Interactions of Particles with Matter – Part 2

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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

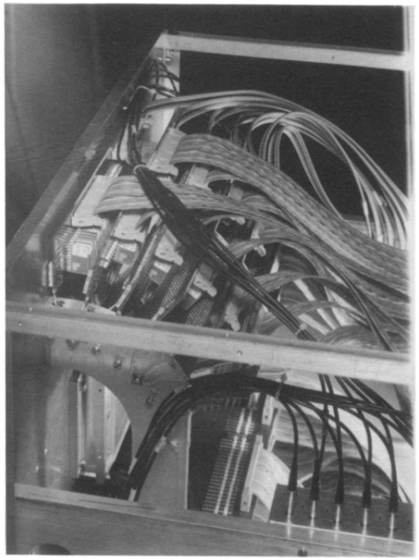
- Brief overview of silicon sensor technologies
- Gaseous detectors for tracking
- Efficiencies and energy resolutions for individual sensors

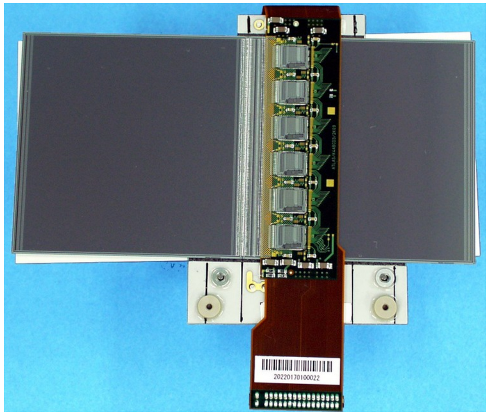
Semiconductor Tracking Detectors

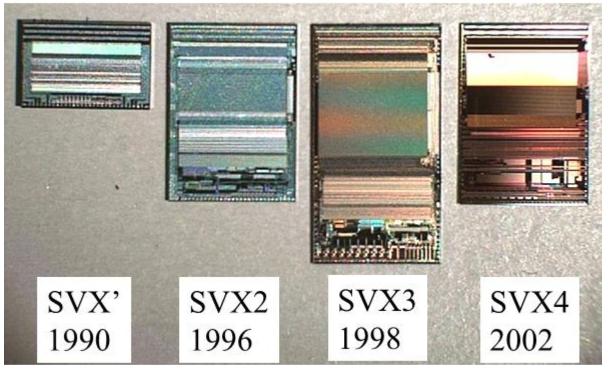
Charged particle trajectory reconstruction (*tracking*) **requires precise position information. Semiconductors are great for this!**

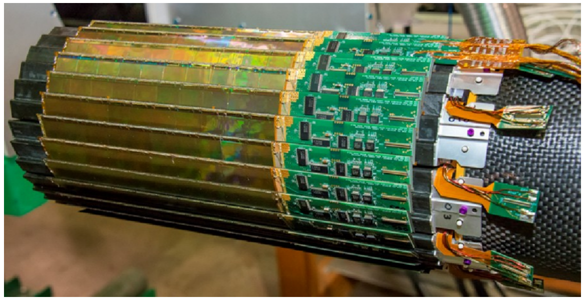
Example Technologies

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



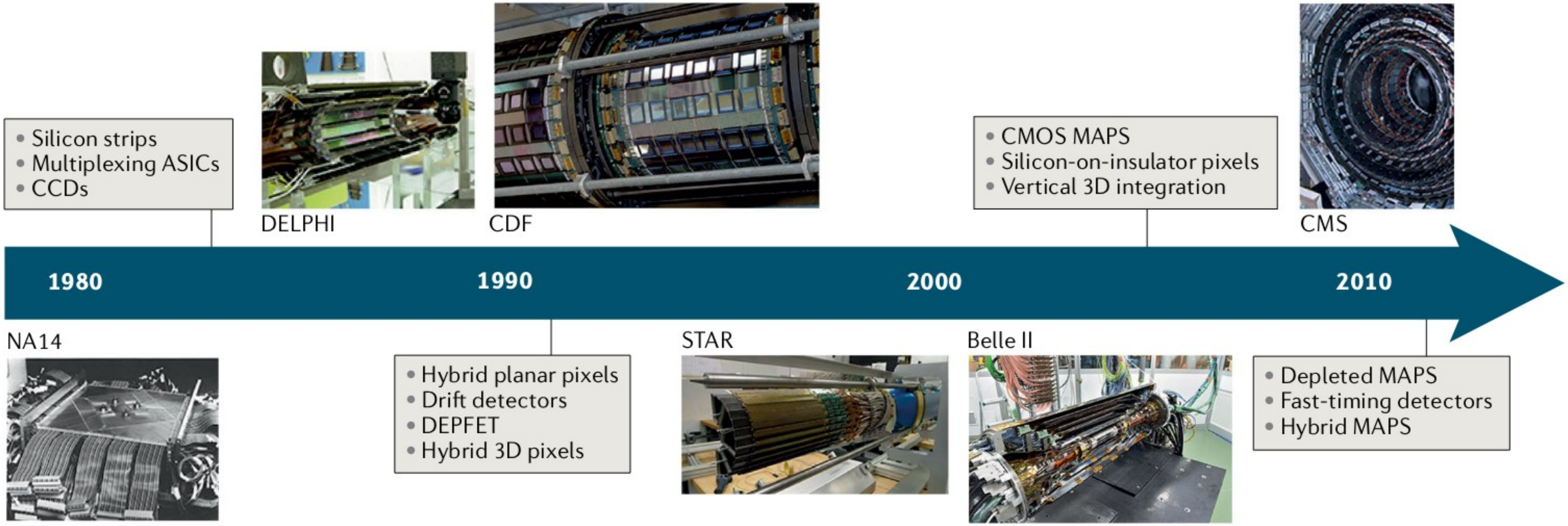






Most devices discussed today will be based on segmented p-n junction diodes.

Silicon Detectors Throughout The Years



- Silicon strips
- Multiplexing ASICs
- CCDs

- CMOS MAPS
- Silicon-on-insulator pixels
- Vertical 3D integration

- Hybrid planar pixels
- Drift detectors
- DEPFET
- Hybrid 3D pixels

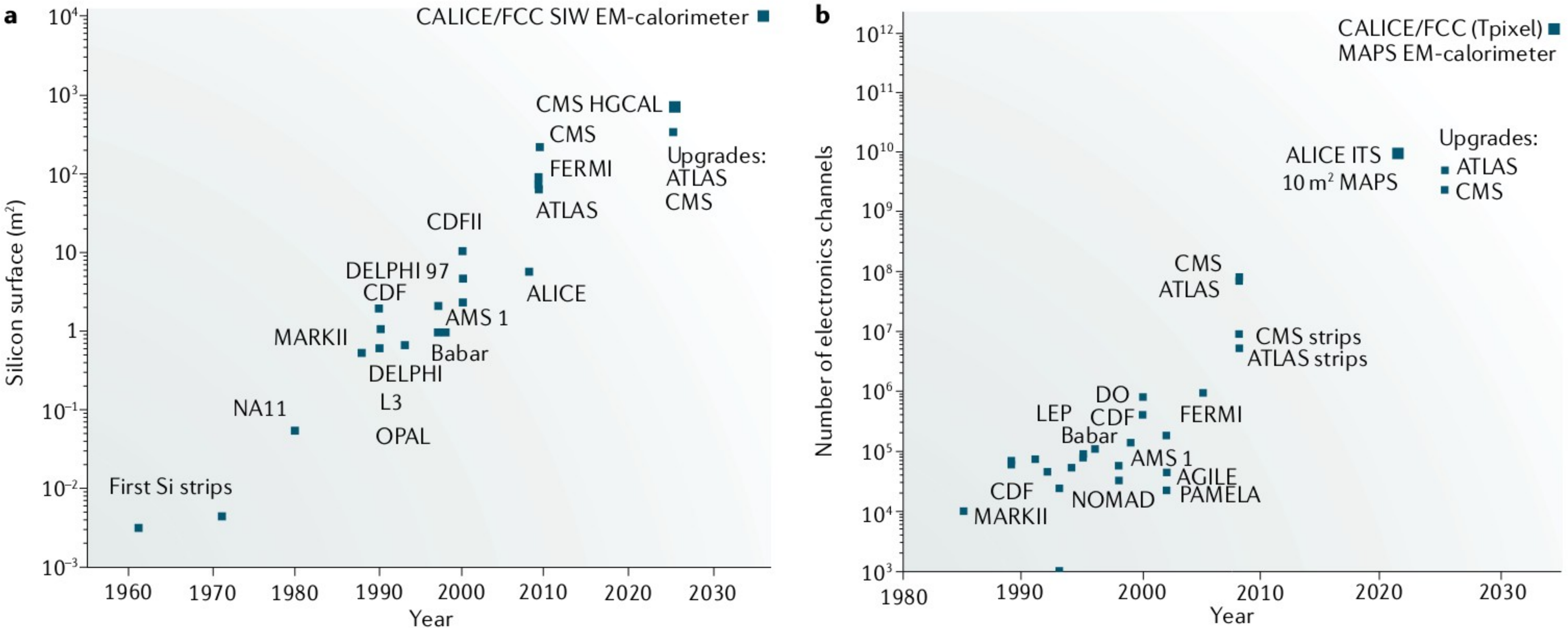
- Depleted MAPS
- Fast-timing detectors
- Hybrid MAPS

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

Silicon Detectors Throughout The Years

Follows Moore’s Law!

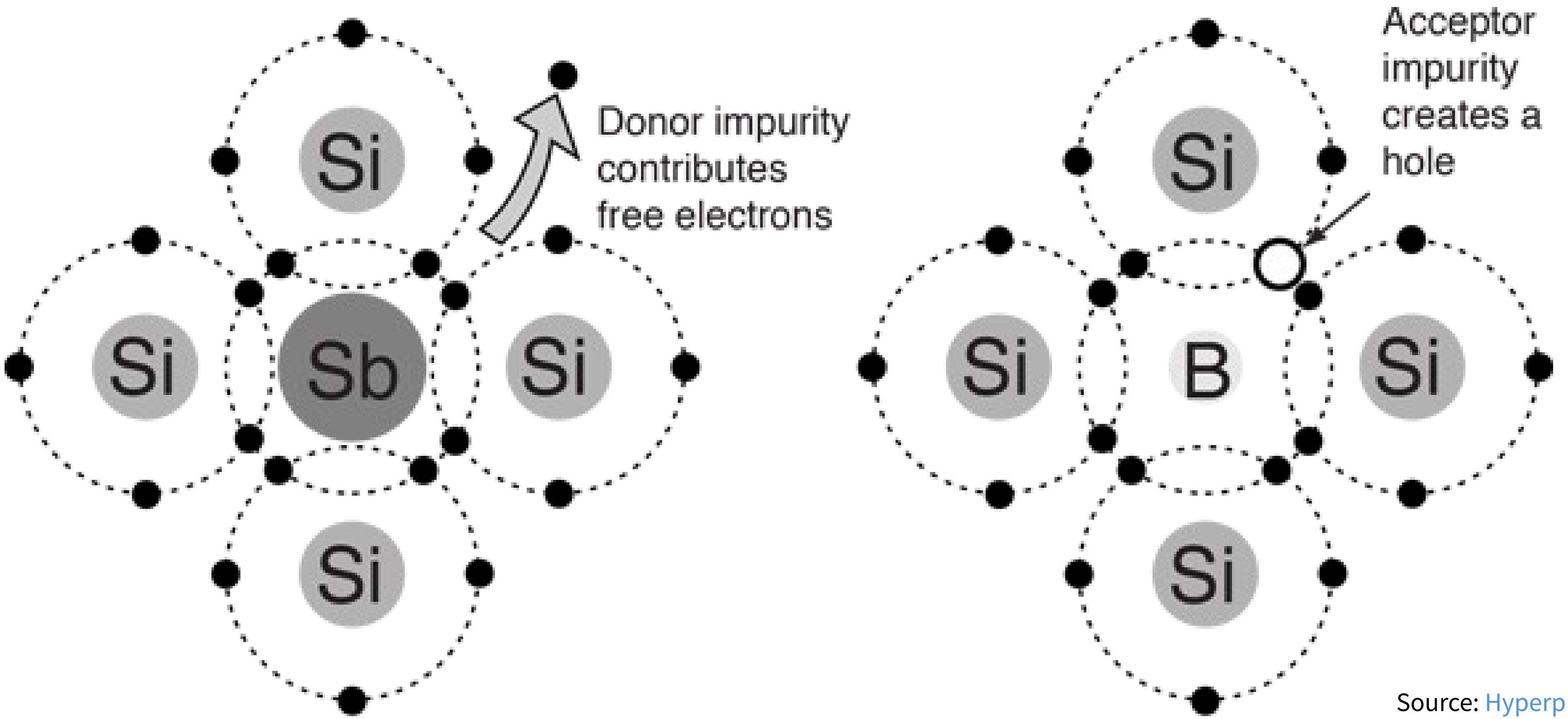
“the number of transistors in an integrated circuit (IC) doubles about every two years”



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

Fast Recap of p-n Junction: Doping

n-type **p-type**



Donor impurity contributes free electrons

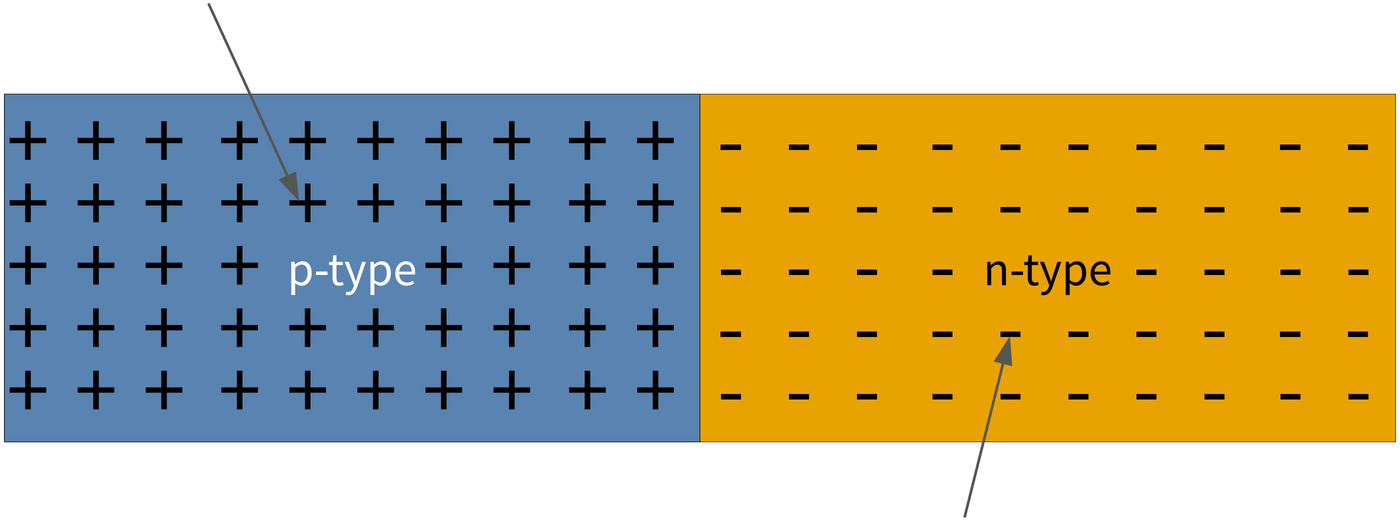
Acceptor impurity creates a hole

Source: Hyperphysics

Two types of doped silicon.

Fast Recap of p-n Junction: Junction

+: **holes** = electrons missing in covalent bonds

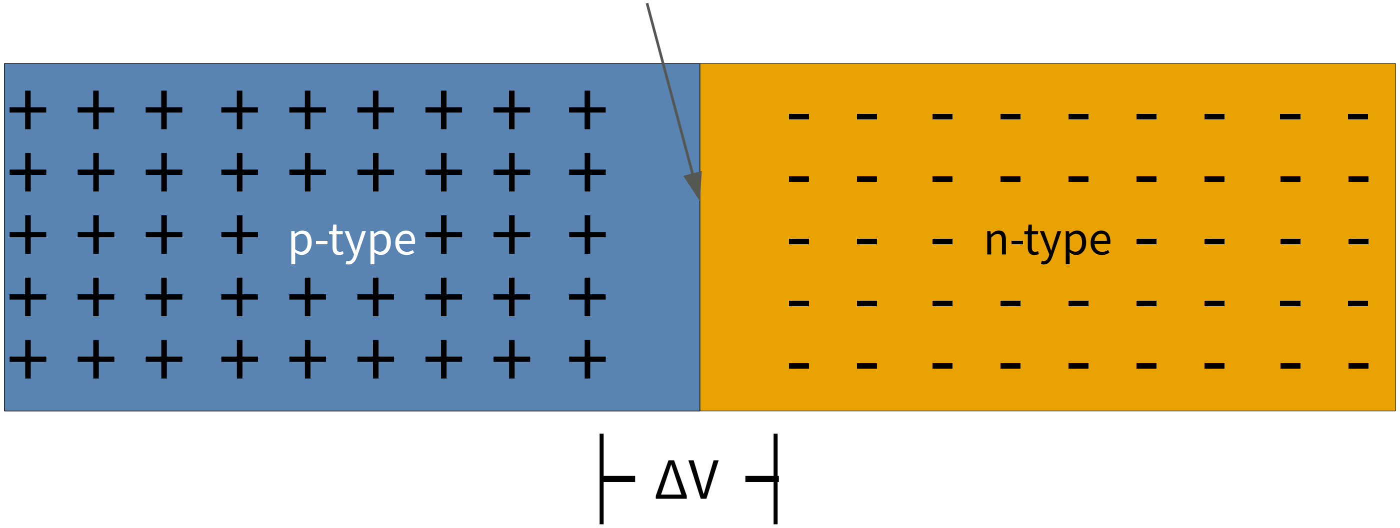


- : **free electrons** = electrons outside of covalent bonds

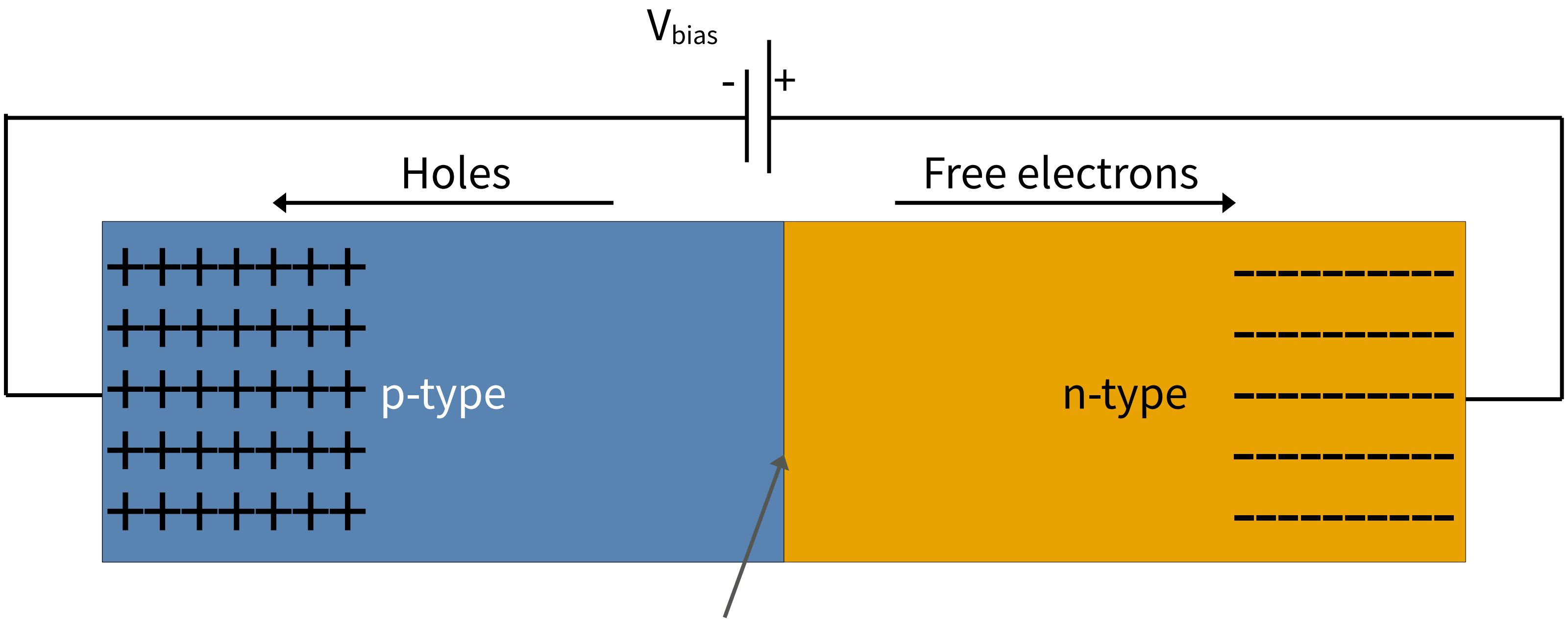
Note: The entire material is neutral! $N_{electrons} = N_{protons}$

Fast Recap of p-n Junction: Equilibrium

Small depletion region as some electrons flow into holes.



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

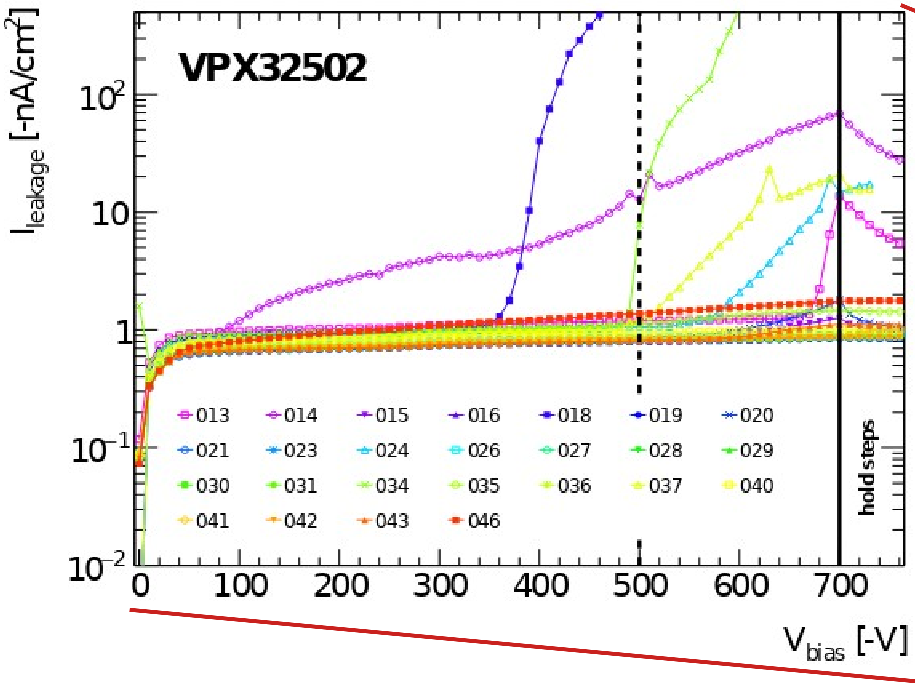


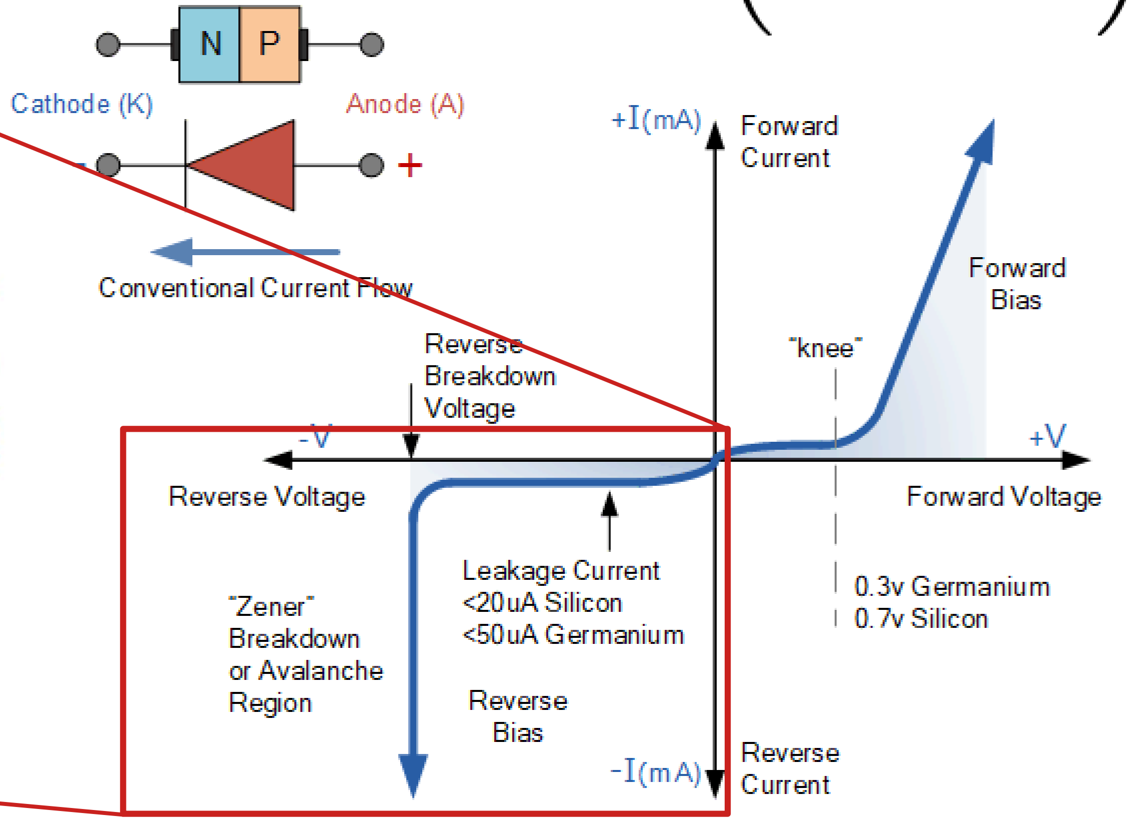
Depletion region:

- 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

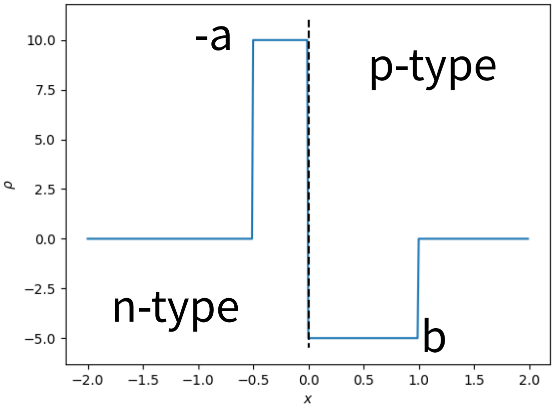
$$aN_n = bN_p$$

Integrate again to get voltage

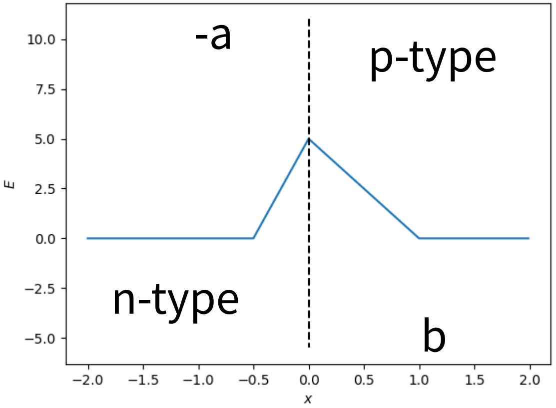
$$V = -\frac{eN_n}{2\epsilon}(x+a)^2 + V_0, -a < x < 0$$

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

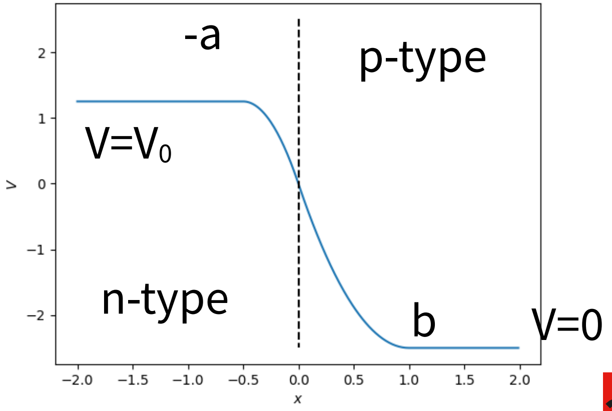
Density



E-field



Potential



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

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

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.

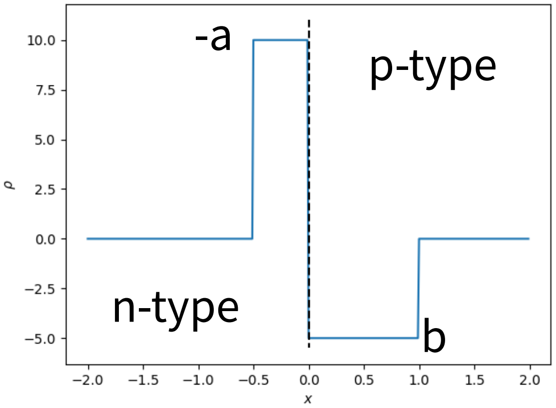
$$b \approx \sqrt{\frac{\epsilon V_0}{eN_p}}, N_n \gg N_p \qquad a \approx \sqrt{\frac{\epsilon V_0}{eN_n}}, N_p \gg N_n$$

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

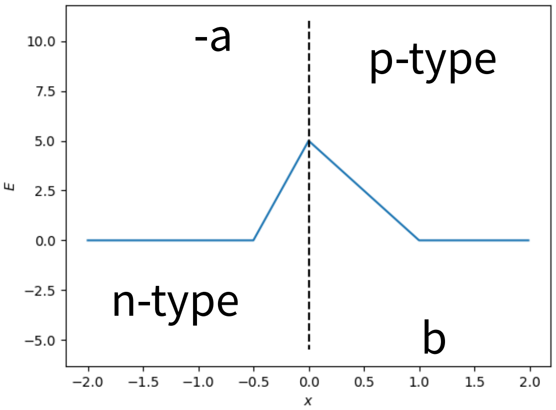
$$\boxed{d \approx \sqrt{\frac{\epsilon V_0}{eN_{\mathrm{min}}}}}$$

Depletion region is driven by the dopand with the smaller concentration.

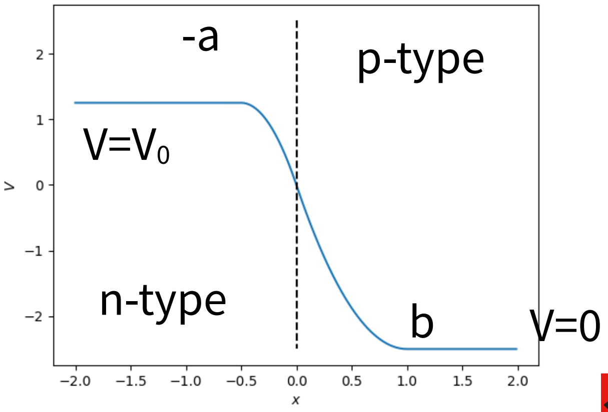
Density



E-field



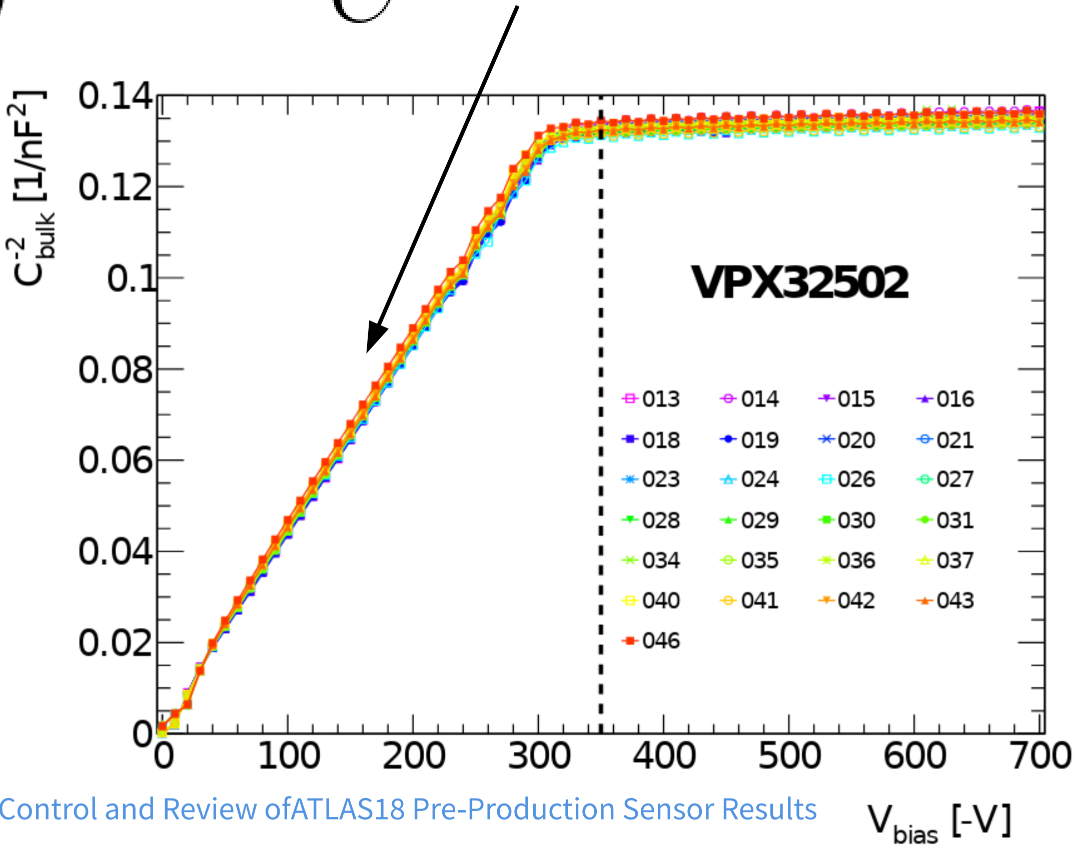
Potential



Depletion Layer

Treat depletion layer as parallel plate capacitor

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



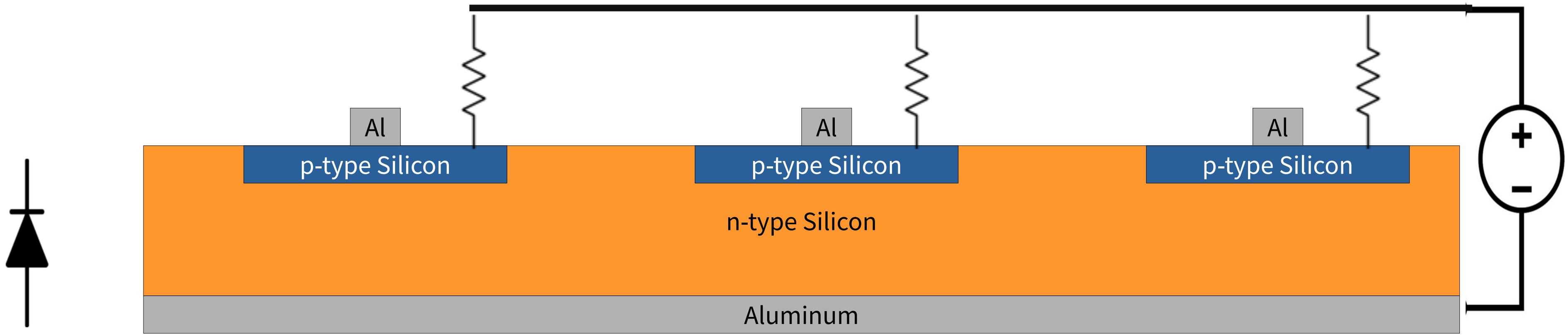
Measure capacitance to find

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

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

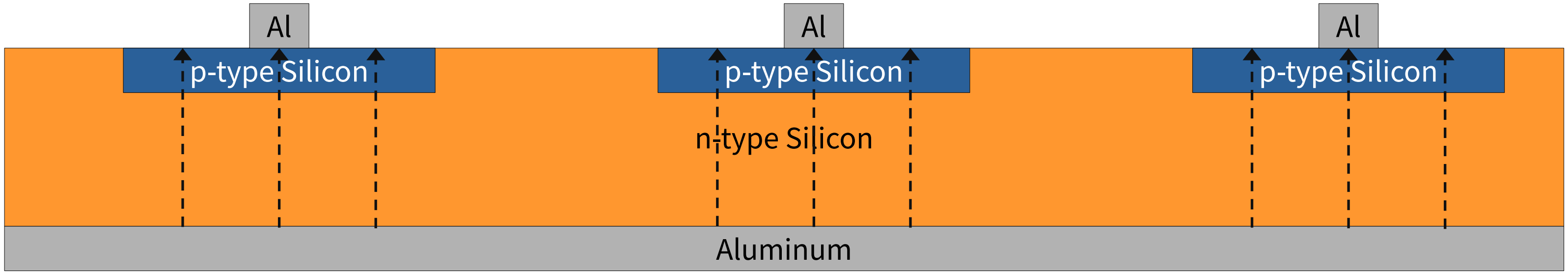
How A Sensor Works

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



How A Sensor Works

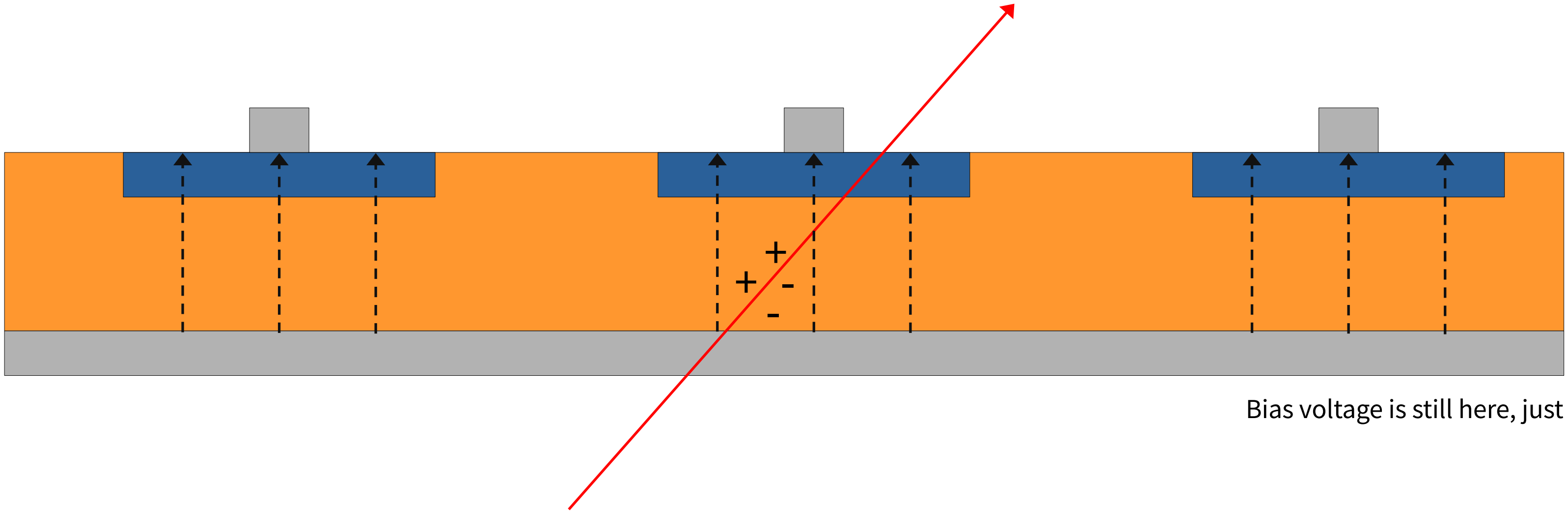
Electric field is formed inside an **insulator**.



Bias voltage is still here, just not shown.

How A Sensor Works

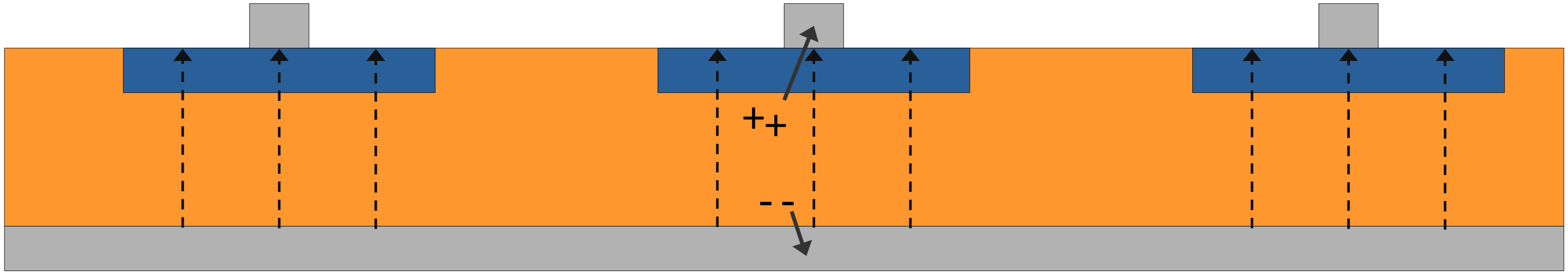
Passing particle excites electrons (**ionizes**) into conducting band.



Bias voltage is still here, just not shown.

How A Sensor Works

Electron/hole pairs travel, creating detectable current.



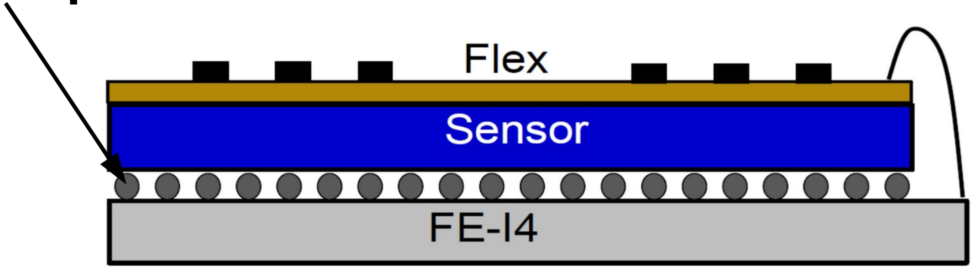
Bias voltage is still here, just not shown.

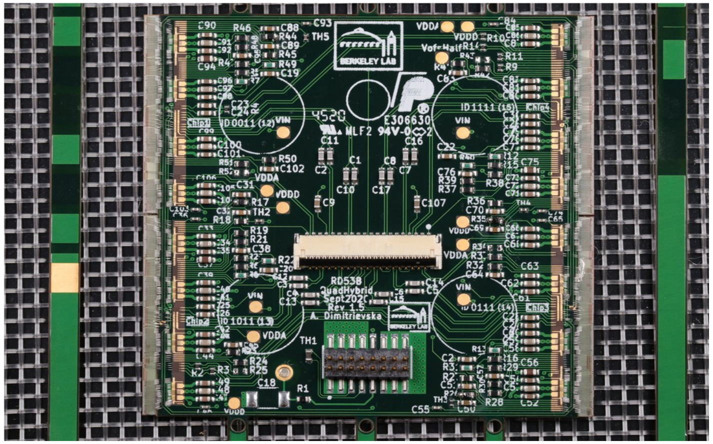
Hybrid Detectors

Readout electronics on PCB’s attached to silicon sensors.

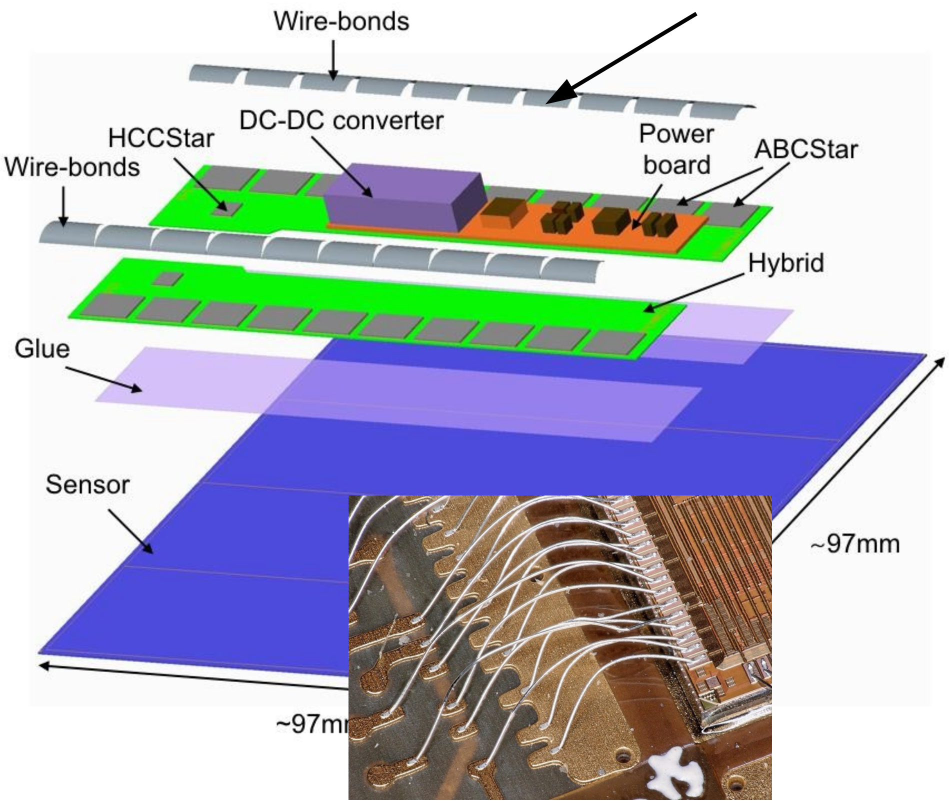
Individual connections to segmented channels in the sensor.

bump bond





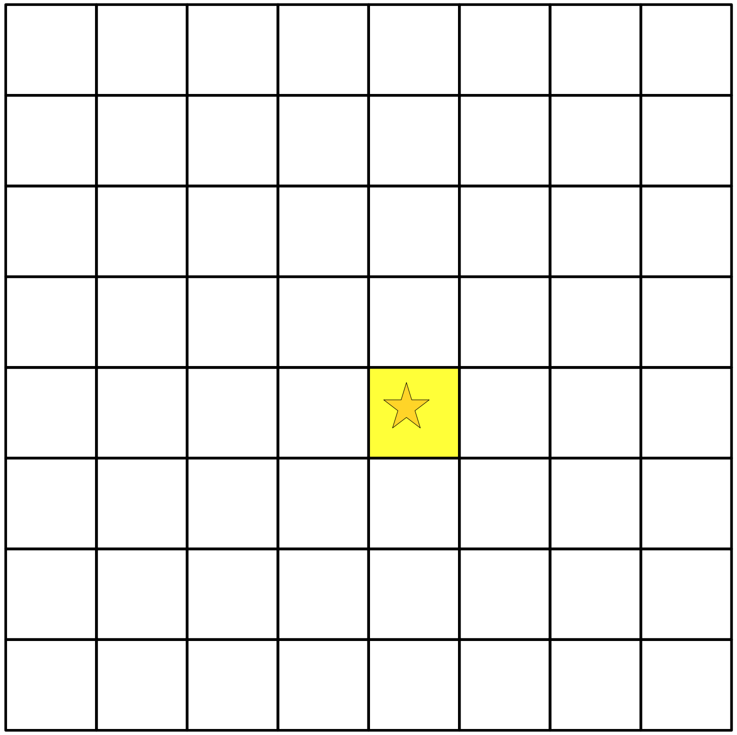
wirebonds



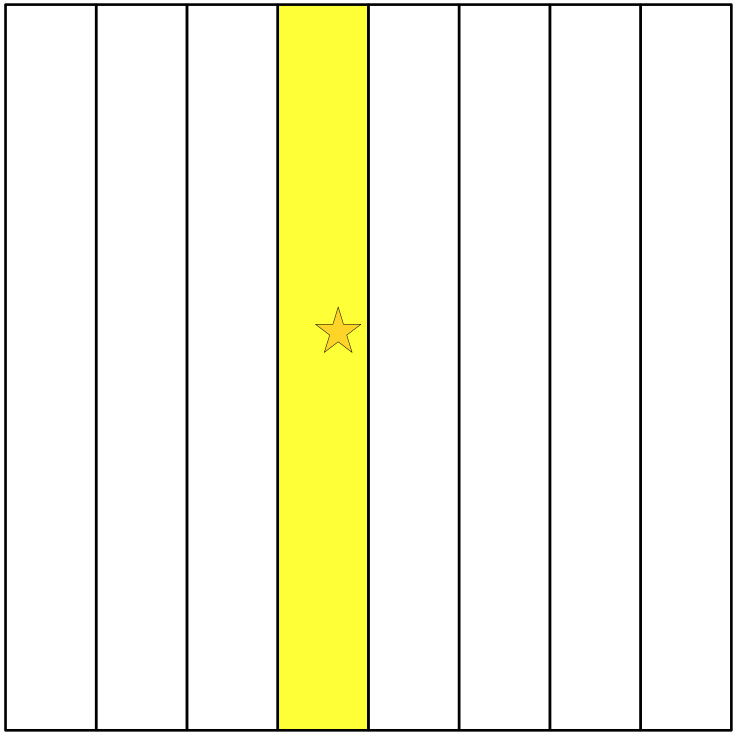
ex: ASIC wirebonded to PCB

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

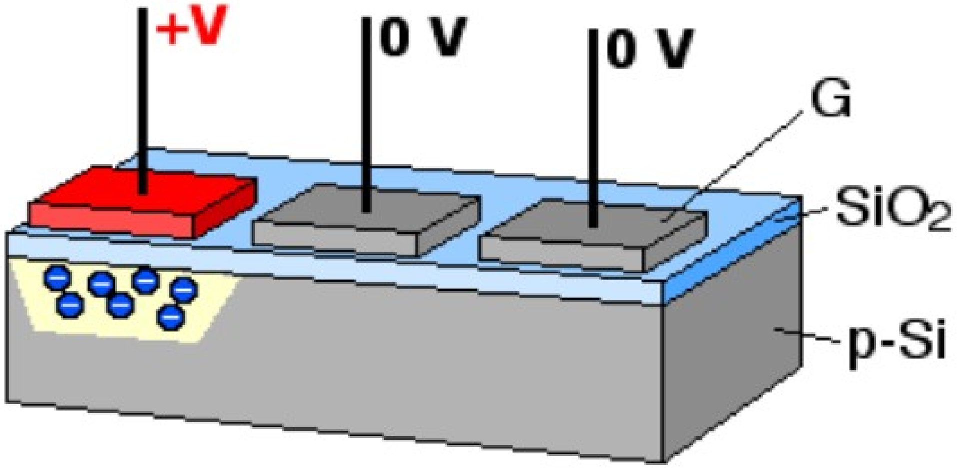
Defines the segmentation
of the sensitive part.

Question:

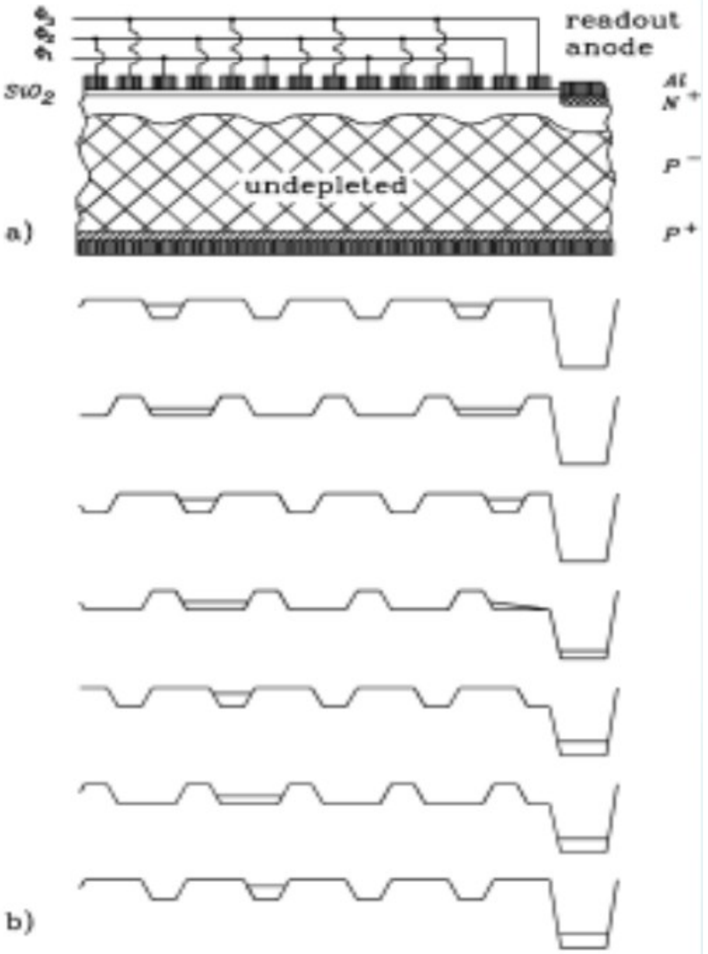
- When do you use a strip vs pixel sensor?
- How to make a strip give a 2D position?

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.**



Monolithic Pixels

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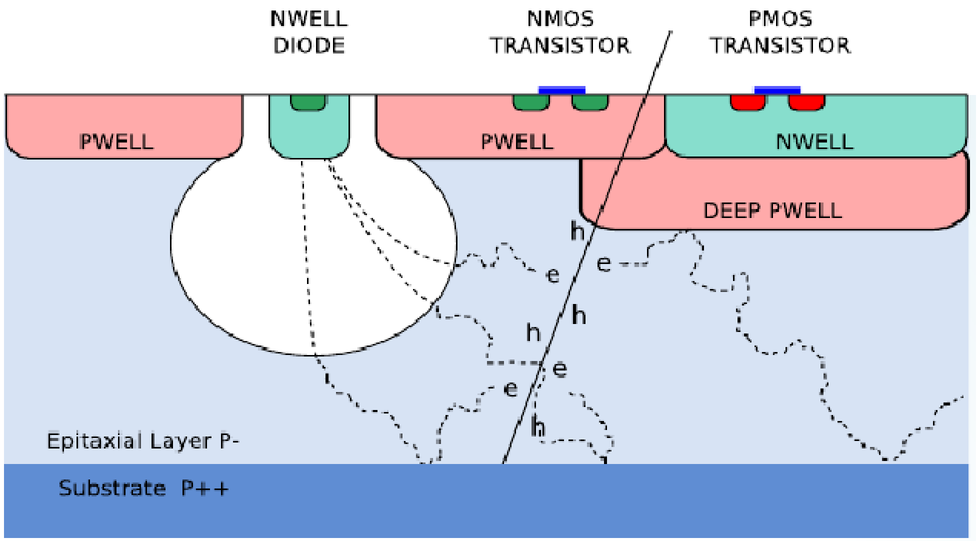
Combine sensor (silicon) with readout electronics (silicon).

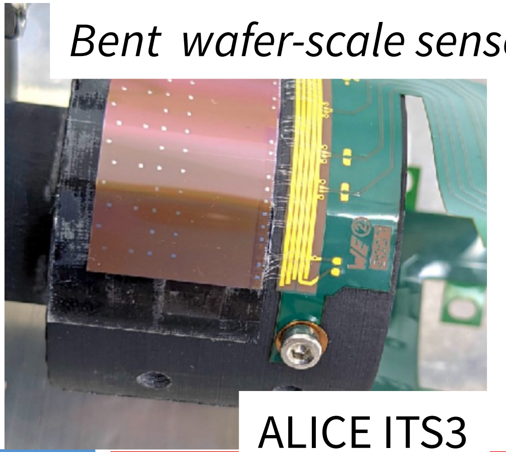
You save half construction time by no mention of glue in meetings.



- **Using CMOS technology for both readout and imagining**
  - $$$$ industry (phone cameras!)
- **Main challenge is fitting all electronics in limited space.**

MAPS = Monolithic Active Pixel Sensor

Bent wafer-scale sensors.

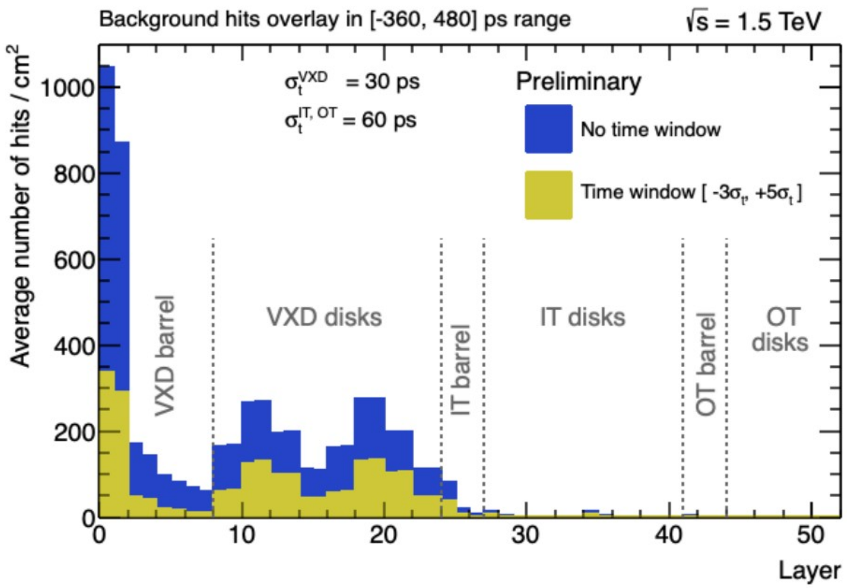


ALICE ITS3

Fast Timing Detectors (4D Tracking)

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

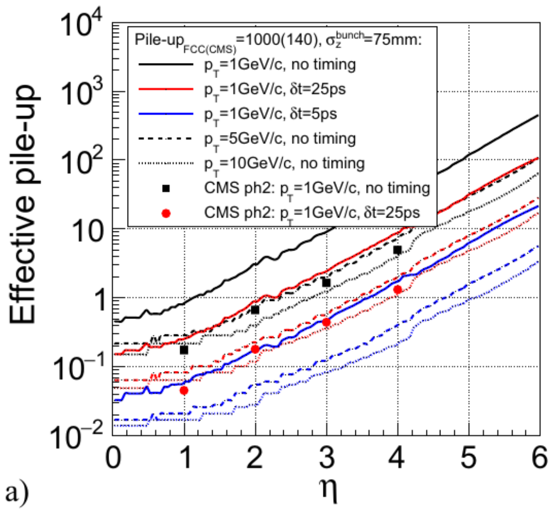
BIB rejection in Muon Collider Detector.



Timing resolution limited by electron drifting to anodes

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

Vertex discrimination in FCChh



Low Gain Avalange Diodes

Attend **Francisca Munoz Sanchez**'s lecture!
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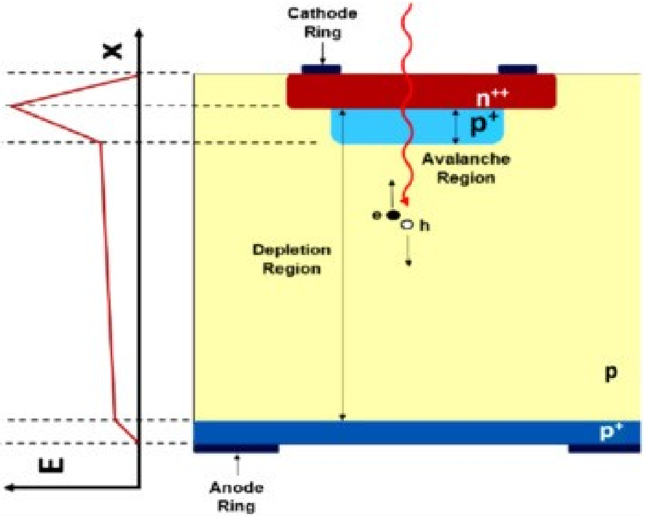
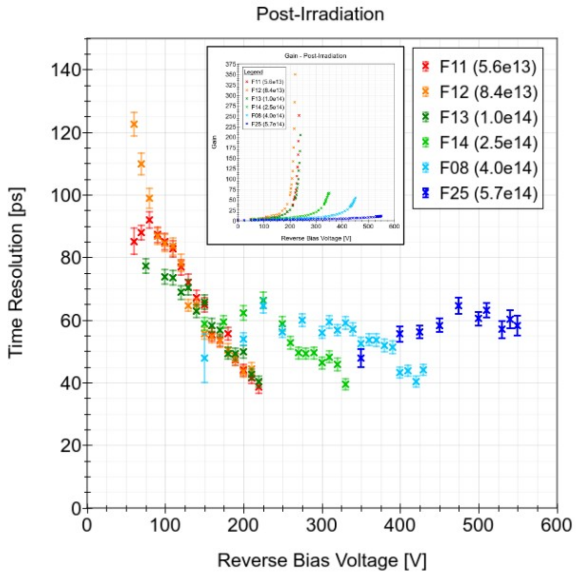
Shorten drift time by making sensors thinner!

- **Thinner sensors collect less charge.**
  - Lower signal-to-noise.
- **LGADs add a "gain layer" with very high E field to cause an avalanche.**
- **Two big challenges**
  - Rad dam: Gain layer less efficient.
  - Fill factor: dead area around pixels.
- **Part of HL-LHC upgrades for a fast timing calorimeter layer (BIG pixels).**





3D Sensors

See **Francisca Munoz Sanchez**’s lecture!
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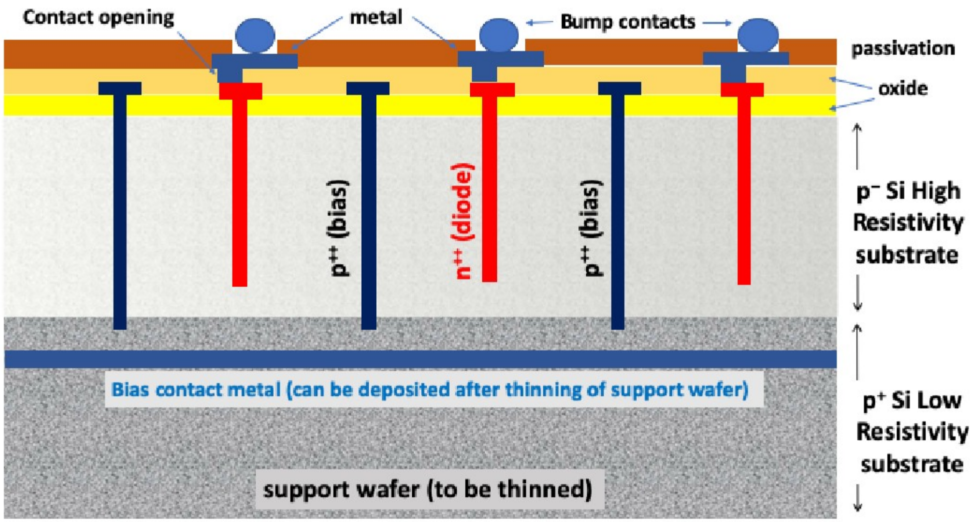
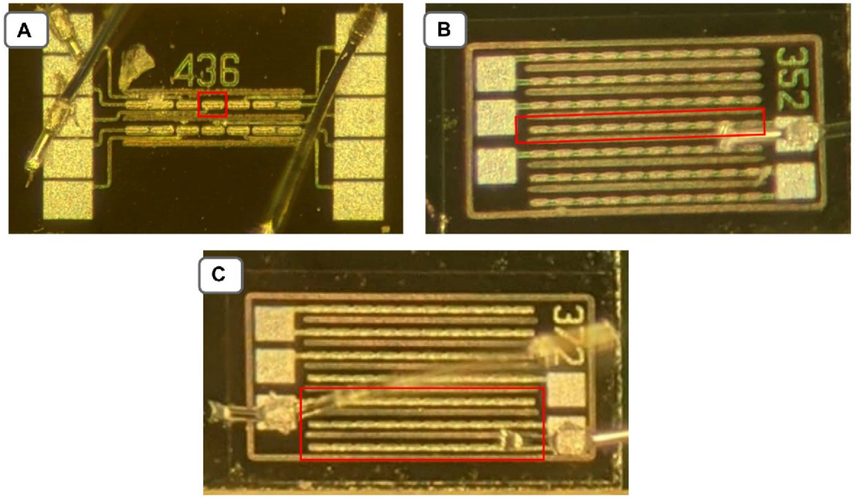
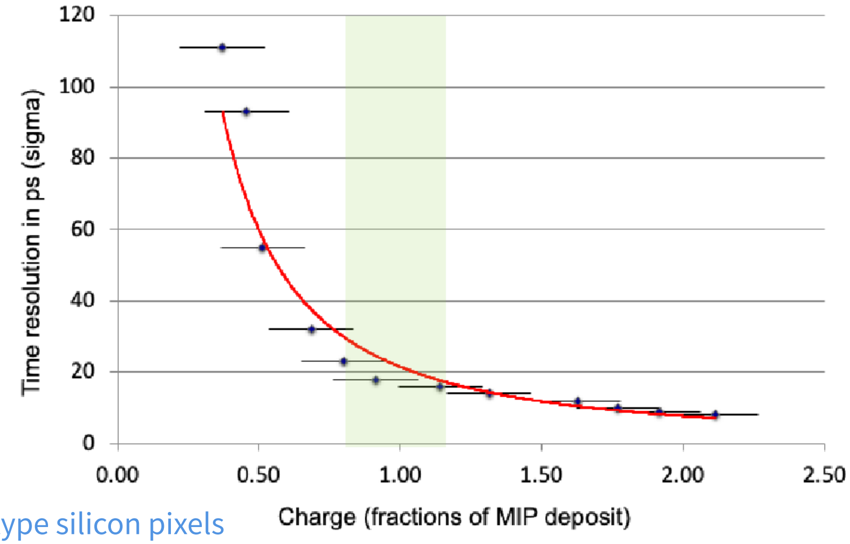
Shorten drift time by putting cathodes into bulk!

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



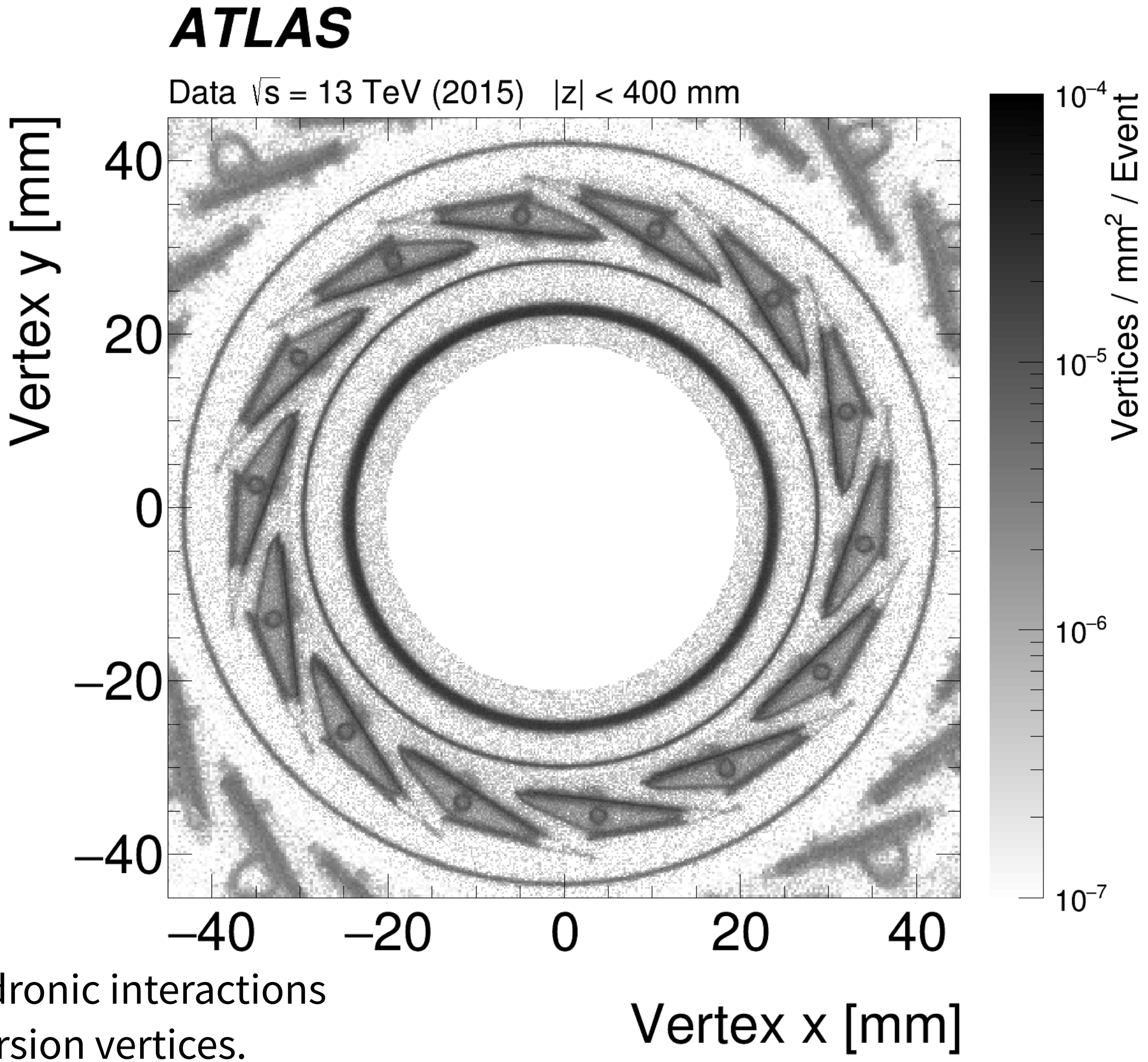




Credit: Charged-particle timing with 10 ps accuracy using TimeSPOT 3D trench-type silicon pixels

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 entire detector.

They are related (for example) coverage of detector:

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

Intrinsic Sensor Resolution: Pulse Heights

1) Transversing particle deposits energy E into detector.
2) Energy E is used to create N signal carriers.
3) Signal carriers propagate to readout electronics.
4) Readout electronics convert signal carriers into a pulse.

pulse height ∝ number of signal carriers ∝ deposited energy

On average, this is a statistical process.

Intrinsic sensor/energy resolution:

How much will pulse height *vary* for a fixed input energy?

Intrinsic Sensor Resolution: Statistics

1)A traversing particle deposits (exactly) *E* energy.

2)Number of signal carrier created is *N* = *E*/*w*.

- *w* is the average energy to create a single signal carrier (e.g. 3.6 eV for silicon)

But signal carrier creation is a random process.

- If signal carriers are created independently → 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.**
  - F≤1, by definition.

$$< N >= FN$$

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

Example Fano Factor Values

Si: Consider energy deposited as ionizing (E_{ion}) and lattice (E_{pho}).

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

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

See chapter 2.2.3 in Speiler for derivation.

Example Theoretical Values

	Fano Factor
Si	0.115
Ge	0.13
GeAs	0.12
Diamond	0.08

Example Measured Values

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

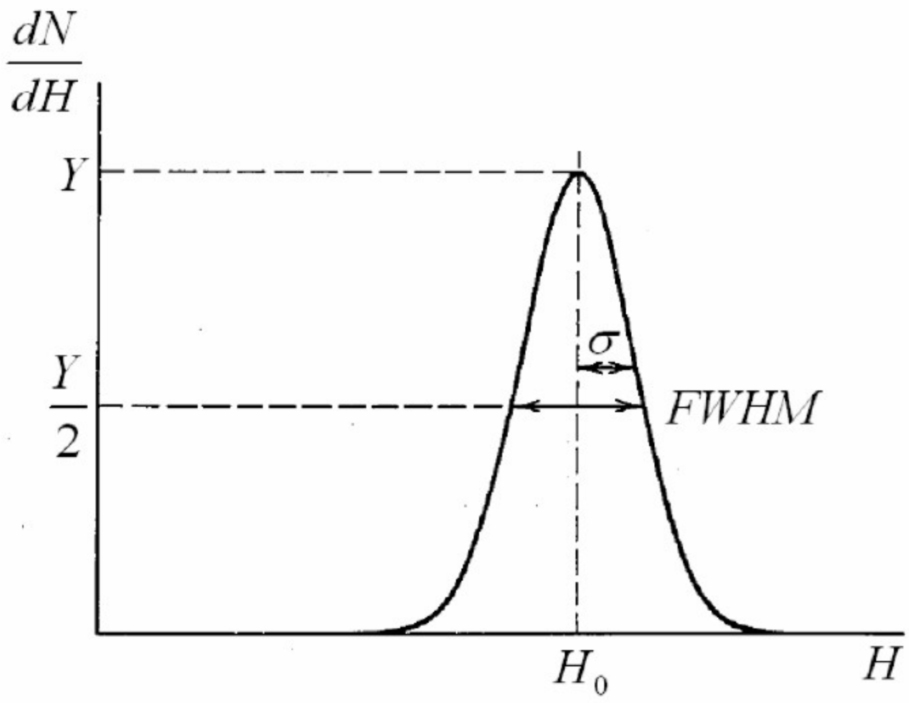
Intrinsic Sensor Resolution: Poisson

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*.

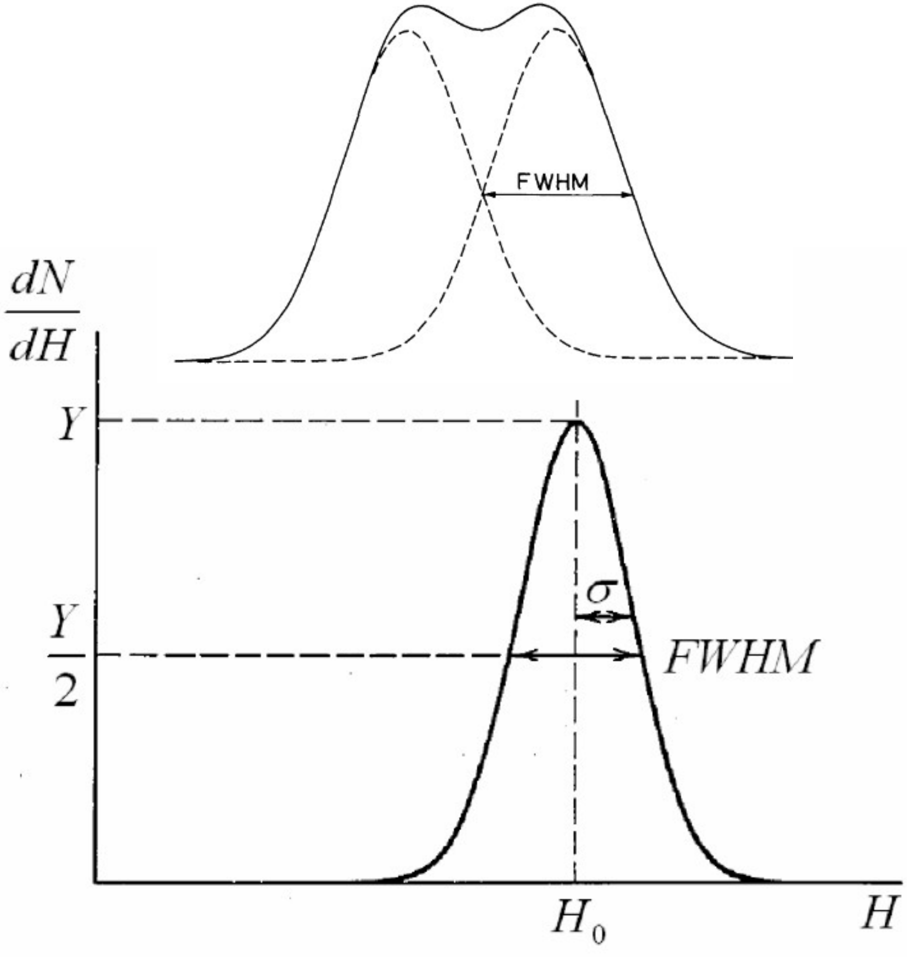
$$\mathrm{FWHM} = 2\sqrt{2\ln 2}\sigma \approx 2.35\sigma$$



Intrinsic Sensor Resolution: Poisson

Relative energy resolution, ΔE, is defined as FWHM/H_0.

Distinguish two peaks when separated by FWHM.



Take *k* to be proportionality.

$H=kN$ $H_0 = k\langle N\rangle$ $\sigma_H=k\sigma_N$

Using prev. equations…

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

Pulse Mode Ionization Chambers

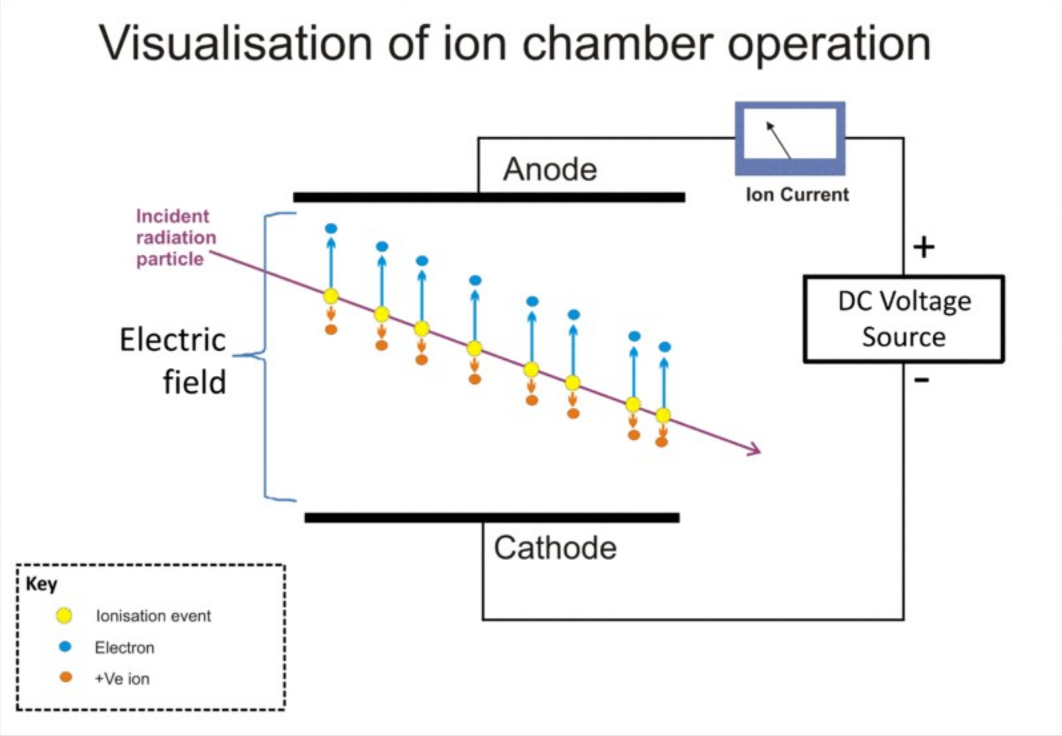
Example to illustrate concept

- 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.

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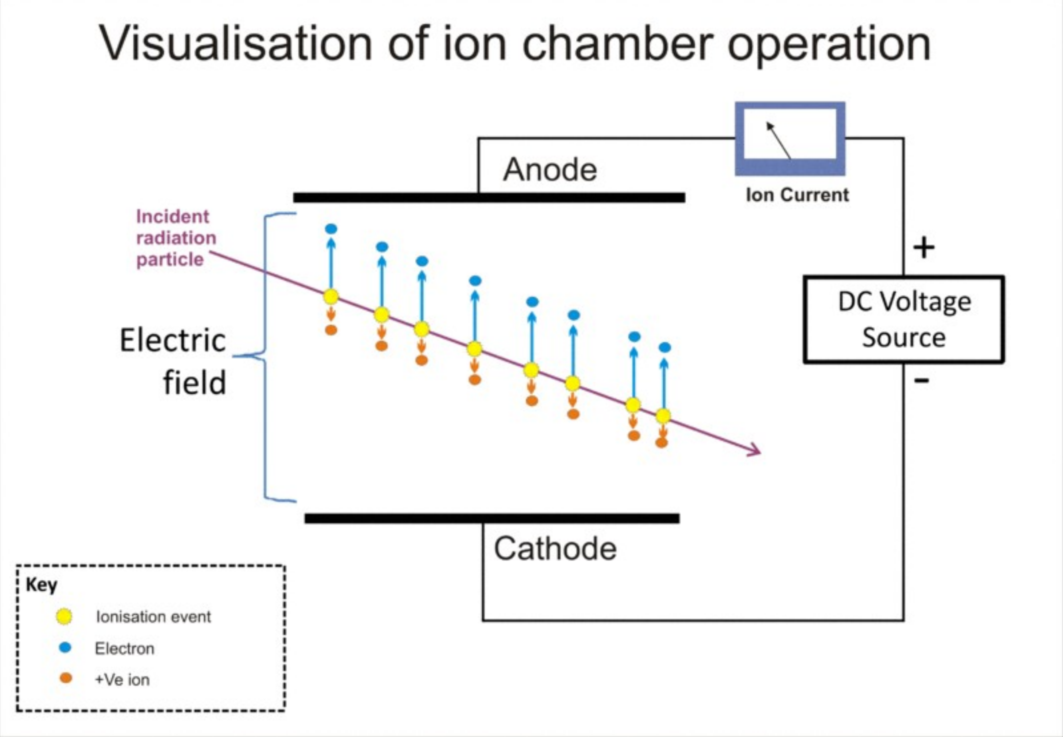
Pulse Mode Ionization Chambers

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


Credit: Wikipedia

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.

$V_0 = V_R + V_{\text{plates}}$

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 $V_R << V_0$

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

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… $d_+ + d_- = d$

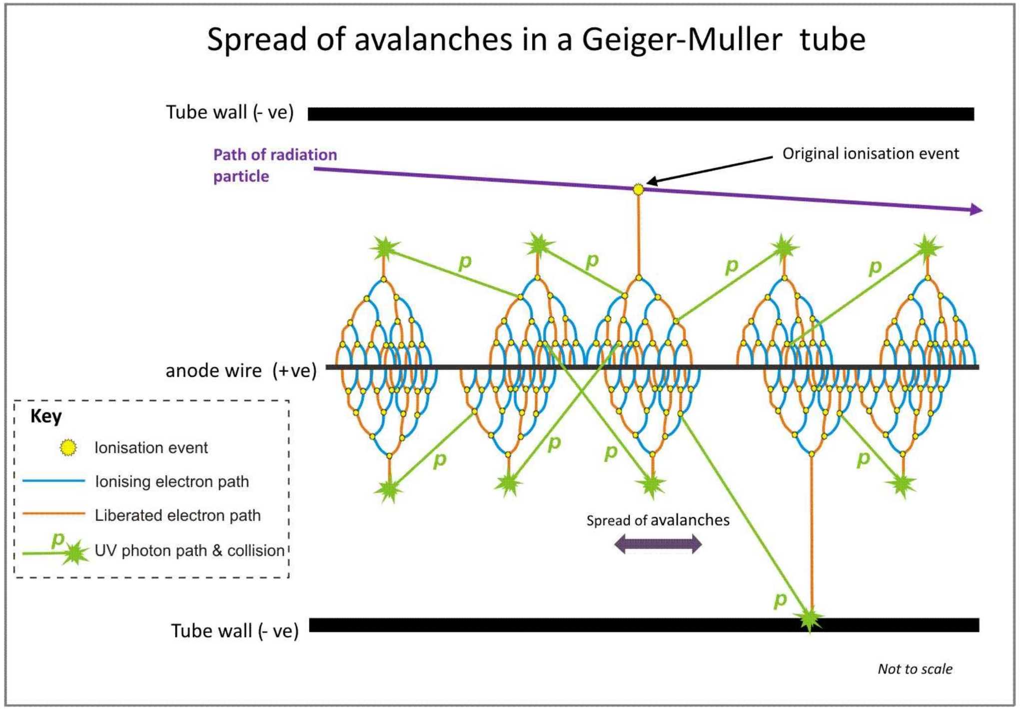
$$\boxed{V_R = \frac{q}{C}}$$

Pulse proportional to charge!

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

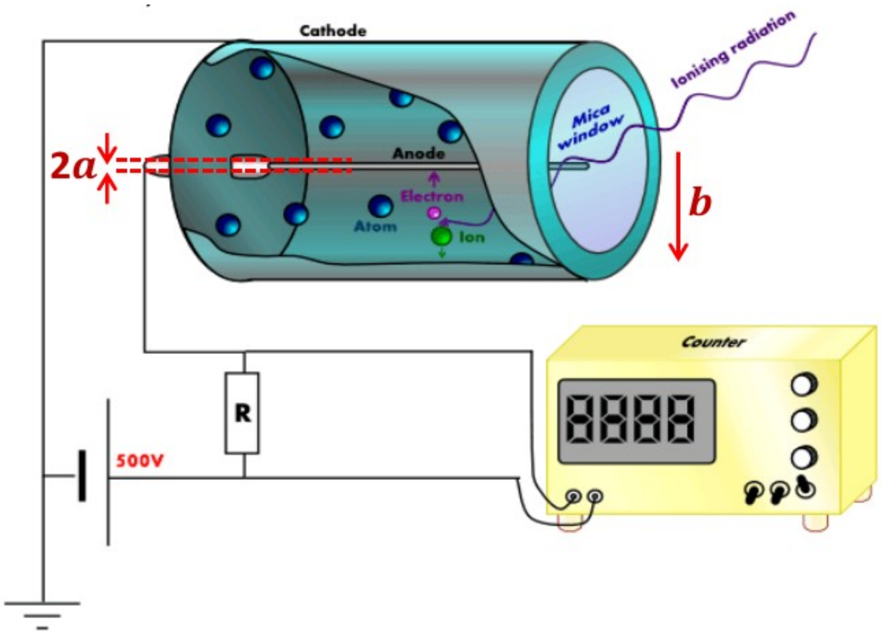
- Cylindrical geometry with a thin wire.
- Electric field is proportional to 1/r.
- Avalanche will occur close to the thin wire.

Formation of Avalanche

E-field in cylinder

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

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.

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

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

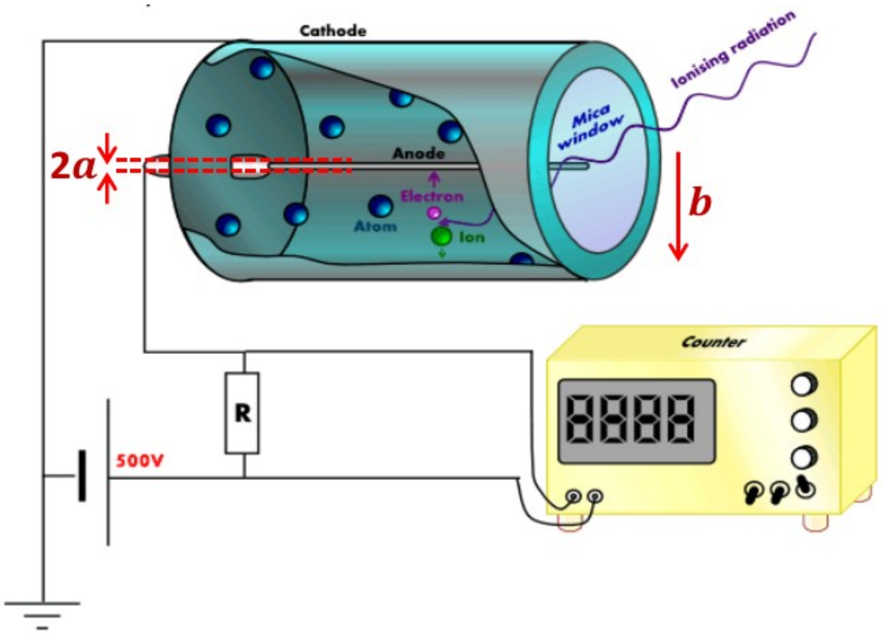
$$t = \frac{1}{2}\left(b^2 - a^2\right) \frac{\ln\left(\frac{b}{a}\right)}{\mu V_0}$$

Drift Time of Ions

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 ≈100 µm, b ≈1cm, V_0 ≈1000V, µ=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...

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

Further Material

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

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