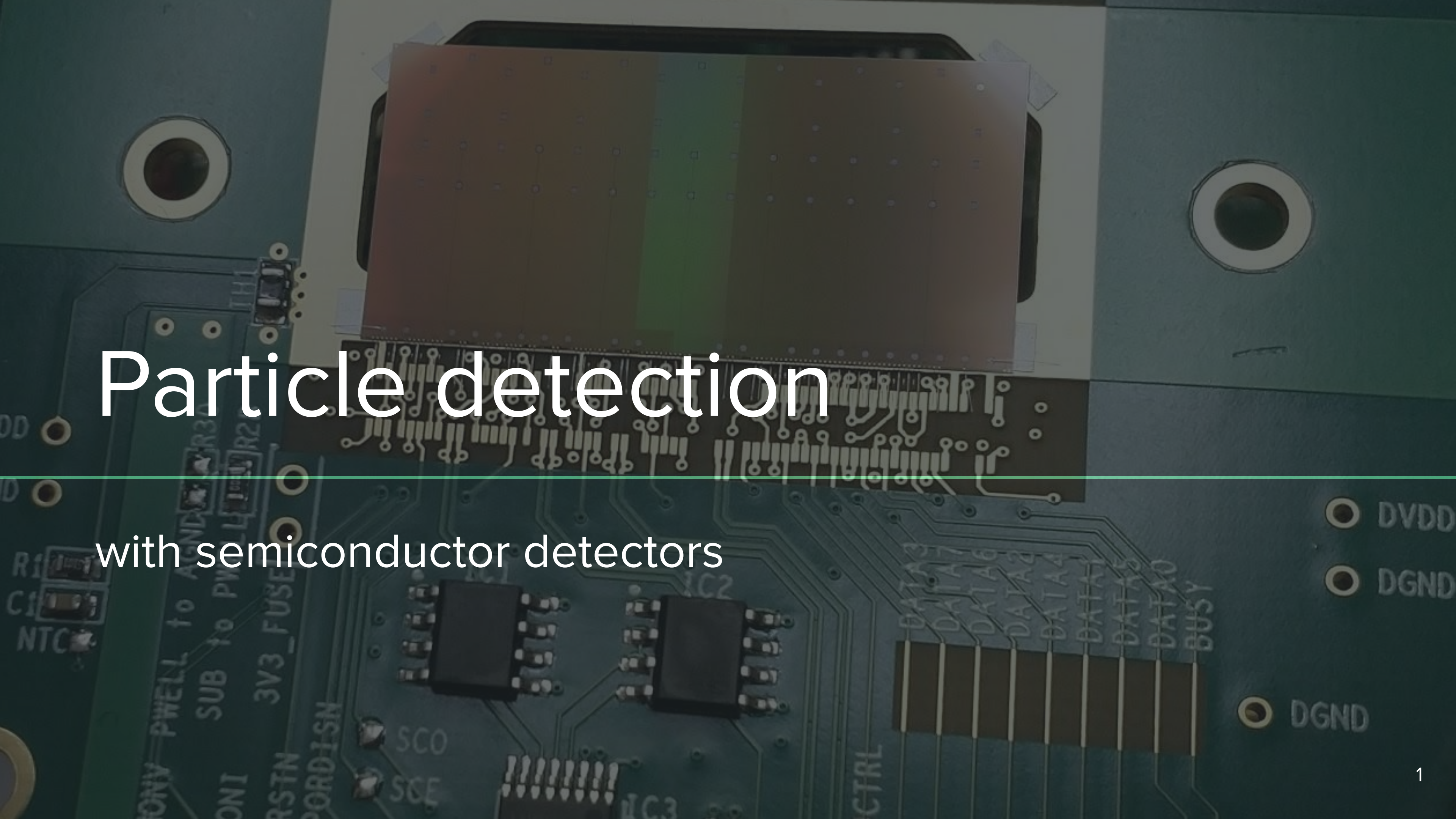


Particle detection

with semiconductor detectors

Pre-work

- Watch: what is a semiconductor? https://www.youtube.com/watch?v=gUmDVe6C-BU
- Watch: how does a transistor work? https://www.youtube.com/watch?v=IcrBqCFLHIY
- Read 10.1.4 (mobility) and 10.3 (the np semiconductor junction and depletion depth) in Techniques for nuclear and particle physics experiments
- Submit a picture of band gaps in semiconductors, insulators, and conductors.
- Answer the questions in the quiz

By the end of today you will be able to…

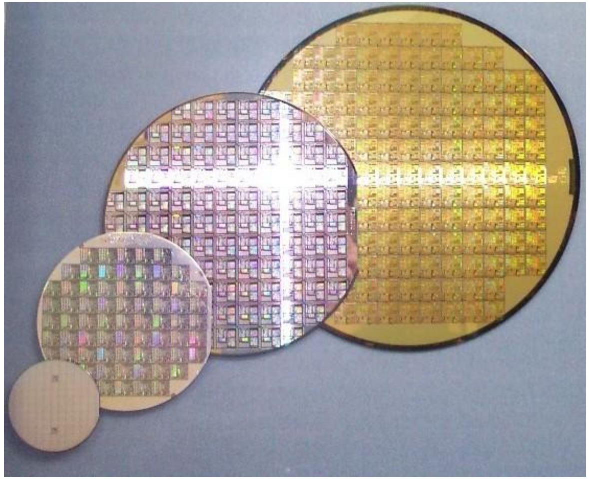
- Explain the difference between a semiconductor, insulator, and conductor
- Explain how a semiconductor can be used to detect particles
- Explain signal creation, detection, propagation, and processing in semiconductor detectors
- Argue for different detector technologies in different applications.

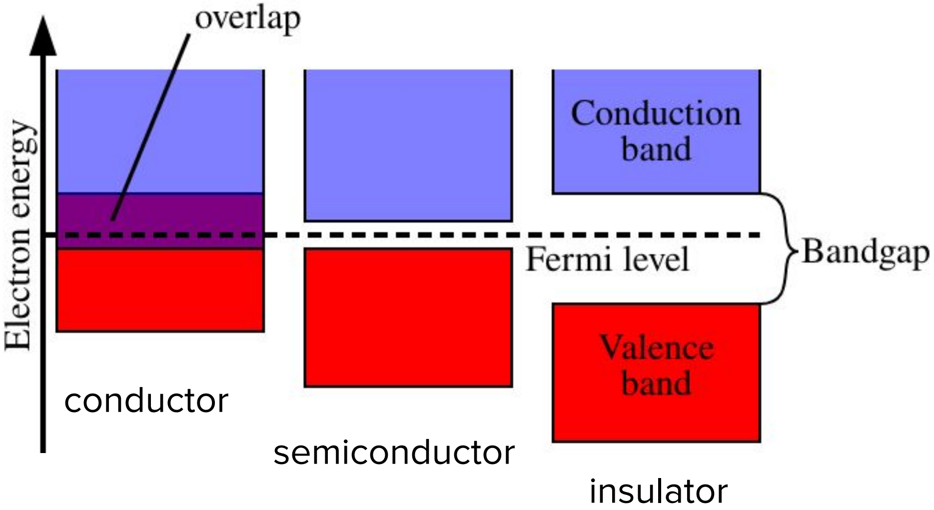
What will not be fully covered until later in the course:

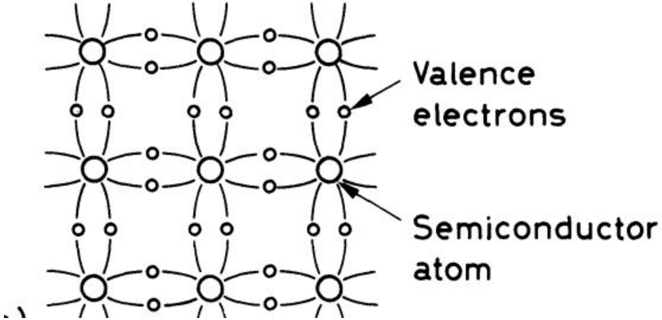
- How to use particle detectors to construct particle tracks
- How to use particle detectors for particle identification

What is a semiconductor?

Semiconductors



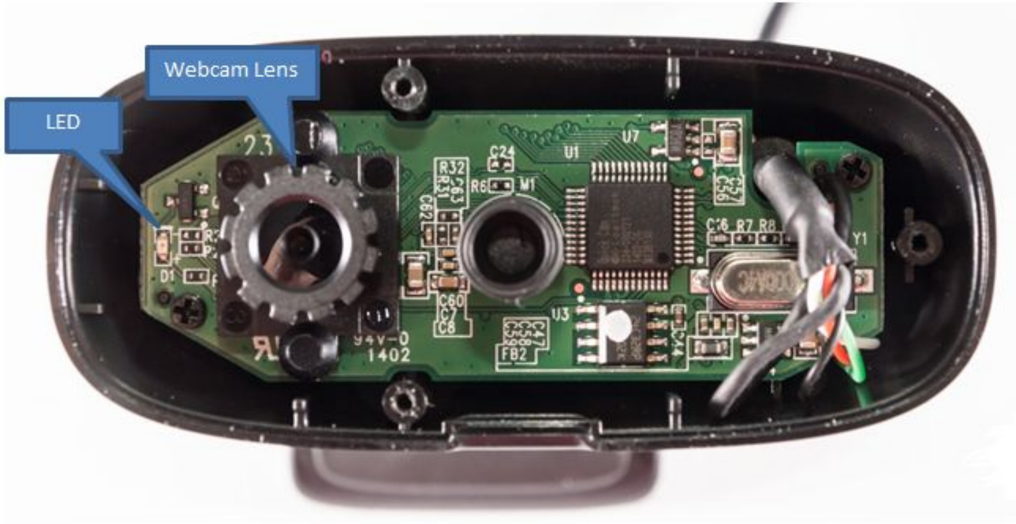


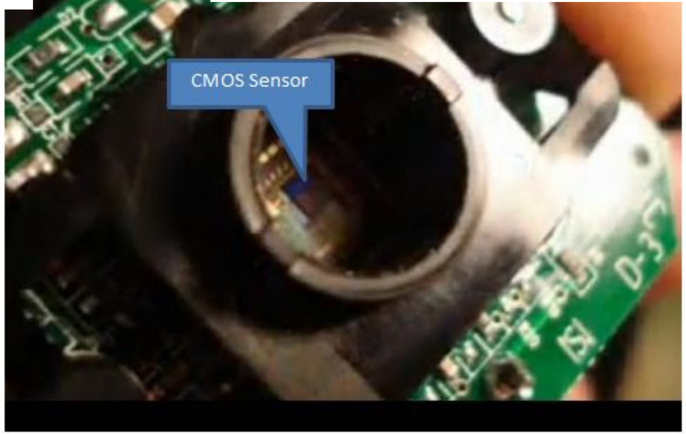


Solid state material: atomic energy levels merge to energy bands

In your webcam

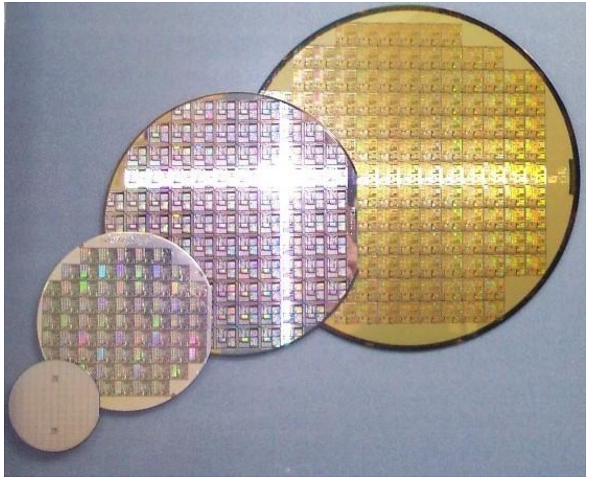
Original camera

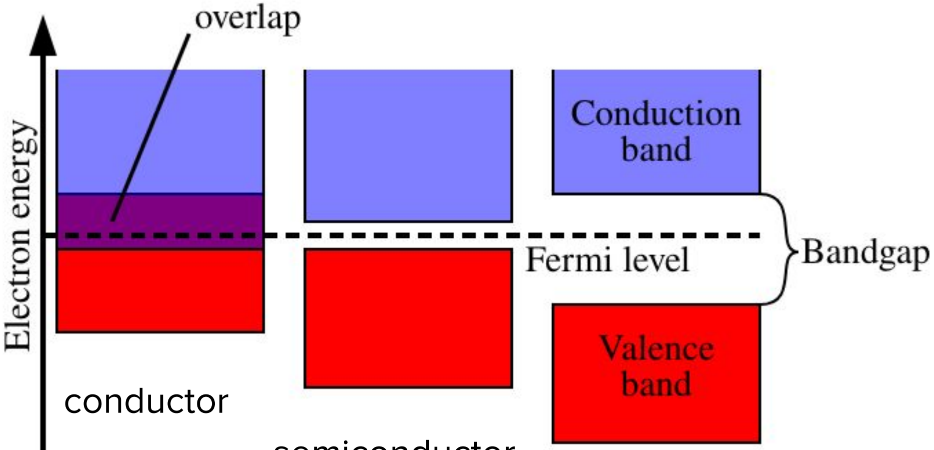




… you have a particle detector!

Semiconductors

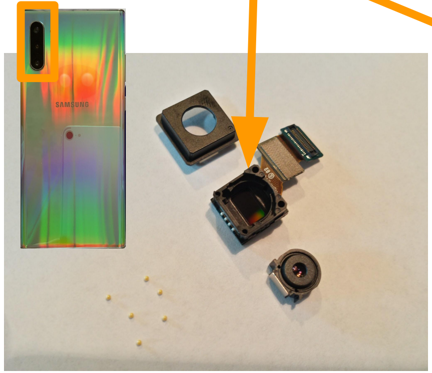


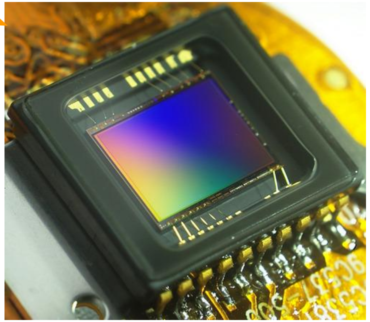


conductor

semiconductor

insulator

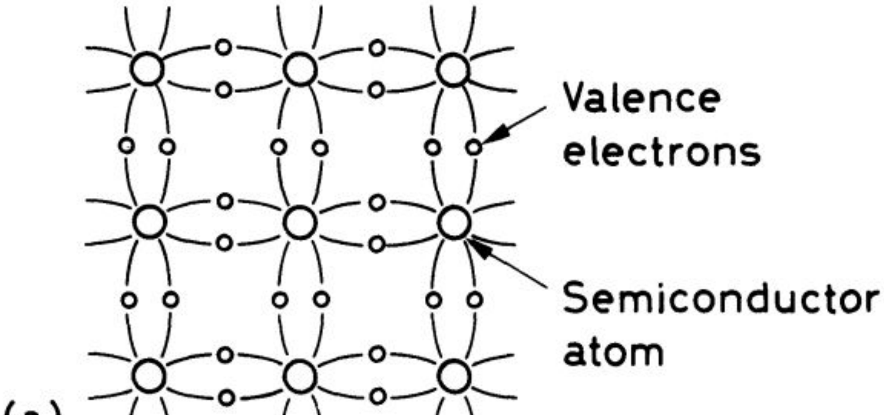




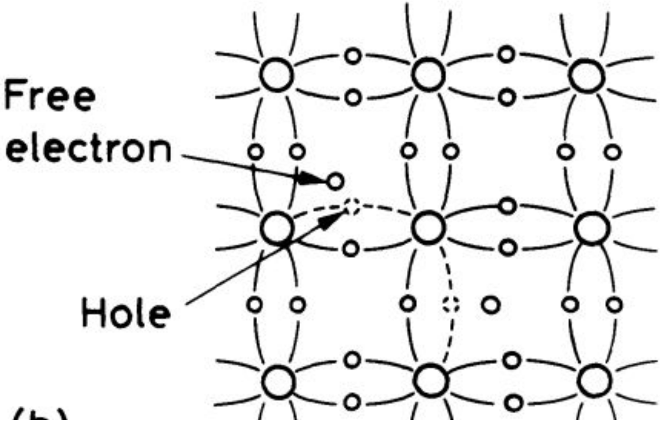
A semiconductor device is easy to manipulate, easily controlled, and makes an excellent sensor

What happened when silicon was heated in the video?

Silicon bonds



Silicon at 0 K: all electrons are bonded



Silicon at higher temperature: through thermal excitations, some electrons are excited and holes are left behind.

Solid state physics: semiconductor statistics

Fermi-Dirac

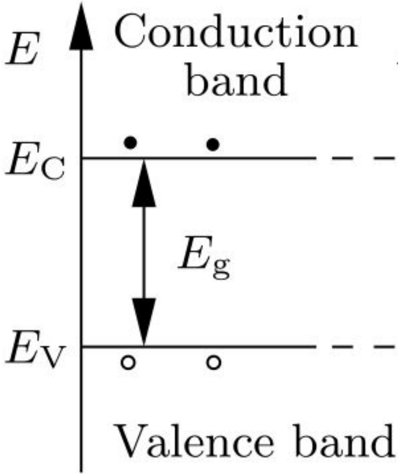
Fermi-Dirac

$$f_e(E) = \frac{1}{e^{(E-E_F)/kT} + 1}$$

Probability that an electron state in the conduction band is filled

$$f_e(E) = \frac{1}{e^{(E-E_F)/kT} + 1}$$

Intrinsic semiconductor



Excited electrons n

Number of holes p

Intrinsic semiconductor

$$np = n_i^2$$

Concentration of acceptor/donor impurities N_A/N_D or N_c/N_v conduction/valence band edge density of states

<<

thermally generated eh pairs

No doping yet!

Carrier concentration

$$n_i = \boxed{N_c} e^{-(E_c - E_F)/kT} = \boxed{N_v} e^{-(E_F - E_v)/kT}$$

N_c: effective density of states at conduction band edge

N_v: effective density of states at valence band edge

Excited electrons n

Number of holes p

Intrinsic carrier concentration

$$n_i = N_c e^{-(E_c - E_F)/kT} = N_v e^{-(E_F - E_v)/kT}$$

The product of electron and hole concentrations

Band gap energy in silicon E_g = 1.12 eV

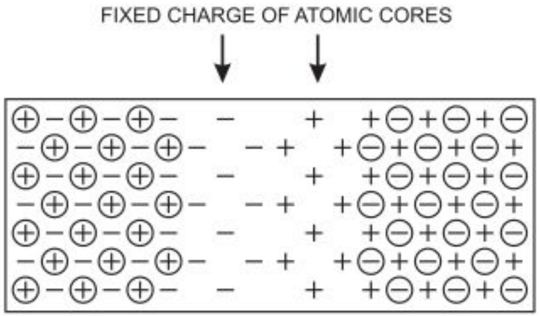
$$n_\mathrm{i} = 1.45 \times 10^{10}\ \mathrm{cm}^{-3}$$

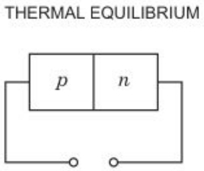
depends only on the gap energy

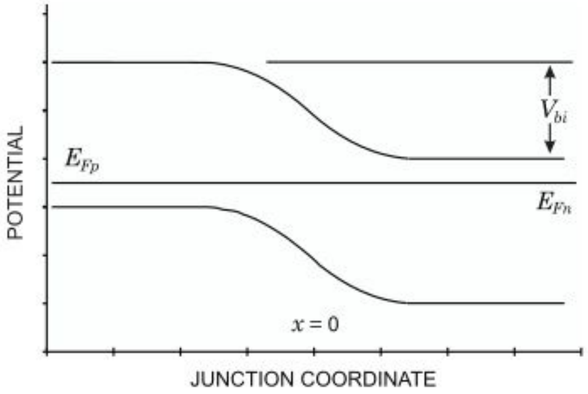
$$\boxed{np = n_i^2} = N_c N_v e^{-(E_c - E_v)/kT} = N_c N_v e^{-E_g/kT}$$

Depletion zone in intrinsic semiconductor

Electrons and holes diffuse through the junction.







This results in a potential difference called the built-in voltage between the p and n regions

No doping yet!

A semiconductor device is easy to manipulate

Charge carriers: **jargon alert**

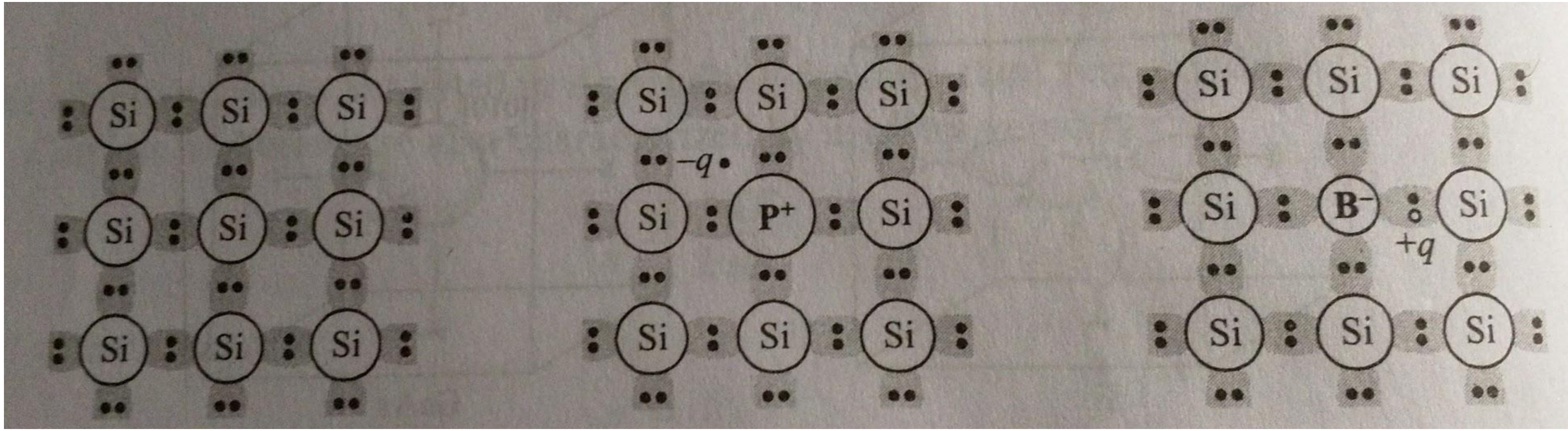
Now, we dope! =)

why?

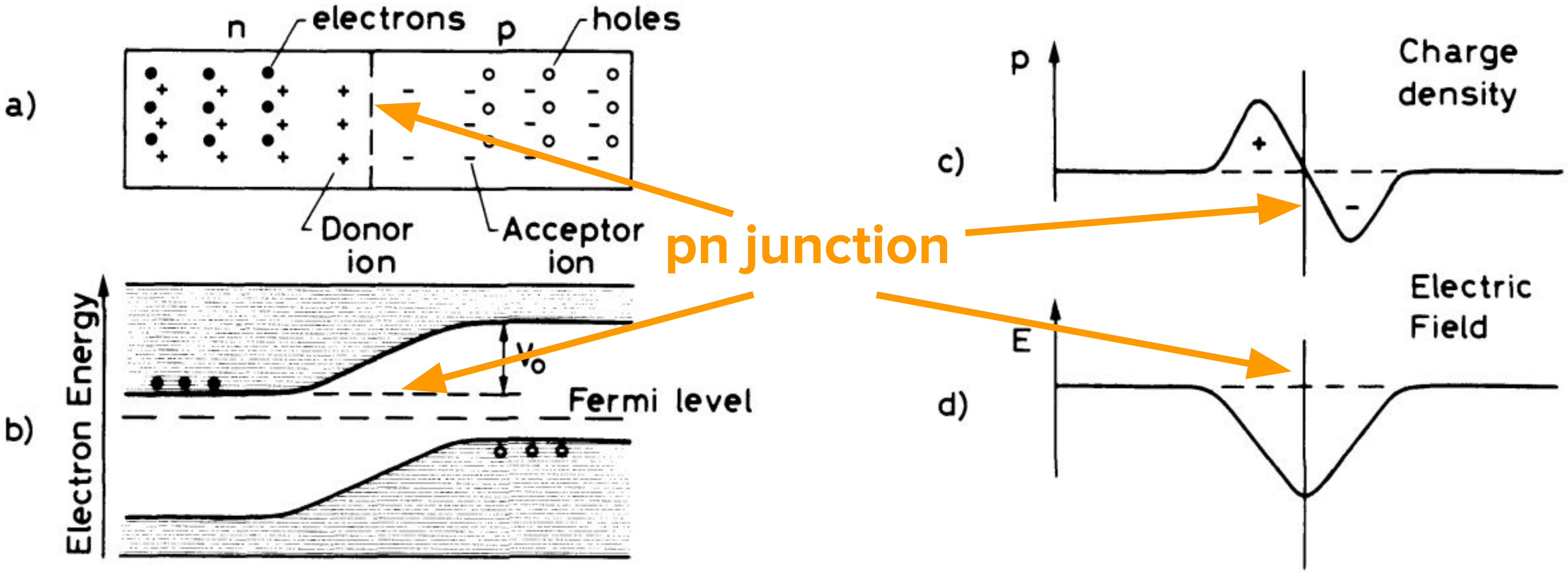
Intrinsic or **pure** or **undoped** semiconductors:
Equal amount of e^- and h carriers

N-type semiconductors are doped with a **donor impurity** that results in **electrons** becoming the **majority carrier** and holes the minority carrier.

P-type semiconductors are doped with an **acceptor impurity** that results in **holes** becoming the **majority carrier** and electrons the minority carrier



join a p-doped and n-doped semiconductor


pn junction

Dope that stuff! Improve performance

Net carrier concentration

$$\Delta n = n - p = N_d^+ - N_a^-$$

$$E_F - E_i = -k_B T \log \frac{N_a - N_d}{n_i}$$

Doping concentration N: commonly expressed in terms of the measurable **resistivity** of the material.

$$\rho = \frac{1}{\mu e N}$$

What was μ?

Dope that stuff! Improve performance

Net carrier concentration

$$\Delta n = n - p = N_d^+ - N_a^-$$

$$E_F - E_i = -k_B T \log \frac{N_a - N_d}{n_i}$$

Doping concentration N: commonly expressed in terms of the measurable **resistivity** of the material.

$$\rho = \frac{1}{\mu e N}$$

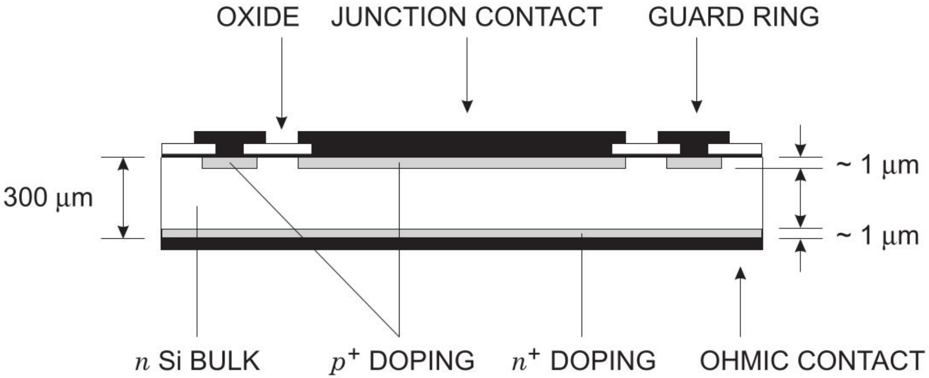
What was μ?

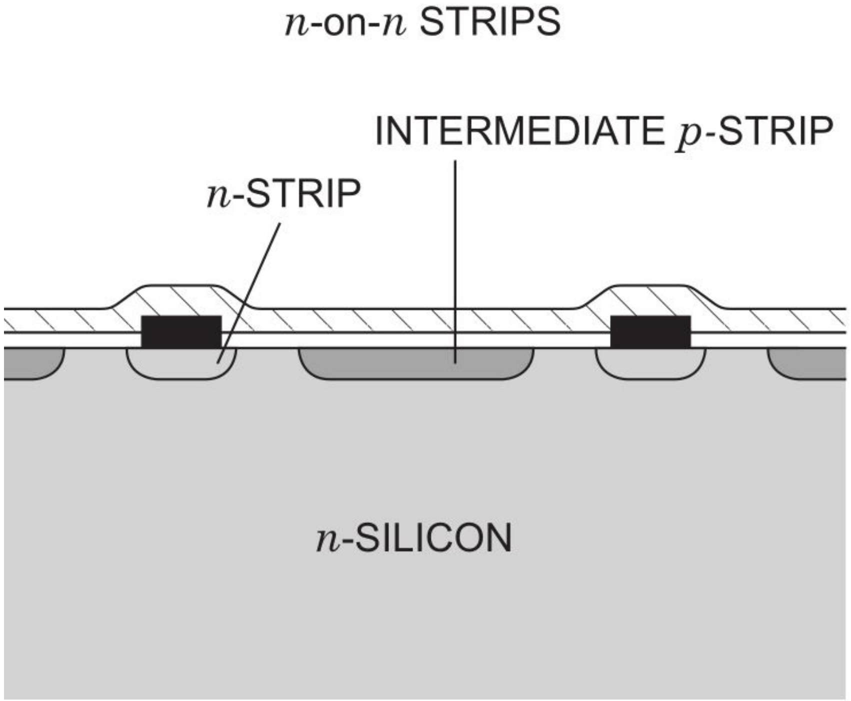
$$\vec{v} = \mu \vec{E}$$

Example silicon diode and strip detector

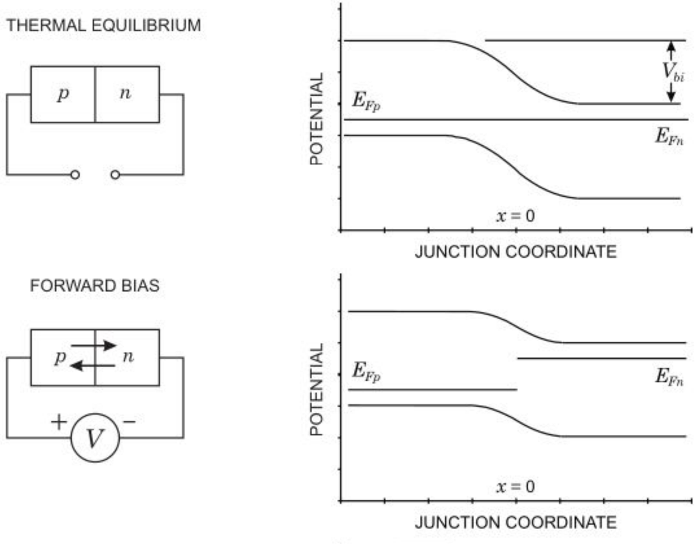
Highly doped surface layer in lightly doped “bulk”

Ohmic contact = back electrode





Fermi level depends on doping concentrations



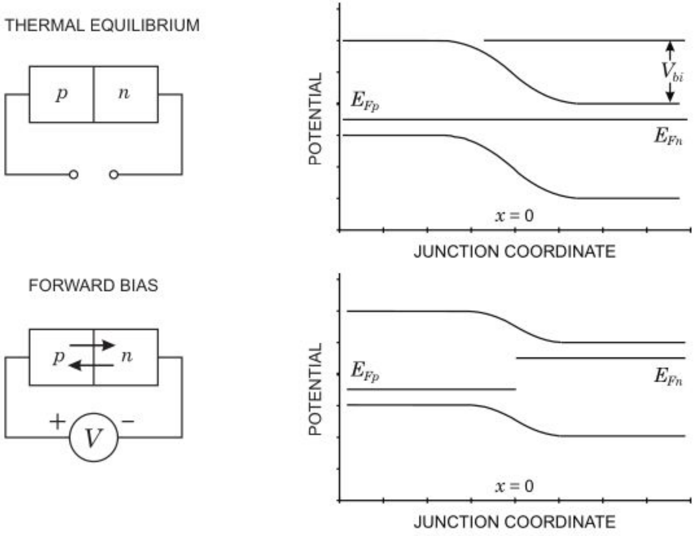
$$\frac{E_c - E_F}{k_B T} = \log\left(\frac{N_c}{N_d - N_a}\right)$$

$$N_d \gg N_a,$$

small $E_c - E_F$

Fermi level close to conduction band edge

Fermi level depends on doping concentrations



$$\frac{E_c - E_F}{k_B T} = \log\left(\frac{N_c}{N_d - N_a}\right)$$

$$\downarrow$$

$$N_d \gg N_a,$$

$$\downarrow$$

small $E_c - E_F$

$$\downarrow$$

Fermi level close to conduction band edge

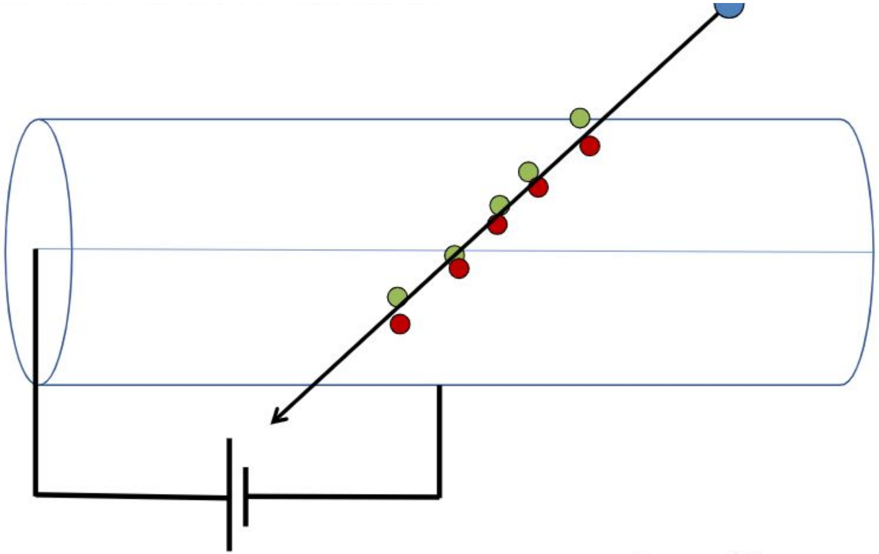
What happened at the pn junction in the video?
Can we detect particles like that?

A signal in a gas detector

Last week:

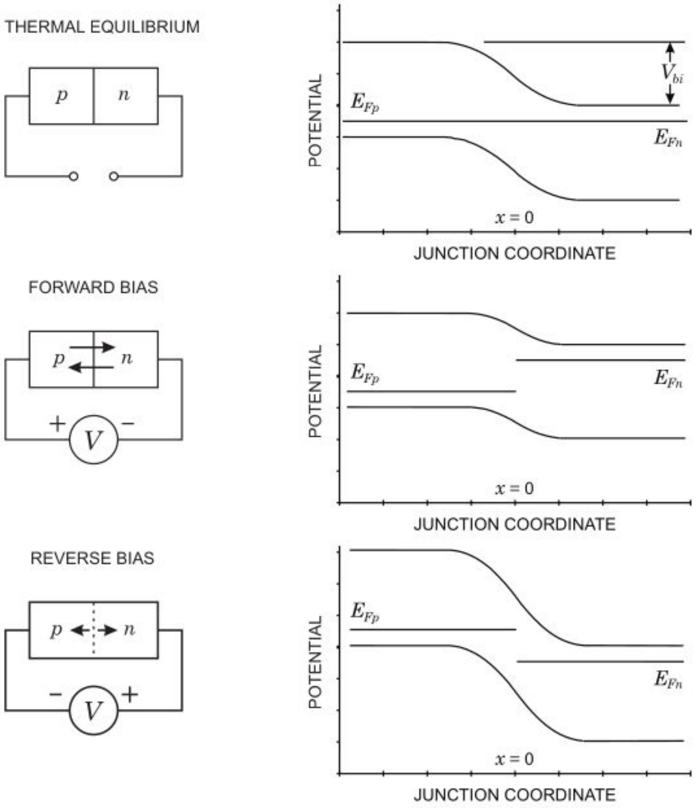
A signal in a gas detector

Last week:



$$E = \frac{1}{s}\frac{V}{\ln(b/a)}$$

Adjust the pn diode to particle detection mode



Increase depletion zone by applying a reverse bias

Particle detection mode!

Reverse bias

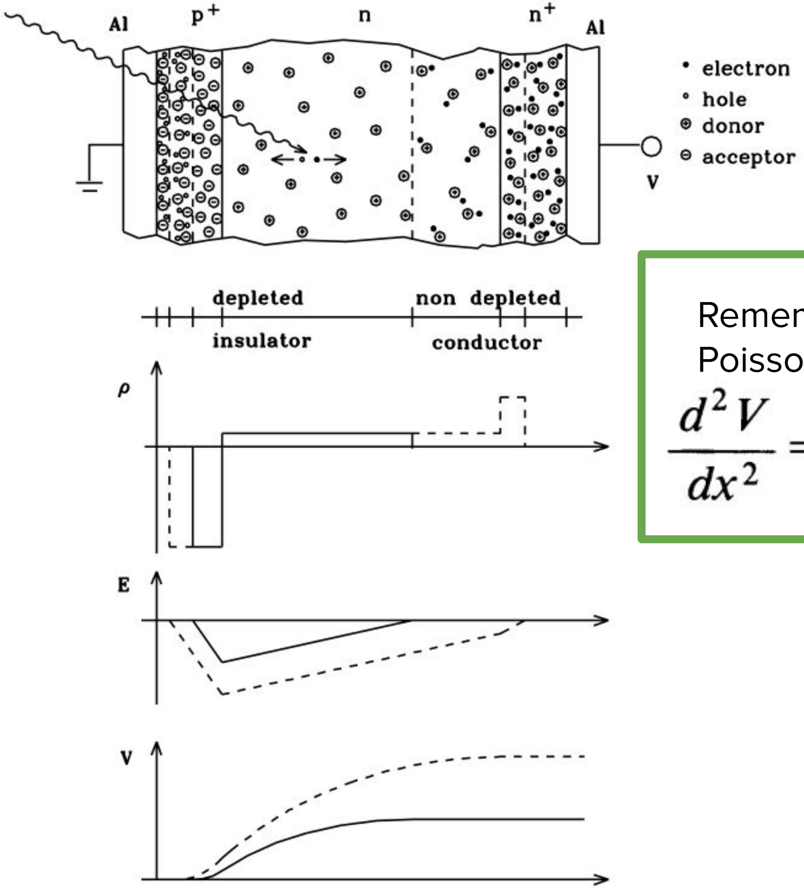
Ideal for particle detection!

Suppress current across junction

Incoming particles **ionize** the atoms creating electron-hole pairs

e$^-$h pairs travel in electric field

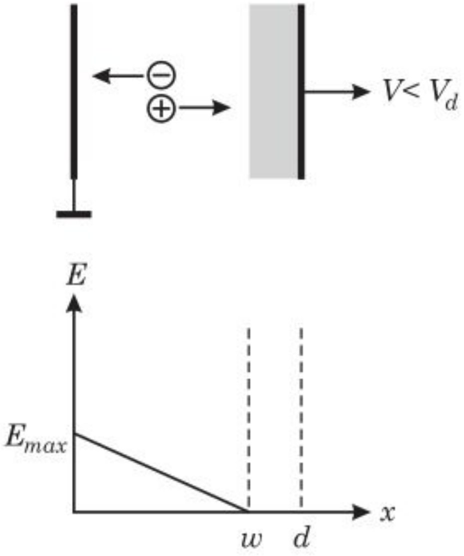
Charge **induced** in electrodes



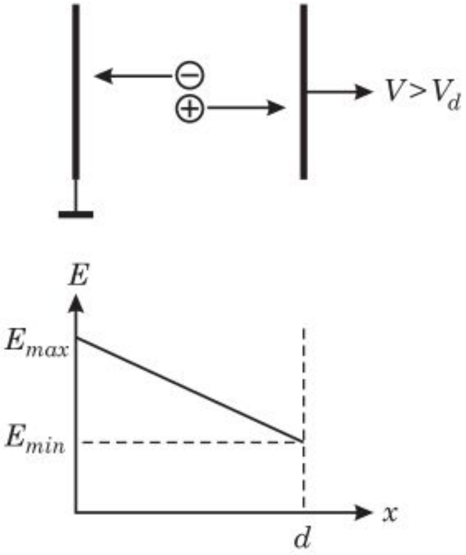
Remember Poisson:

$$\frac{d^2V}{dx^2} = -\frac{\rho(x)}{\varepsilon}$$

Full vs partial depletion



Partial depletion



Overdepletion

Depletion zone

$$\rho(x) = \begin{cases} eN_D & 0 < x < x_n \\ -eN_A & -x_p < x < 0 \end{cases},$$

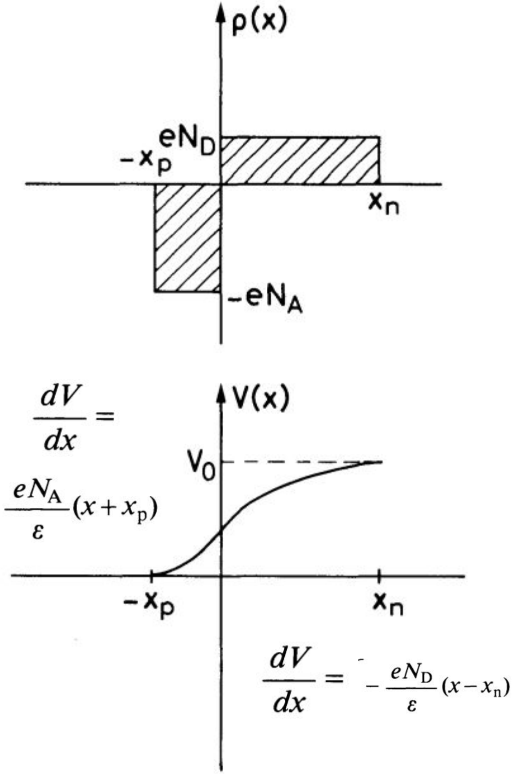
$$d = x_n + x_p = \left(\frac{2\,\varepsilon V_0}{e} \frac{(N_A + N_D)}{N_A N_D} \right)^{1/2}$$

$$N_A \gg N_D$$

$$d \simeq x_n \simeq \left(\frac{2\,\varepsilon V_0}{eN_D} \right)^{1/2}$$

d = depletion depth

We want a large depletion zone! Why?

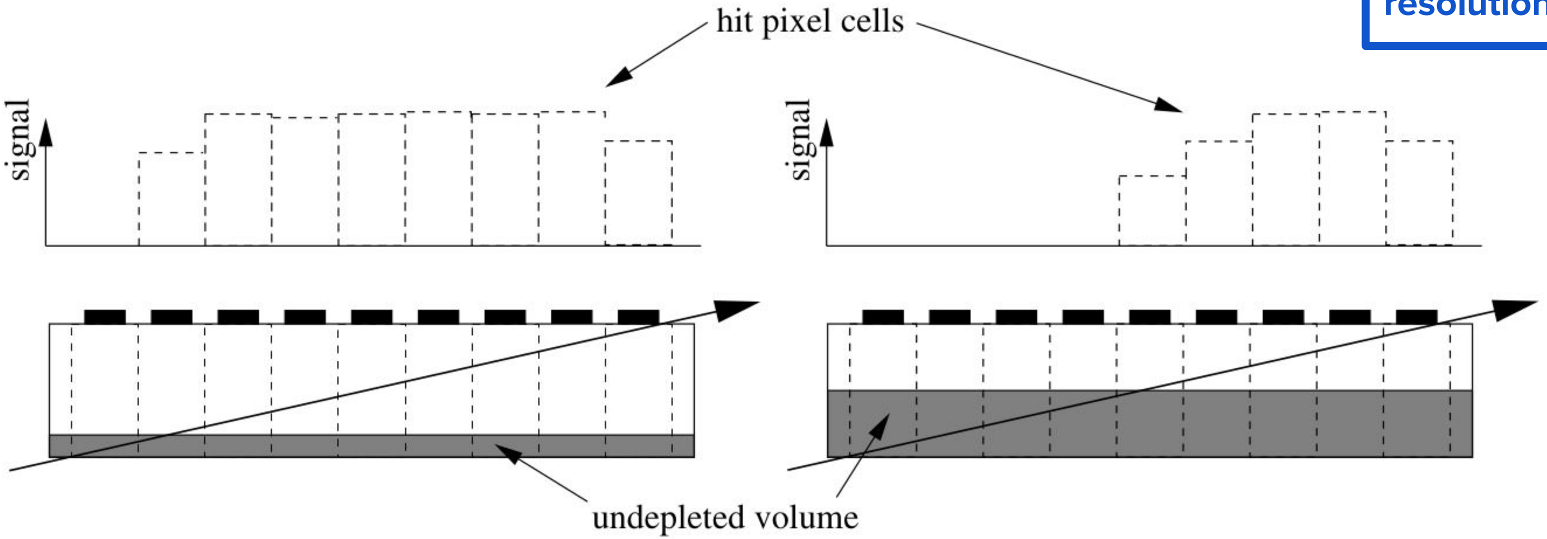


$$\frac{dV}{dx} = \frac{eN_A}{\varepsilon}(x + x_p)$$

$$\frac{dV}{dx} = -\frac{eN_D}{\varepsilon}(x - x_n)$$

Depletion width: the higher, the more signal

Silicon has an excellent position resolution

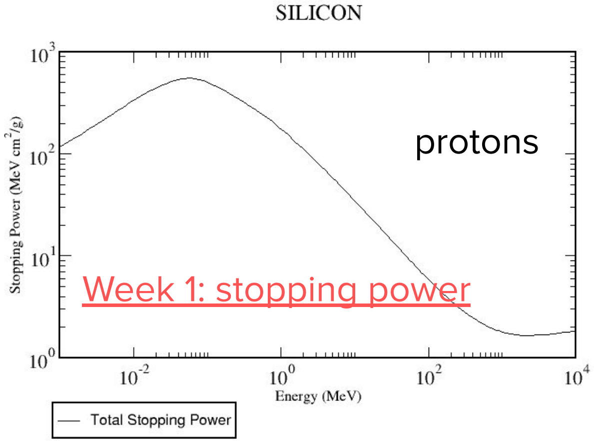


Why does the particle come in at such a shallow angle? Hint: it is on purpose.

dE/dx: electron hole pairs created in silicon

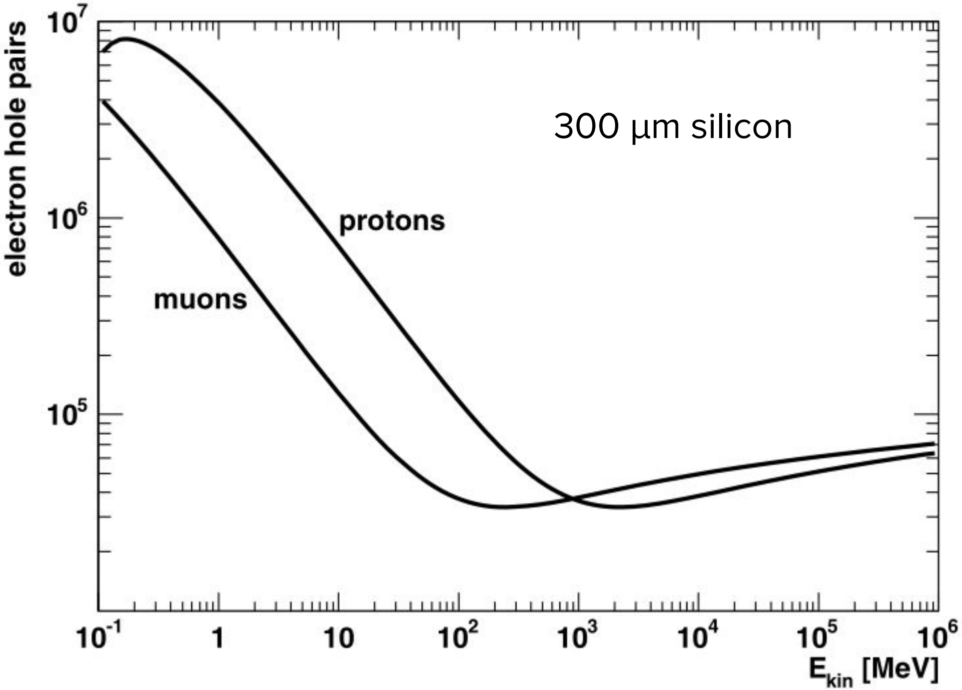
Silicon density at ~293 K: 2.3290 g/cm^3

Silicon mean ionization energy: 3.6 eV



Week 1: stopping power

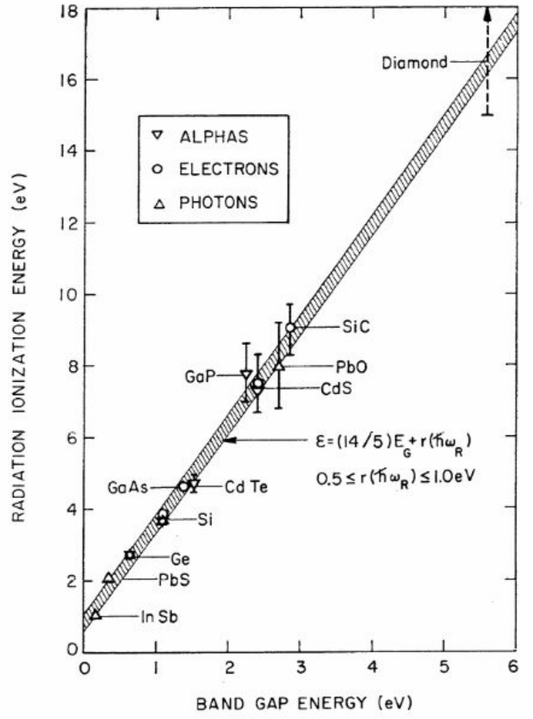
From https://physics.nist.gov



23000 e$^-$ in 300 µm silicon ➔ 2.76 MeV / cm

Band gap vs mean ionization energy

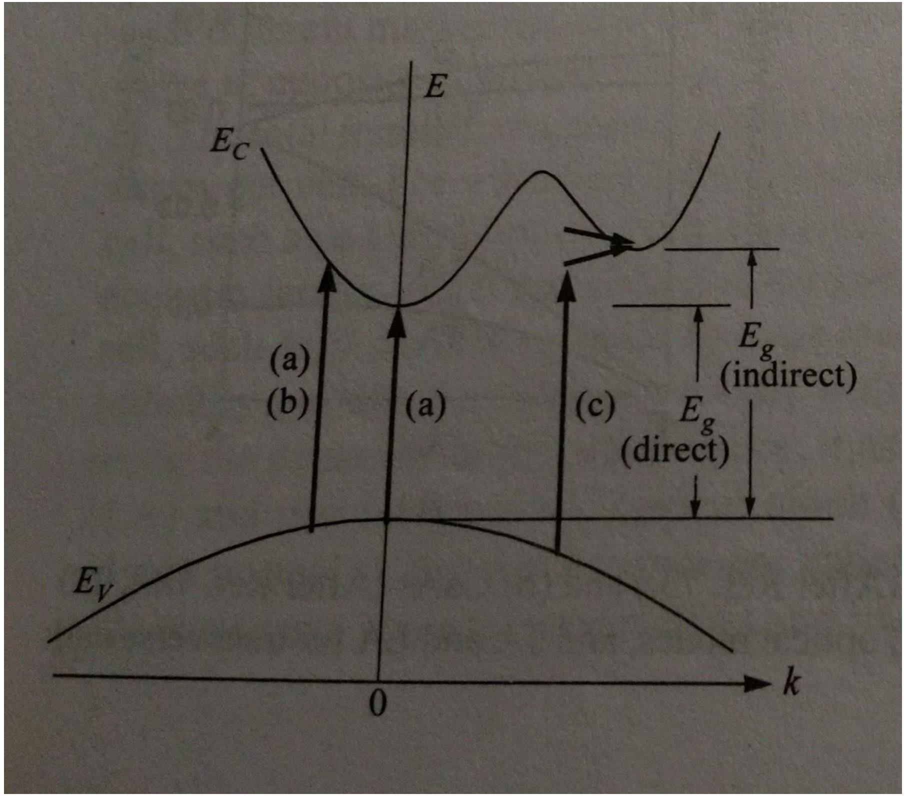
What is the silicon band gap energy? The ionization energy? Why?



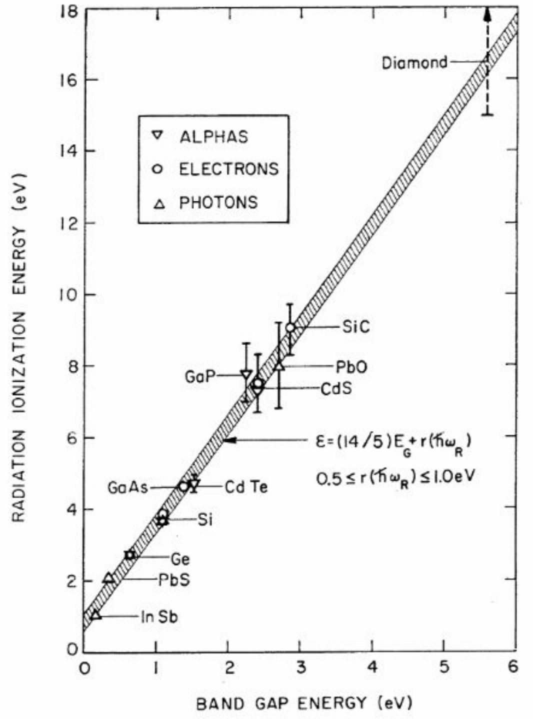
C.A. Klein, J. Applied Physics **39** (1968) 2029

Helmuth Spieler
LBNL

Band gap vs mean ionization energy



What is the silicon band gap energy? The ionization energy? Why?

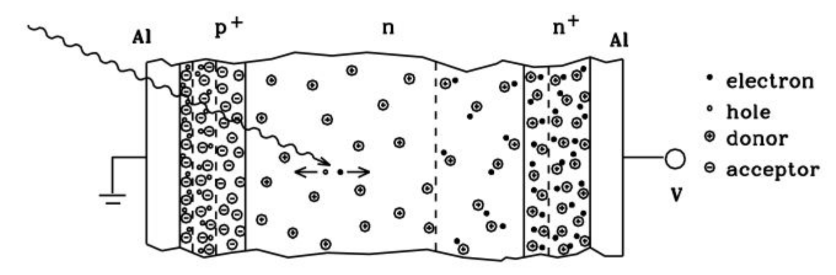


C.A. Klein, J. Applied Physics **39** (1968) 2029

Helmuth Spieler
LBNL

A semiconductor device is easy to manipulate, easily controlled, and makes an excellent sensor

Apply a reverse bias to the diode with pn junction to deplete the sensor of free carriers. The larger this zone, the more sensitive volume for detecting particles.



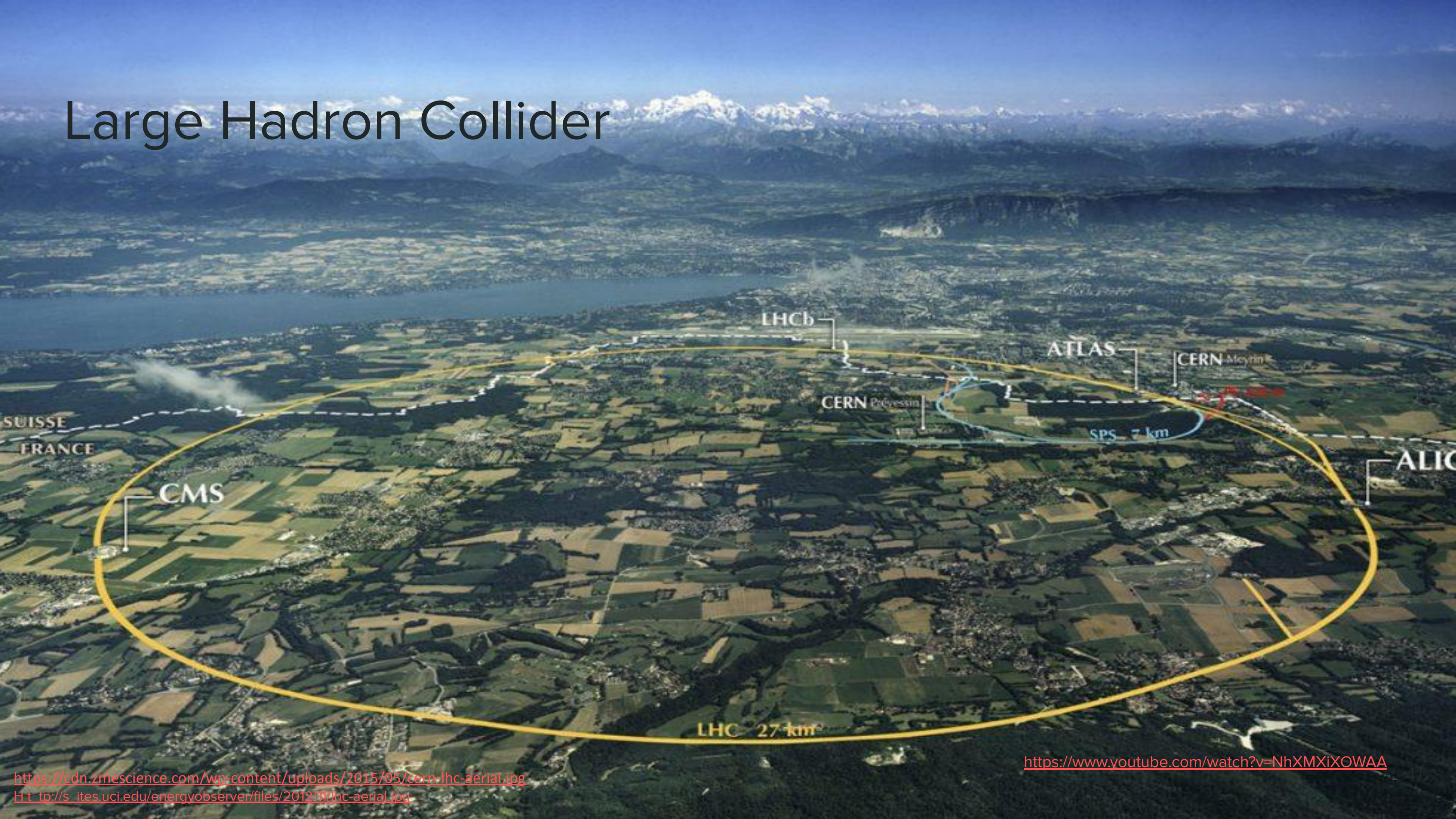
Dope a silicon detector with acceptors or donors to control the depth *w* of your depletion zone.

$$w = \sqrt{2\varepsilon\mu_n\rho_n V_b}$$

Resistivity is inversely proportional to the doping concentration

Semiconductors make excellent sensors: applications

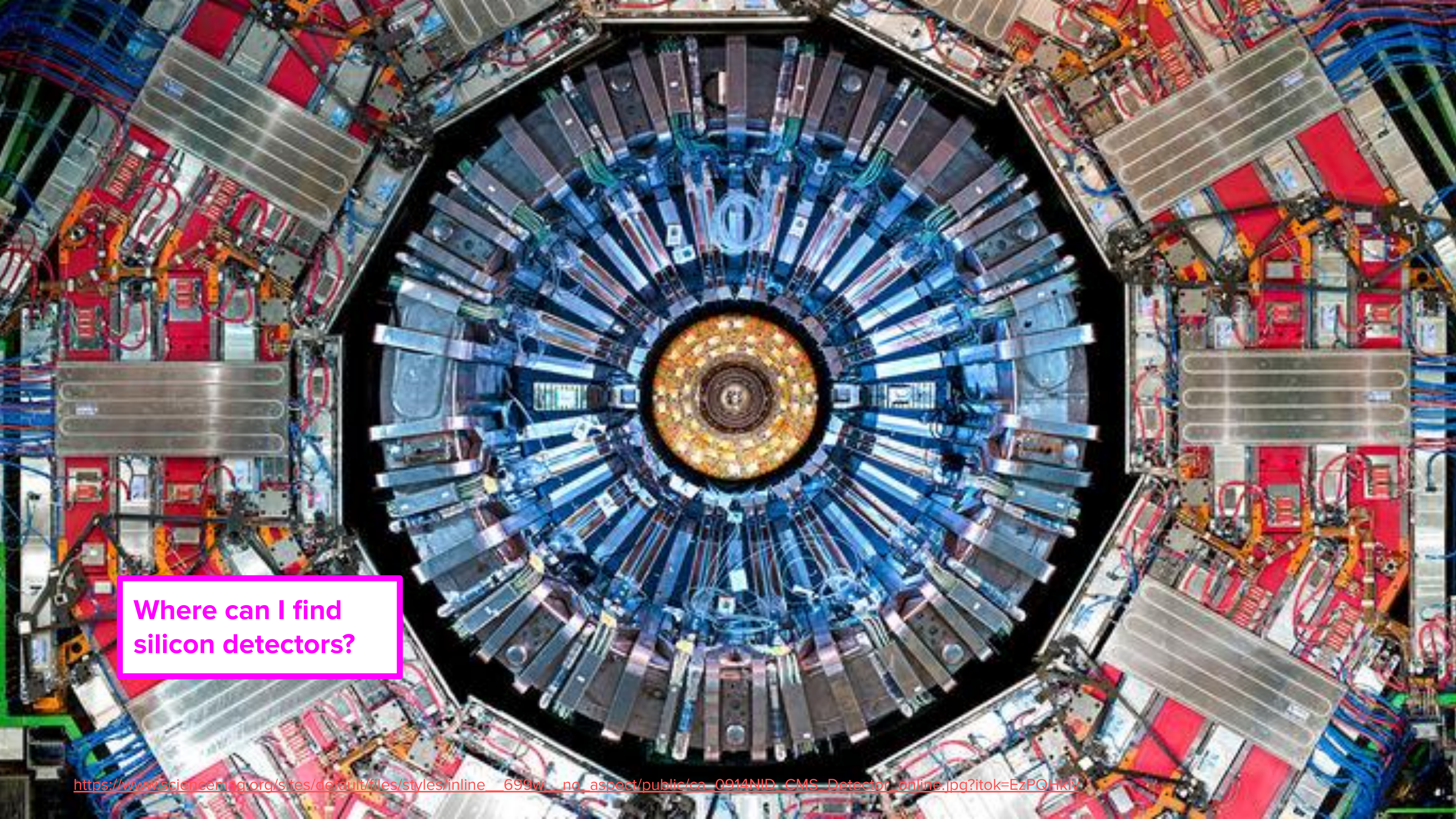
Large Hadron Collider



https://www.youtube.com/watch?v=NhXMXiXOWAA

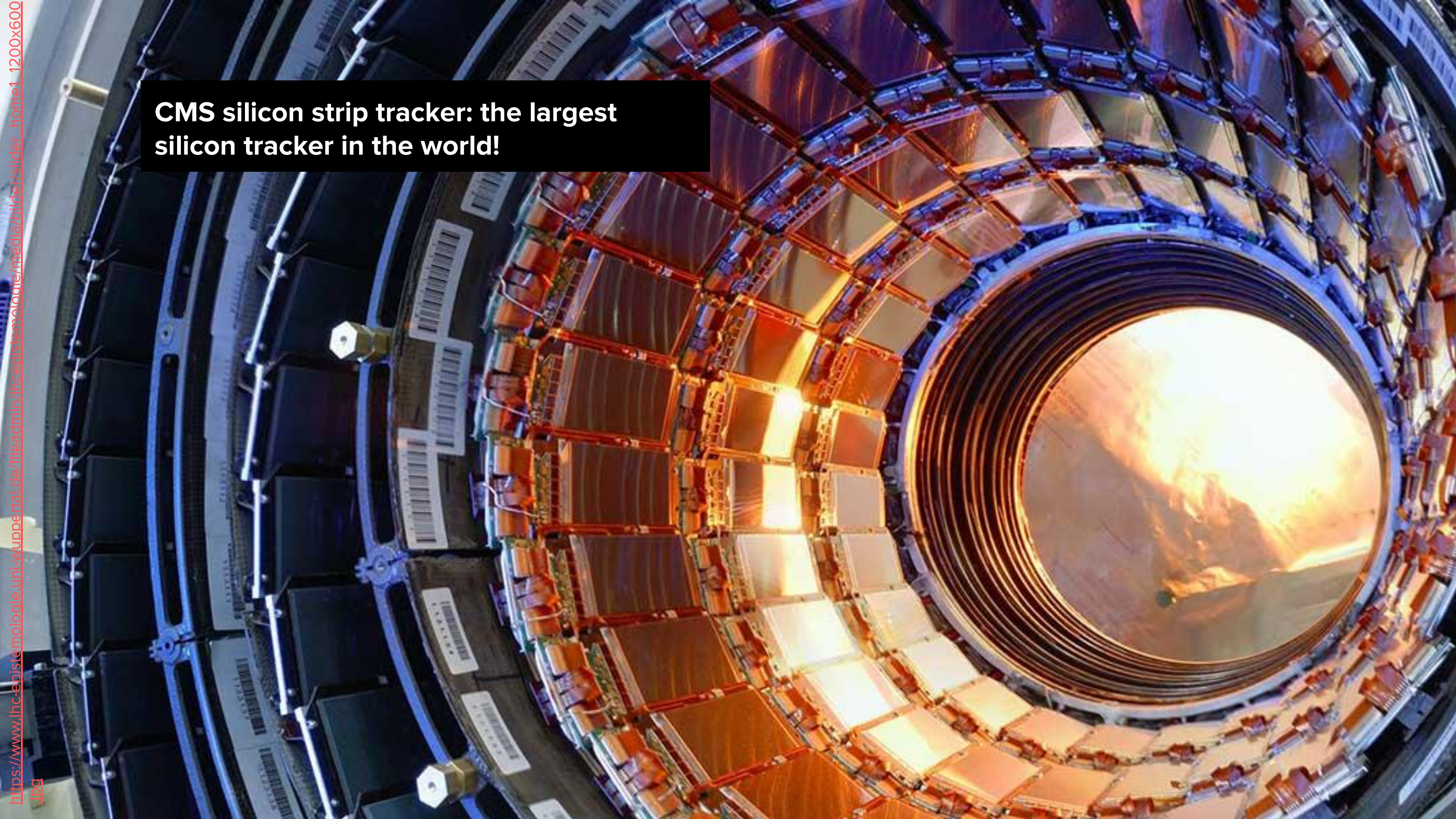
https://cdn.zmescience.com/wp-content/uploads/2015/05/cern-lhc-aerial.jpg

H t tp://s ites.uci.edu/energyobserver/files/2012/11/lhc-aerial.jpg



Where can I find silicon detectors?

https://www.sciencemag.org/sites/default/files/styles/inline__699w__no_aspect/public/ca_0914NID_CMS_Detector_online.jpg?itok=EzPQHklv



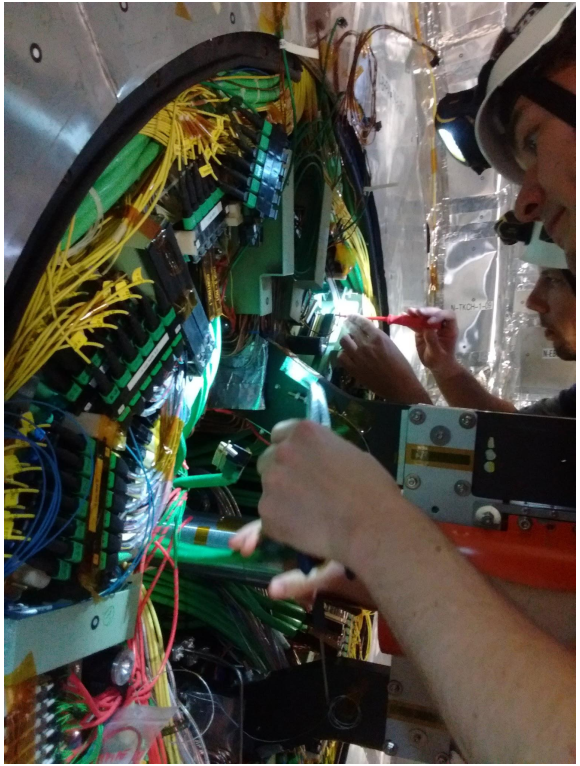
CMS silicon strip tracker: the largest silicon tracker in the world!

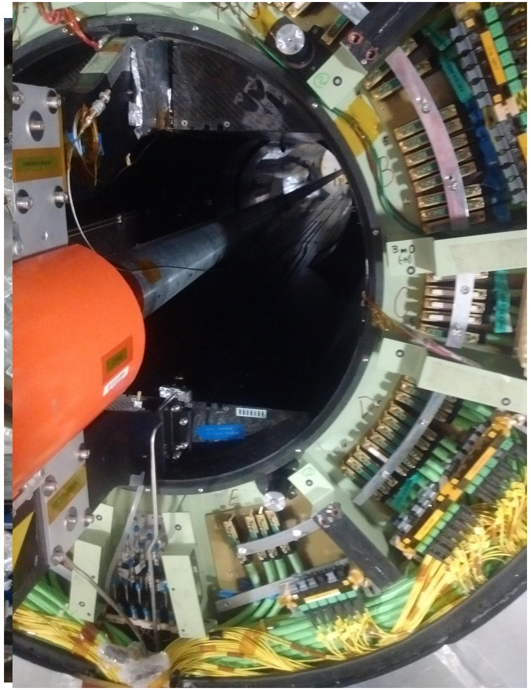
https://www.lhc-epistemologie.uni-wuppertal.de/fileadmin/lhcepistemologie/media/bilder/slider_home1_1200x600.jpg

CMS pixel detector

https://www.sciencemag.org/sites/default/files/styles/inline__699w__no_aspect/public/ca_0914NID_CMS_Detector_online.jpg?itok=EzPQHklv

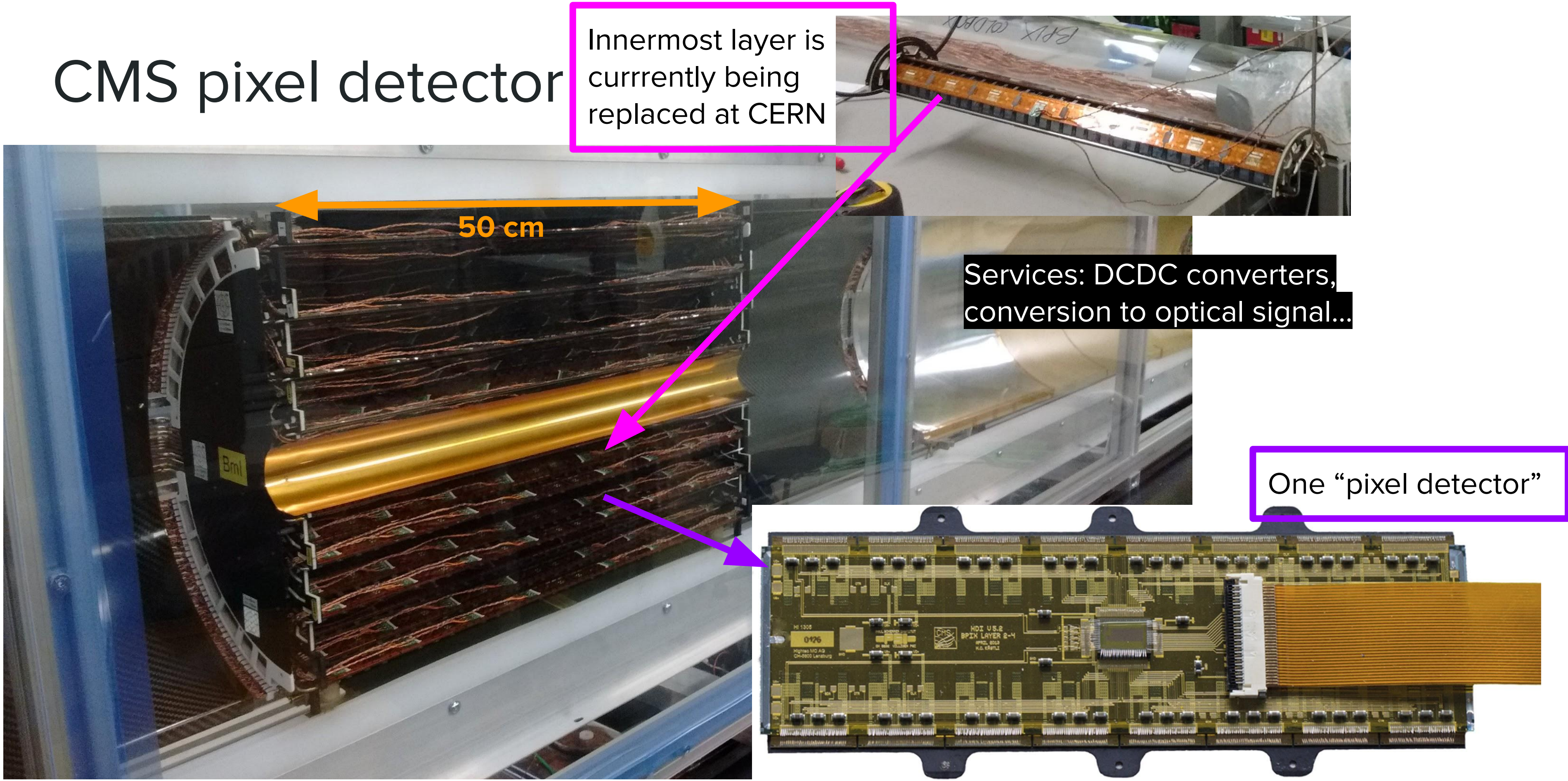
CMS pixel detector removal 2019





How about that ATLAS? ;-)

CMS pixel detector

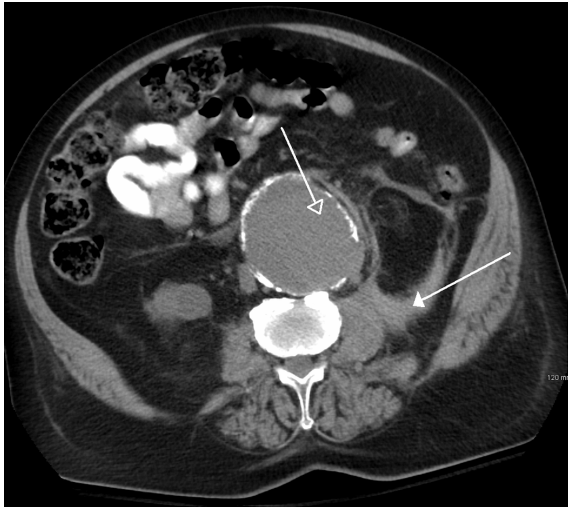


Innermost layer is currrently being replaced at CERN

Services: DCDC converters, conversion to optical signal…

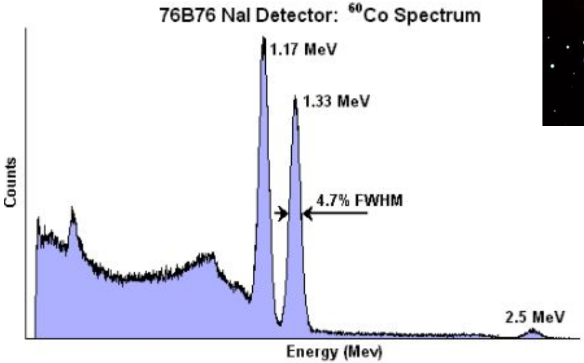
One “pixel detector”

Applications of silicon detectors

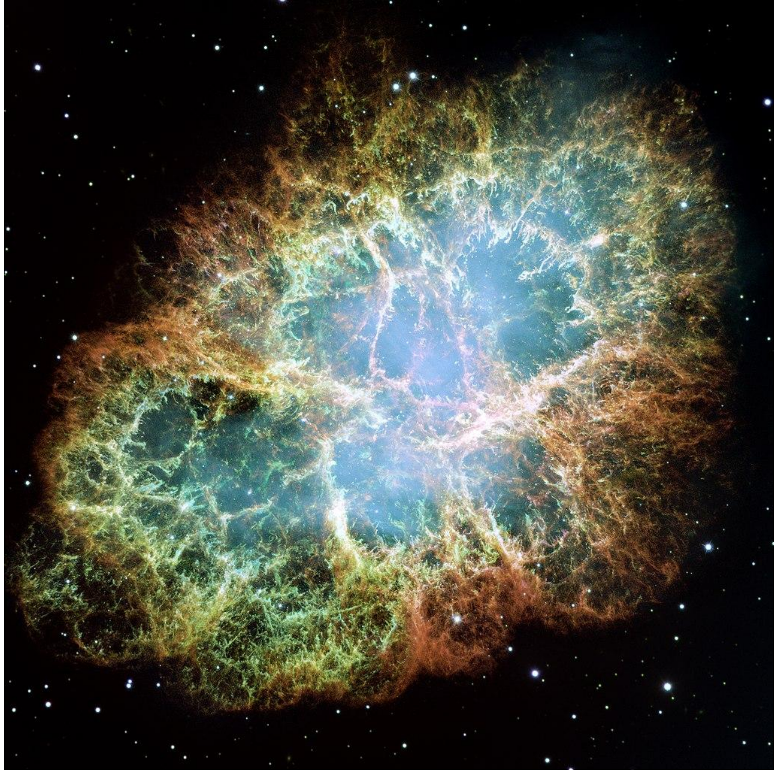


Medical imaging

X-ray imaging

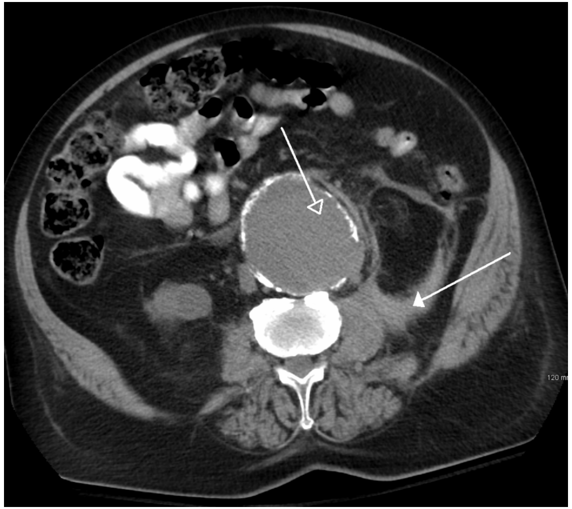


Week 1 X-ray spectroscopy



X-ray astronomy

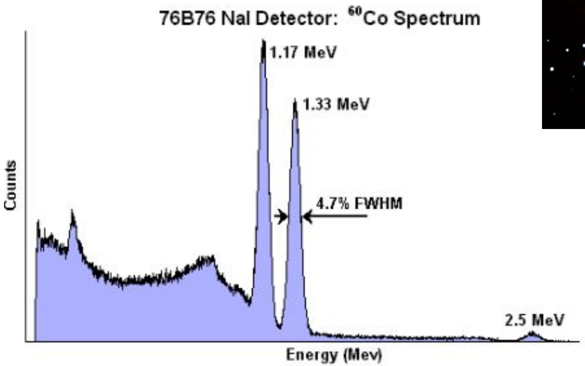
Applications of silicon detectors



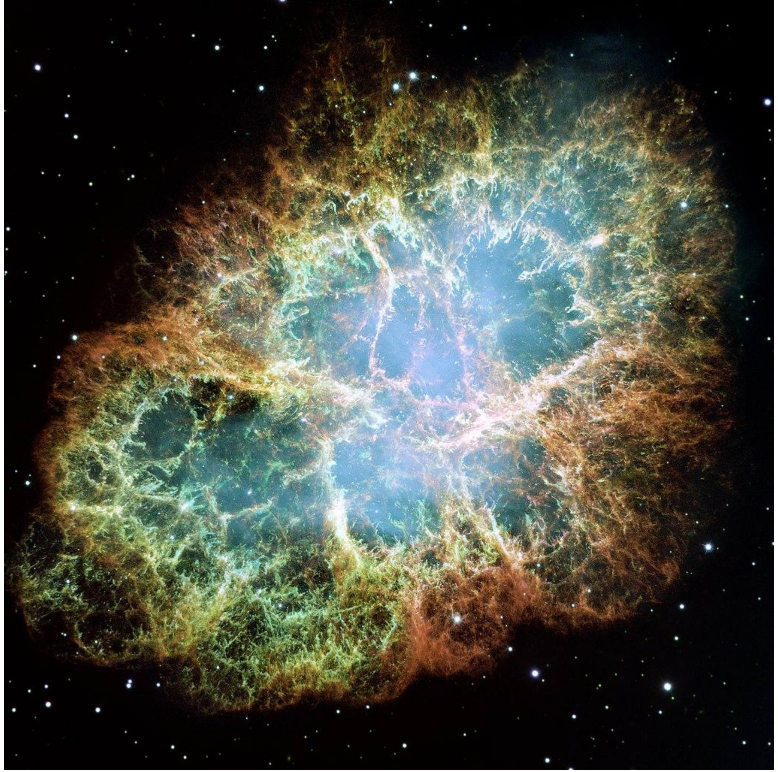
Medical imaging

Need no superfast taking of pictures every second: rather integrate over time to measure energy.

X-ray imaging



Week 1 X-ray spectroscopy

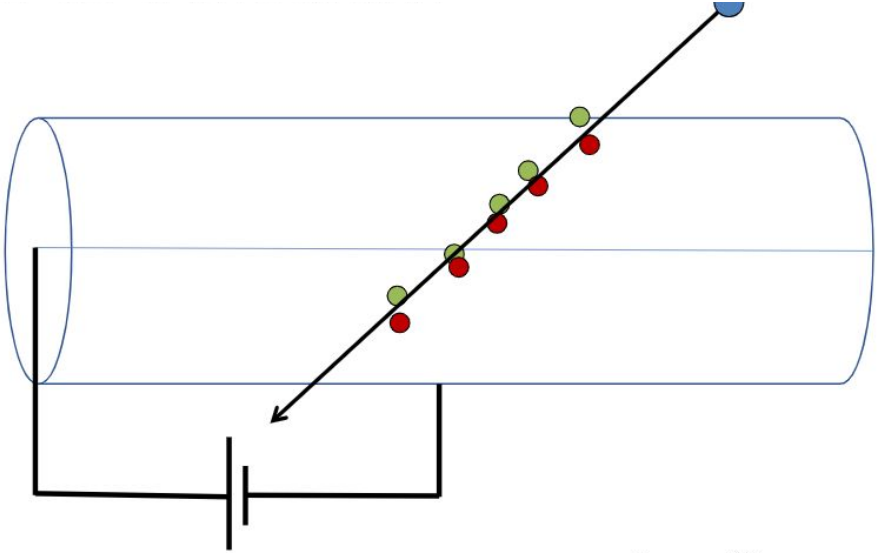


X-ray astronomy

How do we detect particles with a semiconductor?

A signal in a gas detector

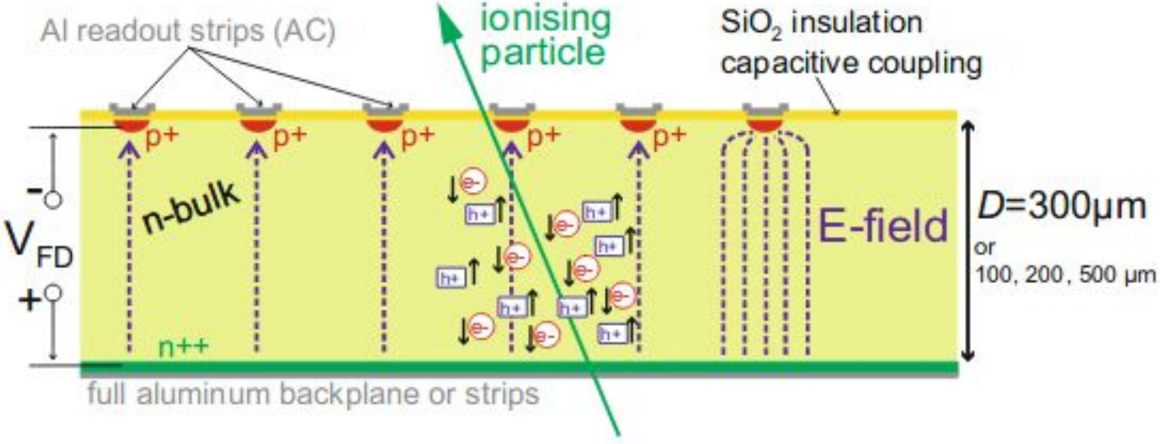
Last week:



$$E = \frac{1}{s}\frac{V}{\ln(b/a)}$$

Ideal signal detection with silicon sensors

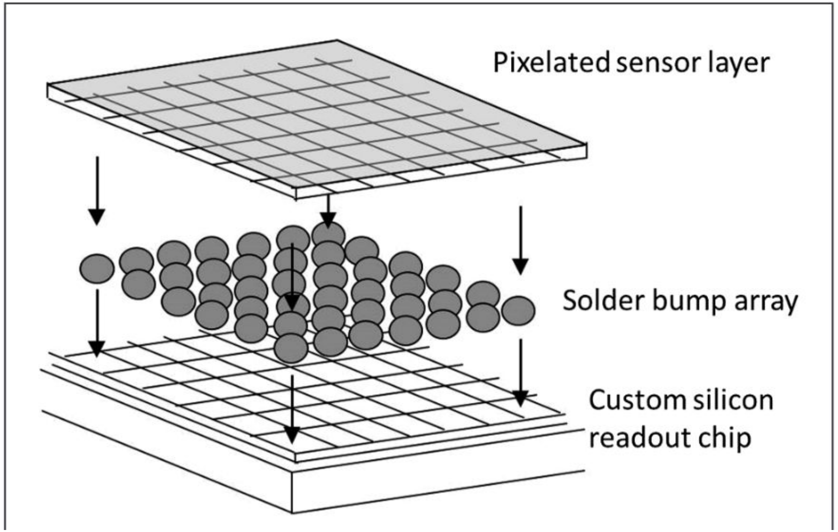
- A minimum ionizing particle (MIP) traveling through a fully depleted region (V_{FD}) creates electron hole pairs
- The charges drift to opposite directions under the electric field
- Within nanoseconds, charges are collected at the readout

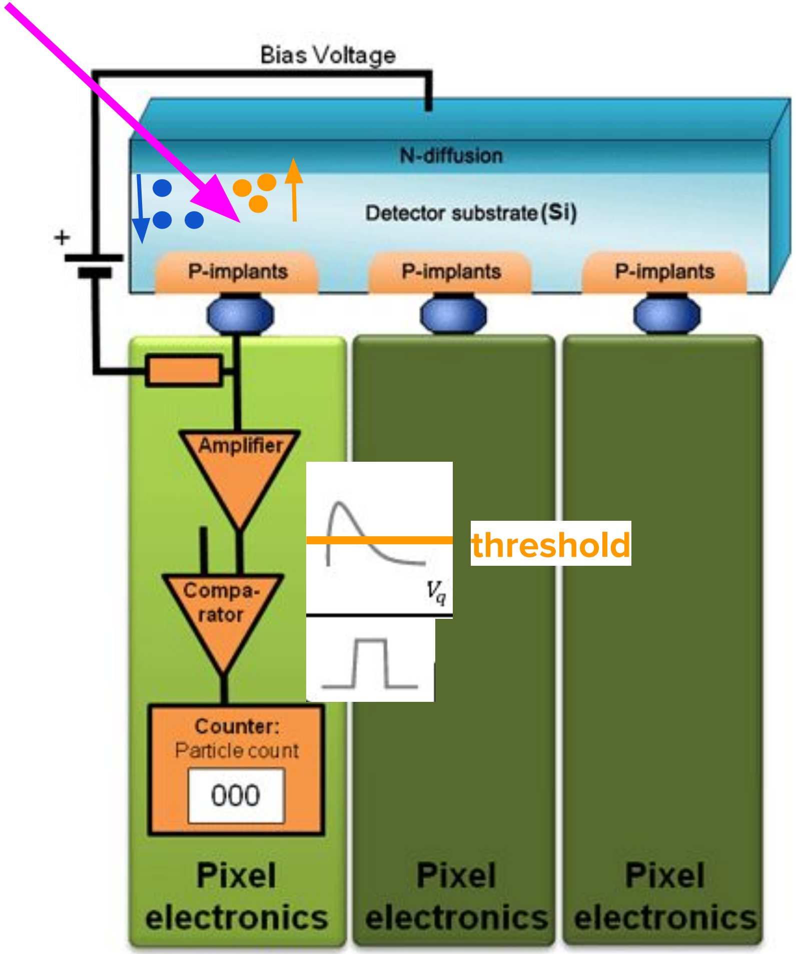


p-in-n silicon sensor

From Frank Hartmann

A hybrid pixel detector





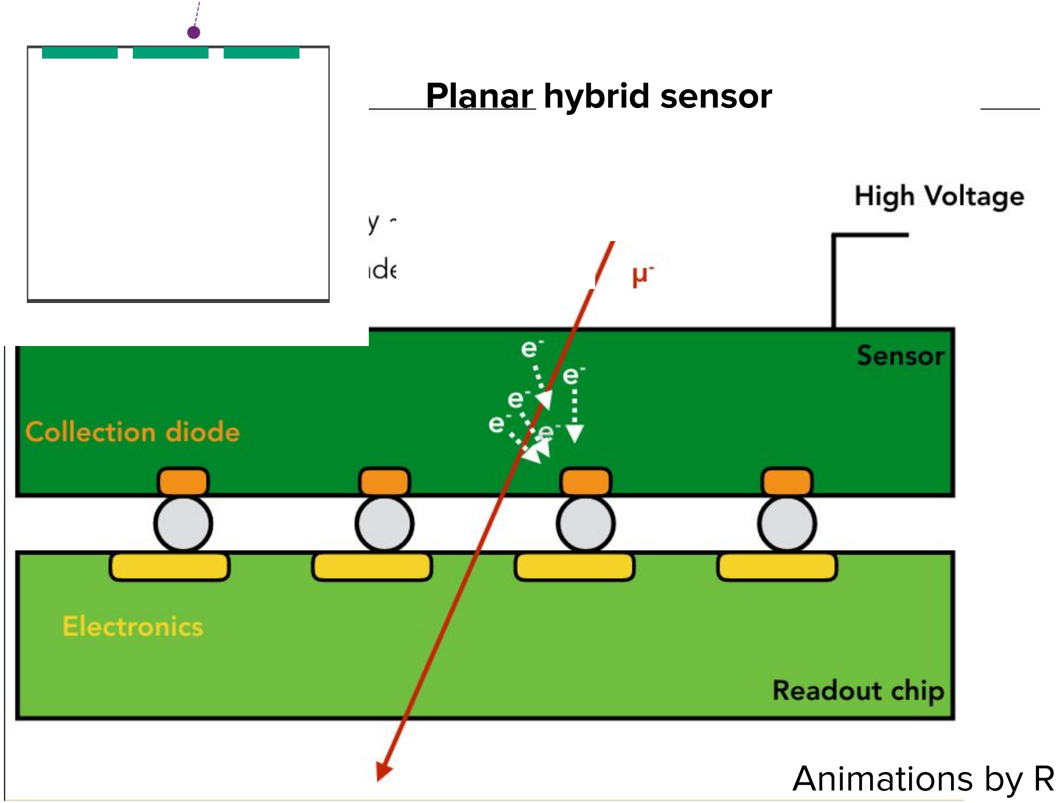
diffusion?

How did signal travel in gas detectors?

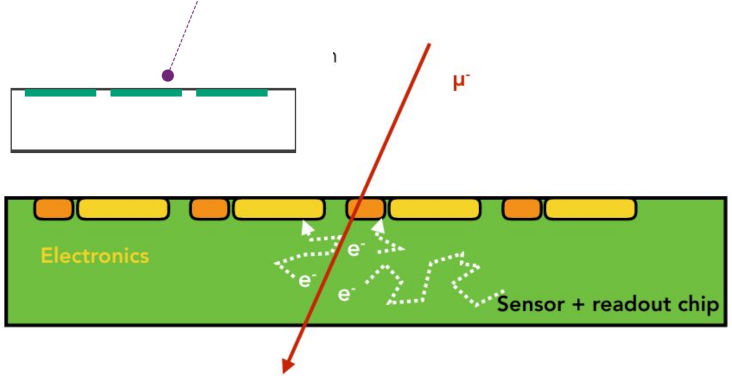
Figures from Daniel Hynds

Drift vs diffusion

Planar hybrid sensor



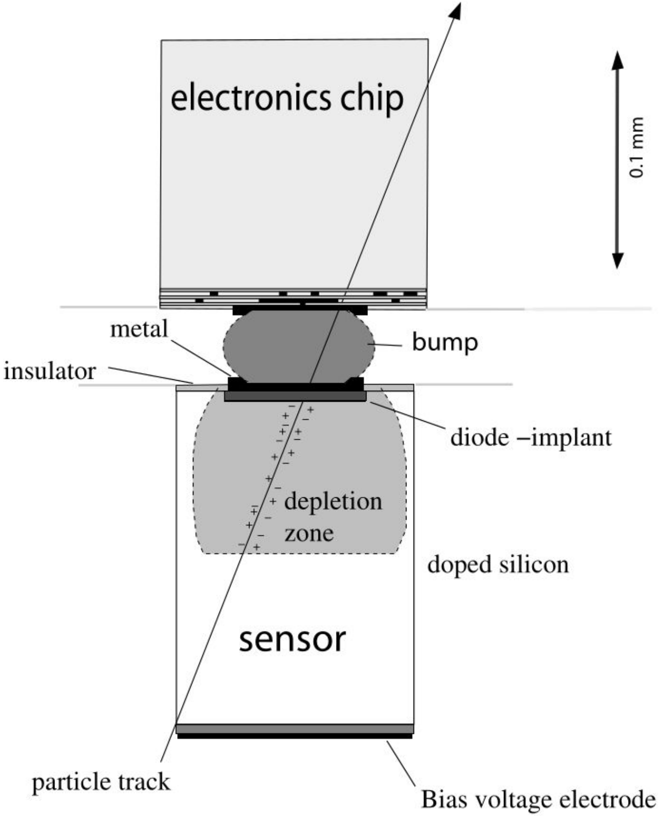
Monolithic sensor

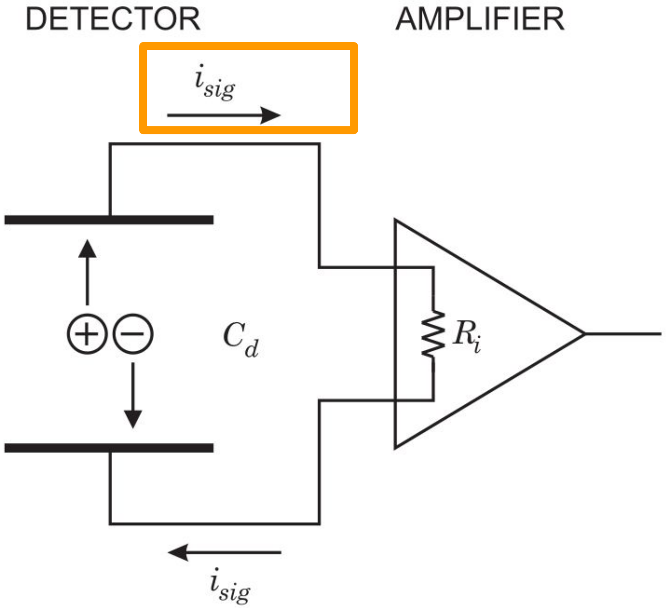


Animations by Robbert Geertsema

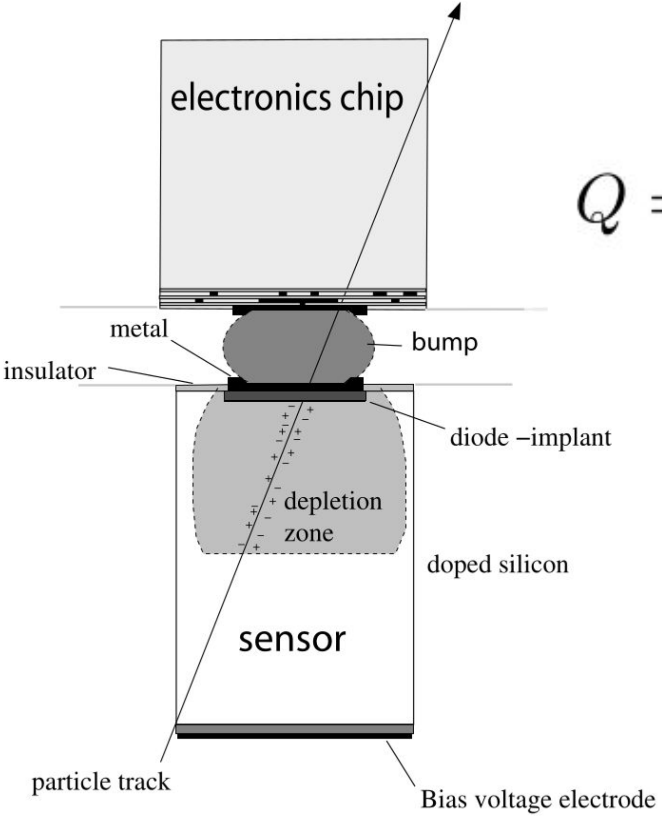
Charge “collection”

Charge is **induced** in the electrodes





Charge is **induced** in the electrodes



$$i = e\boldsymbol{E}_{\mathrm{w}}\boldsymbol{v}$$

E_w weighting field ≠ electric field

$$Q = \int_{t_1}^{t_2} i(t)\,\mathrm{d}t = e\left[\phi_{\mathrm{w}}(\boldsymbol{x}_1) - \phi_{\mathrm{w}}(\boldsymbol{x}_2)\right]$$

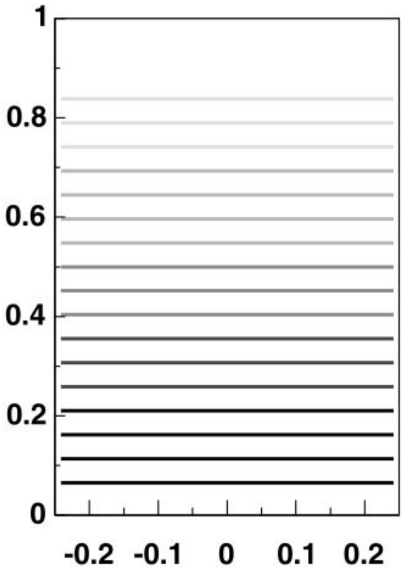
Weighting potential φ_w: set one electrode to unit potential, all others zero ➔ solve Poisson

From Ramo and Shockley

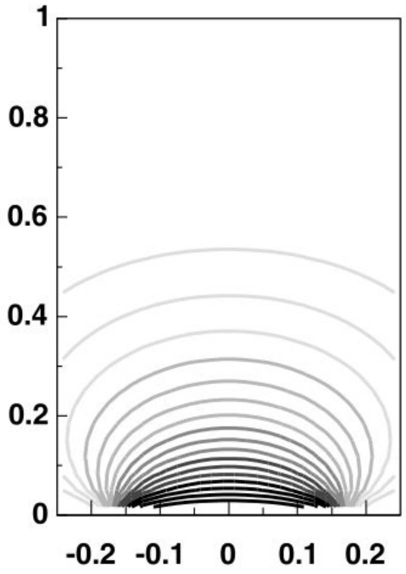
$$\frac{d^2V}{dx^2} = -\frac{\rho(x)}{\varepsilon}$$

Charge is **induced** in the electrodes

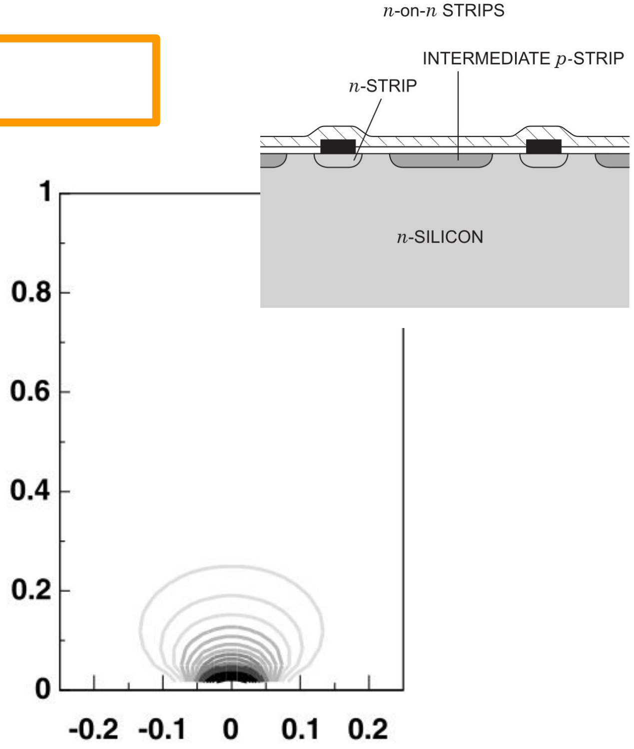
E_w is **not** the electric field! It is the **weighting potential**



Infinite parallel plate



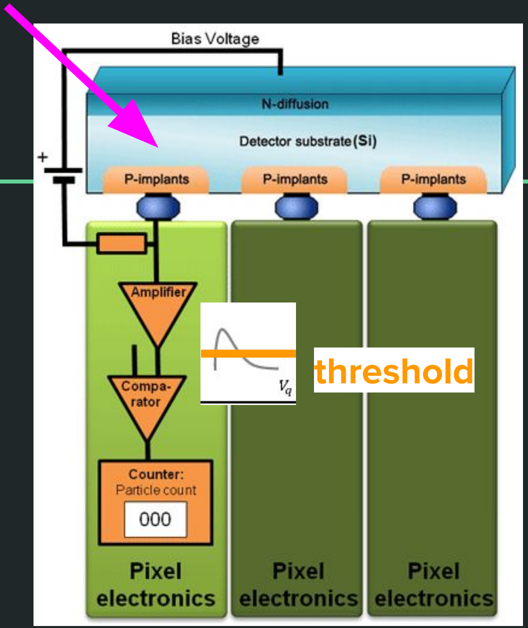
Collection electrode ⅓ wafer thickness



Collection electrode 1/10 wafer thickness

How do we detect particles with a semiconductor?

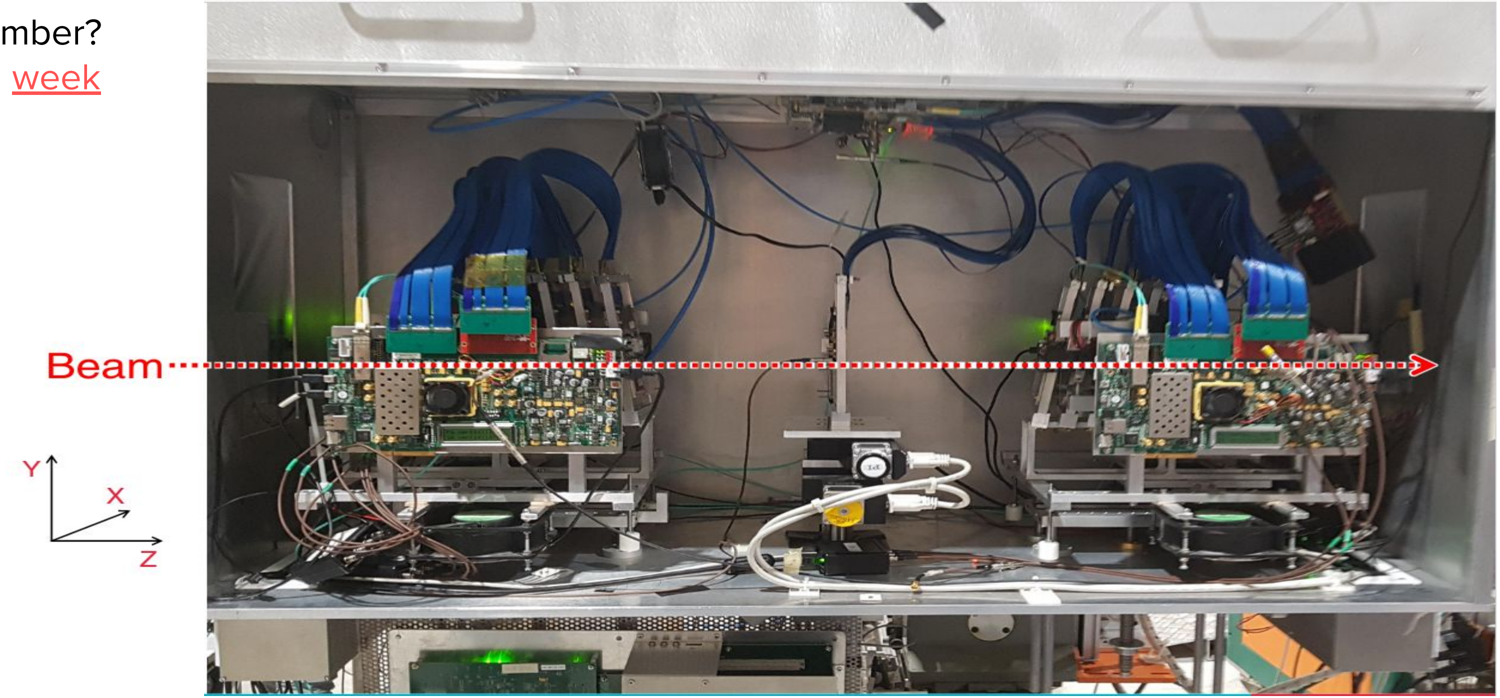
Ionizing radiation creates electron-hole pairs in a sensitive **depleted volume** of silicon. A current is **induced** in electrodes, amplified, and detected as a signal when over threshold.



How do you measure if a semiconductor is an excellent sensor?

Sensor characterization with Timepix telescope

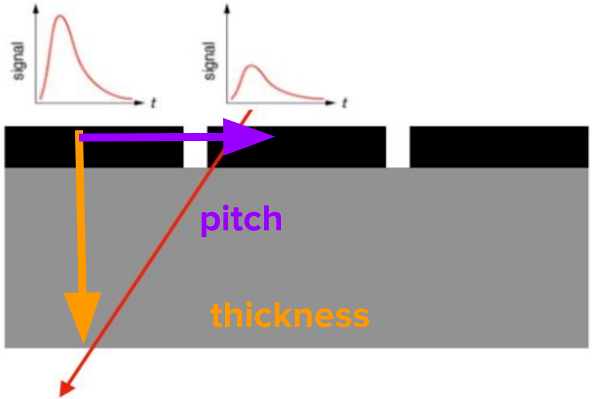
Do you remember?
Mentioned in week 1



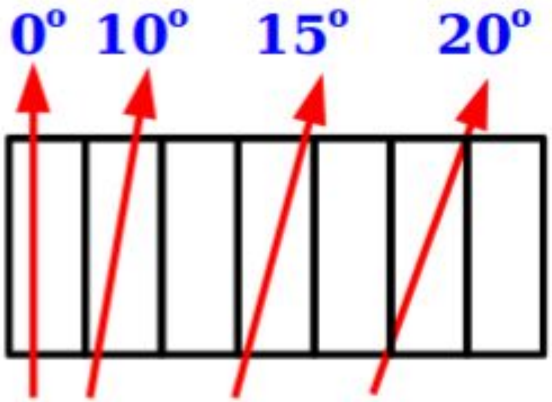
K. Akiba et al 2019 JINST 14 P05026
K. Heijhoff et al 2020 JINST 15 P09035

Pixel cell dimensions and spatial resolution

- Charge sharing depends on pixel **pitch**
- **Best resolution: cluster size of 2 . why?**



Position = weighted average
Resolution < pitch / √12

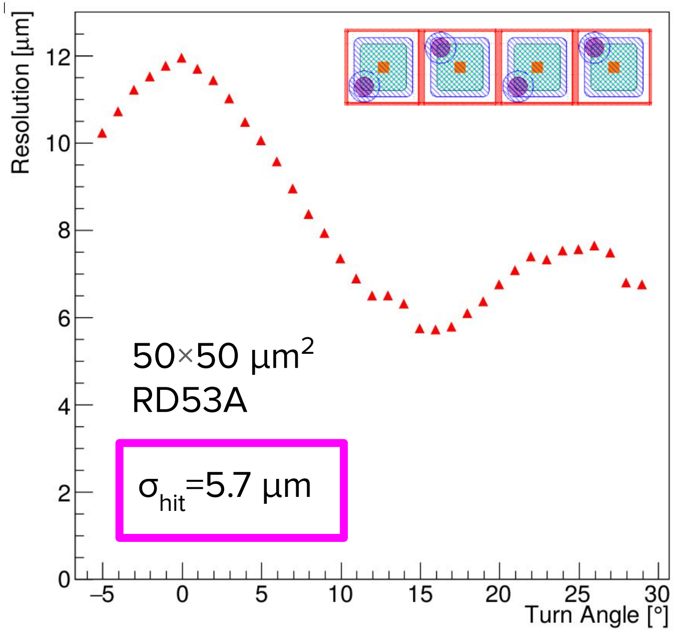


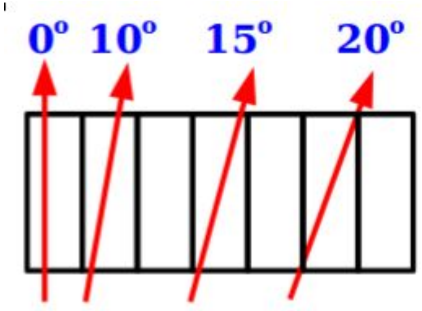
Optimal charge sharing at an angle atan(pitch/depth):
50×50 µm^2: atan(50/150) = 18.4°

What happens if too many pixels share the charge?

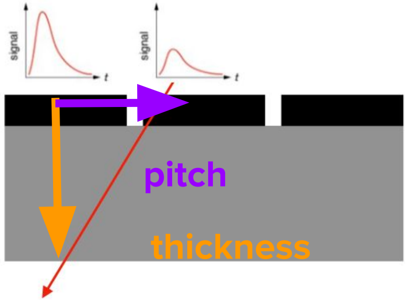
Pixel cell dimensions and spatial resolution

- Charge sharing depends on pixel **pitch**
- **Best resolution: cluster size of 2**





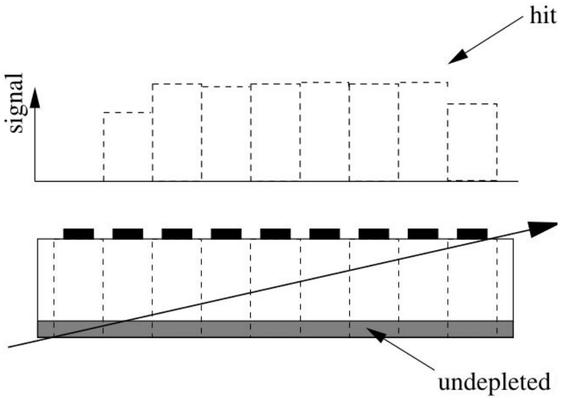
2 pixel charge sharing for 18°

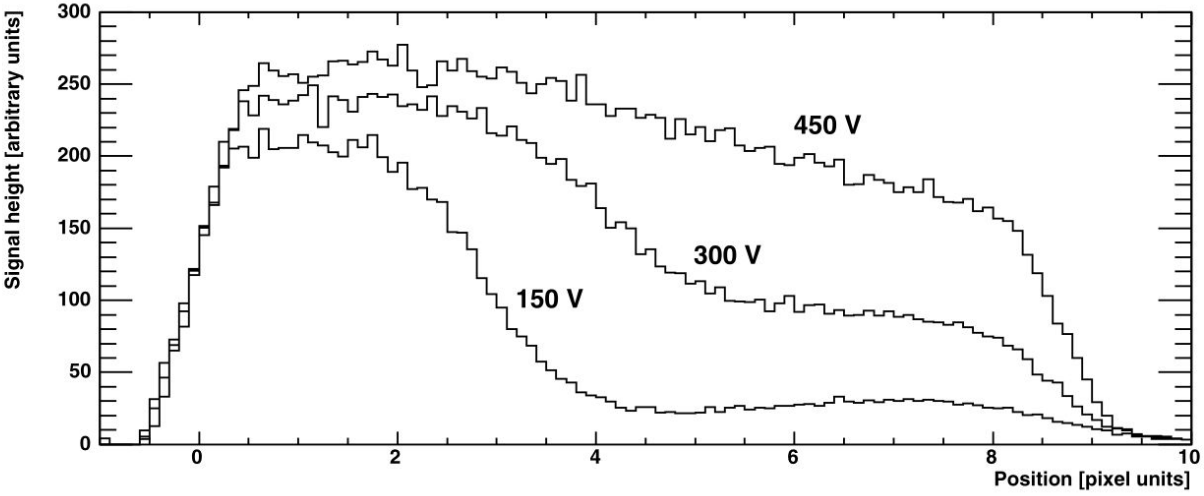


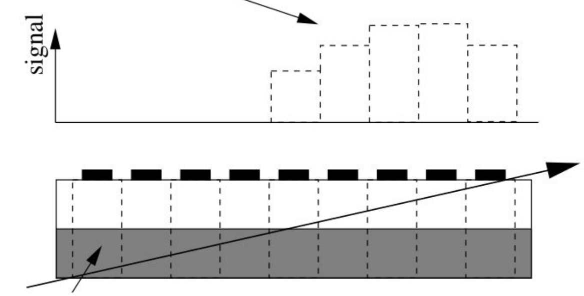
Position = weighted average
Resolution < pitch / √12

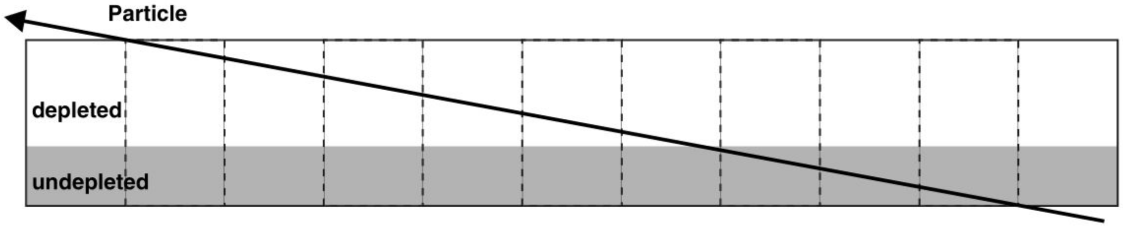
Optimal charge sharing at an angle atan(pitch/depth):
50×50 μm²: atan(50/150) = 18.4°

Measuring depletion depth





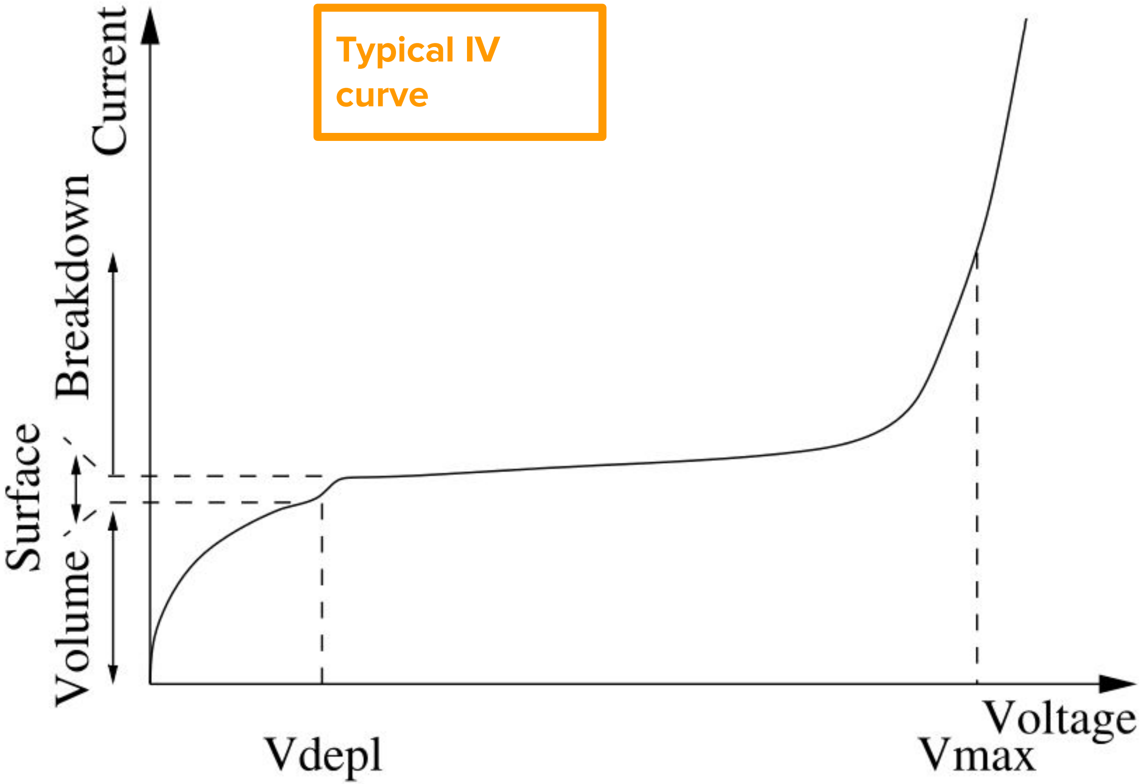




Undepleted volume

Grazing angle method

Measuring the depletion depth



Typical IV curve

How to detect particles with your phone?

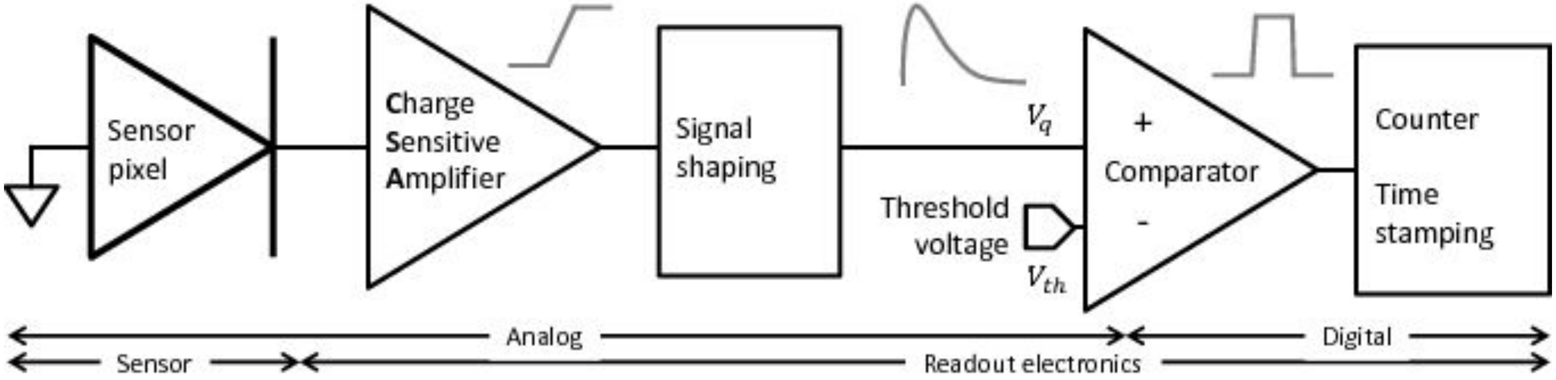
Are semiconductors easy to control?

Noise: capacitance

$$C = \varepsilon_0 \varepsilon_{\mathrm{Si}} \frac{A}{d}$$

For a 20, 000 µm^2 pixel cell on 300-µm-thick silicon this gives a contribution of about 7 fF

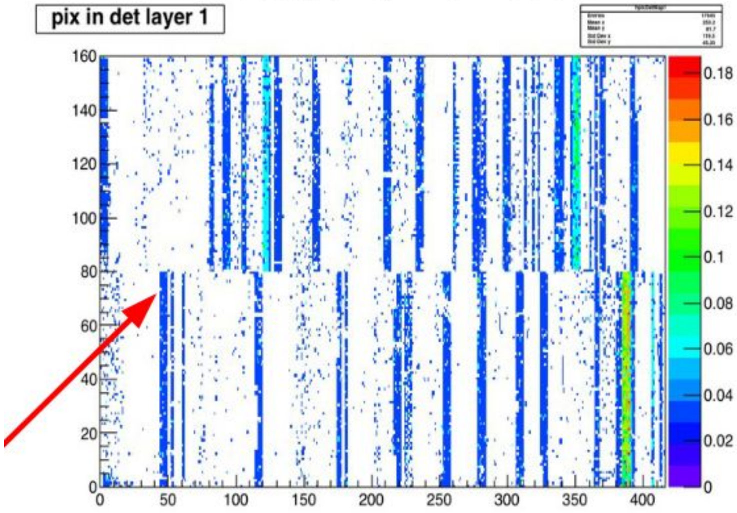
Total capacitance of each pixel to backside determines noise on preamplifier

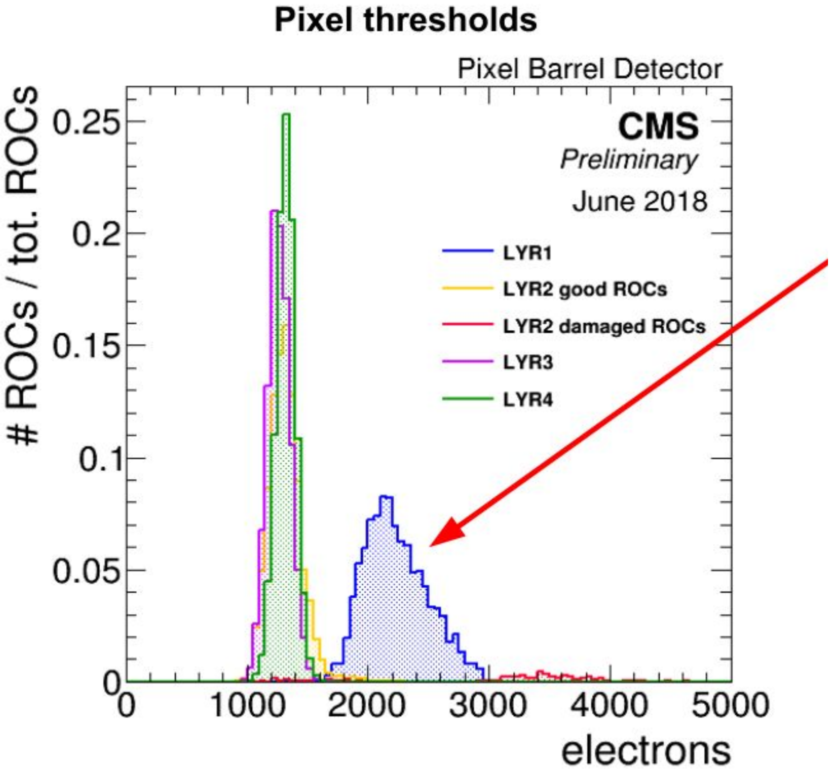


Week 2: brief introduction to electronics

Noise: cross talk

Cross-talk or interpixel capacitance between pixels -- hits where one does not expect hits -- here entire columns!





Thresholds are tuned to pick up signal and not too much noise. **Why are layer 1 thresholds higher?**

Noise: leakage current

Leakage current or dark current: thermal excitations **or** diffusion of free charge carriers from undepleted into depleted region

➡ generation of electron-hole pairs

This is highly temperature dependent:

$$J_{\mathrm{vol}} \propto T^2 \mathrm{e}^{-E_{\mathrm{g}}(T)/2kT} \; .$$

Roughly doubles every 8 K.

Semiconductor = silicon?

Actually, no!

Until 1959
Germanium most common
Silicon worse conductivity because of unstable states at surface

Other materials: diamond (C) 5.5 eV, Gallium arsenide (GaAs) 1.43 eV, Silicon dioxide SiO_2 9 eV … many more!

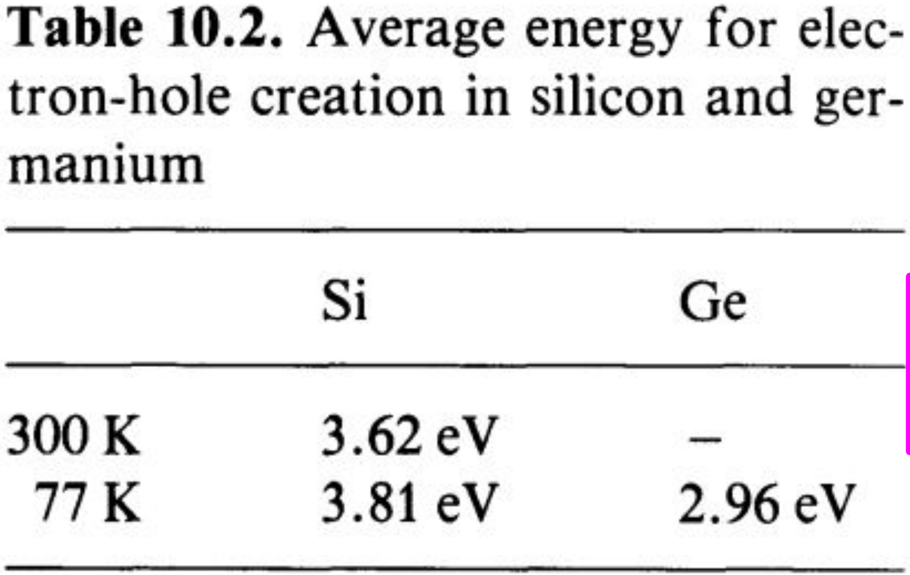


Table 10.2. Average energy for electron-hole creation in silicon and germanium

	Si	Ge
300 K	3.62 eV	–
77 K	3.81 eV	2.96 eV

Lower band gap : **What does that mean?**

Actually, no!

Other materials: diamond (C) 5.5 eV, Gallium arsenide (GaAs) 1.43 eV, Silicon dioxide SiO_2 9 eV … many more!

Until 1959
Germanium most common
Silicon worse conductivity because of unstable states at surface

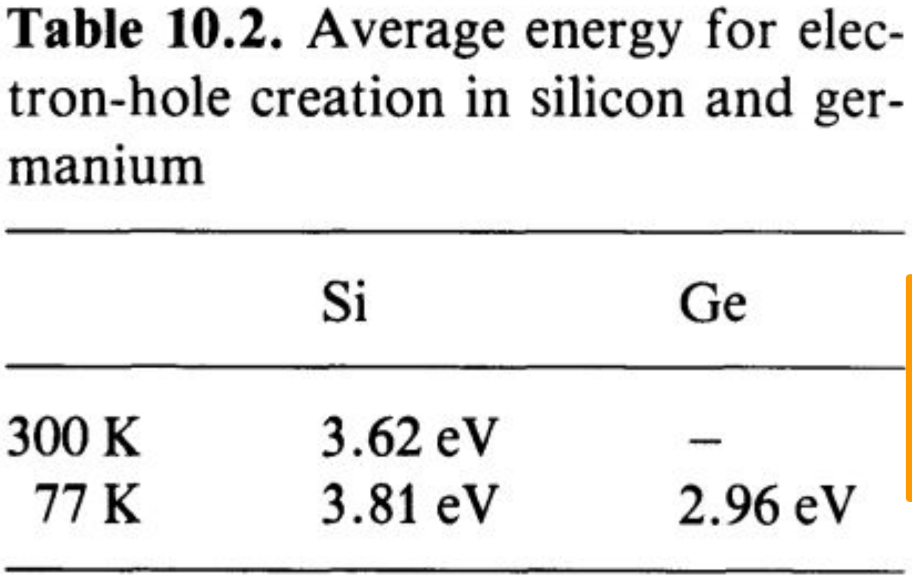


Table 10.2. Average energy for electron-hole creation in silicon and germanium

	Si	Ge
300 K	3.62 eV	–
77 K	3.81 eV	2.96 eV

Lower band gap :
→ larger signal
→ larger leakage current

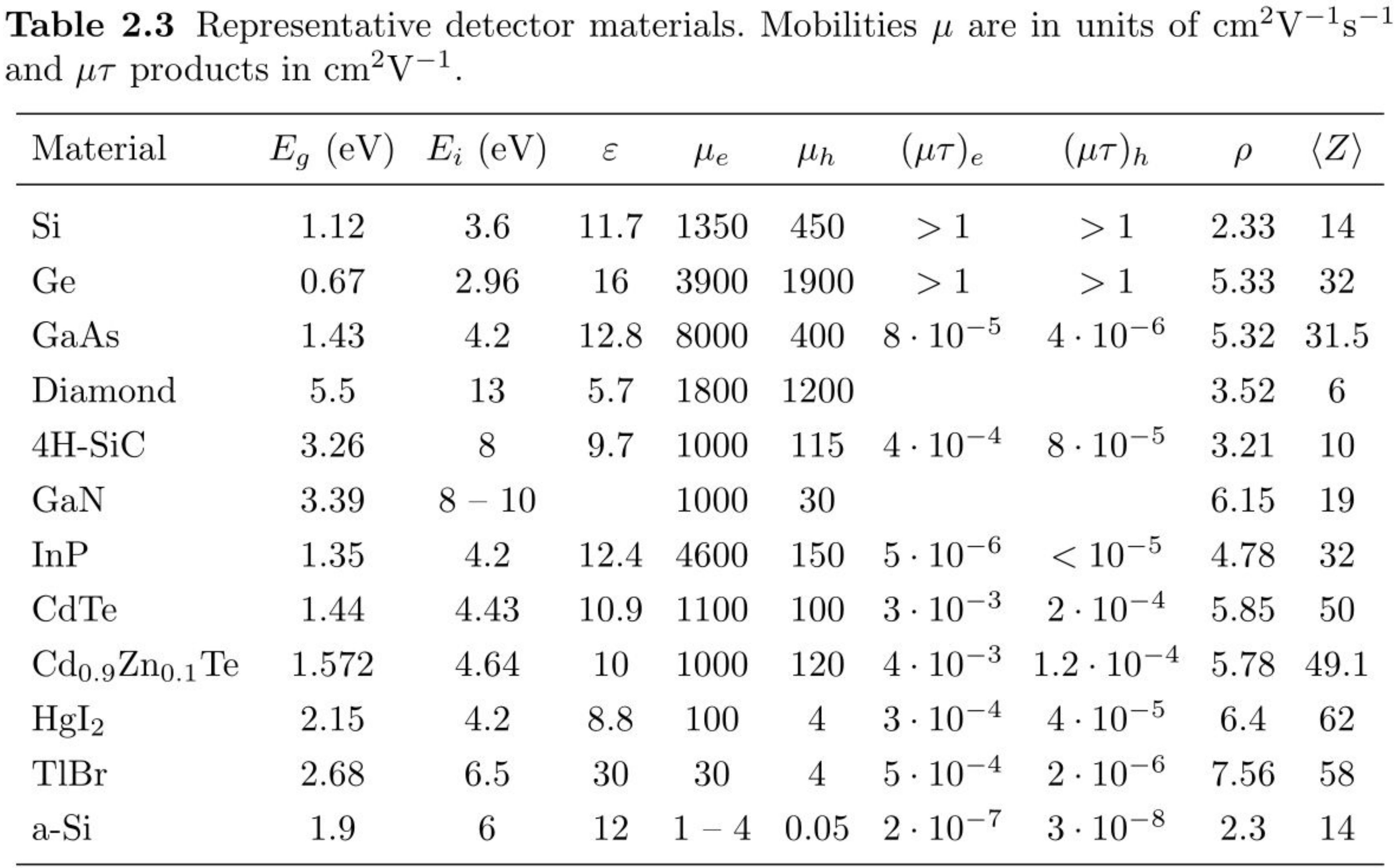


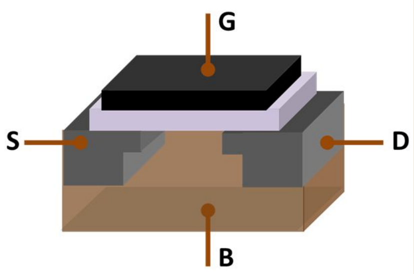
Table 2.3 Representative detector materials. Mobilities μ are in units of $\mathrm{cm^2V^{-1}s^{-1}}$ and $\mu\tau$ products in $\mathrm{cm^2V^{-1}}$.

Material	E_g (eV)	E_i (eV)	ε	μ_e	μ_h	$(\mu\tau)_e$	$(\mu\tau)_h$	ρ	$\langle Z\rangle$
Si	1.12	3.6	11.7	1350	450	>1	>1	2.33	14
Ge	0.67	2.96	16	3900	1900	>1	>1	5.33	32
GaAs	1.43	4.2	12.8	8000	400	$8\cdot10^{-5}$	$4\cdot10^{-6}$	5.32	31.5
Diamond	5.5	13	5.7	1800	1200			3.52	6
4H-SiC	3.26	8	9.7	1000	115	$4\cdot10^{-4}$	$8\cdot10^{-5}$	3.21	10
GaN	3.39	8 – 10		1000	30			6.15	19
InP	1.35	4.2	12.4	4600	150	$5\cdot10^{-6}$	$<10^{-5}$	4.78	32
CdTe	1.44	4.43	10.9	1100	100	$3\cdot10^{-3}$	$2\cdot10^{-4}$	5.85	50
$Cd_{0.9}Zn_{0.1}Te$	1.572	4.64	10	1000	120	$4\cdot10^{-3}$	$1.2\cdot10^{-4}$	5.78	49.1
HgI_2	2.15	4.2	8.8	100	4	$3\cdot10^{-4}$	$4\cdot10^{-5}$	6.4	62
TlBr	2.68	6.5	30	30	4	$5\cdot10^{-4}$	$2\cdot10^{-6}$	7.56	58
a-Si	1.9	6	12	1 – 4	0.05	$2\cdot10^{-7}$	$3\cdot10^{-8}$	2.3	14

Actually, no!

Until 1959
Germanium most common
Silicon worse conductivity because of unstable states at surface

1959 Mohamed Atalla and Dawon Kahng
develop surface passivation: coat silicon surface with SO_2:



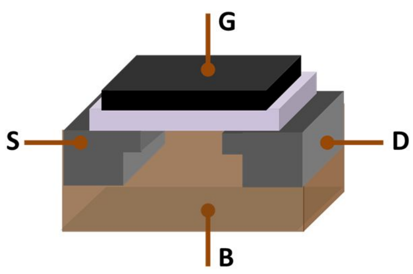
Metal-oxide-semiconductor field-effect transistor

Silicon has a high quality, robust native oxide. This property is unique among semiconductors.

Actually, no!

Until 1959
Germanium most common
Electric signal could not reach electrode in silicon: worse conductivity because of unstable surface states

1959 Mohamed Atalla and Dawon Kahng
develop surface passivation: coat silicon surface with SO_2:



Metal-oxide-semiconductor field-effect transistor

1960-2018 13e22 MOSFETs produced: most frequently manufactured device in history!

Op voorraad - levertijd 3 à 5 we

Prijs Each (In a Pack of 5)

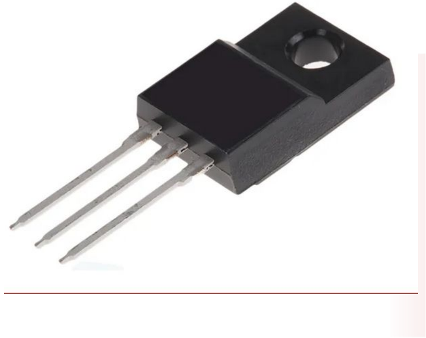
€ 0,78
(excl. BTW)

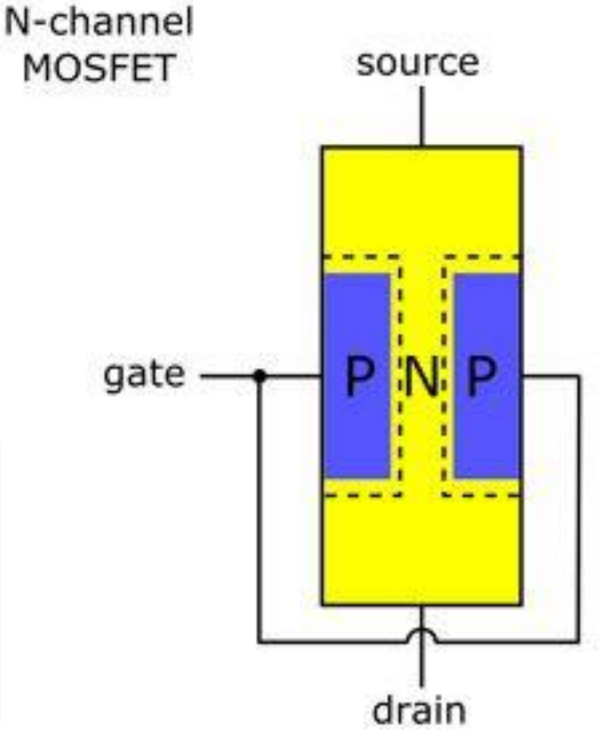
Aantal stuks	Per stuk
5 - 20	€ 0,78
25 - 95	€ 0,686
100 - 245	€ 0,60
250 - 495	€ 0,57
500 +	€ 0,556

*prijsindicatie

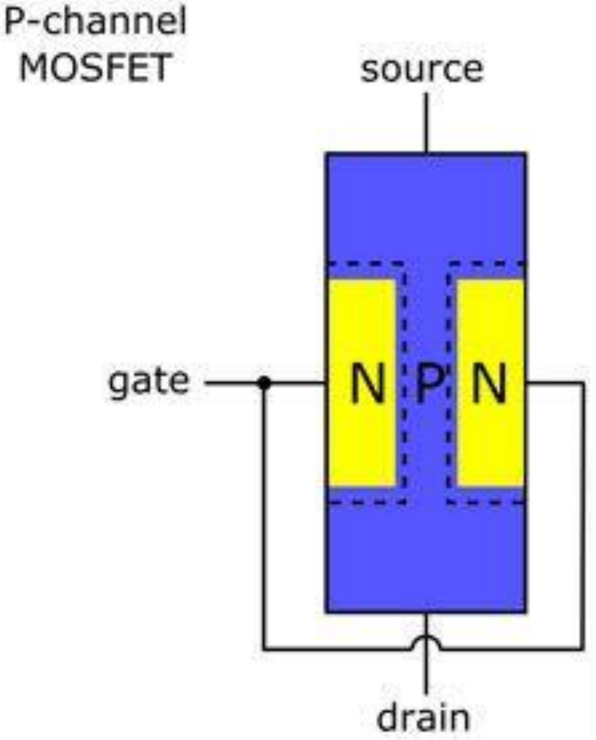
What are the three pins?

MOSFET

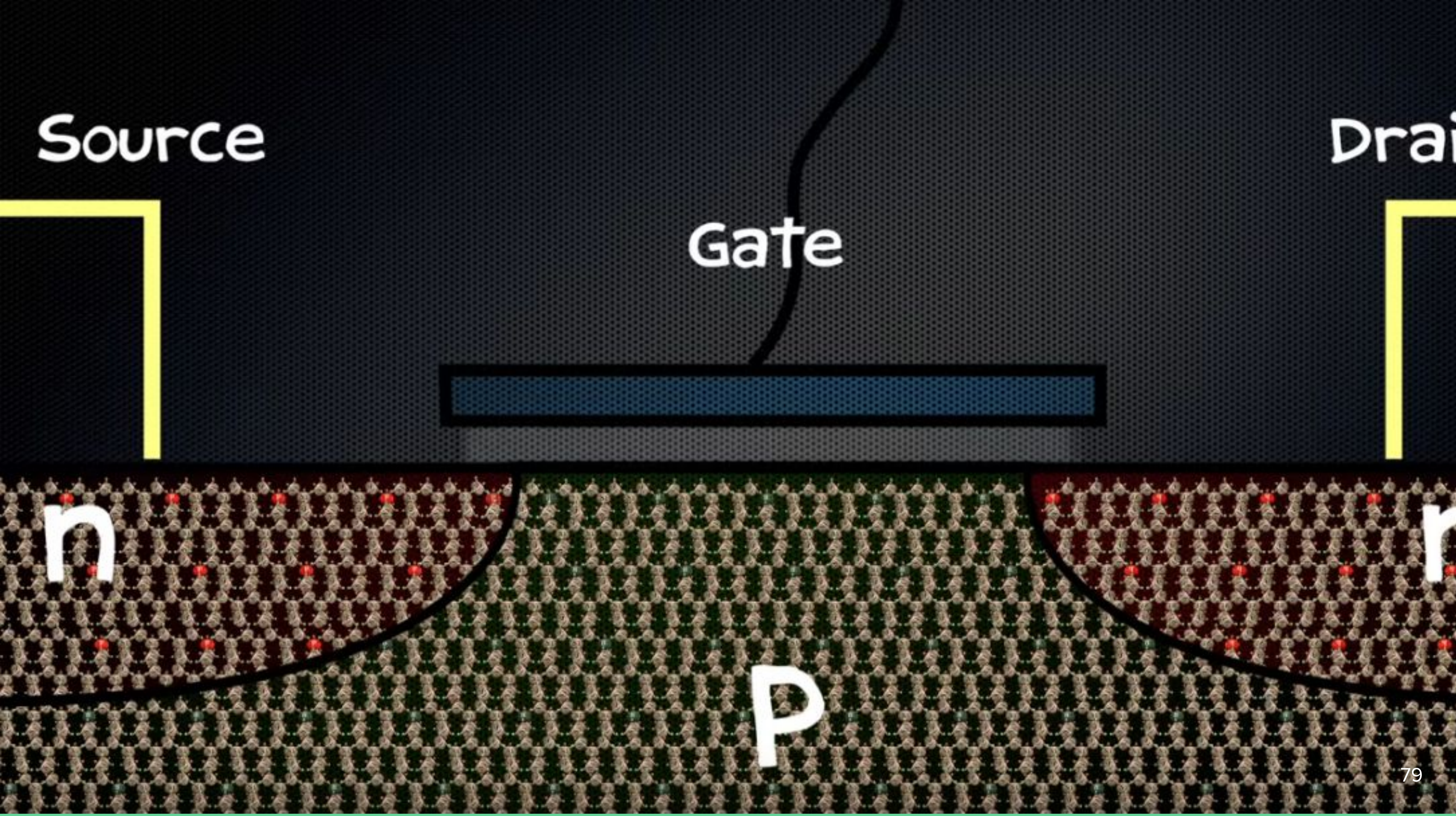




N-channel MOSFET



P-channel MOSFET

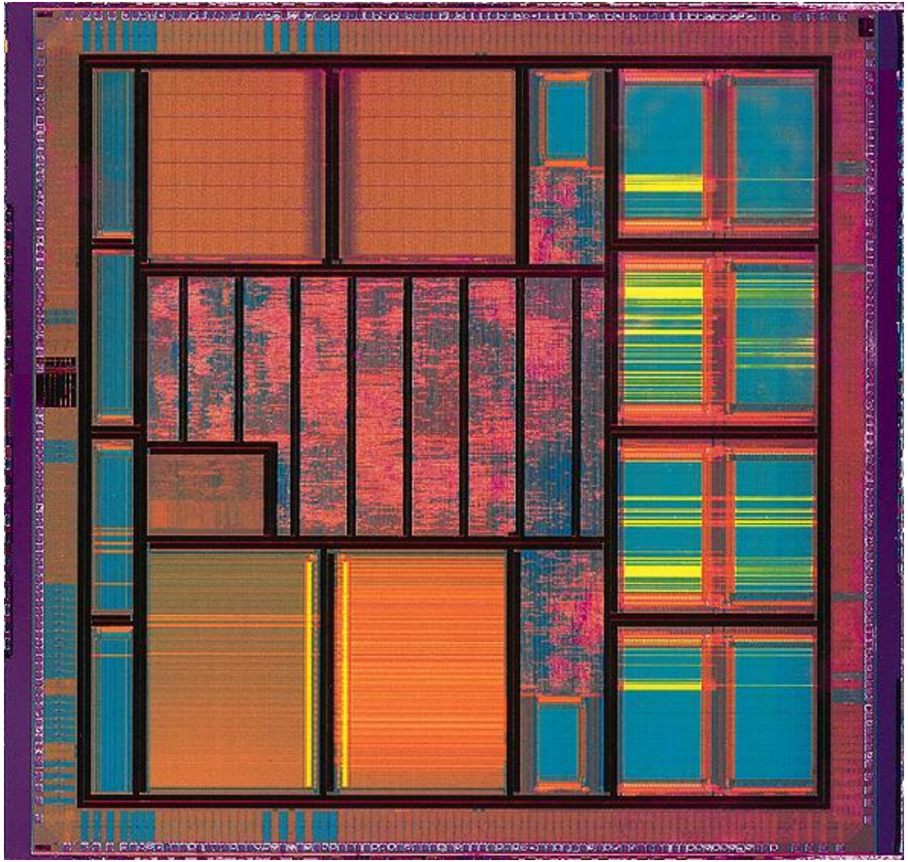

Source
Drai
Gate
n
n
P

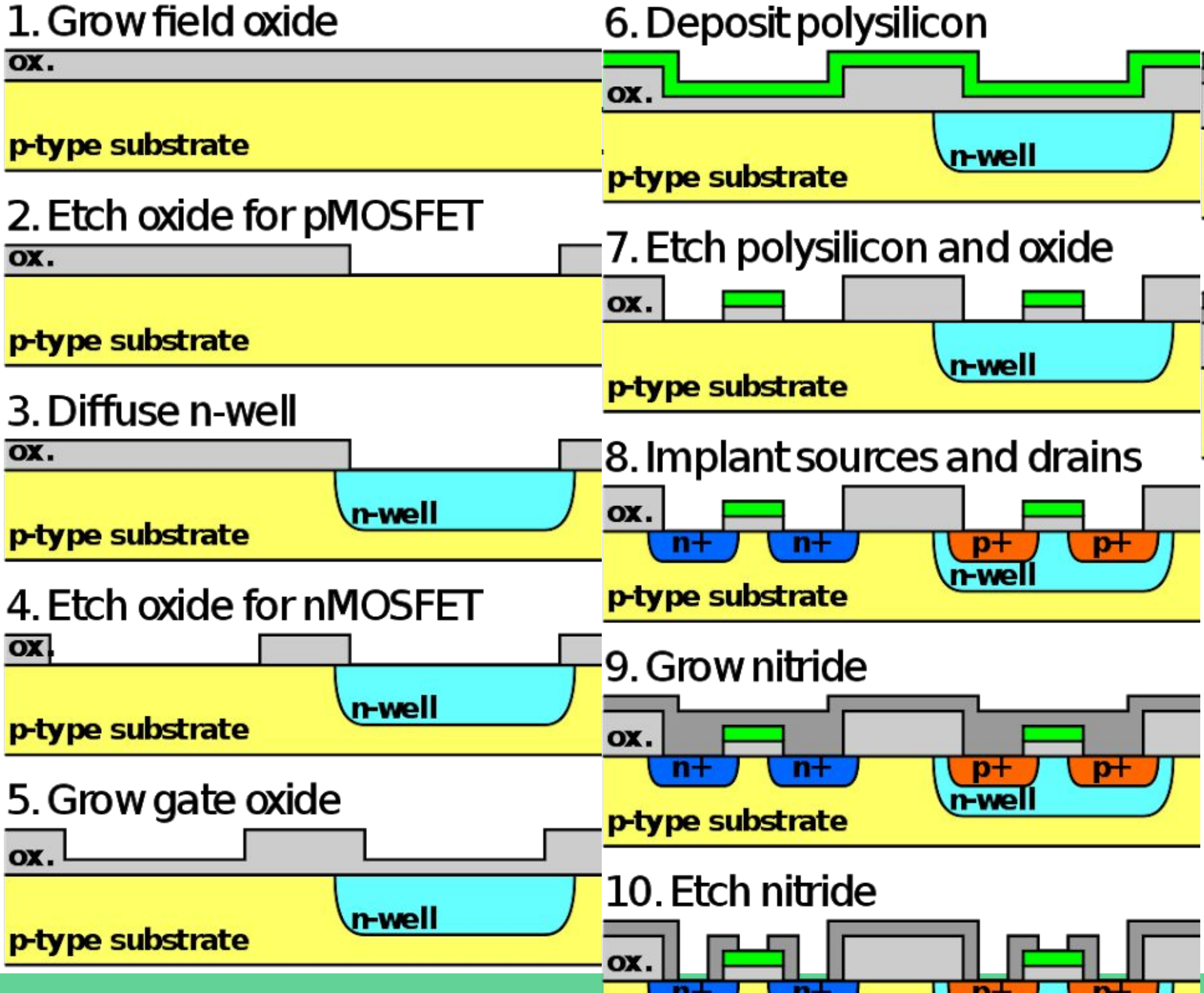
Those tiny things

Very large scale integration: VLSI

Combines many transistors on a single chip to create an integrated circuit

Feature size: 22 nm in the movie. We are only at 180 nm today (CMS pixel still has 250 nm!)




1. Grow field oxide

2. Etch oxide for pMOSFET

3. Diffuse n-well

4. Etch oxide for nMOSFET

5. Grow gate oxide

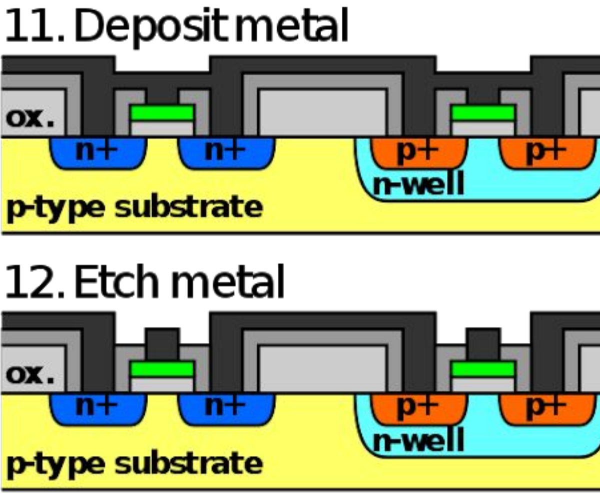
6. Deposit polysilicon

7. Etch polysilicon and oxide

8. Implant sources and drains

9. Grow nitride

10. Etch nitride

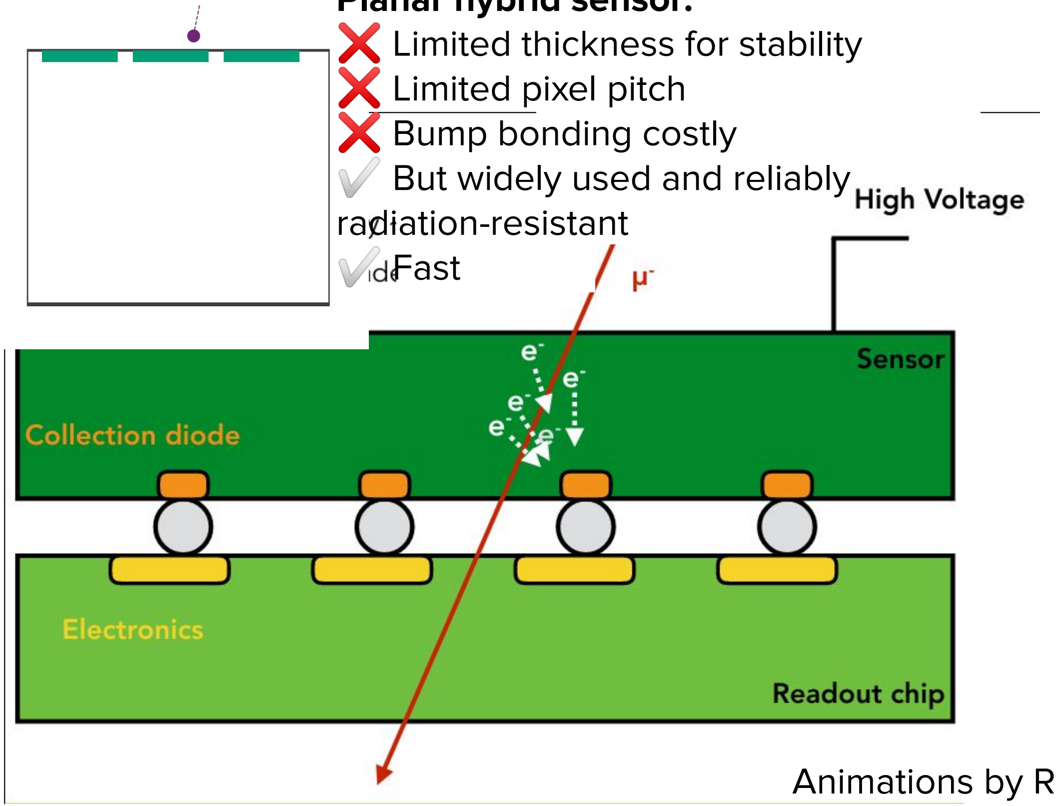

11. Deposit metal

12. Etch metal

A long process to create a CMOS sensor!

A semiconductor device is easy to manipulate, easily controlled, and makes an excellent sensor

Two types of silicon sensors: hybrid vs monolithic

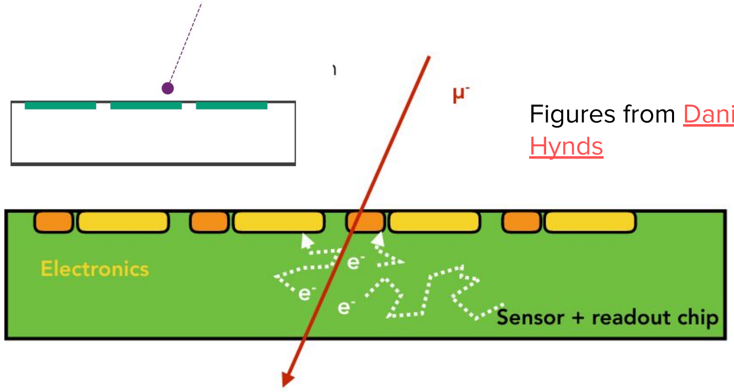


Planar hybrid sensor:

❌ Limited thickness for stability
❌ Limited pixel pitch
❌ Bump bonding costly
✓ But widely used and reliably radiation-resistant
✓ Fast

Monolithic sensor:

✓ Very little material
✓ Low noise
❌ Limited depletion region: slow charge collection by diffusion **but this is improving**
❌ Not very radiation-hard **but this is improving**

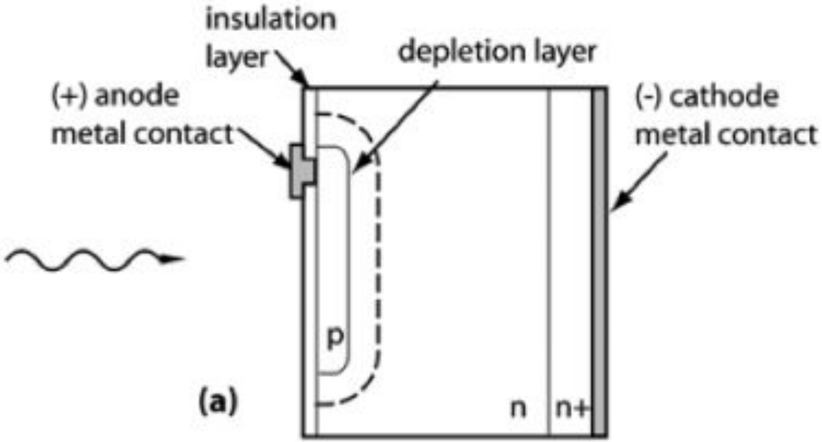


Figures from Daniel Hynds

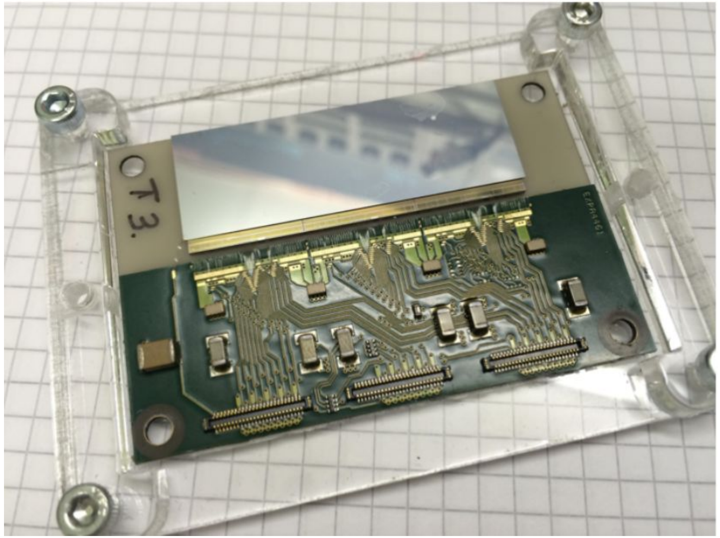
Animations by Robbert Geertsema

Other semiconductor detectors

Timepix -- and Medipix -- were developed at Nikhef



Silicon photomultiplier -- from week 2



An LHCb sensor on Timepix3
Application **S**pecific **I**ntegrated **C**ircuit (ASIC)

Why silicon not gas?

Next generation silicon detectors

Voorjaar
2019

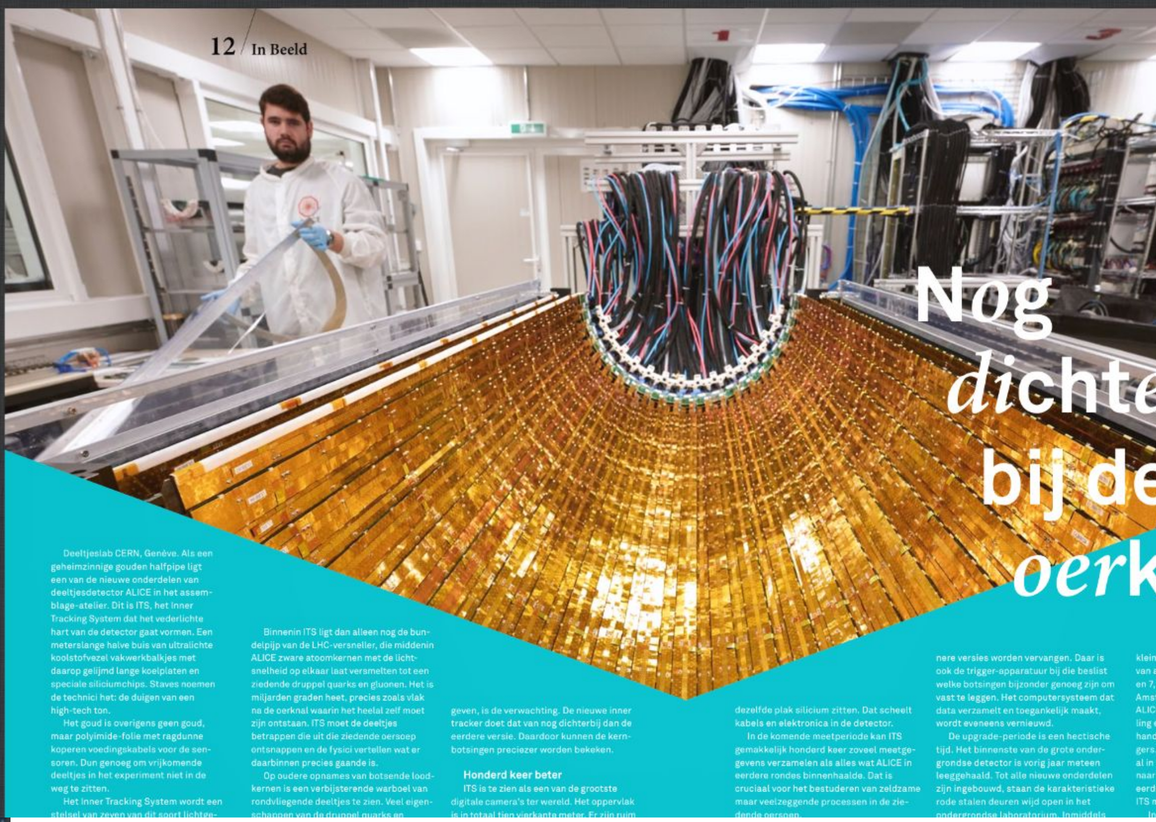
DIMENSIES

Nikhef

Nationaal
instituut voor
subatomaire fysica

UPGRADES
Van CERN tot Gran Sasso:
overal wordt nu gesleuteld
aan de experimenten

ASTRODEELTJES
Vele vensters
op het universum



12 / In Beeld

Nog
dichte
bij de
oerk

Deeltjeslab CERN, Genève. Als een geheimzinnige gouden halfpipe ligt een van de nieuwe onderdelen van deeltjesdetector ALICE in het assemblage-atelier. Dit is ITS, het Inner Tracking System dat het vederlichte hart van de detector gaat vormen. Een meterslange halve buis van ultralichte koolstofvezel vakwerkbalkjes met daarop gelijmd lange koelplaten en speciale siliciumchips. Staves noemen de technici het: de duigen van een high-tech ton.

Het goud is overigens geen goud, maar polyimide-folie met ragdunne koperen voedingskabels voor de sensoren. Dun genoeg om vrijkomende deeltjes in het experiment niet in de weg te zitten.

Het Inner Tracking System wordt een stelsel van zeven van dit soort lichtge-

Binnenin ITS ligt dan alleen nog de bundelpijp van de LHC-versneller, die middenin ALICE zware atoomkernen met de lichtsnelheid op elkaar laat versmelten tot een ziedende druppel quarks en gluonen. Het is miljarden graden heet, precies zoals vlak na de oerknal waarin het heelal zelf moet zijn ontstaan. ITS moet de deeltjes betrappen die uit die ziedende oersoep ontsnappen en de fysici vertellen wat er daarbinnen precies gaande is.

Op oudere opnames van botsende loodkernen is een verbijsterende warboel van rondvliegende deeltjes te zien. Veel eigenschappen van de druppel quarks en

geven, is de verwachting. De nieuwe inner tracker doet dat van nog dichterbij dan de eerdere versie. Daardoor kunnen de kernbotsingen preciezer worden bekeken.

Honderd keer beter

ITS is te zien als een van de grootste digitale camera's ter wereld. Het oppervlak is in totaal tien vierkante meter. Er zijn ruim

dezelfde plak silicium zitten. Dat scheelt kabels en elektronica in de detector.

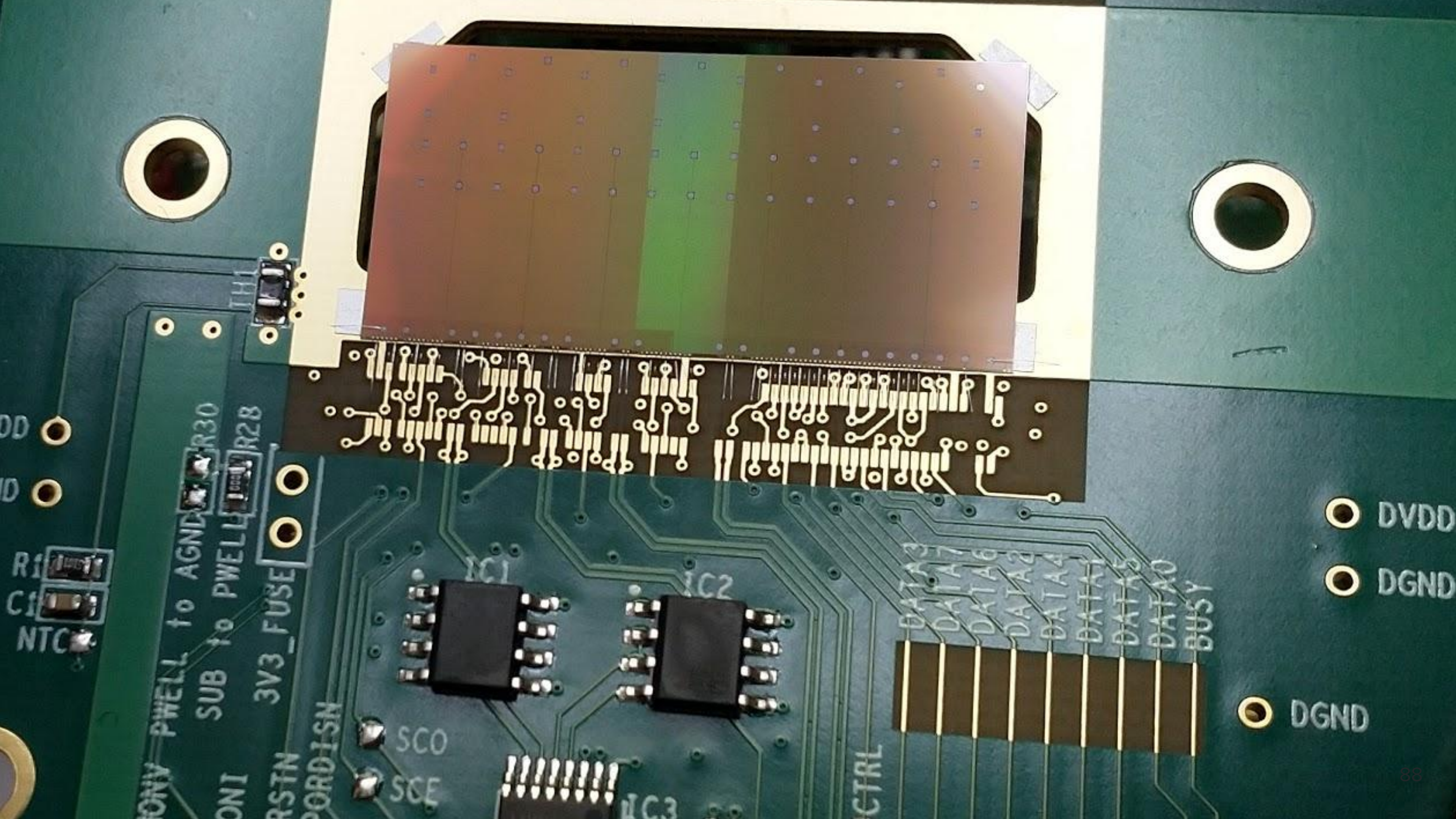
In de komende meetperiode kan ITS gemakkelijk honderd keer zoveel meetgegevens verzamelen als alles wat ALICE in eerdere rondes binnenhaalde. Dat is cruciaal voor het bestuderen van zeldzame maar veelzeggende processen in de ziedende oersoep.

nere versies worden vervangen. Daar is ook de trigger-apparatuur bij die beslist welke botsingen bijzonder genoeg zijn om vast te leggen. Het computersysteem dat data verzamelt en toegankelijk maakt, wordt eveneens vernieuwd.

De upgrade-periode is een hectische tijd. Het binnenste van de grote ondergrondse detector is vorig jaar meteen leeggehaald. Tot alle nieuwe onderdelen zijn ingebouwd, staan de karakteristieke rode stalen deuren wijd open in het ondergrondse laboratorium. Inmiddels

Nikhef R&D group works with LHC experiments and Nikhef electronics group on pixel detectors that are now being installed at the LHC!

Remember from week 1 the ALICE MAPS detector? 0.1% X_0!


DD
D
TH1
R30
R28
R1
C1
NTC
PWELL to AGND
SUB to PWELL
3V3_FUSE
IC1
IC2
IC3
SCO
SCE
RSTN
PORDISN
ONI
CTRL
DATA3
DATA7
DATA6
DATA2
DATA4
DATA1
DATA5
DATA0
BUSY
DVDD
DGND
DGND

Next: how to calibrate a detector?

Additional material

https://cds.cern.ch/record/2637873/files/CERN-THESIS-2018-153.pdf Linxing Meng

Literature

- Slides from Erik Butz (see also here), Simon Spannagel, Freya Blekman, Peter Schleper, Erika Garutti, Ingrid-Maria Gregor
- Book on Pixel detectors by Rossi, Fischer, Rohe, Wermes
- Book on Semiconductor Detector Systems by Helmuth Spieler, see also online notes
- Particle data group review: passage of radiation through matter
- Book on particle radiation by Konrad Kleinknecht
- Book on Techniques in experimental particle physics by WR Leo
- Book on The art of electronics by Horowitz and Hill
- Book on Evolution of silicon sensor technology in particle physics by Frank Hartmann
- Book on Physics of Semiconductor devices by SM Sze and Kwok K Ng
- Book on Semiconductor radiation detectors by Gerhard Lutz

$$\bar{n}_i = \frac{1}{e^{(\varepsilon_i - \mu)/k_{\mathrm{B}}T} + 1}$$

Do you remember?

$$N(E) = \frac{V}{2\pi^2}\left(\frac{2m}{\hbar^2}\right)^{\frac{3}{2}} \sqrt{E - E_0}$$

$$\bar{n}_i = \frac{1}{e^{(\varepsilon_i - \mu)/k_\mathrm{B} T} + 1}$$

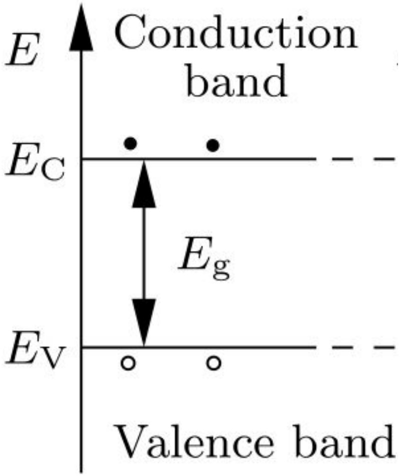
Fermi-Dirac

Do you remember?

Density of states

$$N(E) = \frac{V}{2\pi^2}\left(\frac{2m}{\hbar^2}\right)^{\frac{3}{2}} \sqrt{E - E_0}$$

Intrinsic semiconductor



Intrinsic semiconductor

Concentration of acceptor/donor impurities N_A/N_D << thermally generated eh pairs

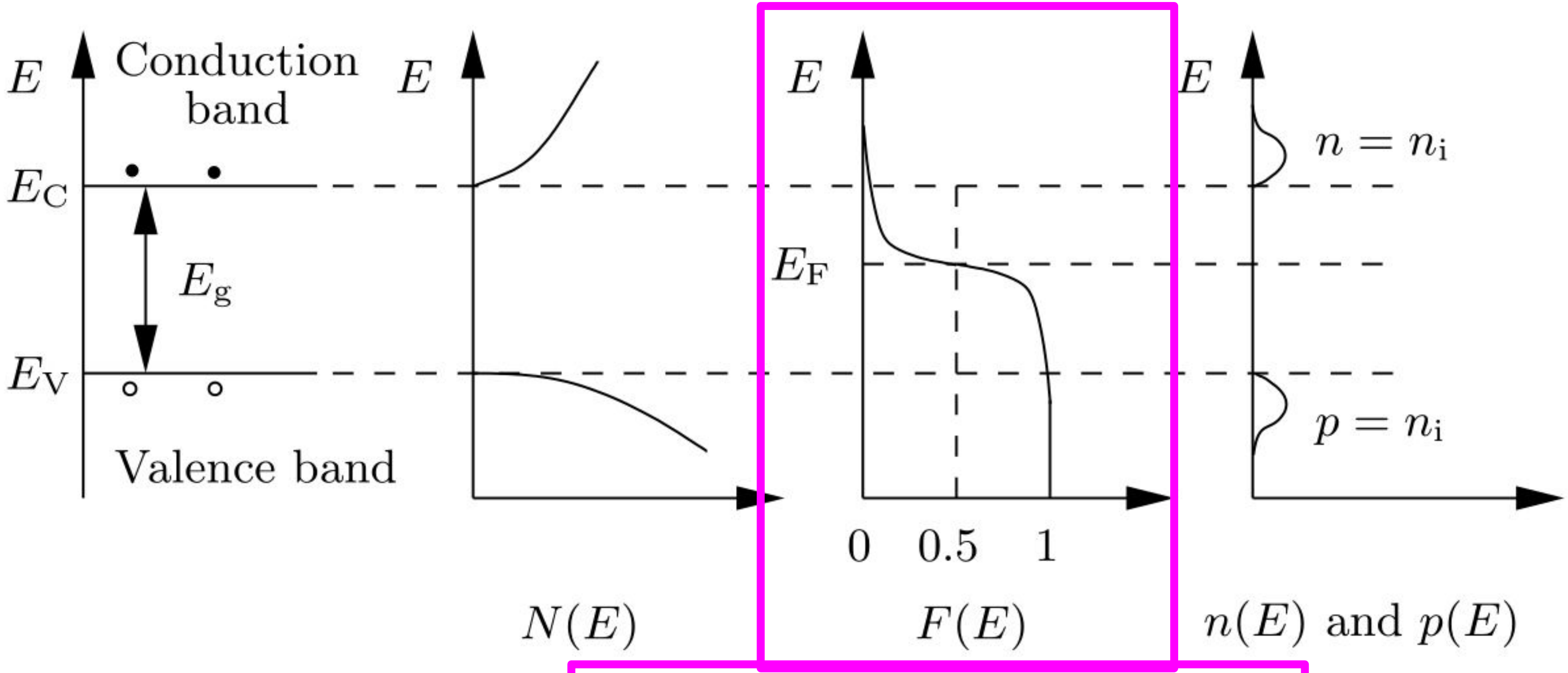
$$np = n_i^2$$

Excited electrons n

Number of holes p

No doping yet!

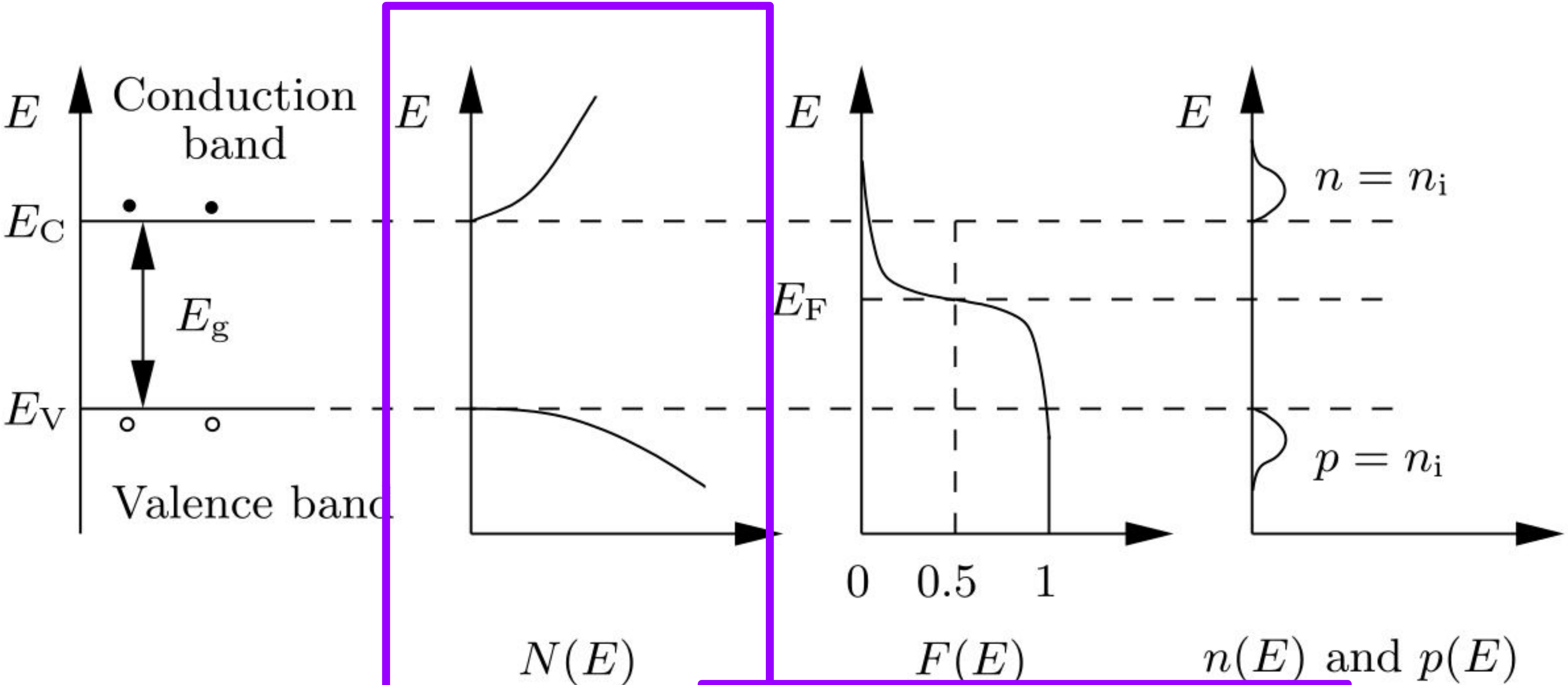
Fermi energy



Fermi function:

$$F(E) = \frac{1}{1 + \mathrm{e}^{(E - E_{\mathrm{F}})/kT}} \approx \mathrm{e}^{-(E - E_{\mathrm{F}})/kT}$$

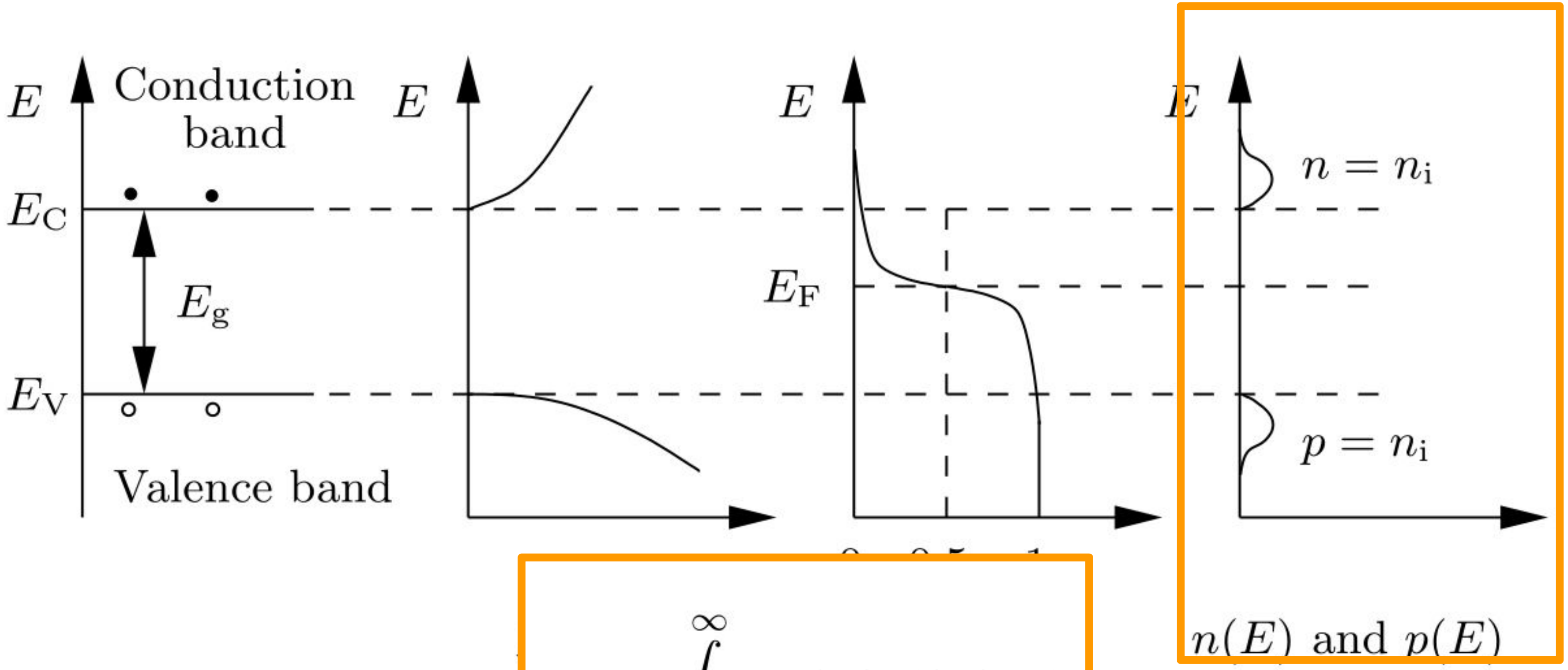
Fermi energy



Density of states

$$N(E)\,\mathrm{d}E = 4\pi\left(\frac{2m_\mathrm{n}}{h^2}\right)^{2/3} E^{1/2}\,\mathrm{d}E$$

Fermi energy

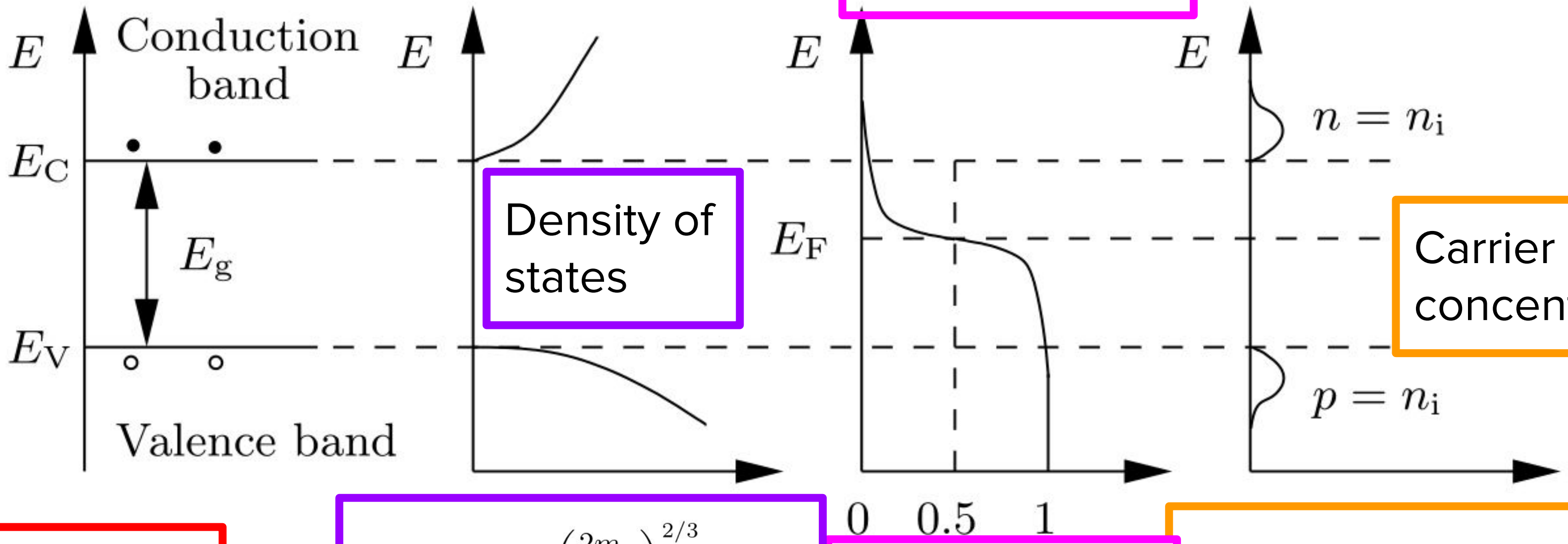


$$n = \int_{E_C \equiv 0}^{\infty} N(E)F(E)\,\mathrm{d}E$$

Carrier concentration

Fermi energy

Fermi function:



Density of states

Carrier concentration

Still no doping!

Band gap energy in silicon E_g = 1.12 eV

$$n_i = 1.45 \times 10^{10}\ \mathrm{cm}^{-3}$$

$$N(E)\,\mathrm{d}E = 4\pi \left(\frac{2m_n}{h^2}\right)^{2/3} E^{1/2}\,\mathrm{d}E$$

$$F(E) = \frac{1}{1 + \mathrm{e}^{(E-E_F)/kT}}$$

$$\approx \mathrm{e}^{-(E-E_F)/kT}$$

$$n = \int_{E_C \equiv 0}^{\infty} N(E)F(E)\,\mathrm{d}E$$

Carrier concentration

$$n_i = N_c e^{-(E_c - E_F)/kT} = N_v e^{-(E_F - E_v)/kT}$$

The product of electron and hole concentrations

depends only on the gap energy

$$\boxed{np = n_i^2} = N_c N_v e^{-(E_c - E_v)/kT} = N_c N_v e^{-E_g/kT}$$

The $np = n_i^2$ relationship is maintained: **law of mass action**

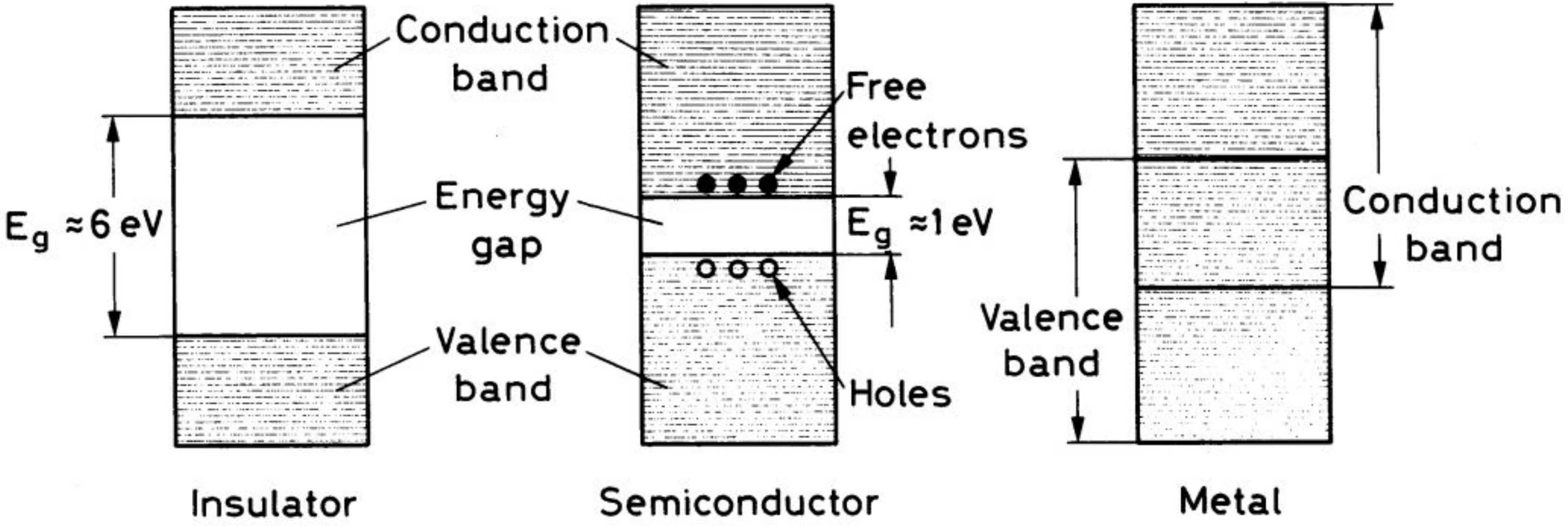
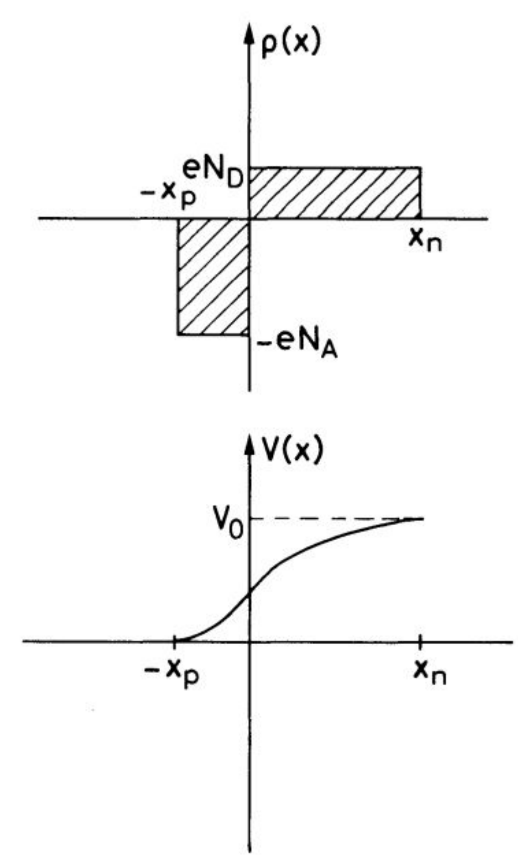


Fig. 10.1. Energy band structure of conductors, insulators and semiconductors

Electrostatics



Poisson

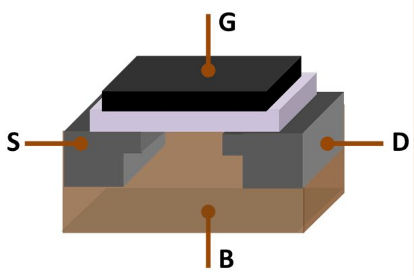
$$\frac{d^2 V}{dx^2} = -\frac{\rho(x)}{\varepsilon}$$

$$\frac{dV}{dx} = \begin{cases} -\dfrac{eN_\mathrm{D}}{\varepsilon}(x - x_\mathrm{n}) & 0 < x < x_\mathrm{n} \\ \dfrac{eN_\mathrm{A}}{\varepsilon}(x + x_\mathrm{p}) & -x_\mathrm{p} < x < 0 \end{cases}$$

Actually, no!

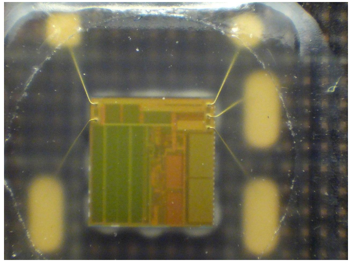
Until 1959
Germanium most common
Silicon worse conductivity because of unstable states at surface

1959 Mohamed Atalla and Dawon Kahng
develop surface passivation: coat silicon surface with SO_2:



Metal-oxide-semiconductor field-effect transistor

1959: first monolithic integrated circuit from silicon
1967: flash memory invented by Kahng and S. Sze → EEPROM



Inside a sim card

Silicon has a high quality, robust native oxide. This property is unique among semiconductors.