Fundamentals of HPGe detectors

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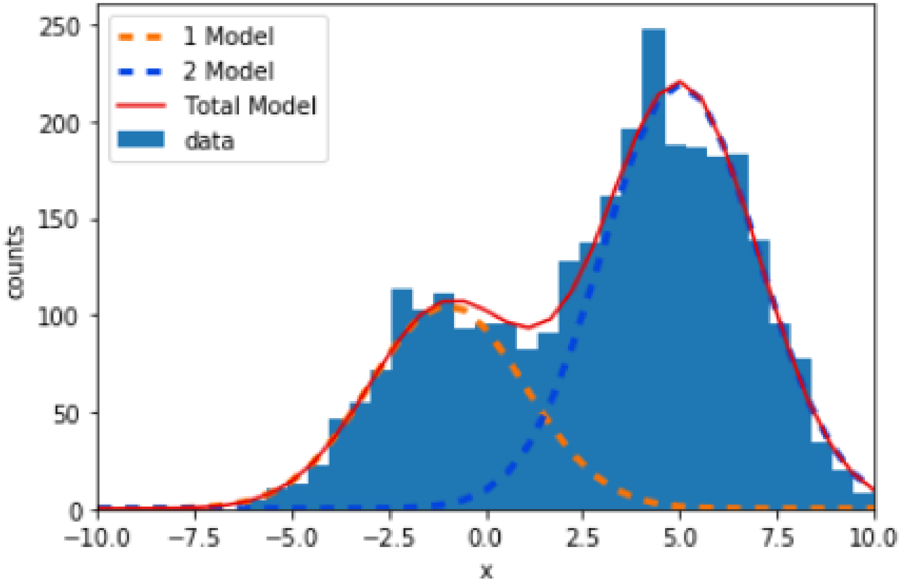
University of South Dakota

Day 1



Day 2

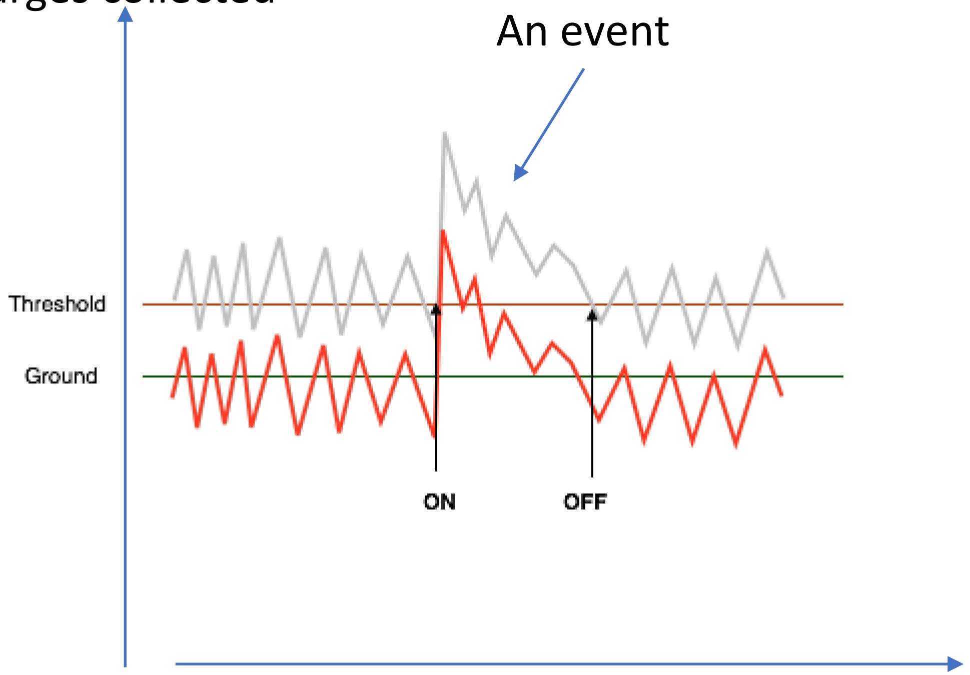
Value in y or the integral is added as an entry to a bin in x in the histogram

∝ Energy that can be collected in our detector

Number of charges collected

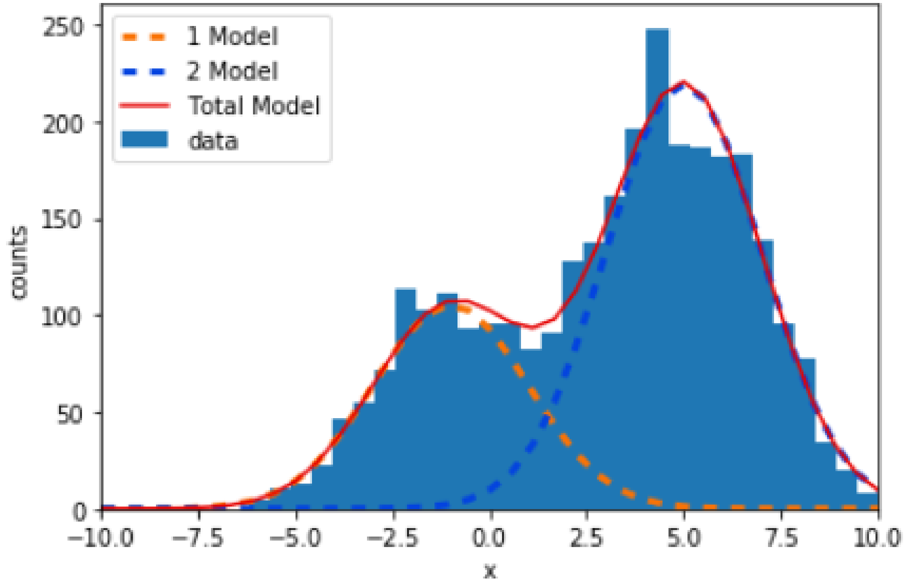
An event

pre-set requirement:



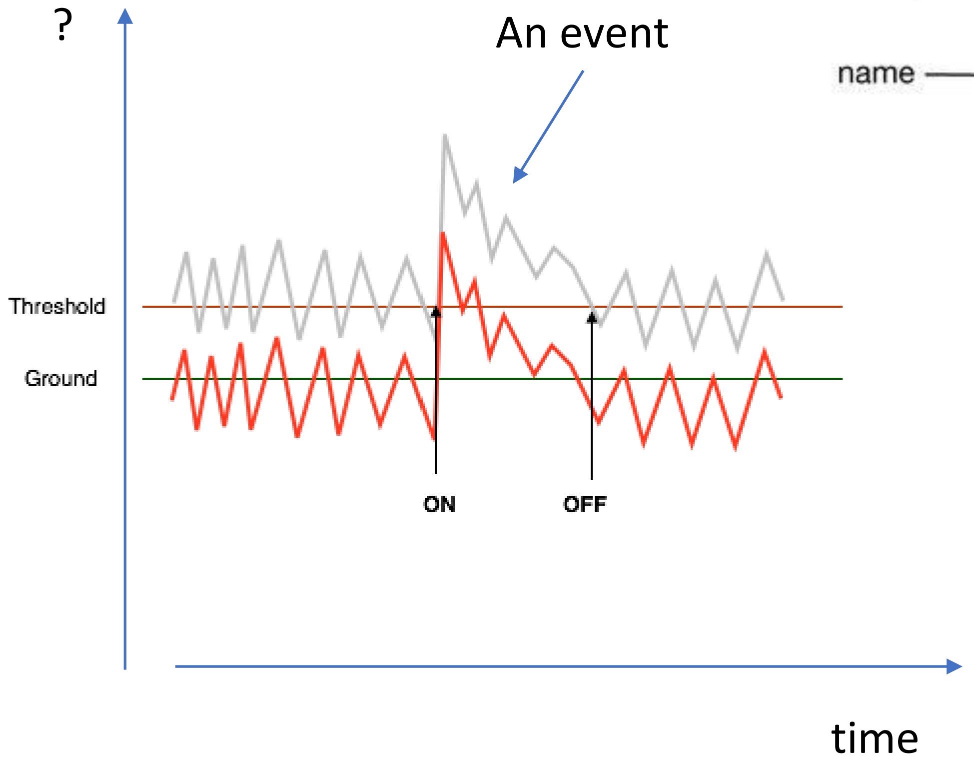
time

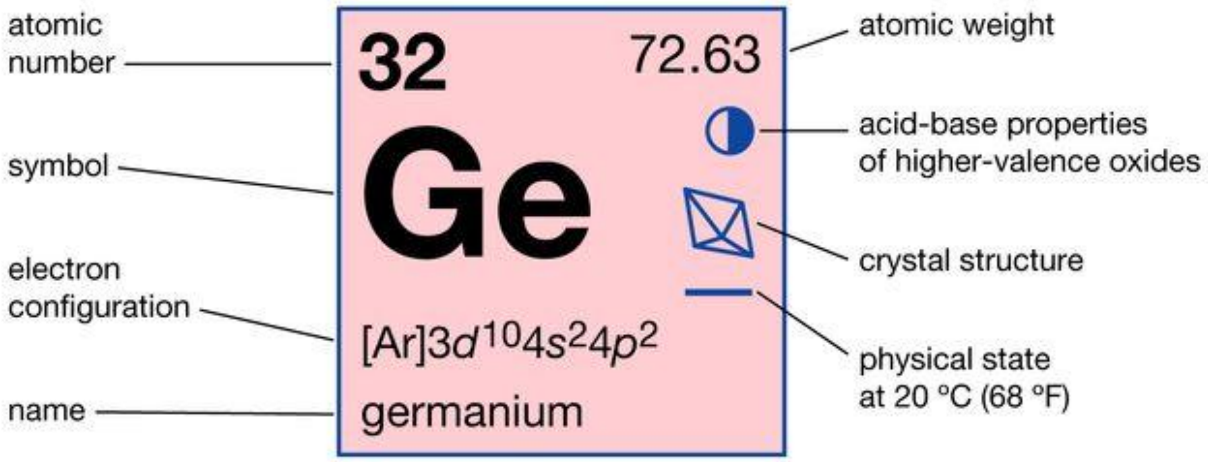
Day 3



Day 2

pre-set requirement:





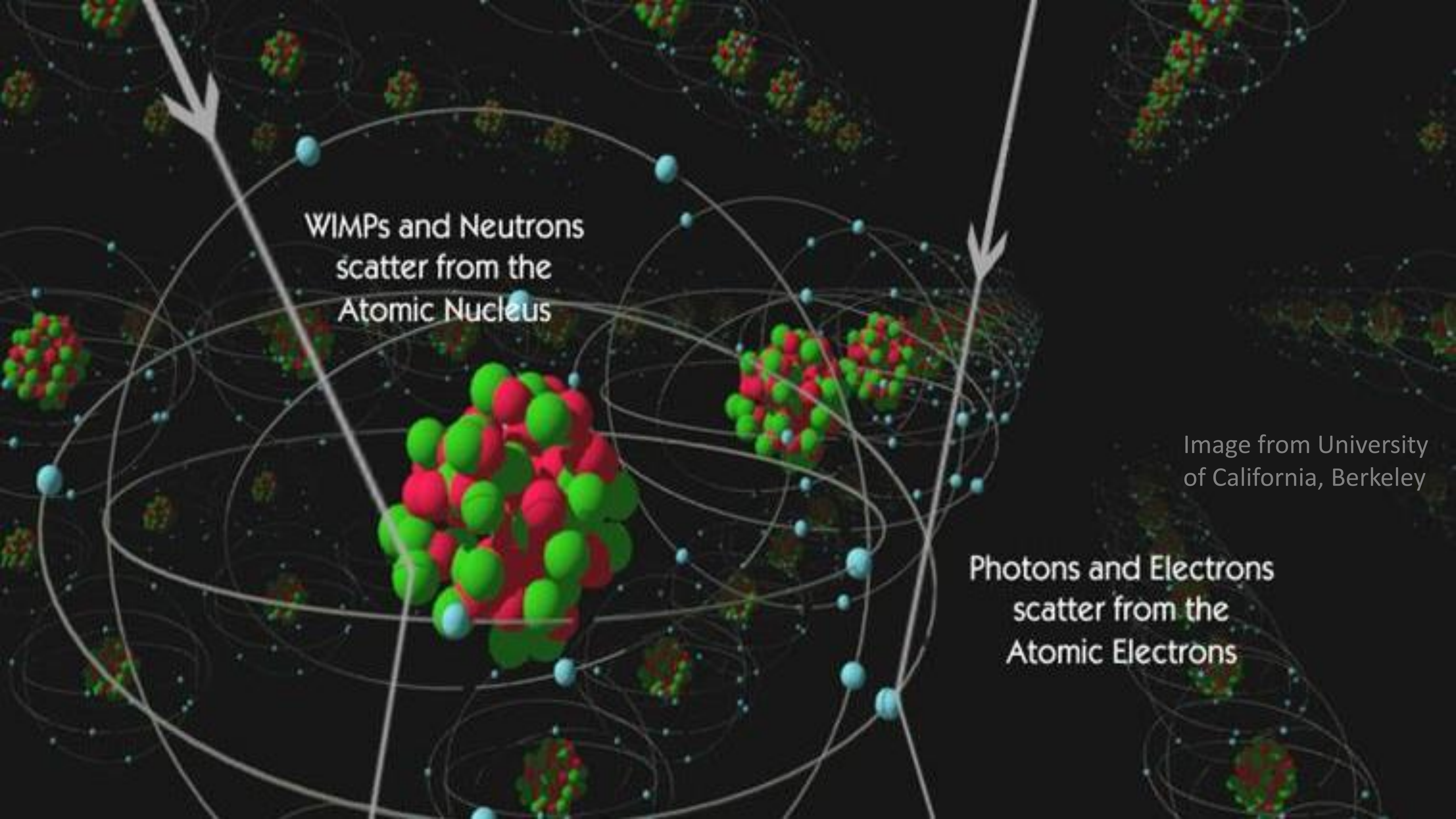
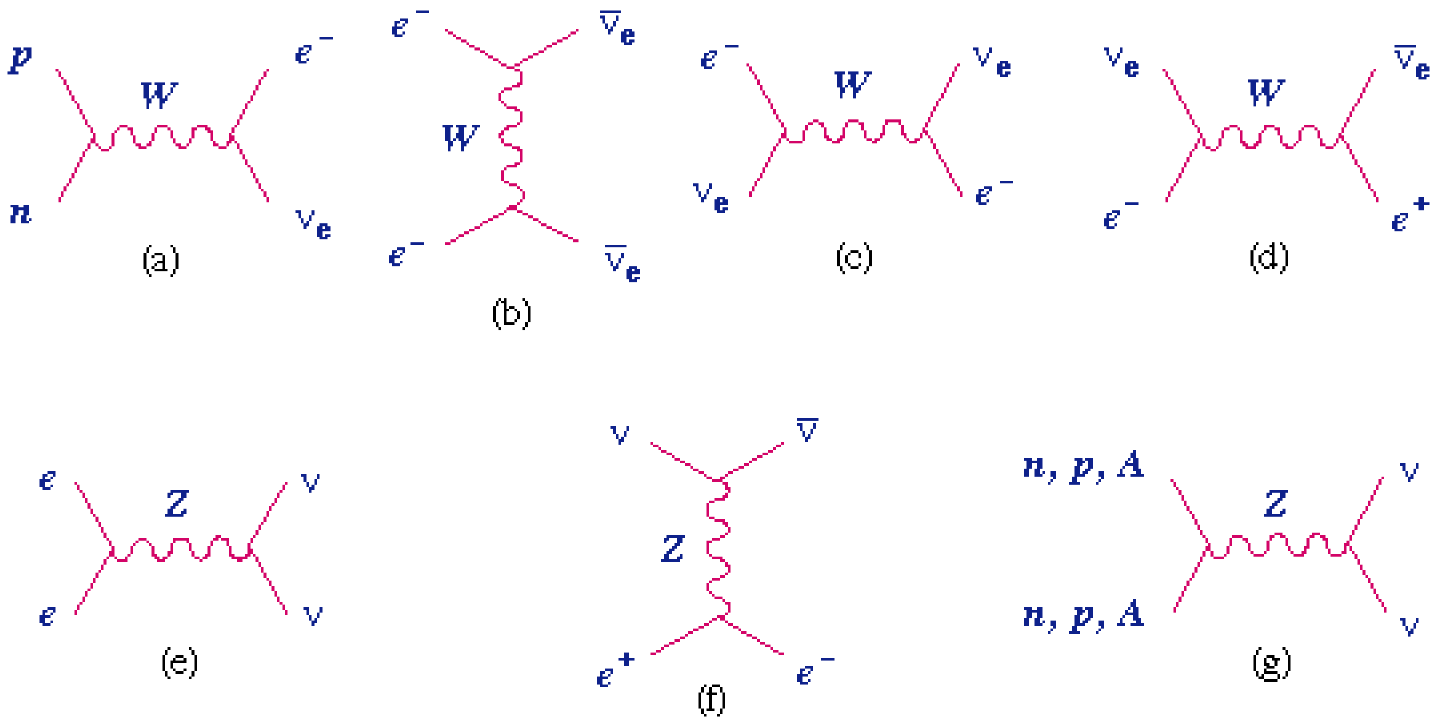


Image from University of California, Berkeley

Neutrino Feynman Diagrams



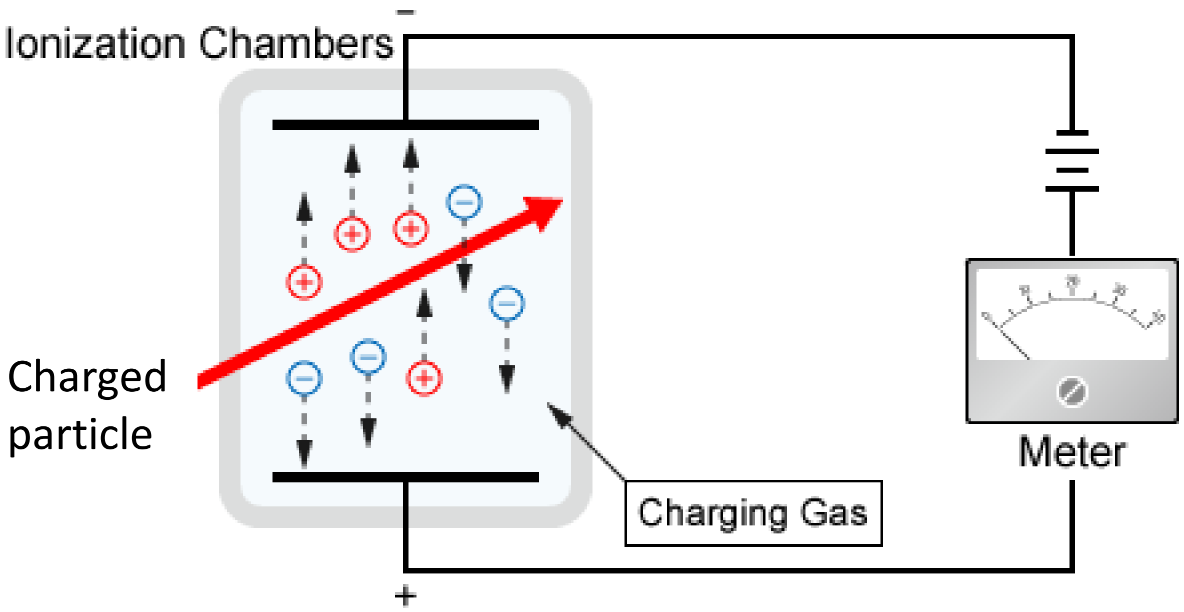
Classify according to whether (1) charged (W) or neutral (Z) current, (2) nucleonic or leptonic, (3) whether energy is exchanged or not. Generally, nucleonic σ larger than leptonic. Diagrams (a)-(f) exchange momentum and energy; diagram (g) exhanges momentum but little energy.

https://aether.lbl.gov/www/projects/neutrino/spn/nuint.html

Ionization

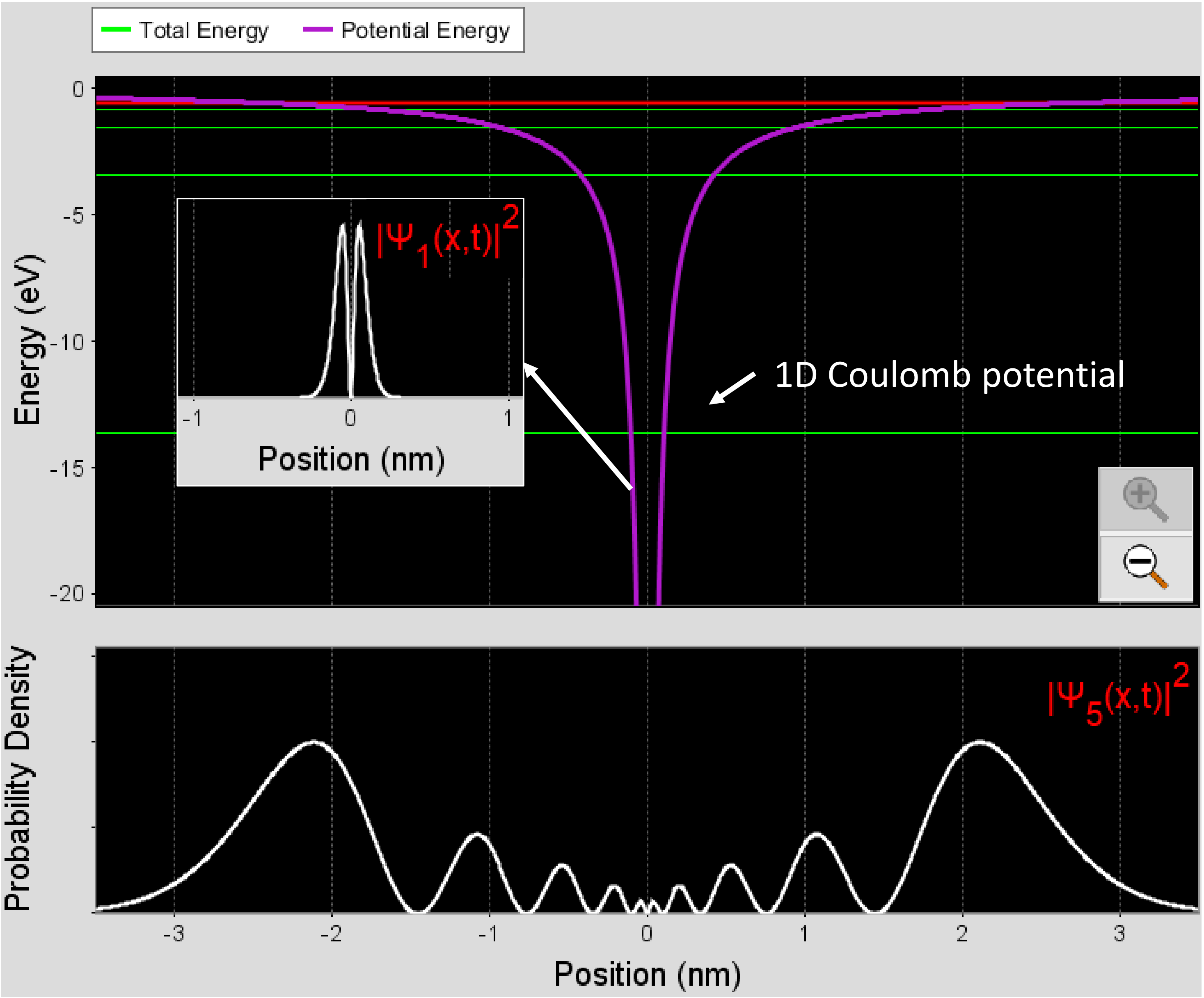
https://www.youtube.com/watch?v=i15ef618DP0

- Charged particles
  - Electrons
  - Ions
- Scattered particles that escape from the detection
  - Neutrino
  - Dark matter
  - Neutrons
  - Gamma-ray

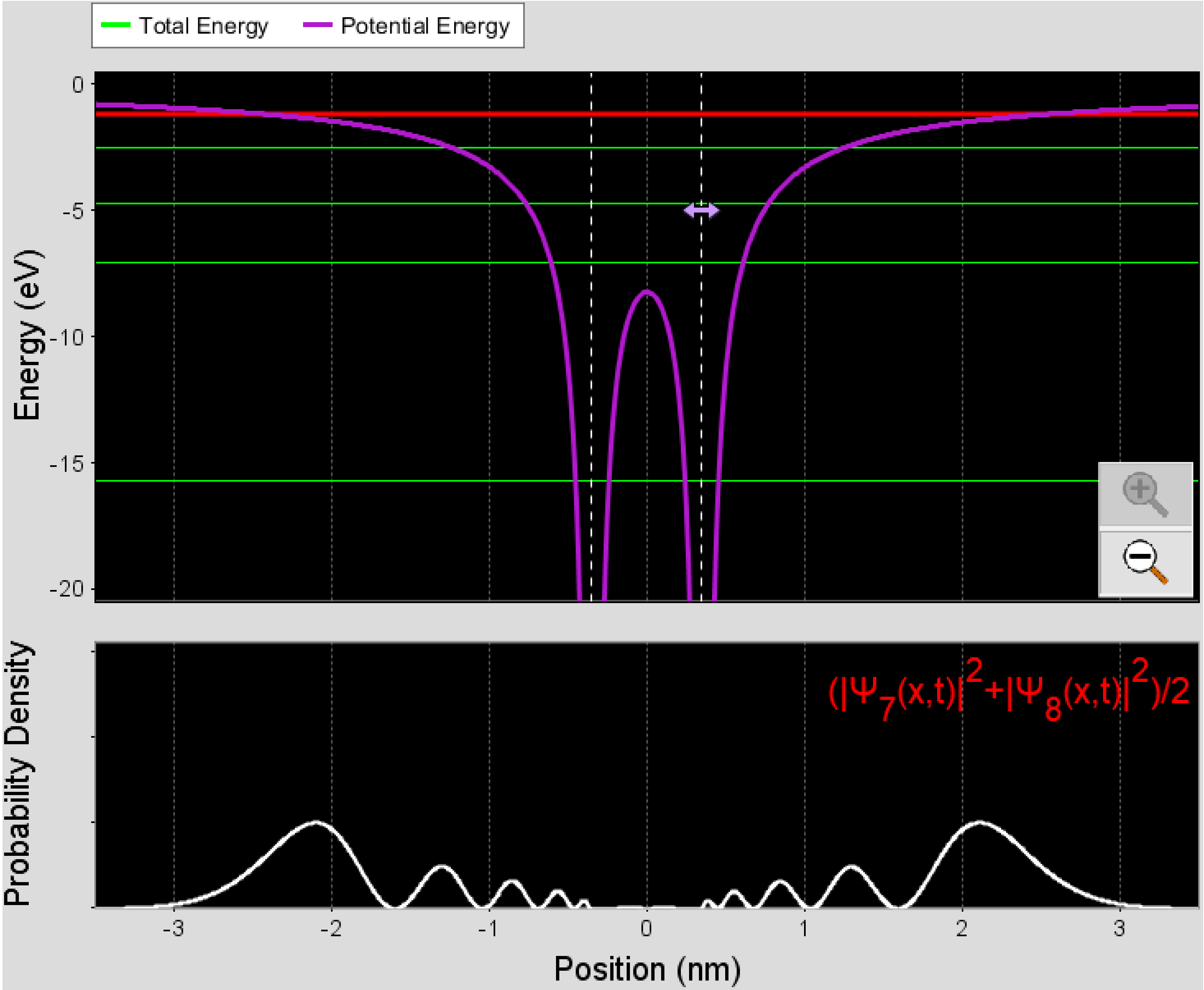


Also works in solid, such as Ge, the track is, however, much shorter

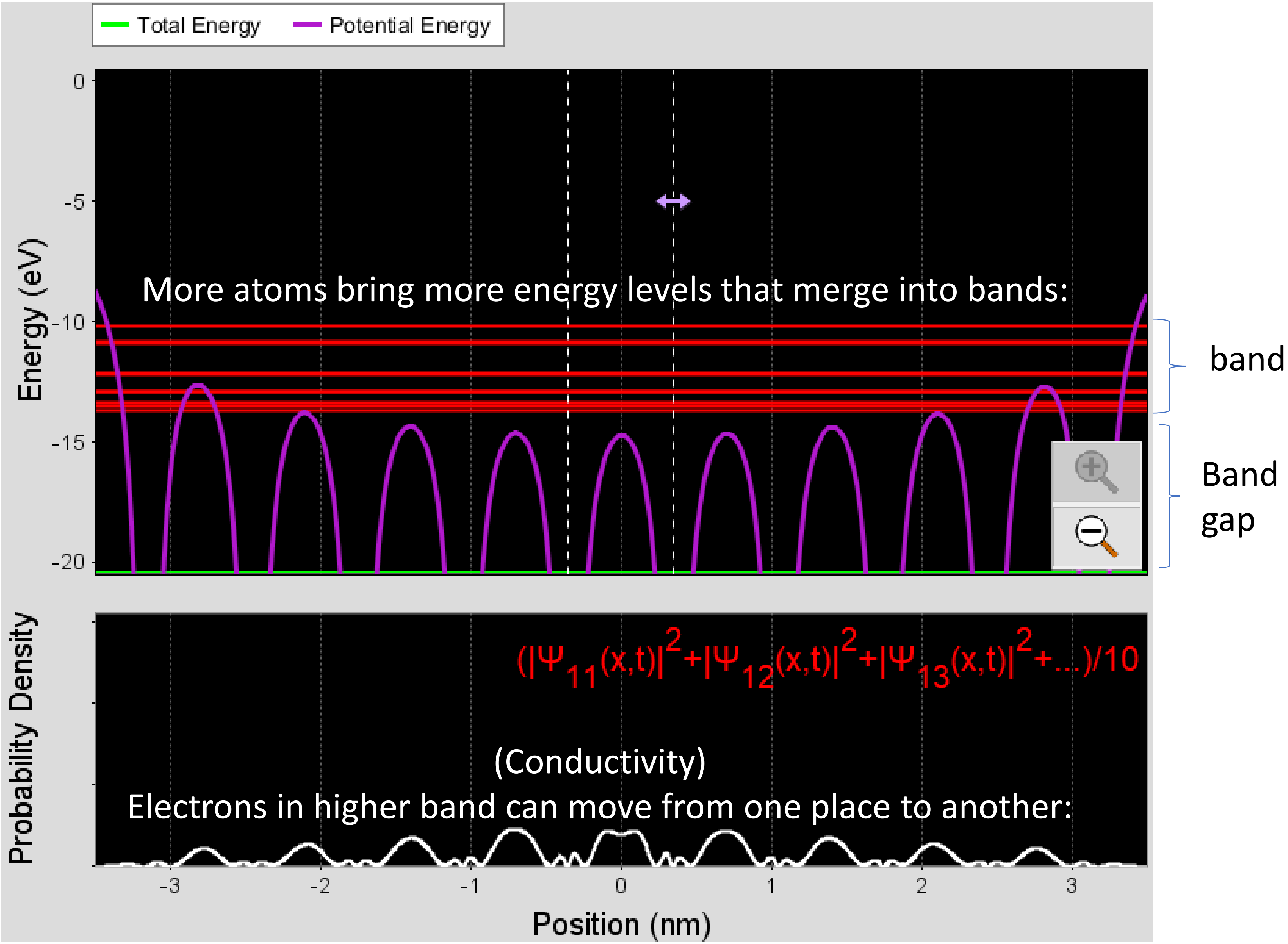
Ions do not move freely in Ge.
It is holes that move around

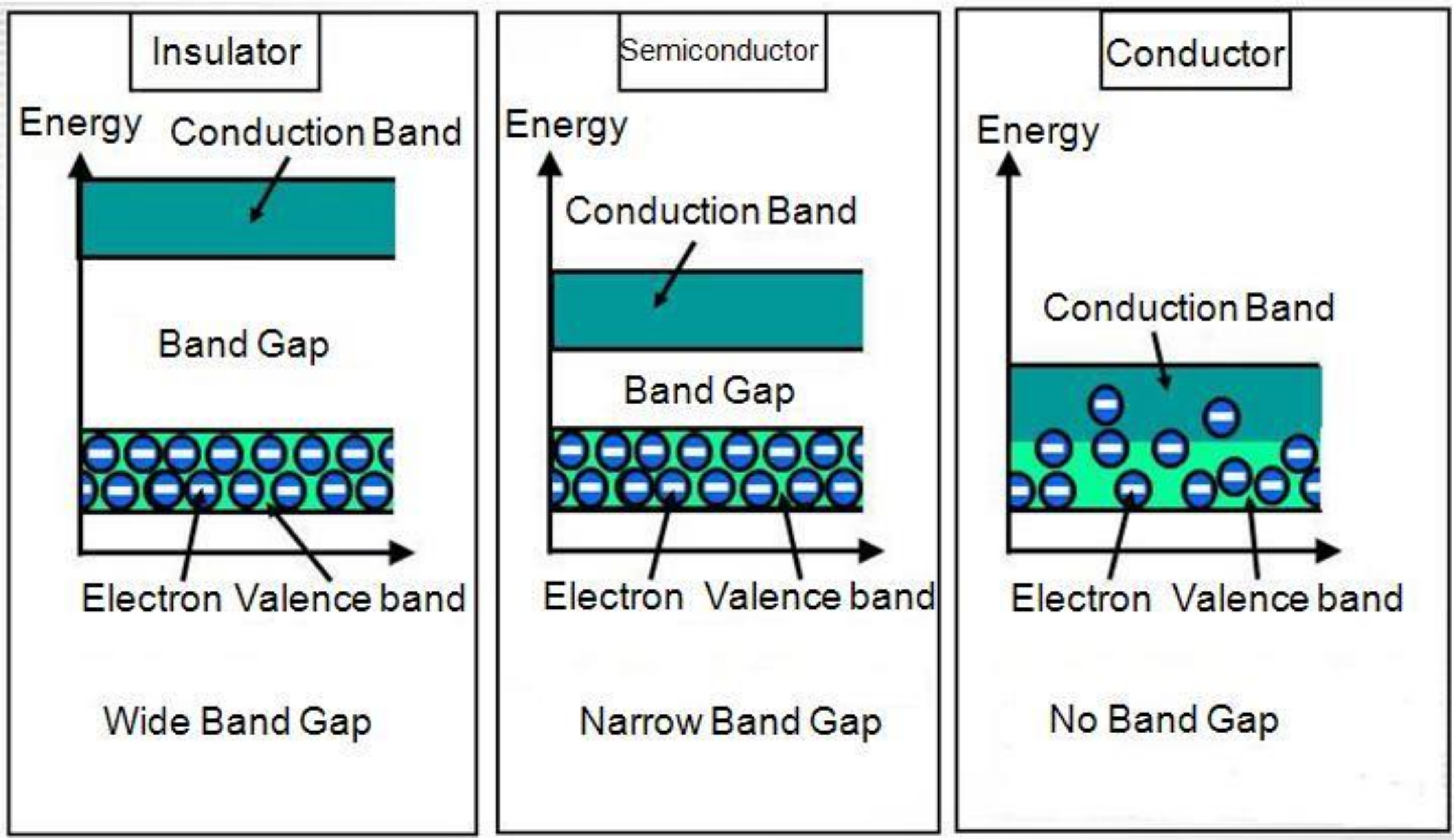


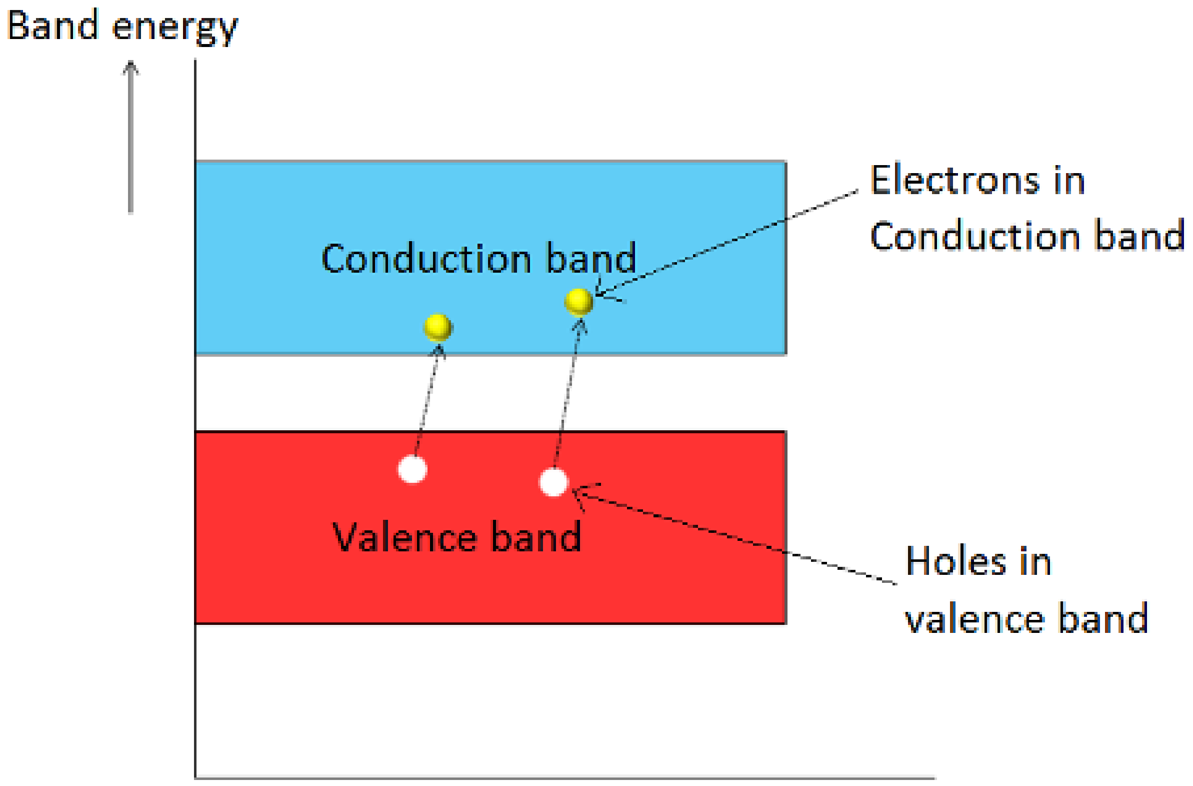
https://phet.colorado.edu/en/simulation/band-structure



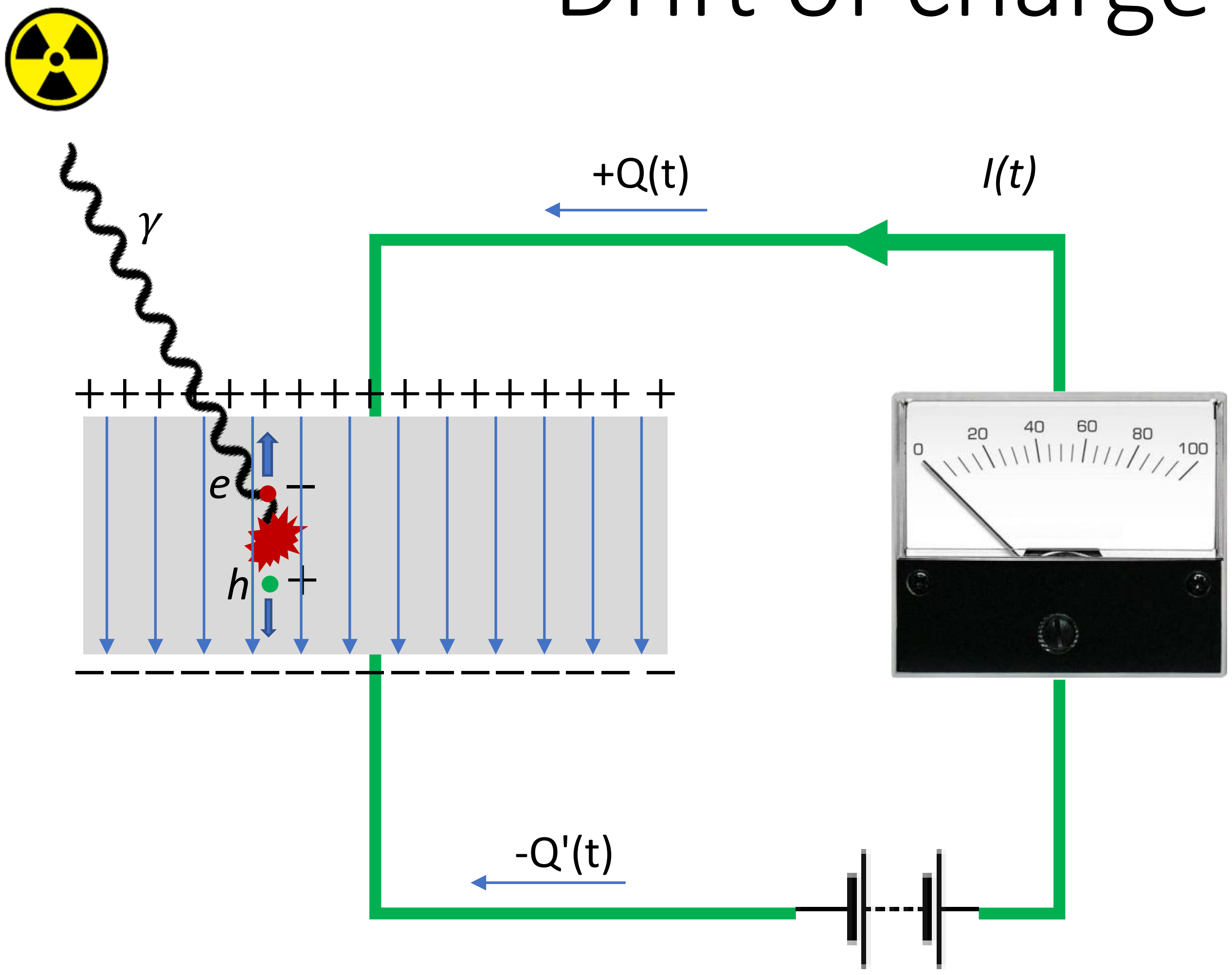
Total Energy
Potential Energy
Energy (eV)
0
-5
-10
-15
-20
Probability Density
$(|\Psi_7(x,t)|^2+|\Psi_8(x,t)|^2)/2$
-3
-2
-1
0
1
2
3
Position (nm)


Total Energy
Potential Energy
0
-5
-10
-15
-20
Energy (eV)
More atoms bring more energy levels that merge into bands:
band
Band gap
Probability Density
(|Ψ11(x,t)|2+|Ψ12(x,t)|2+|Ψ13(x,t)|2+...)/10
(Conductivity)
Electrons in higher band can move from one place to another:
-3
-2
-1
0
1
2
3
Position (nm)

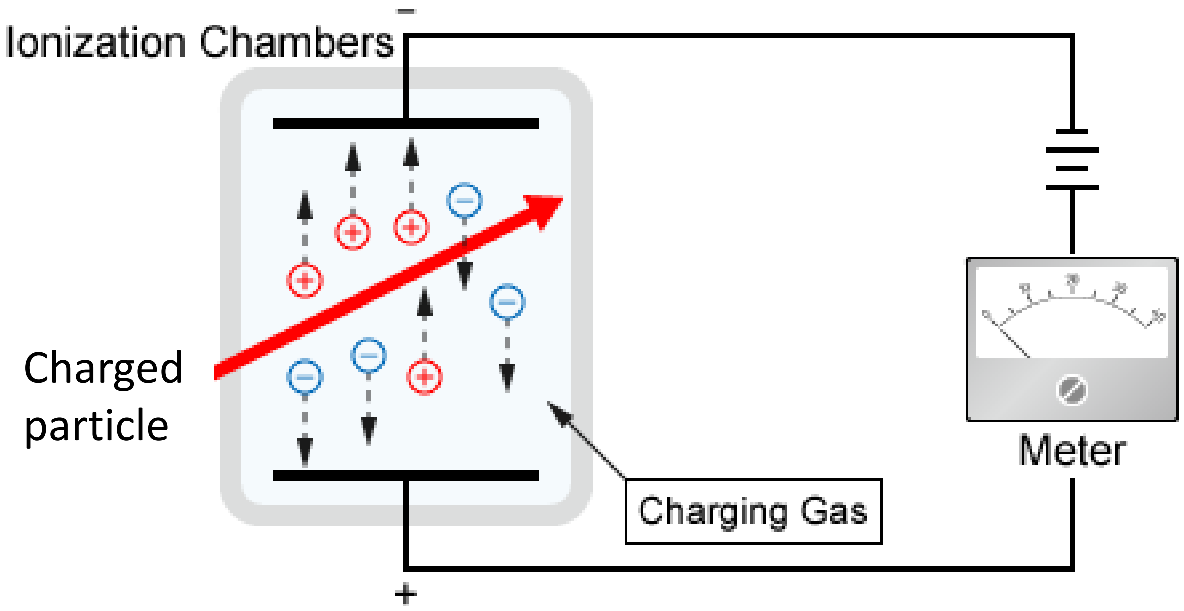

Insulator
Energy
Conduction Band
Band Gap
Electron
Valence band
Wide Band Gap
Semiconductor
Energy
Conduction Band
Band Gap
Electron
Valence band
Narrow Band Gap
Conductor
Energy
Conduction Band
Electron
Valence band
No Band Gap


Band energy
Conduction band
Electrons in
Conduction band
Valence band
Holes in
valence band

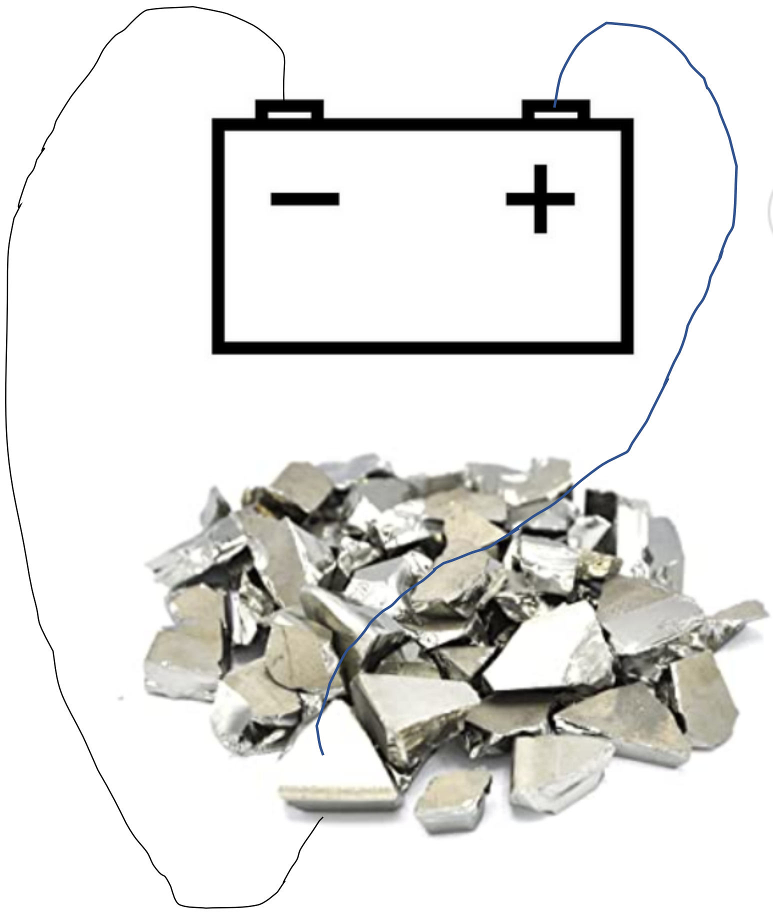
Drift of charge carriers



solid



gas



5N

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Pay $17.35/month for 6 months, interest-free upon approval for the Amazon Prime Rewards Visa Card

Size: **50 Grams**

50 Grams **$104.12**	100 Grams $198.25	250 Grams $470.62

If you apply voltage to two sides of a piece of Ge, what will happen? Answer in kahoot.it

At room temperature, Ge works almost like a conductor

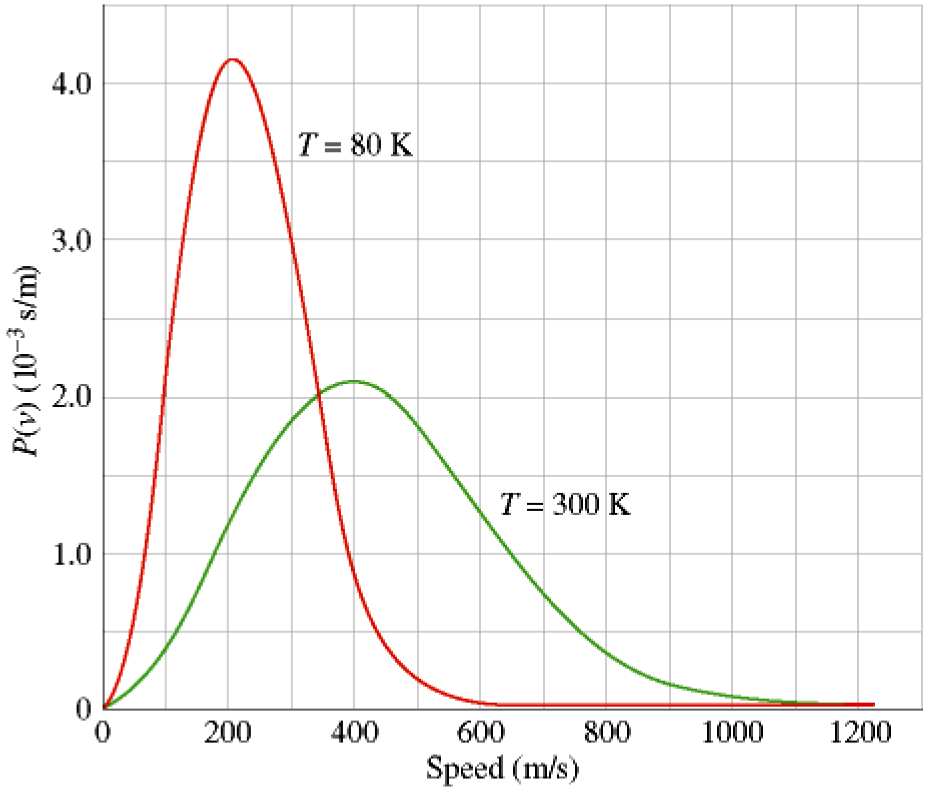
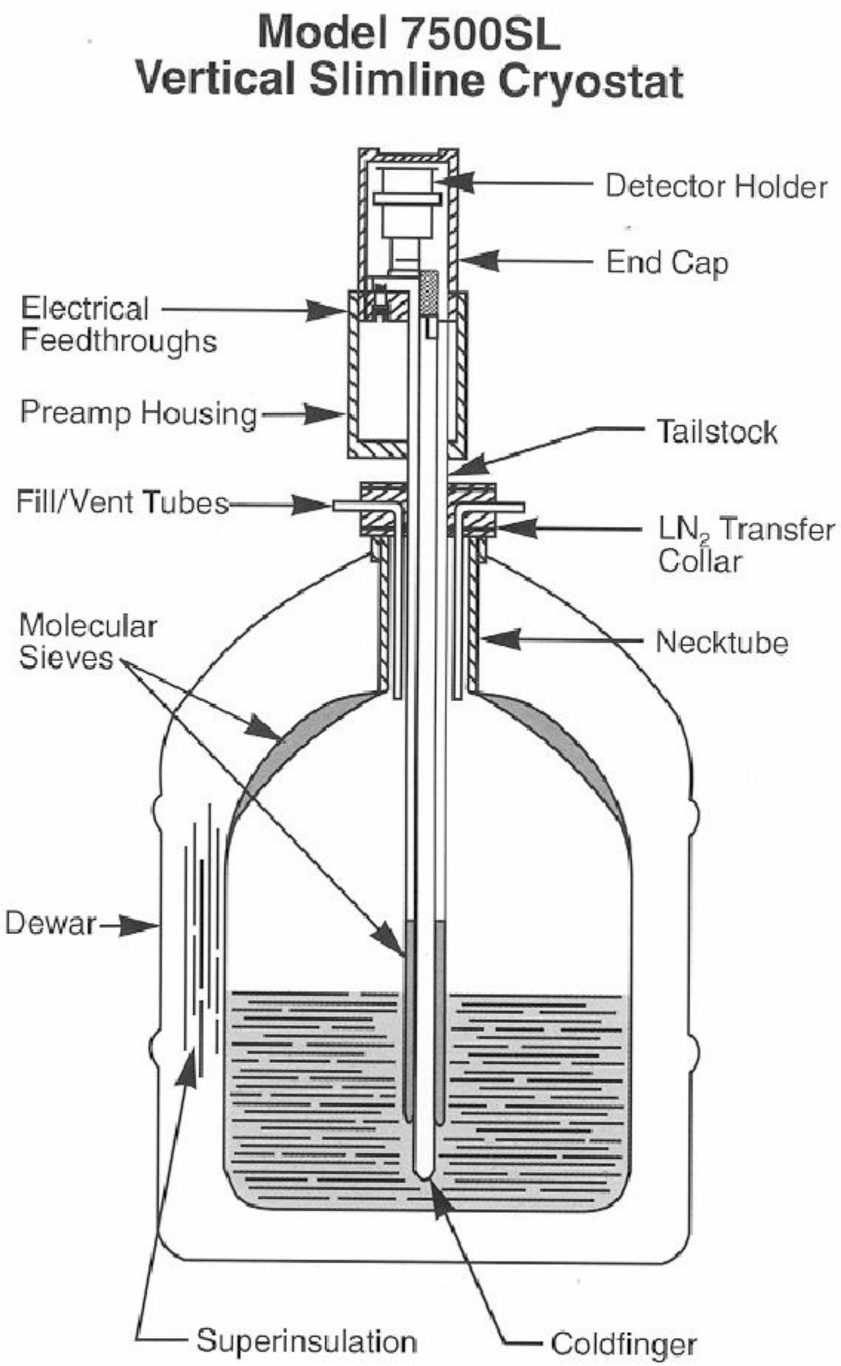


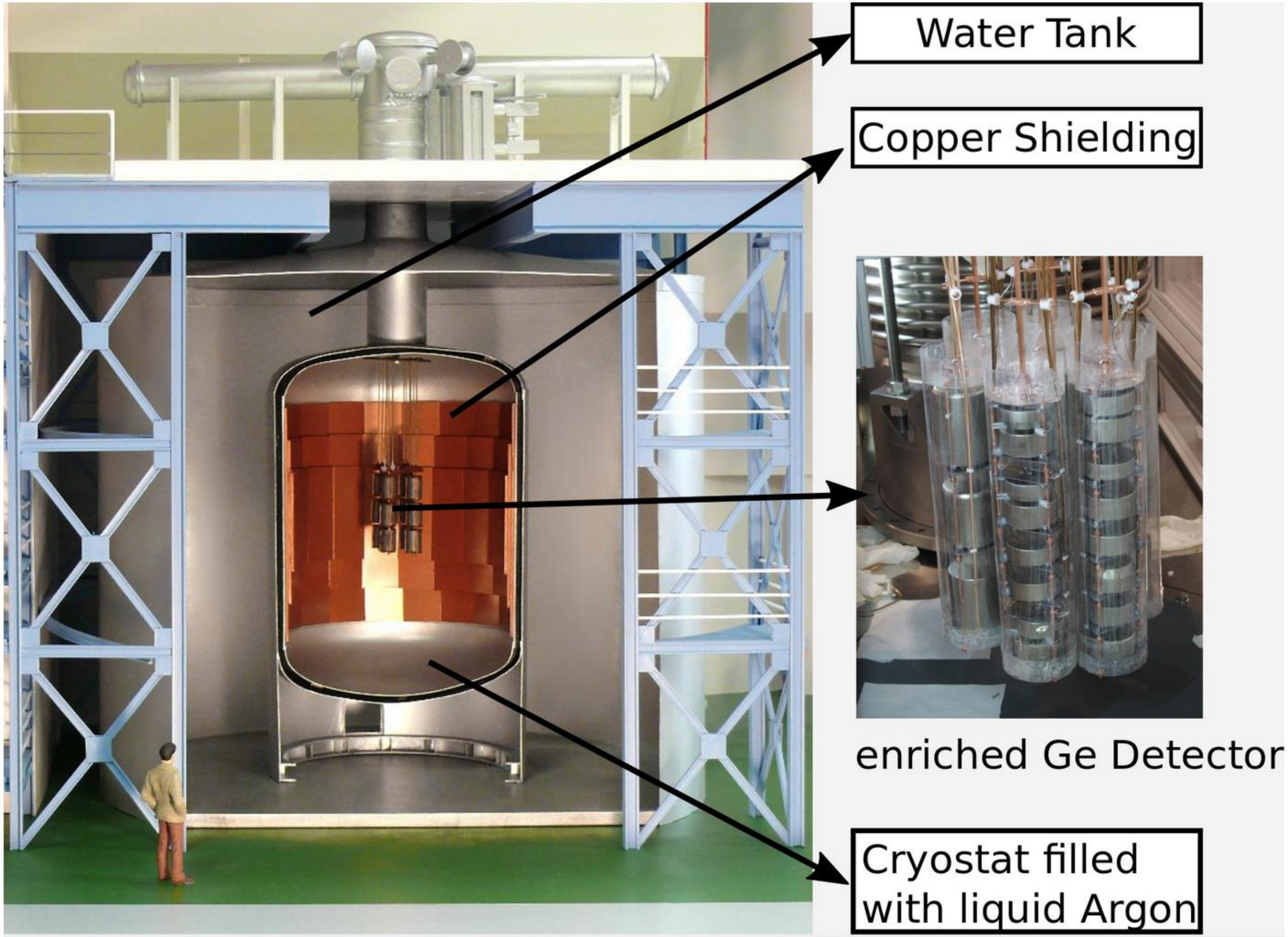
TABLE 1–1 • Band-gap energies of selected semiconductors.

Semiconductor	InSb	Ge	Si	GaAs	GaP	ZnSe	Diamond
E_g (eV)	0.18	0.67	1.12	1.42	2.25	2.7	6.0

Cryostat


Model 7500SL
Vertical Slimline Cryostat
Detector Holder
End Cap
Electrical Feedthroughs
Preamp Housing
Tailstock
Fill/Vent Tubes
LN_2 Transfer Collar
Molecular Sieves
Necktube
Dewar
Superinsulation
Coldfinger


CANBERRA


Water Tank
Copper Shielding
enriched Ge Detector
Cryostat filled
with liquid Argon

GRASEBY INFRARED 17-0187 INFRARED DETECTOR

Condition: **New – Open box**

Price: **US $299.00**

No Interest if paid in full in 6 mo on $99+*

Buy It Now

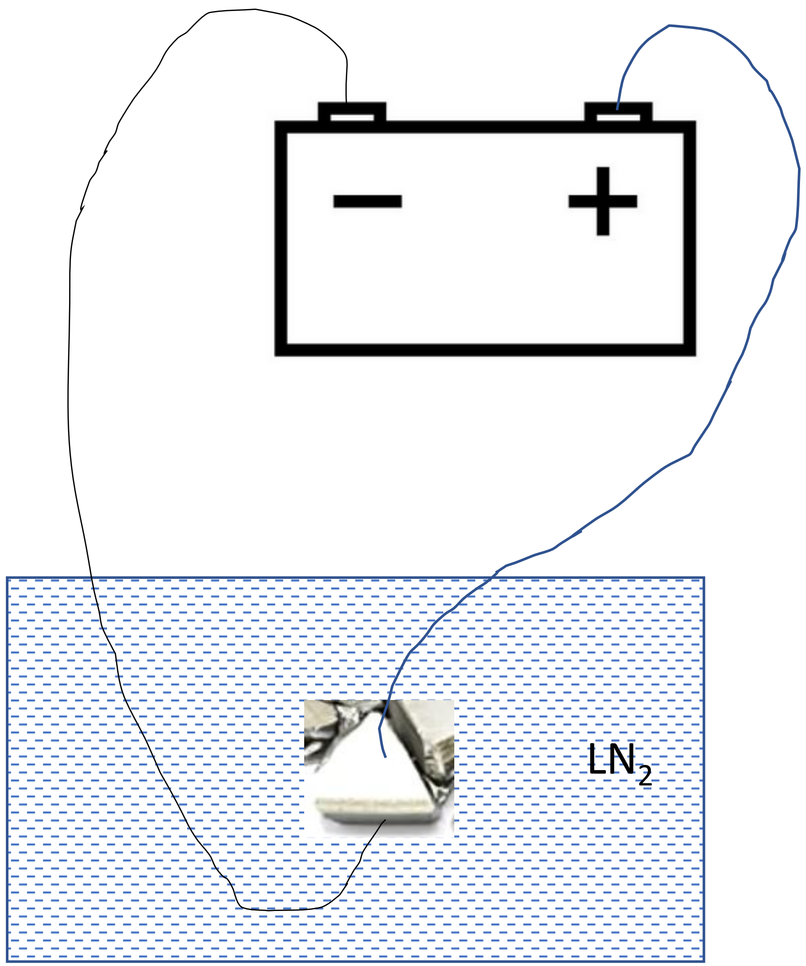
Add to cart

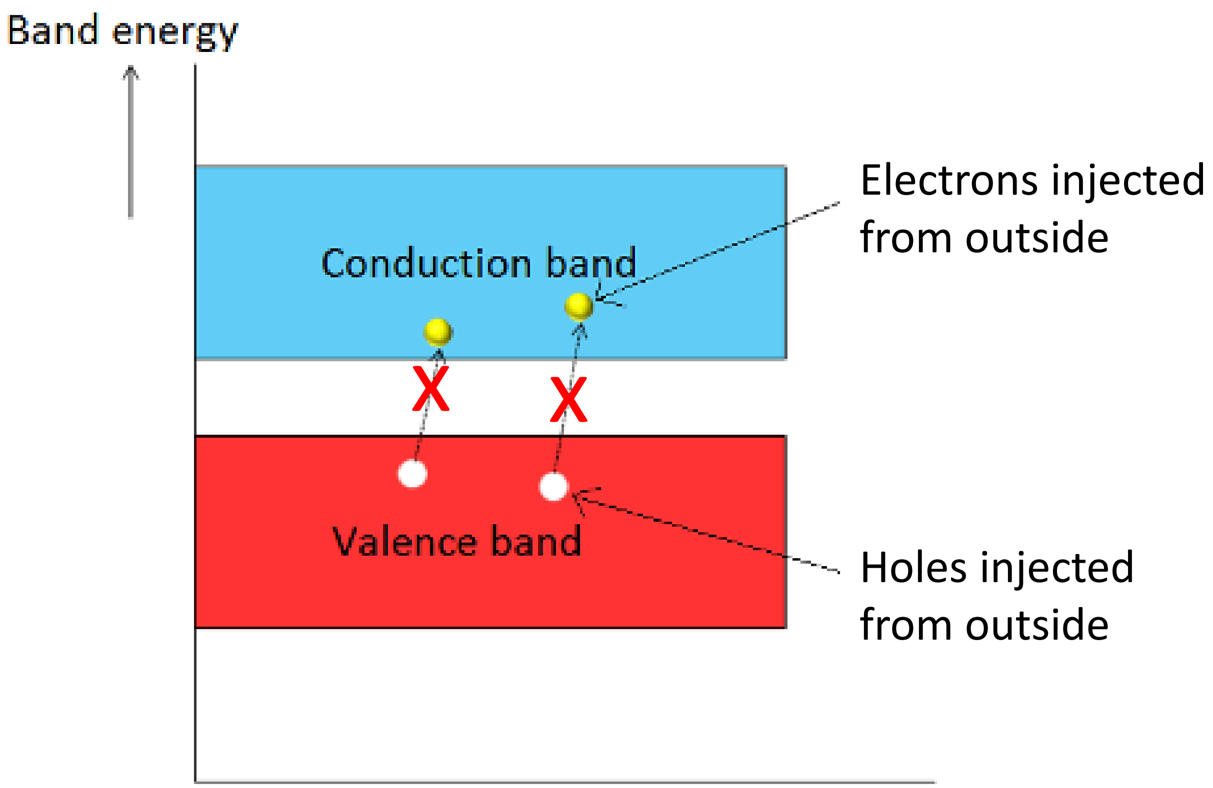
Best Offer:

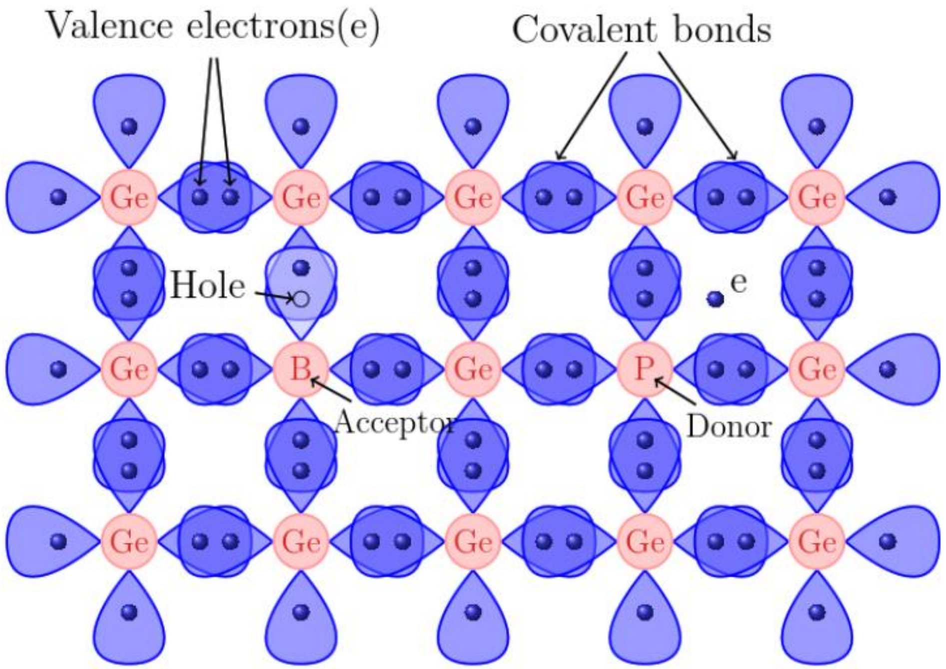
Make Offer

Add to Watchlist

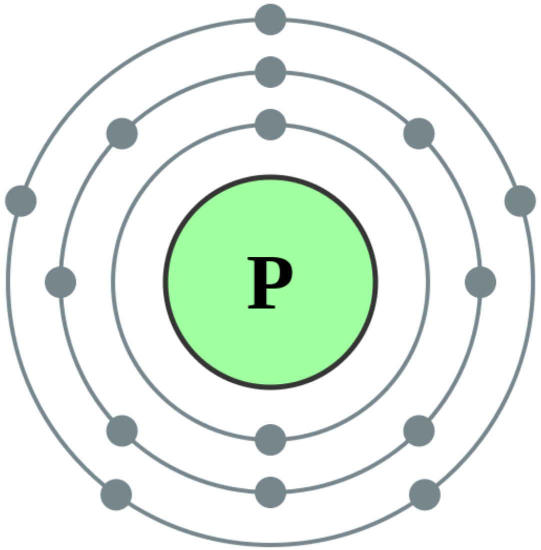
What if we apply voltage on a piece of Ge after we cool it down? Answer it on kahoot.it




Band energy
Conduction band
Electrons injected
from outside
X
X
Valence band
Holes injected
from outside

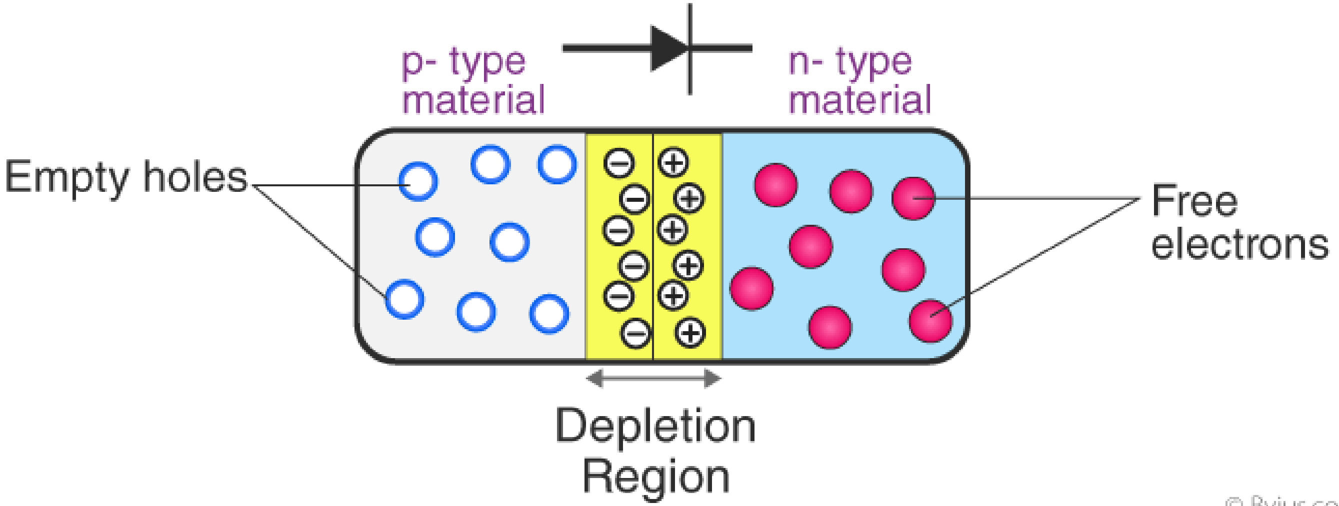


15 protons & 15 electrons

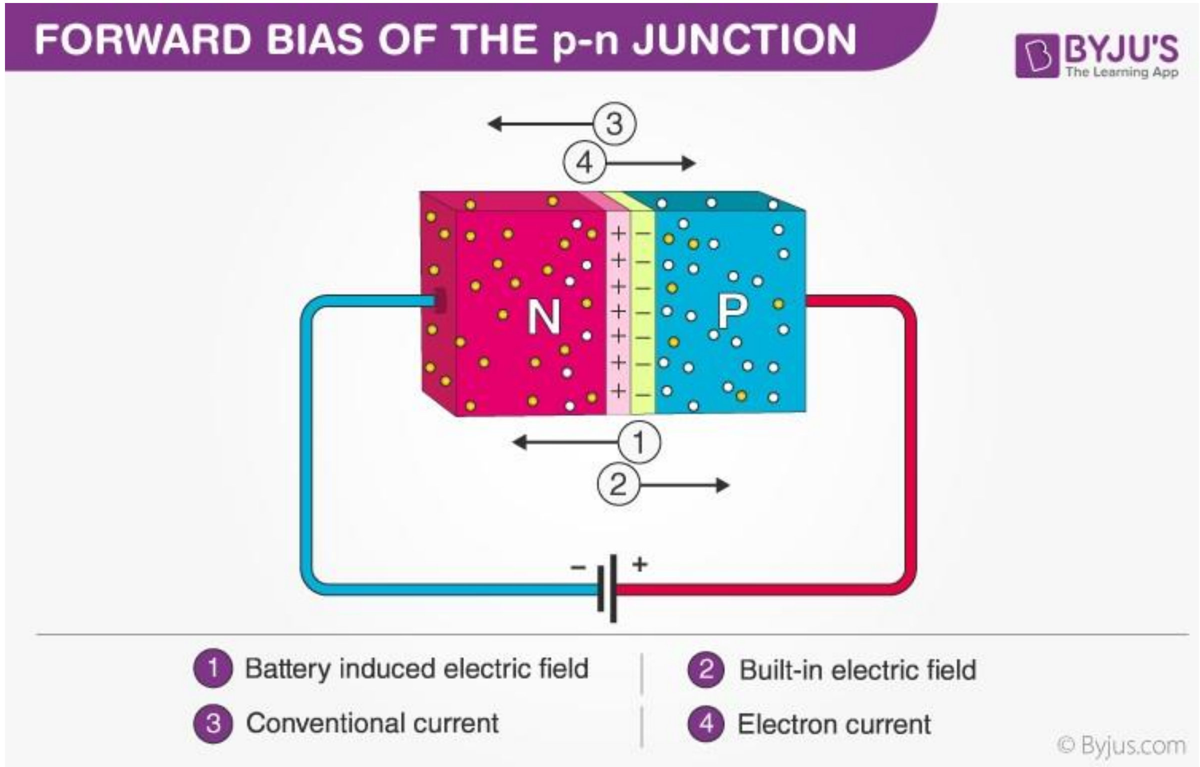


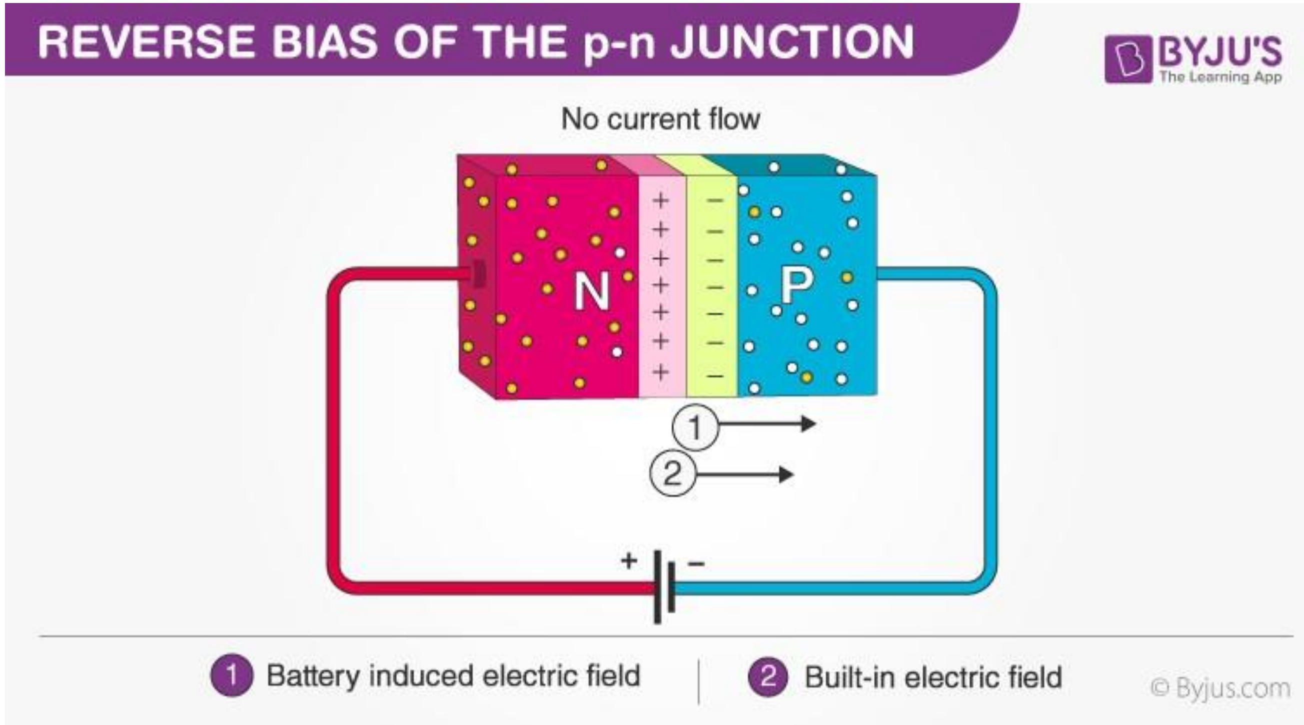
BYJU'S The Learning App

UNBIASED P-N JUNCTION

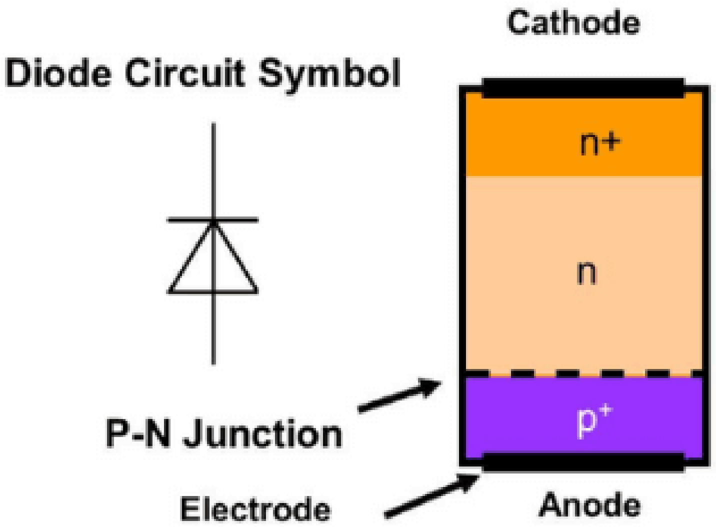


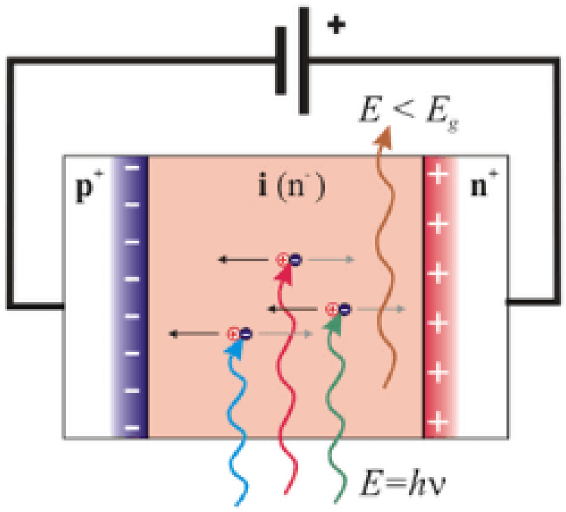
Kahoot.it

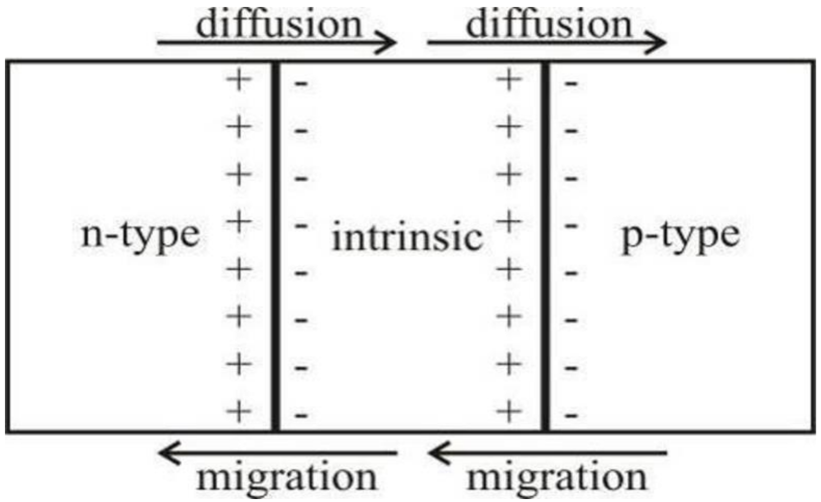

FORWARD BIAS OF THE p-n JUNCTION
BYJU'S
The Learning App
3
4
N
P
1
2
−
+
1 Battery induced electric field
2 Built-in electric field
3 Conventional current
4 Electron current
© Byjus.com


REVERSE BIAS OF THE p-n JUNCTION
BYJU'S
The Learning App
No current flow
N
P
1
2
+
−
1 Battery induced electric field
2 Built-in electric field
© Byjus.com

What is a PIN Diode?

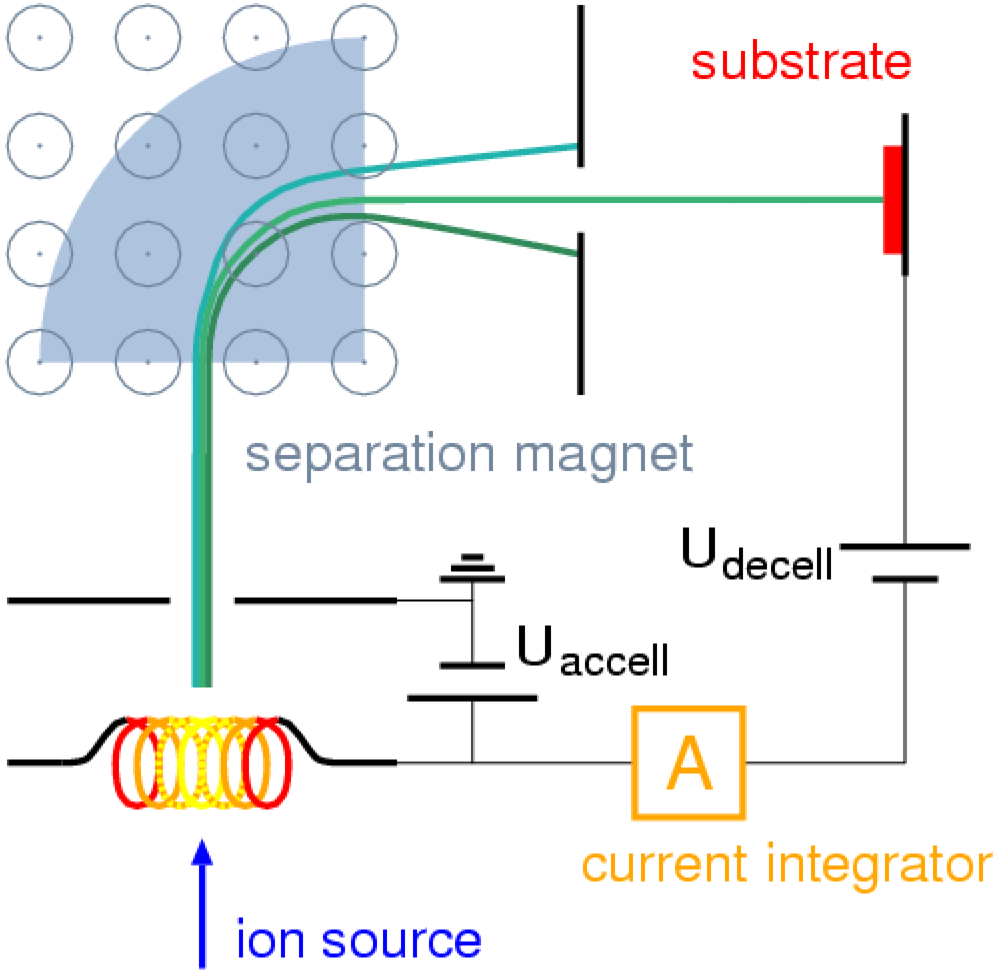




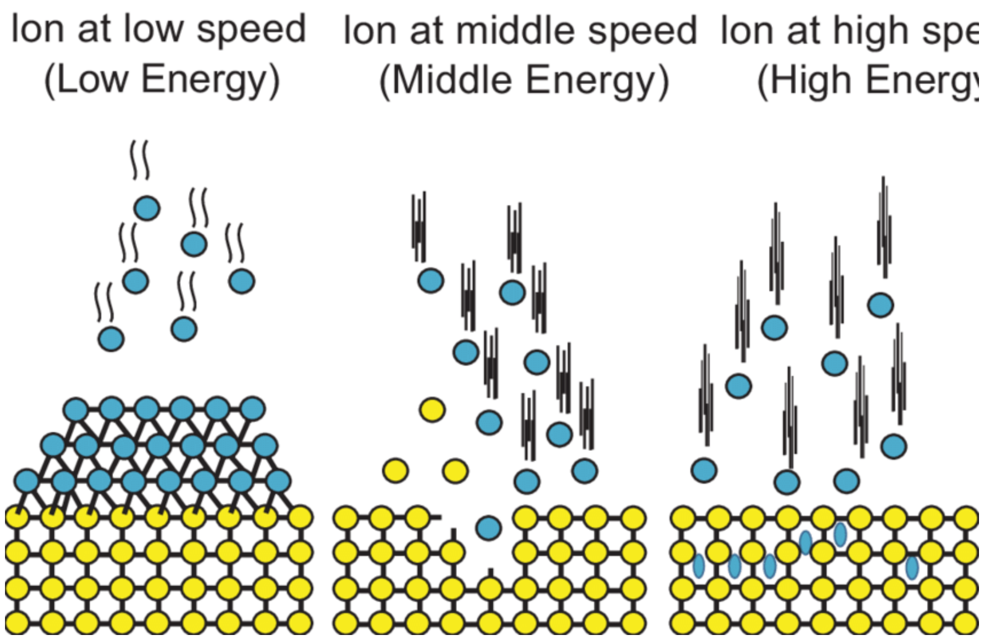


Electrical 4 U

Boron implantation

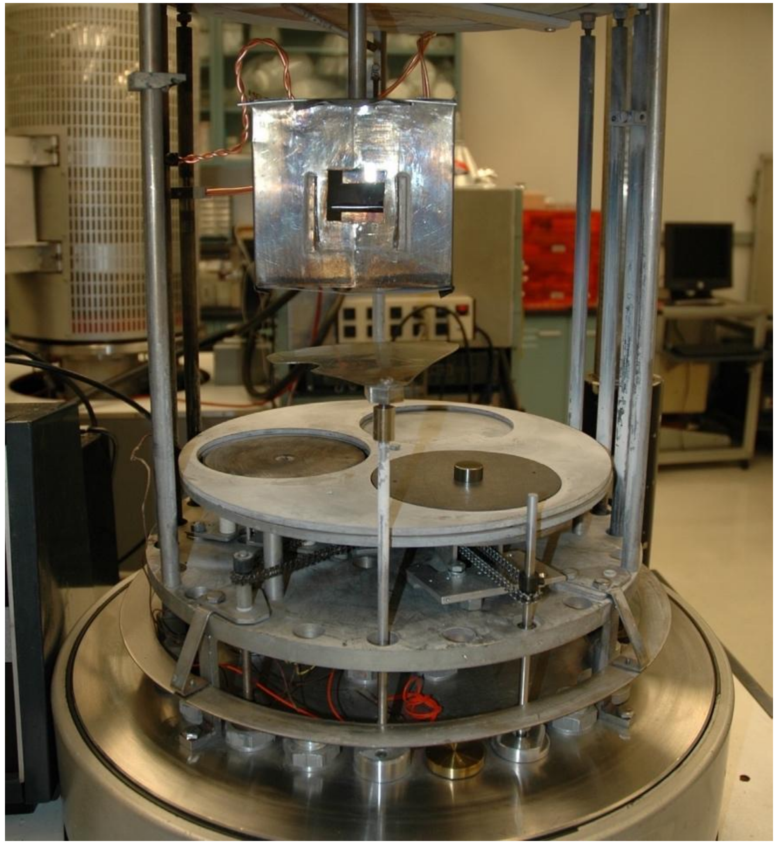


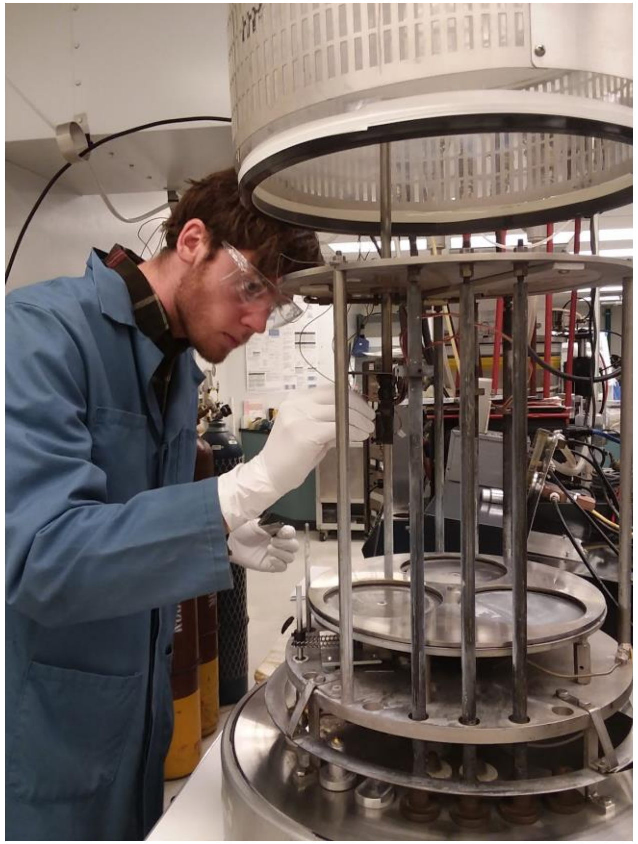
https://en.wikipedia.org/wiki/Ion_implantation



https://www.researchgate.net/figure/Fig-8-Schematic-diagram-of-an-advanced-metal-ion-implantation-method_fig5_250144359

Lithium diffusion





Amorphous Ge contact

Eur. Phys. J. C (2020) 80:667
https://doi.org/10.1140/epjc/s10052-020-8235-9
THE EUROPEAN PHYSICAL JOURNAL C
Regular Article - Experimental Physics

Characterization of high-purity germanium detectors with amorphous germanium contacts in cryogenic liquids

R. Panth[1], J. Liu[1,a], I. Abt[2], X. Liu[2], O. Schulz[2], W.-Z. Wei[1], H. Mei[1], D.-M. Mei[1], G.-J. Wang[1]
[1] University of South Dakota, 414 East Clark Street, Vermillion, SD 57069, USA
[2] Max-Planck-Institut für Physik, Föhringer Ring 6, 80805 Munich, Germany

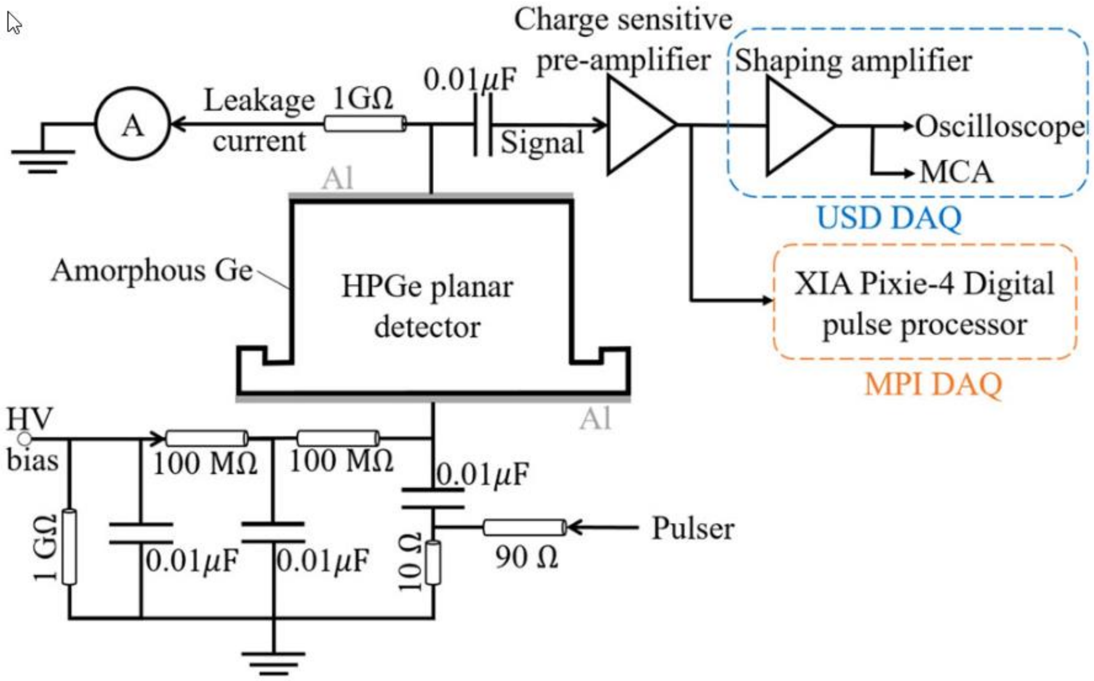


Fig. 3 Electronic circuit for detector characterization

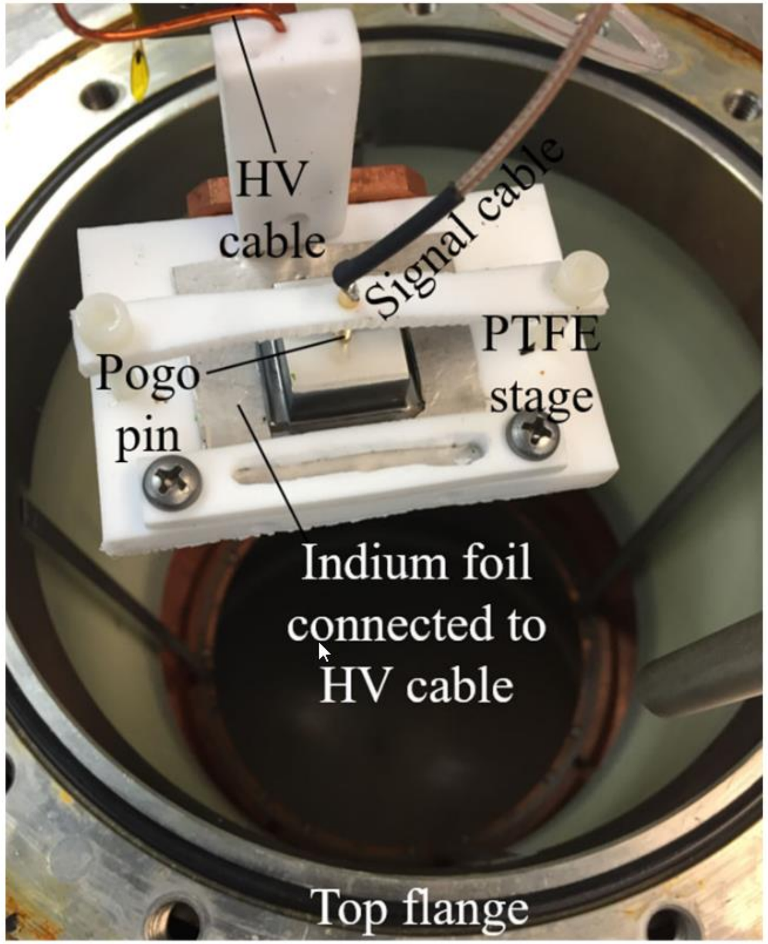
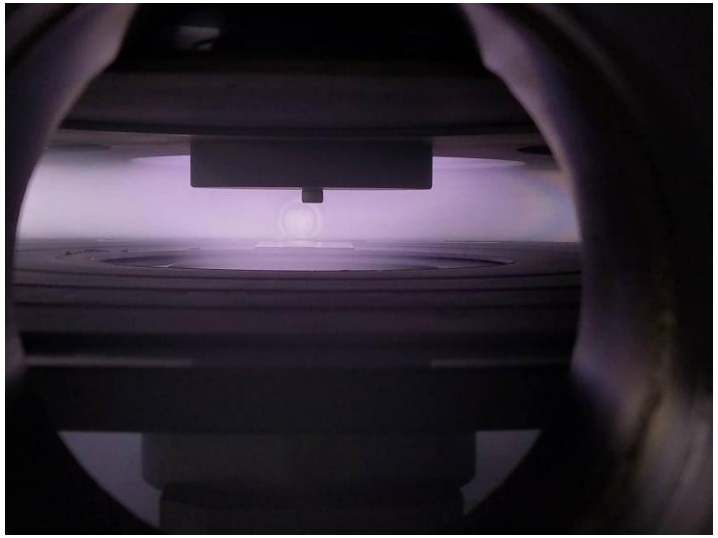
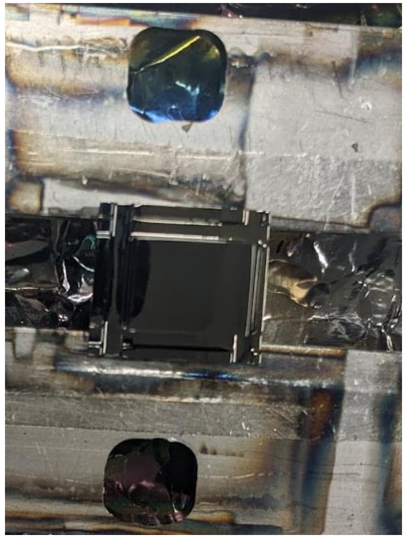
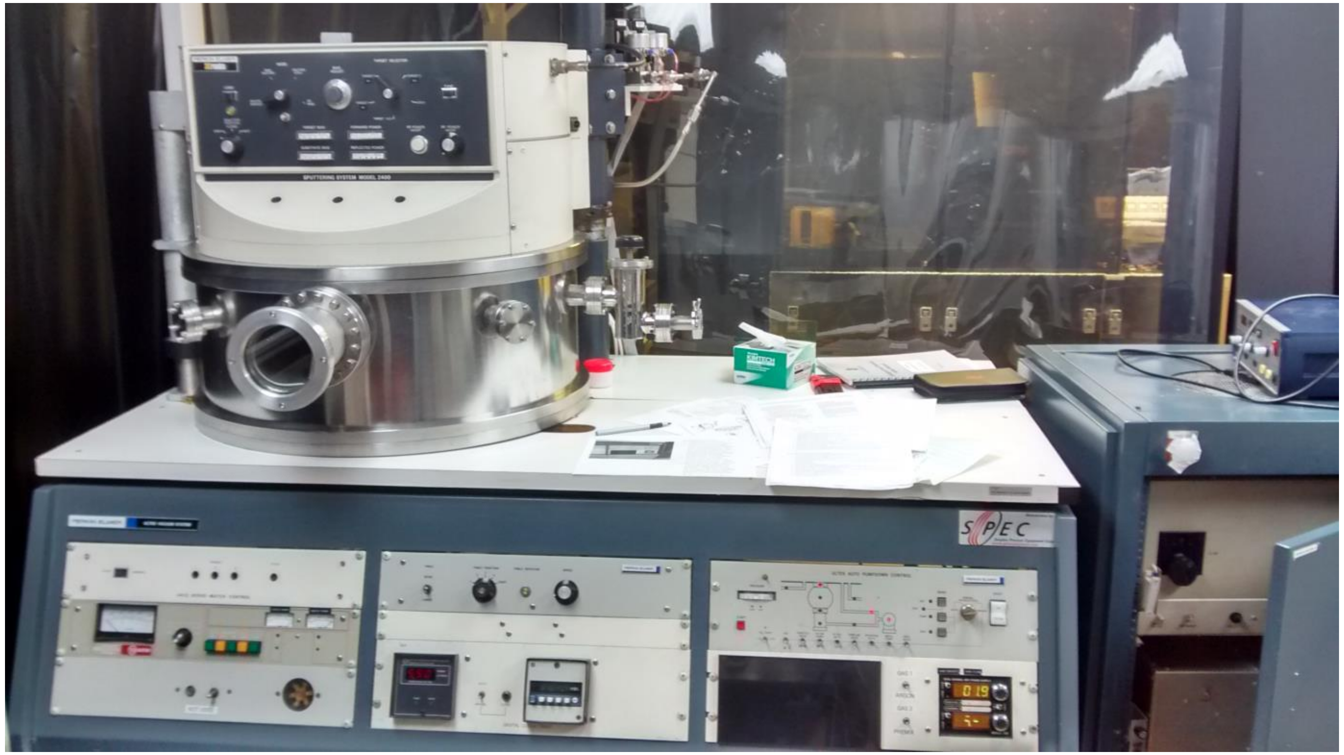


Fig. 7 Detector to be lowered into the MPI cryostat


PERKIN ELMER
TARGET BIAS
FORWARD POWER
SUBSTRATE BIAS
REFLECTED POWER
SPUTTERING SYSTEM MODEL 2400






SPUTTERING SYSTEM MODEL 2400
KIMTECH

M. Amman, 2018, "Optimization of Amorphous Germanium Electrical Contacts and Surface Coatings on High Purity Germanium Radiation Detectors"

http://arxiv.org/abs/1809.03046

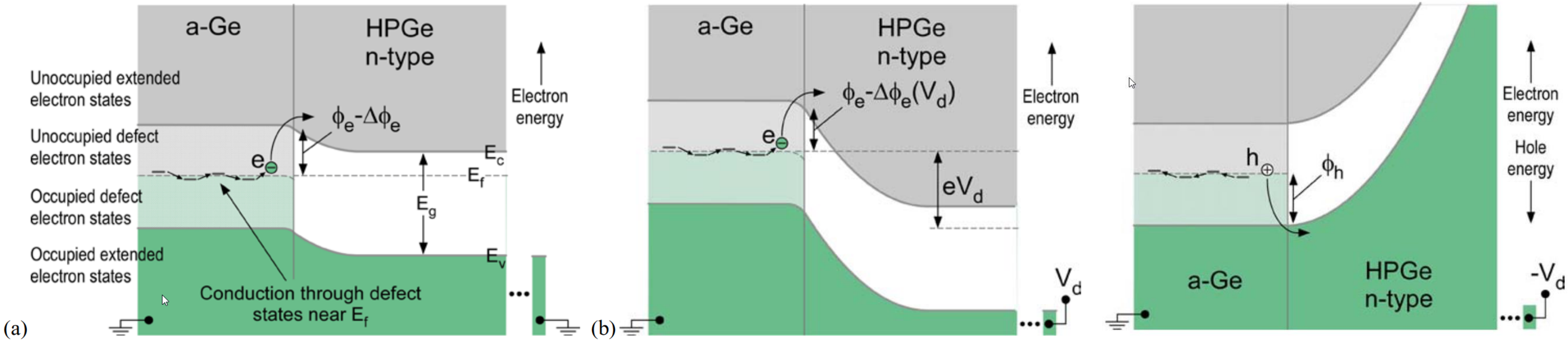
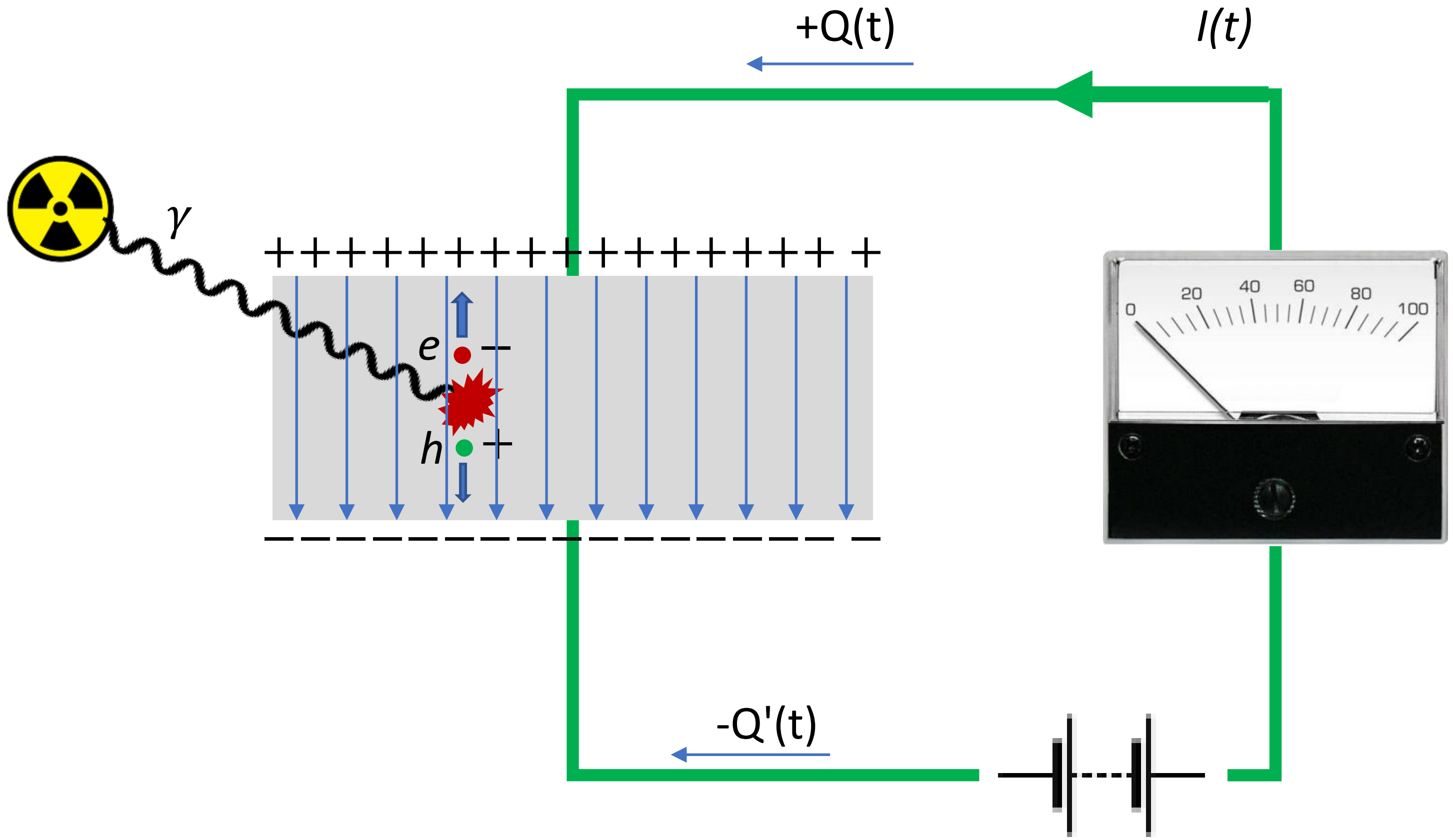


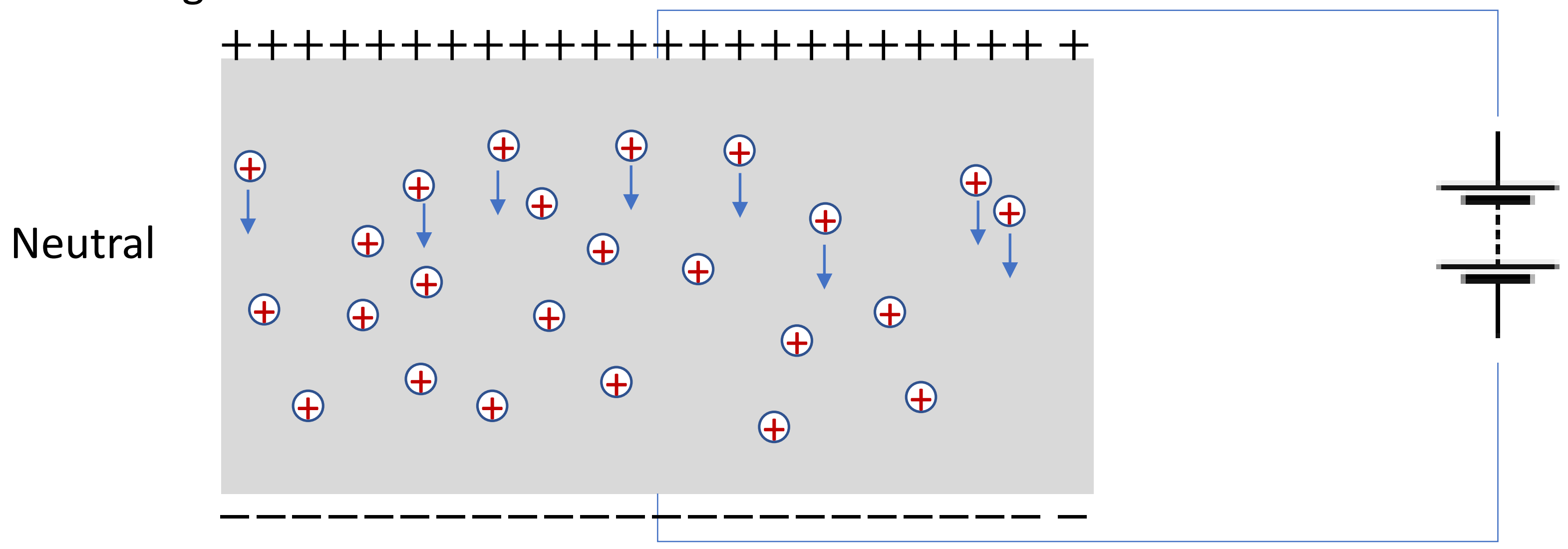
Figure 3.1 Schematic electron energy diagrams of an a-Ge electrical contact on n-type crystalline HPGe. The diagrams show only the a-Ge to crystalline HPGe junction, and do not include the metal layer covering the a-Ge and the electrical contact on the opposing side of the HPGe that are both necessary to produce a complete radiation detector. **(a)** Energy diagram with zero voltage applied across the device. The energies noted in the diagram, E_c, E_v, E_g, E_f, and ϕ_e, are of the conduction band edge, valence band edge, energy gap, Fermi level, and electron barrier. **(b)** Energy diagram with a relatively negative voltage applied to the a-Ge contact. This results in an increase of the depletion region near the contact. A reduction $\Delta\phi_e$ of the electron energy barrier occurs due to the penetration of the field into the a-Ge.



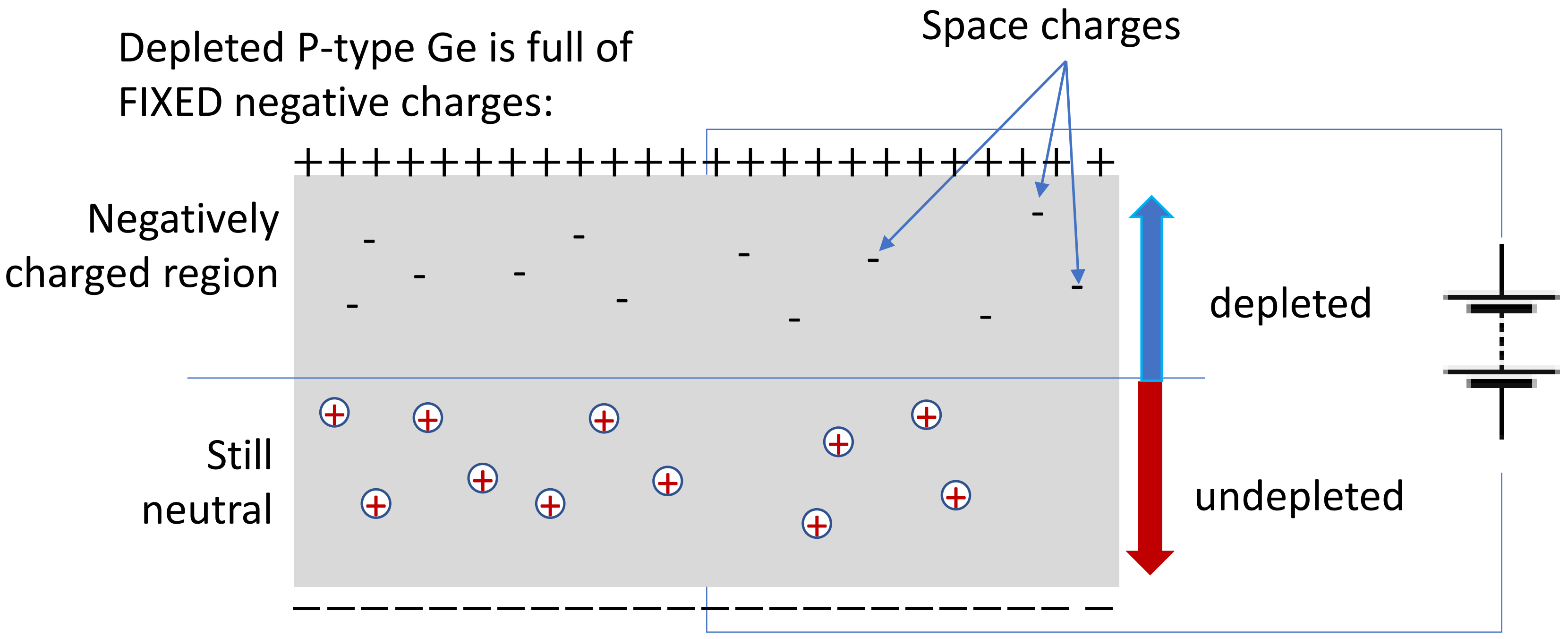
γ
e
h
+Q(t)
I(t)
-Q'(t)
0
20
40
60
80
100

Depletion of FREE-moving charges

P-type Ge is full of FREE-moving holes:



Depletion of FREE-moving charges

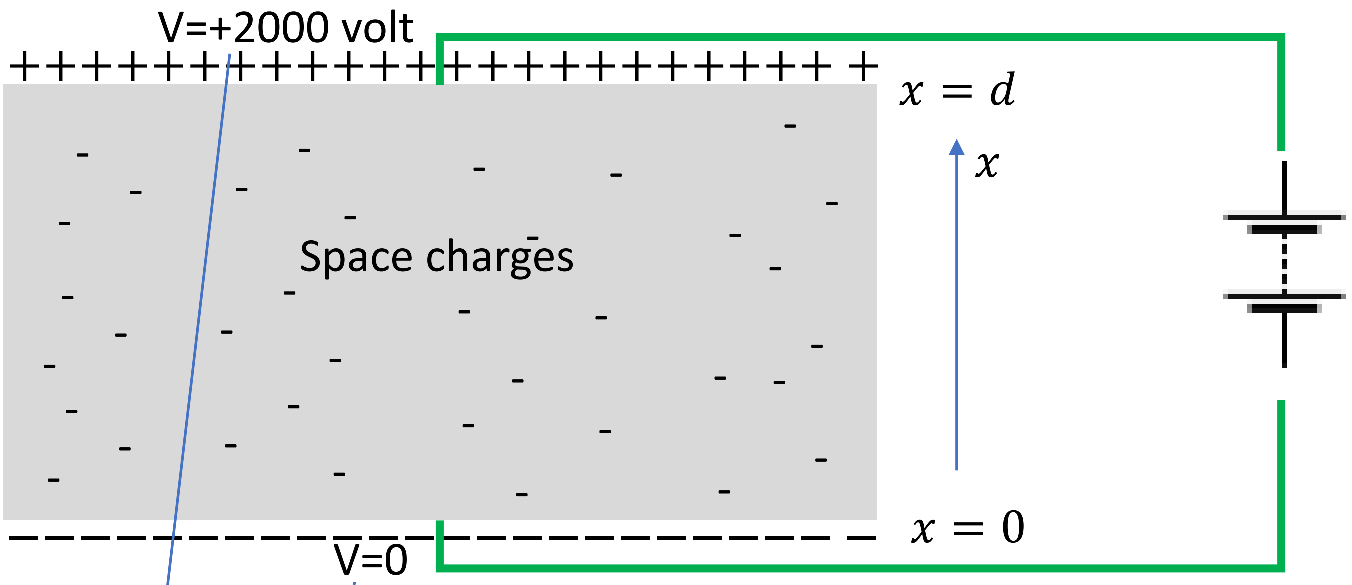


A depleted p-type Ge detector is negatively charged
A depleted n-type Ge detector is positively charged

Voltage distribution

Space charge density

Poisson's equation: $$\frac{d^2V}{dx^2} = -\frac{\rho}{\varepsilon}$$



https://www.wolframalpha.com/input/?i=V%27%27(x)%3Da

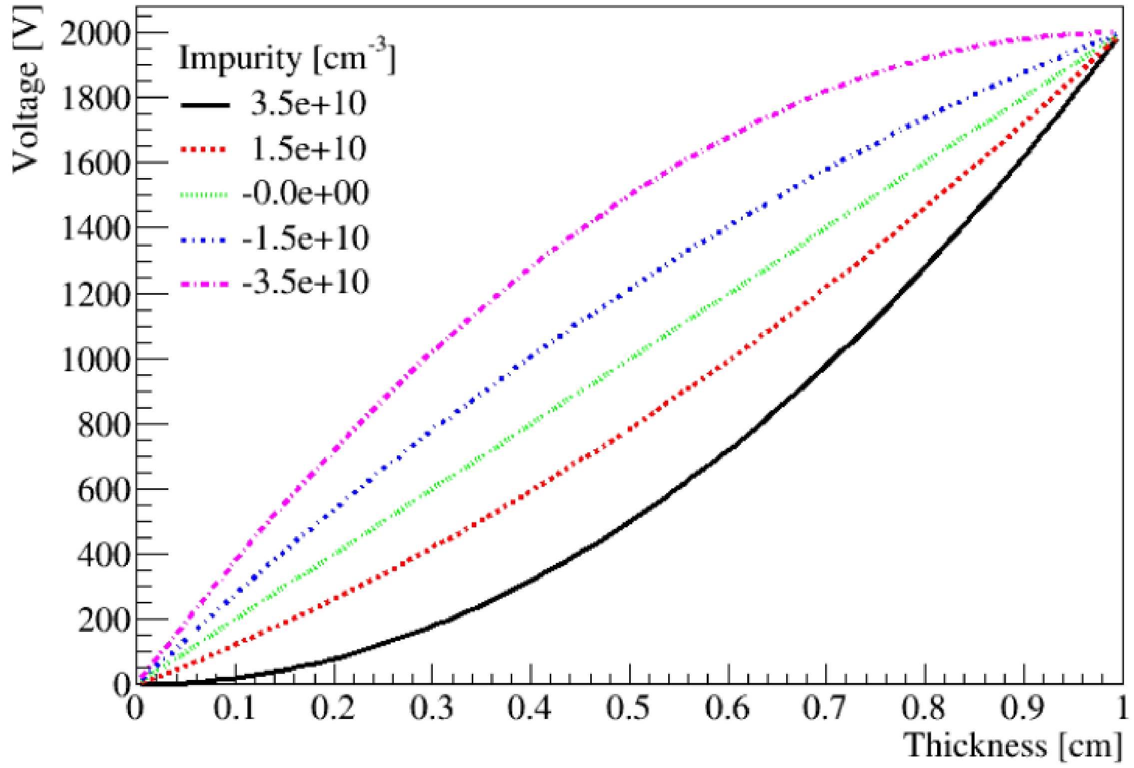
$$V = -\frac{\rho}{2\varepsilon}x^2 + C_2x + C_1$$

$$E = -\frac{dV}{dx} = \frac{\rho}{\varepsilon}x - C_2$$

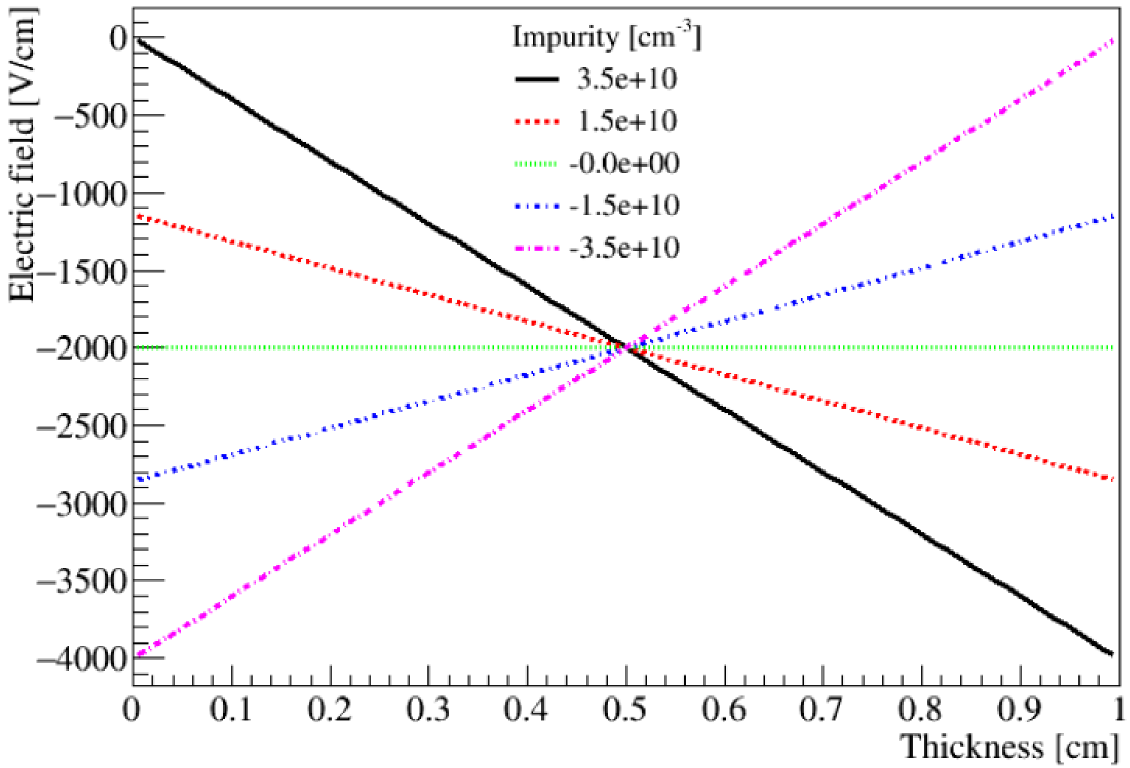
Space charges play an important role in determining E!

Voltage & E distributions in planar detectors

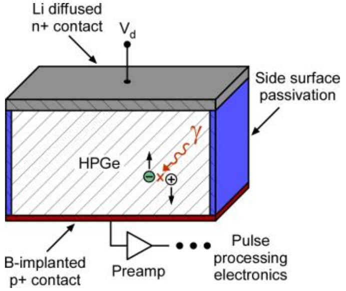
$$V = -\frac{\rho}{2\varepsilon}x^2 + C_2 x + C_1$$



$$E = -\frac{dV}{dx} = \frac{\rho}{\varepsilon}x - C_2$$

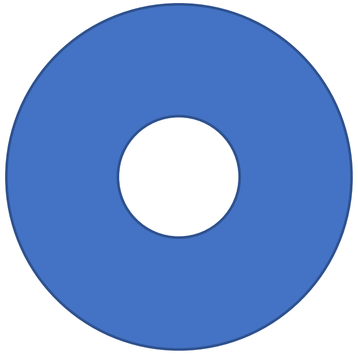


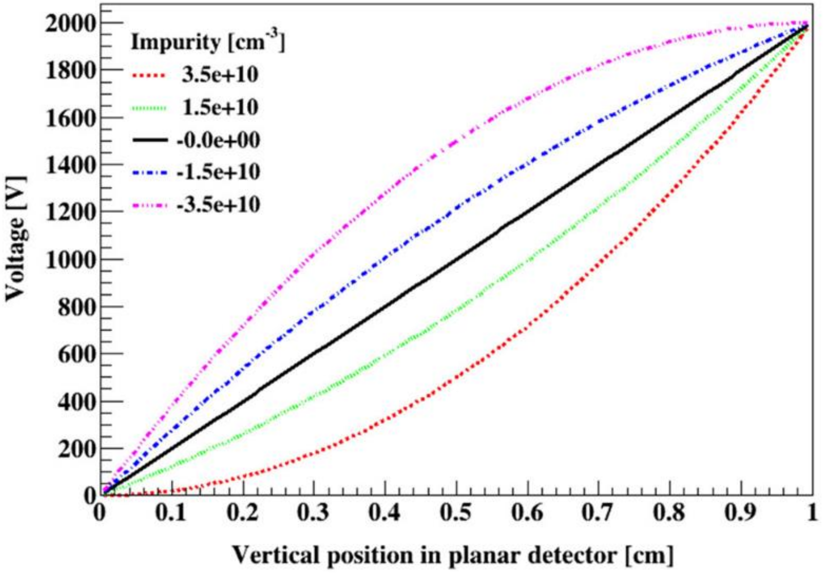
Geometry matters $\nabla^2 V(\mathbf{x}) = -\frac{\rho(\mathbf{x})}{\varepsilon}$

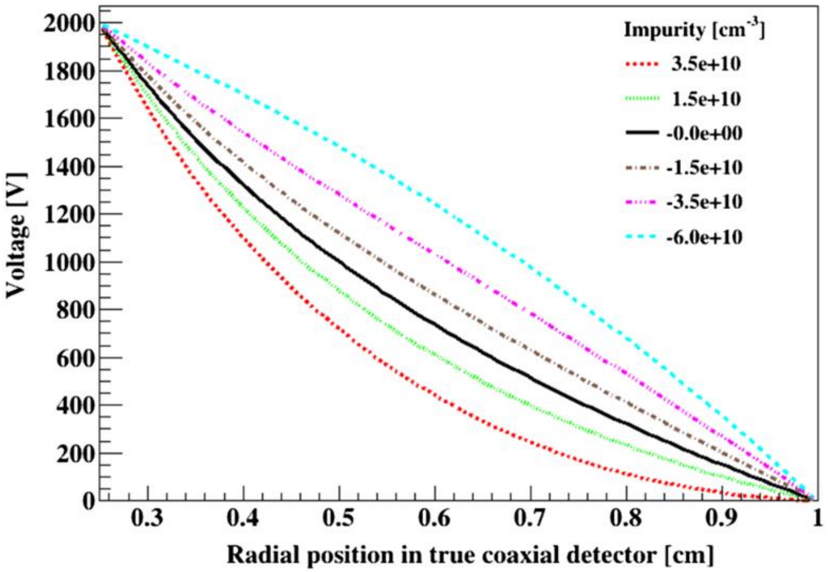


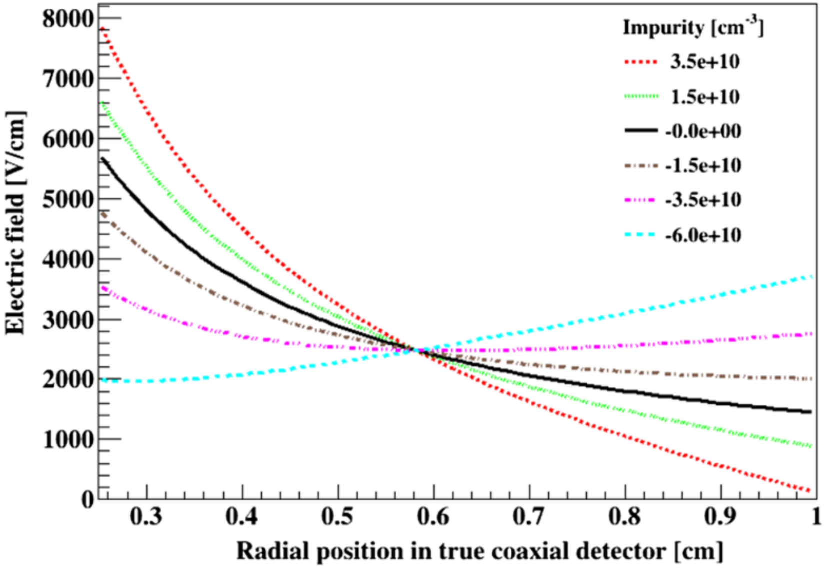
$$\frac{\mathrm{d}^2 V}{\mathrm{d}x^2} = -\frac{\rho}{\varepsilon}$$

$$\frac{1}{r}\frac{\mathrm{d}}{\mathrm{d}r}\left(r\frac{\mathrm{d}V}{\mathrm{d}r}\right) = -\frac{\rho}{\varepsilon}$$







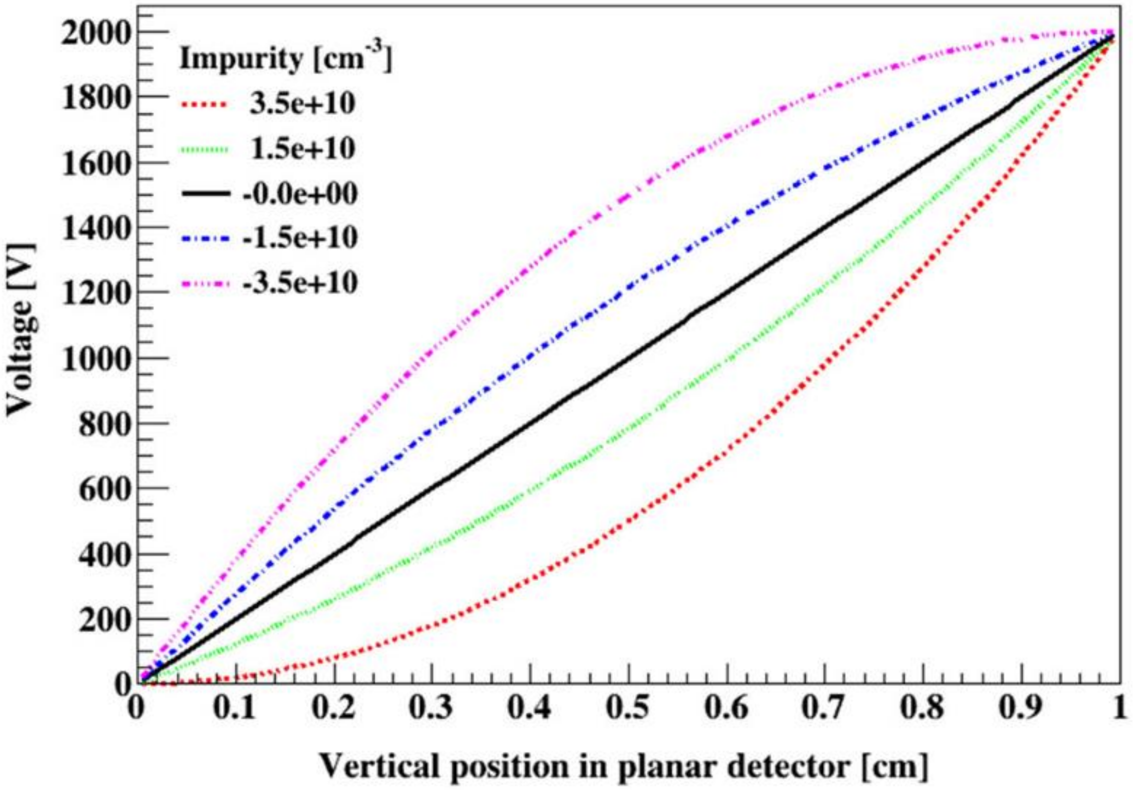


Exercise

- Market price of 5N (99.999%) Ge ingots: ~ \$1k/kg
- If we have managed to deplete a piece of 5N Ge, estimate the space charge density in it
  - Avogadro constant: 6×10^{23}
  - Ge density: 5.5 g/cm^3
  - Atomic weight of Ge: ~73, C: ~12
  - A mole of C weighs 12 g

Answer

- 1 mol C : 12 g → 1 mol of Ge: 73 g
- 1 cm^3 Ge contains 5.5/73 mol of Ge atoms
- That is 5.5/73 x 6 x 10^{23} Ge atoms
- It only has 5.5/73 x 6 x 10^{23} x ~0.001% impurity atoms (5N material)
- That is ~4.6 x 10^{17} impurity atoms per cm^3
- Some are doners, others are acceptors
- Space charge density: ~ $10^{13\text{-}15}/cm^3$

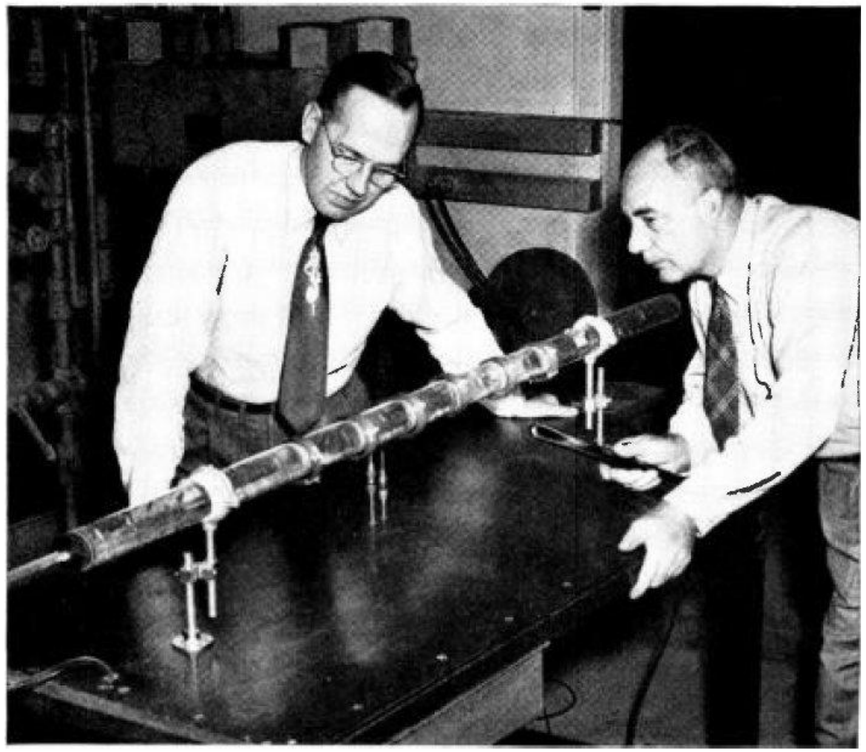


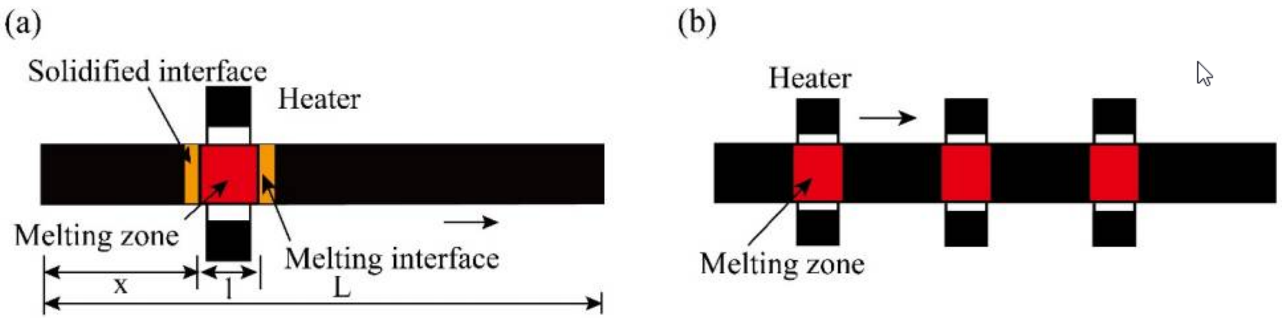
Further purification is necessary

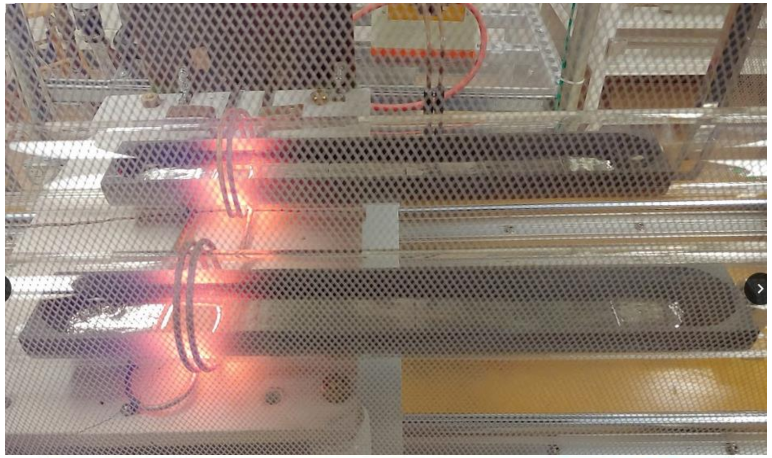
https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8072940

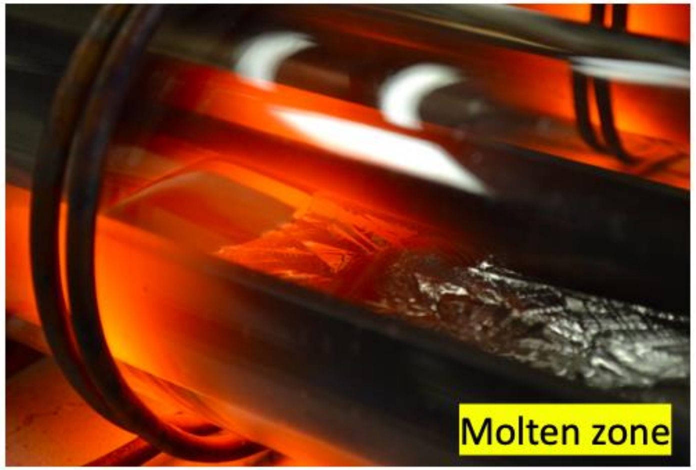
Zone refining

- invented by John Desmond Bernal
- further developed by William G. Pfann (left) in Bell Labs (1953)
- as a method to prepare high purity materials
- mainly semiconductors, for manufacturing transistors
- first commercial use was in germanium
- refined to one atom of impurity per ten billion



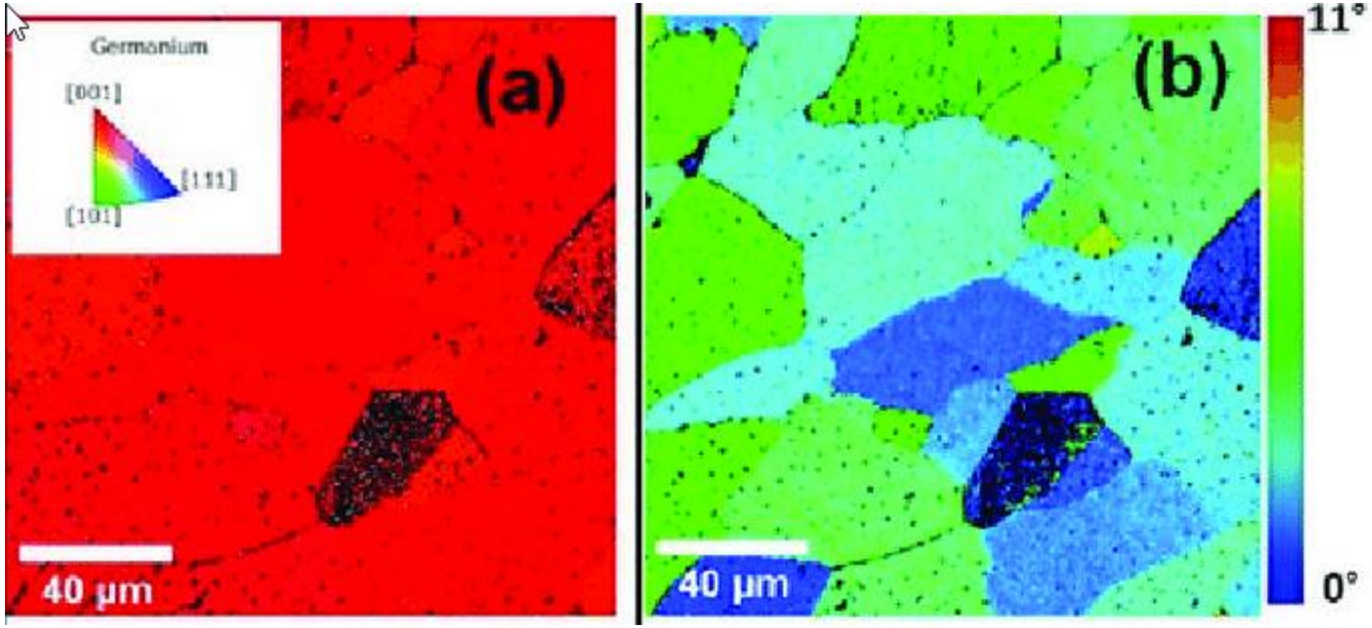






https://en.wikipedia.org/wiki/Zone_melting

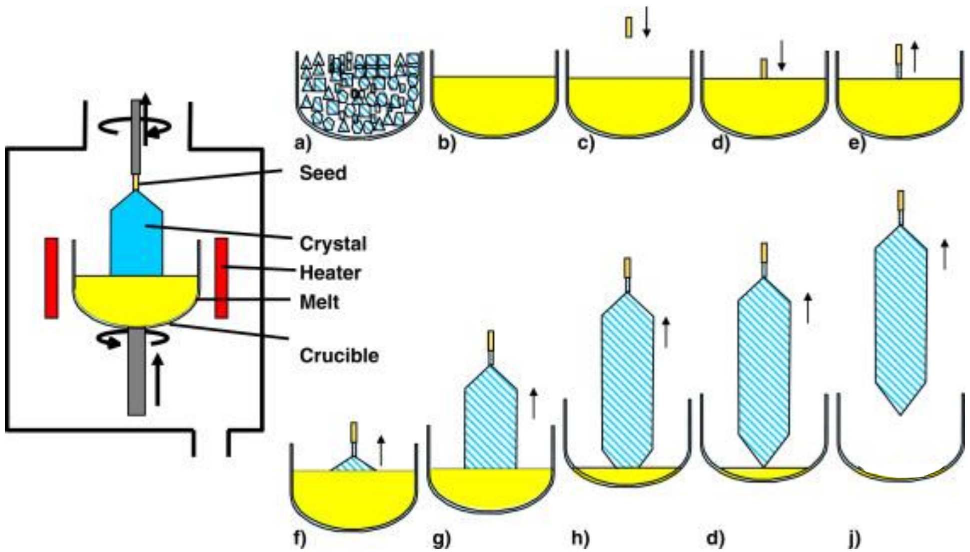
Poly crystal

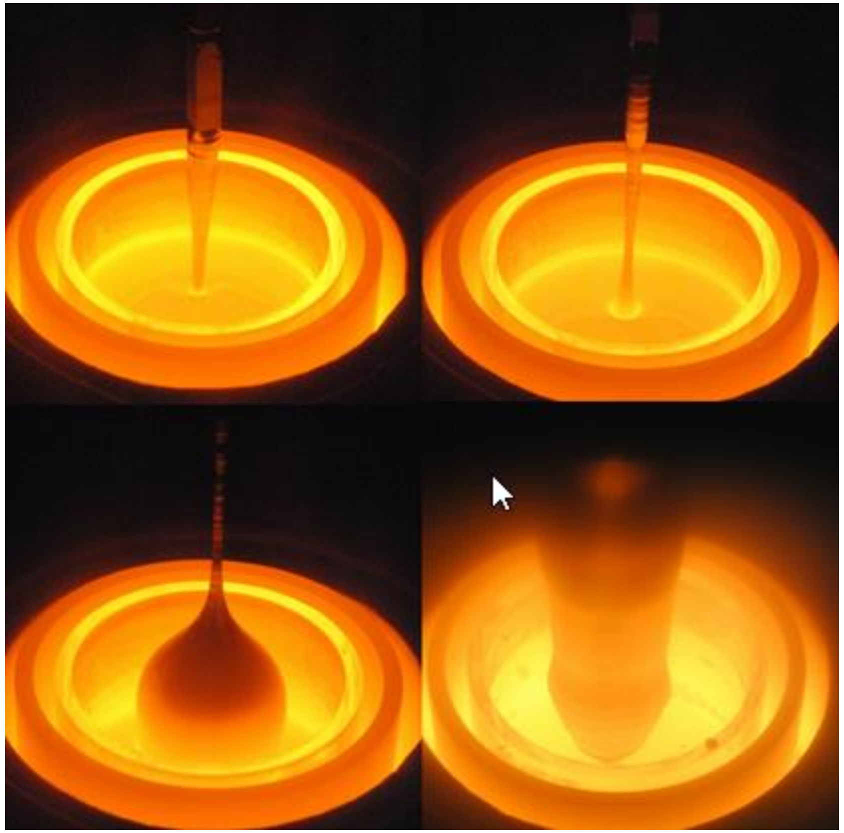


https://www.researchgate.net/figure/a-EBSD-map-of-Ge-surface-showing-the-preferred-001-growth-of-grains-b-grain-and_fig4_272266177 https://en.wikipedia.org/wiki/Czochralski_method

Crystal growth

Polish scientist Jan Czochralski invented the method in 1915 while investigating the crystallization rates of metals. He made this discovery by accident: instead of dipping his pen into his inkwell, he dipped it in molten tin, and drew a tin filament, which later proved to be a single crystal





https://www.sciencedirect.com/topics/chemistry/czochralski-process

Impurity profile

Eur. Phys. J. C (2020) 80:230
https://doi.org/10.1140/epjc/s10052-020-7786-0
THE EUROPEAN PHYSICAL JOURNAL C
Special Article - New Tools and Techniques

HPGe detector field calculation methods demonstrated with an educational program, GeFiCa

Jianchen Li, Jing Liu[a], Kyler Kooi
Department of Physics, University of South Dakota, 414 East Clark Street, Vermillion, SD 57069, USA

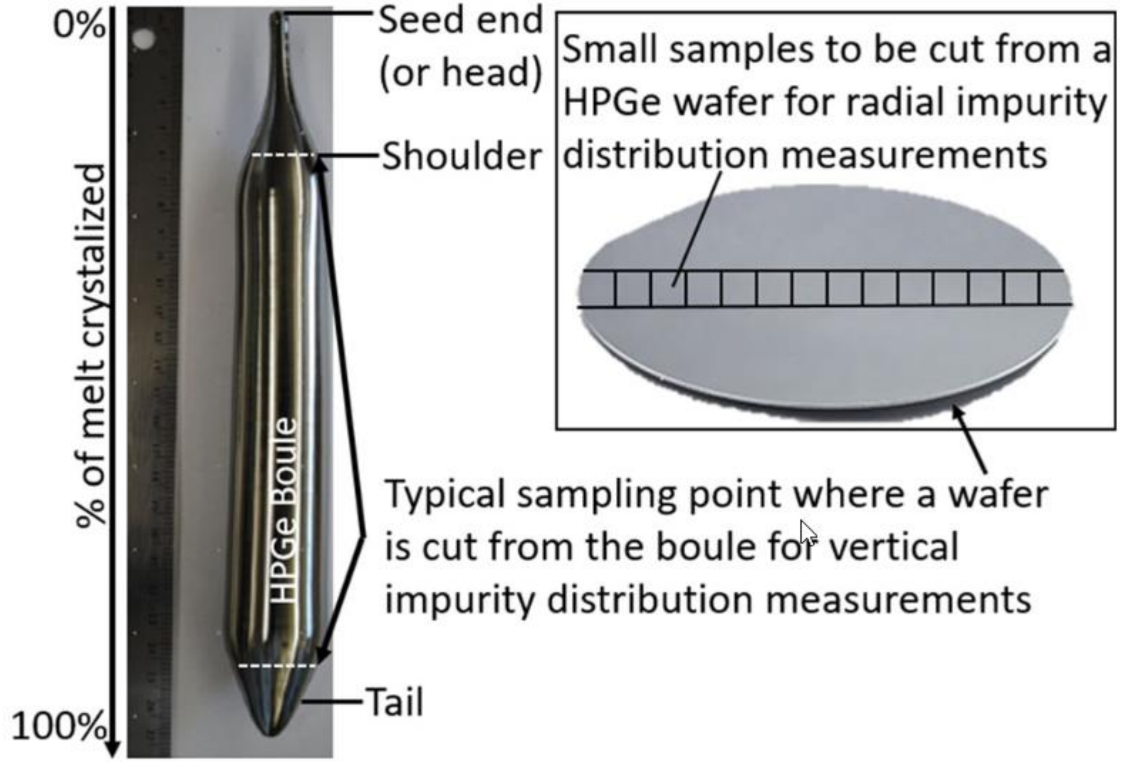


Fig. 2 A HPGe single-crystal boule pulled using the Czochralski method, and a HPGe wafer cut from the boule for impurity measurements

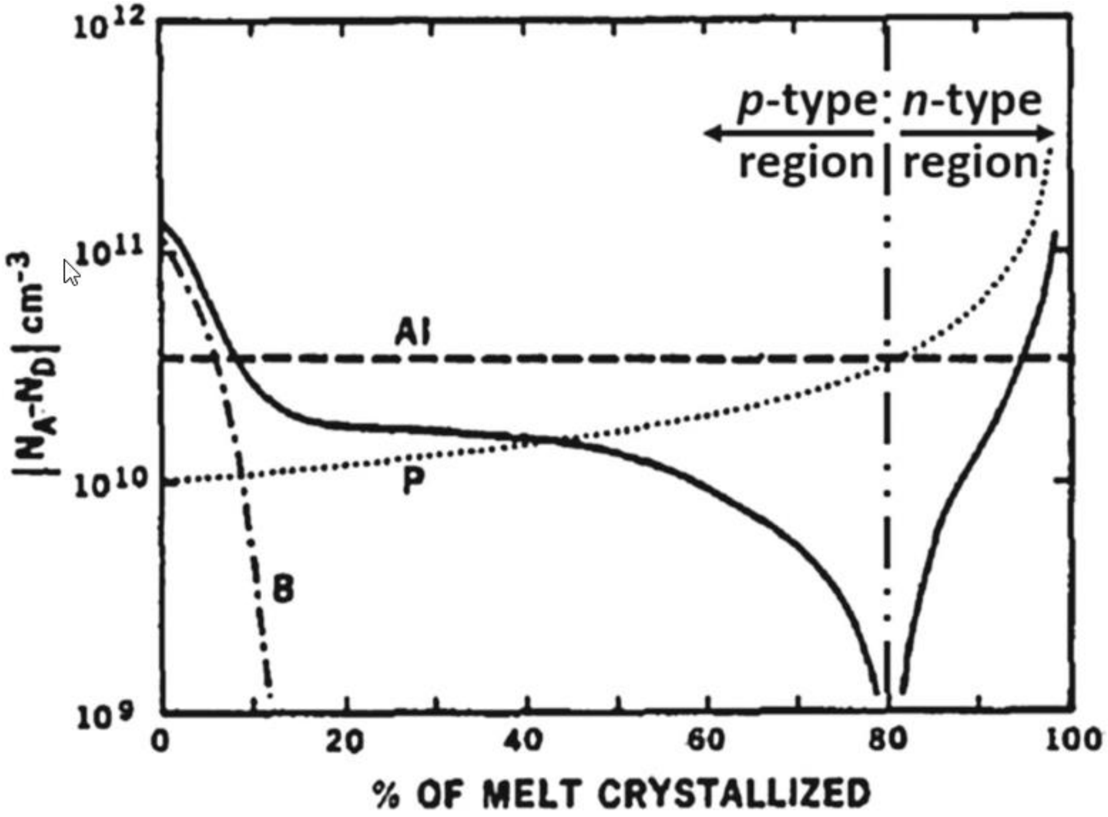
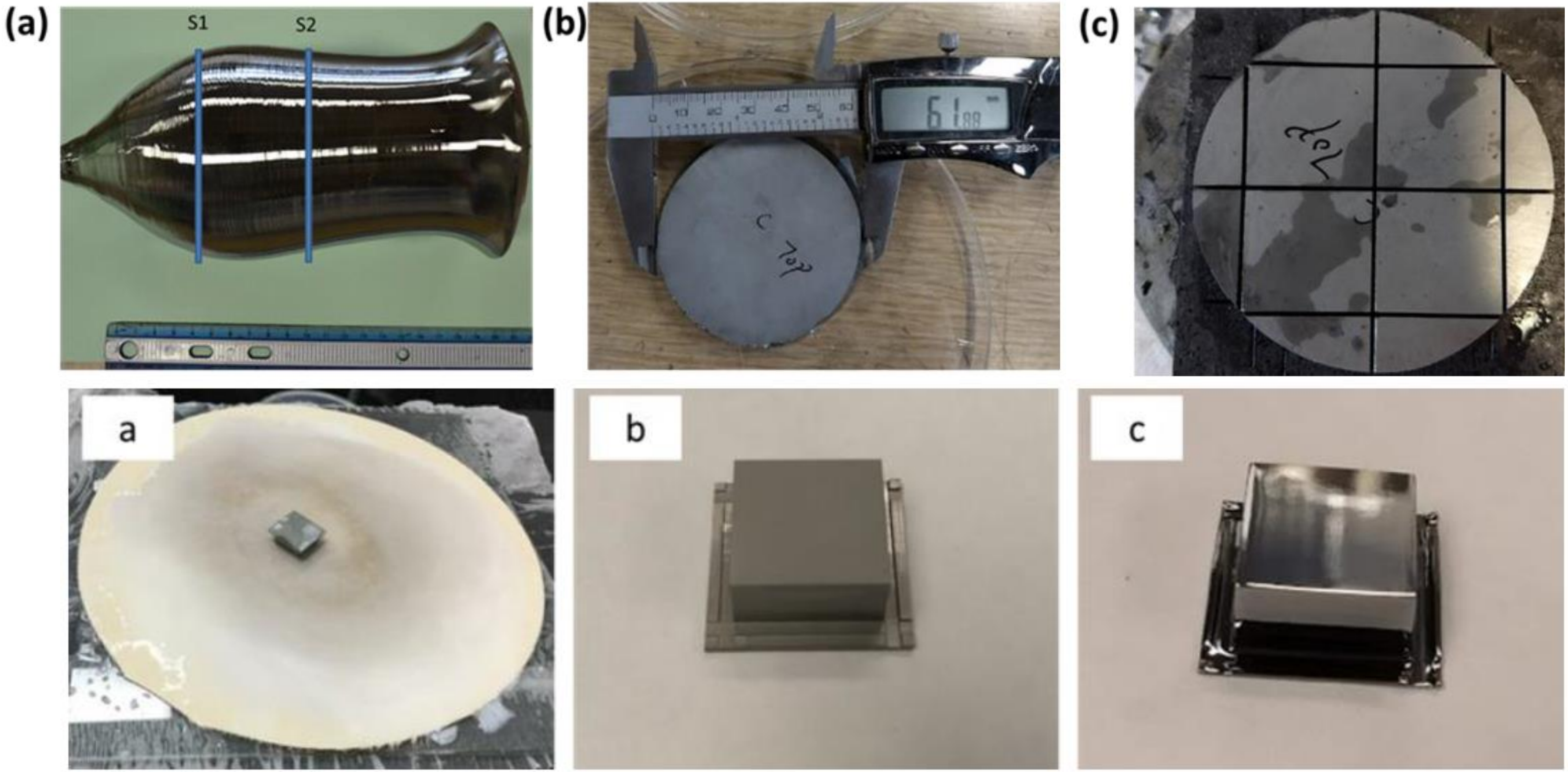


Fig. 3 A typical vertical net impurity concentration profile of a HPGe single-crystal boule, taken from [30]

Doi:10.1088/1748-0221/14/02/P02019

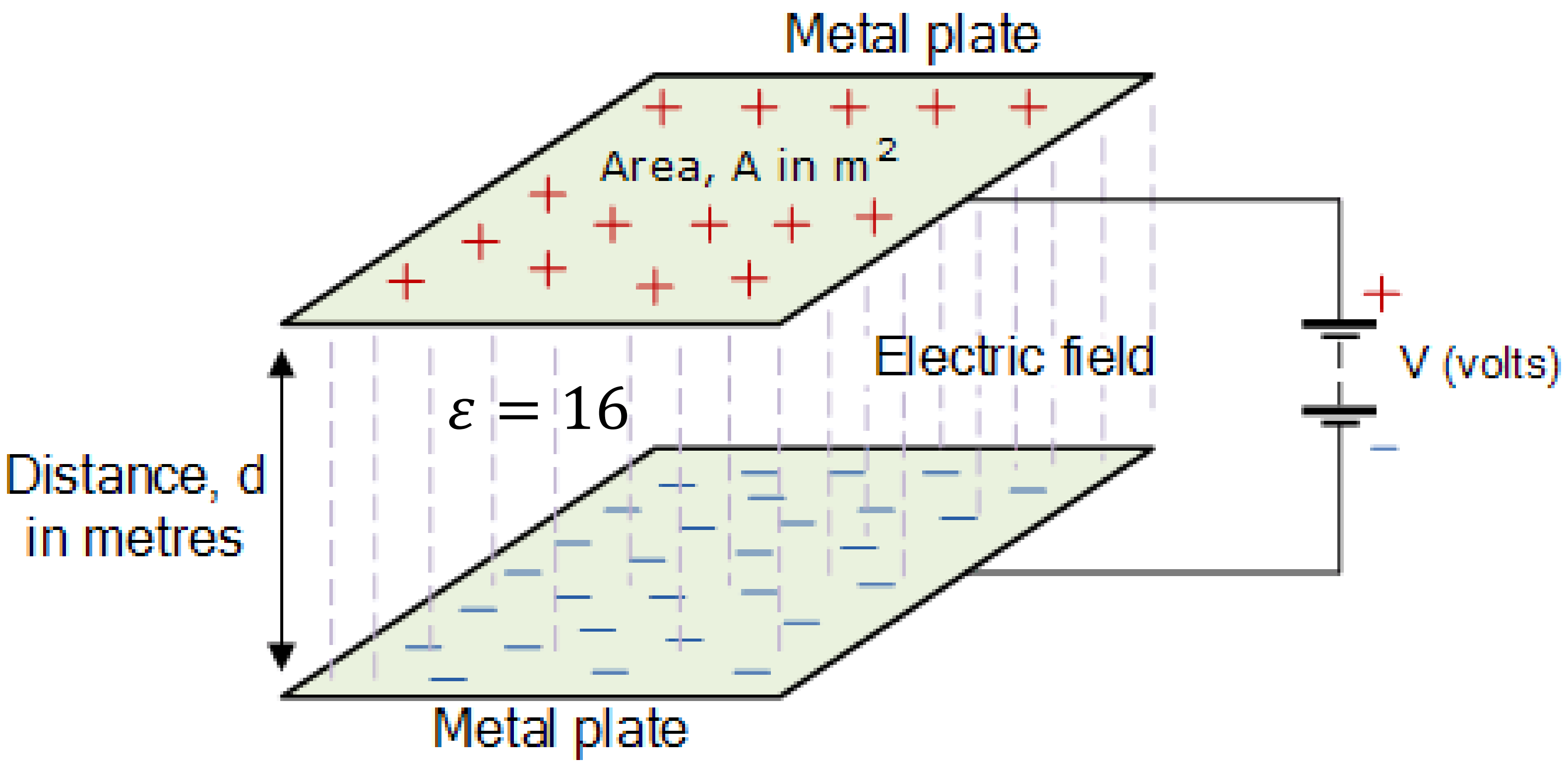
Planar detector fabrication procedure



Summary

- Charged particles create electron-hole pairs in semiconductor
  - Ge needs to be cooled into a semiconductor
- To extract them out of the solid, we need to create E field
  - P-I-N junction needs to be created on surfaces (contacts)
  - Space charges (impurities) need to be reduced (crystal purification & growth)
    - Working Ge detector is not neutral (p-type is negative, n-type is positive)
  - Shape of detector can be optimized to have more uniform E across
    - Both boundary conditions and space charge distributions change E

Capacitance of a planar detector



https://www.electronics-tutorials.ws/capacitor/cap_4.html

Capacitance of a parallel capacitor

σ = charge density

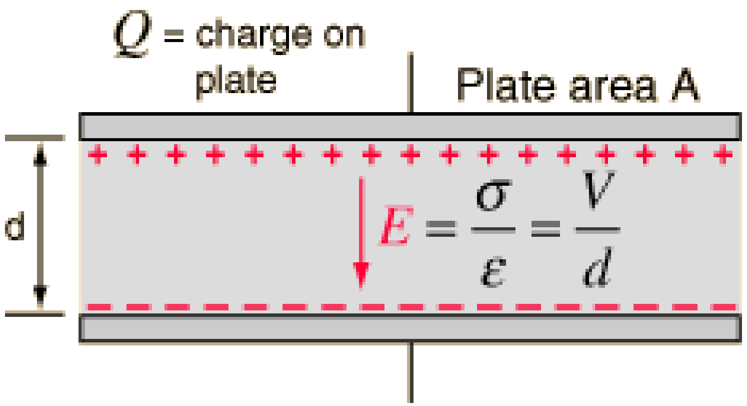
ε = permittivity

$$E = \frac{\sigma}{\varepsilon} \qquad \sigma = \frac{Q}{A}$$

Definition of C

$$C = \frac{Q}{V} = \frac{Q}{Ed} = \frac{Q\varepsilon}{\sigma d} = \frac{QA\varepsilon}{Qd} = \frac{A\varepsilon}{d}$$

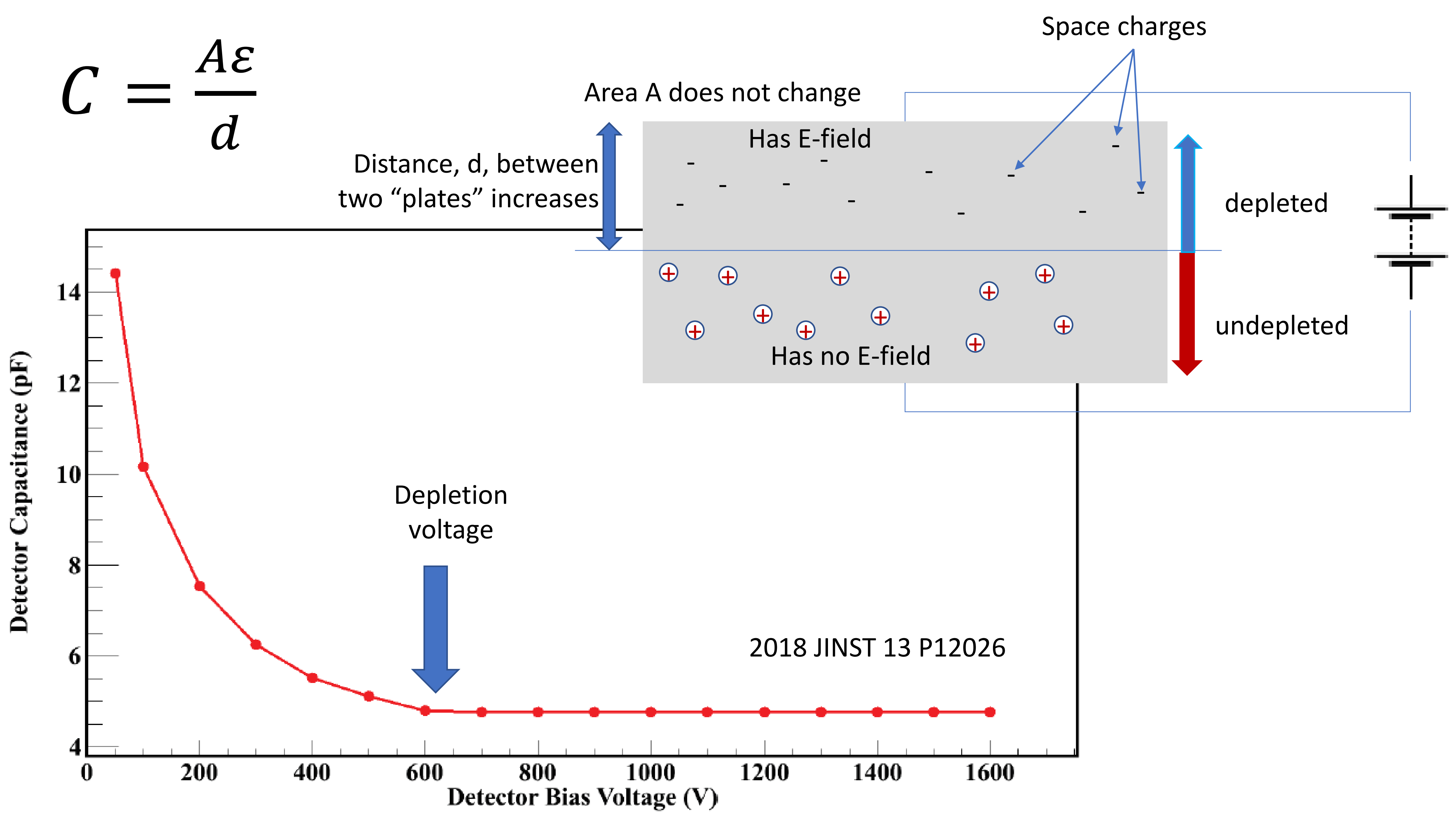
$$V = \frac{\text{work done}}{\text{charge}} = \frac{Fd}{q} = Ed$$



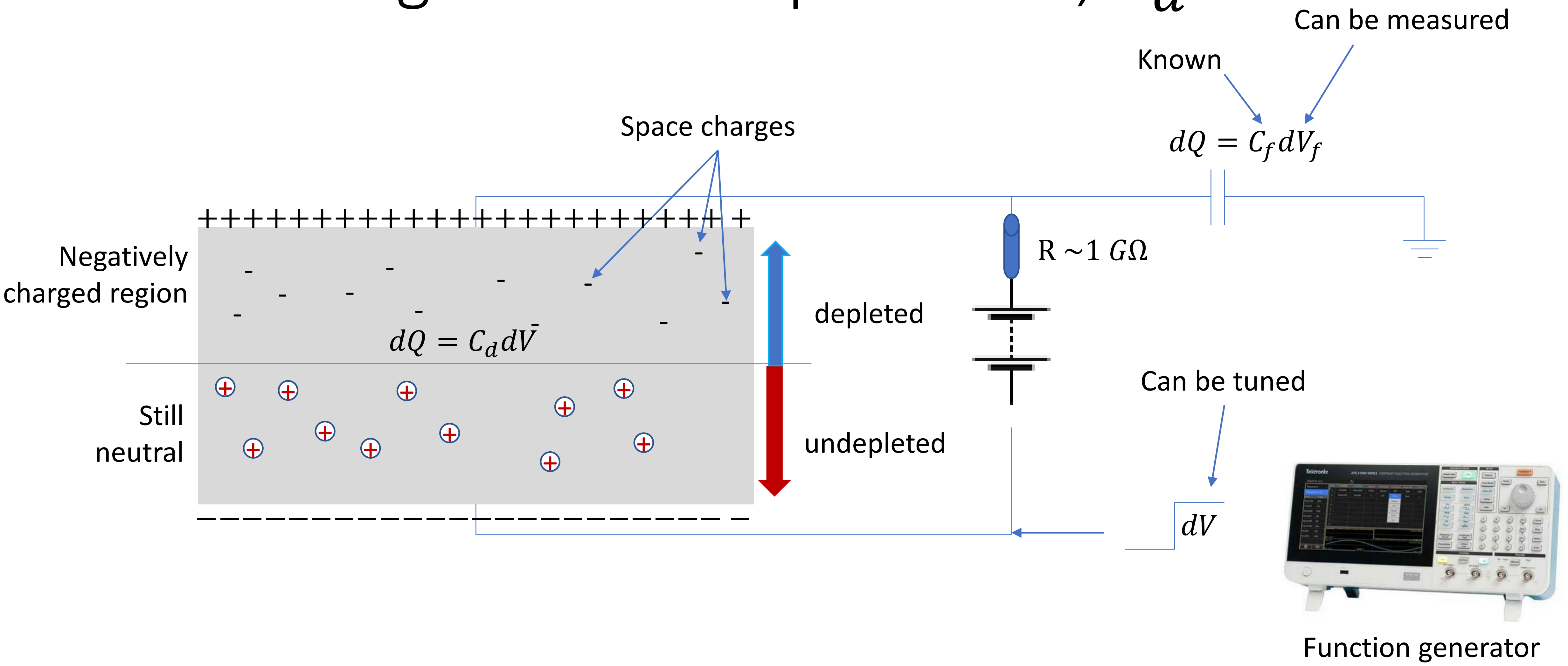
Kahoot.it

http://hyperphysics.phy-astr.gsu.edu/hbase/electric/pplate.html

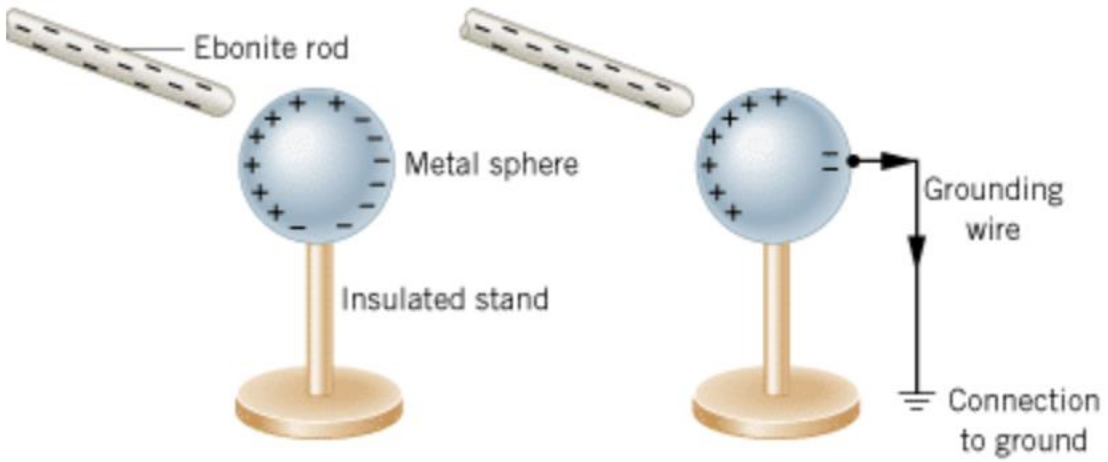
$$C = \frac{A\varepsilon}{d}$$

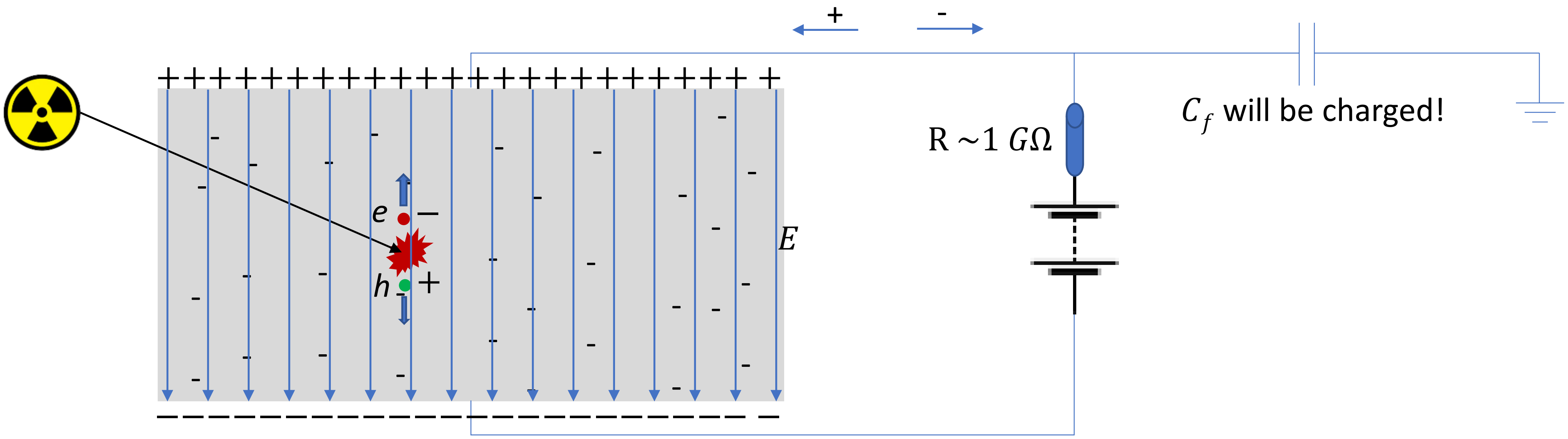


Measuring detector capacitance, C_d



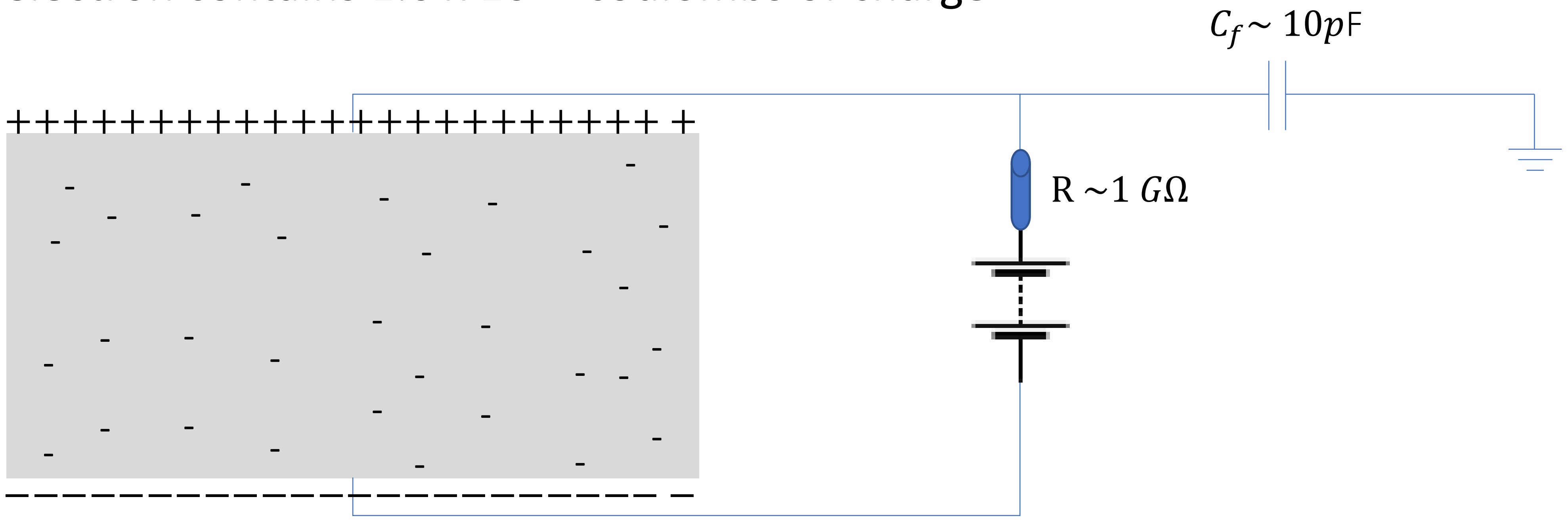
Transient signal





Exercise

- A $0\nu\beta\beta$-decay deposits ~ 2 MeV energy in our Ge detector, how much voltage we can measure in the following circuit?
  - On average, 2.9 eV is needed to create 1 pair of electron and hole
  - One electron contains 1.6 x 10^{-19} coulombs of charge



$$Q = \frac{2 \times 10^{6}\ \text{eV}}{2.9\ \text{eV}} \; 1.6 \times 10^{-19}$$

V=Q/C~ 11 mV

Exercise

- A $0\nu\beta\beta$-decay deposits ~ 2 MeV energy in our Ge detector, how much voltage we can measure in the following circuit?
  - On average, 2.9 eV is needed to create 1 pair of electron and hole
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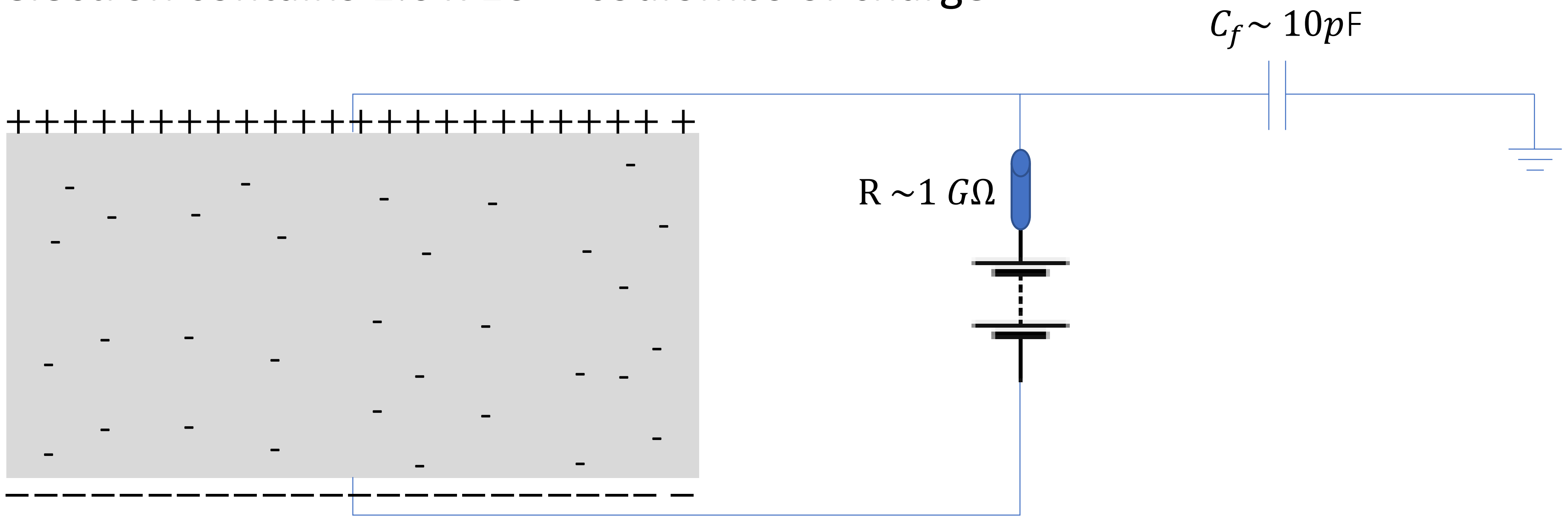
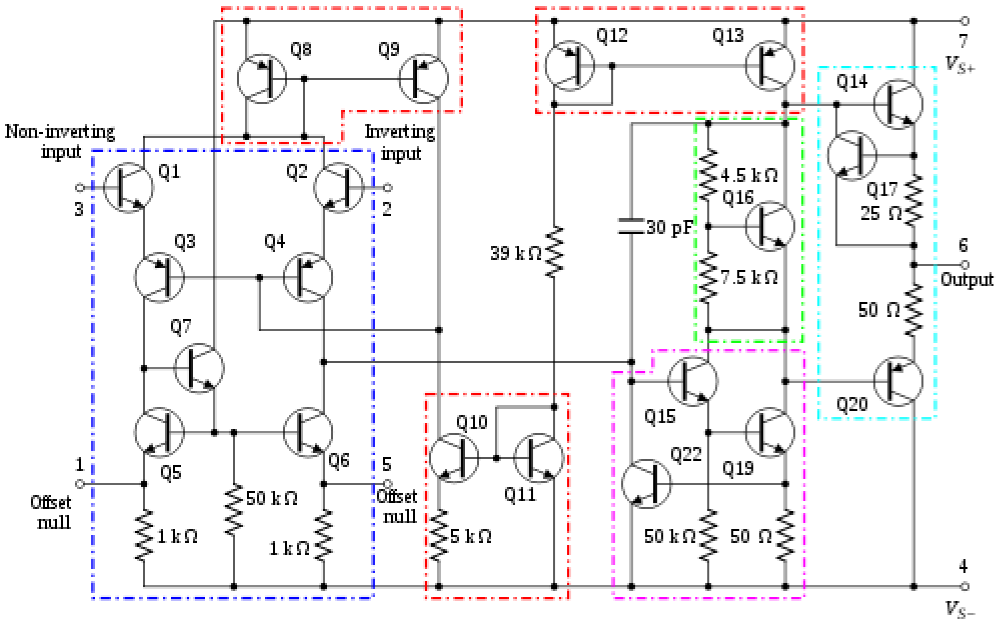
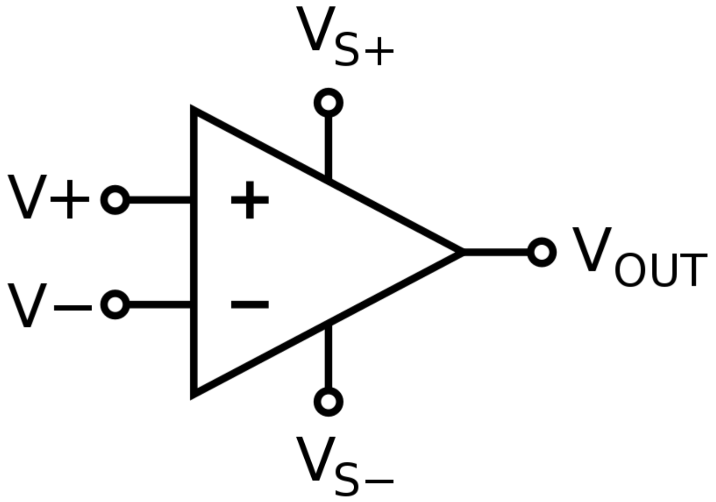


Operational amplifier

A component-level diagram
of the common 741 op-amp:

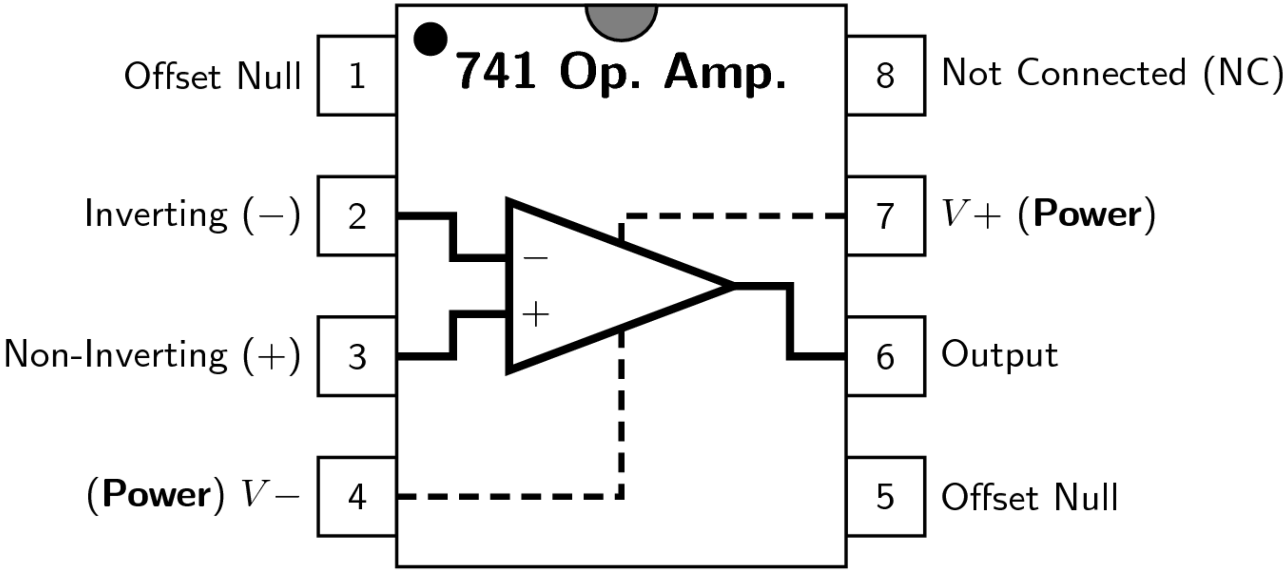


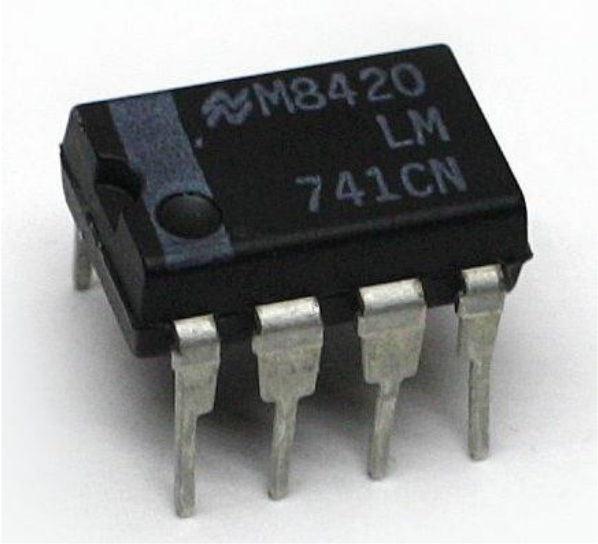


output potential (relative to circuit ground) is typically 100,000 times larger than the potential difference between its input terminals.

https://en.wikipedia.org/wiki/Operational_amplifier

Operational amplifier

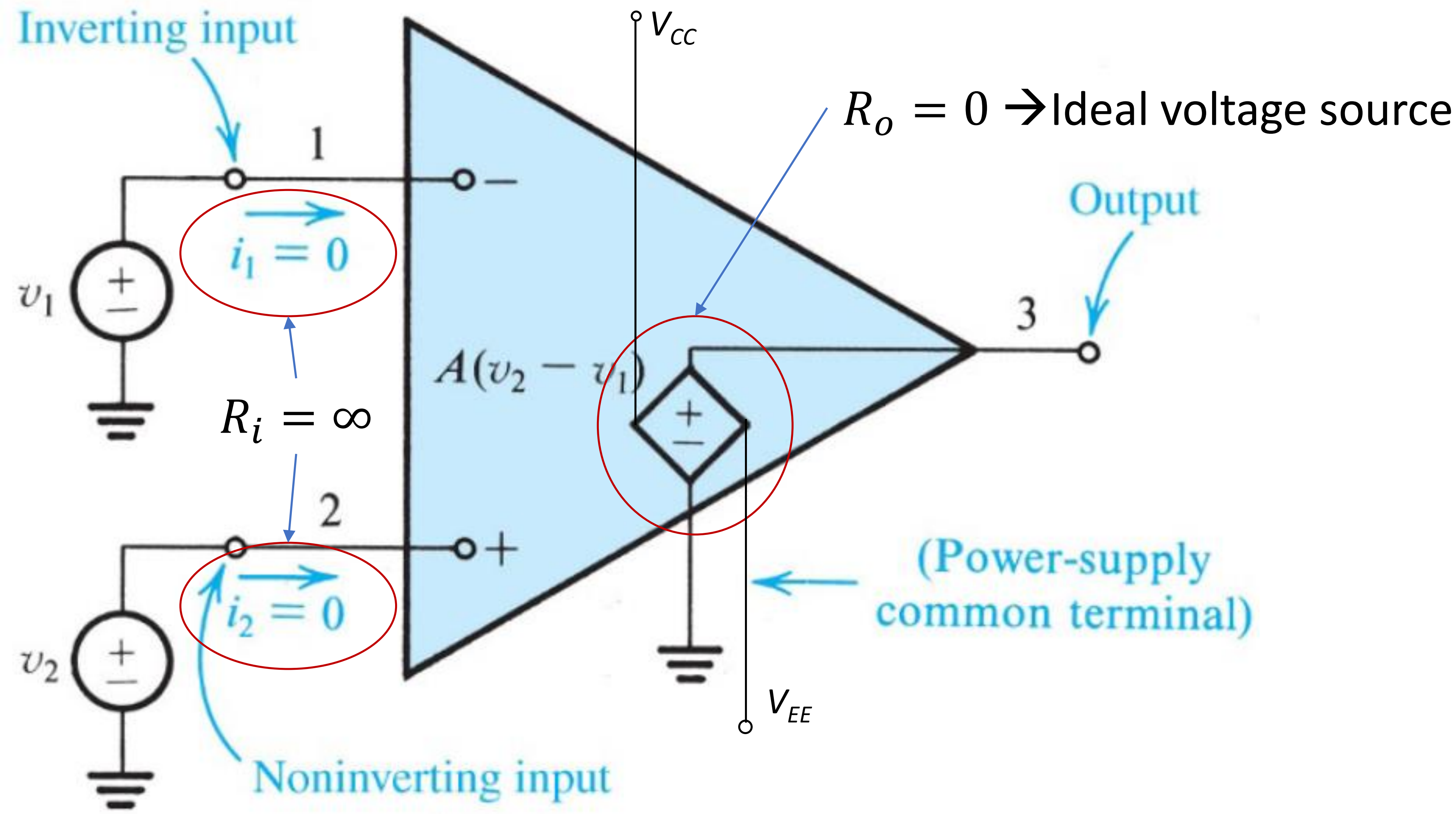




Ideal operational amplifier

- Infinite gain
- Infinite bandwidth

Input resistance R_i:
It is measured by connecting an ideal ohmmeter between the input of the device and common ground



Charge sensitive amplifier

Inverting voltage amplifier

Feedback capacitor

$$v_o = -Av_i$$

Voltage gain~∞

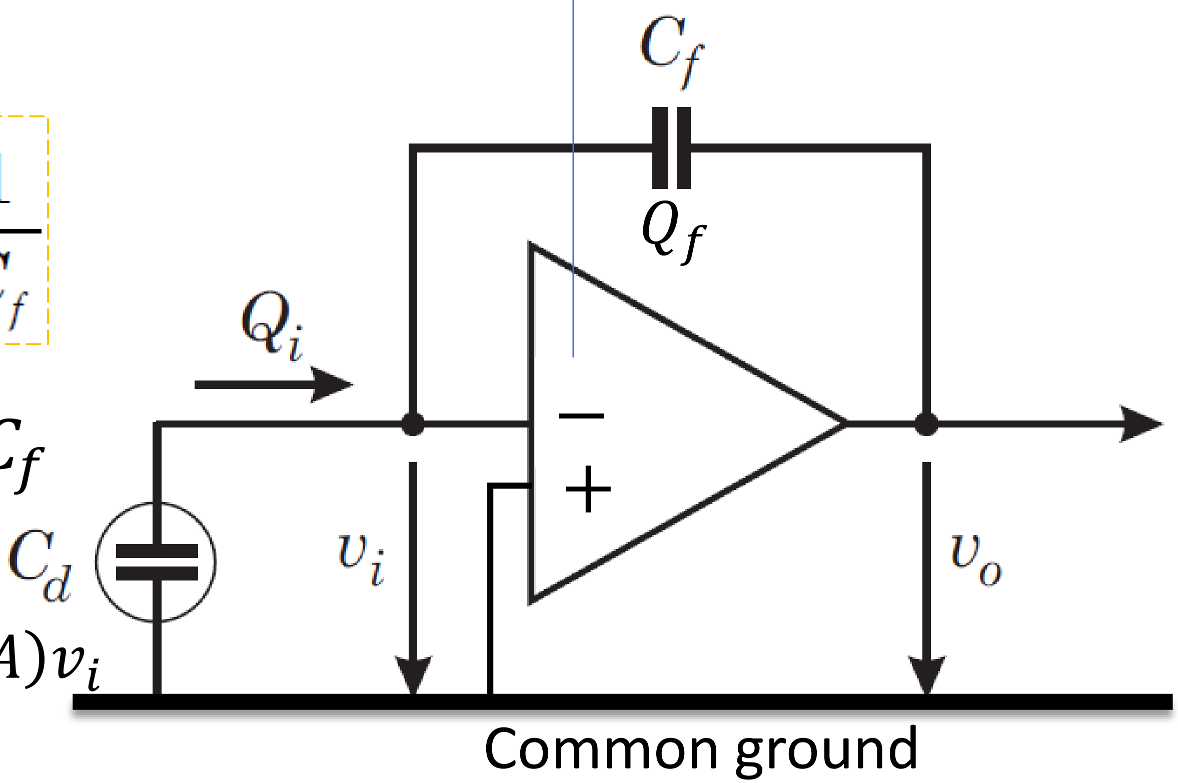
$$A_Q = \frac{V_o}{Q_i} = \frac{-A\cdot v_i}{C_i\cdot v_i} = \frac{-A}{C_i} = \frac{-A}{-(A+1)}\cdot\frac{1}{C_f} \approx \frac{1}{C_f}$$

$$C_i = \frac{Q_i}{v_i} = Q_f/v_i = -(A+1)C_f$$

Since no charge can flow into opt-amp ($R_i = \infty$), $Q_i = Q_f = C_f v_f = -C_f(1+A)v_i$

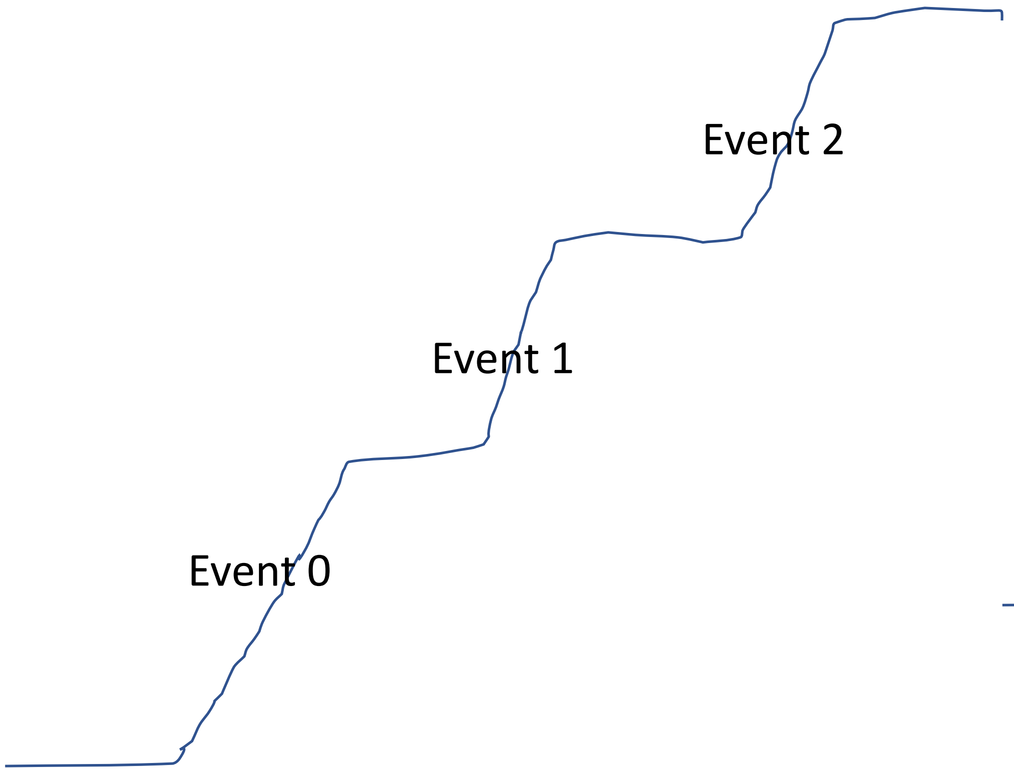
$$v_f = v_o - v_i = -Av_i - v_i = -(1+A)v_i$$

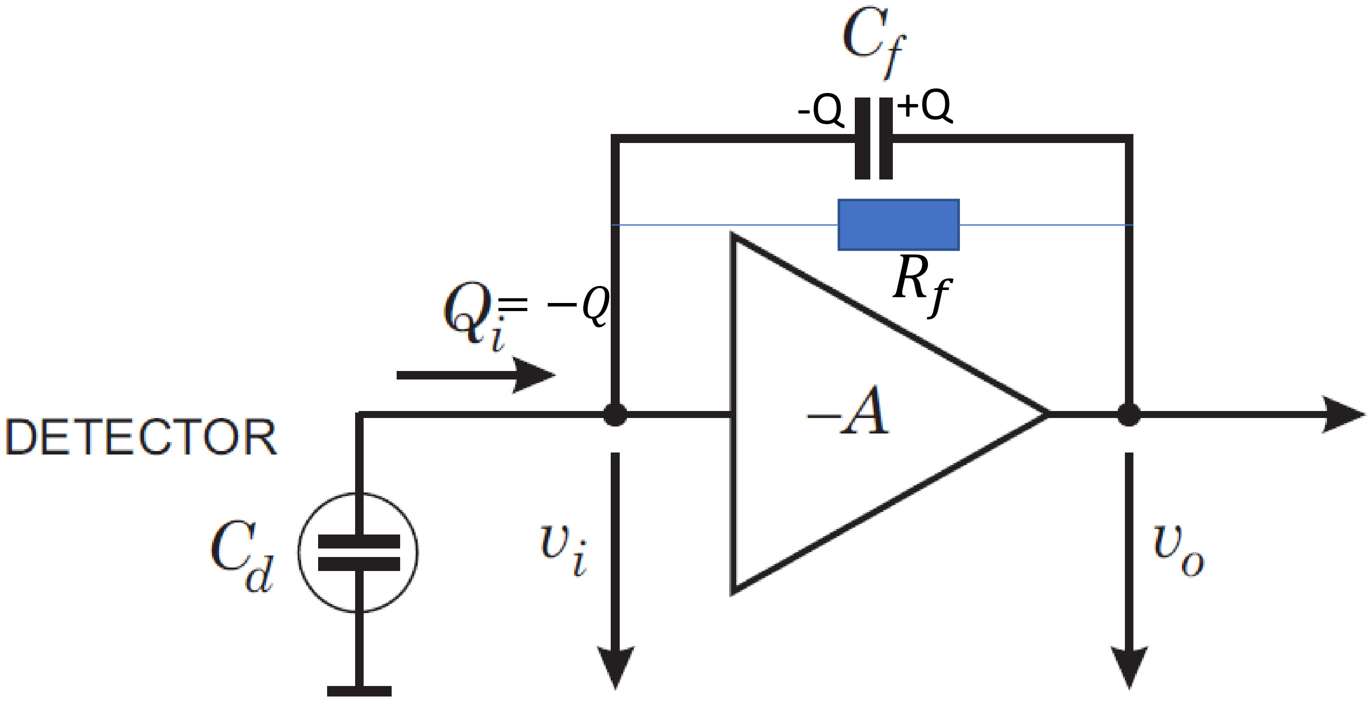
$$v_o = -Av_i$$

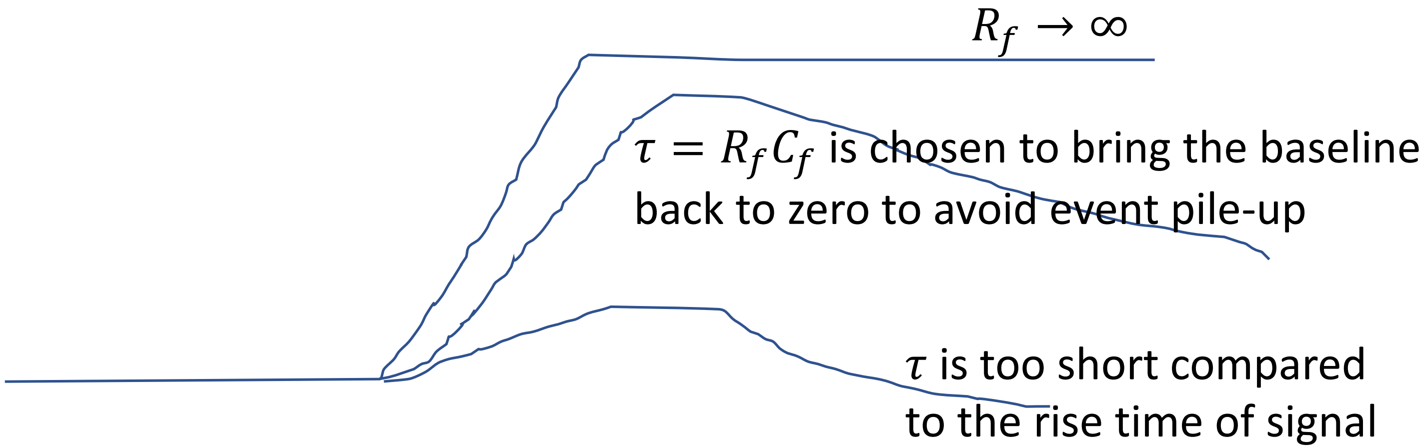


Feedback resistor

Event pile-up without R_f:







Practice: is a large R_f preferred in 0vbb experiments?

Complete circuit

Eur. Phys. J. C (2020) 80:667
https://doi.org/10.1140/epjc/s10052-020-8235-9
THE EUROPEAN PHYSICAL JOURNAL C
Regular Article - Experimental Physics

Characterization of high-purity germanium detectors with amorphous germanium contacts in cryogenic liquids

R. Panth[1], J. Liu[1,a], I. Abt[2], X. Liu[2], O. Schulz[2], W.-Z. Wei[1], H. Mei[1], D.-M. Mei[1], G.-J. Wang[1]
[1] University of South Dakota, 414 East Clark Street, Vermillion, SD 57069, USA
[2] Max-Planck-Institut für Physik, Föhringer Ring 6, 80805 Munich, Germany

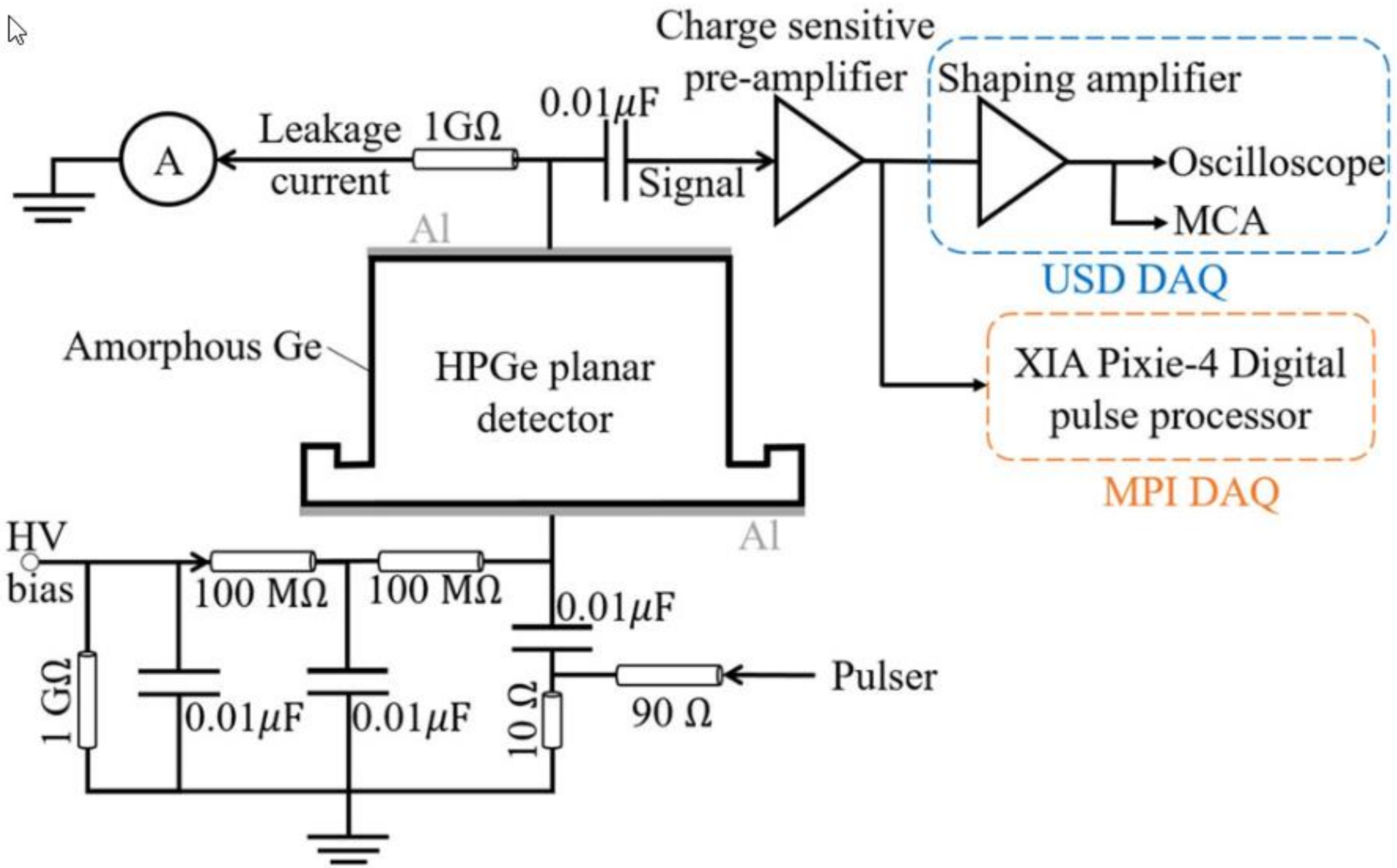
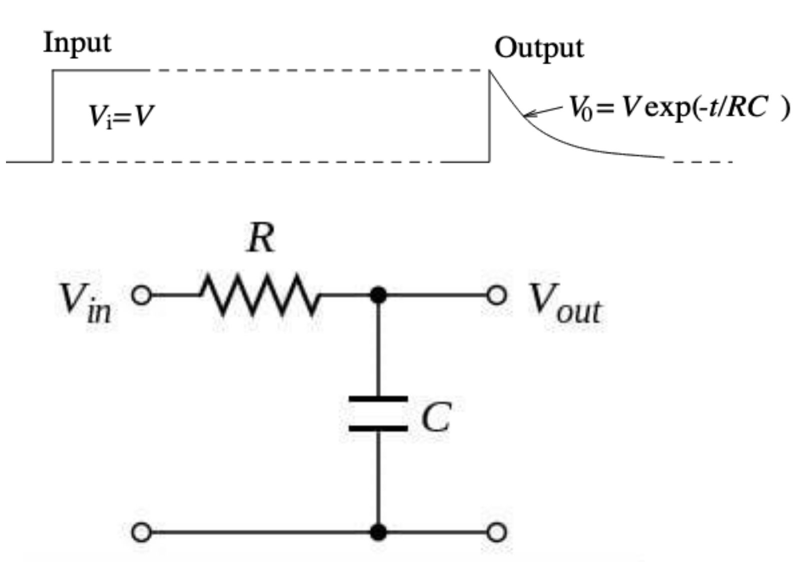
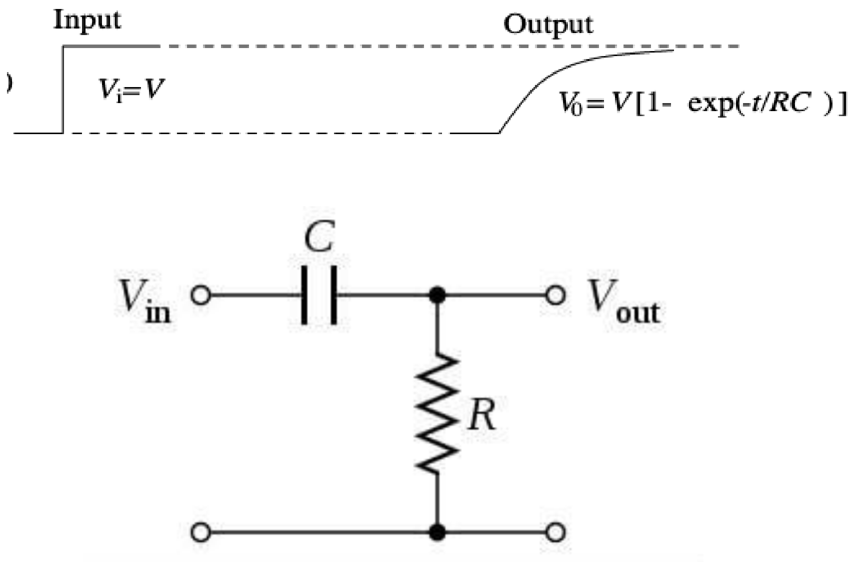


Fig. 3 Electronic circuit for detector characterization

https://www.arrow.com/en/research-and-events/articles/rc-circuit-basics-low-high-pass-filtering-and-formulas

Filters



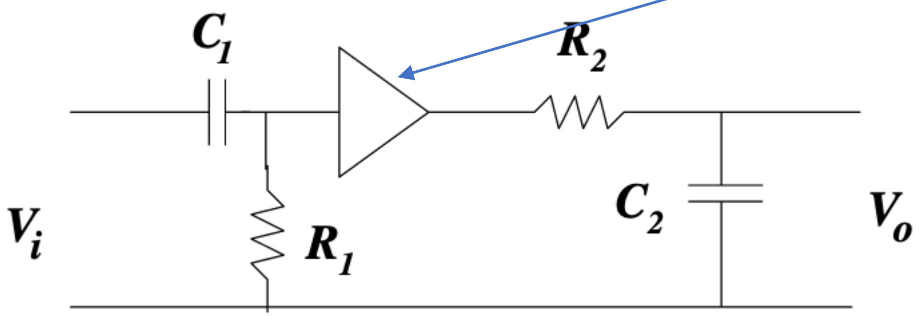


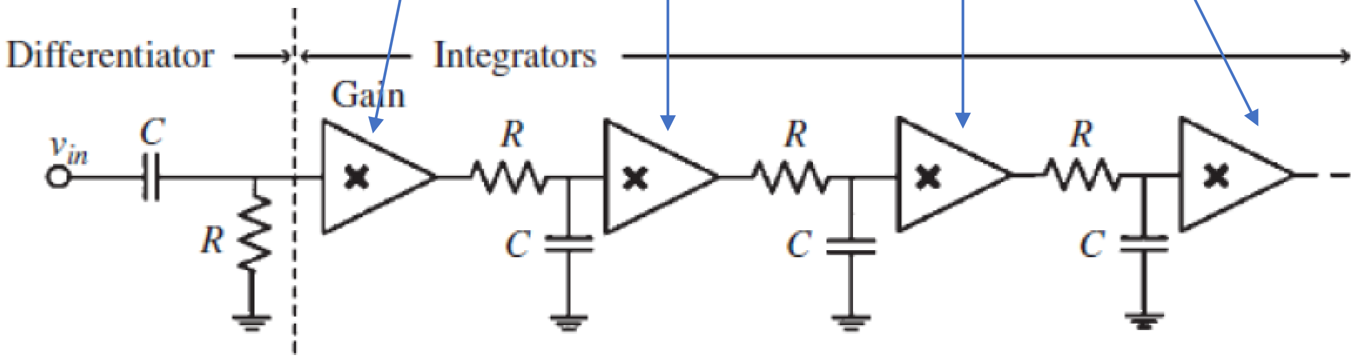
because the capacitor never reaches a full charge when the input frequency is too high, the capacitor can intercept current that would otherwise go to the output of the circuit as it pulses. As a result, the electrical output approaches zero above a particular frequency.

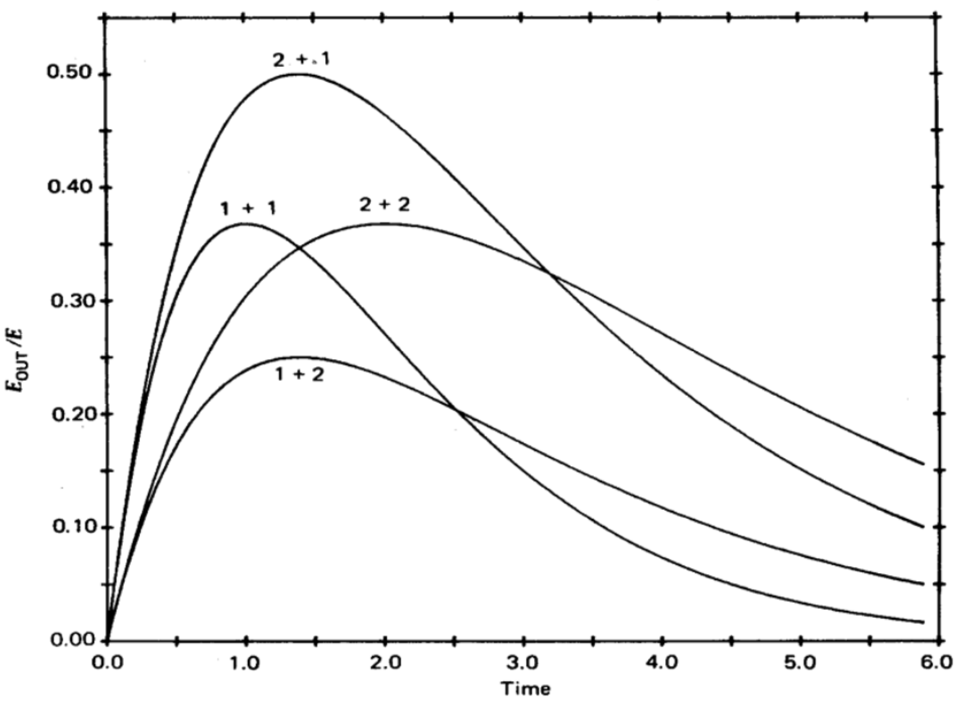
high-frequency signals can pass, while the capacitor blocks any frequencies that are too low.

Shaping amplifier

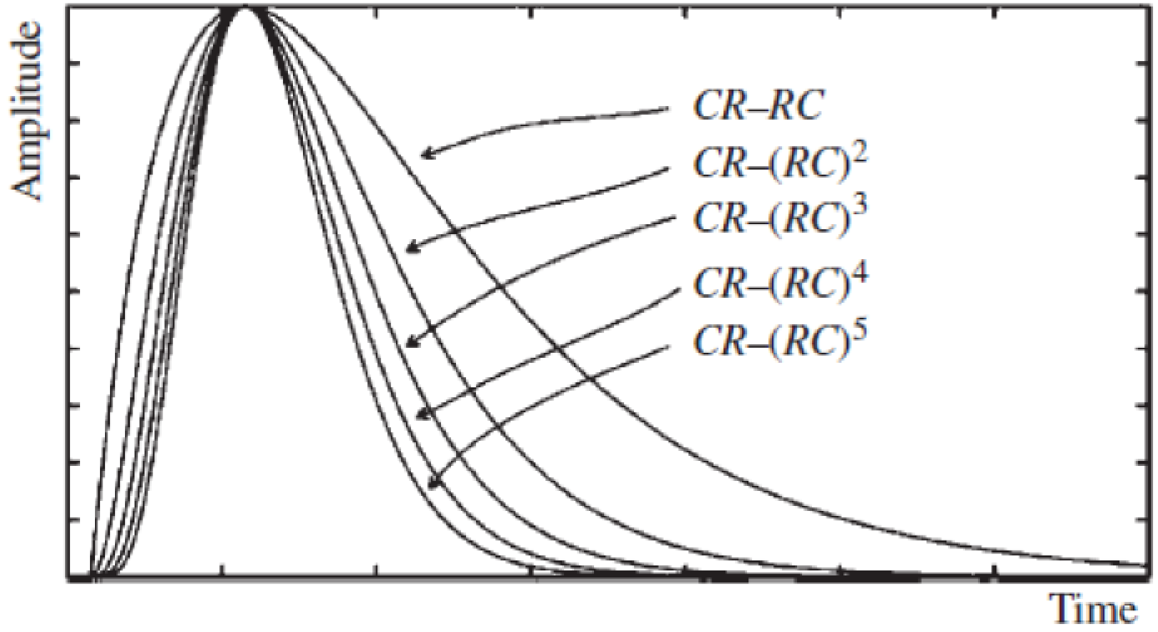
infinite input impedance and zero output impedance,
serves to isolate individual networks



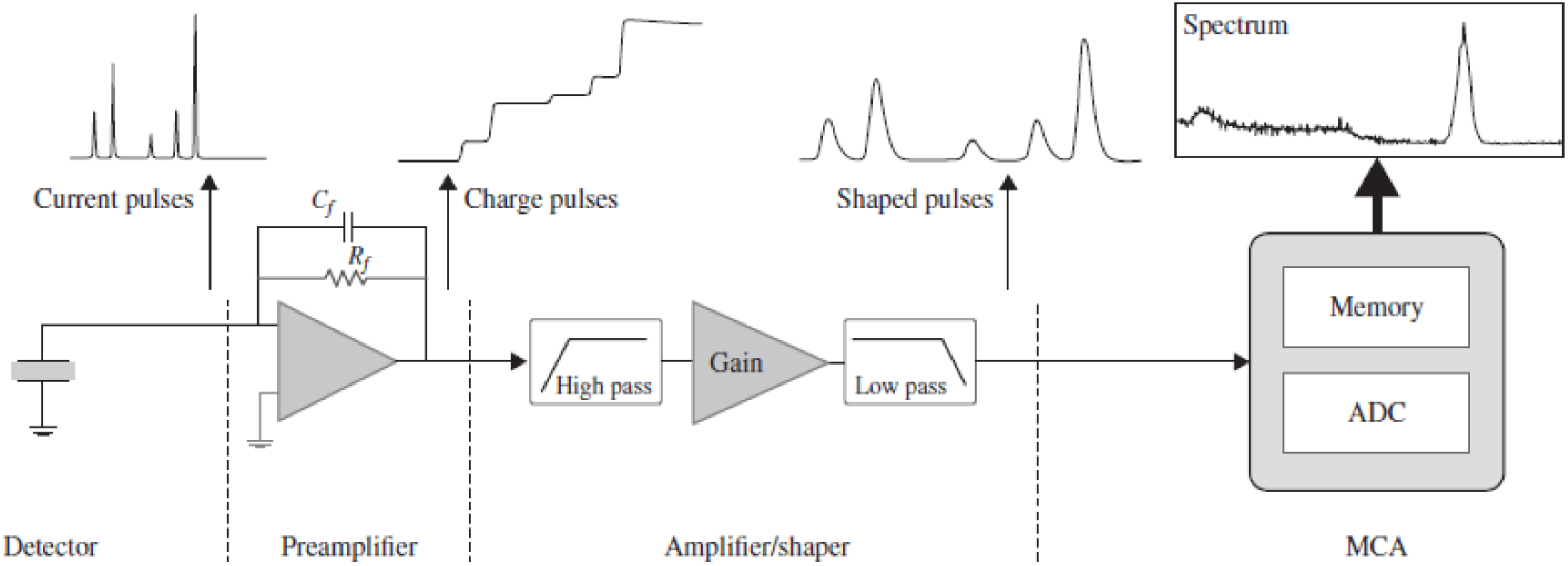




Gaussian shaping



Analog pulse processing chain



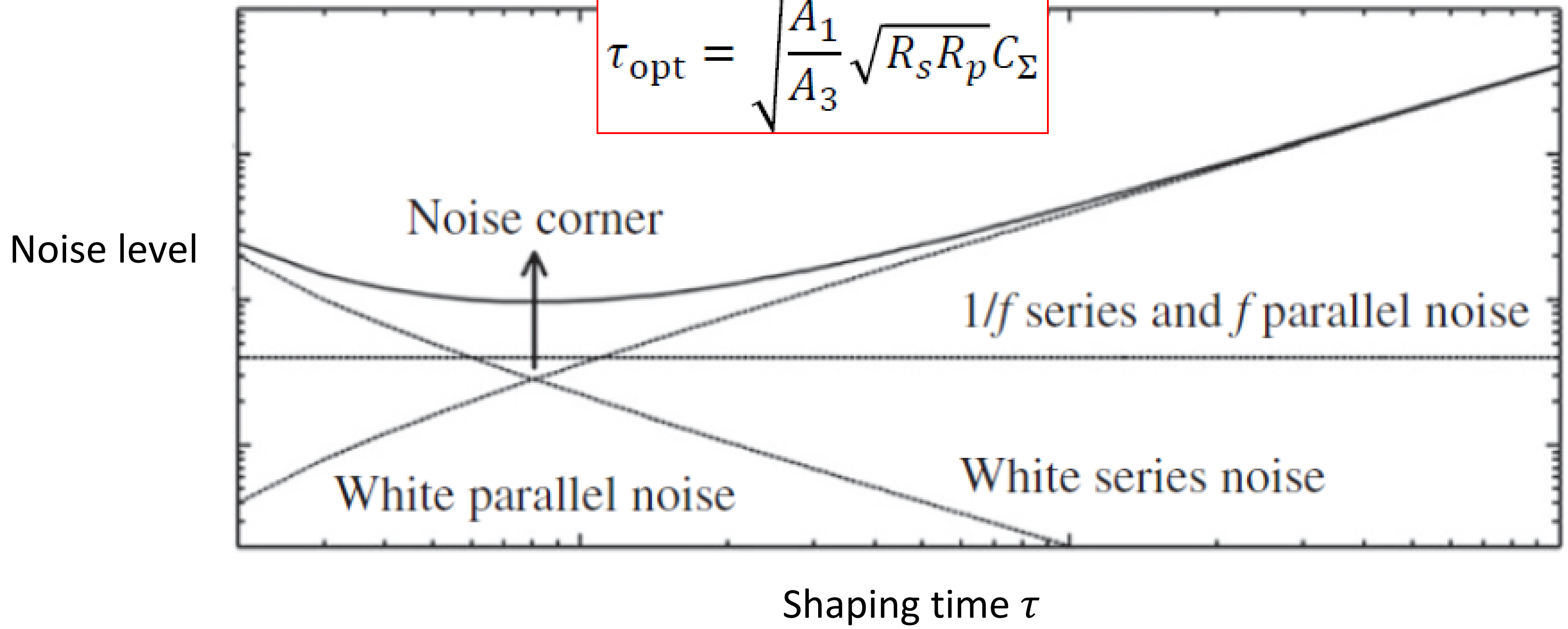
Noise VS shaping time

If a commercial pre-amp is used, there is nothing to tune. One just need to find a good shaping time to achieve the lowest noise that the pre-amp can deliver.

$$= e^2 \cdot \left[\frac{4kTR_s}{8\tau} C_\Sigma^2 + \frac{\tau}{8} \cdot \frac{4kT}{R_p} + \frac{A_F}{2} C_\Sigma^2\right]$$

$$ENC^2 = \frac{A_1}{\tau} \cdot 4kTR_s C_\Sigma^2 + A_2 \cdot 2\pi A_F C_\Sigma^2 + A_3 \tau \cdot \frac{4kT}{R_p}$$

$$\tau_{\text{opt}} = \sqrt{\frac{A_1}{A_3}} \sqrt{R_s R_p} C_\Sigma$$



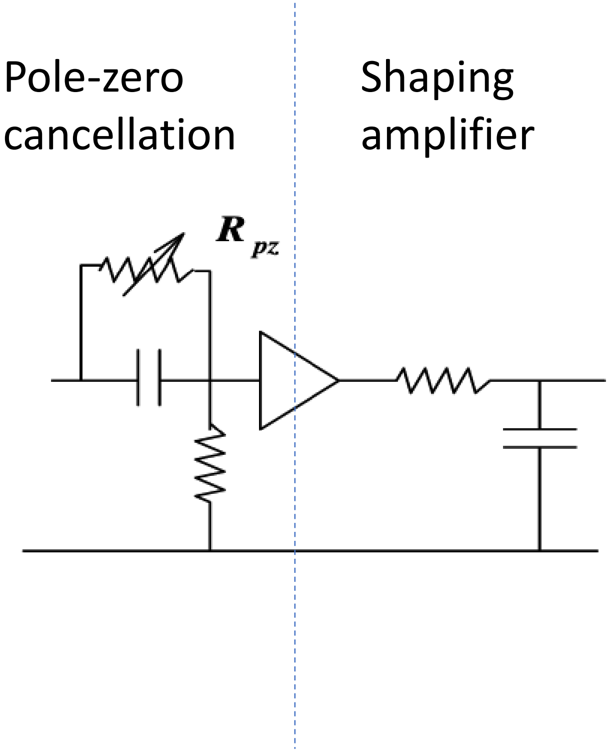
Pole-zero cancellation

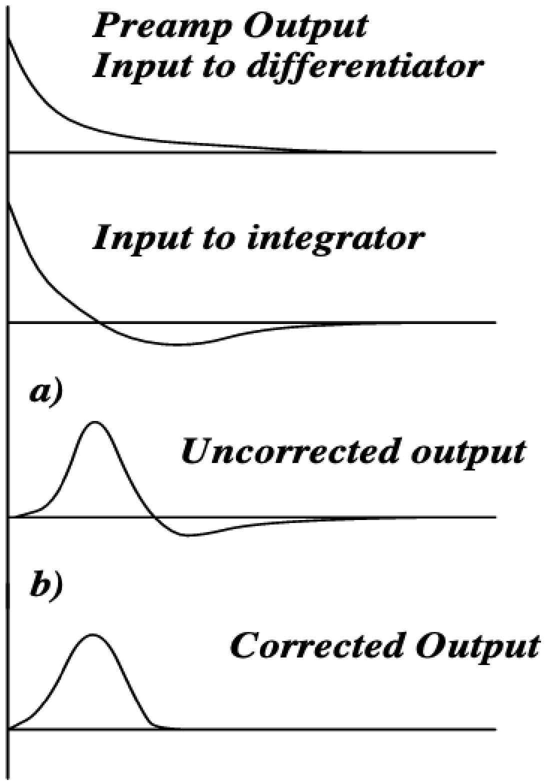
Real life:

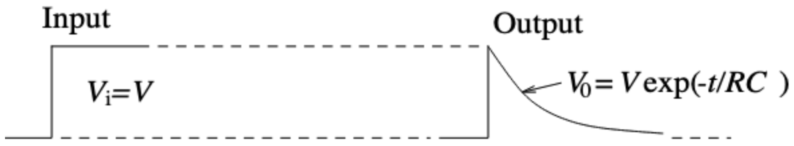
Ideal case

Pole-zero cancellation

Shaping amplifier

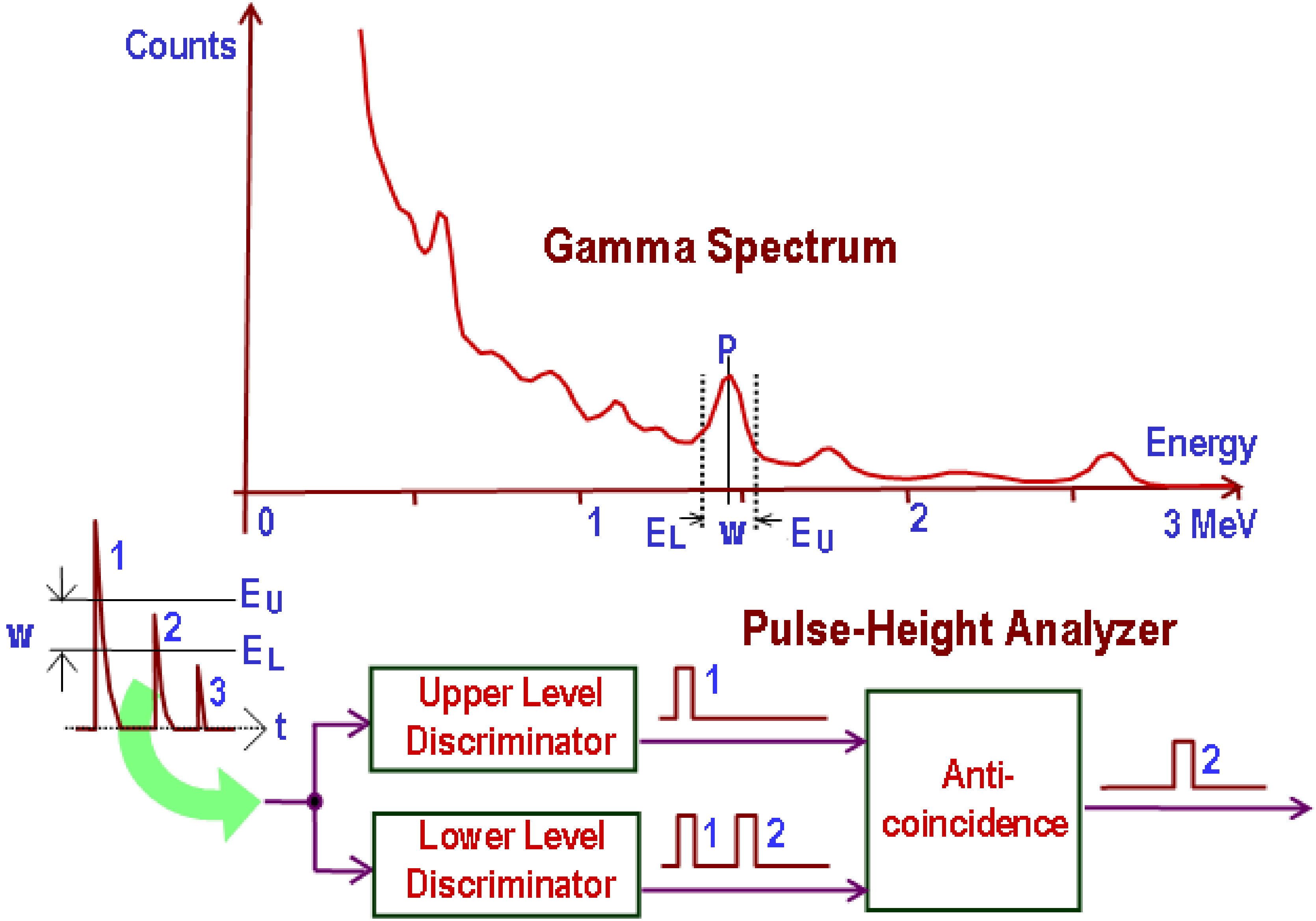






https://en.wikipedia.org/wiki/Multichannel_analyzer

MCA



Summary

- Transient signal (dQ) is extracted from the bias loop through a capacitor
  - Process of depletion can be monitored this way (dQ=VdC)
  - dQ created by energy deposition can also be extracted this way
- Charge-sensitive amplifier is used to convert collected Q to V
- Shaping amplifier is used to
  - Amplify small signals
  - Reduce the influence of pulse pile-up (step function to gaussian)
  - Reduce electronic noise by choose a good shaping time to limit bandwidth
- Pole-zero is used to reduce overshoot
- Signals after shaping can be binned into a histogram in MCA (hardware) for statistic analysis