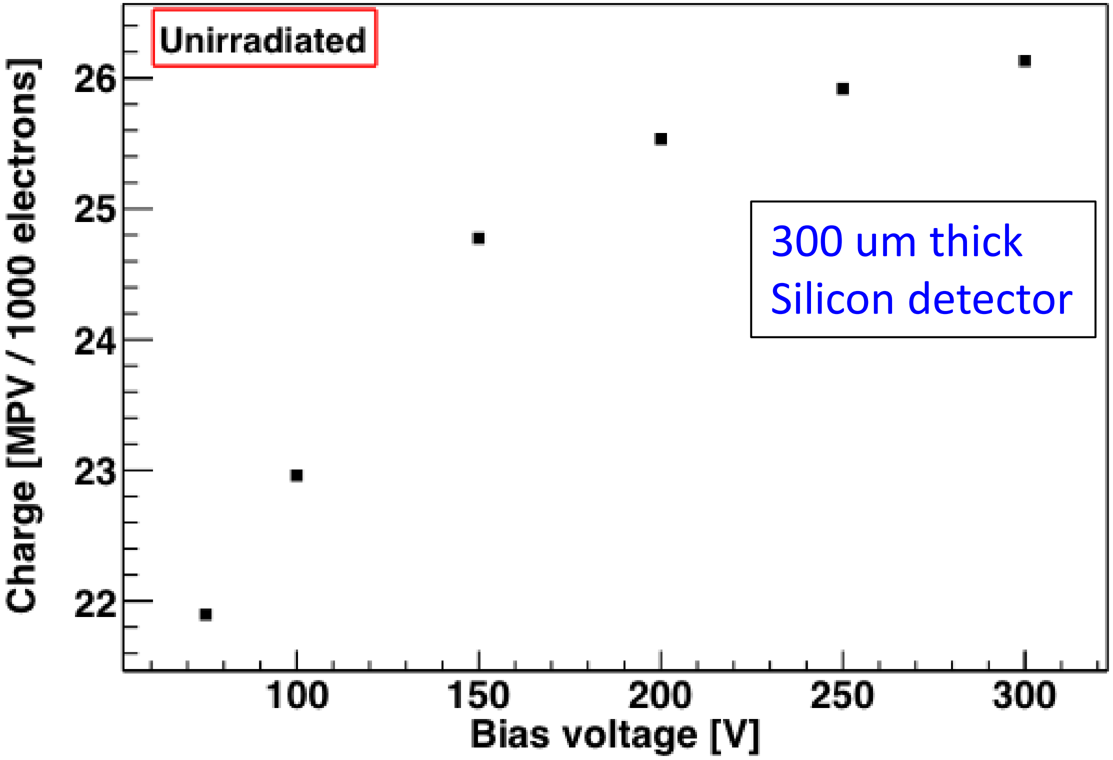
Landau+Gaussian fit

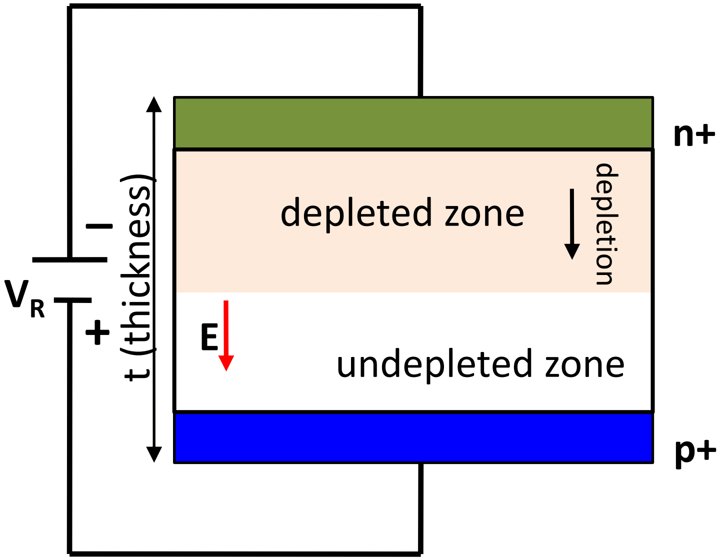


- Ionization energy loss follows Landau statistics
- Random electronic noise centered at zero is Gaussian

Charge vs applied bias

- Collected charge increases until full depletion is reached

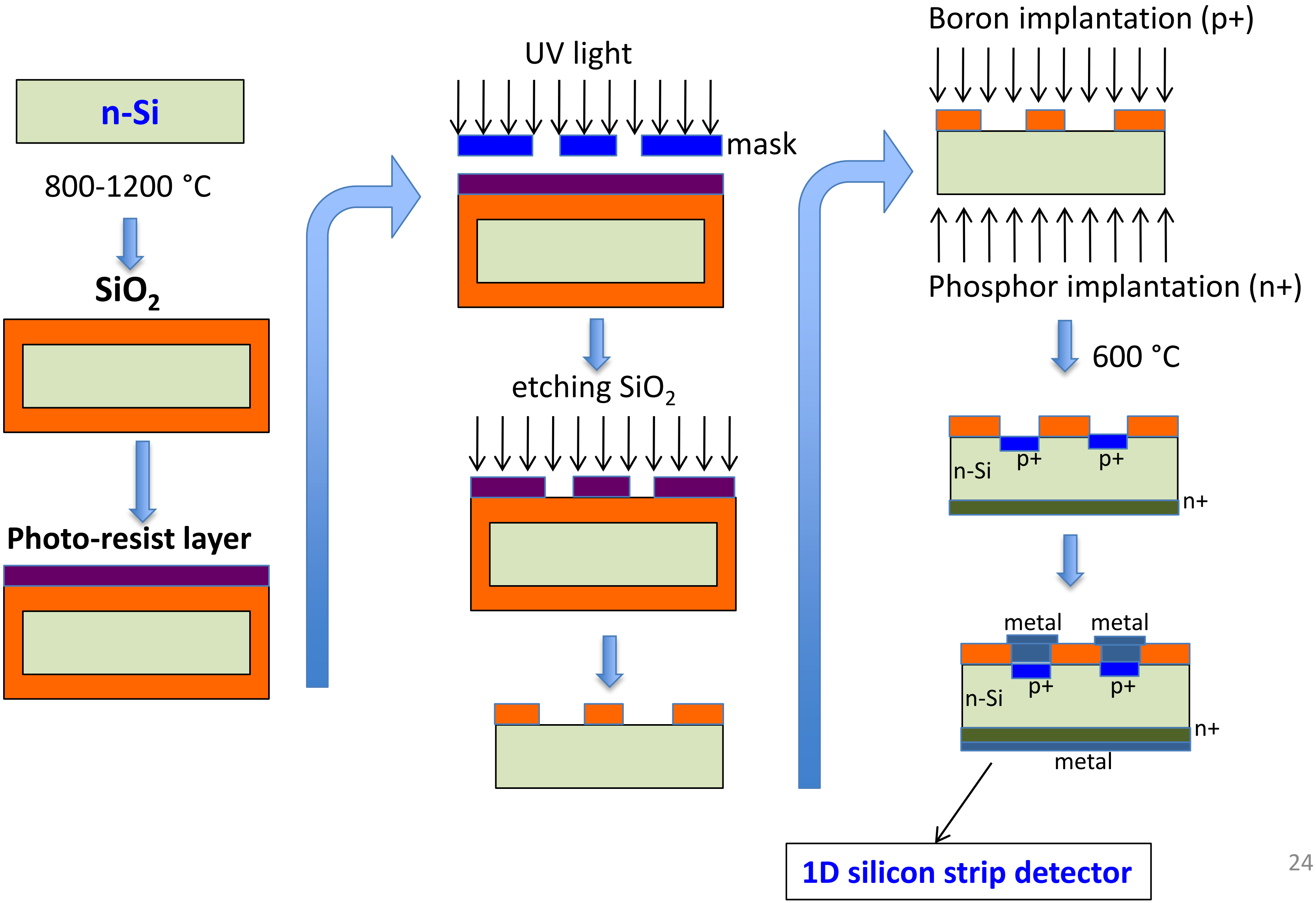




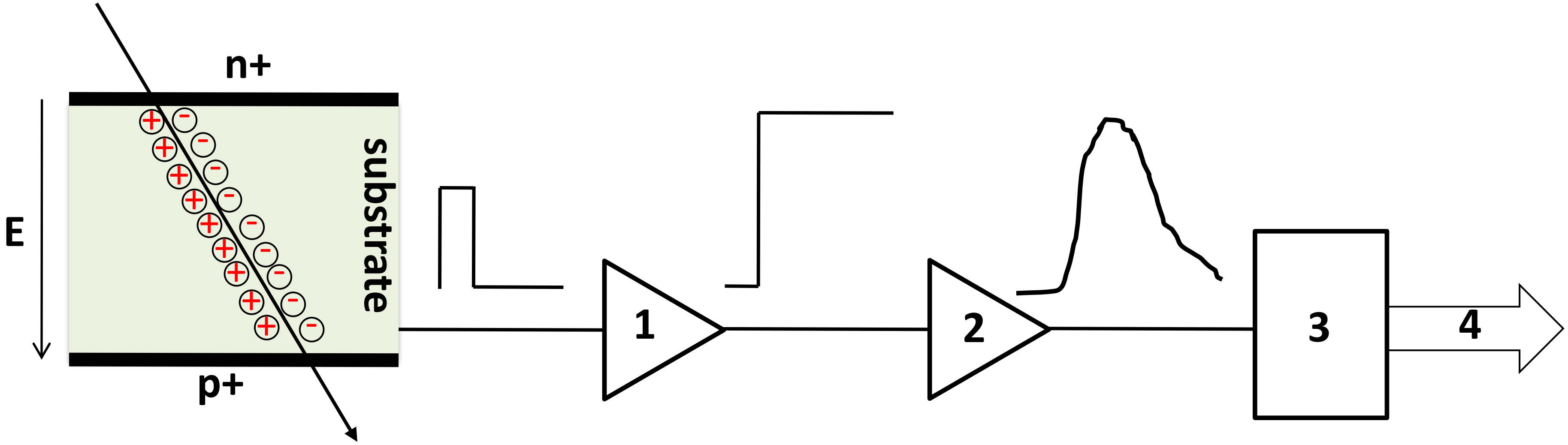
Silicon wafer fabrication

- Hyper-pure polysilicon chunks
- Melt and add impurity to make n-type (P) or p-type (B)
- Pour into a mold to make a polysilicon cylinder
- Melt onto a mono-crystal silicon seed by means of RF power
- Seed and melted polysilicon rotations are opposite to grow a round shape mono-crystal ingot
- Employ a grindwheel to form the ingot into a desirable diameters
- Cut ingot into wafers by means multi-wire-sawing
- Lapping to flatten wafers
- Chemical etching to smoothen wafers
- Edge rounding for wafer robustness

Device processing



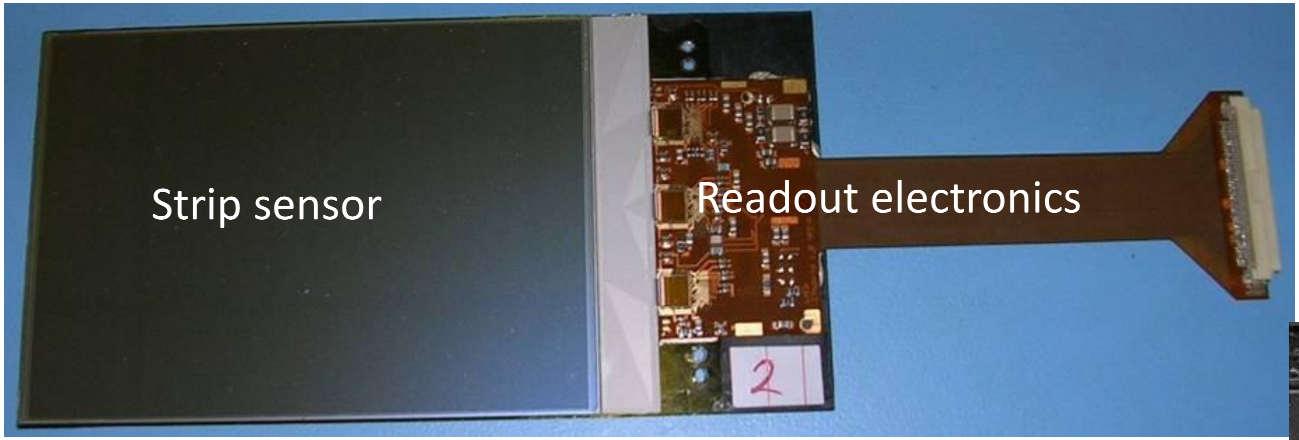
Principle of operation



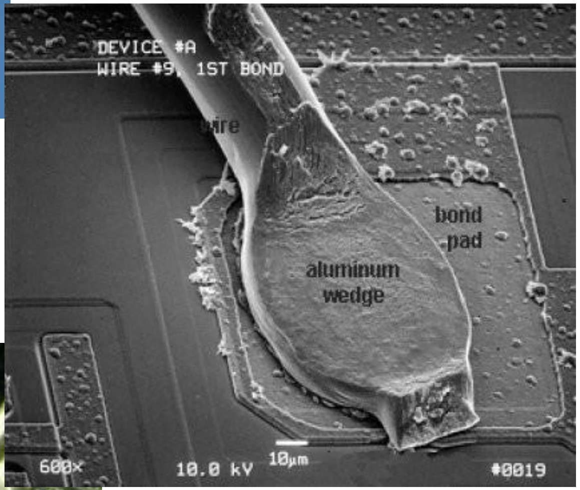
1. Preamplifier: amplifying small sensor signal
2. Pulse shaper: improving signal-to-noise ratio by filtering signal and attenuating electronic noise
3. Analog-to-Digital Converter (ADC)
4. Buffer: Store data

Front-end electronics add noise to signal (smearing). Low noise readout is essential

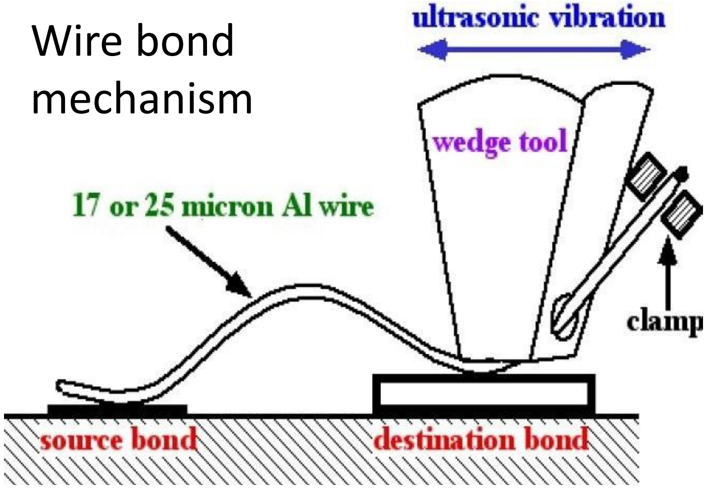
A silicon strip detector



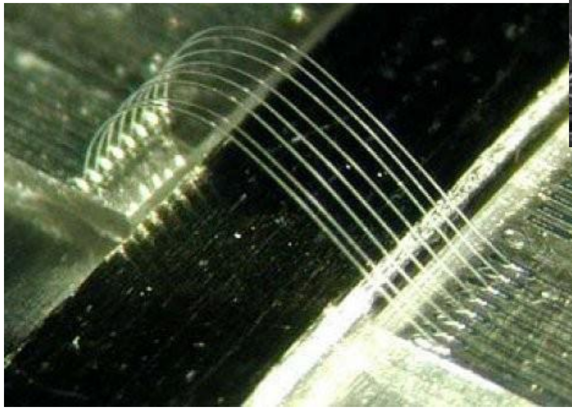
Wire bond (SEM image)



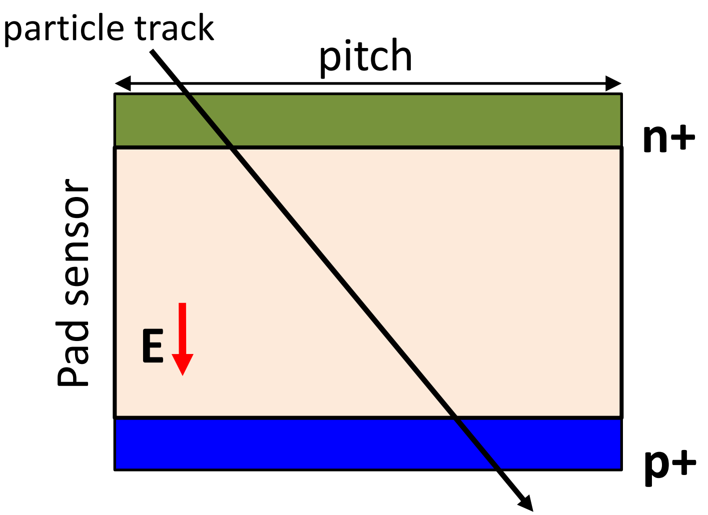
Wire bond mechanism



Wire bonds

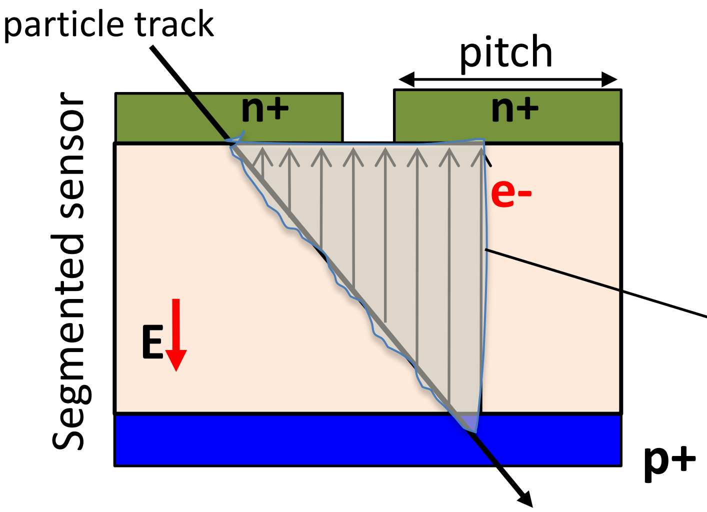


Position resolution



$$\sigma_{\text{hit}}^2 = \int_{-\text{pitch}/2}^{\text{pitch}/2} \frac{x^2}{\text{pitch}} dx = \frac{\text{pitch}^2}{12}$$

$$\boxed{\sigma_{\text{hit}} = \frac{\text{pitch}}{\sqrt{12}}}$$

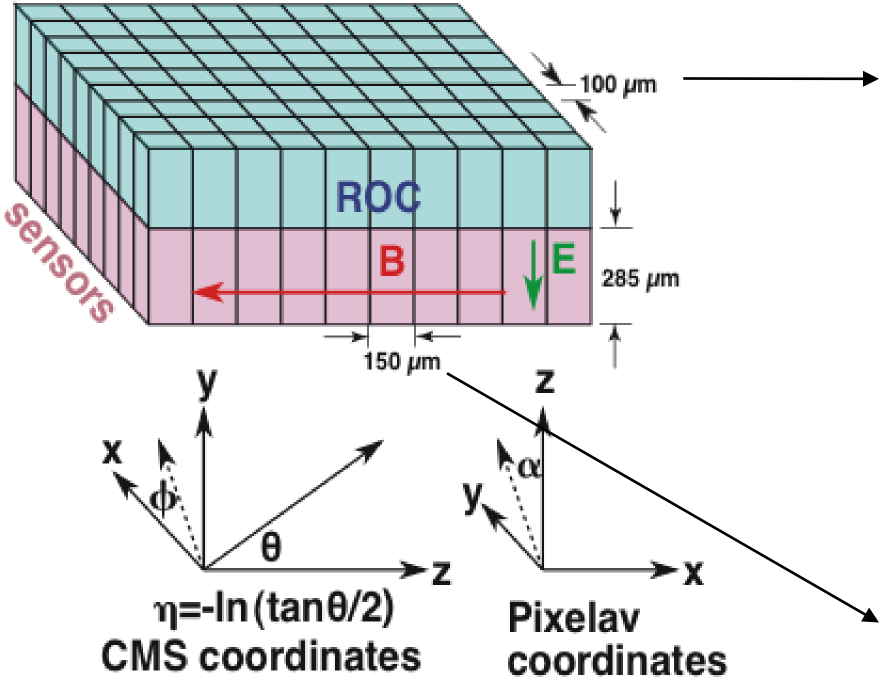


- Charge interpolation improves spatial resolution

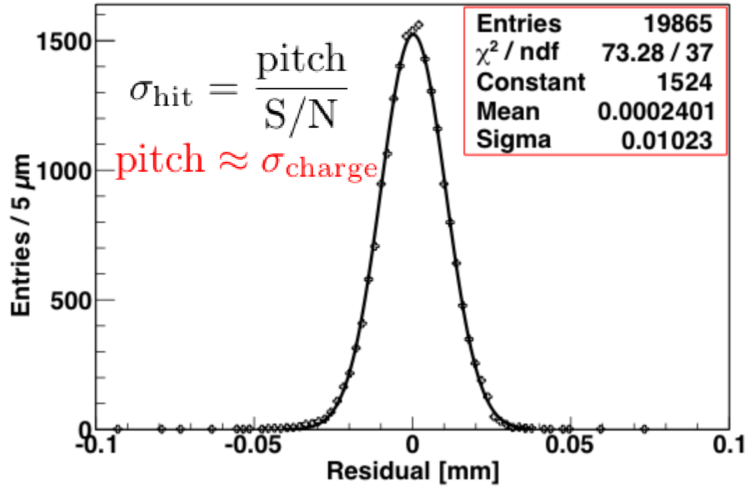
$$\sigma_{\text{hit}} = \frac{\text{pitch}}{S/N}$$

$$\text{pitch} \approx \sigma_{\text{charge}}$$

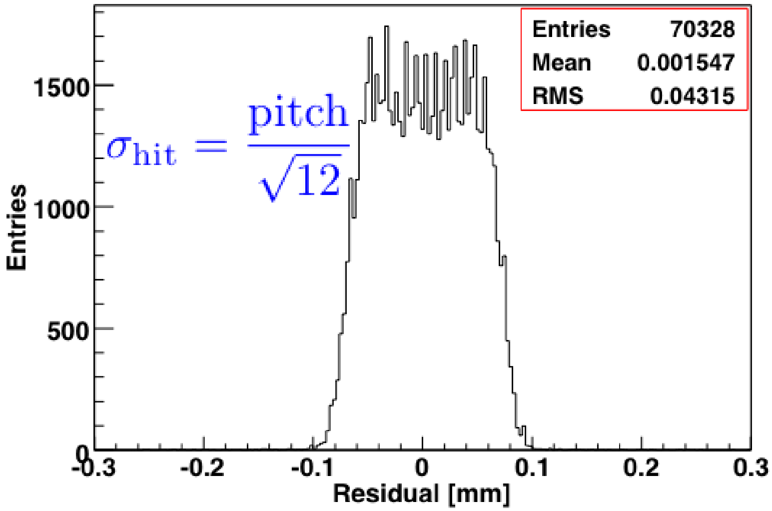
Position resolution



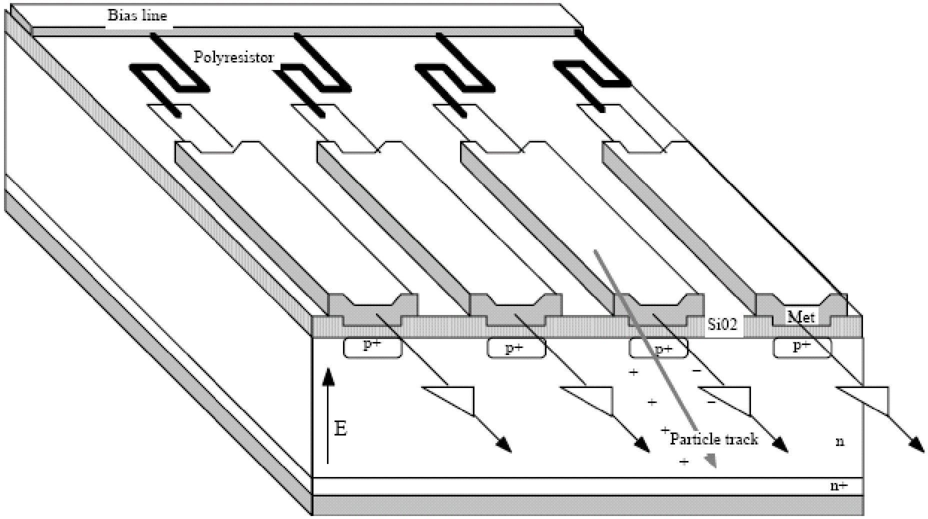
Charge interpolated spatial resolution

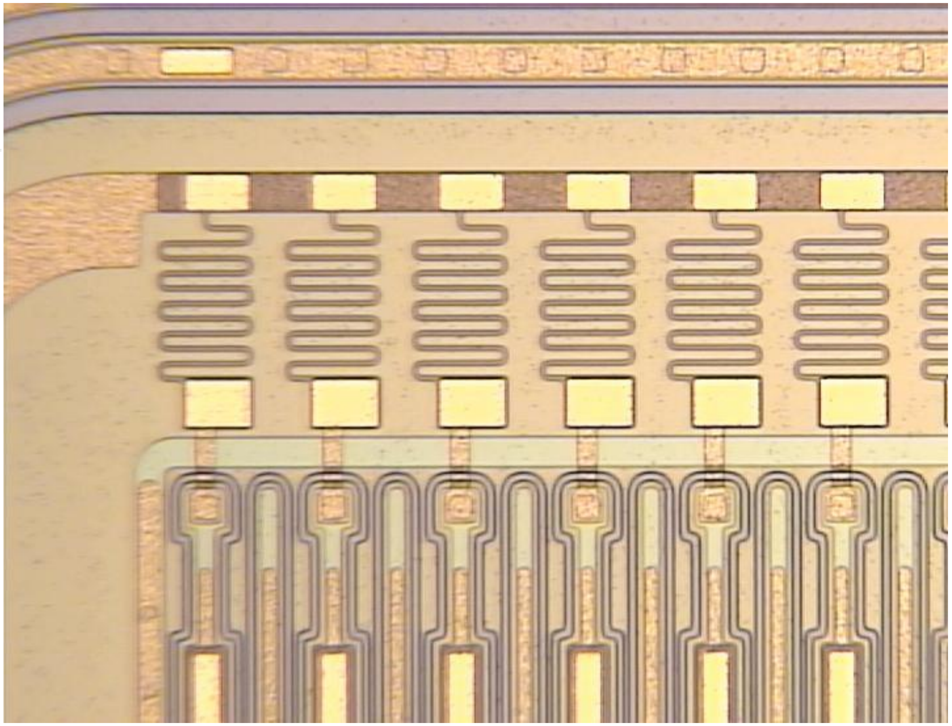


Binary spatial resolution

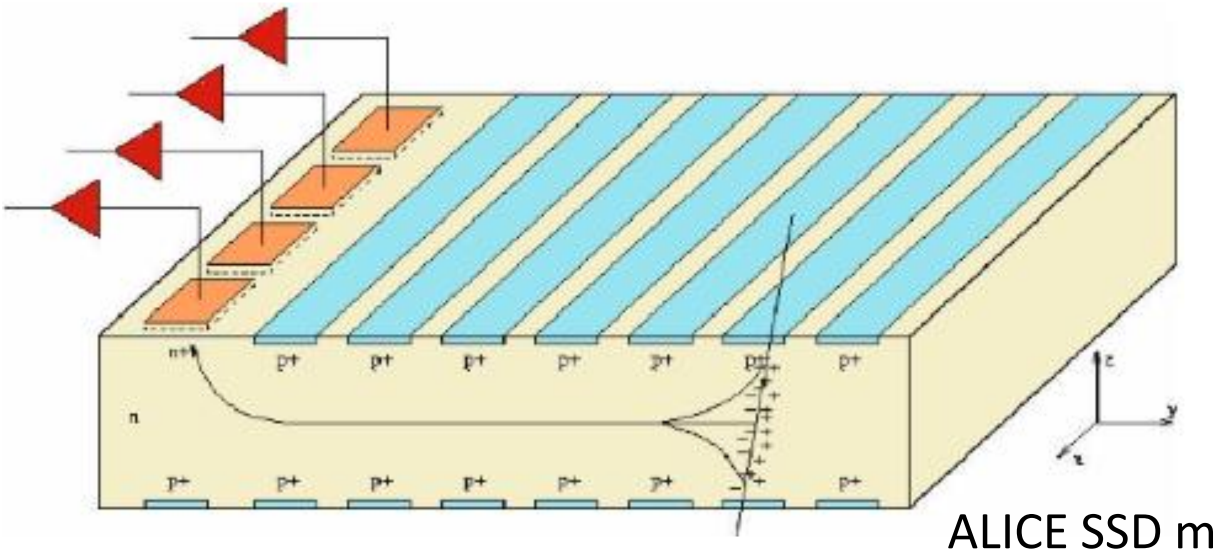


Microstrip detectors (1D)

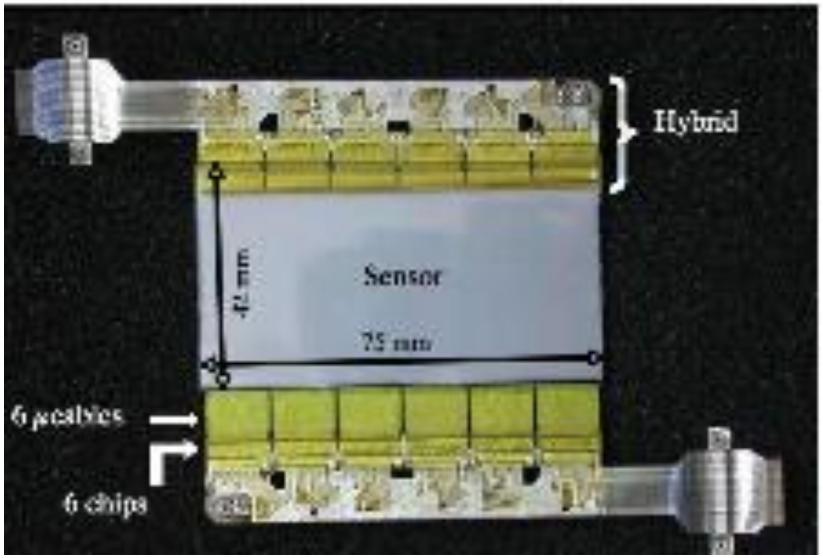




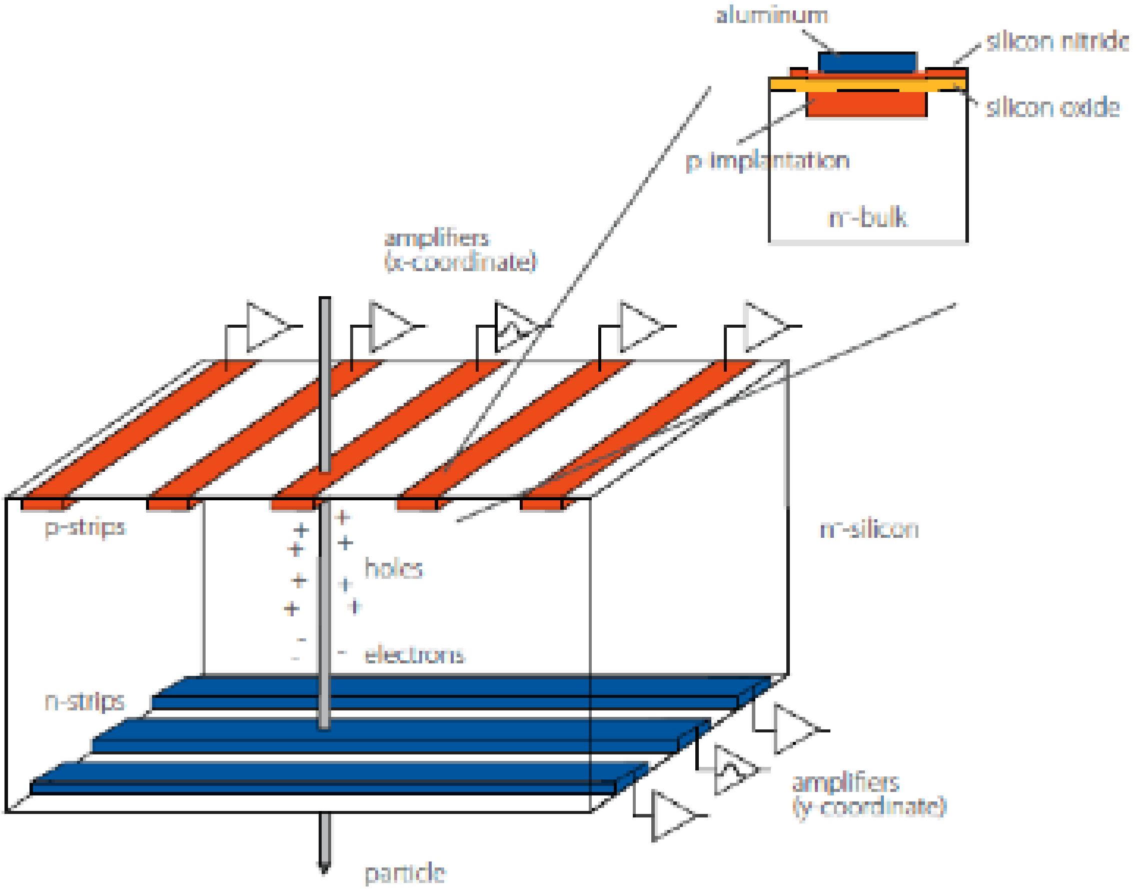
Silicon drift detector (SSD)



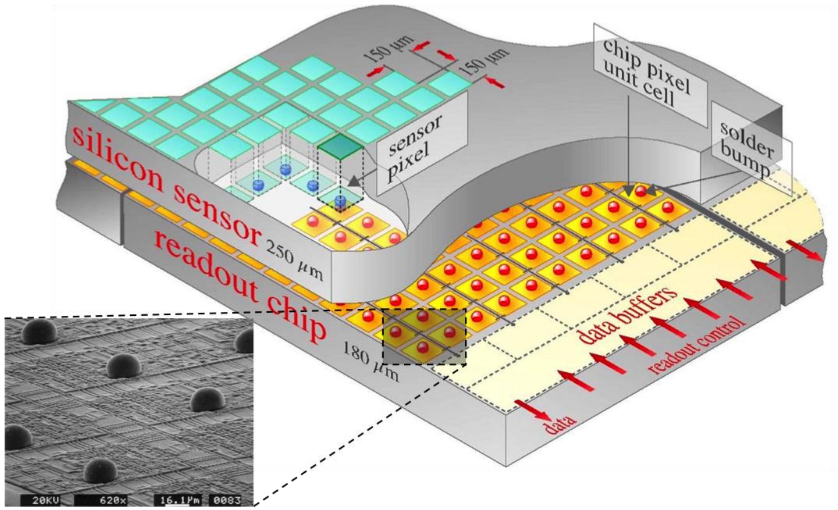
ALICE SSD module



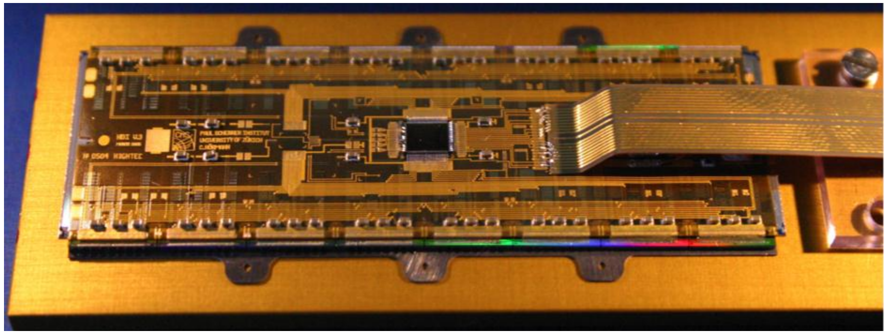
Double-side strip detector

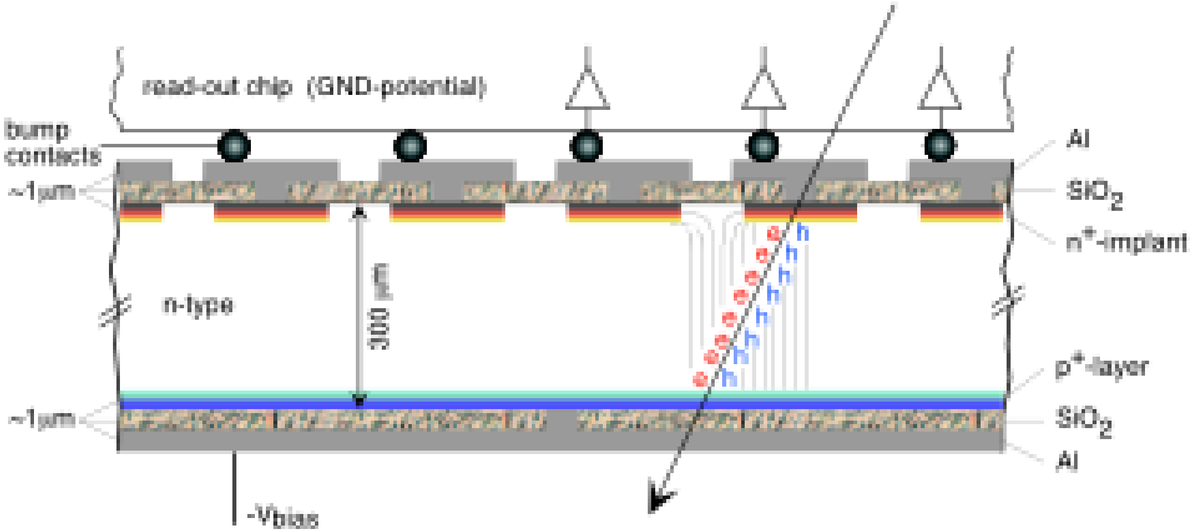


Pixel detector

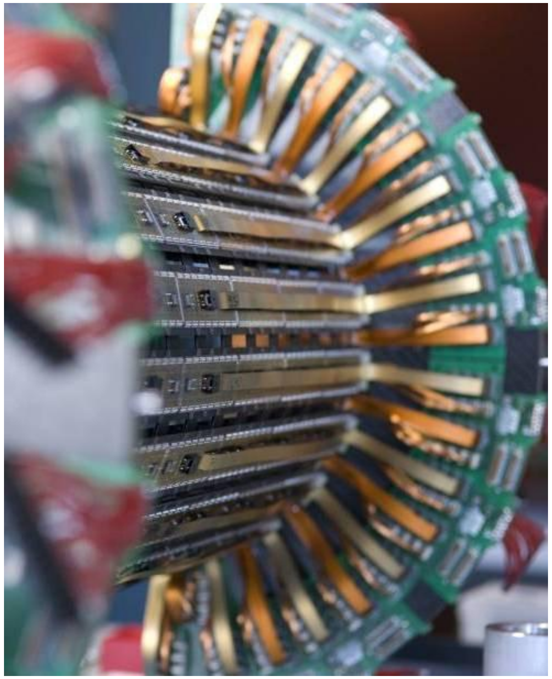


CMS BPIX module

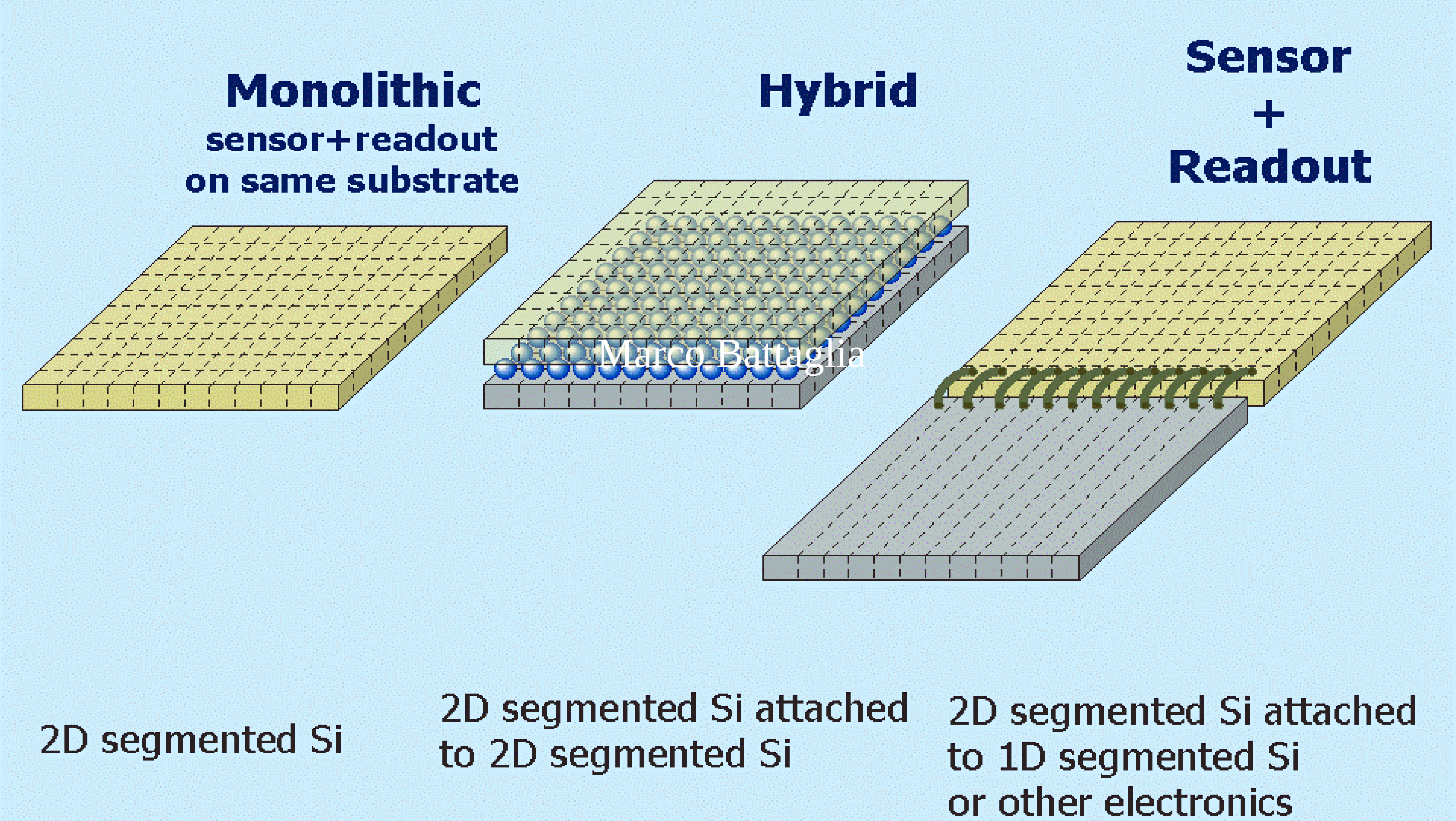




CMS barrel pixel detector



Detector topology



Monolithic
sensor+readout
on same substrate

Hybrid

**Sensor
+
Readout**

2D segmented Si

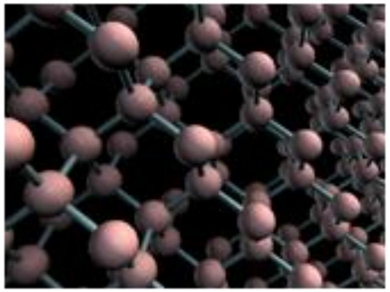
2D segmented Si attached
to 2D segmented Si

2D segmented Si attached
to 1D segmented Si
or other electronics

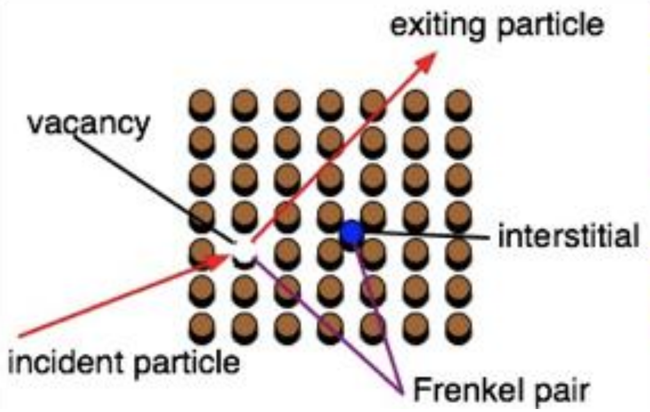
Marco Battaglia, EDIT 2012, Silicon Track, February 2012

Radiation damage

1) nuclear particle (i.e. p,n etc.) collides with a lattice atom,
2) the lattice atom is kicked out from it position leaving behind a vacancy
3) the displaced atom can collide others creating more interstitial positions (clusters)

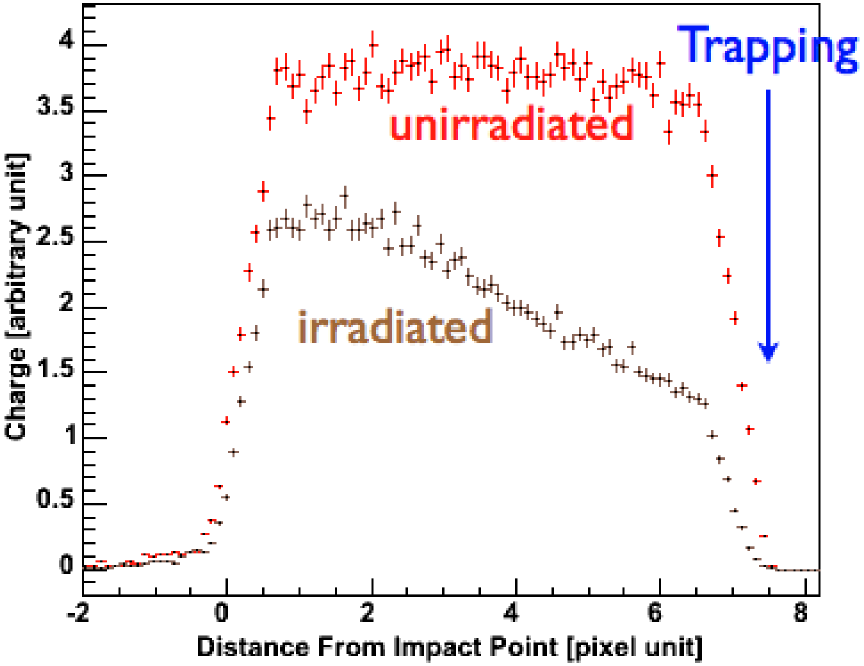


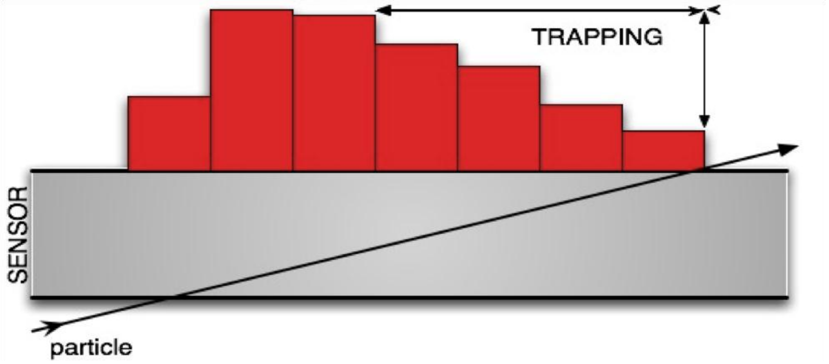
Si Atoms



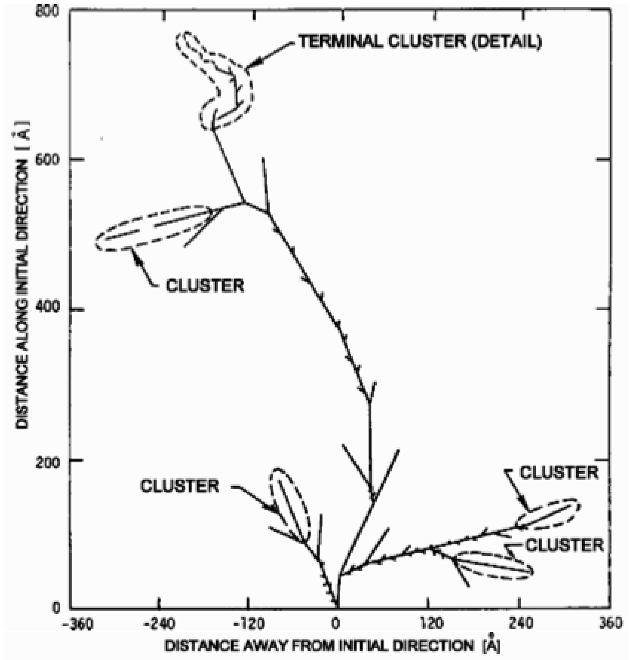
- an energetic nuclear particles knocks out an atom resulting Frenkel pairs (defects)
- above 150 K 90 % of pairs recombined (thermal vibrations in lattice)

Radiation damage





Recoil after 1 MeV neutron collision



Radiation induced damages

- cause severe signal losses across sensor thickness

Signal loss can be covered partially

- by increasing high voltage

But high voltage

- degrades the position resolution

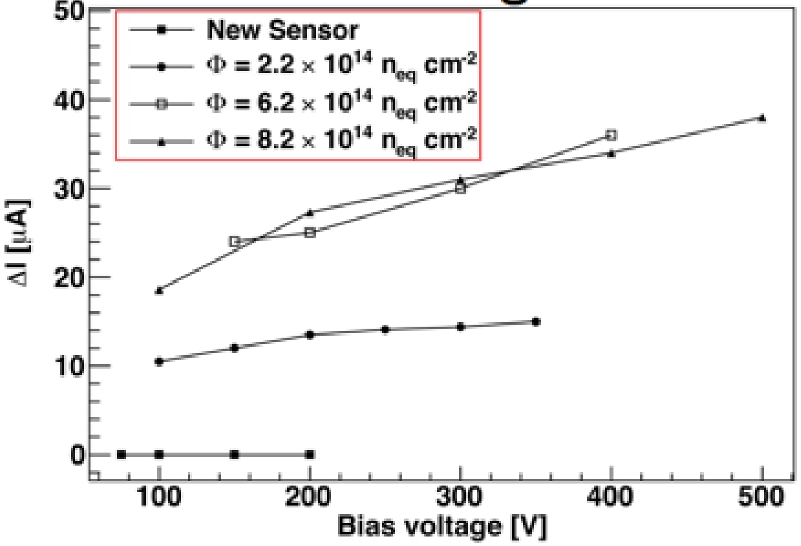
Radiation damage effects

- Leakage current increases $\Delta I = \alpha \Phi V$
  - ΔI change in current in volume V
  - α is damage constant
  - Φ is time-integrated radiation flux
- Depletion voltage increases

  $V_{FD} = q|N_{eff}|d^2 /2\varepsilon\varepsilon_0$
  - $N_{eff} = |N_{donor}-N_{acceptor}|$
  - $\varepsilon\varepsilon_0$ permittivity
  - d is sensor thickness
- Charge collection degrades
- Position resolution degrades

Radiation damage – leakage current

measured leakage current



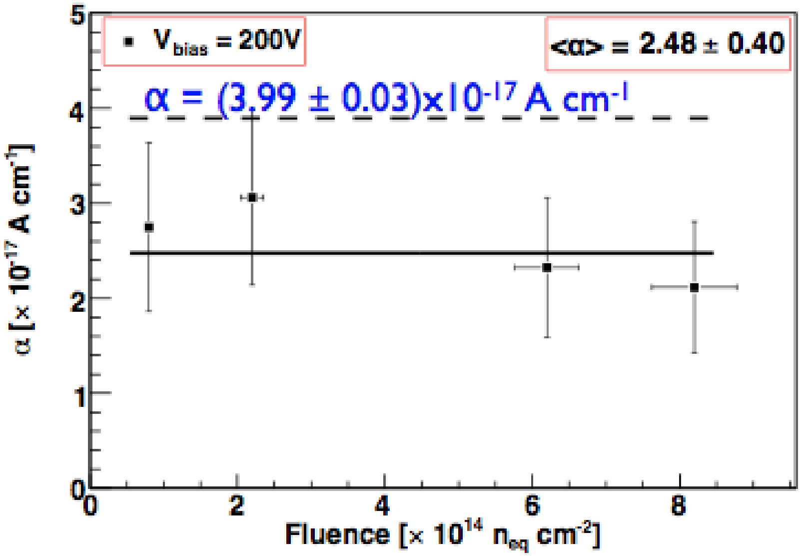
$$\alpha = \frac{\Delta I}{V \cdot \Phi}$$

α - damage rate

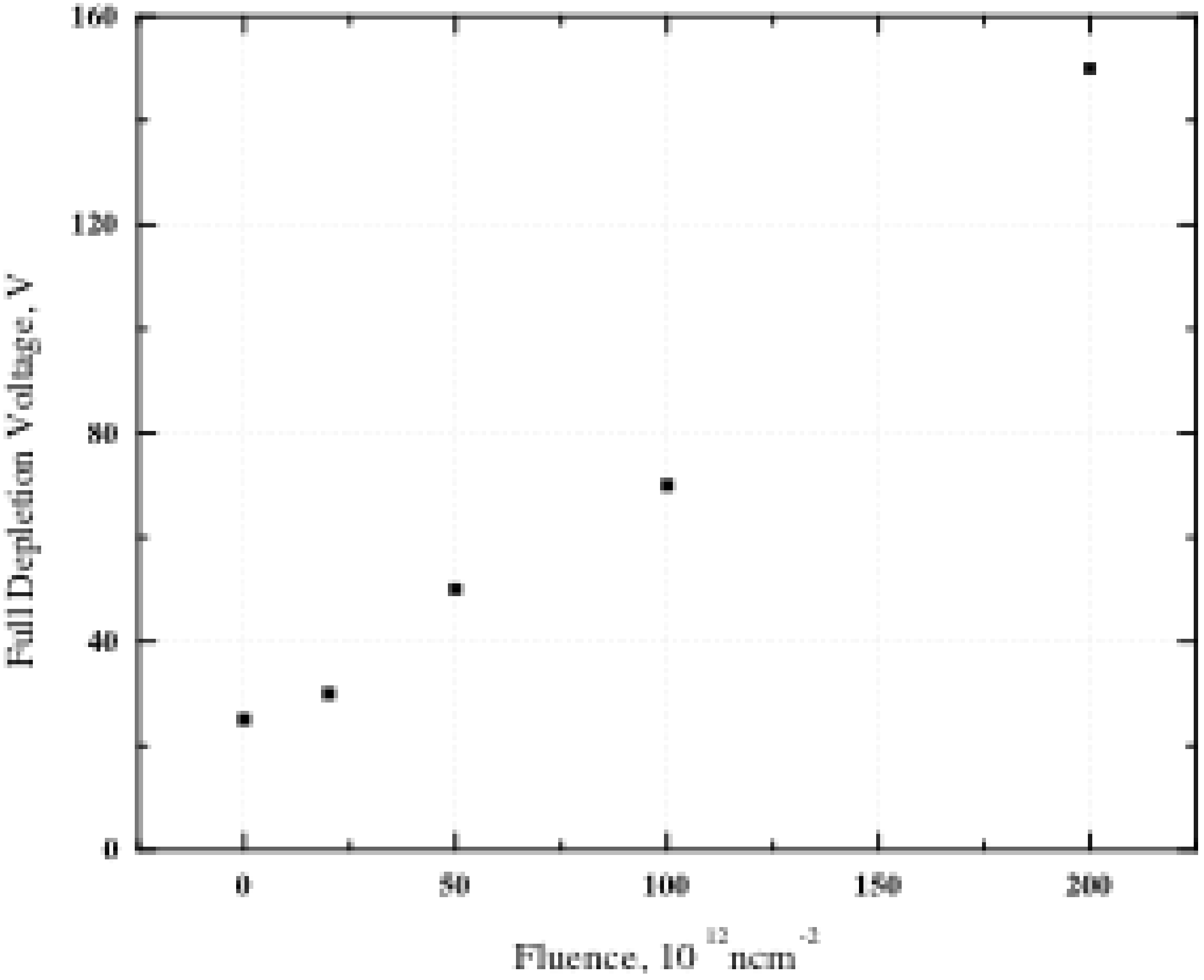
Φ - fluence

ΔI - leakage current

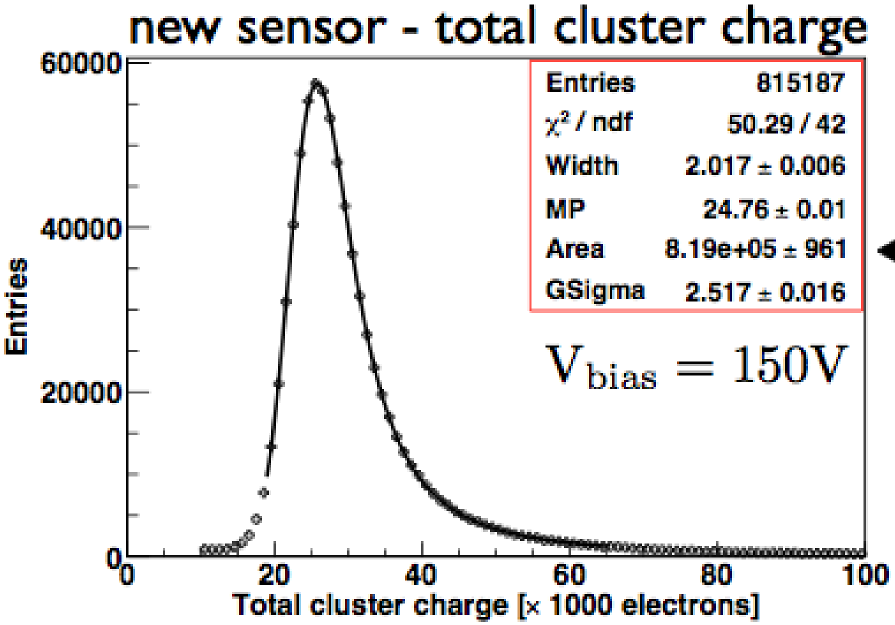
V - volume (0.018 cm^3)



Radiation damage - V_{FD}

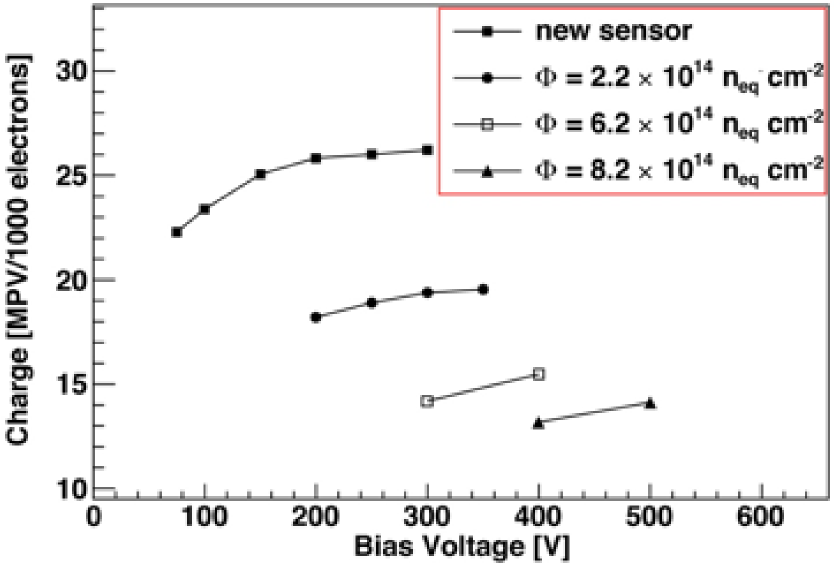


Radiation damage – charge collection



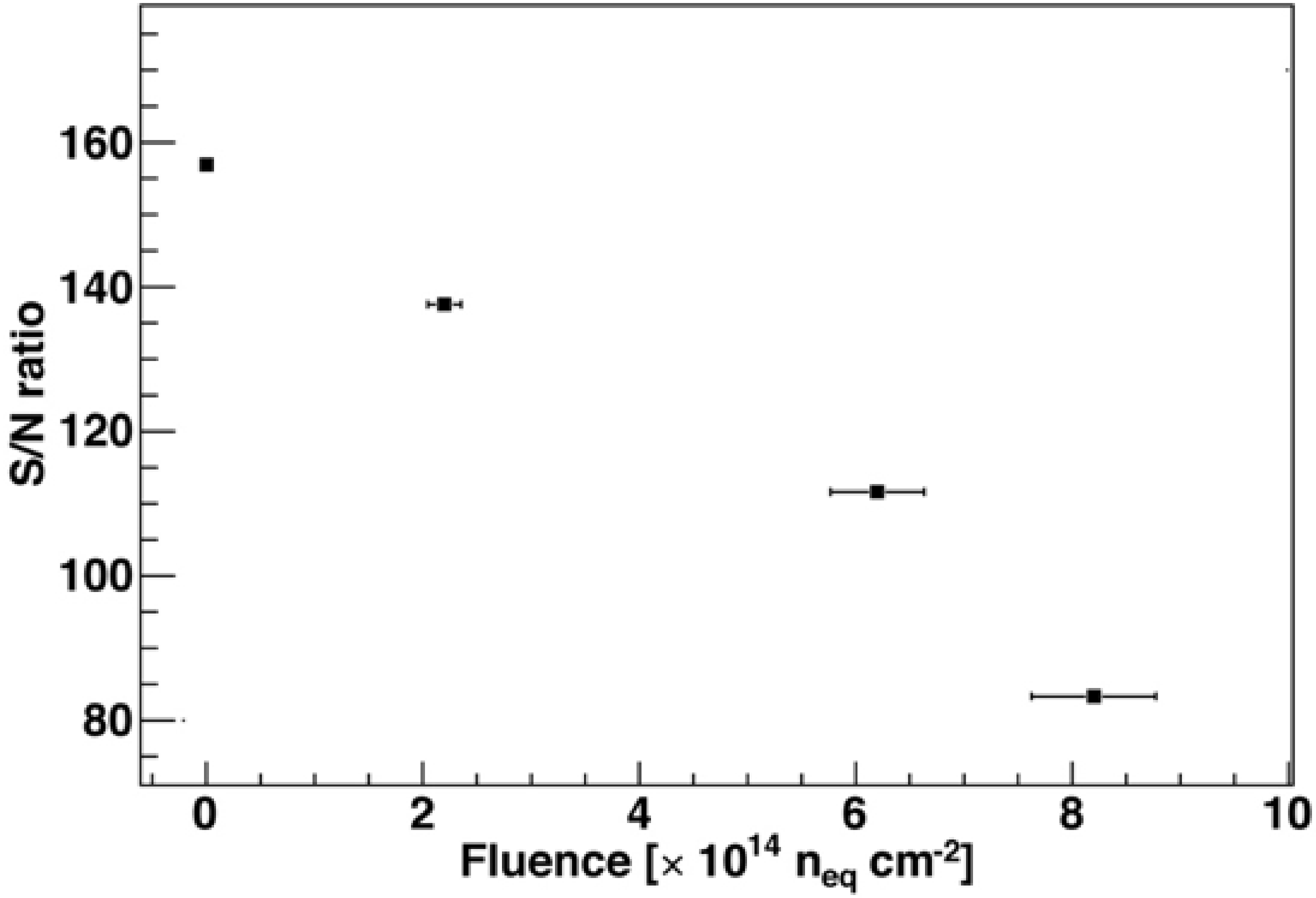
Gaussian convoluted with a Landau function fit to total cluster charge

- measurable Landau most probable values (MP) are shown
- charge collection decreases with irradiation
- higher bias voltage can recover some lost charge



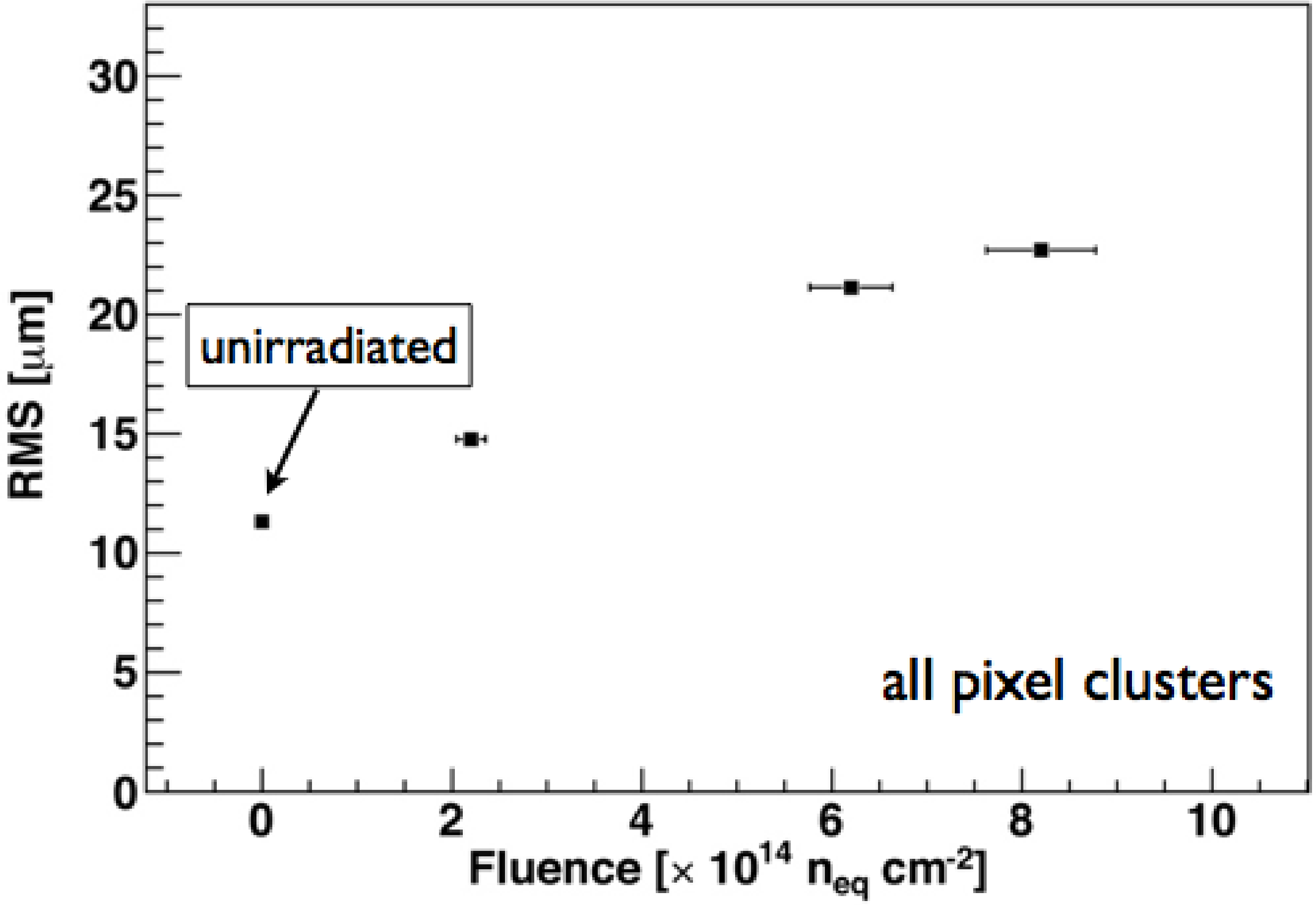
Radiation damage – S/N

- signal (S) is the MP value of the Landau fit
- noise (N) is from the noise test



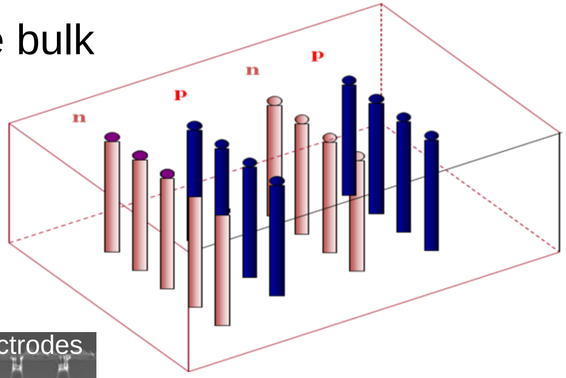
Radiation damage – spatial resolution

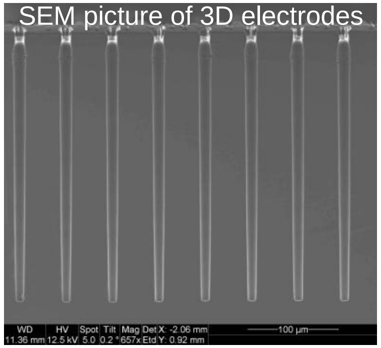
- overall resolution (RMS) decreases with irradiation



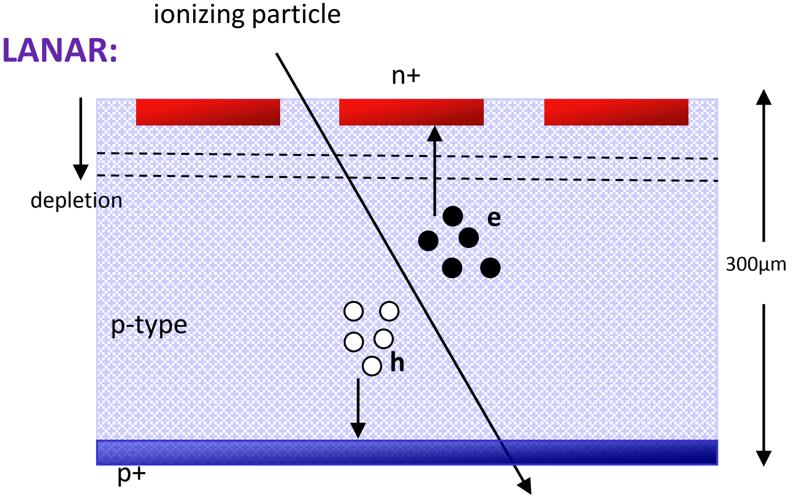
Radiation harder approaches – 3D

- p+ and n+ electrodes are arrays of columns that penetrate into the bulk
- Lateral depletion
- Charge collection is sideways
- Superior radiation hardness due to smaller electrode spacing:
  - smaller carrier drift distance
  - faster charge collection
  - less carrier trapping
  - lower depletion voltage
- Higher noise
- Complex, non-standard processing

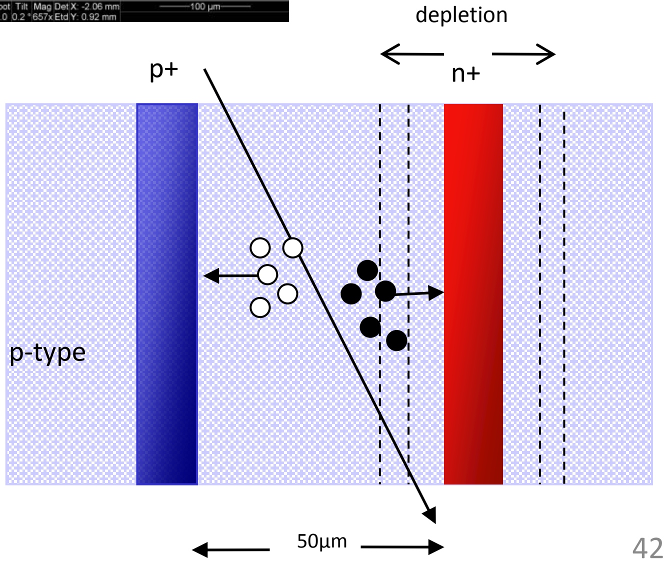



SEM picture of 3D electrodes

PLANAR:

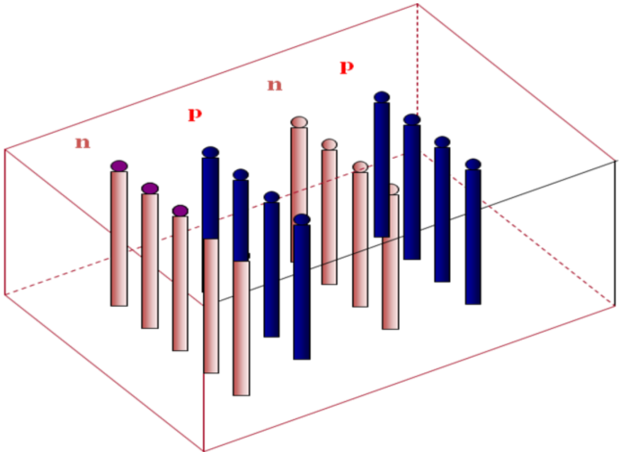


3D:

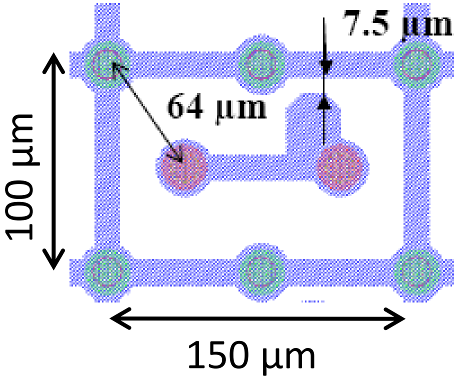


Radiation harder approaches – 3D

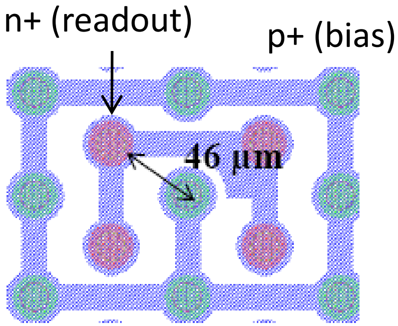
SINTEF 3D
(200 µm thick)



2E Configuration

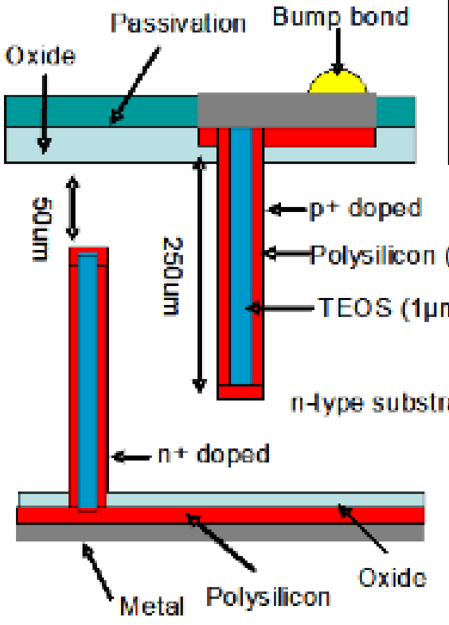


4E Configuration

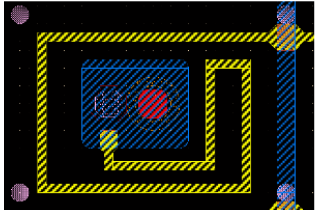


Single-side etching

CNM 3D (200 µm thick)

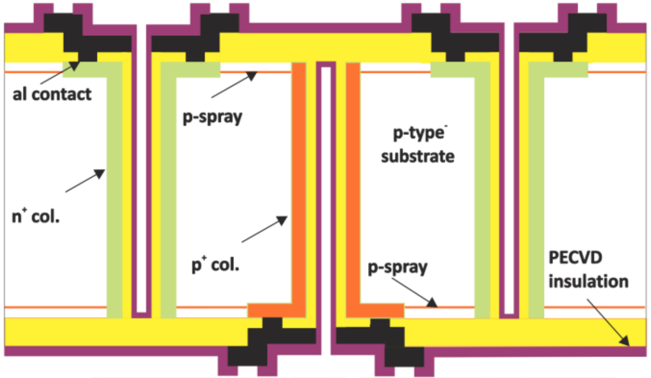


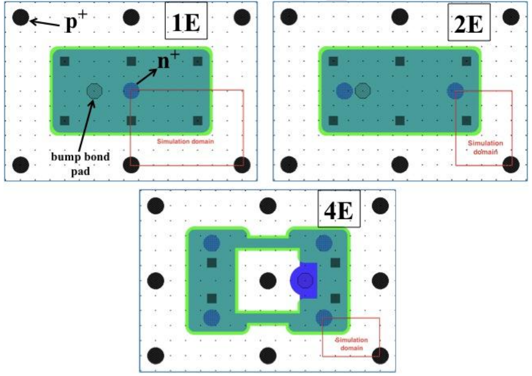
1E Configuration



Double-side etching

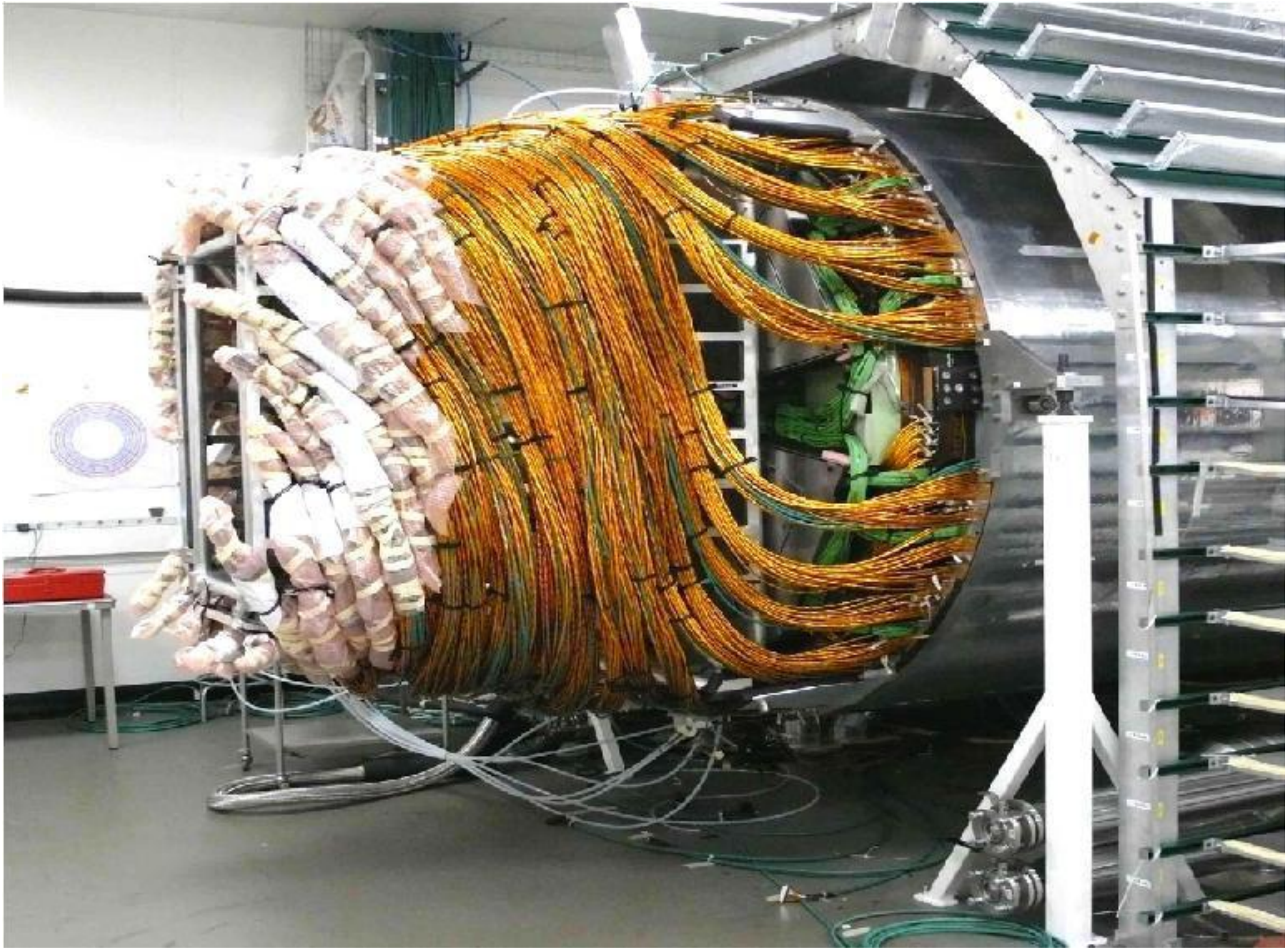
FBK 3D (200 µm thick)





Double-side etching

COMPLEXITY – CMS Tracker



References

- Sze, Physics of semiconductor devices, 2nd Edition
- Helmuth Spieler, Semiconductor Detector Systems
- Olaf Steinkamp, Experimental Methods of Particle Physics, 2011
- Enver Alagoz, Simulation and beam test measurements of the CMS pixel detector, PhD Thesis, 2009
- Daniela Bortoletto, An introduction to semiconductor detectors, Vienna Conference, VCI 2004