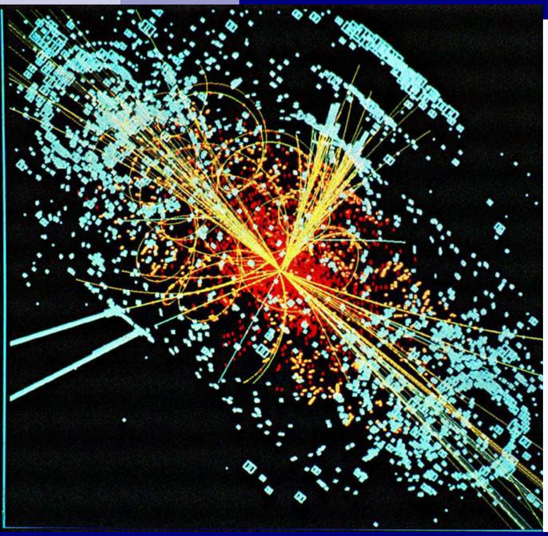
HEPCAT Summer School

University of California, San Diego

June 23, 2023

SILICON DIODE DETECTORS: PRINCIPLES AND APPLICATIONS



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and the
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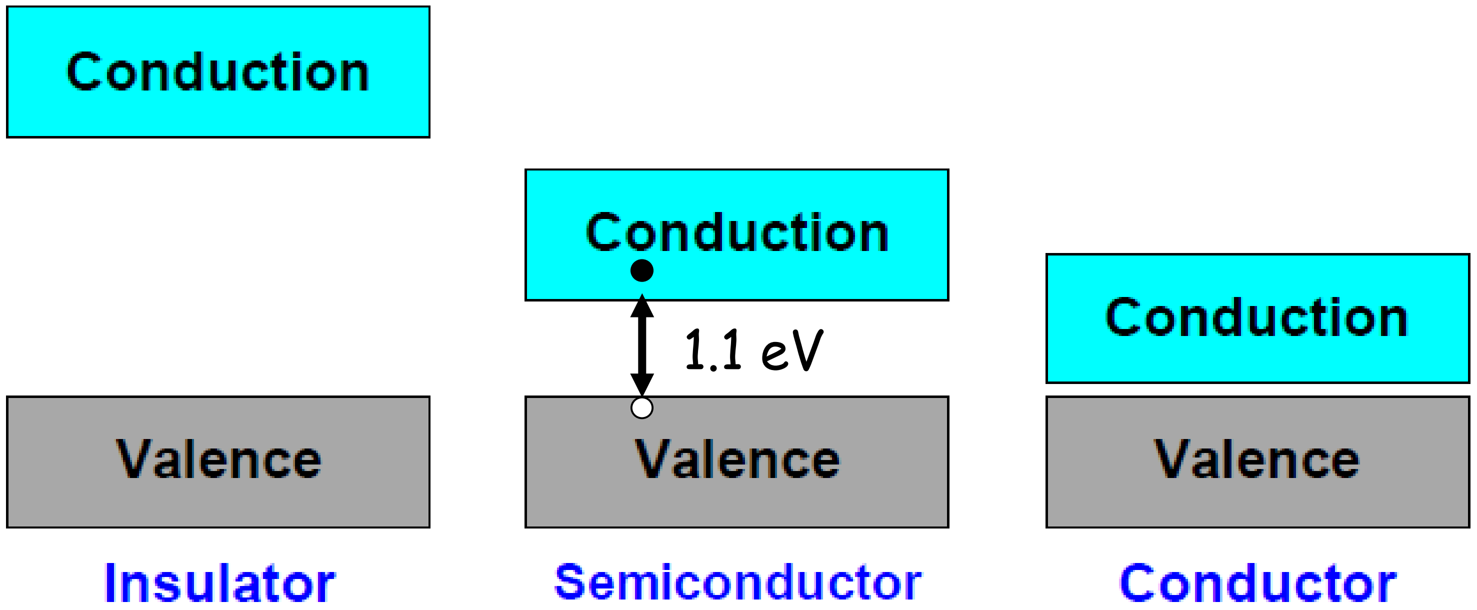
http://scipp.ucsc.edu/~schumm/talks/public_talks/HEPCAT_Silicon

Introduction and Outline

Pervasive technology in Nuclear & Particle Physics, technology fields, medicine, energy, defense, ….

- Semiconductor principles and the diode junction
- Signal generation, transport and collection
- Electronic noise and readout
- Precise timing principles
- LGADs
- Wrap-up

Silicon is a **semiconductor**



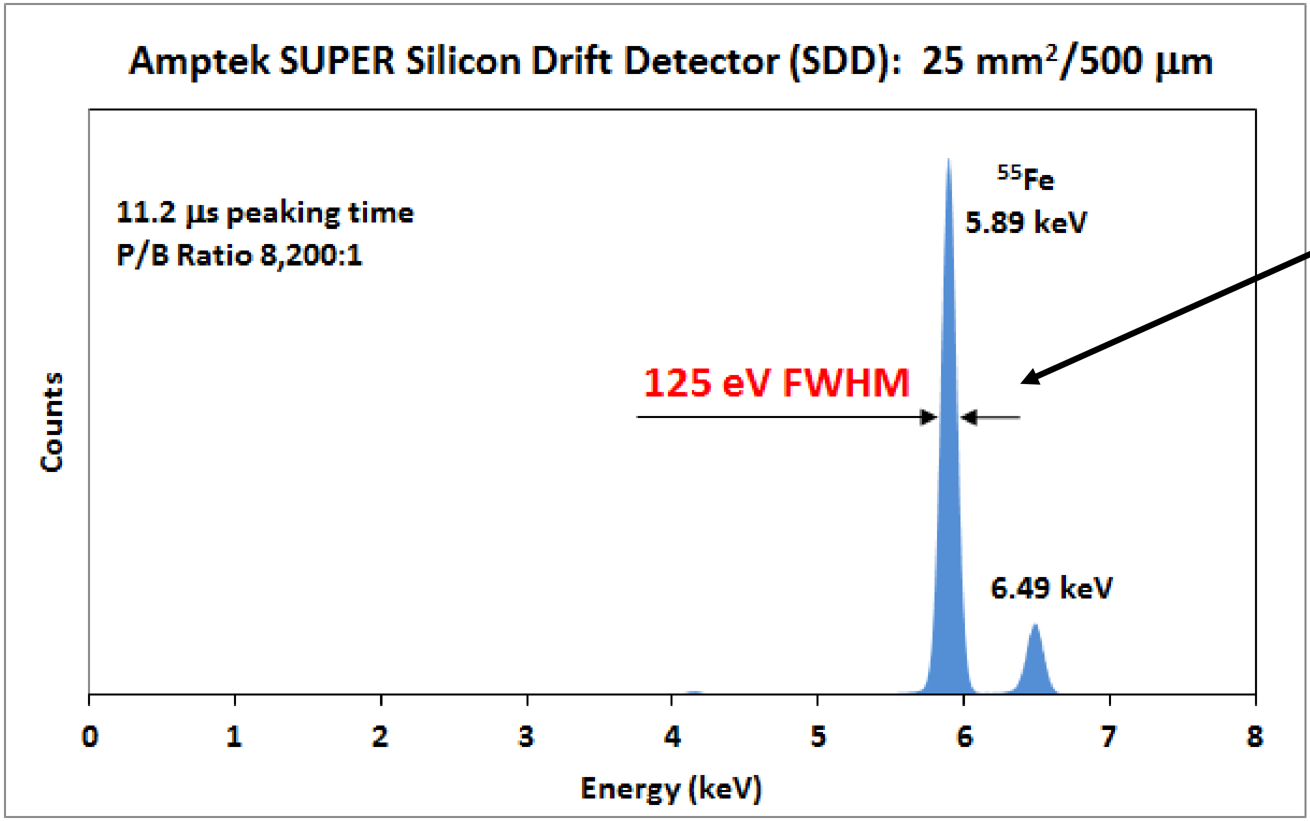
Average electron-hole-pair creation energy is 3.6 eV, of which 2.5 eV is heat (phonons) and the rest potential energy

Classical "Bulk" Silicon Detectors

Historically, precision spectroscopy; do the math!

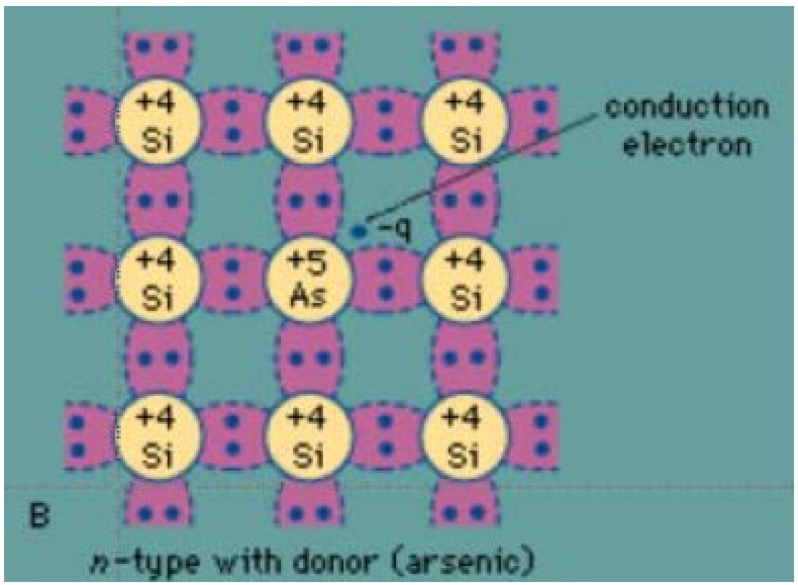
^{55}Fe has 5.89 keV γ ➔ (5890 eV) / (3.6 eV per pair) = 1640 pairs

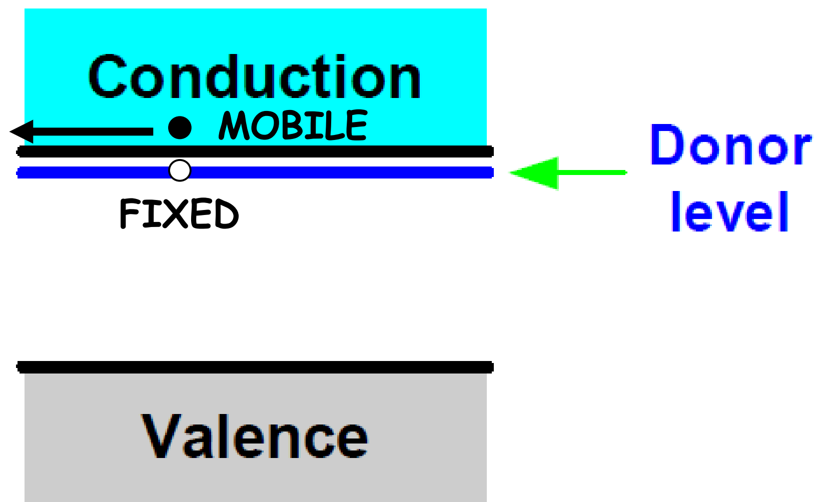
Poisson error (relative) = $\sqrt{1640}$ / 1640 = 2.5 %



That's narrow!!

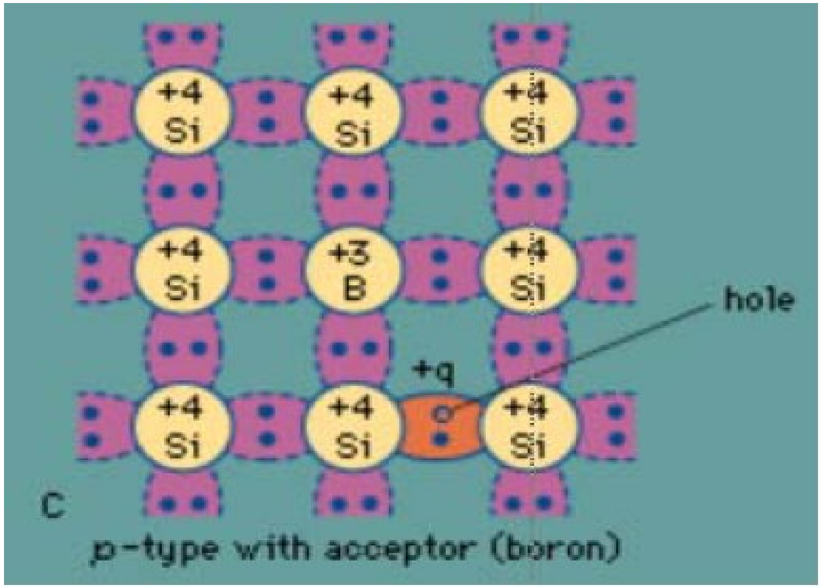
But impurities are an issue… can contribute electrons

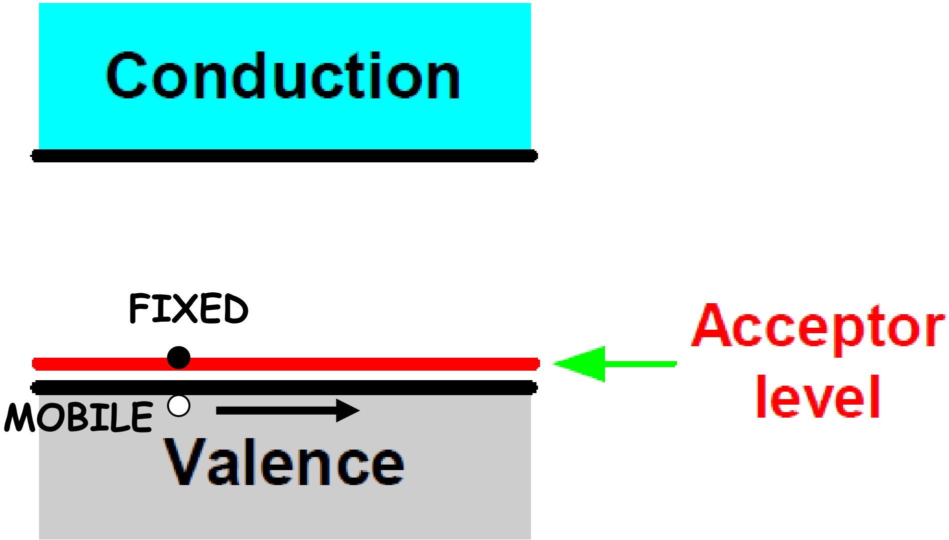




N-type material

Or holes…





P-type material

Silicon and Tracking

Either way, significant ***leakage current*** even for relatively pure silicon!

But: 1970s, microlithography techniques improved to allow for electrode patterning at the ~100 μm or better level; e.g.

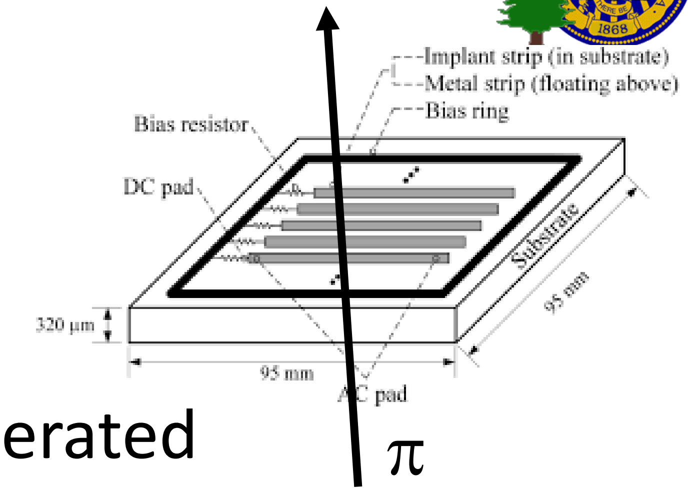
$$100\ \mu\text{m} / \sqrt{12} = 29\ \mu\text{m}$$

position resolution, significantly better than gaseous position detectors ("trackers"). In 1980s, position resolution at 5 μm level achieved (finer strips, charge sharing).

Enticing!! But need to **go thin** to avoid scattering track.

Bulk Silicon Blues

Consider 300 μm thick sensor

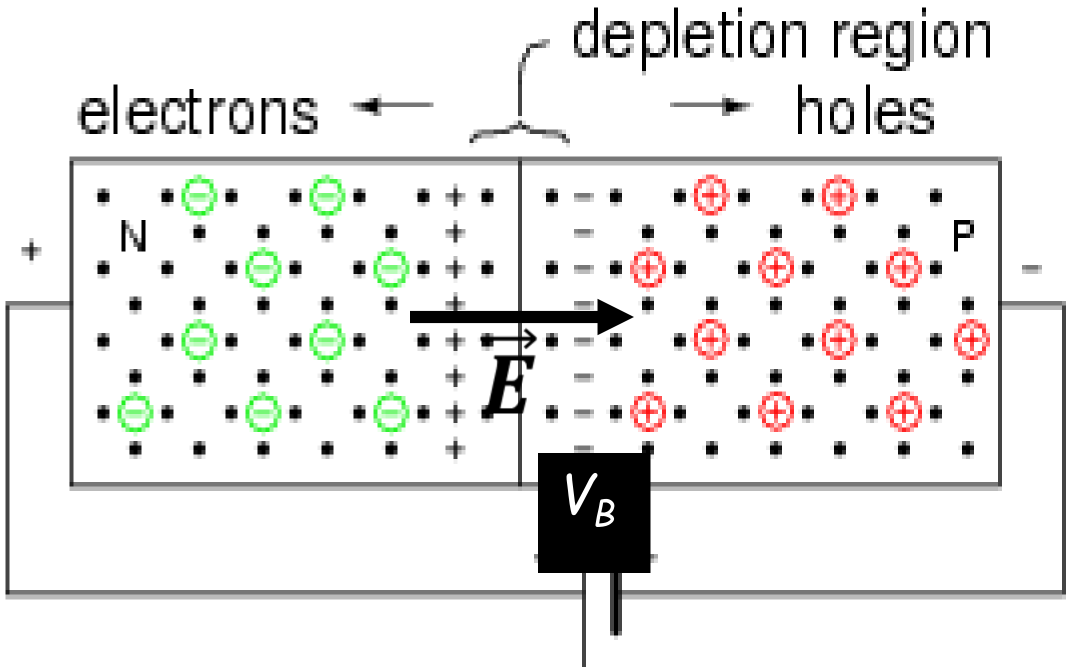


- ➔ Mean deposition of fast particle about 80 keV (250-300 eV/μm)
- ➔ 80,000/3.6 = 22,000 e-h pairs generated

You're going to have a lot of channels so noise hit rate must be low

- ➔ S/N of 10 or greater!
- ➔ Equivalent detector noise of 2,000 electrons or less
- ➔ Can't be done with leaky detectors (fluctuations in leakage current much great than this!).

The Solution: The Silicon Diode Detector

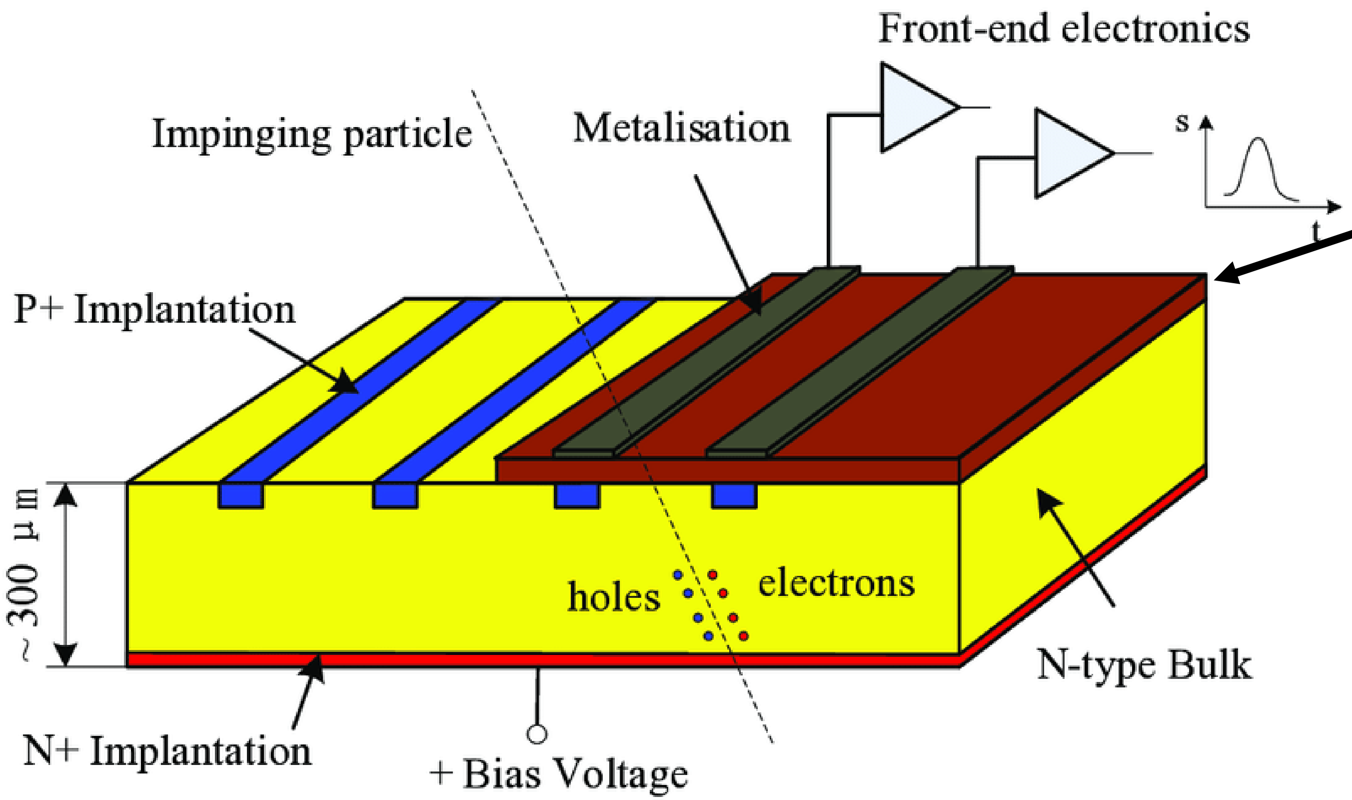


Adjoin N and P type materials. Area free of mobile charge is "depletion zone" (fixed background charge remains ➔ E-field!

Apply reverse bias (diode!) ➔ eventually **fully deplete** highest purity side; significant field in depletion region

Most sensors run with one side fully depleted.

"p on n" sensor – highly-doped p "implants" deplete n "bulk" when sufficient reverse bias field applied; typically 20-100 V does it!



Optional insulator layer

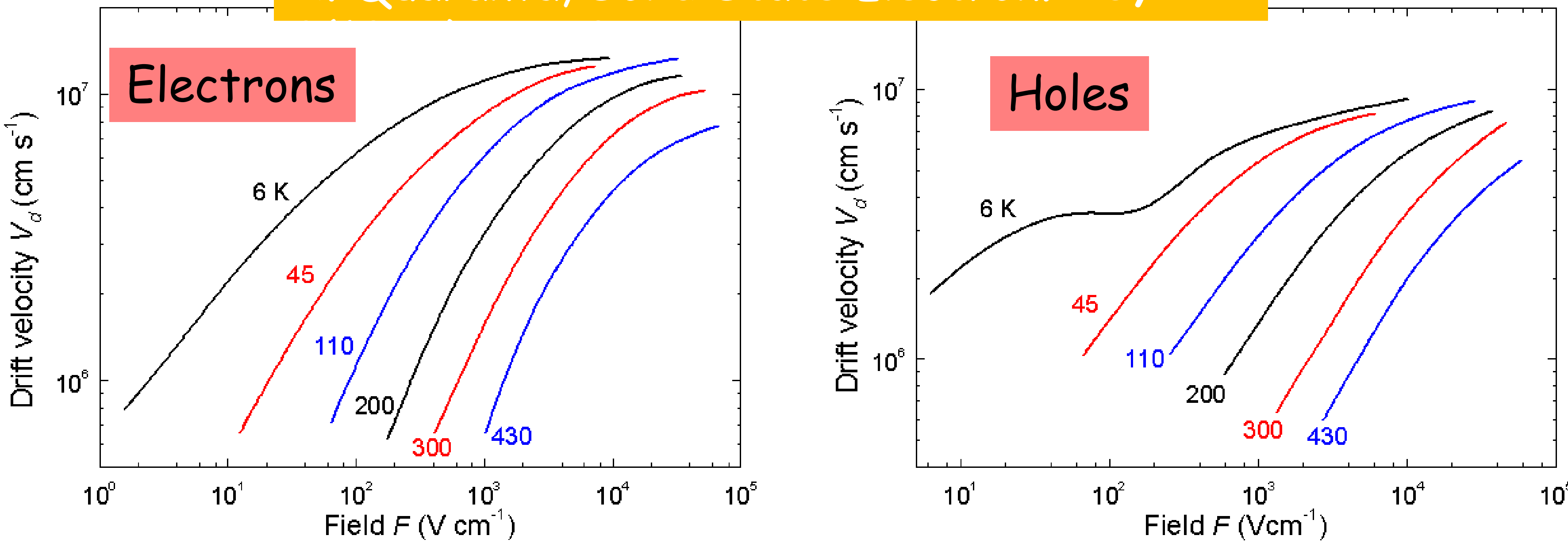
"AC-coupled" if included;

"DC-coupled" if not.

SIGNAL DEVELOPMENT AND DETECTION

Carrier Drift in Silicon

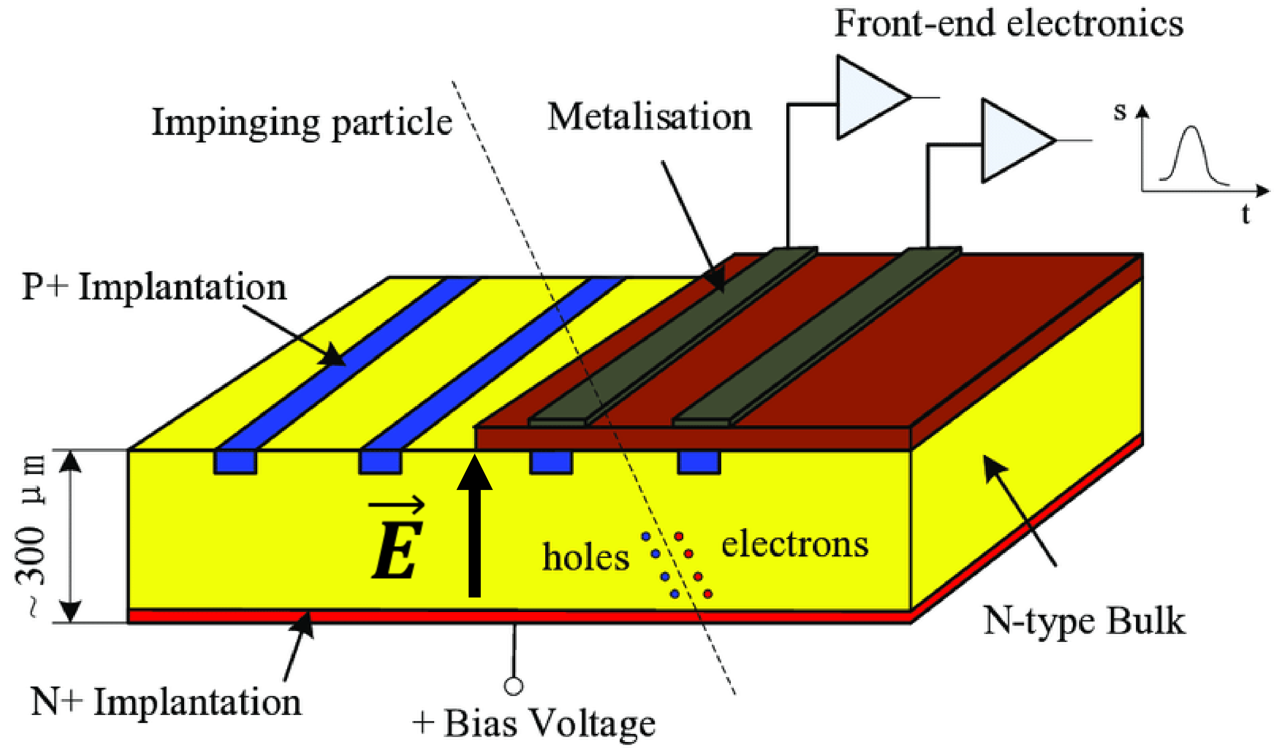
Jacoboni, C., C. Canali, G. Ottaviani, and A. A. Quaranta, *Solid State Electron.* **20**,



Note that 10^4 V/cm over 100 μm is 100 V

- "Saturated" drift velocity is about 10^7 cm/s, or about **100 μm/nsec**
- Try to remember this number for fast timing discussion

Signal Development in Systems with Drift

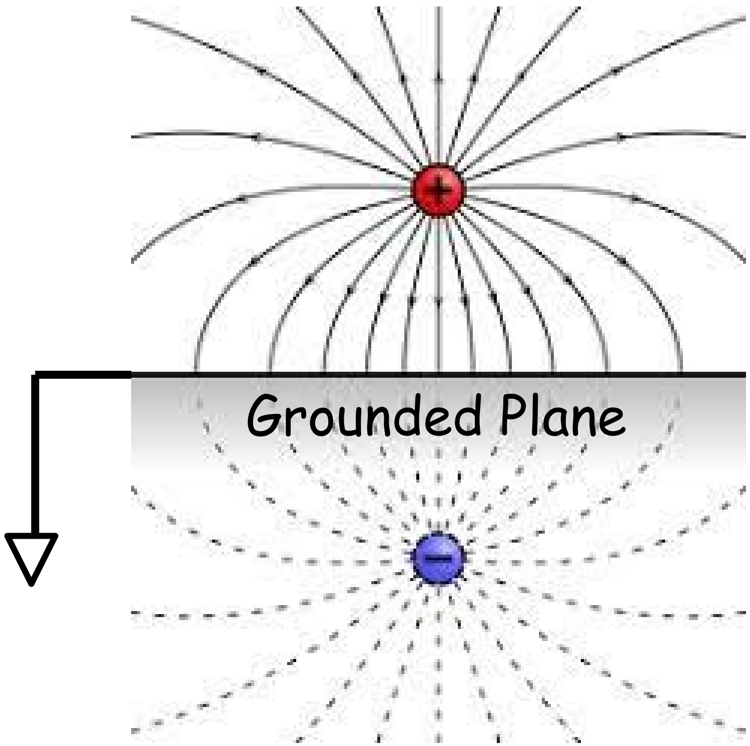


Naïve: Signal arises from electroncs and holes getting collected and the electrons running through the amp to neutralize the holes

Truth: Image charge, energy conservation ➔ **Ramo's Theorem**

Physics 101: Image Charge

Remember the principle of **image charge** from UG E&M…

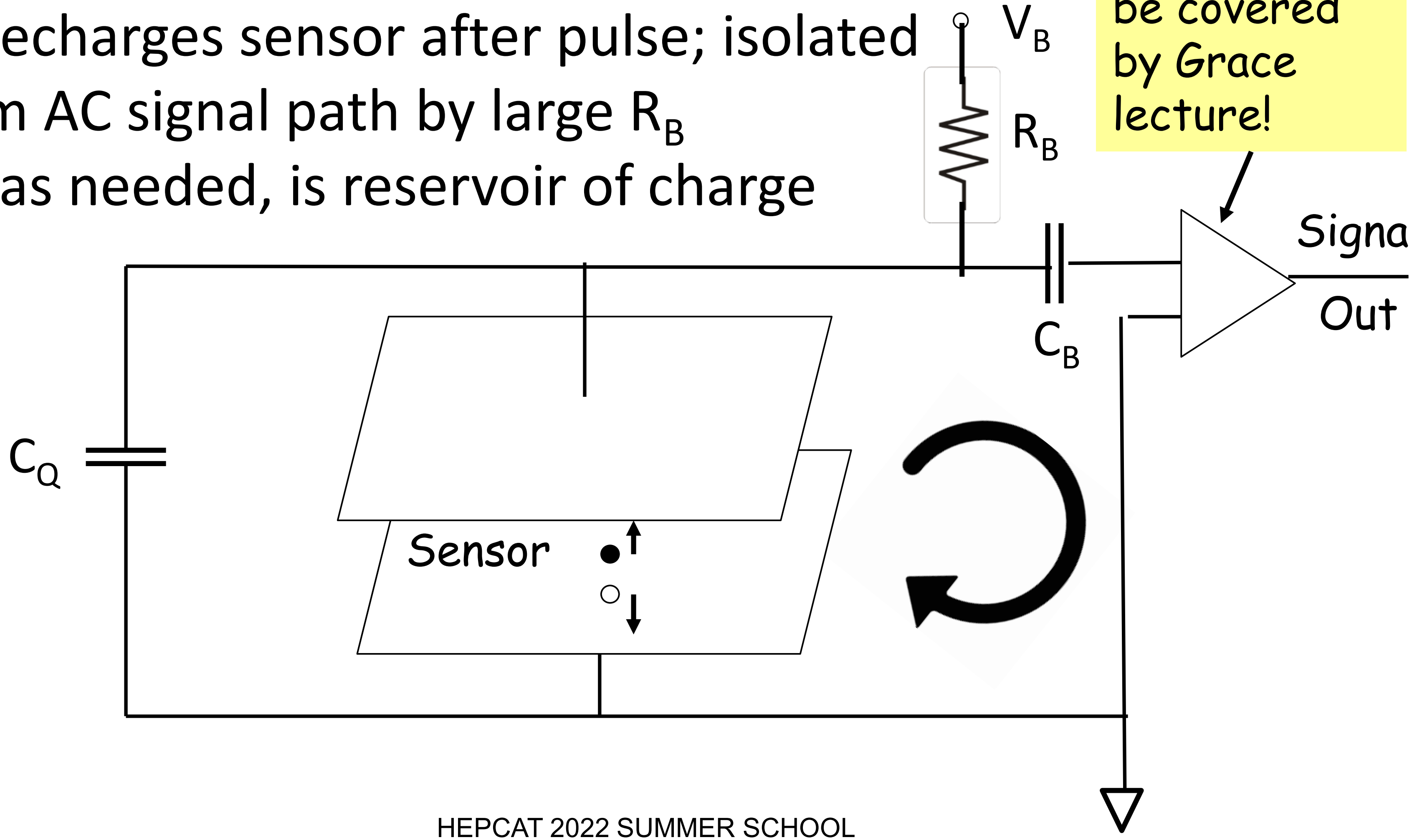


- Electron is real; "positron" is a convenient fiction
- Field below the plane produced by superposition of field from electron and **from distribution of charge on constant-potential plane**
- As electron moves from -∞ to plane, exactly one + charge moves from ground onto plane
- **This charge motion is the signal current!**

Currents run in loops

- C_B blocks bias voltage (large, so AC short)
- V_B recharges sensor after pulse; isolated from AC signal path by large R_B
- C_Q, as needed, is reservoir of charge

Electronics (ASICs) to be covered by Grace lecture!



Signal Current for Non-Planar Electrodes

What if collection electrode is not a single plane, but instead a pattern of electrodes?

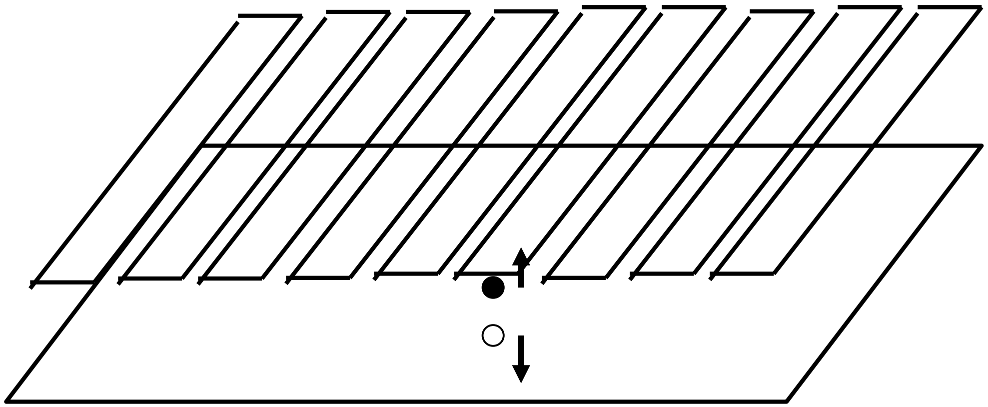


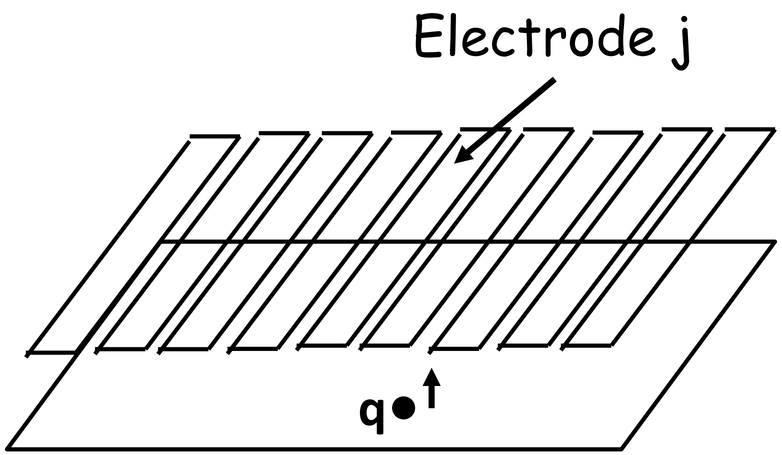
Image charge will be drawn onto electrodes at differing rates, depending on position and speeds of electrons and holes

A mess to calculate; made simple by **Ramo's Theorem**

Ramo's Theorem

What is current on electrode j induced by motion of electron (or hole) at point P?

- Define $\overrightarrow{E_W}$ as field created by holding *j* at 1V and grounding every other electrode (**"weighting field"**)
- Let $\vec{v}$ be charge's velocity



Then **Ramo's Theorem** states that

$$I_j = q\vec{v} \cdot \overrightarrow{E_W}$$

Note: collected charge $Q_{coll} = \int I\, dt$ is 0 unless charge is collected on the electrode under question!

A WORD OR TWO ON READOUT NOISE

Life Isn't Perfect: Readout Noise

Define some quantities that are associated with sources of **readout noise**:

C = Sensor capacitance (important!)

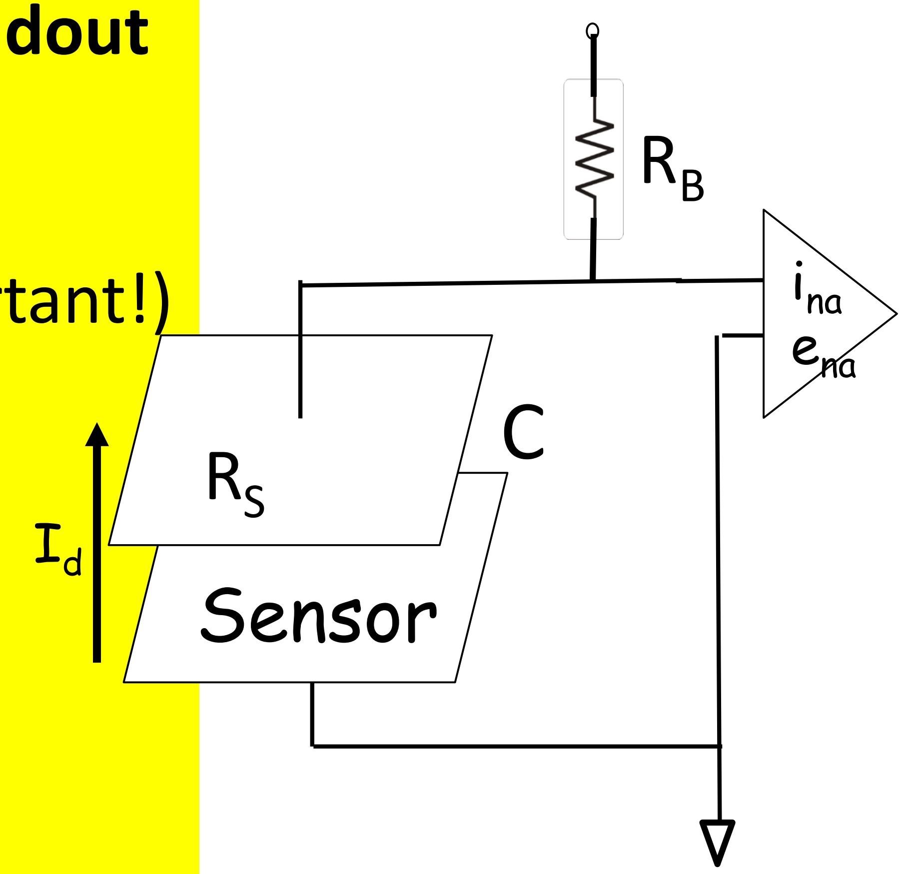
R_S = electrode resistance

i_{na} = amplifier current noise

e_{na}= amplifier voltage noise

R_B= bias resistance

I_d = Sensor leakage current



Readout Noise Master Formula

H. Spieler, *Semiconductor Detector Systems*, Oxford Press, 2005.

- Noise level in equivalent electrons
- Strictly speaking, applies to "lumped elements" (separate C, R_S)

Signal-shape parameters (of order 1)

$$Q^2 = F_i \tau \left(2eI_d + \frac{4kT}{R_B} + i_{na}{}^2 \right) + \frac{F_v C^2}{\tau} \left(4kTR_s + e_{na}{}^2 \right)$$

Amplifier shaping time (1/Bandwidth)

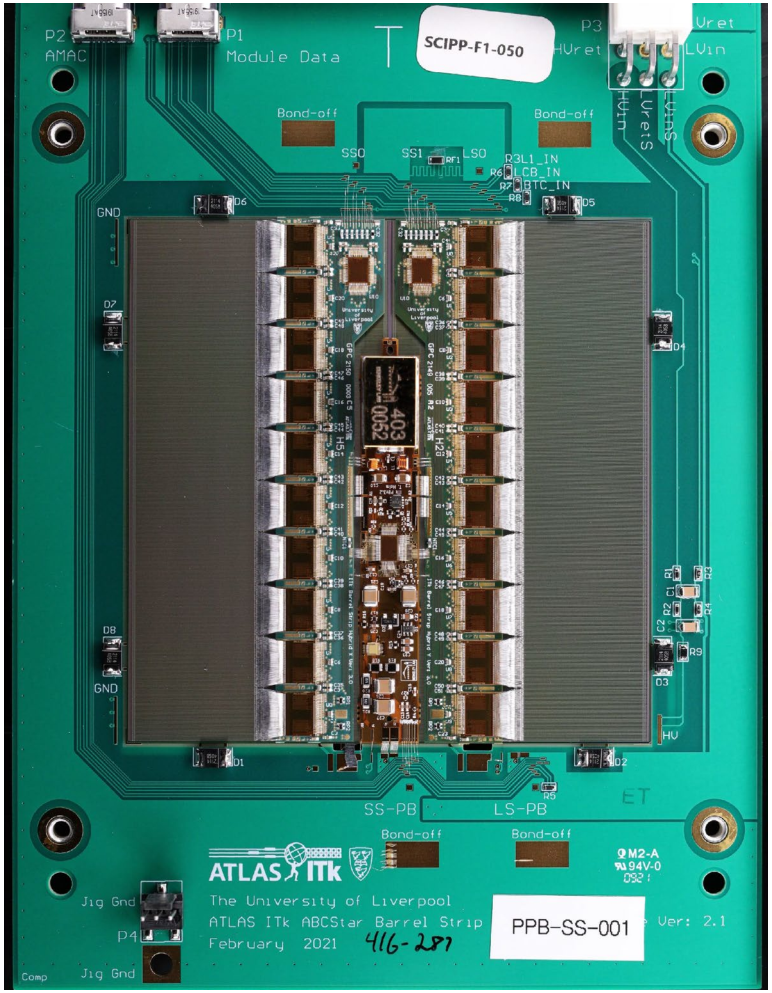
A notable term is the **$(F_v/\tau)\, C^2\, e^2_{na}$** term, which varies with electrode size and separation ➔ Beware of sensor capacitance, esp. for fast signals!

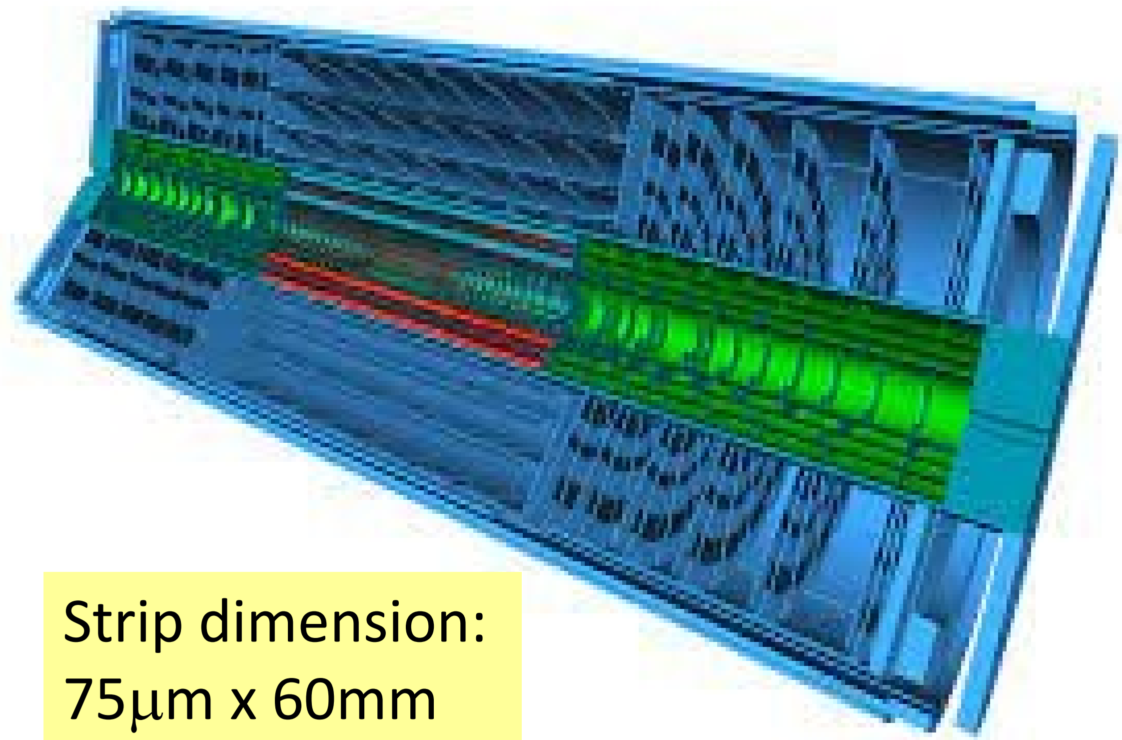
General rule of thumb: signal-to-noise of 12:1 for efficient operation

TWO BASIC APPLICATIONS: STRIPS AND PIXELS

Application: ATLAS ITK Strips

The basic module is shown at left. The ITK tracker for the ATLAS Upgrade (online ~2026) is shown below. Outer (blue) elements are strips. Inner elements are pixels.



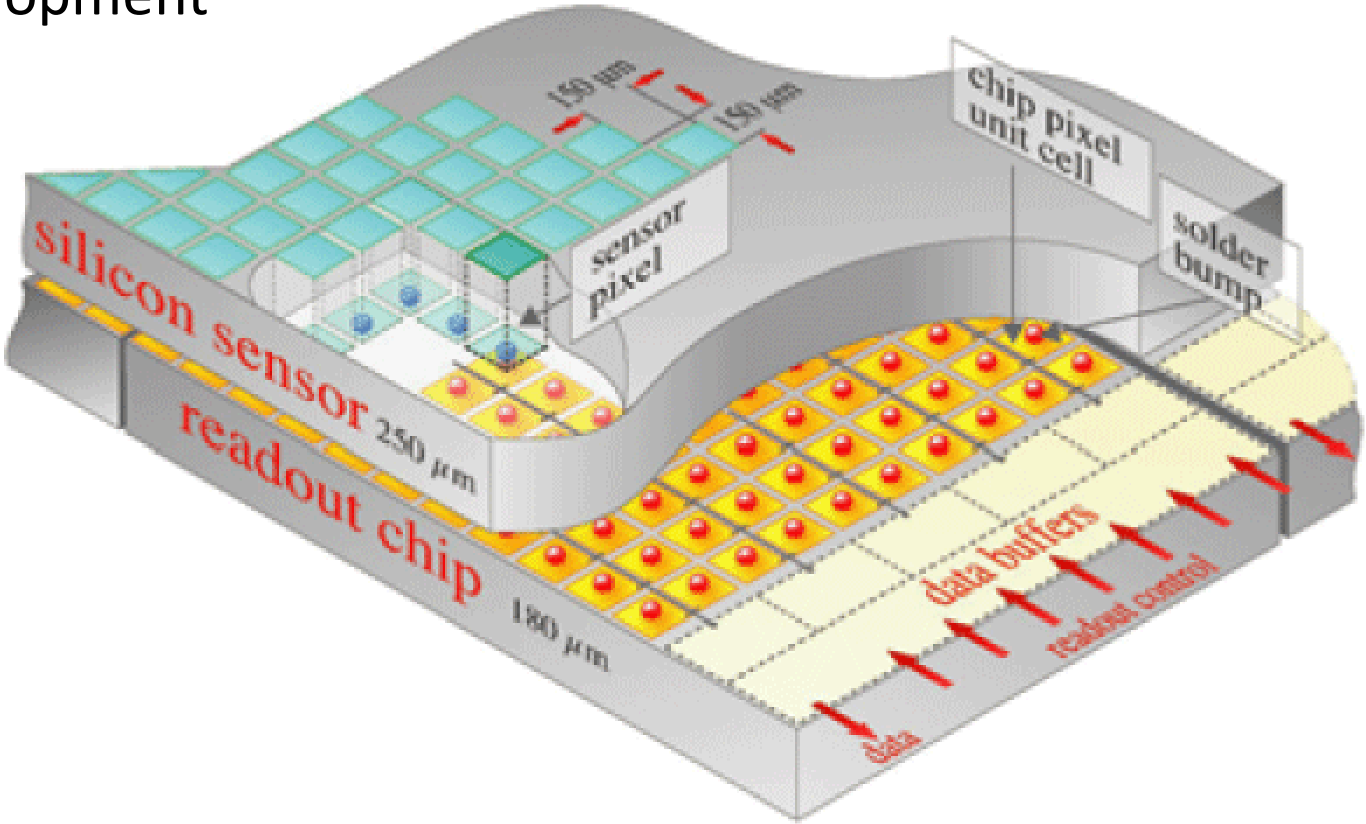


Strip dimension: 75μm x 60mm

Application: CMS Pixels

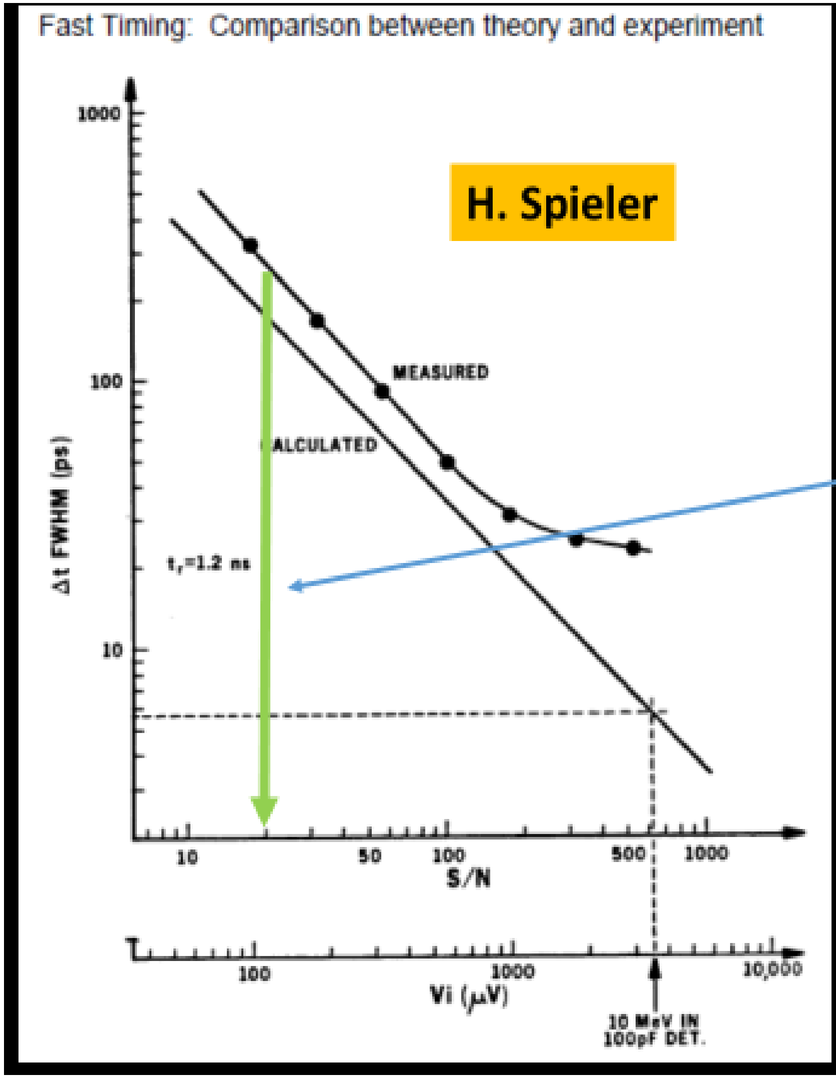
Pixel dimension is 150x150 μm^2 ➔ Signal to noise not major challenge

High-density readout and interconnects required significant development



PRECISE TIMING WITH SILICON DIODE SENSORS

Silicon Fast Timing: First Issue is Signal-to-Noise

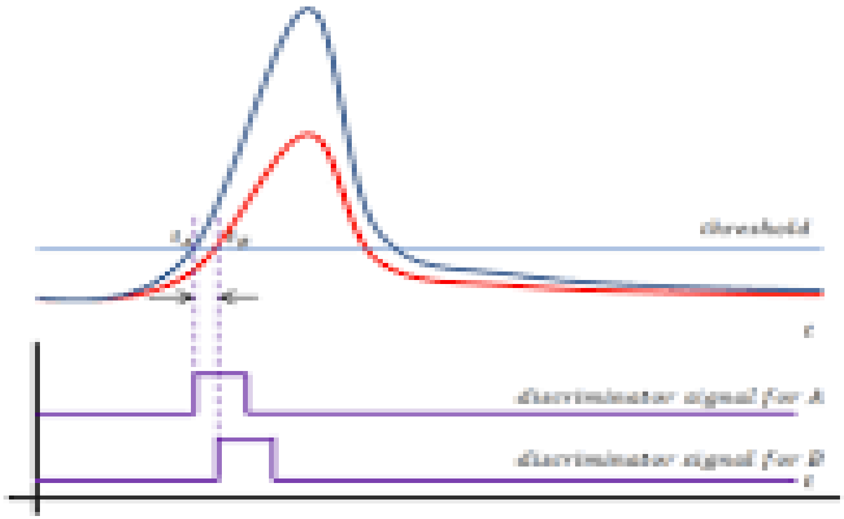


- Developed for nuclear physics, with large (MeV) energy absorption scales
- Achieved σ_t ~ 25 psec for S/N of several hundred
- BUT: Typical particle physics application is minimum-ionizing particle through 300μm of silicon ➔ S/N is of order 20:1
- Timing resolution of order 300 psec
- IDEA: Go very thin (< 100 μm) to speed things up; boost S/N with GAIN

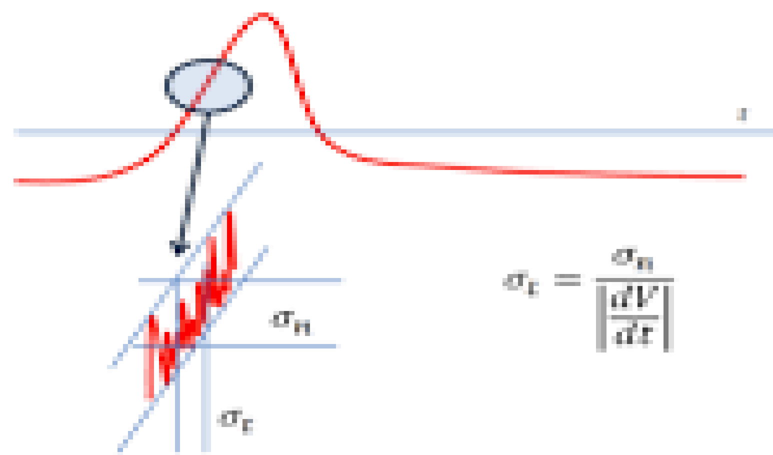
➔ Low Gain Avalanche Detector (LGAD)

Why is S/N Critical?

Timing provided by instant of crossing of a threshold. Uncertainty introduced by signal-size dependent slew rate (**time-walk**) and readout noise (**jitter**).



Time walk effect

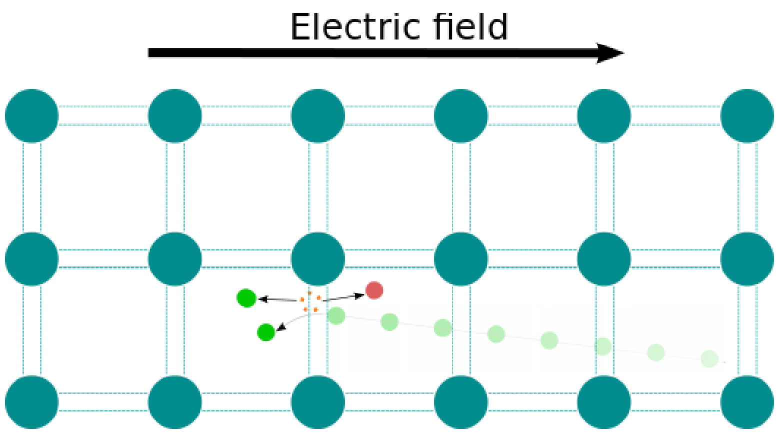


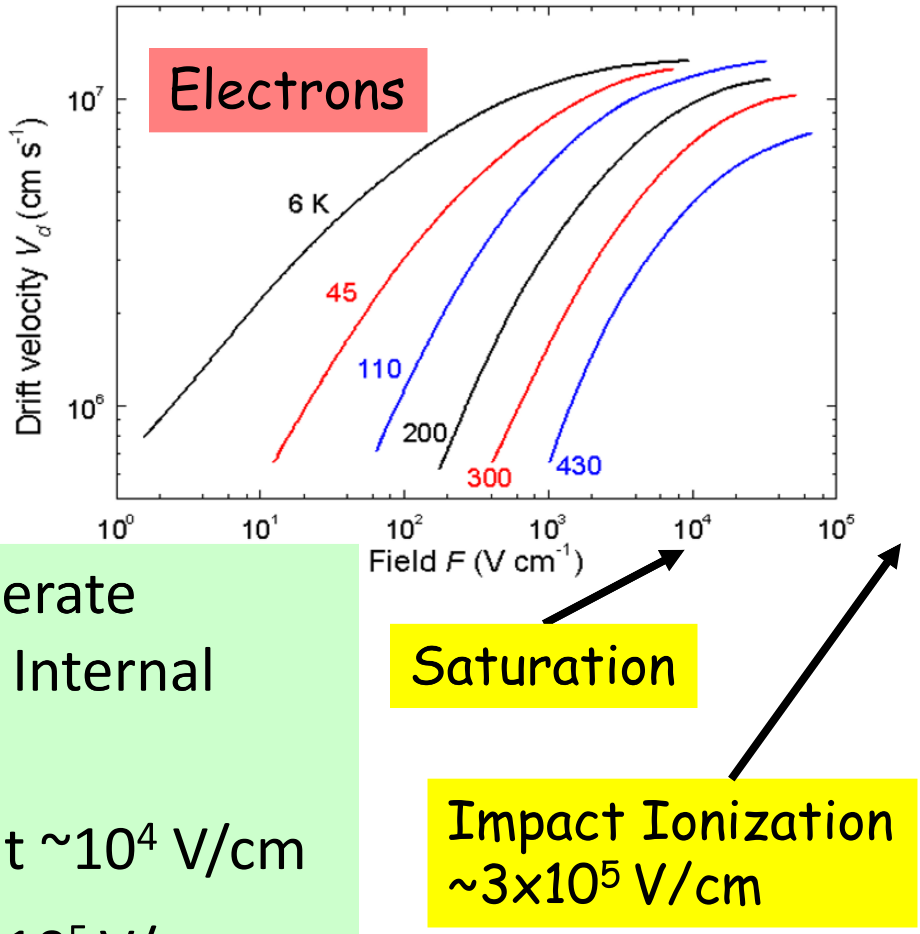
Jitter effect

Time-walk treatments (pulse-height dependent corrections; constant-fraction discrimination) usually effective

➔ Jitter remains dominant contribution (dV/dt proportional to signal size, so minimized by maximizing S/N) ➔ **GAIN!**

Impact Ionization



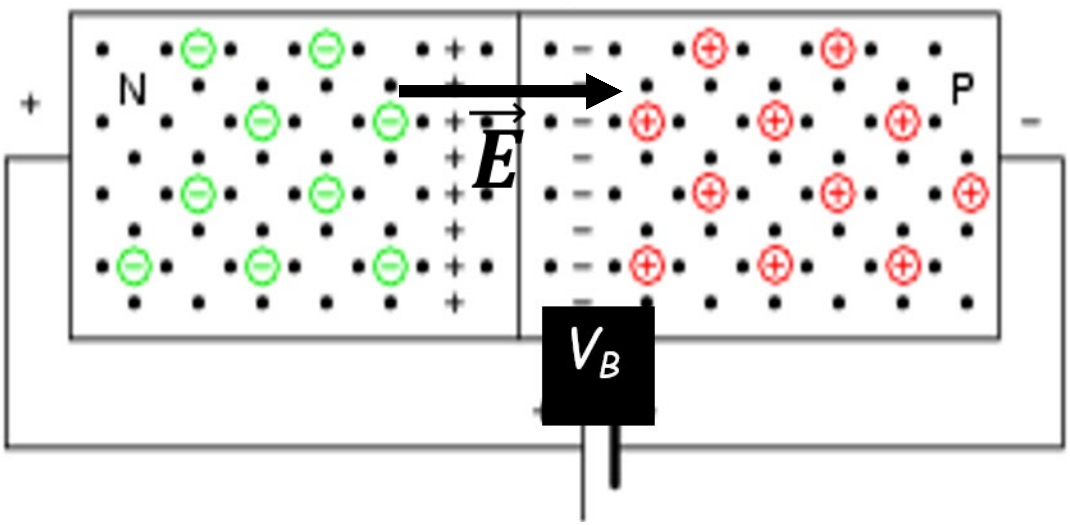


- At very high field, charges can liberate additional electron-hole pairs ➔ Internal gain!
- Electron drift velocity saturates at ~10^4 V/cm
- Impact ionization turns on at ~$3\text{x}10^5$ V/cm

How to get these high fields inside the silicon ?!

Brute force won't cut it: 3×10^5 V over 300 μm is 10 kV!

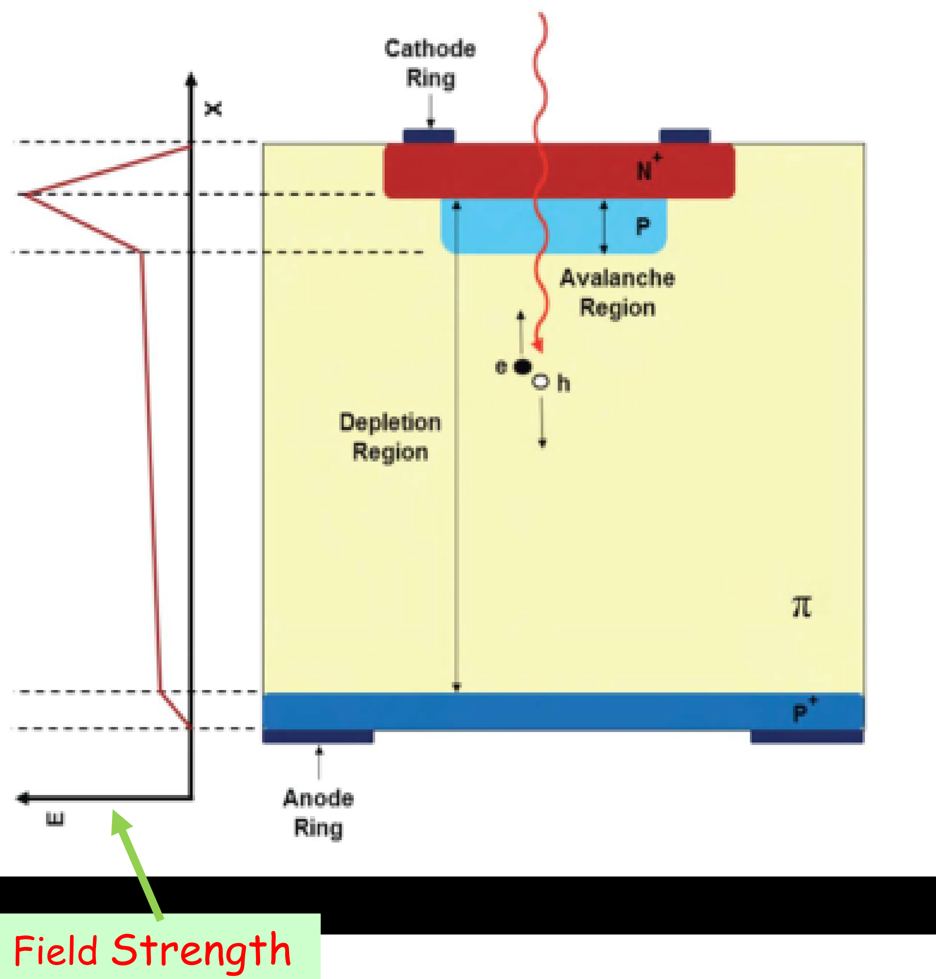
Instead, note that depletion zone has residual net distribution of fixed charges (of opposite sign to that of the mobile carries!)



Graded doping is the solution!

Graded-Dopes Silicon Diode Sensors: The LGAD

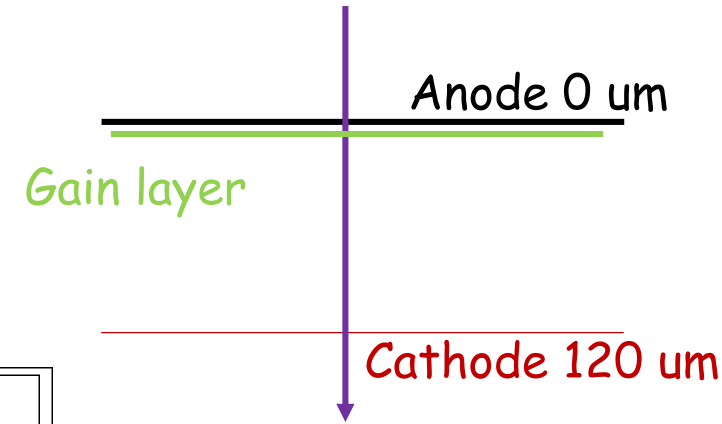
Low-Gain Avalanche Detectors (LGADs)

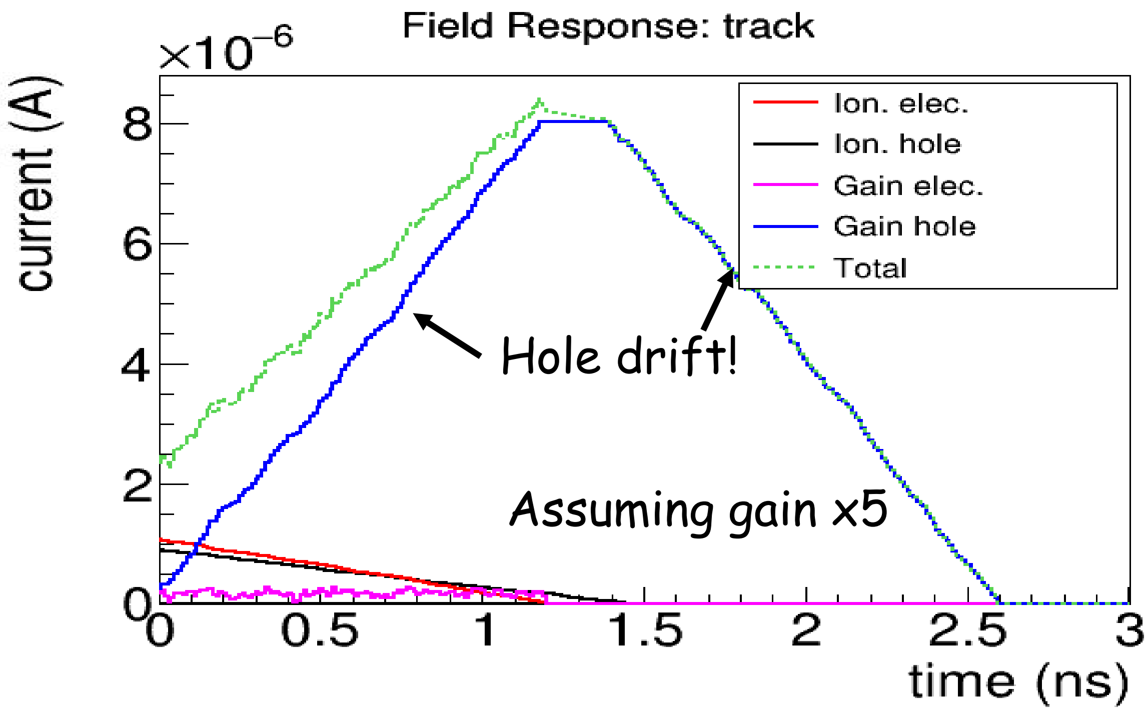


- Bulk region "π" is moderately doped
- Heavily doped "P" ("avalanche" or "gain") layer creates high field and leads to gain
- Heavily-doped "n+" implant is very thin (standard for silicon diode detectors)
- Gain typically in the 10-100 range

Deconstruction of LGAD Signal Development

For an idealized MIP that deposits its energy uniformly as it traverses the sensor bulk





Primary source of signal is from gain holes as they drift back towards the cathode

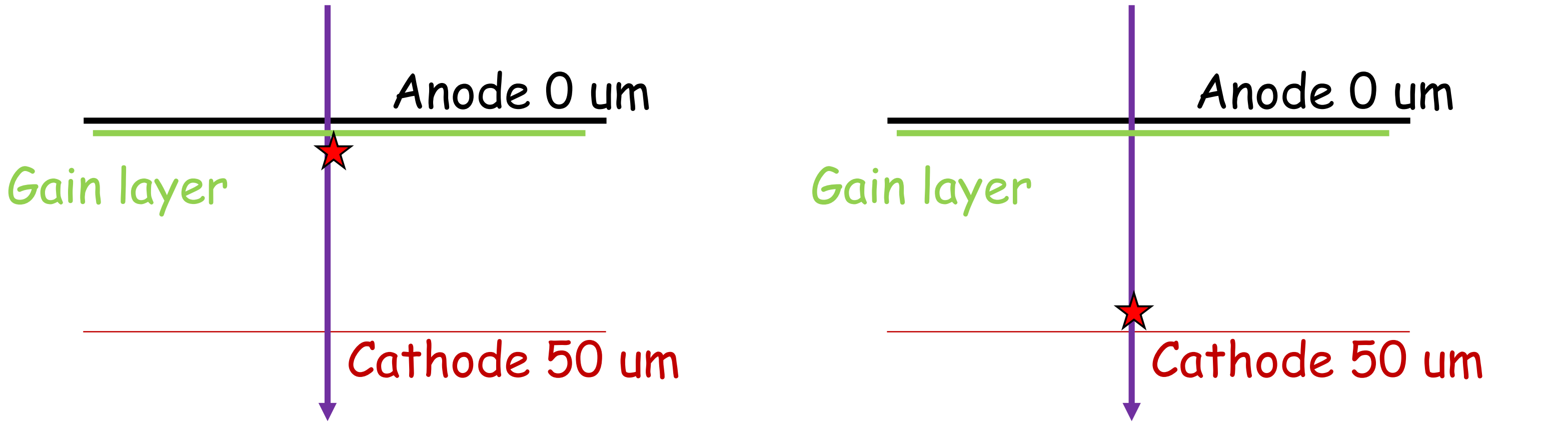
Slew rate dV/dT set by **gain** (more gain ➔ more holes!)

Figures stolen shamelessly from Xin Qian, Brookhaven NL

Signal Deposition Fluctuations ("Landau Term")

Charge deposition is stochastic – a rare head-on strike of an electron deposits a huge amount of charge ("Landau distribution")

Consider rare scenario where almost all charge deposited at one point



Signal initiated when electrons arrive at gain layer, in second case

(50 um) / (100 um/ns) = 500 ps

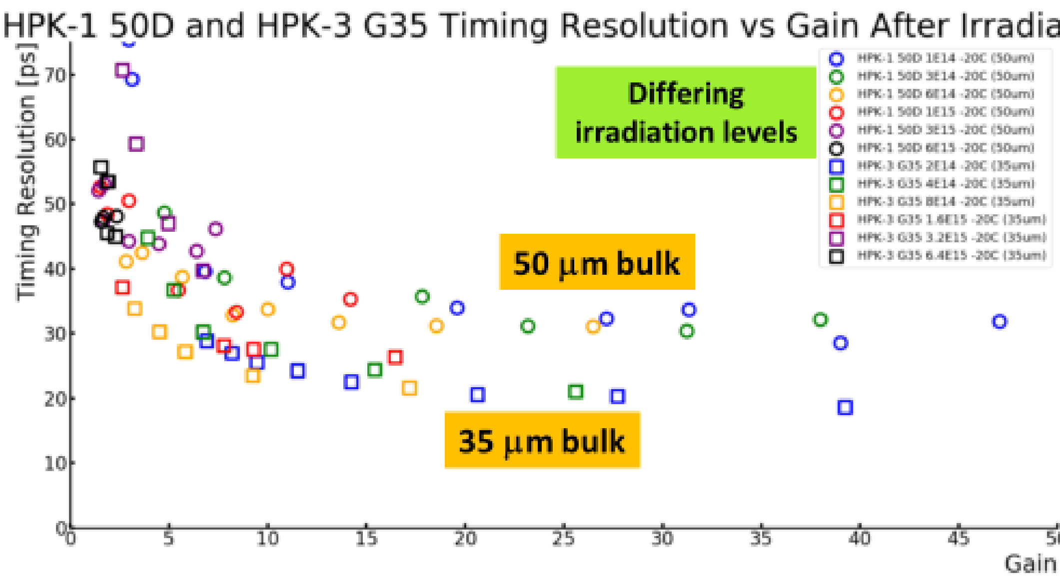
later than the first case, very large compared to ~20 ns timing goal!

➔ Deposition ("Landau") fluctuations can contribute significant error

Combined Timing Resolution and Case for Thin!

$$\sigma_t^2 = \sigma_{Time-Walk}^2 + \sigma_{Jitter}^2 + \sigma_{Landau}^2$$

Bulk Thickness and Landau Contribution



20 ps resolution achieved for light-to-moderate irradiation

- Jitter term suppressed at high gain → Landau contribution becomes dominant
- Improves with thinning of bulk, as expected

As long as you can get to high gain, thinner is better. But…

Will Thinner Continue to Help?

Going even thinner (20 um LGADs are becoming available) will certainly allow for further reduction of the Landau term.

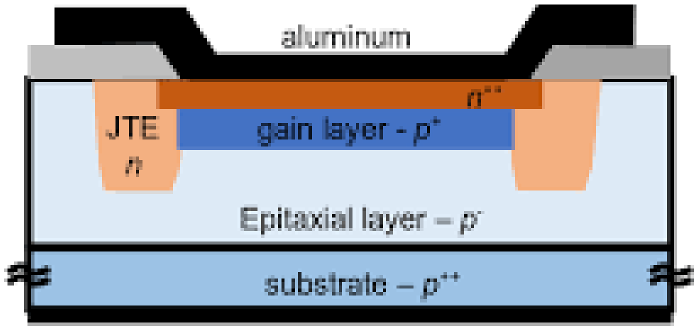
However, let's remember what we learned about readout noise:

$$Q^2 = F_i \tau \left(2eI_d + \frac{4kT}{R_B} + i_{na}{}^2 \right) + \frac{F_v C^2}{\tau} \left(4kTR_s + e_{na}{}^2 \right)$$

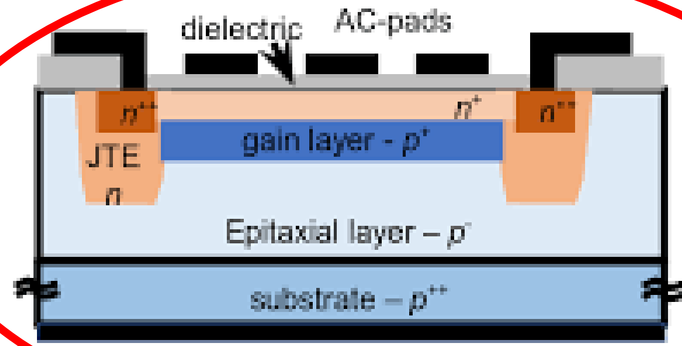
- To take advantage of thinner sensors, will need to go to faster risetimes (smaller τ).
- In addition sensor capacitance is inversely proportional to thickness (larger C).
- May well be becoming an electronics optimization project (and bear in mind that minimizing e_{na} requires increasing the power draw).

LGAD Breeds

Std LGAD



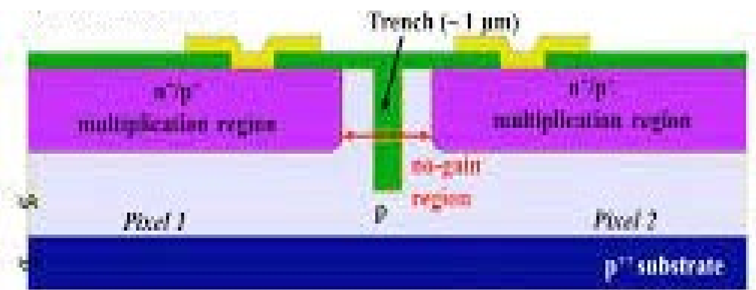
Traditional LGAD



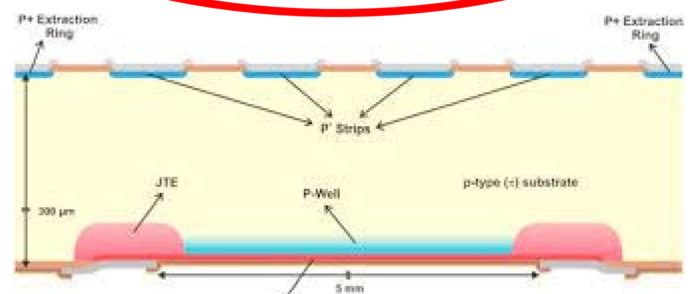
AC LGAD

AC- LGAD

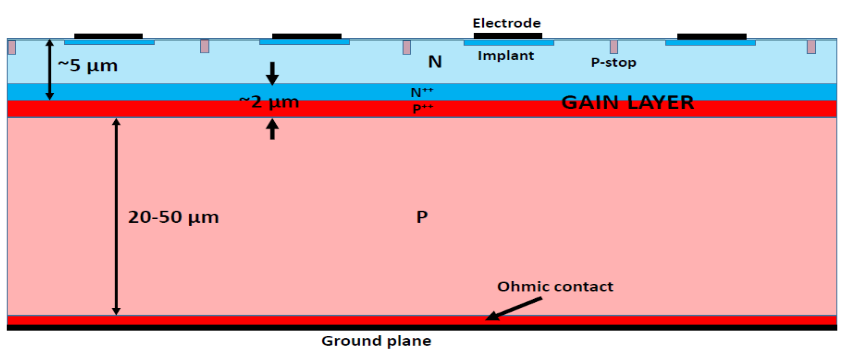
Interesting one..



Trench-Isolated LGAD



Inverse LGAD

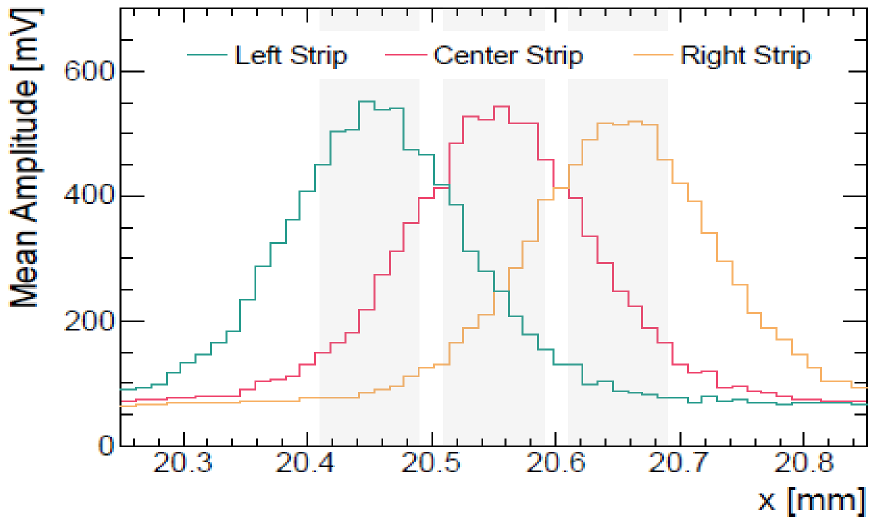


Deep-Junction LGAD

AC LGAD Advantages

The planar geometry of the p-n junction avoids gaps in the high-field gain region

Electrodes can be patterned in arbitrary shapes and sizes on top of the insulating layer



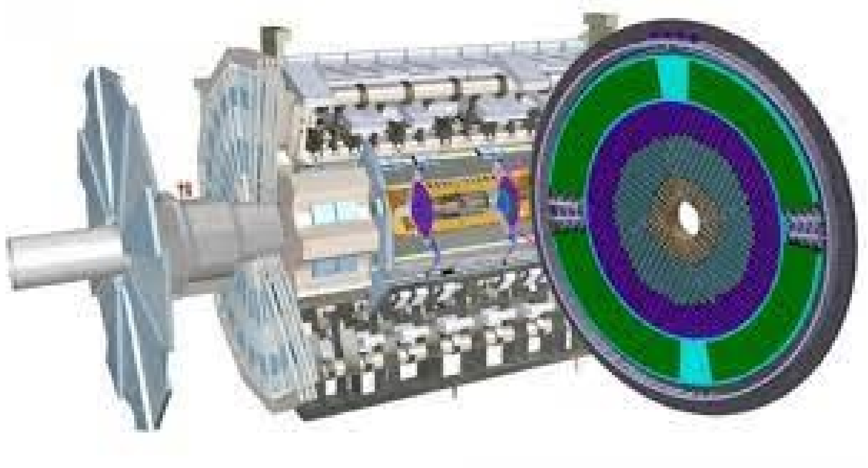
Gabriele D'Amen, BNL

Charge is shared among channels, to a degree potentially tunable via the n^+ doping level

➔ **good spatial resolution** even for relative sparse electrode pattern

LGAD Applications

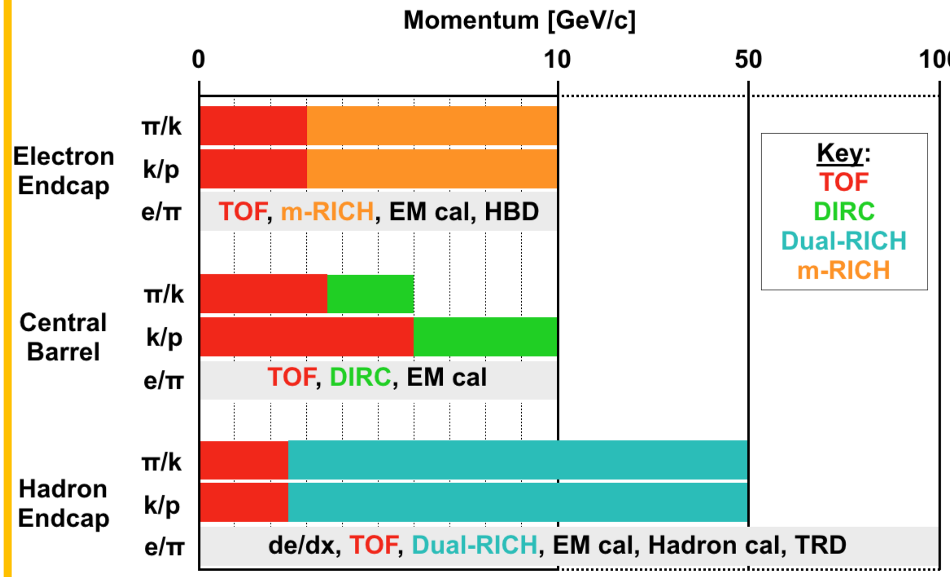
ATLAS HGTD



Timing layer for LHC Upgrade

- Add timing point to each track
- Additional dimension for identifying vertex of origin
- Mitigate "pileup" effects from ~200 collisions per beam crossing
- First-ever application
- Makes use of 1.3x1.3 mm^2 "conventional" LGADs

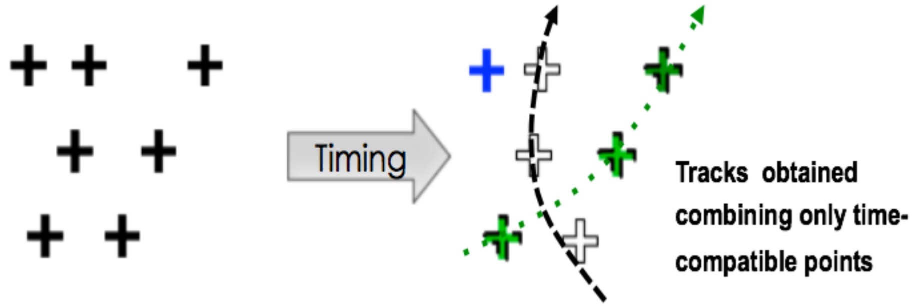
ELECTRON-ION COLLIDER



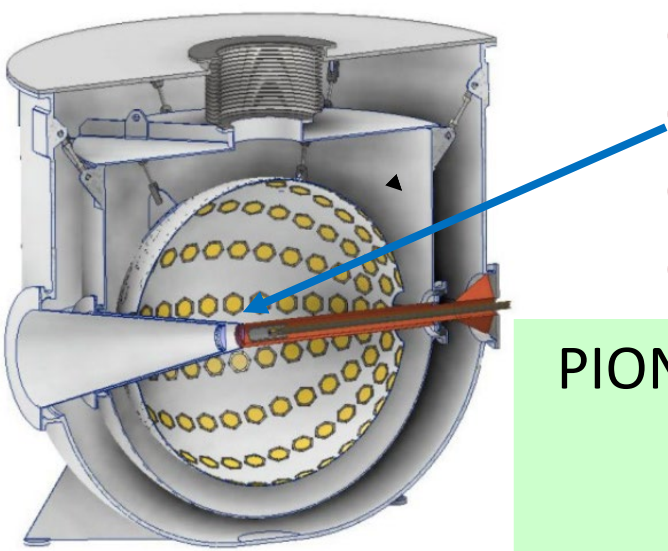
Time-of-flight particle ID for Electron-Ion-Collider detector

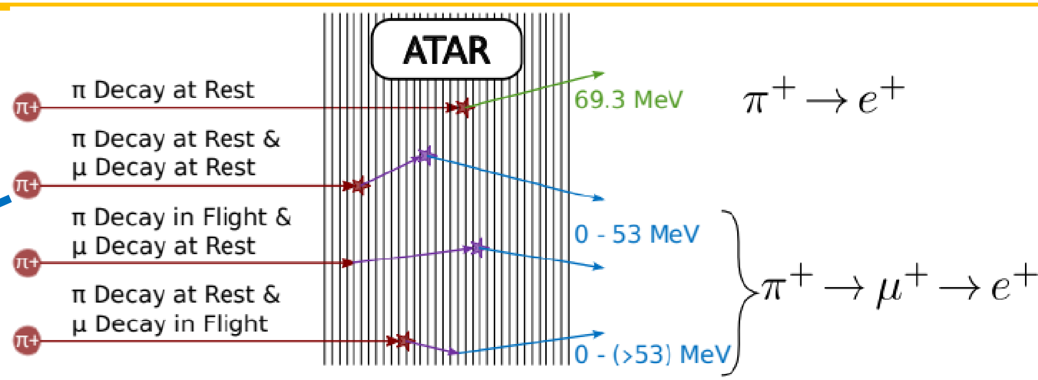
- Necessary at low momentum
- Requires most precise possible timing
- Calls for AC LGAD solution

More LGAD Applications



4-D tracking (position and timing for each space-point), particularly for high-density applications (Future Hadron Collider)



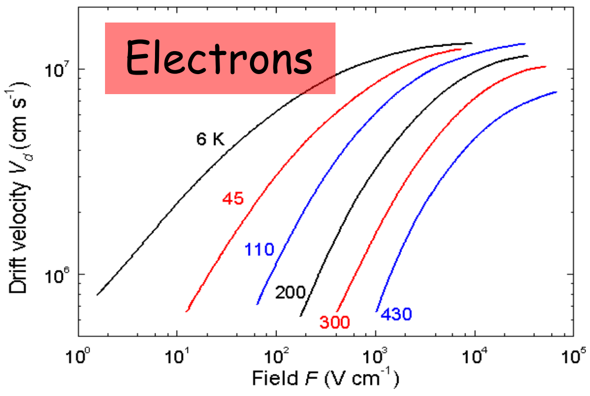


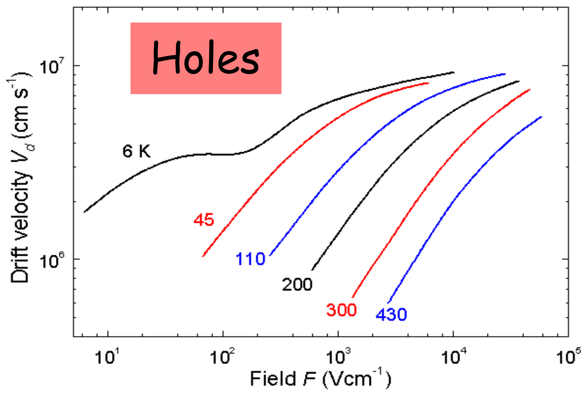
PIONEER Experiment (rare pion-decay test of EW sector physics)

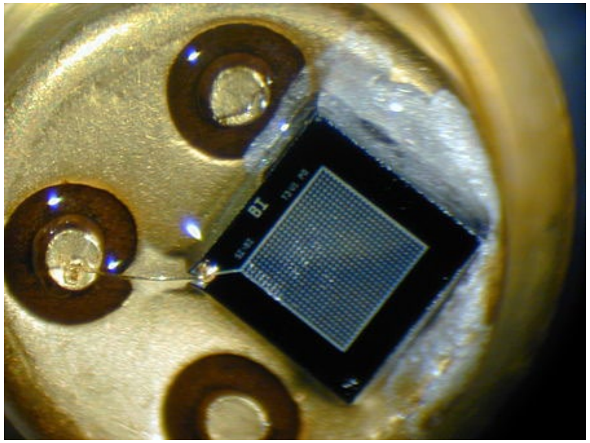
Active Target (ATAR) Subdetector

Silicon Photomultipliers (SIPMs)

While holes are more sluggish than electrons, they too induce impact ionization for high enough fields ➔ "Geiger Mode" achieved







Silicon Photomultipliers

- Achieve Geiger Mode gain of $10^5 - 10^6$
- Can provide timing as precise as LGADs
- Can experience significant dead time and after-pulsing
- Single-photon detection ➔ broad array of applications within and outside of HEP (LIDAR, threat detection, sorting/recycling, …)

Wrap-Up

We've covered the basics of semiconductor detector physics and applications, although in a cursory way

LGADs are a new development (first prototypes about 6 years old now) and still a lot of creative and optimizing activity going on

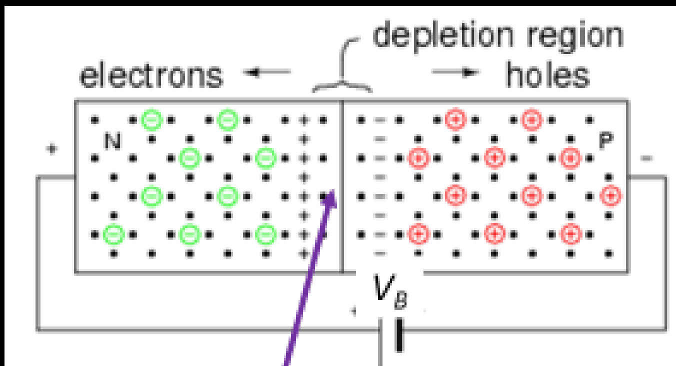
Many of these topics are just a light touch on a much deeper field, but hopefully this overview is useful

HEPCAT consortium institutions are a major driver in this area, so opportunities to participate are very close at hand!

Enjoy your SoCal weekend!!!

BACKUP

LGAD Capacitance Profiling

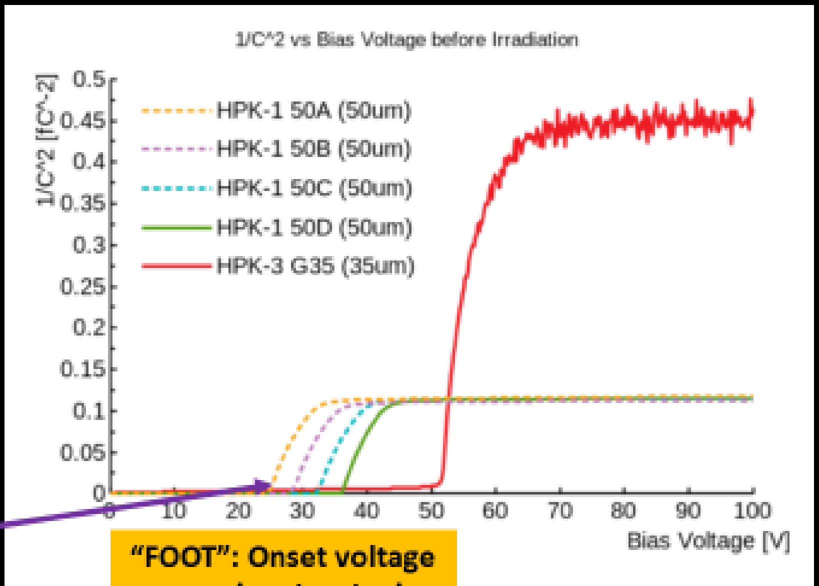


- Increasing reverse-bias voltage V_B increases depletion depth and thus reduces capacitance
- Larger doping density requires greater voltage step per unit increase in depletion depth

➔ Rate of change of C with V yields doping density:

$$N = \frac{2}{\frac{d(1/C^2)}{dV_B}} \bullet \frac{1}{\varepsilon q A^2}$$

Depleting thing gain layer requires a relatively large voltage ➔ **"FOOT"**, which reveals gain layer doping



"FOOT": Onset voltage proportional to doping density

12/12/2018 B. A. Schumm CPAD2018 12

SIPMs

These lectures are divided into three (unequal) sections…

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