

Lecture: Semiconductor Detectors

**Chapter 10.1, 10.2, 10.3, 10.4,
10.5.2, 10.5.4, 10.7.2, 10.7.3, 10.9**

There are mainly two types of semiconductor materials: **Silicon and Germanium**

Advantages

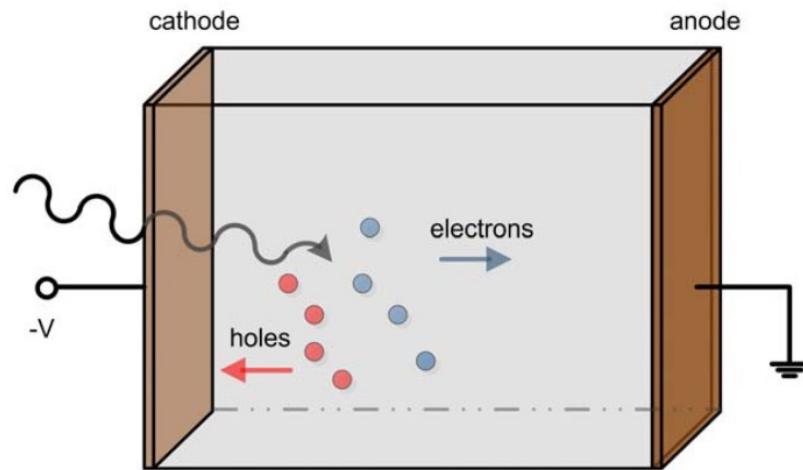
$w(\text{Ge}) = 2.96 \text{ eV}$	$\xrightarrow{\text{gamma rays}}$	$w(\text{NaI}) = 25 \text{ eV}$	Scintillator detectors
$w(\text{Si}) = 3.81 \text{ eV}$	$\xrightarrow{\text{charged particle}}$	$w(\text{Air}) = 36 \text{ eV}$	Gas detectors

- ✓ 10 times improved energy resolution
- ✓ Dense $\rightarrow$ Large stopping power. Efficient detectors, however,
 - For gamma ray detection, NaI(Tl), LaBr₃(Ce) or any inorganic scintillator detector is more efficient than Ge due to their high Z number (i.e. high density)
 - For charged particle detection, instead, Si is more efficient than any gas detector! (because of the same reason)
- ✓ Fast response time, not as fast as plastic (organic scintillators).

Dis-advantages

- Germanium requires cooling
- Radiation damage

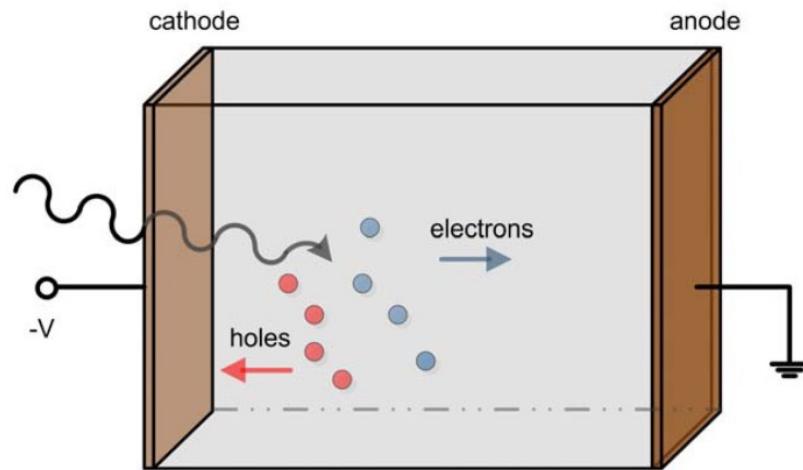
Detection mechanism: electron-hole (e-h) pair creation in solid-state material



Planar configuration of a semiconductor detector. The cathode is applied with a negative voltage and anode grounded. Electron-hole pairs excited by gamma rays are swept by the bias voltage.

Figure: <https://www.mdpi.com/1424-8220/13/2/2447>

Detection mechanism: electron-hole (e-h) pair creation in solid-state material



Planar configuration of a semiconductor detector. The cathode is applied with a negative voltage and anode grounded. Electron-hole pairs excited by gamma rays are swept by the bias voltage.

gas detectors: e-ion creation in gas

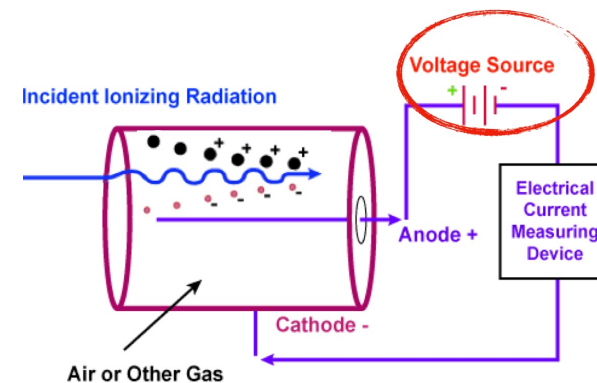


Figure: <https://www.mdpi.com/1424-8220/13/2/2447>

Solid equivalent of an ionization chamber

Today

Semiconductor physics

- Energy bands
- Intrinsic semiconductors
- General characteristic of Ge and Silicon materials
 - charge carriers
 - Intrinsic charge carrier concentration
 - Mobility
 - Internal impurities

Doping & pn junction

- n-type / p-type
- Diffusion & recombination
- Depletion region
- Built-in electric field

Making a radiation detector

- Reverse bias
- Large sensitive volume
- Charge collection
- Pulse height $\propto$ deposited energy

HPGe detectors

- Ge(Li) $\rightarrow$ HPGe
- Cooling
- Detector geometries & arrays

Detector comparison

- HPGe, NaI(Tl), LaBr₃(Ce)
- Energy resolution & efficiency

Today

Semiconductor physics

- Energy bands
- Intrinsic semiconductors
- General characteristic of Ge and Silicon materials
 - charge carriers
 - Intrinsic charge carrier concentration
 - Mobility
 - Internal impurities

Doping & pn junction

- n-type / p-type
- Diffusion & recombination
- Depletion region
- Built-in electric field

Making a radiation detector

- Reverse bias
- Large sensitive volume
- Charge collection
- Pulse height $\propto$ deposited energy

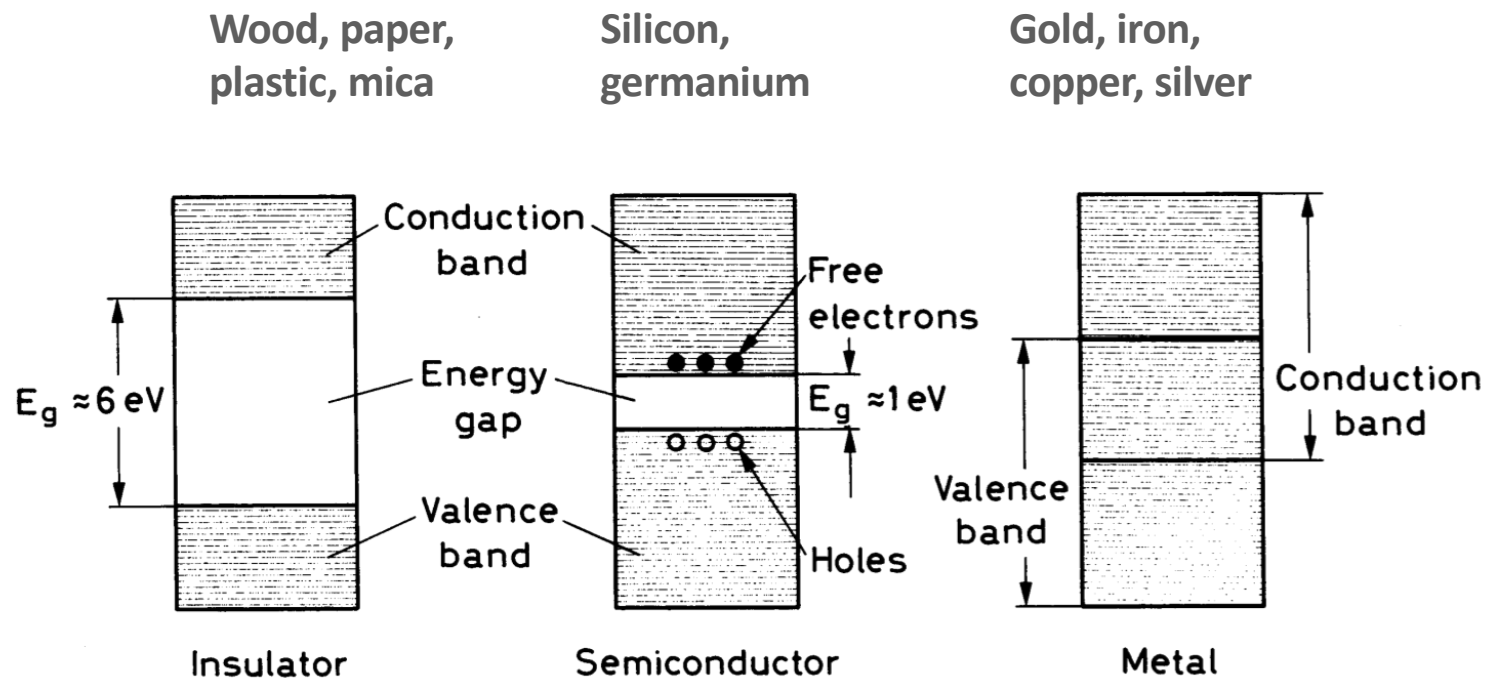
HPGe detectors

- Ge(Li) $\rightarrow$ HPGe
- Cooling
- Detector geometries & arrays

Detector comparison

- HPGe, NaI(Tl), LaBr₃(Ce)
- Energy resolution & efficiency

Energy band structure of “pure”/“intrinsic” solid materials



Insulator in room temperature:

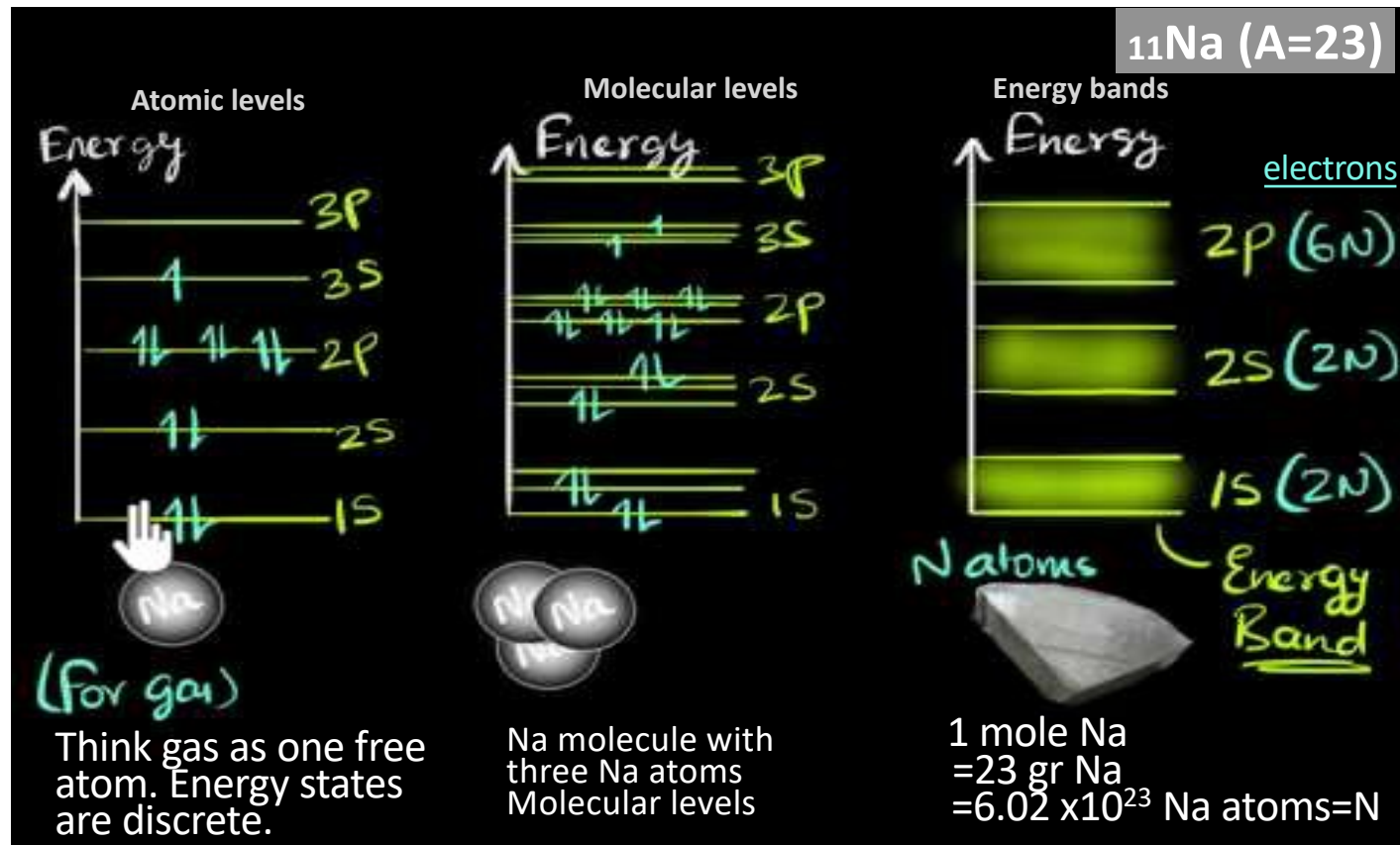
Thermal energy is not sufficient to excite electrons to the conduction band

Applied electric field will not cause any current signal at the output.

Conductor in room temperature:

There are already free electrons in the conduction band since there is no forbidden band gap separating valence and conduction band. Any applied voltage will create current signal at the output.

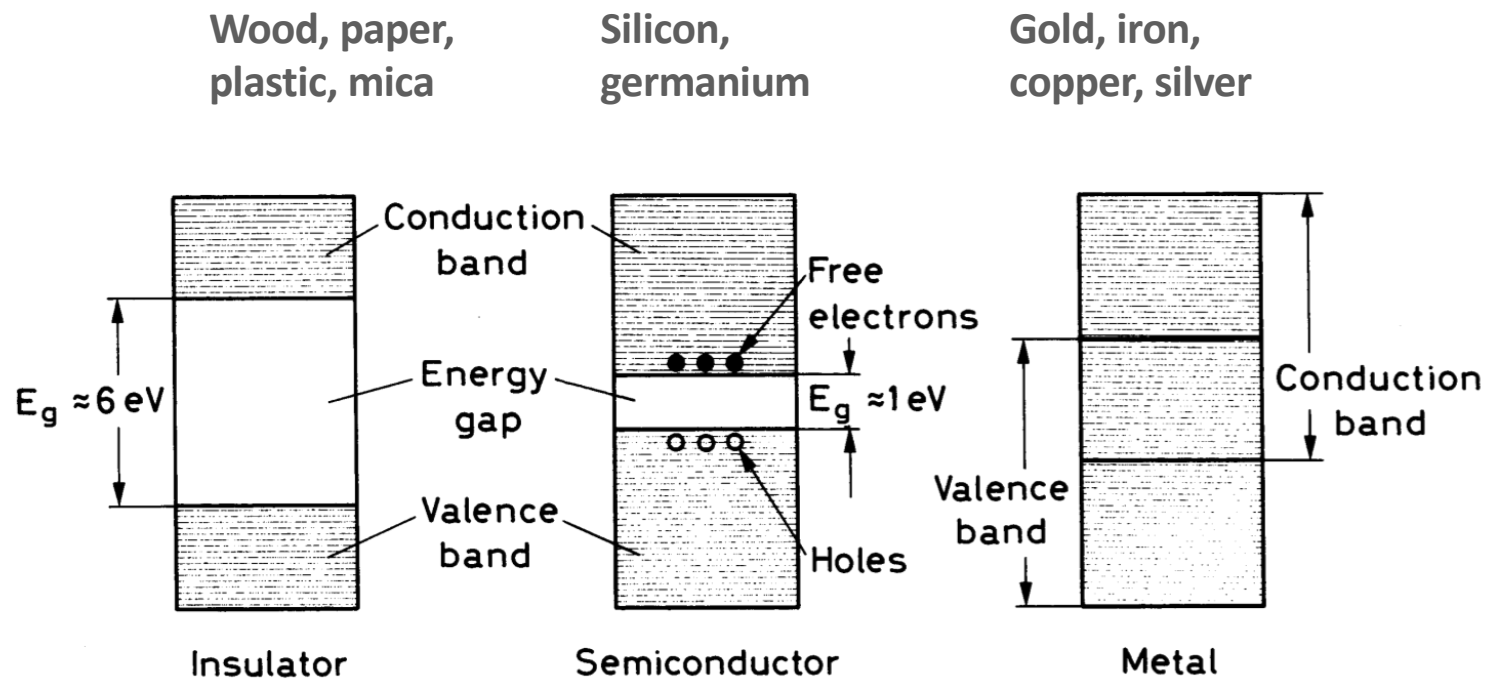
Band theory of solids



<https://www.khanacademy.org/science/in-in-class-12th-physics-india/in-in-semiconductors/in-in-band-theory-of-solids/v/band-theory-of-solids-class-12-india-physics-khan-academy>

Watch the video for a great explanation of the band structure of solid materials!!!

Q: what was the band gap energy in pure inorganic crystals like NaI, CsI, LaBr₃?



Semiconductors in room temperature:

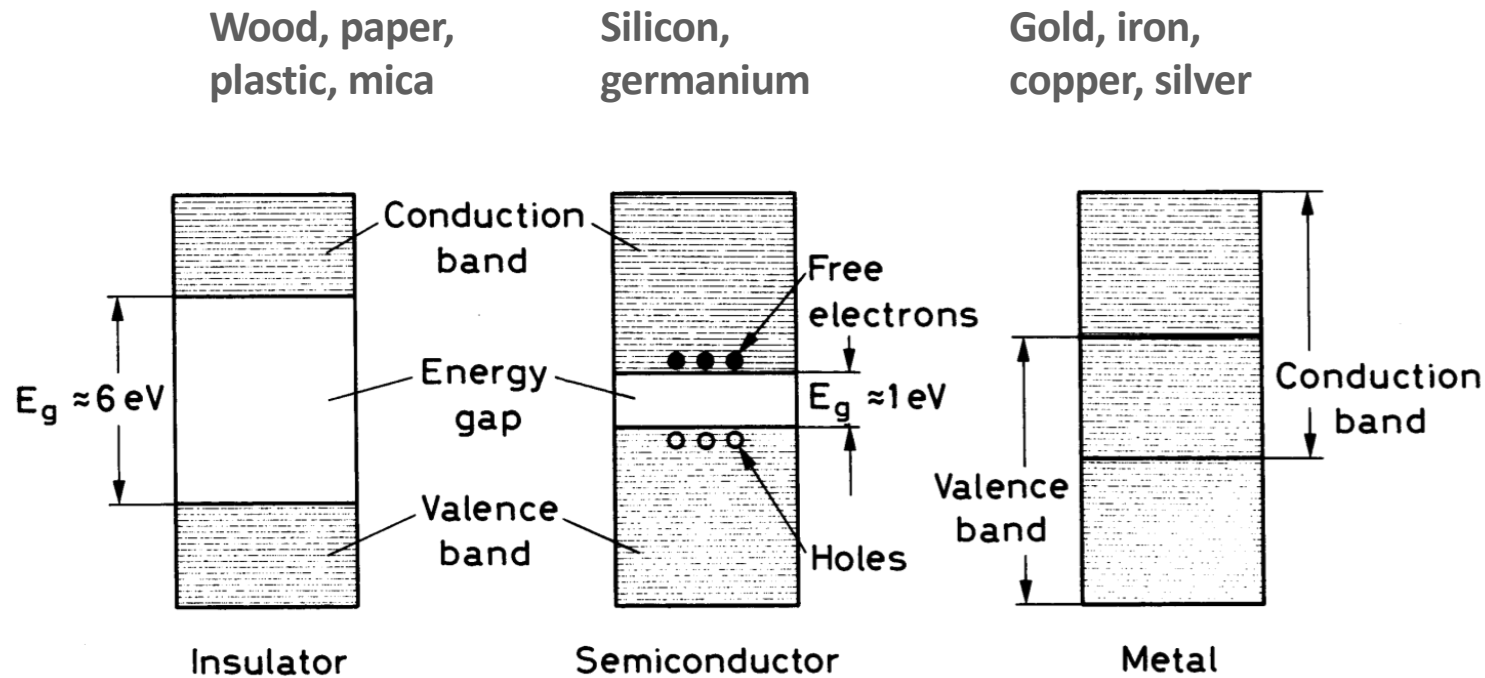
Thermal energy may excite electrons to the conduction band

Applied electric field will cause a small current signal at the output

If the semiconductor is cooled, almost all the electrons in the conduction band will fall into the valence band and thus the conductivity of the semiconductor will decrease.

A: ~ 6 eV.

So NaI, CsI, LaBr₃ crystals are insulators!!!



Semiconductors in room temperature:

Thermal energy may excite electrons to the conduction band

Applied electric field will cause a small current signal at the output

If the semiconductor is cooled, almost all the electrons in the conduction band will fall into the valence band and thus the conductivity of the semiconductor will decrease.

“Intrinsic” semiconductors

❑ intrinsic semiconductors

Semiconductors that are chemically pure, in other words, free from impurities

❑ Internal impurities

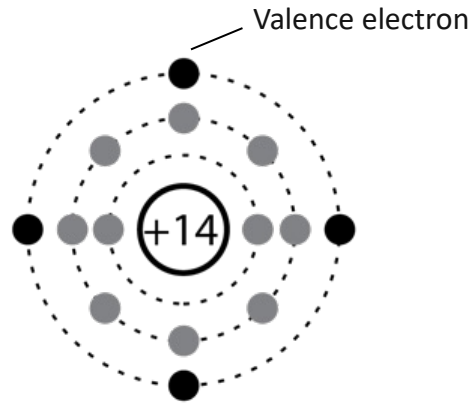
In reality, there is no such a pure semiconductor crystal but some impurities always reside, even after the best purification processes.

❑ the number of excited electrons is equal to the number of holes and denoted with

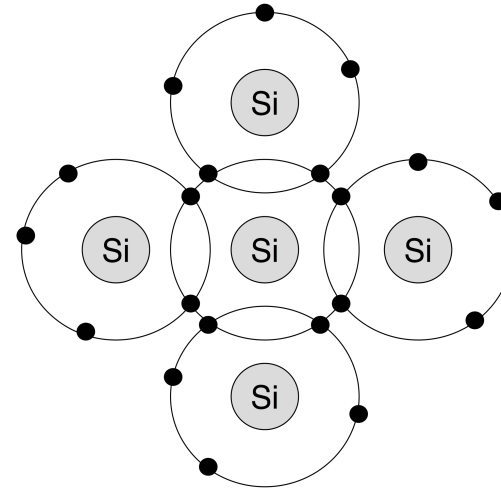
$$n_i = n_e = n_h$$

Semiconductor with their own internal impurities are called intrinsic semiconductors.

2,8,4



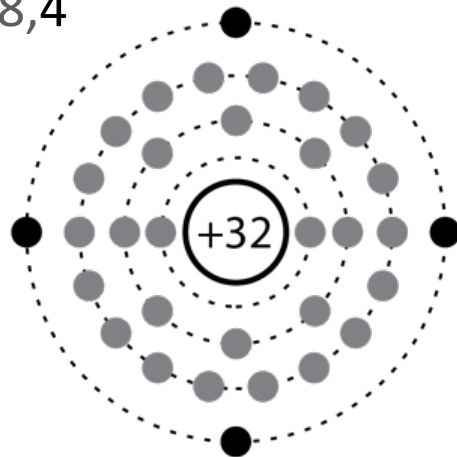
Silicon (Z=14)



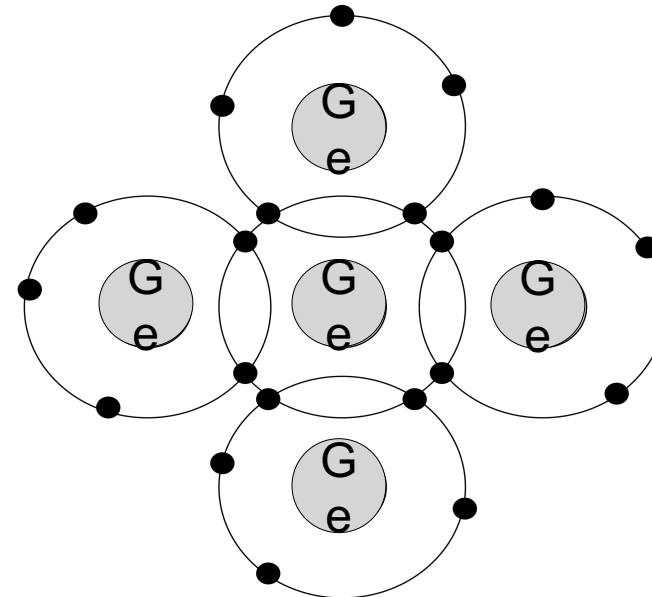
Si, Ge (Group IV), 4 valence electrons are “shared” between atoms in their chemical bonding (covalent*).

**A covalent bond is a chemical bond that involves the sharing of electron pairs between atoms.*

2,8,18,4

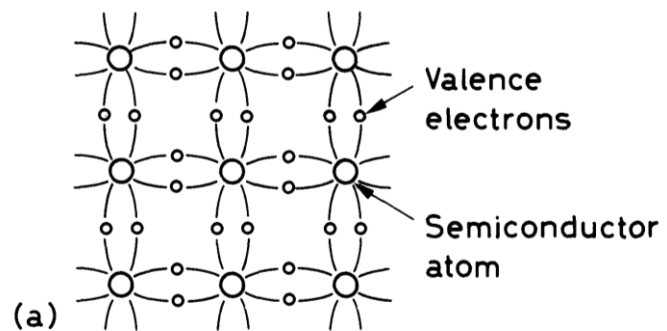


Germanium (Z=32)



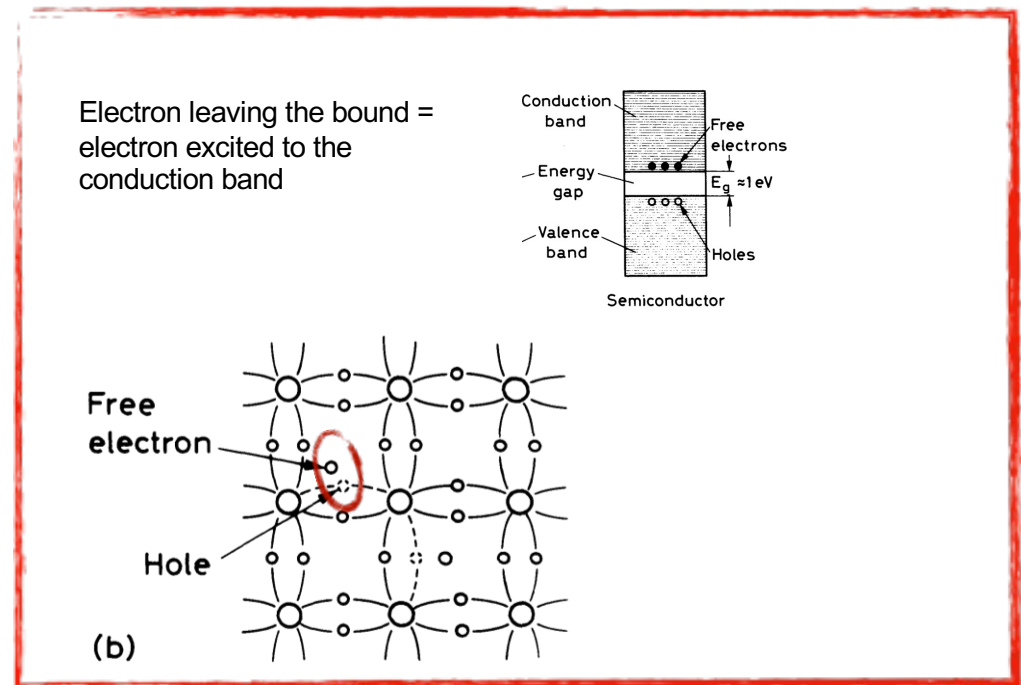
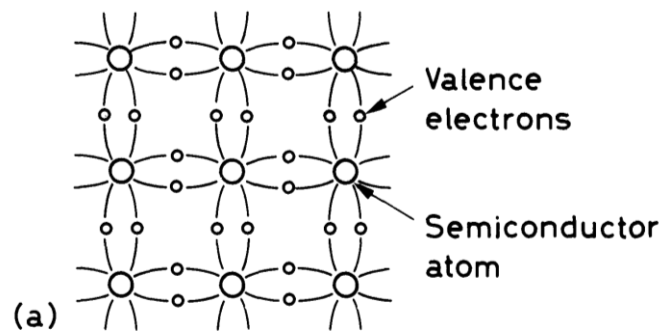
General characteristics of Ge and Si materials

- **charge carriers**
- intrinsic charge carrier concentration
- mobility
- Internal impurities: recombination and trapping



(a) at 0 K ($=-273.15^{\circ}\text{C}$), all electrons are in their place participating in bonding

At 0 K, there are no free charge carriers. Now I heat the crystal. What happens?



(a) at 0 K ($= -273.15^\circ \text{C}$), all electrons are in their place participating in bonding

(b) at higher temperatures (for example at room temperatures, $\sim 300 \text{ K} = 25^\circ \text{C}$) Some electrons might leave their covalent bonding and drift throughout the crystal, leaving vacancy, so-called "hole"

There, we have charge carriers which are both **free electrons** (negative charge carrier) and **holes** (positive charge carrier)

Matching question

What carries the signal in each detector?

Match the detector on the left (1–4) with the correct charge carrier(s) on the right (A–D).

Detector

1

Semiconductor detector

2

Scintillator detector

3

PMT

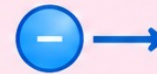
4

Gas detector

What carries the signal?

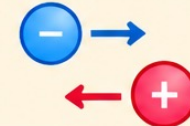
A

Electrons



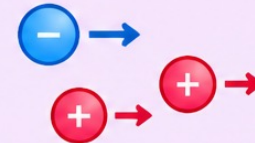
B

Electrons + holes



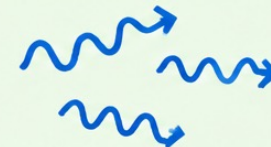
C

Electrons + ions



D

Photons (light)



Answer

Detector

Gas detector

Semiconductor

Scintillator

PMT

What carries the signal?

electrons + ions

electrons + holes

Photons

Electrons

General characteristics of Ge and Si materials

- charge carriers
- **intrinsic charge carrier concentration**
- mobility
- Internal impurities: recombination and trapping

Intrinsic charge carrier concentration

$$n_i \propto T^{3/2} \exp\left(-\frac{E_g}{2kT}\right)$$

Higher T , more thermal carriers
Larger E_g , fewer thermal carriers

n_i : charge carrier concentration (i =electron/hole)

E_g : Energy gap at 0K (= -273.15 °C)

T : Temperature

k : Boltzmann constant

	Ge	Si
E_g	~0.67 eV	~1.12 eV
n_i at 300 K	$2.5 \times 10^{13} \text{ cm}^{-3}$	$1.5 \times 10^{10} \text{ cm}^{-3}$

- Concentration of total Ge/Si atoms ~ **$10^{22} \text{ atoms/cm}^3$**
- **Too little** charge carrier concentration in Ge/Si materials

Note that so far we did not consider any incoming radiation to the detector material. We tried to understand what is happening to the semiconductor in the room temperature.

General characteristics of Ge and Si materials

- charge carriers
- intrinsic charge carrier concentration
- **mobility**
- Internal impurities: recombination and trapping

Mobility: How easily an electron or ion can move through matter.
 The matter was gas in the gas detectors (electron and ion).
 Now it is a solid material. Electron and hole in semiconductors.

μ : mobility

u : drift velocity

E : electric field applied

$$\mu = \frac{u}{E}$$

$$\mu_h = \frac{u_h}{E}$$

$$\mu_e = \frac{u_e}{E}$$

Table 10.1. Some physical properties of silicon and germanium

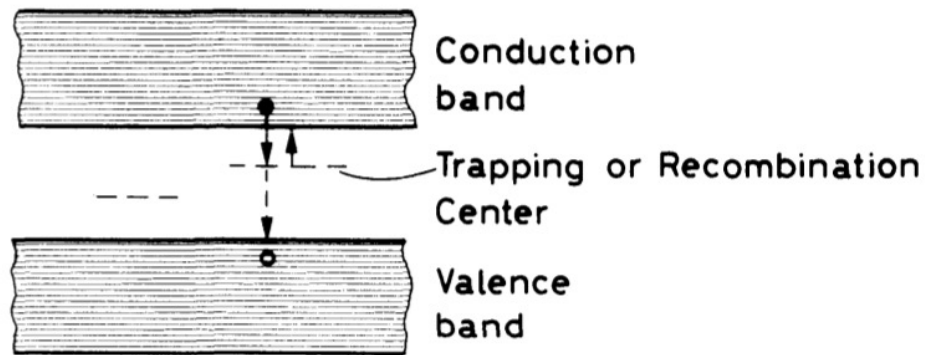
	Si	Ge
Atomic number Z	14	32
Atomic weight A	28.1	72.6
Density [g/cm ³]	2.33	5.32
Dielectric constant (relative)	12	16
Intrinsic resistivity (300 K) [Ω cm]	230000	45
Energy gap (300 K) [eV]	1.1	0.7
Energy gap (0 K) [eV]	1.21	0.785
Electron mobility (300 K) [cm ² /Vs]	1350	3900
Hole mobility (300 K) [cm ² /Vs]	480	1900

- *Ge is more conductive or metallic than Si*
- *Ge needs cooling because of its smaller energy gap*
- *Higher mobility $\rightarrow$ faster charge transport and charge collection*
- *For the same electric field, Ge has higher electron and hole mobility than Si.*

~ 300 K (Kelvin) = 25 °C

General characteristics of Ge and Si materials

- charge carriers
- intrinsic charge carrier concentration
- mobility
- **Internal impurities: recombination and trapping**



Recombination and trapping are unwanted effects due to impurities in semiconductors. Three processes are possible. The last two are the most occurring ones.

1-Direct recombination: very rare

2-Recombination center:

Deep levels: Keep charge for long time

- After a certain holding time, electron might be released back to the conduction band

If $t_r \gg t_c$, **signal is lost!!** (t_c : charge collection time)

- OR the recombination center will catch a hole and now the electron and the hole will recombine and cancel out. **Signal is lost!!**

3-Trapping center:

Trapping Center is capable of trapping only one type of the charge carrier. Either electron or hole but not both. In that case again if $t_t \gg t_c$, **signal is lost!!**

One center causes many recombination or trapping

Today

Semiconductor physics

- Energy bands
- Intrinsic semiconductors
- General characteristic of Ge and Silicon materials
 - charge carriers
 - Intrinsic charge carrier concentration
 - Mobility
 - Internal impurities

Doping & pn junction

- n-type / p-type
- Diffusion & recombination
- Depletion region
- Built-in electric field

Making a radiation detector

- Reverse bias
- Large sensitive volume
- Charge collection
- Pulse height $\propto$ deposited energy

HPGe detectors

- Ge(Li) $\rightarrow$ HPGe
- Cooling
- Detector geometries & arrays

Detector comparison

- HPGe, NaI(Tl), LaBr₃(Ce)
- Energy resolution & efficiency

So far we went through general characteristics of the Ge and Si semiconductors such as:

- charge carriers
- intrinsic charge carrier concentration
- mobility
- Internal impurities from recombination and trapping
- **Now we are going to dope and put two semiconductor materials together!**



a “pure”
semiconductor

Intrinsic material has relatively
few carriers.

Electrical behaviour is mainly
set by thermal excitation.

a “pure”
semiconductor

D
o
p
e

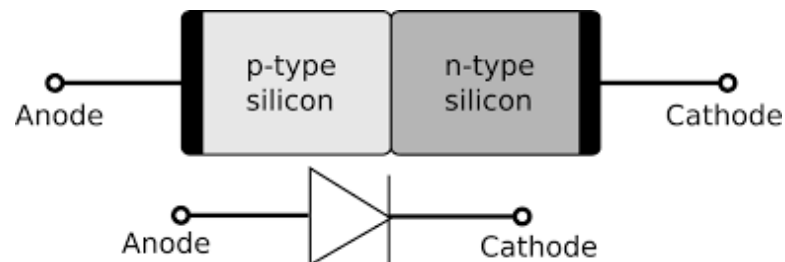
Donor → more electrons → n-type.
Acceptor → more holes → p-type.

D
o
p
e

P-type
semiconductor

We deliberately control the
carrier population.

N-type
semiconductor



Now we can engineer a junction
and depletion region

Doped Semiconductors

- Recombination and trapping occur because of the “internal” impurities of the crystal. They ruin the performance of the detectors.
- Doping: intentional impurities introduce shallow donor or acceptor levels (that retain the electrons or holes for **short periods of time**) .
- After doping, the semiconductor will have either more electrons (n-type) or more holes (p-type)
- **Donors provide mobile electrons → n-type.**
Acceptors provide mobile holes → p-type.
- Doping lets us control the carrier concentration and create a pn junction.

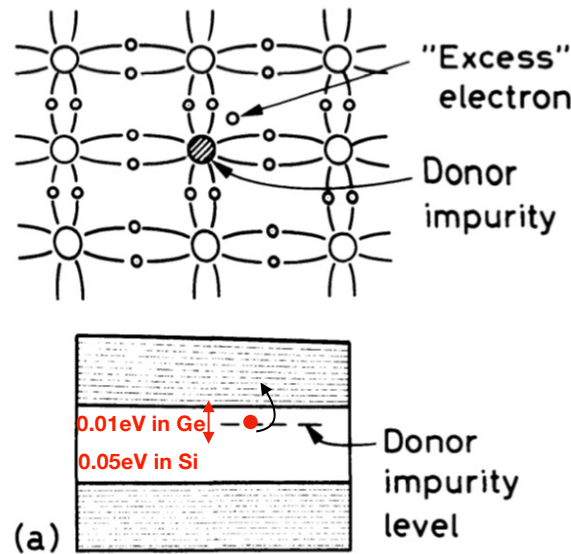
Common dopants for Si and Ge

Acceptors		Donors		
	⁵ B	⁶ C		
¹² Mg	¹³ Al	¹⁴ Si	¹⁵ P	¹⁶ S
³⁰ Zn	³¹ Ga	³² Ge	³³ As	³⁴ Se
⁴⁸ Cd	⁴⁹ In	⁵⁰ Sn	⁵¹ Sb	⁵² Te
II	III	IV	V	VI

Adopted from https://physics.bgu.ac.il/COURSES/LAB_C/XRAYS/Basic%20Semiconducturs.pdf

⁷Li (Z=3) is not in this list. It is in Group I with one valence electron. Perhaps it would work as a donor! Lithium ion drifting process.. We will see it later today.

Donor (Pentavalent: 5 valence electrons)



$n=n_e=10^{17}$ electrons $\rightarrow$ majority charge carriers
 $p=n_h=10^3$ holes $\rightarrow$ minority charge carriers
n-type

- Pentavalent dopant has one extra valence electron.
- The extra electron is weakly bound.
- Only a small energy is needed to make it mobile.
- Electrons become majority carriers.

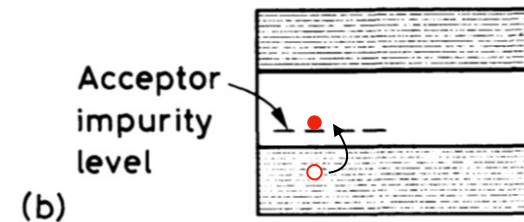
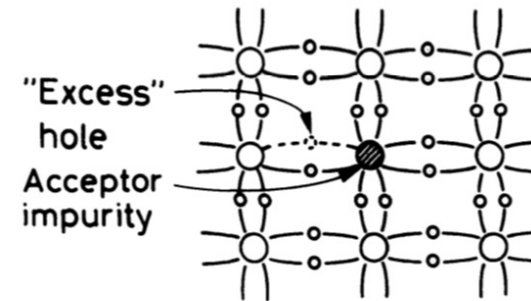
Electrical conductivity is determined by the flow of the electrons (n_e) (holes play a small role)

- Amount of dopant used is usually around 10^{13-17} atoms/cm³
 This amount is very small compared to the concentration of total Ge/Si atoms $\sim 10^{22}$ atoms/cm³
- Dopant amount can be higher up to 10^{20} atoms/cm³ and such doped materials are called heavily doped and indicated with a plus sign $\rightarrow p^+$ and n^+

- Trivalent dopant has one fewer valence electron.
- It can accept an electron from the lattice.
- The missing electron is represented as a hole.
- Holes become majority carriers.

Electrical conductivity is determined by the flow of the holes (electrons play a small role)

Acceptor (trivalent: 3 valence electrons)



electrons —> minority charge carriers

holes —> majority charge carriers

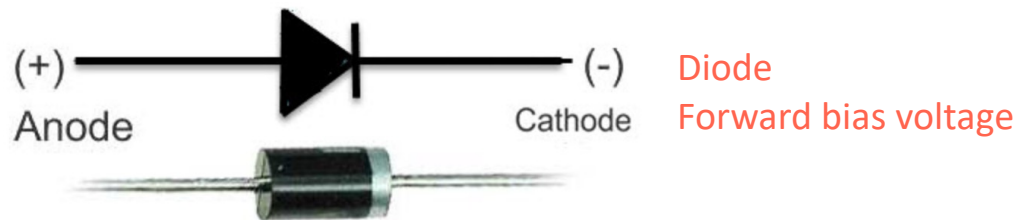
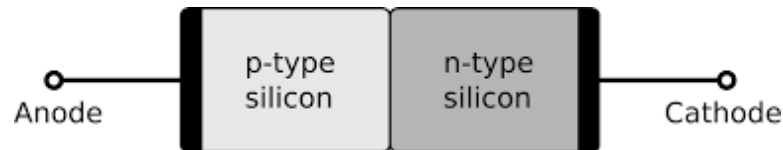
p-type

Read Leo page#221

Semiconductor junction

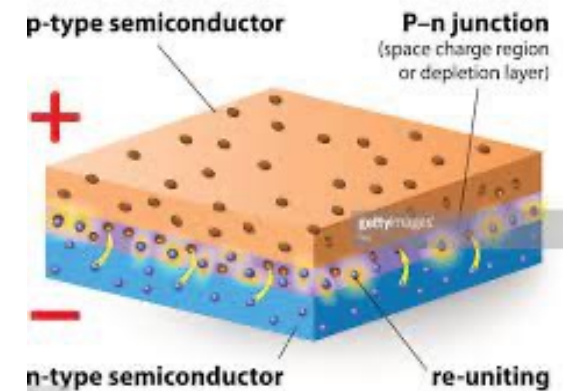
Once we have n- and p-type semiconductor materials, we can make a **functioning semiconductor detector** through **Junction**

- The p–n junction creates a depletion region with an electric field.
- With reverse bias, the depletion region can be made much larger — forming the sensitive volume of the detector.



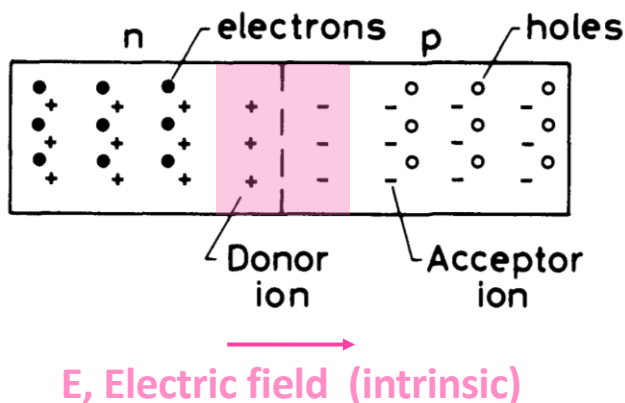
Photodiode
Reversed bias voltage

P-N JUNCTION



pn junction

pn junction is formed by the **juxtaposition** of a p-type semiconductor with an n-type material.



- electron
- hole
- + Ionized donor atom
- Ionized acceptor atom

1. Before contact

n-side: mobile electrons
p-side: mobile holes

2. Bring together

Electrons diffuse $n \rightarrow p$
Holes diffuse $p \rightarrow n$

3. Diffusion + recombination

Carriers recombine near interface
Mobile carriers are depleted

4. Fixed ions $\rightarrow E$

Ionized donors/acceptors remain
They create the internal E field

Depletion region:

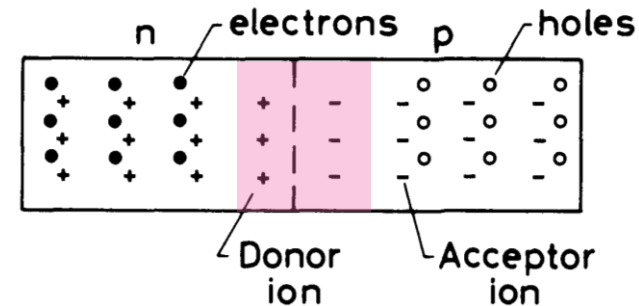
- E: zone of electric field
- $V (=1 \text{ V})$ Contact potential
- Mobile carriers are depleted $\rightarrow$ very low leakage current.
- I have a question!

Key question: “Why is a region with few mobile carriers + an electric field exactly what we want for a radiation detector?”

Key question: “Why is a region with few mobile carriers + an electric field exactly what we want for a radiation detector?”

Answer: radiation creates electron–hole pairs in the depletion region, and the electric field sweeps them to the electrodes before they recombine.

Depth of the depletion layer:



Silicon

$$d \approx \begin{cases} 0.53 (\rho_n V_0)^{1/2} \mu\text{m} & \text{n-type} \\ 0.32 (\rho_p V_0)^{1/2} \mu\text{m} & \text{p-type} \end{cases}$$

Germanium

$$d \approx \begin{cases} (\rho_n V_0)^{1/2} \mu\text{m} & \text{n-type} \\ 0.65 (\rho_p V_0)^{1/2} \mu\text{m} & \text{p-type} \end{cases}$$

(10.23)

Resistivity=1/conductivity

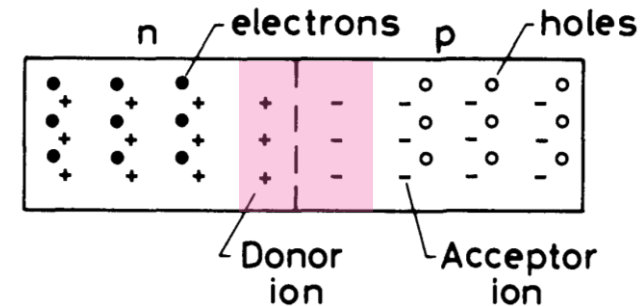
where ρ is in $\Omega \text{ cm}$ and V_0 in Volts. If we take typical values of $\rho \sim 20000 \Omega \text{ cm}$ for high-resistivity n-type silicon and $V_0 = 1 \text{ V}$, this yields $d \approx 75 \mu\text{m}$, which is a rather small sensitive depth.

**We want bigger depletion layer.
We must apply bias voltage!!**

By the way: Why do we want a large depletion region?



Depth of the depletion layer:



Silicon

$$d \approx \begin{cases} 0.53 (\rho_n V_0)^{1/2} \mu\text{m} & \text{n-type} \\ 0.32 (\rho_p V_0)^{1/2} \mu\text{m} & \text{p-type} \end{cases}$$

Germanium

$$d \approx \begin{cases} (\rho_n V_0)^{1/2} \mu\text{m} & \text{n-type} \\ 0.65 (\rho_p V_0)^{1/2} \mu\text{m} & \text{p-type} \end{cases}$$

(10.23)

Resistivity=1/conductivity

where ρ is in $\Omega \text{ cm}$ and V_0 in Volts. If we take typical values of $\rho \sim 20000 \Omega \text{ cm}$ for high-resistivity n-type silicon and $V_0 = 1 \text{ V}$, this yields $d \approx 75 \mu\text{m}$, which is a rather small sensitive depth.

**We want bigger depletion layer.
We must apply bias voltage!!**

Answer:

- Small depletion region → Small sensitive volume.
- Radiation outside it may not give fully collected charge.
- Detector volume is limited.

Today

Semiconductor physics

- Energy bands
- Intrinsic semiconductors
- General characteristic of Ge and Silicon materials
 - charge carriers
 - Intrinsic charge carrier concentration
 - Mobility
 - Internal impurities

Doping & pn junction

- n-type / p-type
- Diffusion & recombination
- Depletion region
- Built-in electric field

Making a radiation detector

- Reverse bias
- Large sensitive volume
- Charge collection
- Pulse height $\propto$ deposited energy

HPGe detectors

- Ge(Li) $\rightarrow$ HPGe
- Cooling
- Detector geometries & arrays

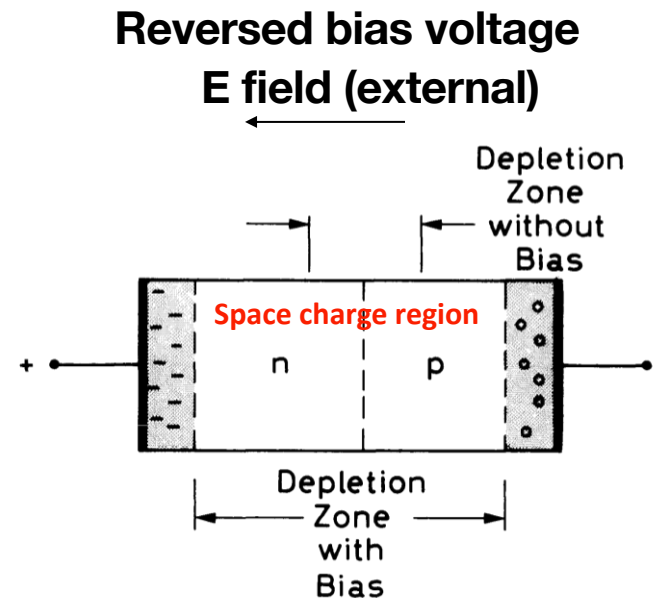
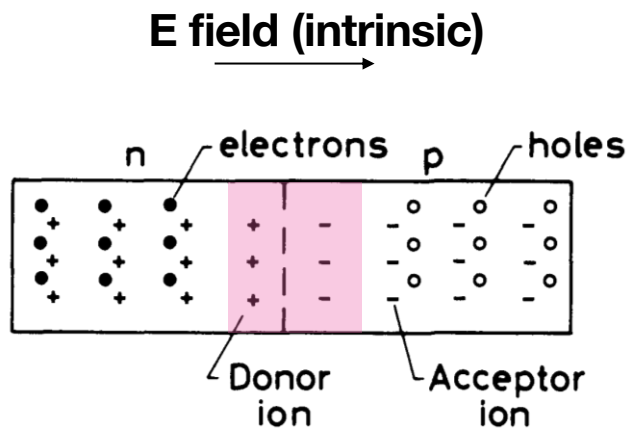
Detector comparison

- HPGe, NaI(Tl), LaBr₃(Ce)
- Energy resolution & efficiency

Reversed Bias Voltage:

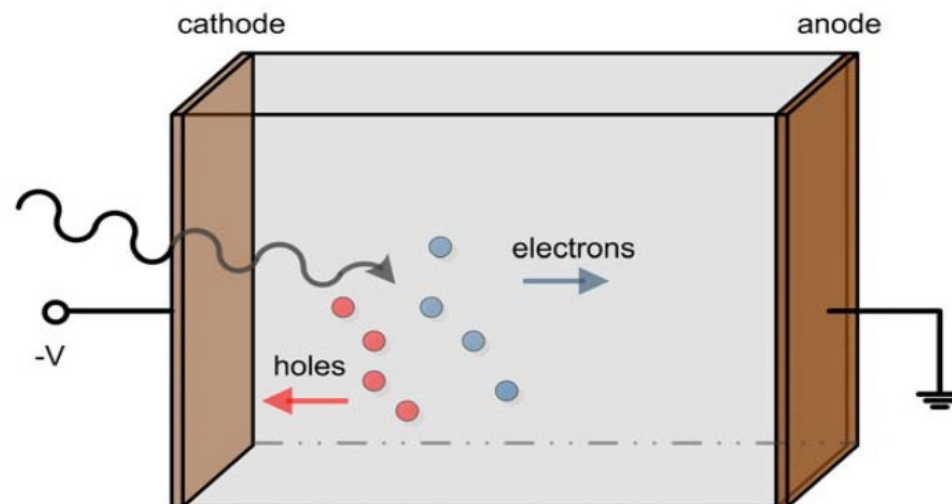
- RB voltage is a negative voltage to the p-side
- Main purpose: to increase the depletion zone
- The electric field becomes useful for charge collection.
- Voltage value: 4000-5000 V for germanium (less for silicon)
- Large depleted volume → practical detector.

Negative voltage on the p-side will attract holes away from the junction
positive voltage will attract electrons in the n-side.



Now we made our semiconductor work as a detector!

1. Doping controls carriers $\rightarrow$ n-type and p-type
2. p + n $\rightarrow$ depletion region $\rightarrow$ few mobile carriers + electric field
3. Reverse bias enlarges the depletion region $\rightarrow$ large sensitive volume
4. Radiation deposits energy $\rightarrow$ creates excited electrons
5. Electron-hole pairs are created $\rightarrow$ useful signal carriers
6. Electric field collects charge $\rightarrow$ electrons and holes reach contacts
7. Collected charge becomes a pulse $\rightarrow V_{\text{pulse}} \propto E_{\text{dep}}$



Characteristics of SC detectors:

Small w

Small $w \rightarrow$ more e-h pairs for the same $E_{\text{dep}} \rightarrow$ smaller statistical fluctuations

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

Large depletion region

large active / sensitive volume

Sufficient electric field causes efficient charge collection, thus good linearity

Typical HPGe detectors operate at several kV reverse bias.

n: collection efficiency
Q: Collected charge
C: detector capacitance
E: Energy deposited, E_{dep}

$$V = \frac{Q}{C} = n \frac{E}{wC}$$

High mobility

fast charge collection

Mobilities determine the current in the semiconductor detectors
This contributes to linearity : $V \propto E$

Characteristics of SC detectors:

Low leakage current

low electronic noise

$$(\text{FWHM})_{\text{overall}}^2 = (\text{FWHM})_{\text{statistical}}^2 + (\text{FWHM})_{\text{noise}}^2 + (\text{FWHM})_{\text{drift}}^2 + \dots$$

Low Fano factor

excellent intrinsic energy resolution

$$F \sim 0.12$$

$$R = 2.35 \sqrt{\frac{F}{J}} = 2.35 \sqrt{\frac{Fw}{E}}$$

Low thermal carrier concentration

appropriate temperature, especially for Ge

Cooling:

($T = 77\text{K}$ or -196°C) for Ge(Li)

($T < 110\text{K}$ ($< -163^\circ\text{C}$) for HPGe



Ge detector + dewar filled with a liquid nitrogen

Please read and go through material below:

Leakage current & Efficiency: Leo pp: 229-230

Bias Voltage, temperature effects, radiation damage: Leo pp:
243-245

Today

Semiconductor physics

- Energy bands
- Intrinsic semiconductors
- General characteristic of Ge and Silicon materials
 - charge carriers
 - Intrinsic charge carrier concentration
 - Mobility
 - Internal impurities

Doping & pn junction

- n-type / p-type
- Diffusion & recombination
- Depletion region
- Built-in electric field

Making a radiation detector

- Reverse bias
- Large sensitive volume
- Charge collection
- Pulse height $\propto$ deposited energy

HPGe detectors

- Ge(Li) $\rightarrow$ HPGe
- Cooling
- Detector geometries & arrays

43

Detector comparison

- HPGe, NaI(Tl), LaBr₃(Ce)
- Energy resolution & efficiency

Types:

Eda



Germanium detectors —> gamma-ray detection

Silicon Diode Detectors —> charged particle detection



Trine

Germanium detectors

- GeLi Detectors
- HPGe Detectors
 1. Planar
 2. Coaxial

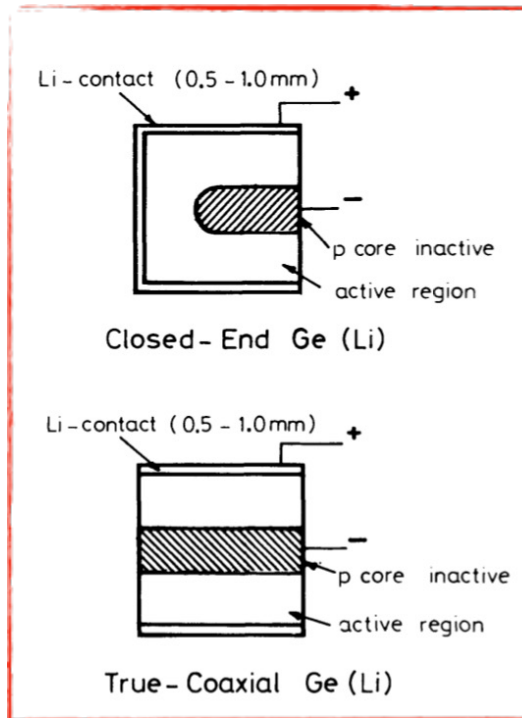
lithium ion drifting process (Z=3 Group I element)

- In order to increase the conductivity, one could add equal amount of donor and acceptor impurities but this is a very difficult process to manage.
- Instead, in 1960 Pelle developed the lithium drifting method for compensating p-type silicon and germanium:

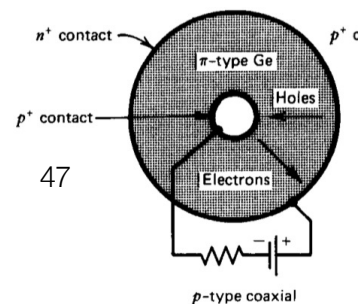
Lithium is diffused onto the surface of a p-type material. (Note that Lithium (Z=3) acts as a donor with one valence electron.) This changes that end of the semiconductor into an n-type material. The concentration of lithium drops off in a Gaussian manner so that the junction between the n-type and p-type regions lies at some depth under the surface.

Ge(Li) detectors

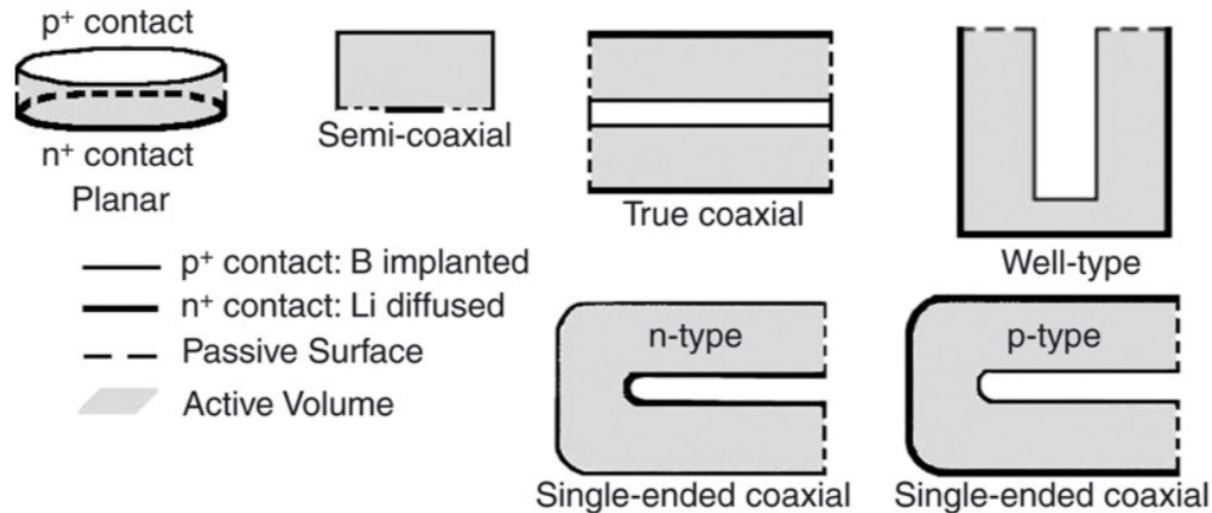
pronounced as “jelly”



- Year 1960 was innovative for a new doping method
- Lithium was used as doping
- Li has 1 valence electron and acts as donor in Ge
- Ge is doped by “diffusion” of Li (high mobility)
- After a drifting time of weeks or months a thickness of the compensated layer of up to 35 mm can be achieved for a coaxial detector.
- Creating Ge(Li) type detector material takes time.



HPGe detectors



- In the late 1970s
- Pure samples of the detector material could be prepared only for germanium material
- The production process of a detector is much faster since no time-consuming drifting process is needed.
- The commercial production of Ge(Li) detectors was given up around 1980 when the volume of HPGe detectors became competitive with the volume of Ge(Li) detectors
- Large, high-purity Ge crystals can be produced, typically several centimeters in size. We will see that soon.
- Quite expensive

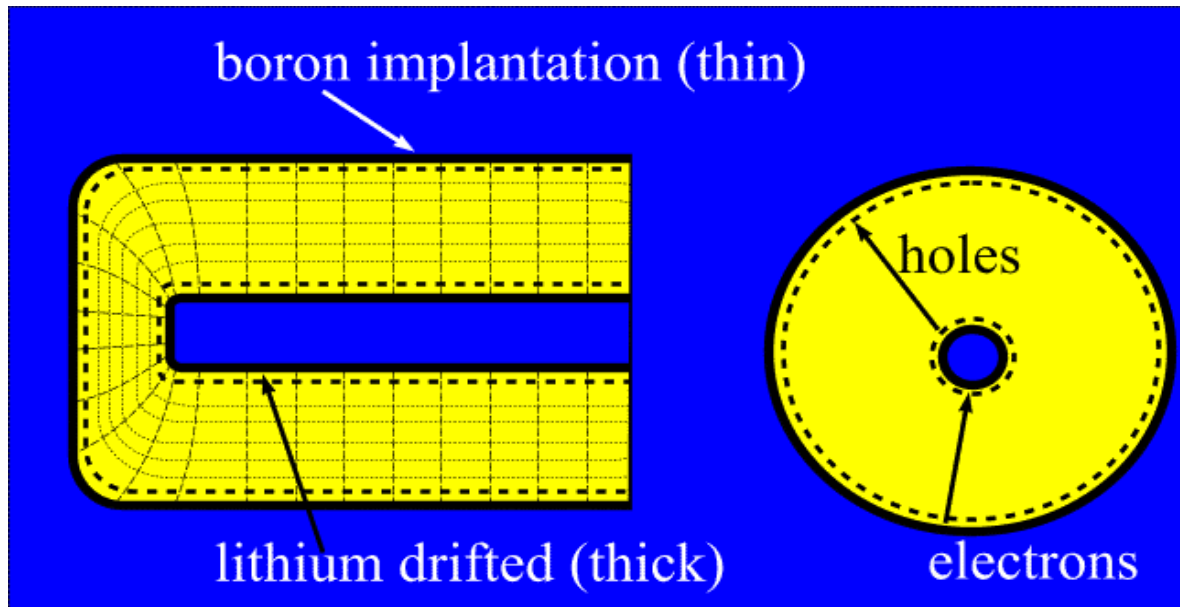
$$d = \left(\frac{2\epsilon V}{eN} \right)^{1/2}$$

d: depletion layer
V: applied High voltage
N: net impurity concentration in the bulk germanium
E: dielectric constant

For a typical intrinsic germanium material,
 $N=10^{13}$ atoms/cm³
For HpGe → $N=10^{10}$ atoms/cm³

Operated at 77 Kelvin using liquid nitrogen.

Example to an n-type Coaxial

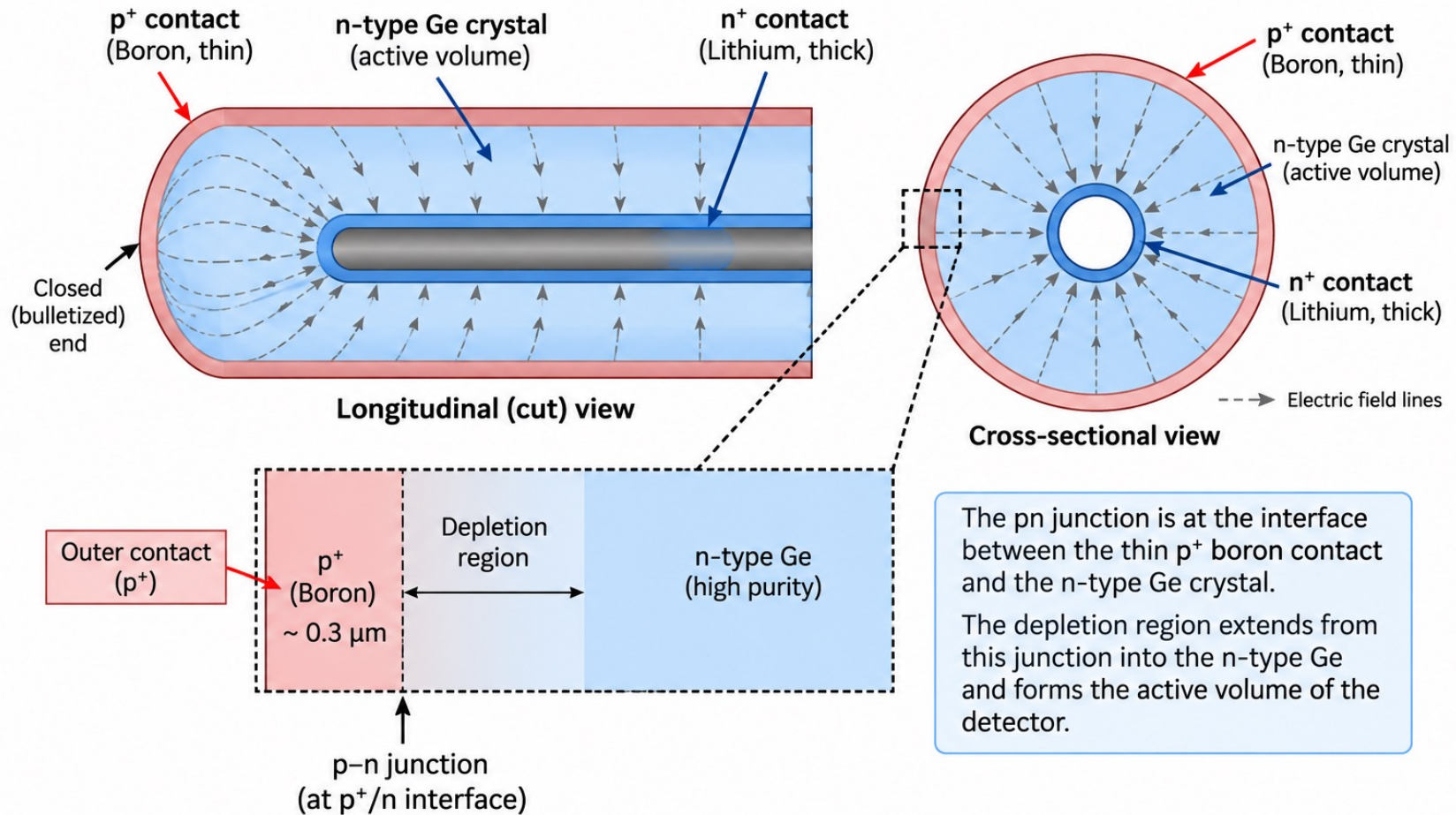


- Li diffusion is used to form the n+ contact
- Boron is ion implanted to produce the p+ contact.
- In the figure:
Lithium is thick and boron is thin.
SO, this is an n-type Ge crystal.

	Outer Contact	Inner
Contact		
n-type	p(B)	n(Li)
p-type	n(Li)	p(B)
n ~ 600 μm - 1 mm, p contact is very thin ~ 0.3 μm .		

Q: Where is the junction??!!

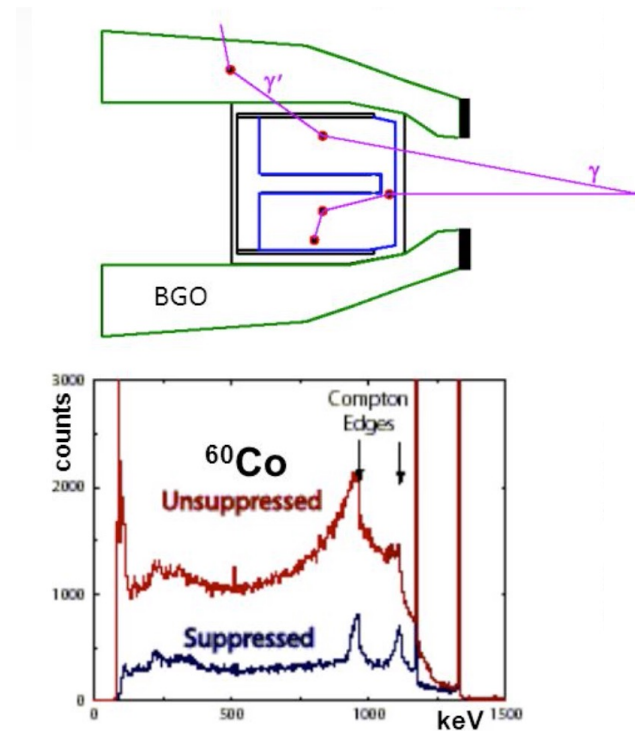
Closed-end coaxial HPGe detector (n-type)



BGO Compton suppression



ROSPHERE at Bucharest, Romania



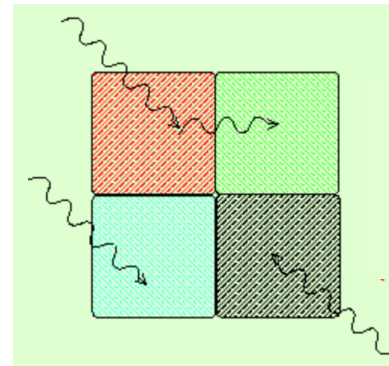
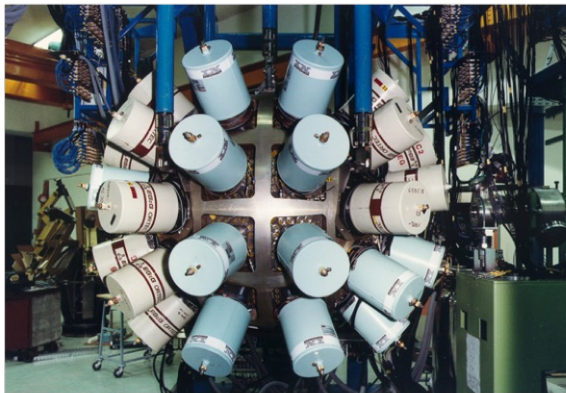
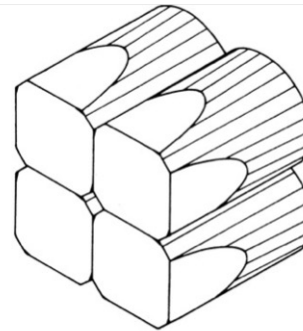
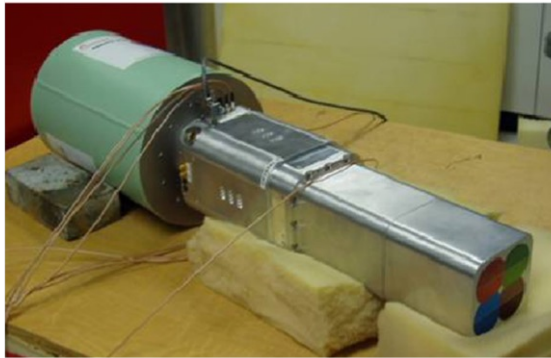
For large Ge arrays: **P/T (Peak to Total) Ratio** improves from 20% to 60%

51

$$P/T = \frac{\text{counts in the full-energy peak}}{\text{total counts in the spectrum}}$$

4π -Ge Arrays: Segmented crystals

Clover (4-fold segmentation)



Addback

Fig. 15. Eurogam II at IReS Strasbourg.

MINIBALL at CERN/ISOLDE

6-fold segmentation

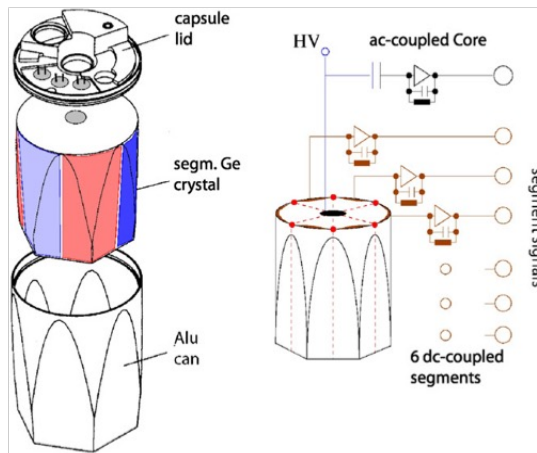
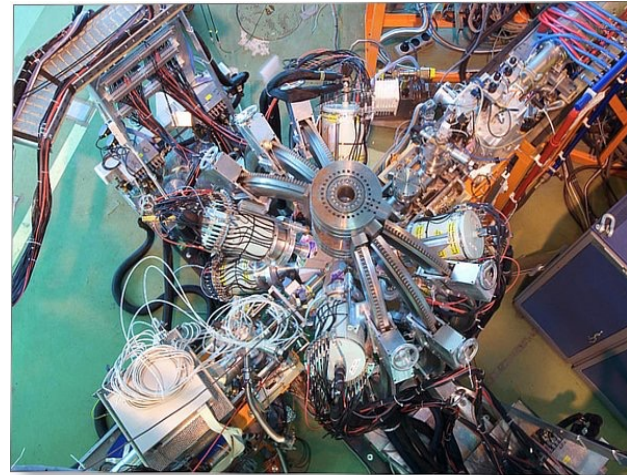
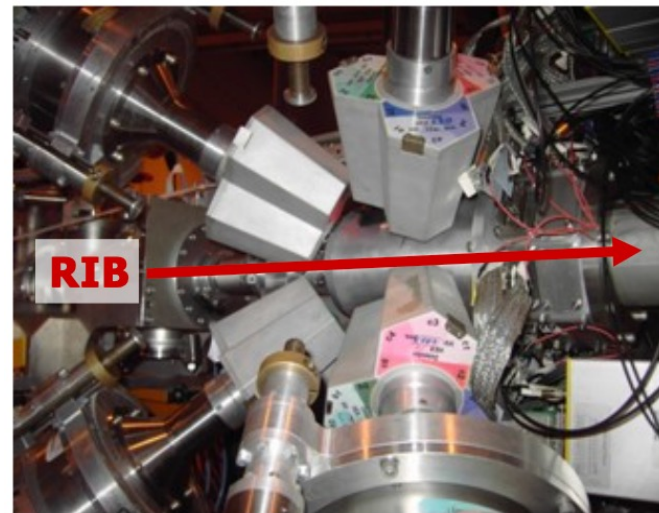
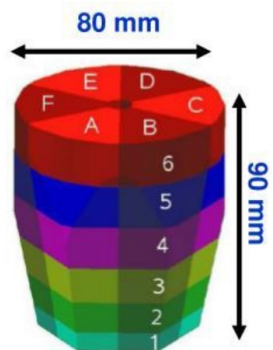
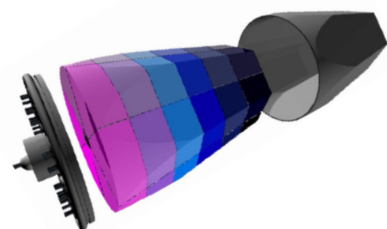


Fig. 23. The segmented MINIBALL detector.

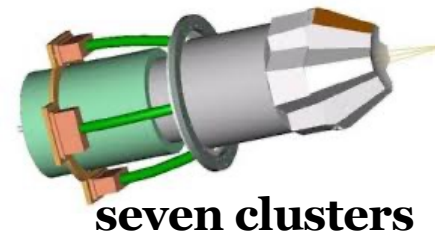




4π -Ge Arrays: Highly segmented *HPGe* arrays



triple clusters



seven clusters

36-fold segmentation

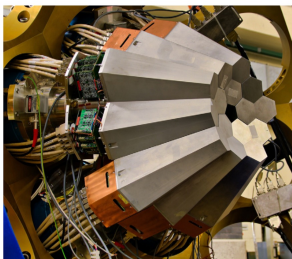
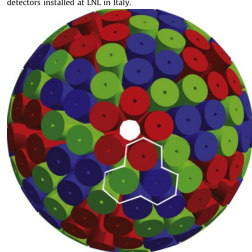
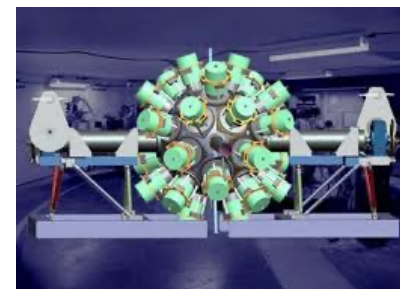
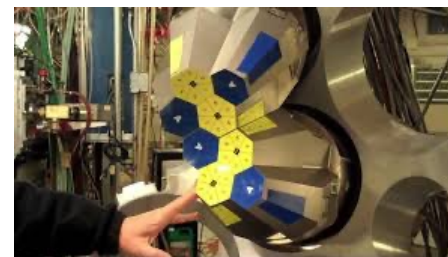


Fig. 6. (Colour online) Photograph of the setup with five AGATA triple cluster detectors installed at LNL in Italy.



AGATA, Europe



GRETA, USA

Today

Semiconductor physics

- Energy bands
- Intrinsic semiconductors
- General characteristic of Ge and Silicon materials
 - charge carriers
 - Intrinsic charge carrier concentration
 - Mobility
 - Internal impurities

Doping & pn junction

- n-type / p-type
- Diffusion & recombination
- Depletion region
- Built-in electric field

Making a radiation detector

- Reverse bias
- Large sensitive volume
- Charge collection
- Pulse height $\propto$ deposited energy

HPGe detectors

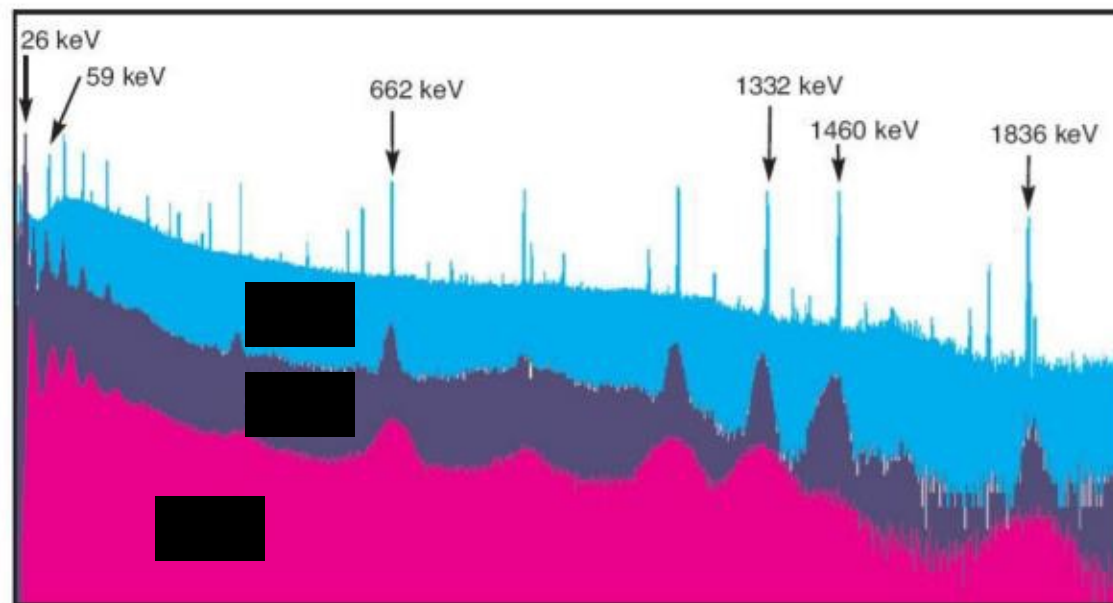
- Ge(Li) $\rightarrow$ HPGe
- Cooling
- Detector geometries & arrays

55

Detector comparison

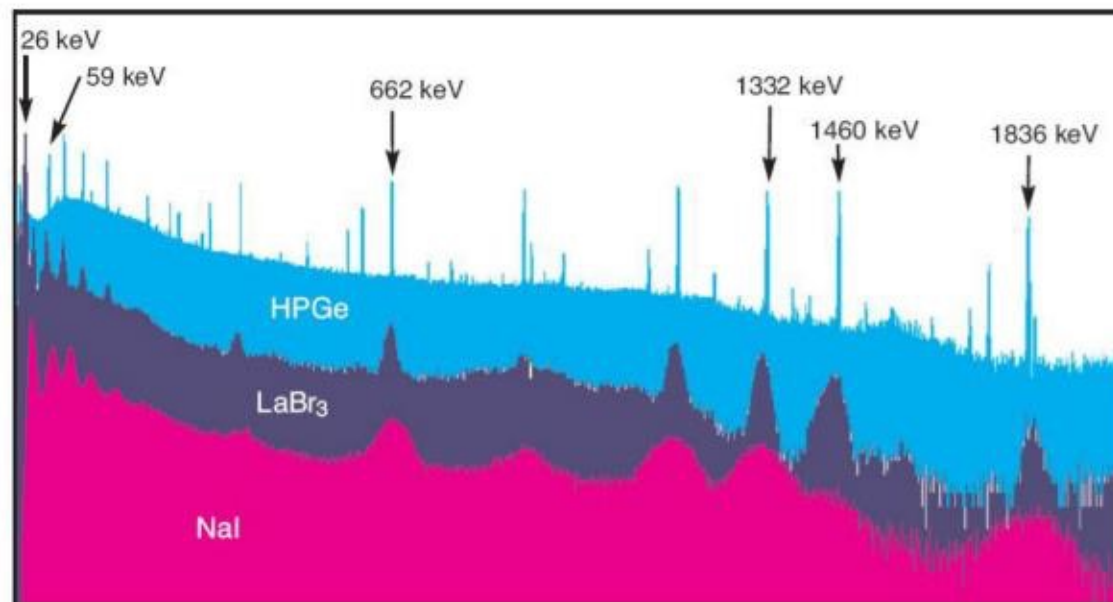
- HPGe, NaI(Tl), LaBr₃(Ce)
- Energy resolution & efficiency

Comparison of HPGe, NaI, and LaBr



Match colours to each detector type!!

Comparison of HPGe, NaI, and LaBr₃



Which one has the best energy resolution?

Which one has highest efficiency for the same volume?

Which one has the fastest time response ?

Which one is the most expensive? Why?

Detector Type	Resolution @622 keV (%)	Density (g/cc)	Photoelectron Yield Relative to NaI	Primary Decay Time (usec)
LaBr ₃ (Ce)	2.8 - 4.0	5.29	130	0.026
NaI(Tl)	7	3.7	100	0.230
HPGe	0.2 (1.3 keV)	5.35	N/A	N/A

Which one has the best energy resolution? HPGe

Which one has highest efficiency for the same volume? $\text{LaBr}_3(\text{Ce})$

Which one has the fastest time response? $\text{LaBr}_3(\text{Ce})$

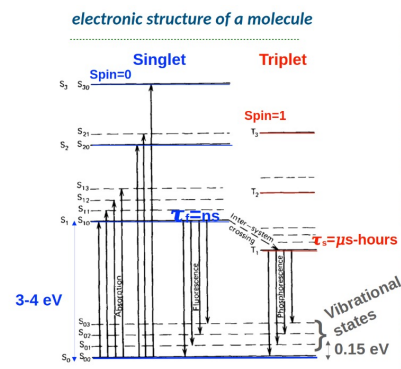
Which one is the most expensive? Why? HPGe. LaBr_3 is relatively expensive compared with conventional scintillators such as $\text{NaI}(\text{Tl})$, but HPGe detector systems are generally more expensive because of the high-purity Ge material and cooling requirements.

Detector Type	Resolution @622 keV (%)	Density (g/cc)	Photoelectron Yield Relative to NaI	Primary Decay Time (usec)
$\text{LaBr}_3(\text{Ce})$	2.8 - 4.0	5.29	130	0.026
$\text{NaI}(\text{Tl})$	7	3.7	100	0.230
HPGe	0.2 (1.3 keV)	5.35	N/A	N/A

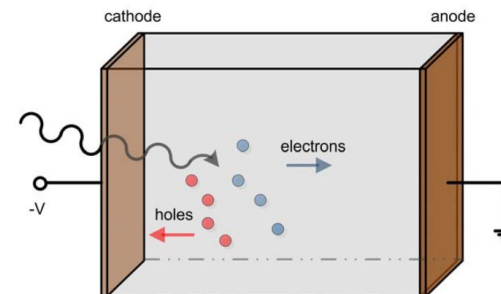
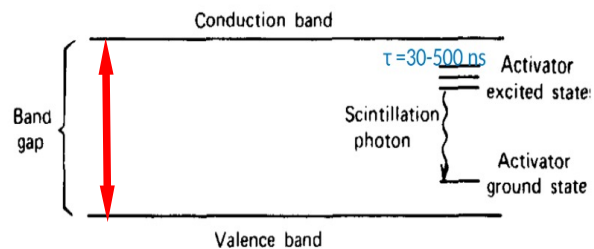
Photocathode



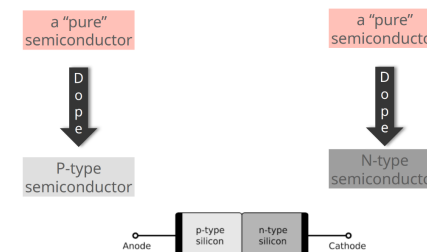
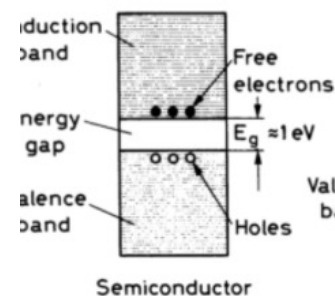
Organic



Inorganic



Silicon, germanium



Plastic scintillators
Charged particles
TOF measurements, fast timing

Liquid scintillators
Neutron detection

Gamma rays

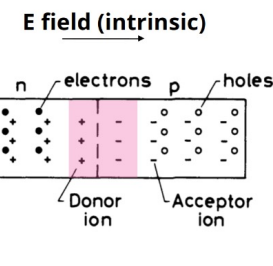
NaI(Tl)
CsI(Tl)
LaBr3(Ce)

Compton suppression
BGO

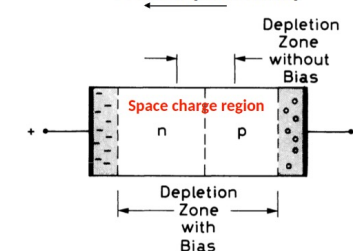
Electron hitting the organic scintillator will excite many electrons from the ground state to the excited states

Photon hitting the inorganic scintillator will give its energy to one electron via PA, CS, PP

Now that energetic electron will excite many electrons from the ground state to the excited states



Reversed bias voltage



Germanium (HPGe)
Gamma rays

Silicon (Si)
Heavy-charged particles
electrons

Questions to you

- Why do we prefer germanium ($Z=32$) to silicon ($Z=14$) for gamma-ray detection? Can you explain by giving numerical values?
- How do semi-conductor detectors work? Draw and explain the concept of energy bands in this context. What are the charge carriers in semi-conductor materials?
- What type of preamplifier would you suggest for Germanium detectors? Explain reasoning. (Hint: Get help from Lecture 8 pulse signal processing.)
- Should Preamplifier amplify the signal from the detector output significantly? Why should Preamplifier should stay very close to the germanium detector output?
- How does a Germanium detector work (depletion layer, pn junction)?
- Why do you have to cool Germanium detectors? Explain why it is important to increase the bias voltage in small steps.
- What is the effect of Compton suppression? What type of detectors are used for Compton suppression? And why?