Interactions of Particles with Matter – Part 2

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May 19, 2023

UNIVERSITY OF BIRMINGHAM

Two Lectures

Lecture 1: Mechanics of Particle Interactions with Matter

- Define "particle" interactions with "matter"
- Ionizing Radiation
- Non-Ionizing Radiation

Lecture 2: Detecting Particle Interactions with Matter

- Efficiencies and energy resolutions for individual sensors
- Brief overview of silicon sensor technologies
- Gaseous detectors for tracking
- Signal formation in a single diode

Further Reading

This is a survey lecture to summarize many mechanisms.

The following are references for a more in-depth understanding.

Particle Data Group's Review

1 *34. Passage of Particles Through Matter*

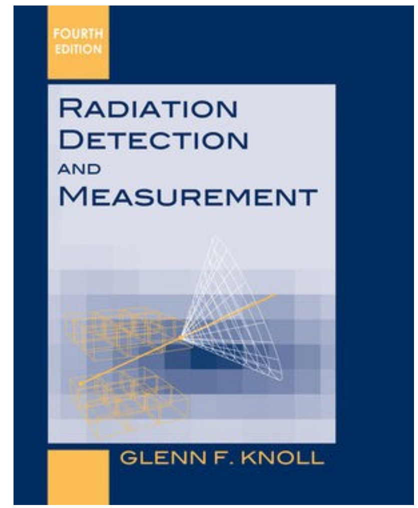
34. Passage of Particles Through Matter

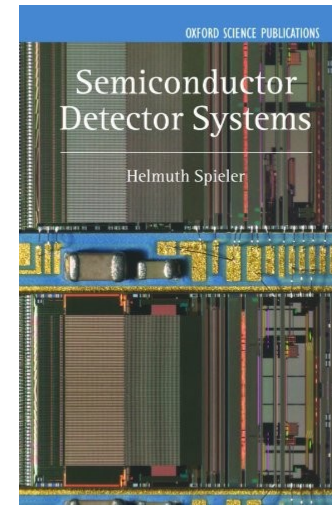
Revised August 2021 by D.E. Groom (LBNL) and S.R. Klein (NSD LBNL; UC Berkeley).

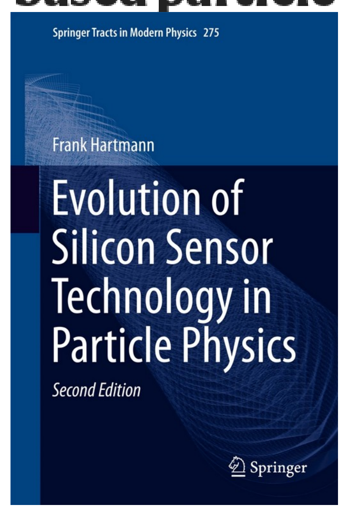
Applications of silicon strip and pixel-based particle tracking detectors

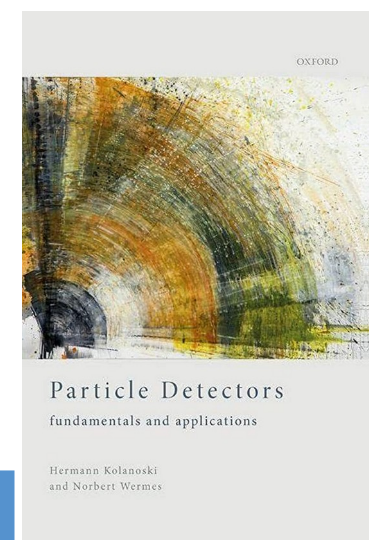
Philip Allport

Nature Reviews Physics **1**, 567–576 (2019) | Cite this article









Material based on Phil Allport's.

Example Types of Particles

How about other particles (muons, pions, taus)?

- **Ions**
  - protons, alpha particles, fission fragments
  - straight tracks
- **Electrons (β particles)**
  - Negative and positive
  - Scattered tracks
- **Neutrons**
  - Interact only with nucleons
- **Photons**
  - gamma-rays and X-rays
  - Interact with atoms/electrons

Charged Particles

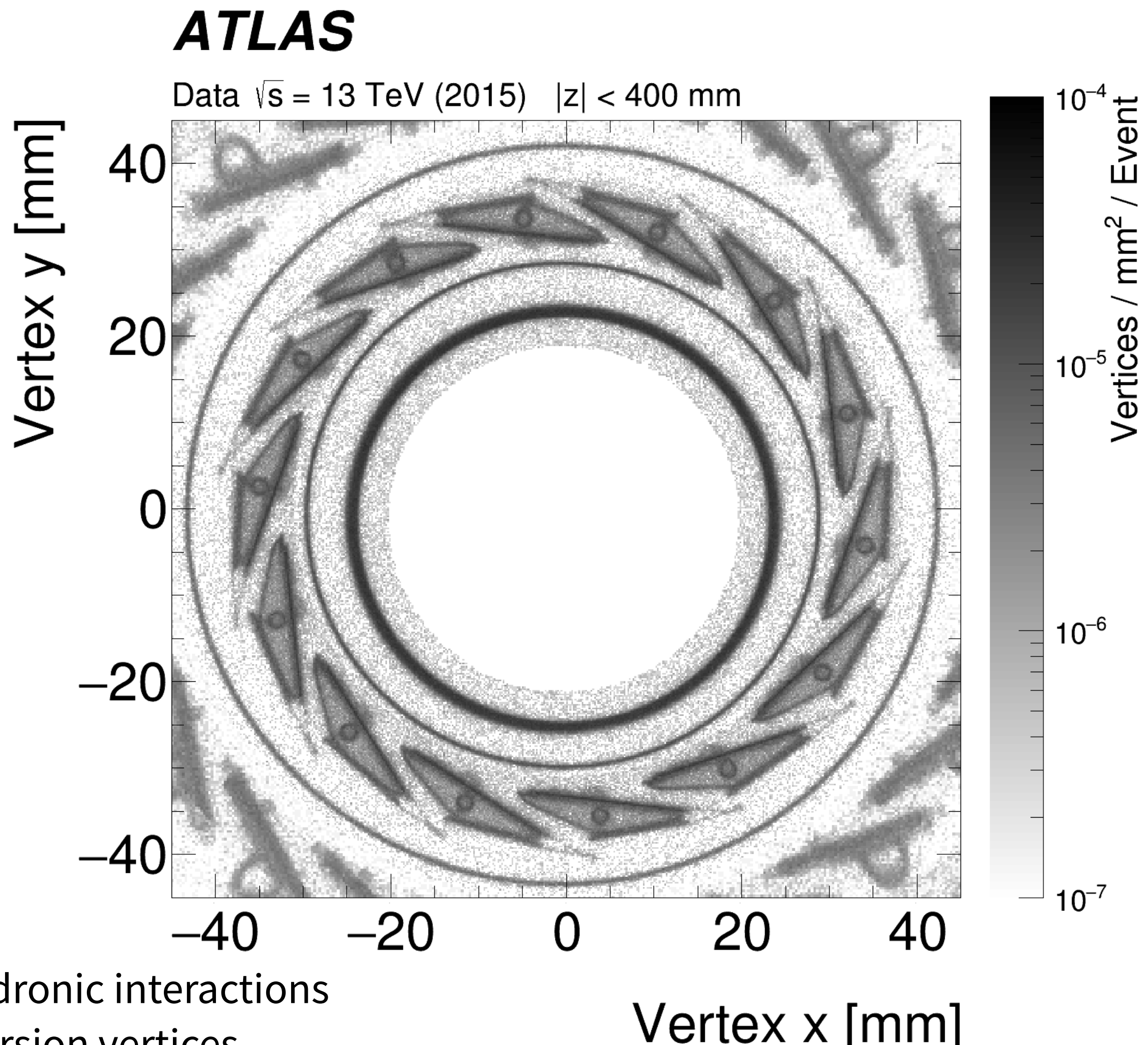
- Ionize atoms along the way
- Can be followed via a "track"

Neutral Particles

- Identified via secondary tracks

ATLAS Inner Most Pixel Layer

Study of the material of the ATLAS inner detector for Run 2 of the LHC



Reconstructed hadronic interactions and photon conversion vertices.

Sensor Efficiency Definitions

Intrinsic efficiency measures efficiency of detector element.

$$\epsilon_{\text{int}} = \frac{\text{number of pulses detected}}{\text{number of incident particles}}$$

ε_{int}(charged) ≈ 1 ε_{int}(neutral) << 1

Absolute efficiency measures efficiency of entire detector.

$$\epsilon_{\text{abs}} = \frac{\text{number of pulses detected}}{\text{number of emitted particles}}$$

Point source subtended by Ω solid angle of detector.

They are related (for example) coverage of detector:

$$\epsilon_{\text{abs}} = \frac{\Omega}{4\pi}\epsilon_{\text{int}}$$

Intrinsic Sensor Resolution: Statistics

Energy deposition is a random process.

1) A traversing particle deposits (exactly) E energy.
2) Number of signal carrier created is N = E/w.
   - w is the energy to create a single signal carrier

- Creating a carrier is a random and independent event
  - Poisson statistics!

$$< N >= N$$

$$\sigma_N = \sqrt{N}$$

Intrinsic Sensor Resolution: Fano Factor

Signal carrier are *not independent events*.

- **(Fixed) input of energy is *absorbed in different ways*.**
- ***Total energy absorbed* must equal (fixed) input energy.**

- **Fano Factor (F) is a correction to account for these variations.**
  - Also a random process, usually with a very small variance.
  - $F \leq 1$, by definition.

$$< N >= FN$$

$$\sigma_N = \sqrt{FN}$$

Example Fano Factor Values

Consider energy deposited as ionizing (E_{ion}) and lattice (E_{phonon}).

$$E = E_{ion} N_{ion} + E_{pho} N_{pho}$$

Correlated statistical variations in N_{ion} and N_{pho}, as E is fixed.

See chapter X in Speiler for derivation.

Example Theoretical Values

	Feno Factor
Si	0.115
Ge	0.13
GeAs	0.12
Diamond	0.08

Example Measured Values

	Feno Factor
Ar (gas)	0.20 ± 0.01/0.02
Xe (gas)	0.13 ± 0.29
CZT	0.089 ± 0.05

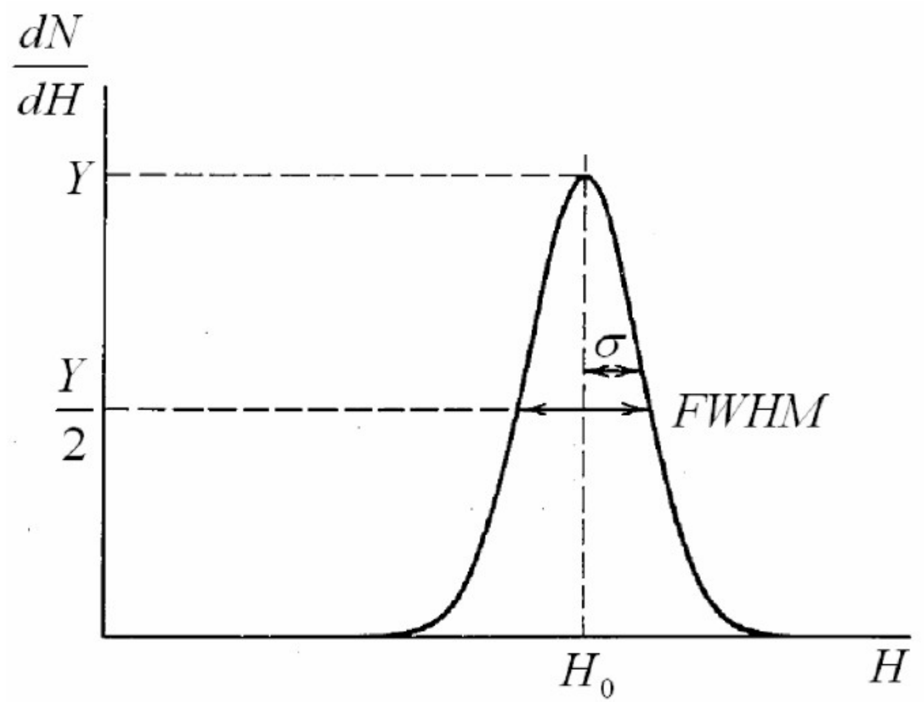
Intrinsic Sensor Resolution: Poisson

For large <N>, Poisson distribution ~ Gaussian distribution.

$$P(N) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{(N- < N >)^2}{2\sigma^2} \right)$$

Experimentally, we measure Full Width at Half Maximum (FWHM) of pulse heights, H ∝ N.

$$\mathrm{FWHM} = 2\sqrt{2\ln 2}\sigma \approx 2.35\sigma$$



Intrinsic Sensor Resolution: Poisson

Energy resolution, ΔE, is defined as FWHM/H_0.

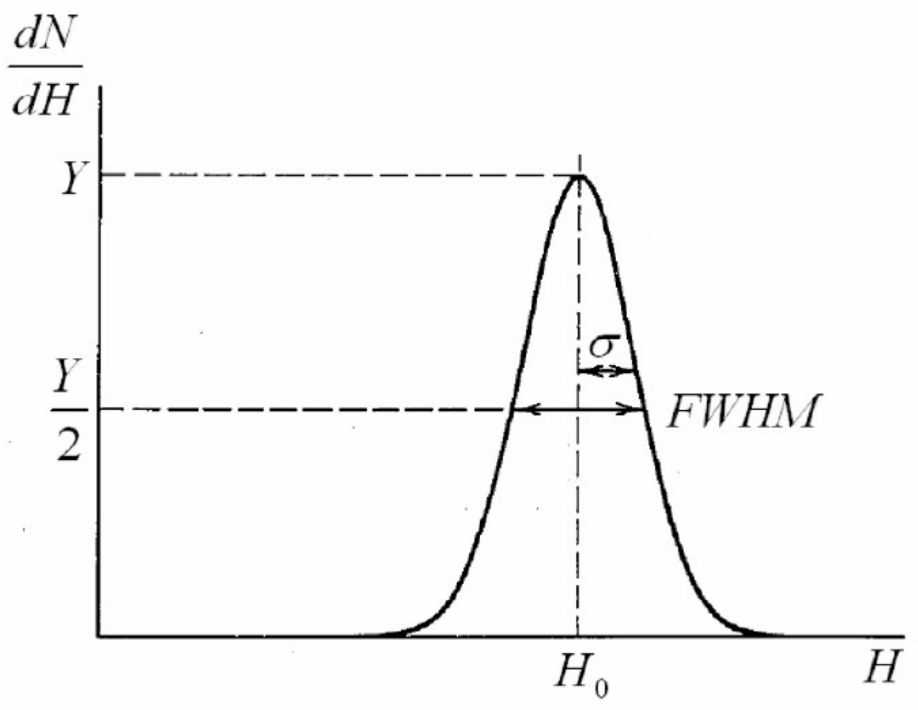
Distinguish two peaks when separated by FWHM.

Take k to be proportionality.

$H = kN$; $H_0 = k\langle N \rangle$

Using prev. equations…

$$\Delta E = 2.35\sqrt{\frac{Fw}{E}}$$

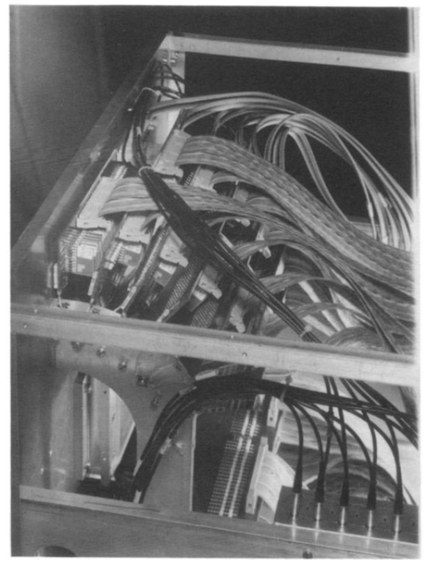


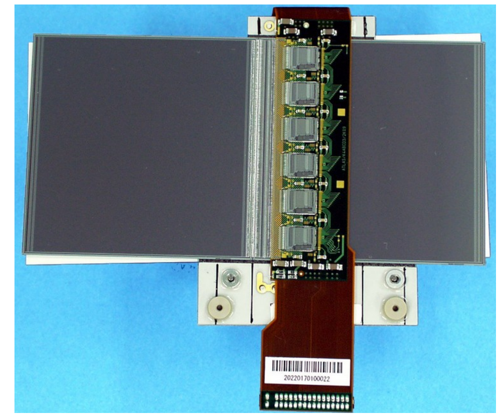
Intrinsic Sensor Resolution: Poisson

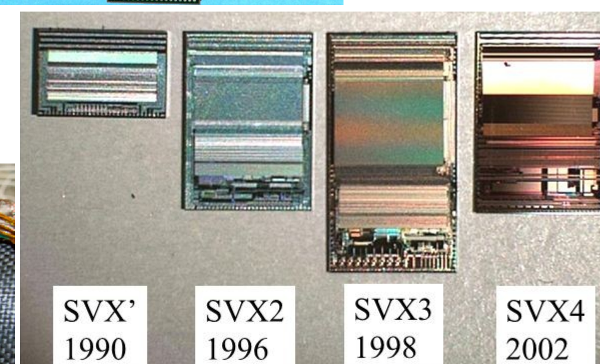
Charged particle trajectory reconstruction (*tracking*) **requires precise position information. Semiconductors are great for this!**

Example Technologies

- Strip detectors
- Silicon drift detectors
- Hybrid pixel detectors
- Monolithic pixel detectors
- Charged Coupled Devices
- 4D detectors (timing)
- 3D pixels

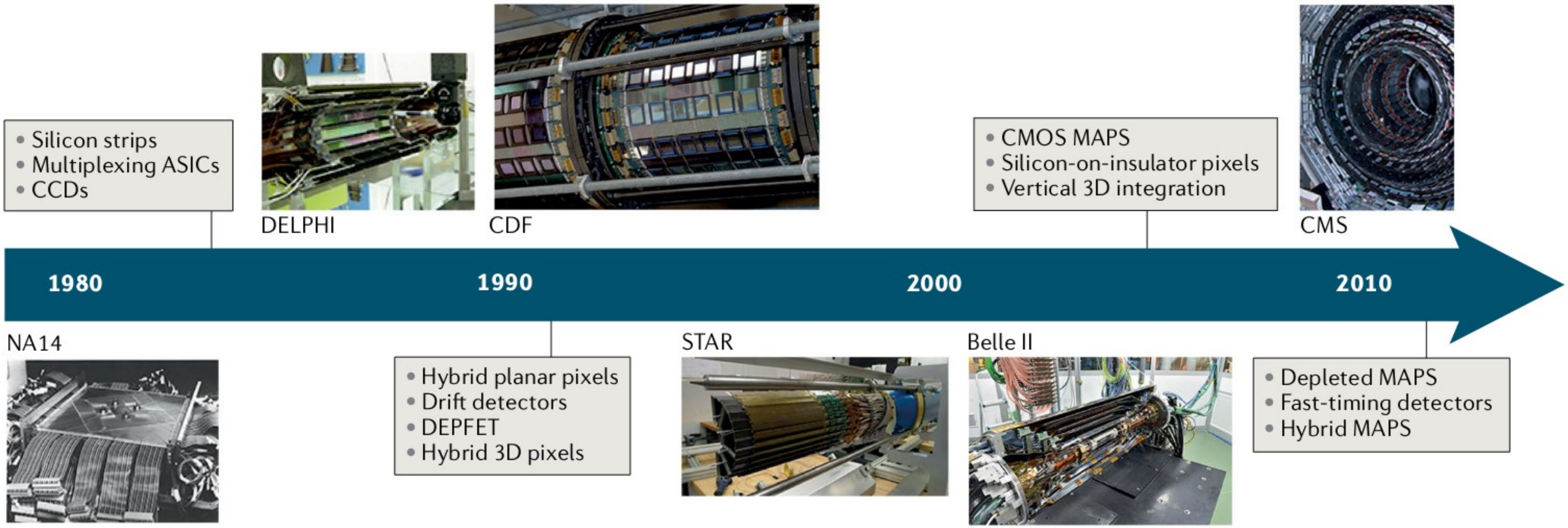






Most devices discussed today will be based on segmented p-n junction diodes.

Silicon Detectors Throughout The Years

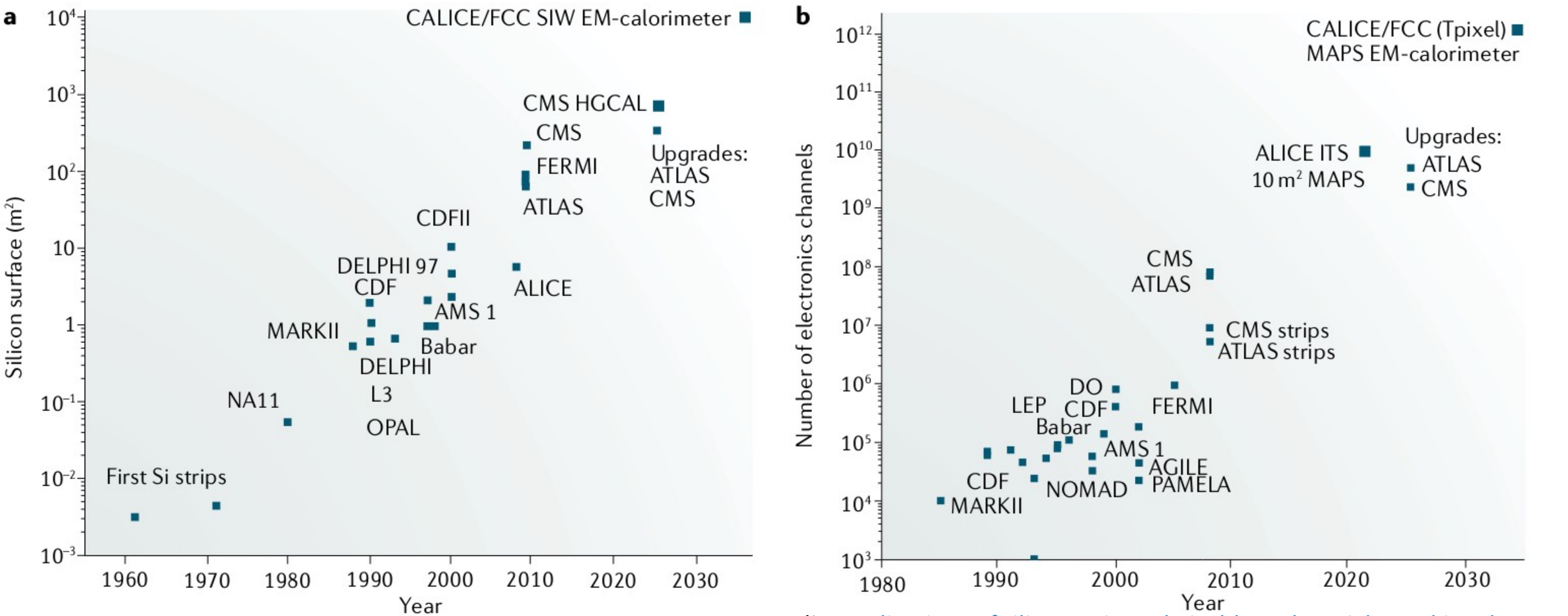


Credit: Applications of silicon strip and pixel-based particle tracking detectors

Silicon Detectors Throughout The Years

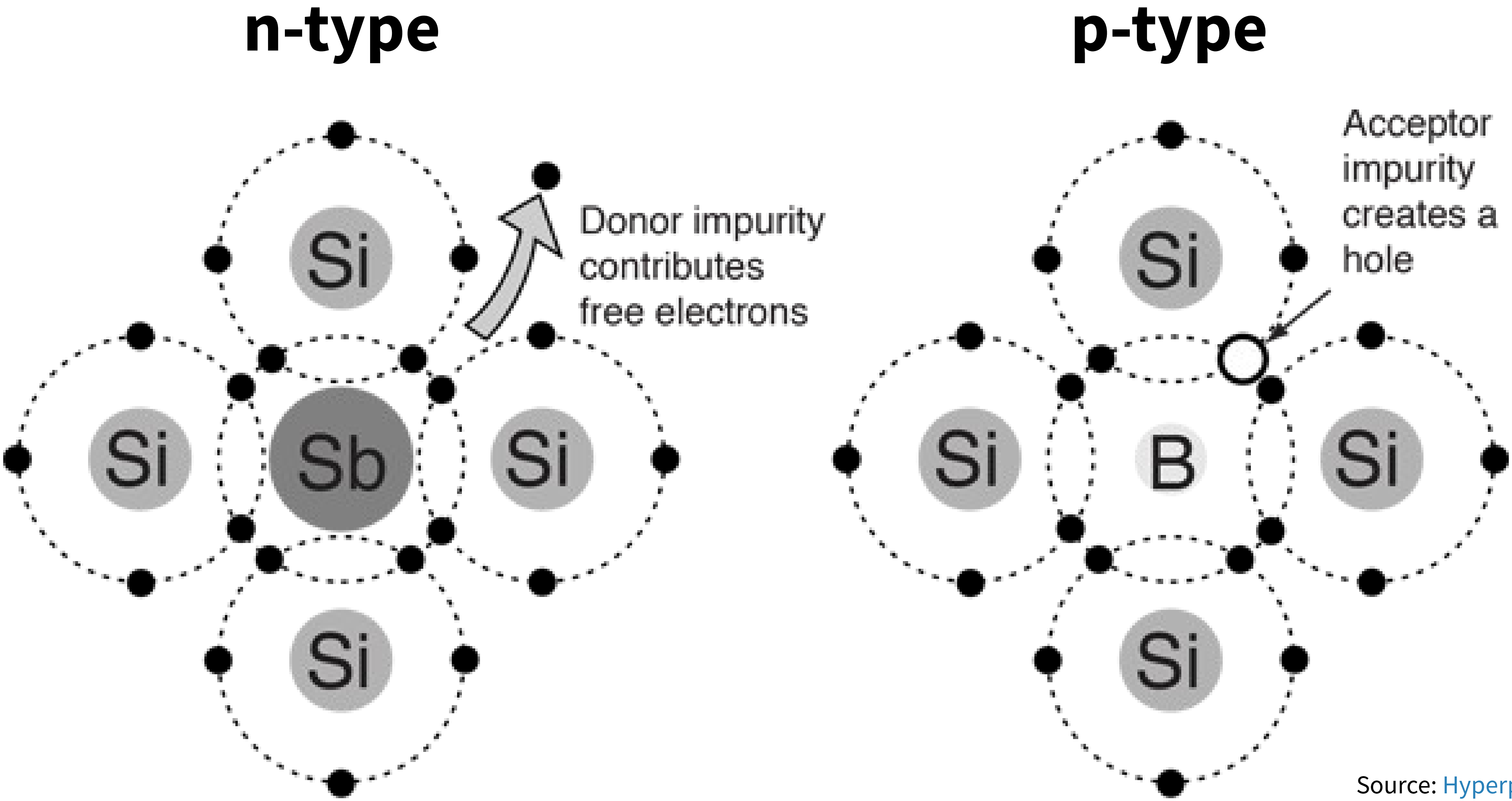
Follows Moore's Law!

"the number of transistors in an integrated circuit (IC) doubles about every two years"



Credit: Applications of silicon strip and pixel-based particle tracking detectors

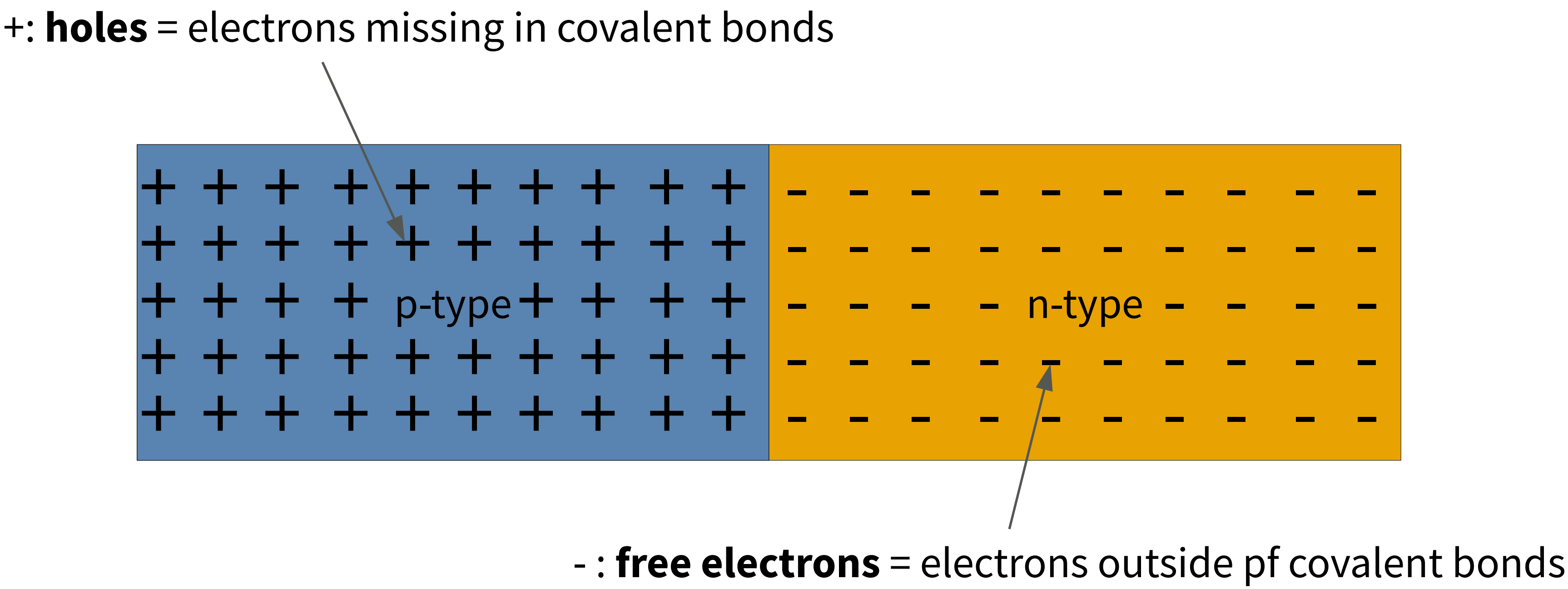
Fast Recap of p-n Junction: Doping



Source: Hyperphysics

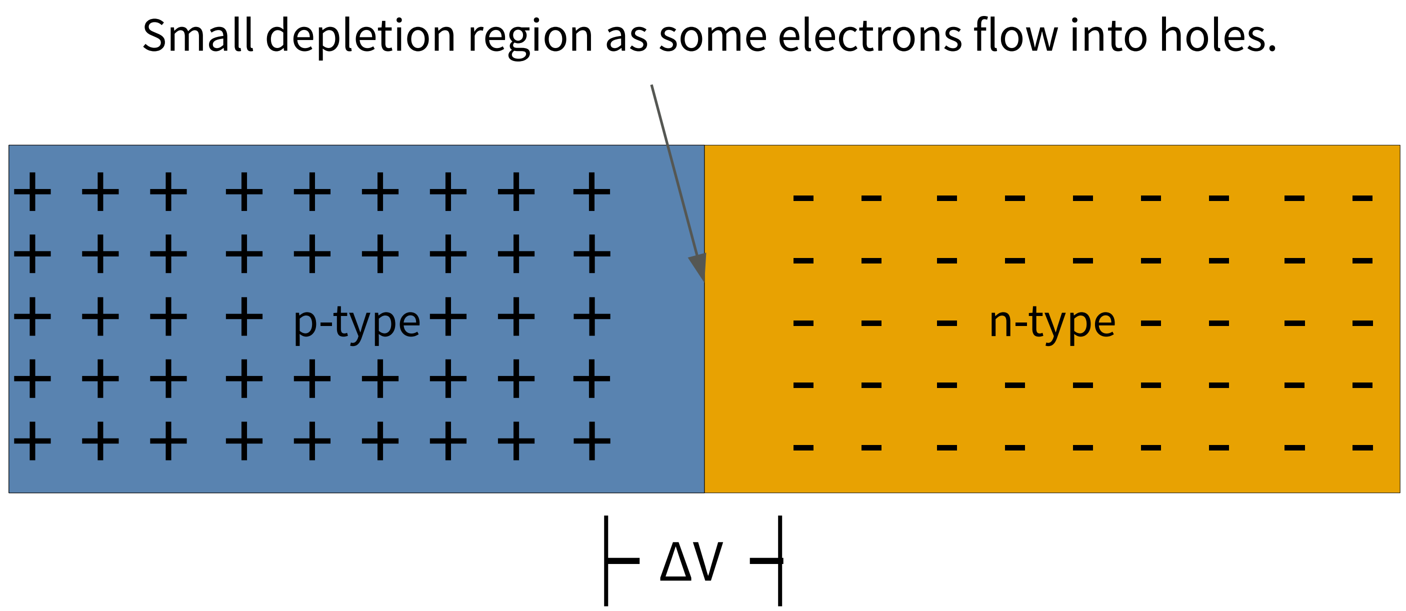
Two types of doped silicon.

Fast Recap of p-n Junction: Junction

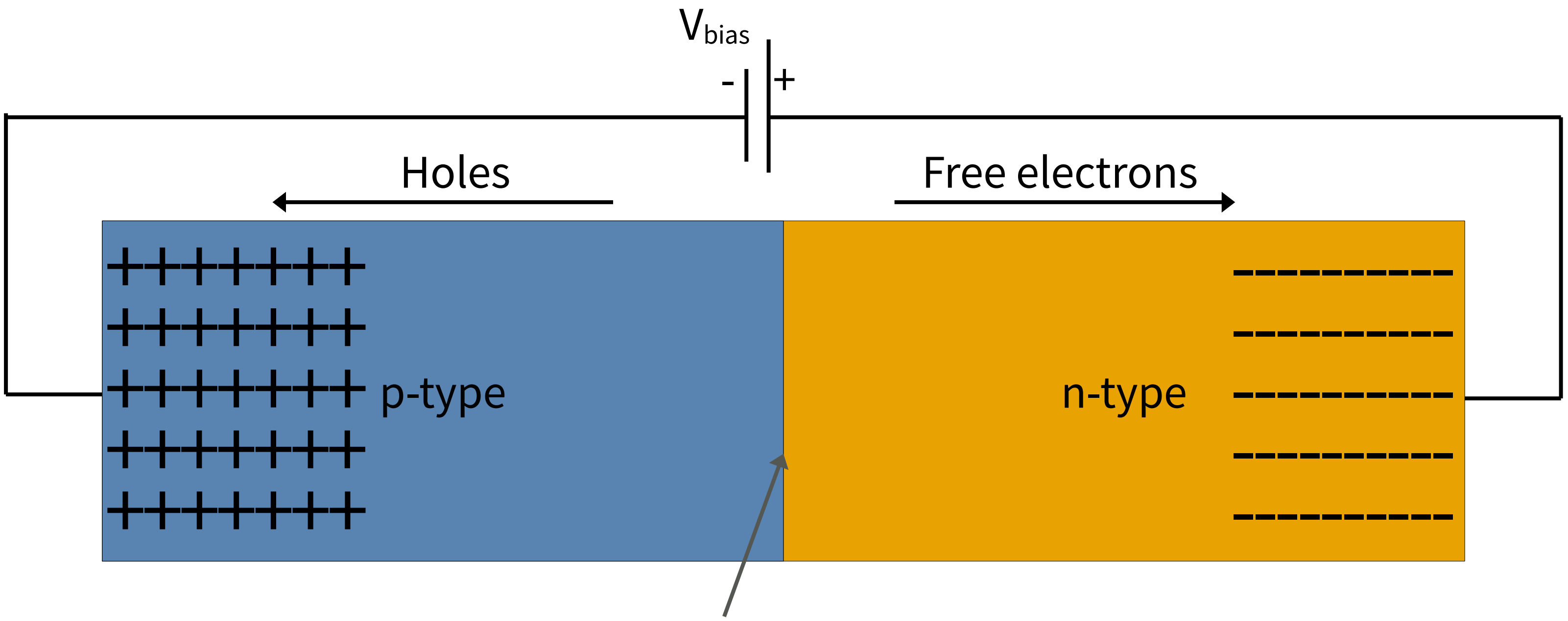


Note: The entire material is neutral! $N_{electrons} = N_{protons}$

Fast Recap of p-n Junction: Equilibrium



Fast Recap of p-n Junction: Reverse Biased Junct.

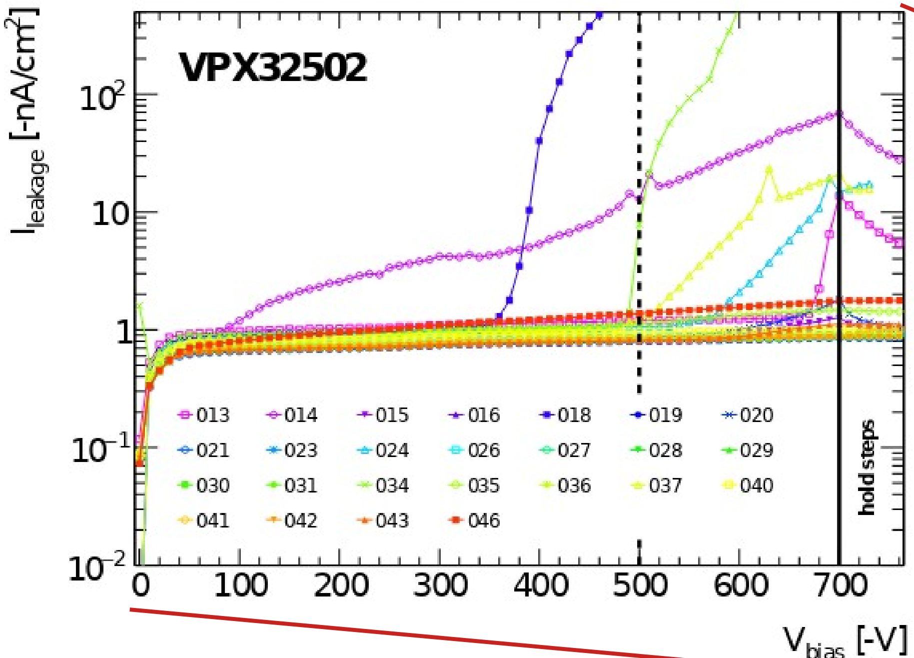


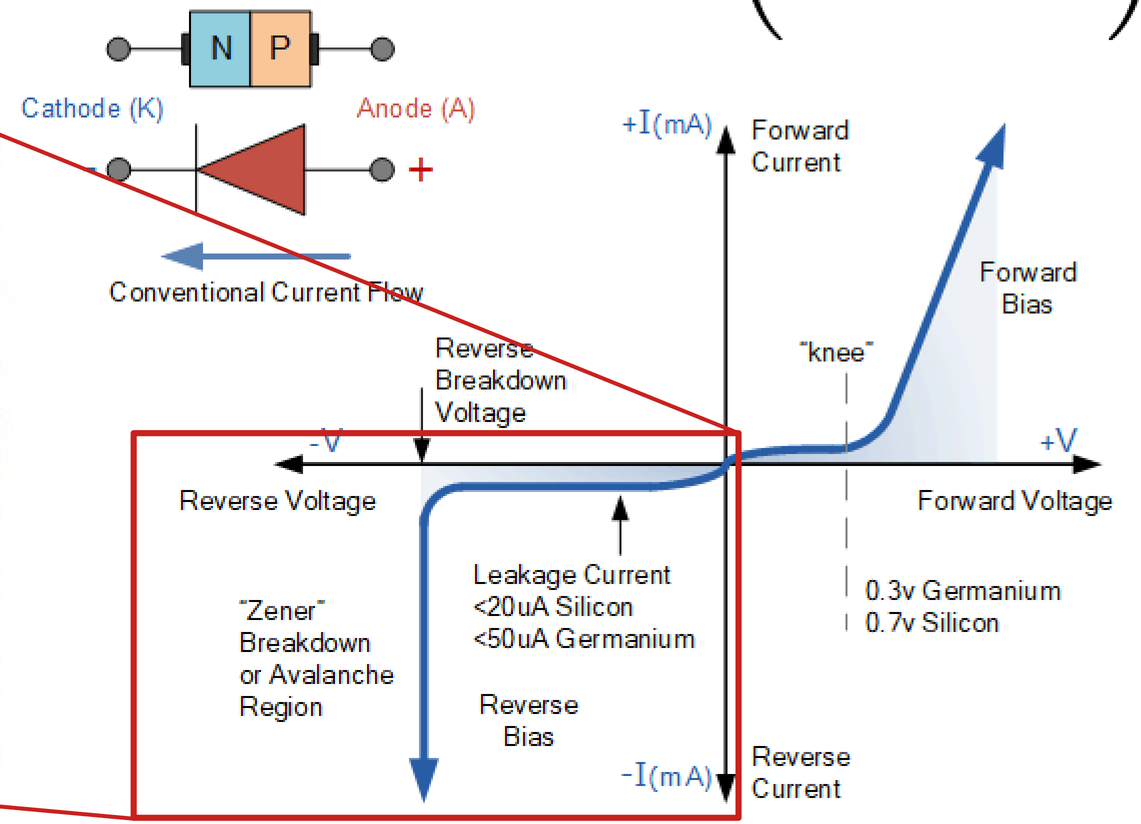
Depletion region:

- Missing holes and free electrons in the middle.
- Develops ΔV opposing V_{bias} at equilibrium.
- ΔV prevents any current from flowing.

Fast Recap of p-n Junction: IV Curve

$$J = J_0 \left(e^{\frac{qV}{kT}} - 1 \right)$$





Sensors operate in Reverse Bias

Credit: PN Junction Diode

Credit: ATLAS ITk Strip Sensor Quality Control and Review ofATLAS18 Pre-Production Sensor Results

Space Charge Region

Consider a 1D sensor. Following Poisson's equation

$$\frac{d^2V}{dx^2} = -\frac{\rho}{\epsilon}$$

ρ = charge density

ϵ = dielectric constant

Assume all dopands ionized up to *a* in n-type and *b* in p-type

$\rho_n = eN_n$ n-type $\qquad \rho_p = -eN_p$ p-type

Integrate once to get E-field as linear

$$E = \frac{eN_n}{\epsilon}(a + x), -a < x < 0$$

$$E = \frac{eN_p}{\epsilon}(b - x), 0 < x < b$$

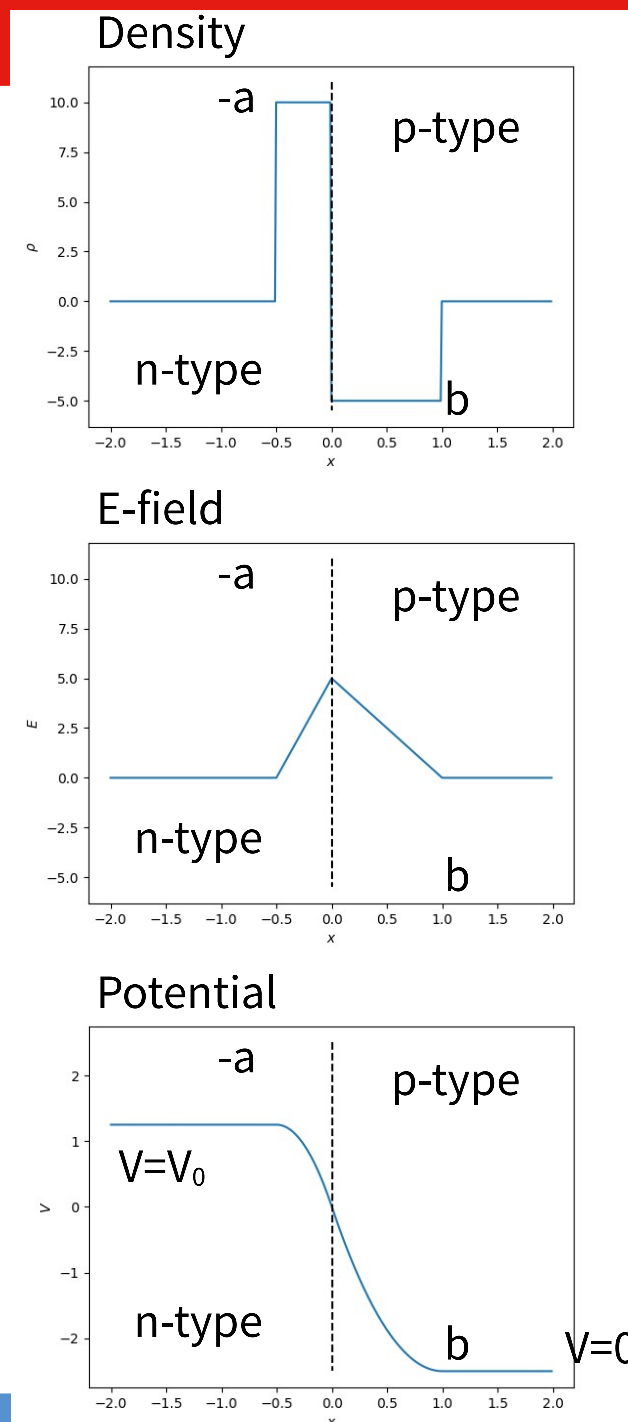
E must be continuous at x=0

$$aN_n = bN_p$$

Integrate again to get voltage

$$V = -\frac{eN_n}{2\epsilon}(x + a)^2 + V_0, -a < x < 0$$

$$V = +\frac{eN_p}{2\epsilon}(x - b)^2, 0 < x < b$$



Depletion Depth

Require potential to be continuous at x=0

$$\frac{eN_p}{2\epsilon}b^2 = V_0 - \frac{eN_n}{2\epsilon}a^2$$

Solving for applied voltage, V_0, and applying E-field continuity

$$V_0 = \frac{e}{2\epsilon}\left(N_p b^2 + N_n a^2\right) = \frac{e}{2\epsilon}N_p b\,(b+a)$$

Take $N_n >> N_p$, making b >> a. $aN_n = bN_p$

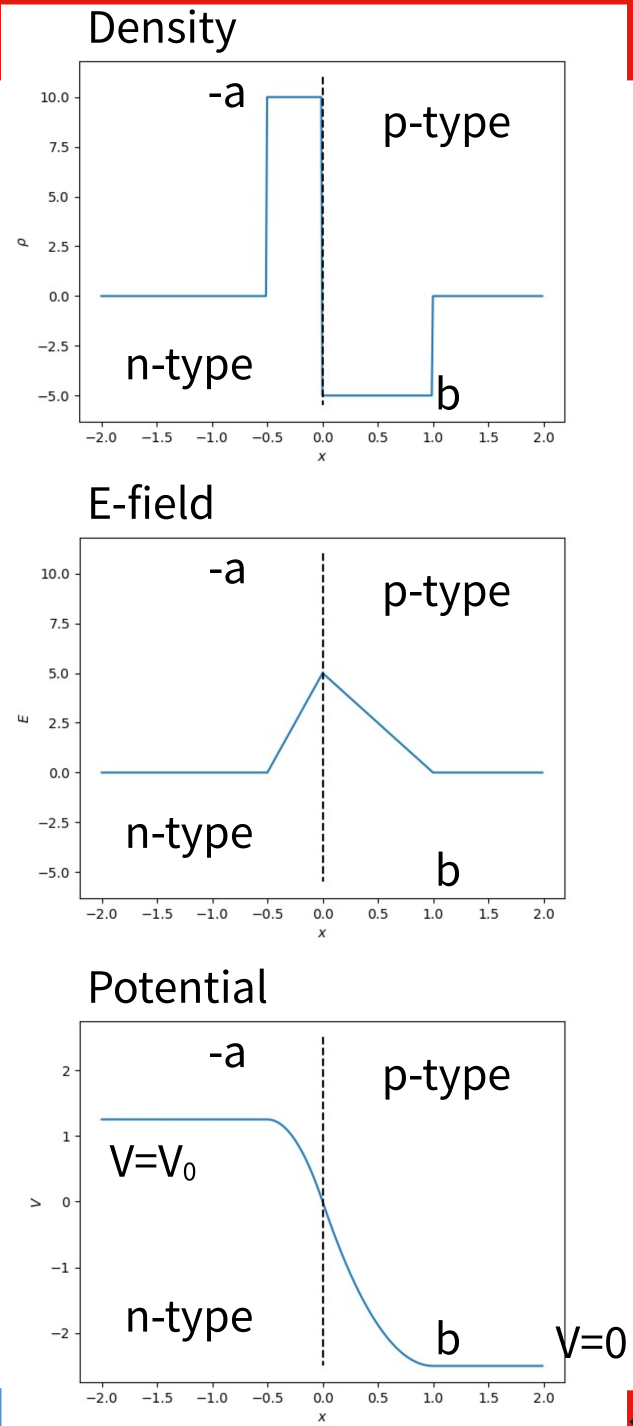
$$V_0 = \frac{e}{2\epsilon}N_p b^2$$

Solving for distances.

$$b \approx \sqrt{\frac{e\epsilon V_0}{eN_p}}, N_n >> N_p \qquad a \approx \sqrt{\frac{e\epsilon V_0}{eN_n}}, N_p >> N_n$$

Or more generally, take $N_{min}=\min(N_p, N_n)$

$$d \approx \sqrt{\frac{e\epsilon V_0}{eN_{\text{min}}}}$$



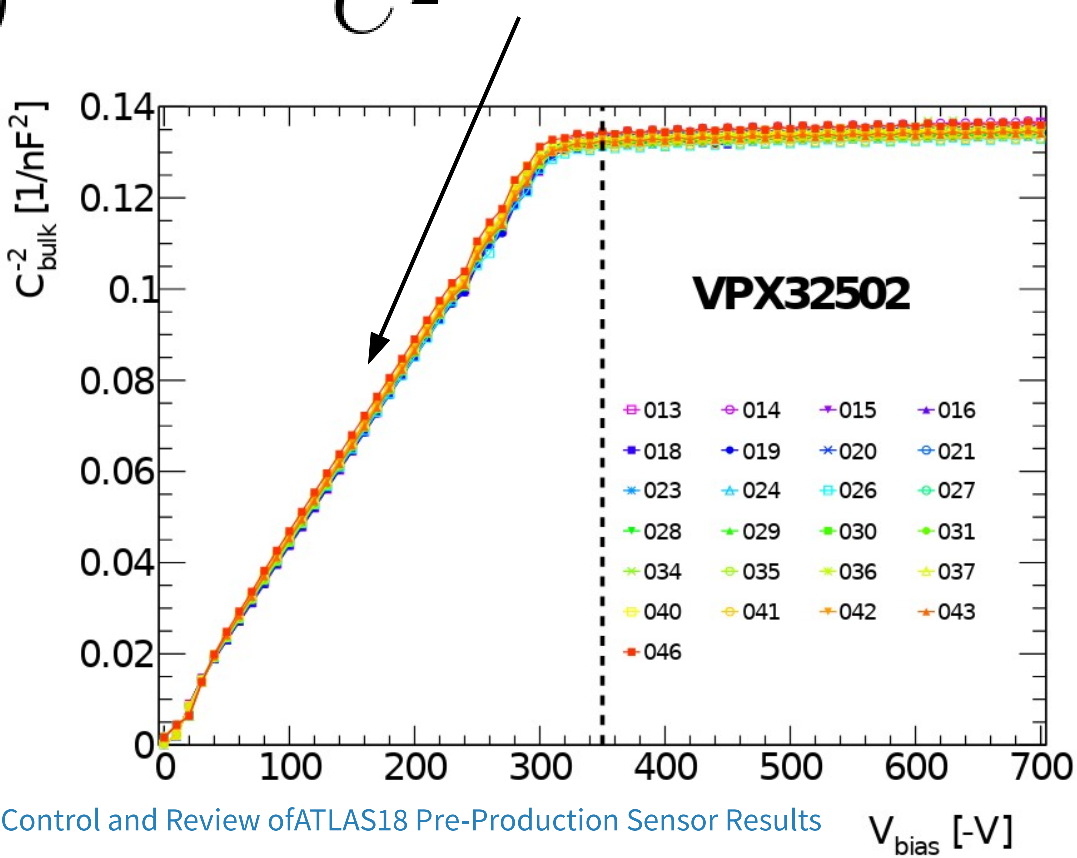
Depletion Layer

Treat depletion layer as parallel plate capacitor

$$C(V) = \frac{\epsilon_0 \epsilon_{r,\mathrm{Si}} A}{d(V)} \qquad \frac{1}{C^2} \propto V$$

Measure capacitance to find

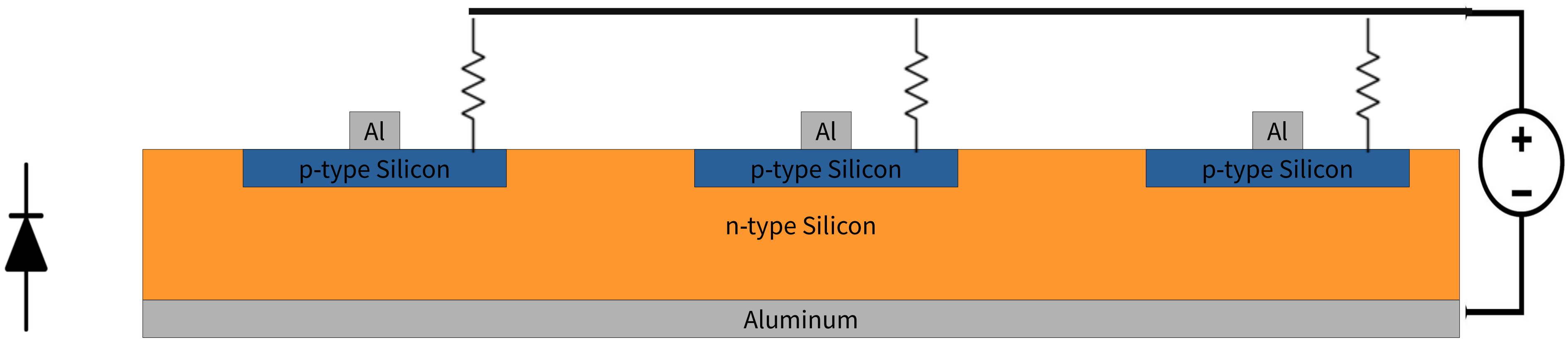
- N_{min} (doping amount)
- Substrate resistivity



Credit: ATLAS ITk Strip Sensor Quality Control and Review ofATLAS18 Pre-Production Sensor Results

How A Sensor Works

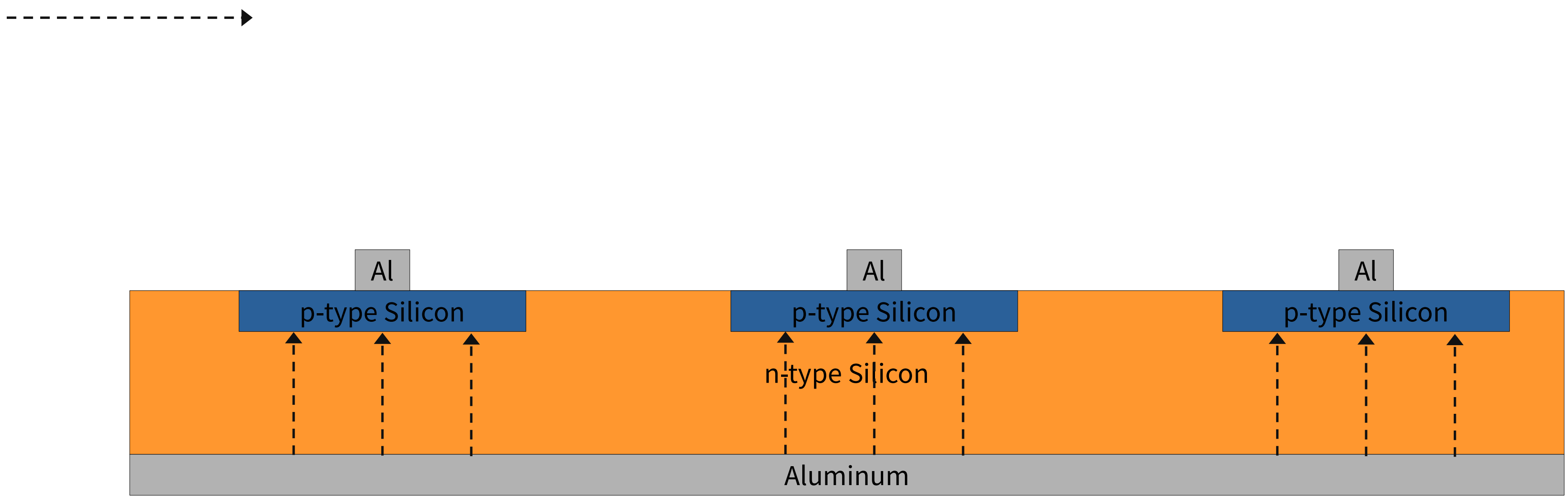
A sensor is just a **reverse biased diode**.



Bonus Topic: How do p-n junctions (diodes) work?

How A Sensor Works

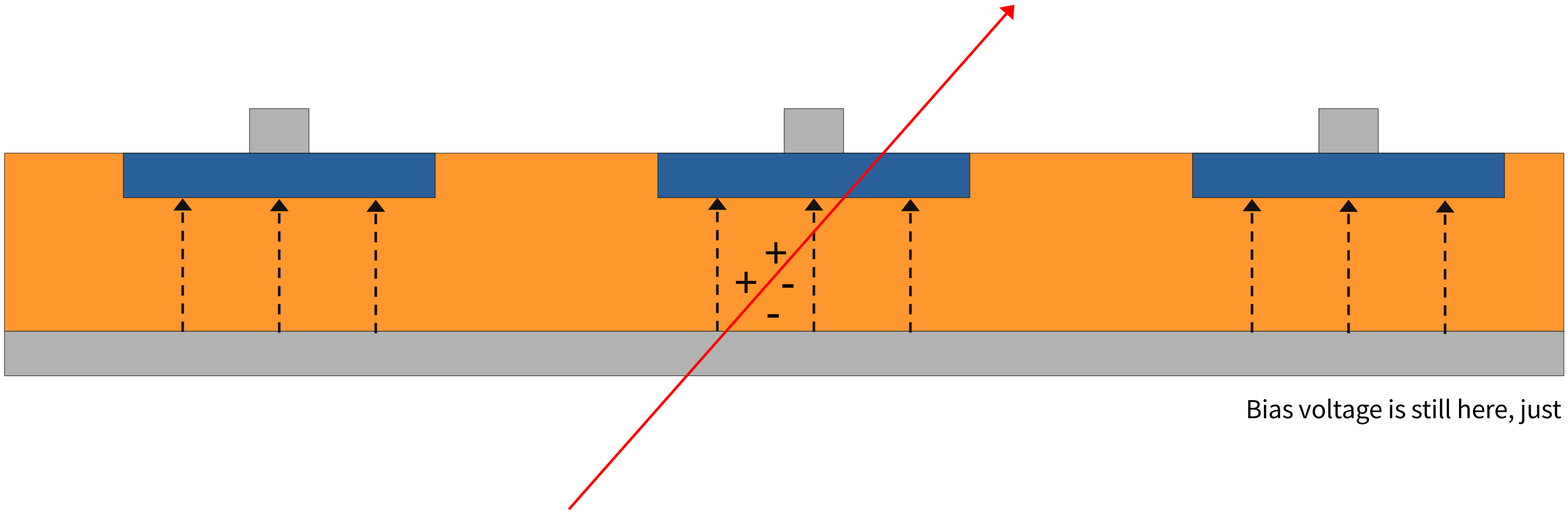
Electric field is formed inside an **insulator**.



Bias voltage is still here, just not shown.

How A Sensor Works

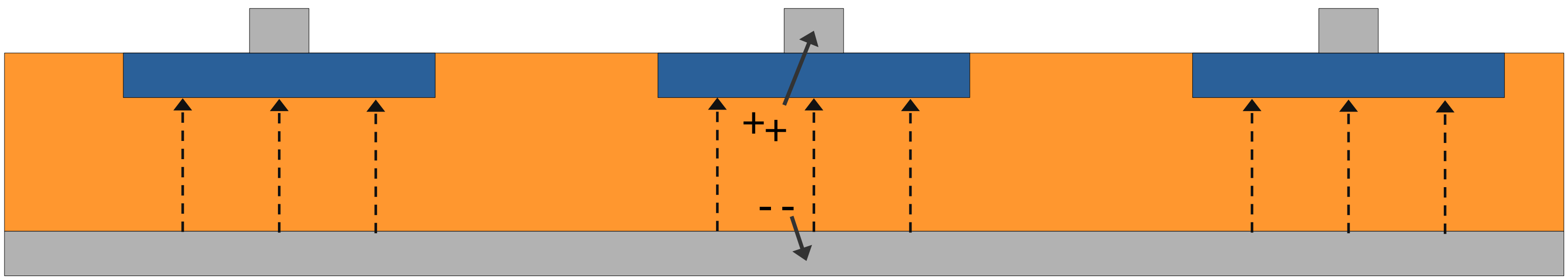
Passing particle excites electrons (**ionizes**) into conducting band.



Bias voltage is still here, just not shown.

How A Sensor Works

Electron/hole pairs travel, creating detectable current.



Bias voltage is still here, just not shown.

Silicon Drift Detectors

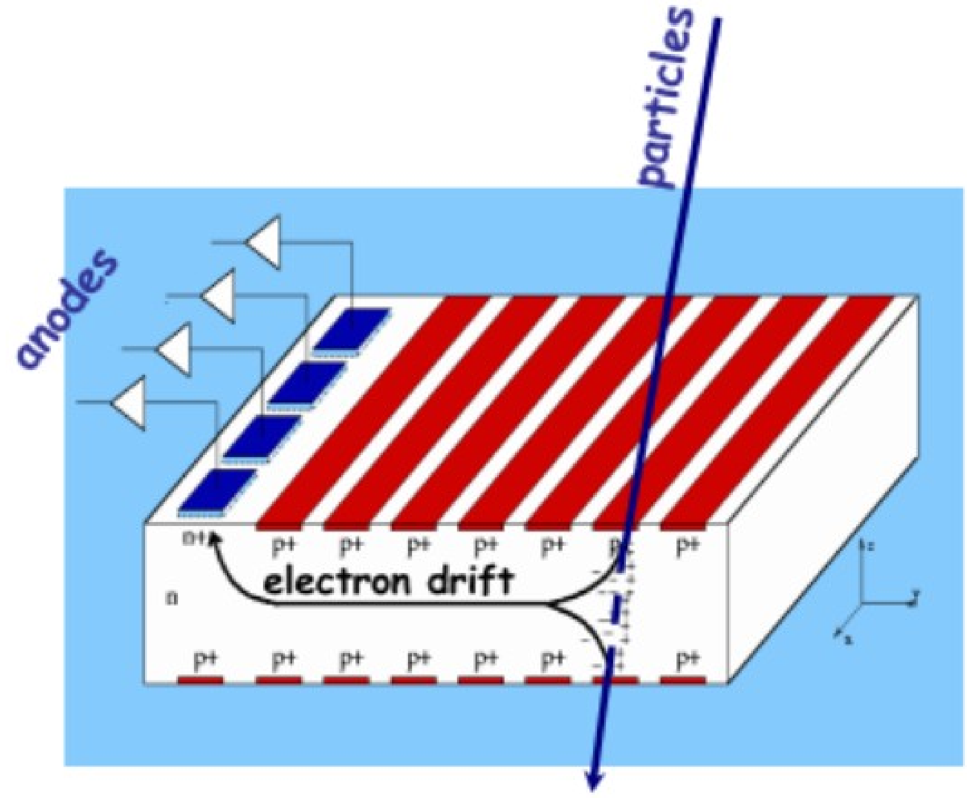
Use drift time to determine incidence position.

Like a gas drift chamber, but in solid state.

- **Few readout channels.**
- **Only for low flux of particles.**

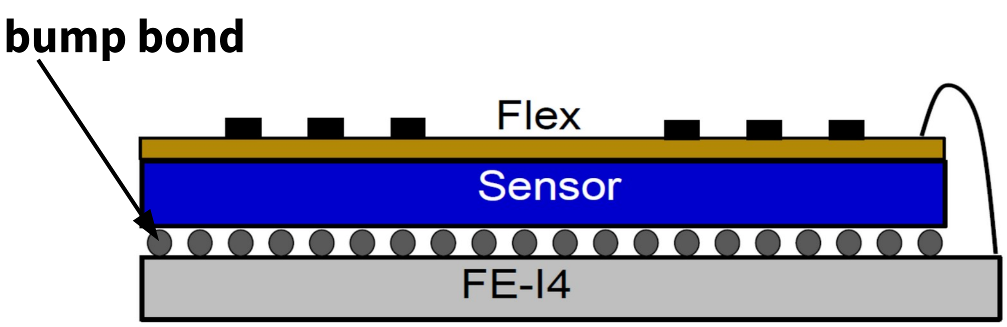
- **Electron mobility, μ, varies**
  - Inhomogenities
  - Radiation damage

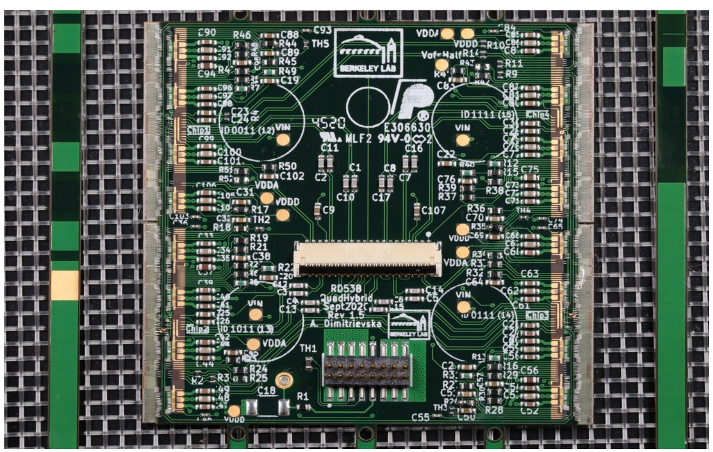
$$v_{drift} = \mu E$$

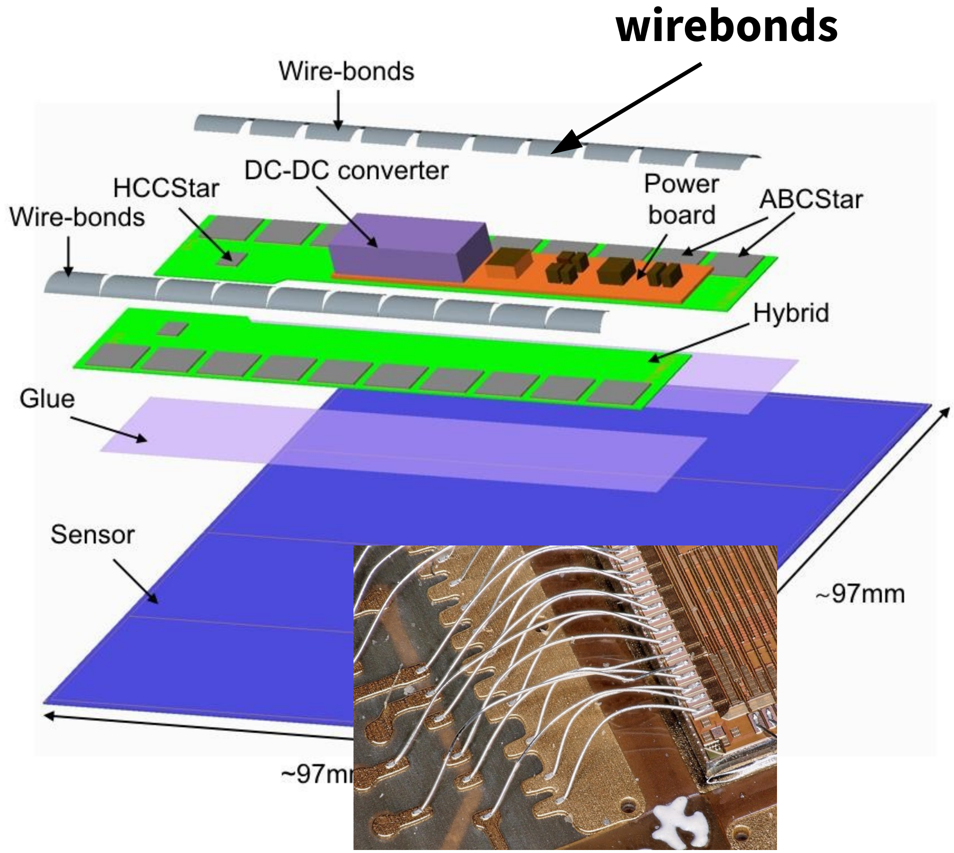


Readout electronics on PCB’s glued to silicon sensors.

Individual connections to segmented channels in the sensor.



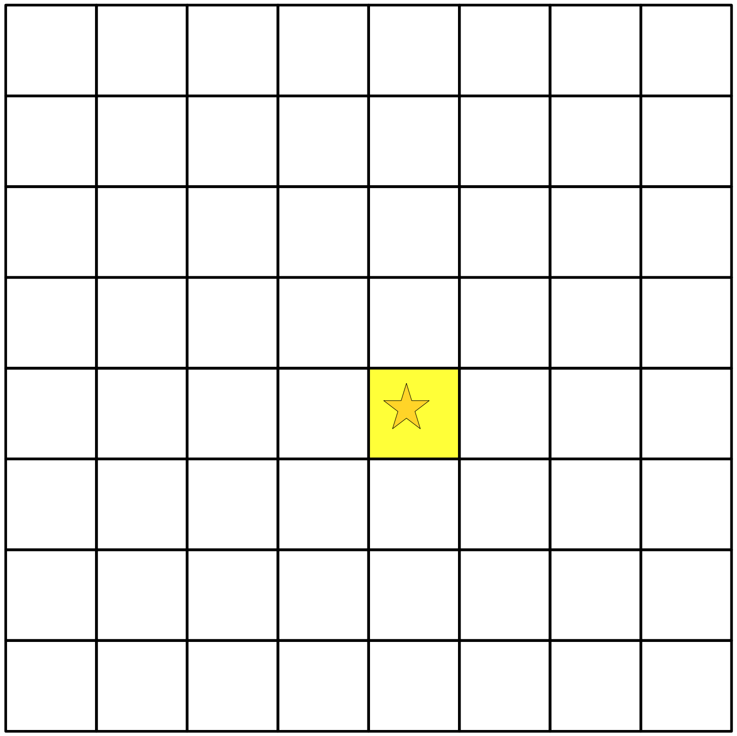




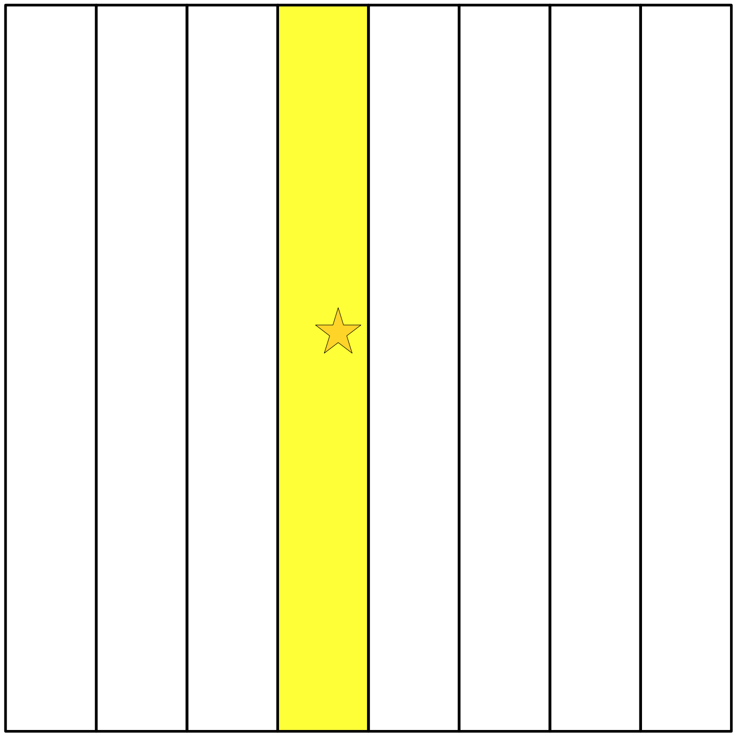
ex: ASIC wirebonded to PCB

Strips Vs Pixels

A **pixel** is just a short **strip**.



ITk Pixel example: 50 µm x 50 µm



ITk Strip example: 75 um x 5 cm

Defines the segmentation of the sensitive part.

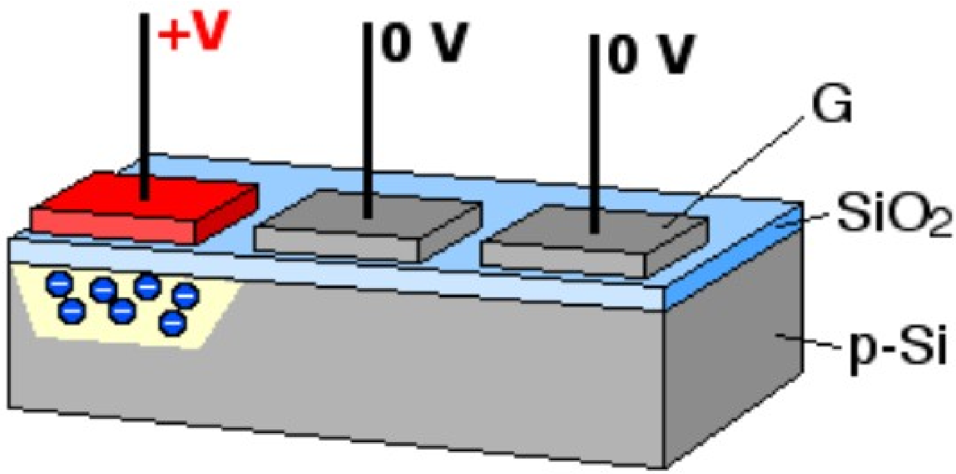
Question:

- When do you use a strip vs pixel sensor?
- How to make a strip give a 2D position?

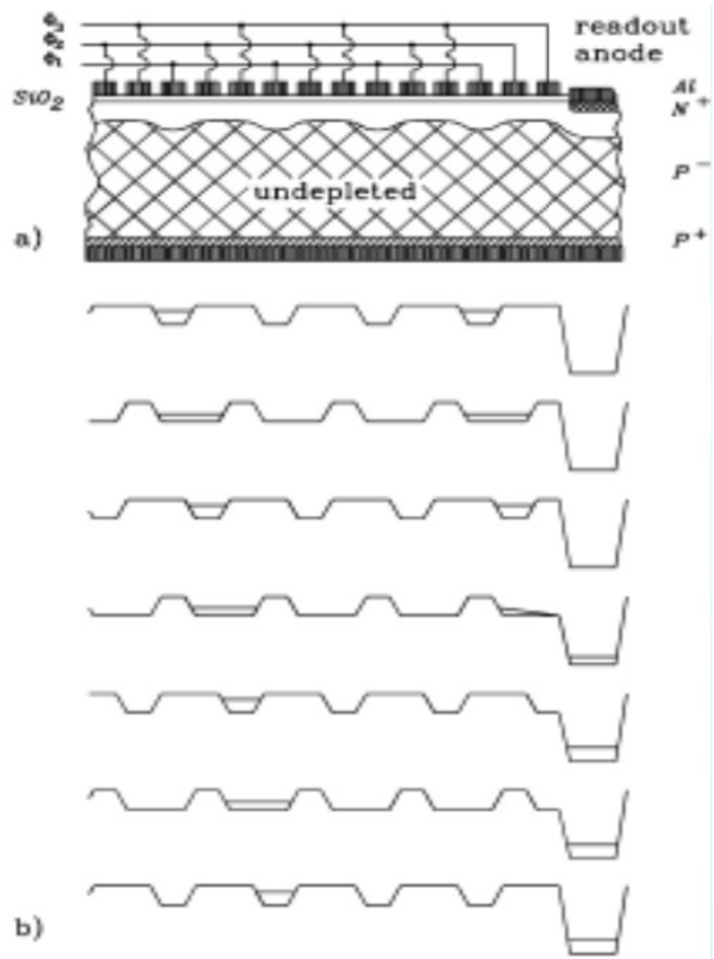
Charged Coupled Devices (CCD)

1)Use a SiO_2 (insulator) layer to trap charge.

2)Scan through pixelated contacts, transferring charge one at time.



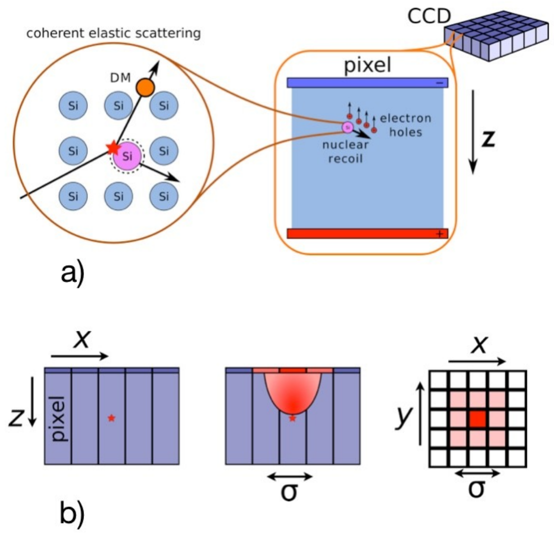
- Shared readout electronics.
  - Multiple channels with less space (~µm pixels)
- Very slow readout.
- Sensitive to radiation damage.

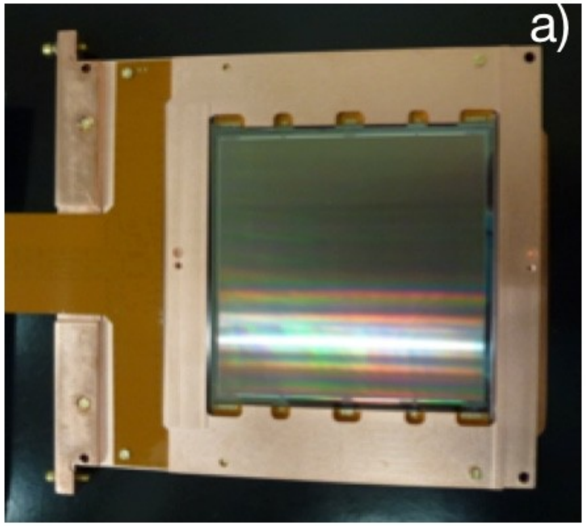


Charged Coupled Devices (CCD)

- **Heavily used for optical imagining.**
  - Examples: cameras, x-ray imagining, telescopes astronomy
- **Need to mask detector during readout to avoid smearing.**
  - Cameras mask out adjacent column, transfer to it after exposure and readout.
- **Most commercial systems moving to CMOS Imagining Sensors.**

DAMIC experiment searches for DM-nucleus recoil inside CCDs.



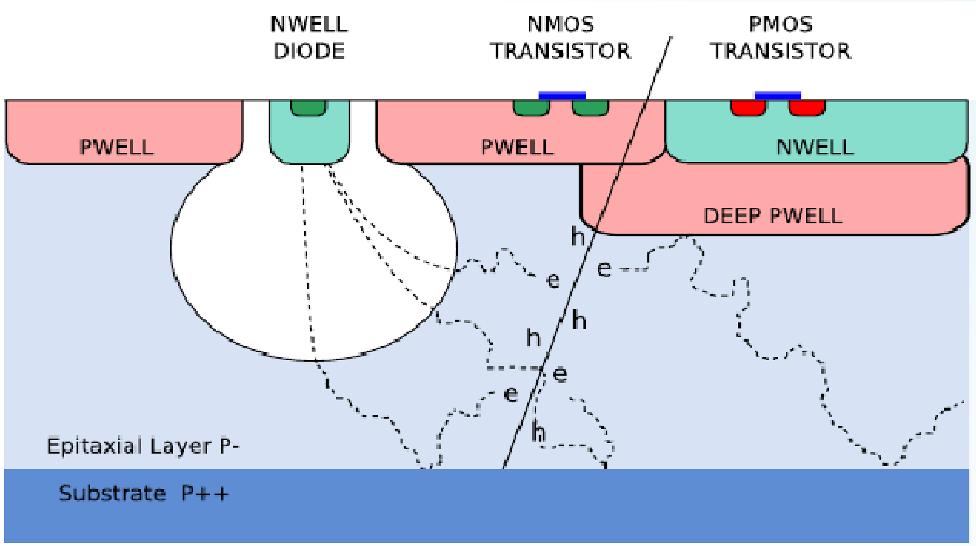


Monolithic Pixels

Attend **Eva Vilella Figueras**'s lecture!
May 23, 2023

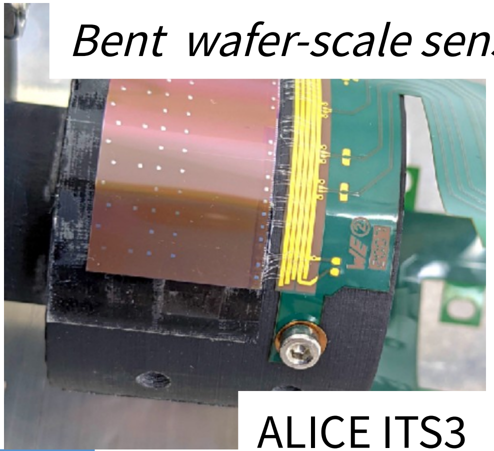
Combine sensor (silicon) with readout electronics (silicon).

You save half construction time by no mention of glue in meetings.



- **Using CMOS technology for both readout and imaging**
  - $$$$ industry (phone cameras!)
- **Main challenge is making them radiation hard.**

Bent wafer-scale sensors.



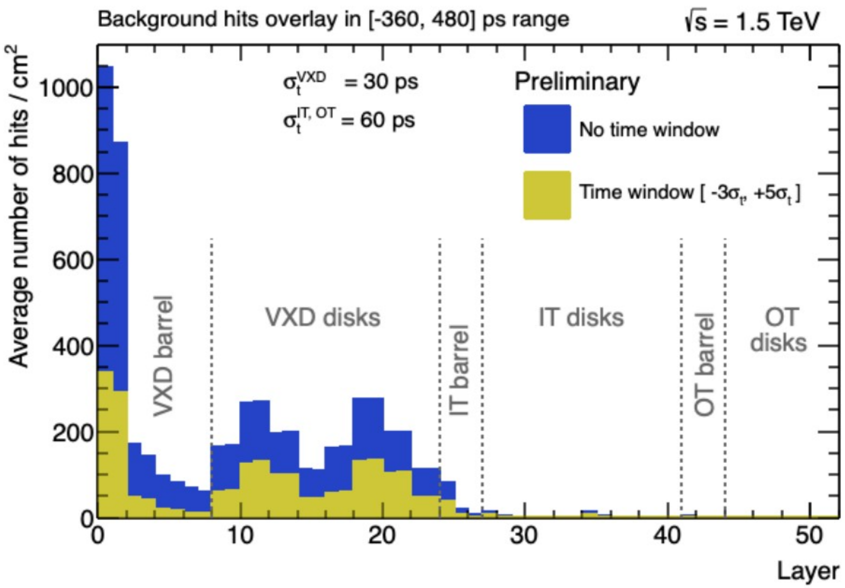
ALICE ITS3

MAPS = Monolithic Active Pixel Sensor

Fast Timing Detectors (4D Tracking)

Future detectors require timing (~*ps*) in addition to position.

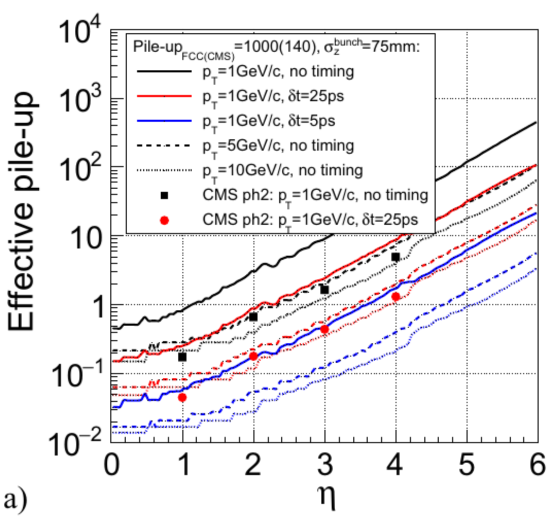
BIB rejection in Muon Collider Detector.



Timing resolution limited by electron drifting to anodes

- $v_{drift} \approx 100$ um / ns
- $t_{collection}(300\ \mu m) \approx 3$ ns

Vertex discrimination in FCChh

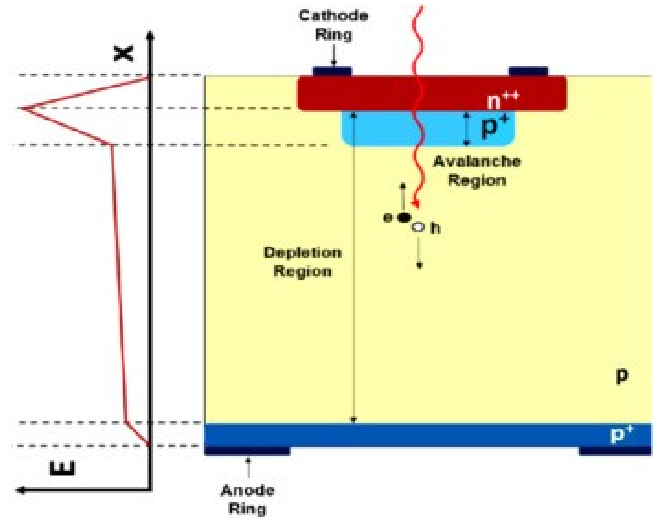


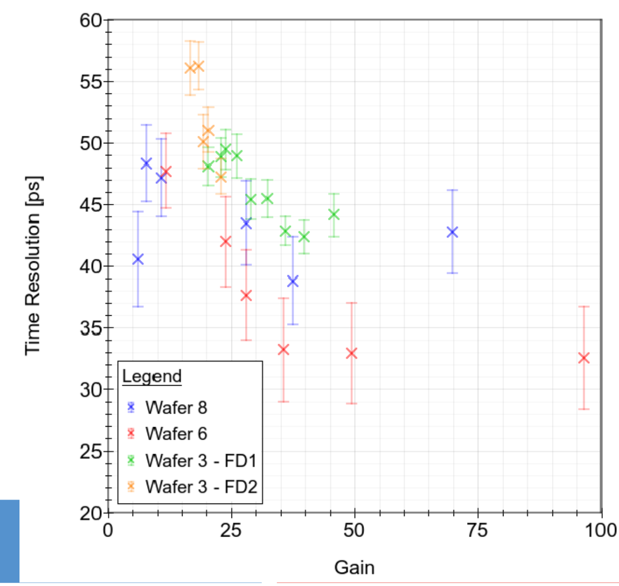
Low Gain Avalange Diodes

Attend **Francisca Munoz Sanchez**'s lecture!
May 23, 2023

Shorten drift time by making sensors thinner!

- **Thinner sensors collect less charge.**
  - Lower signal-to-noise.
- **LGADs add a "gain layer" with very high E field to cause an avalanche.**
- **Radiation damage is biggest challenge**
  - Gain layer becomes less efficient.
- **Part of HL-LHC upgrades for a fast timing calorimeter layer (BIG pixels).**



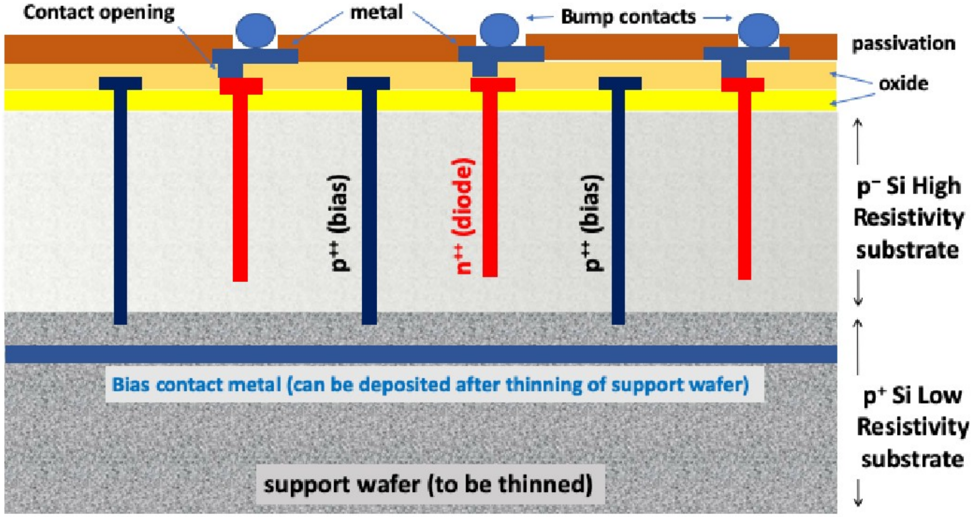


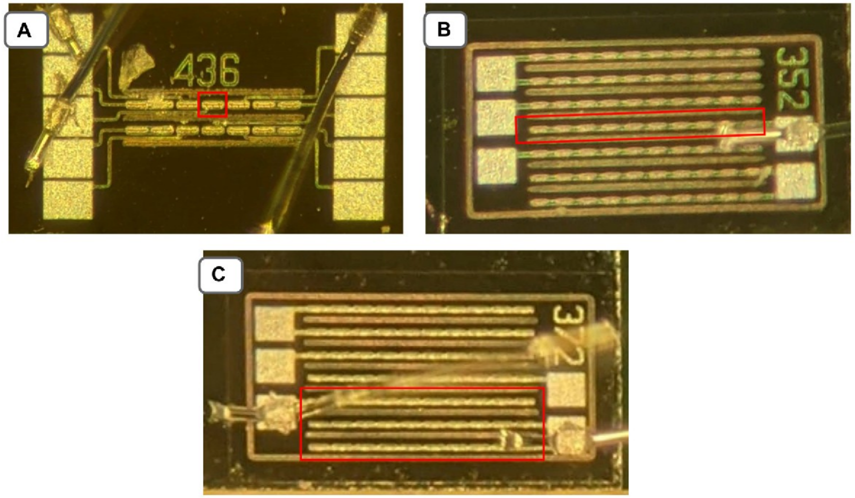
3D Sensors

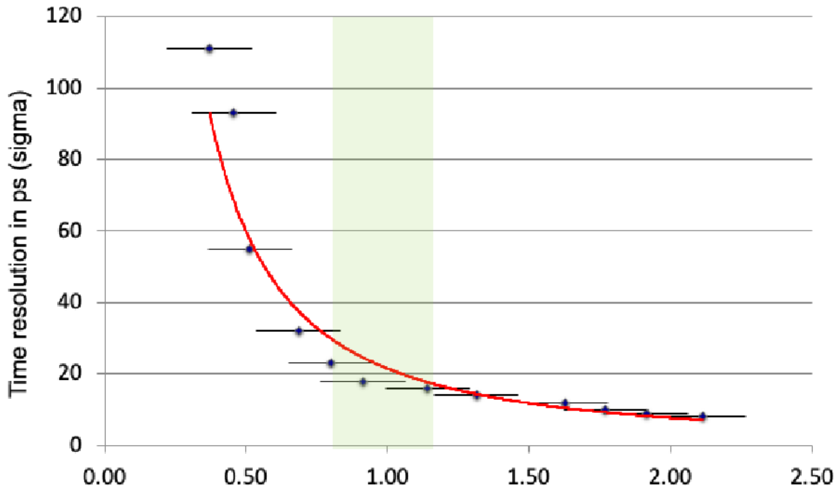
See **Francisca Munoz Sanchez**'s lecture!
May 16, 2023

Shorten drift time by putting cathodes into bulk!

- **No need for a gain layer.**
- **Used in part of ATLAS detector.**
  - Test of technology.
- **Good radiation hardness.**







Credit: Charged-particle timing with 10 ps accuracy using TimeSPOT 3D trench-type silicon pixels

Pulse Mode Ionization Chambers

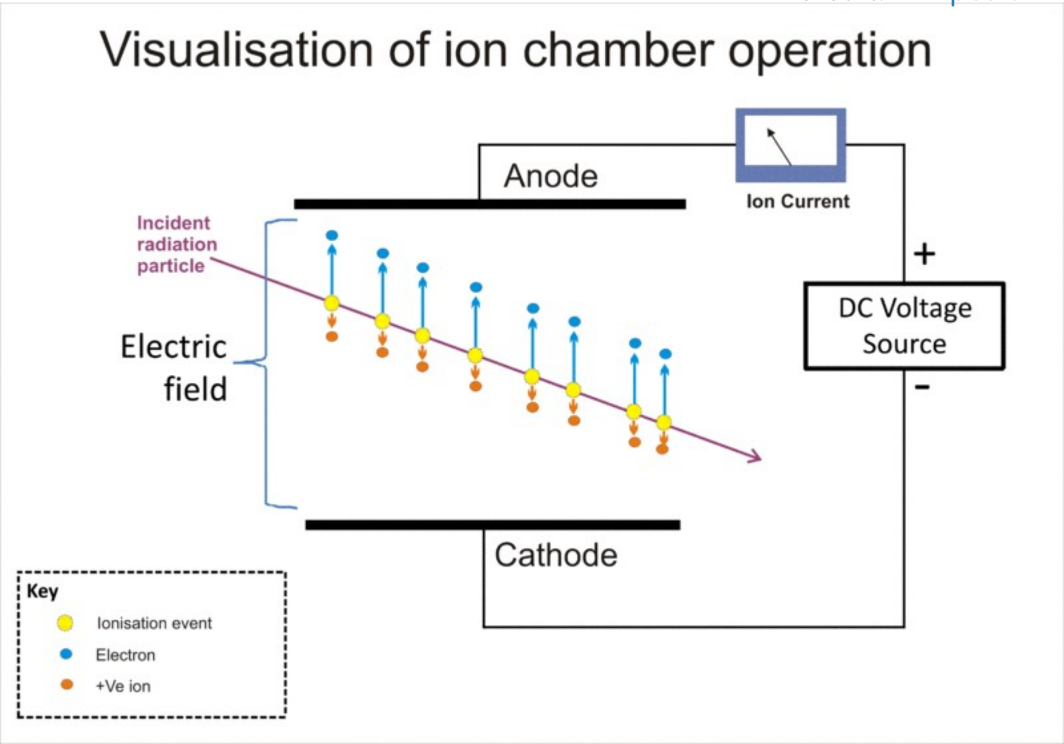
Example to illustrate concept

- Chamber filled with gas.
- Two parallel plates with voltage.

Operation

1) Traversing charged particle ionizes gas atoms.
2) Ions drift toward cathode, electrons drift toward anode.
3) Charge* is as a pulse in the current.

Credit: Wikipedia

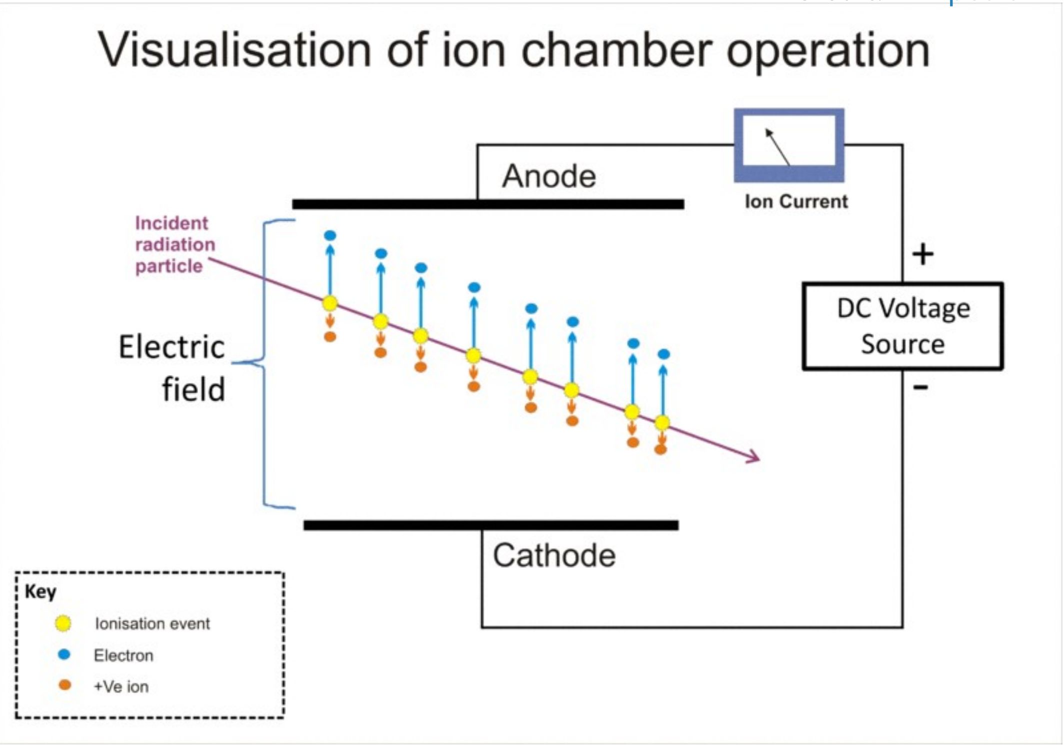


* Current is not arrival of charges at plates. It happens "instantly" via changes (new charges) in the E-field. See Shockley–Ramo theorem.

Attend **Philipp Windischhofer**'s lecture!
May 23, 2023

Pulse Mode Ionization Chambers

Credit: Wikipedia



What is the size of pulse?

- V_R = voltage across sense resistor in "Ion Current"
- V_0 = voltage on DC source
- $\frac{1}{2}CV^2$ = energy stored in plates

From energy conservation:

$$\frac{1}{2}CV_0^2 = \frac{1}{2}C(V_0 - V_R)^2 + qEd_+ + qEd_-$$

Initially: Voltage on plates is from PS.

$V_0 = V_R + V_{plates}$

work done by moving charge

Pulse Mode Ionization Chambers

$$\frac{1}{2}CV_0^2 = \frac{1}{2}C(V_0 - V_R)^2 + qEd_+ + qEd_-$$

Expand and rearrange

Assume $V_R << V_0$

$$CV_0V_R - \frac{1}{2}CV_R^2 = qE(d_+ + d_-)$$

More rearranging, $E=V_0/d$

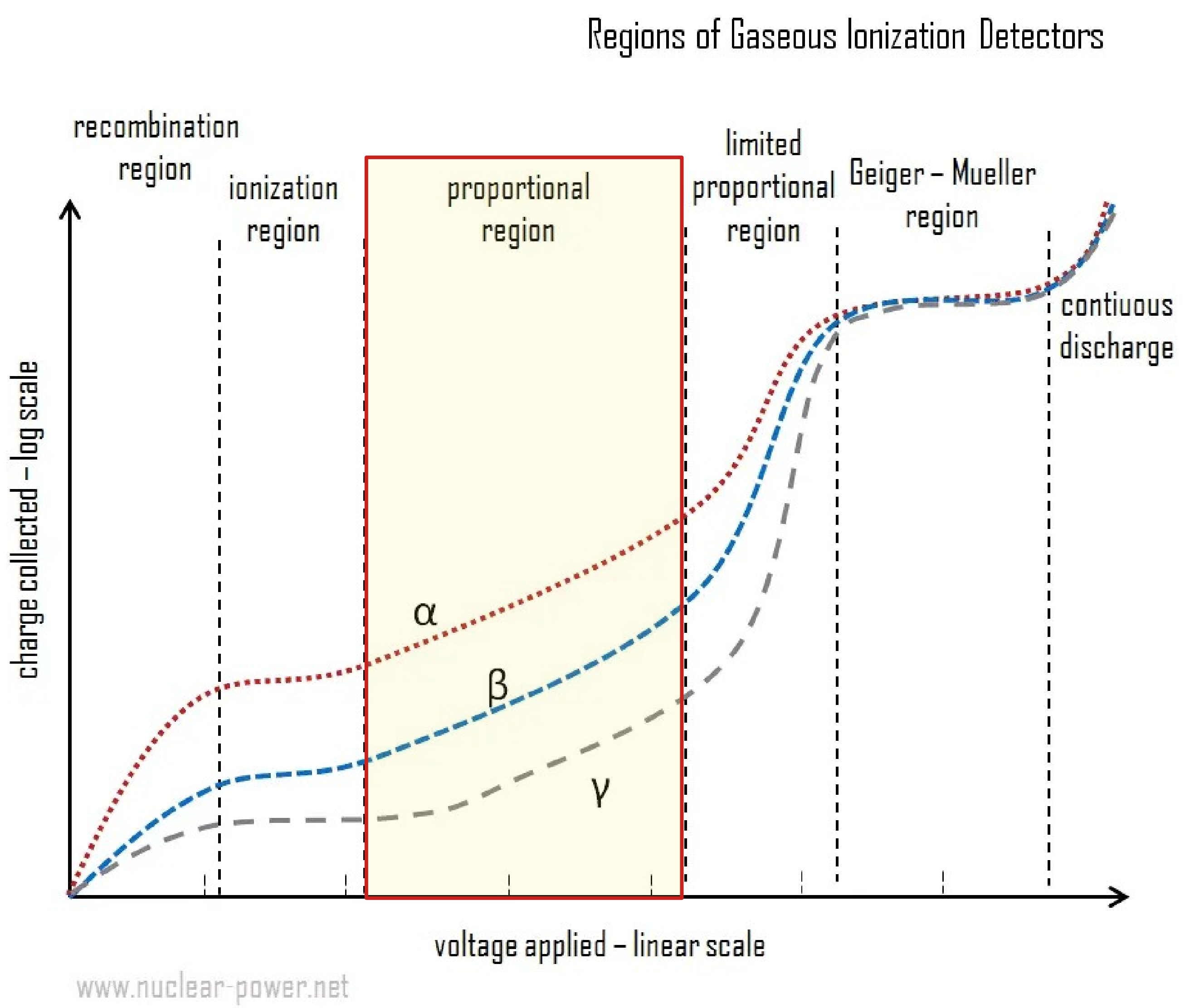
$$V_R = \frac{qE}{CV_0}(d_+ + d_-) = \frac{q}{Cd}(d_+ + d_-)$$

Distance by ions / electrons transverse the plates… $d_+ + d_- = d$

$$V_R = \frac{q}{C}$$

Pulse proportional to charge!

Pulse Mode Ionization Chambers

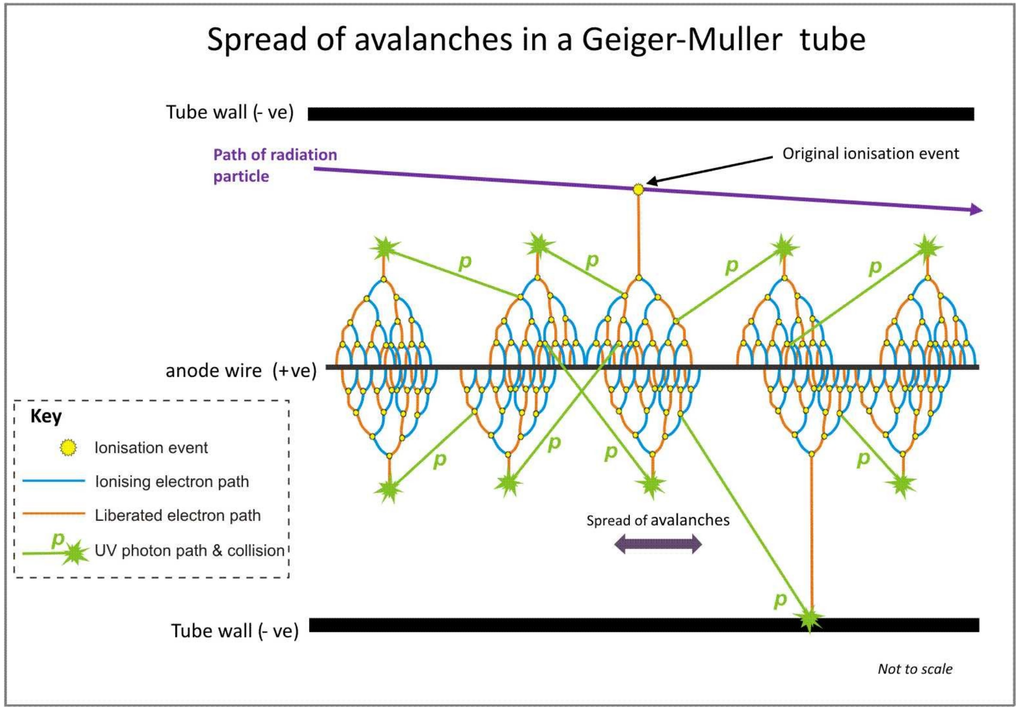


Credit: What is Proportional Region – Ionization Detector – Definition

Geiger-Muller Region

- **Ionized electrons gain energy as they are accelerated.**
- **At high energies, they can ionize further atoms.**
  - Starts to happen at ~10^6 V/m.
- **Repeat… you get an avalanche.**

Credit: Wikipedia



Usual Geiger-Muller detector

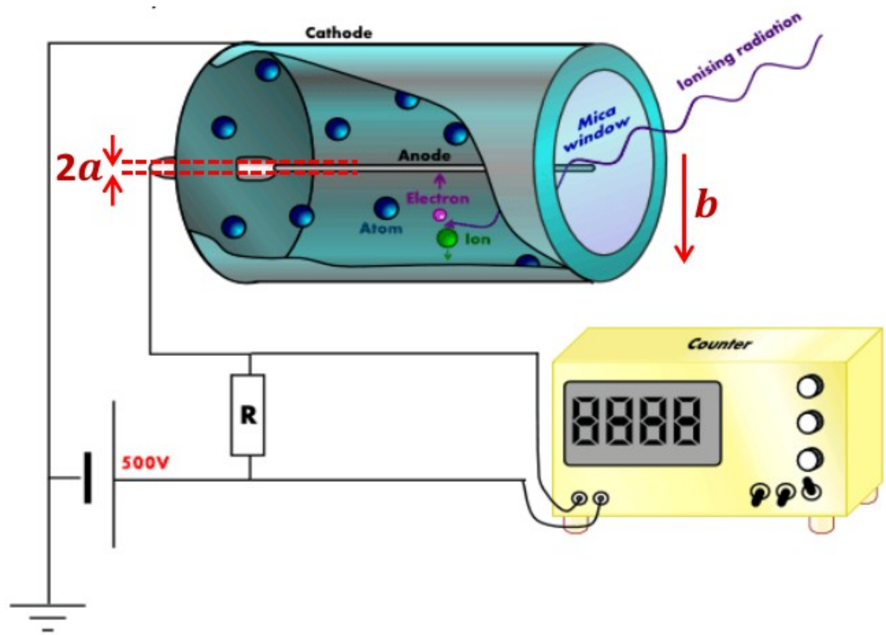
- Cylindrical geometry with a thin wire.
- Electric field is proportional to 1/r.
- Avalanche will occur close to the thin wire.

Formation of Avalanche

E-field in cylinder

$$E(r) = \frac{V}{r \ln\left(\frac{b}{a}\right)}$$

a ≈100 μm, b ≈1cm → 10^6 V/m when r < 0.2 mm



- **Electron contribution very small → short distance traveled**
  - Pulse mostly from positive ions.
- **Positive ions take long time to travel (heavy)**
  - Pulse develops much faster (Shockley–Ramo theorem!)

Drift Time of Ions

Starting from drift velocity in cylinders.

$$\frac{dr}{dt} = v_{\mathrm{drift}} = \mu E = \frac{\mu V_0}{\ln\left(\frac{b}{a}\right) r}$$

Integrate to get distance at time t.

$$\int_a^r r\,dr = \frac{\mu V_0}{\ln\left(\frac{b}{a}\right)} \int_0^t dt$$

Start at anode (formation of most ions)

…

$$\frac{1}{2}\left(r^2 - a^2\right) = \frac{\mu V_0}{\ln\left(\frac{b}{a}\right)} t$$

Use r=b to get flow from cathode to anode

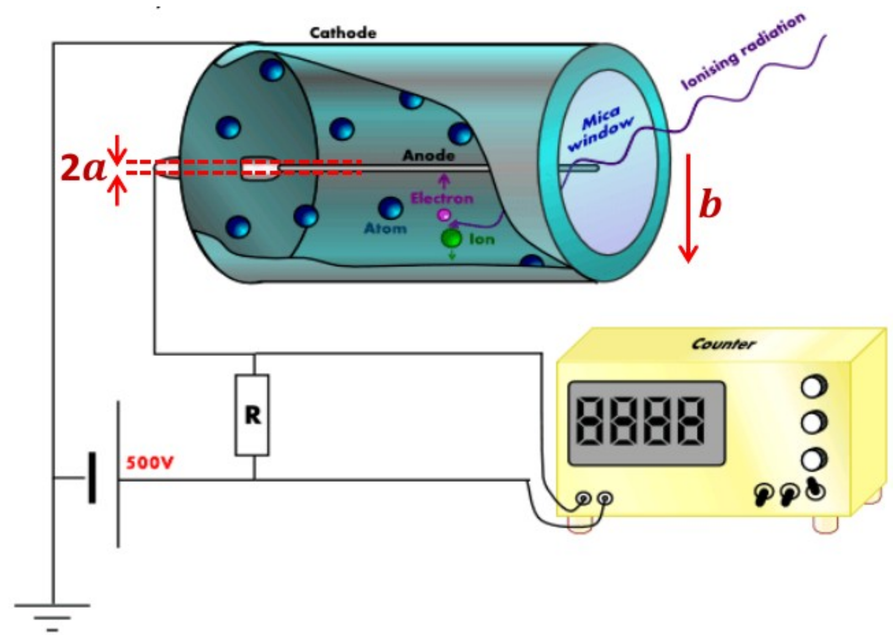
$$t = \frac{1}{2}\left(b^2 - a^2\right) \frac{\ln\left(\frac{b}{a}\right)}{\mu V_0}$$

Formation of Avalanche

Time for furthest ion to reach cathode

$$t = \frac{1}{2}\left(b^2 - a^2\right)\frac{\ln\left(\frac{b}{a}\right)}{\mu V_0}$$

$a \approx 100\ \mu m$, $b \approx 1 cm$, $V_0 \approx 1000 V$, $\mu = 10^{-4}\ m^2 / Vs$



- **In a typical detector, this is 2 ms (slow!)**
- **Half of pulse height achieved when ln(r/a) = ½ ln(b/a)**
  - r = 0.1cm, giving 20us (fast!)

Exercise: use conservation of energy to show that the pulse height after ions traveled a distance r is…

$$V_R = \frac{q}{C\ln\left(\frac{b}{a}\right)}\ln\left(\frac{r}{a}\right)$$

Two Stars and a Wish

Feedback is very welcome!

Two Stars: What are two new things you learned or were explained well?

Wish: What is something you would want to learn about or should be explained better?

https://forms.gle/AZdV5rbhWKCEF3QE6