

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**

Semiconductor

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

Advantages

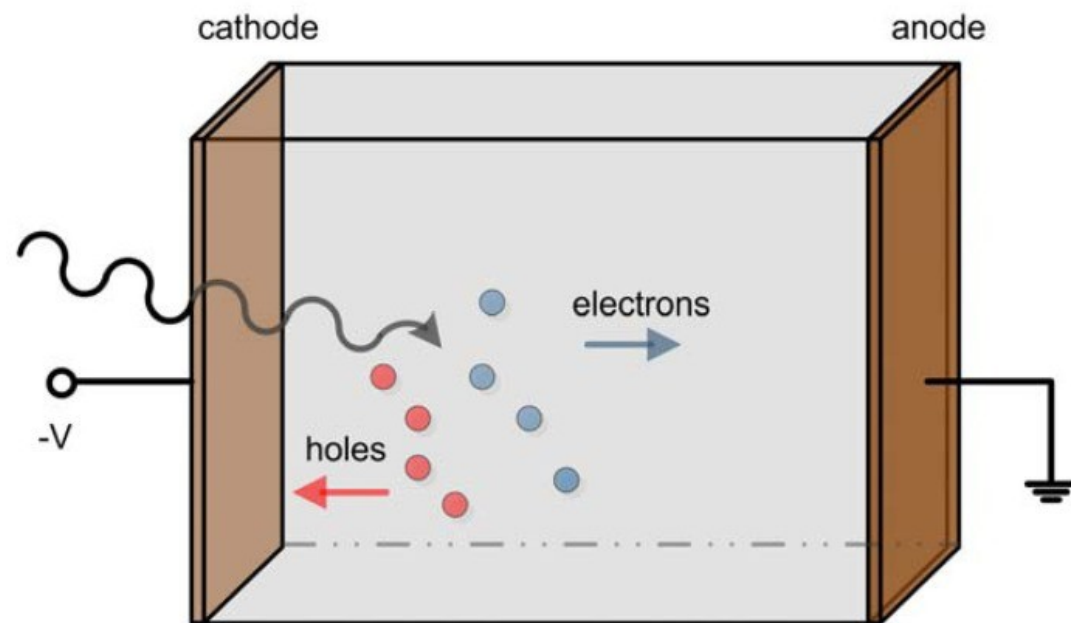


- ✓ 10 times improved energy resolution
- ✓ Dense-→ Large stopping power. Efficient detectors, however,
 - For gamma ray detection, NaI(Tl), LaBr₃(Ce) or any inorganic scintillator detector is more efficient due to their high Z number (i.e. high density)
 - For charged particle detection, instead, Si 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

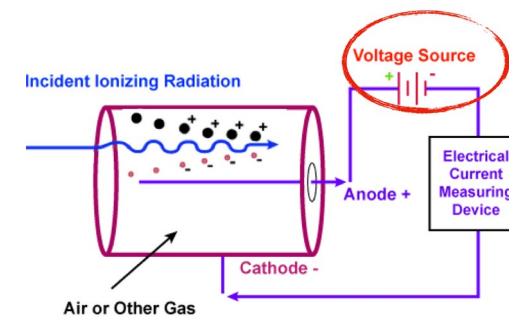
Detection mechanism: electron-hole (e-h) pair creation in solid-state material



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.

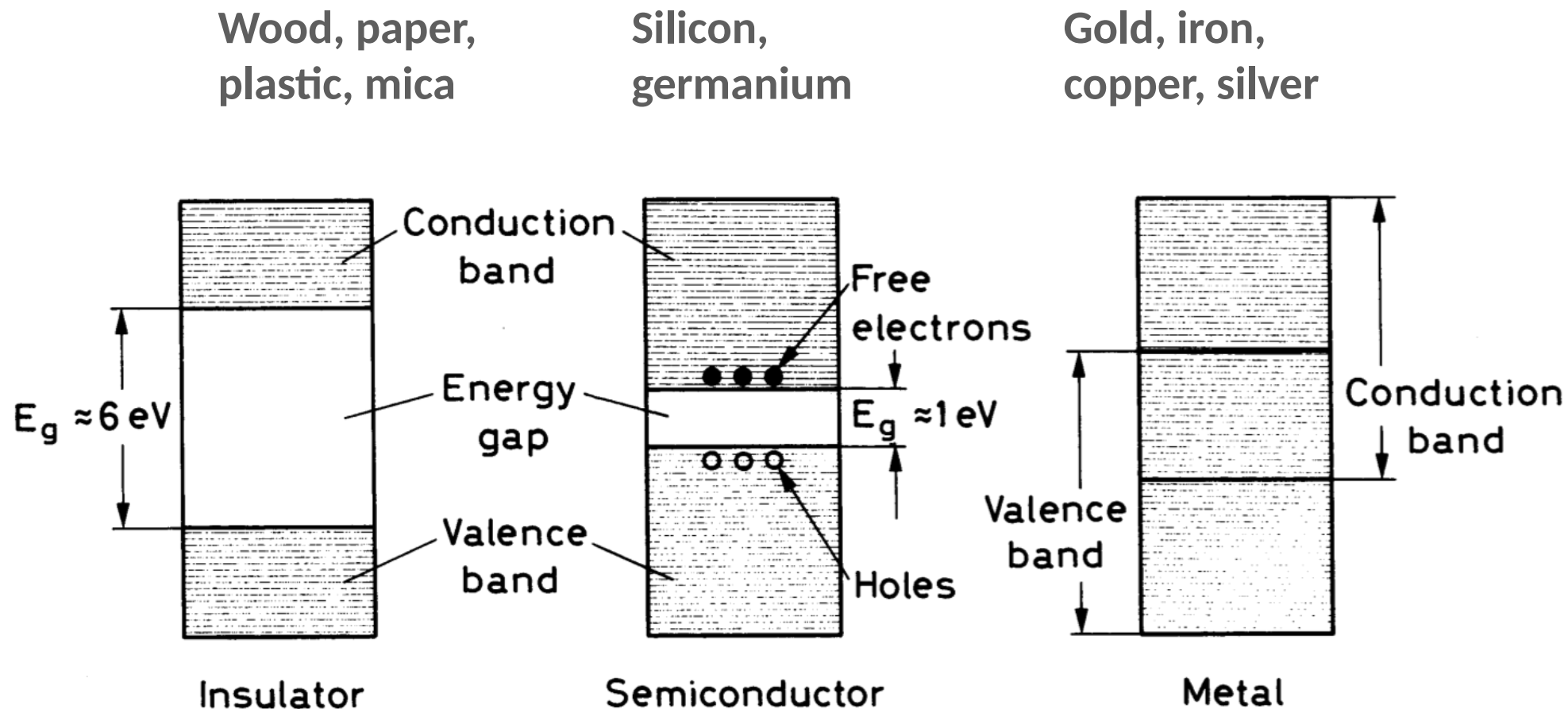
Figure: <https://www.mdpi.com/1424-8220/13/2/2447>

gas detectors: e-ion creation in gas



Solid equivalent of an ionization chamber

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



Insulator in room temperature:

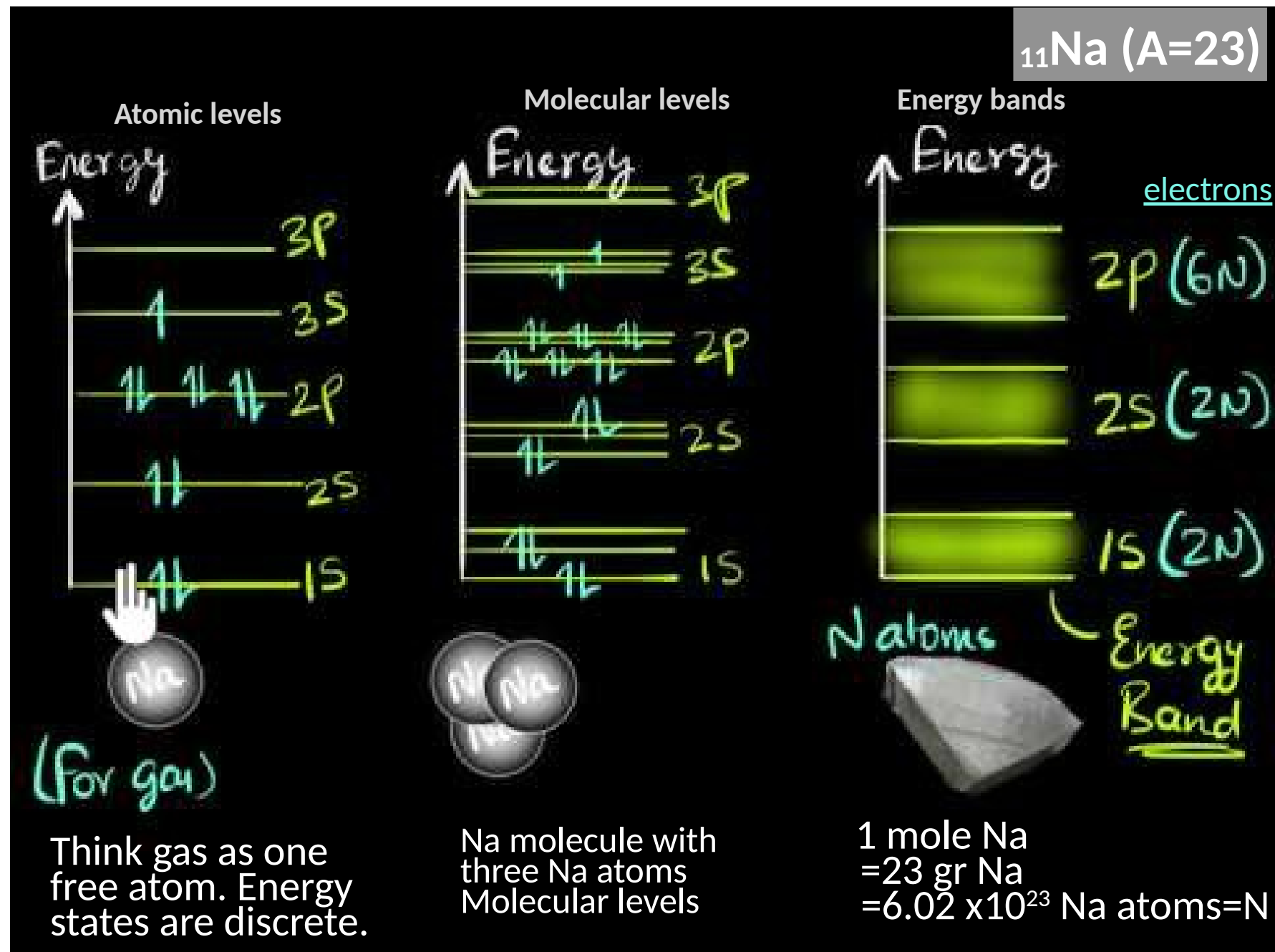
Thermal energy is not sufficient to excite electrons to the conduction band

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

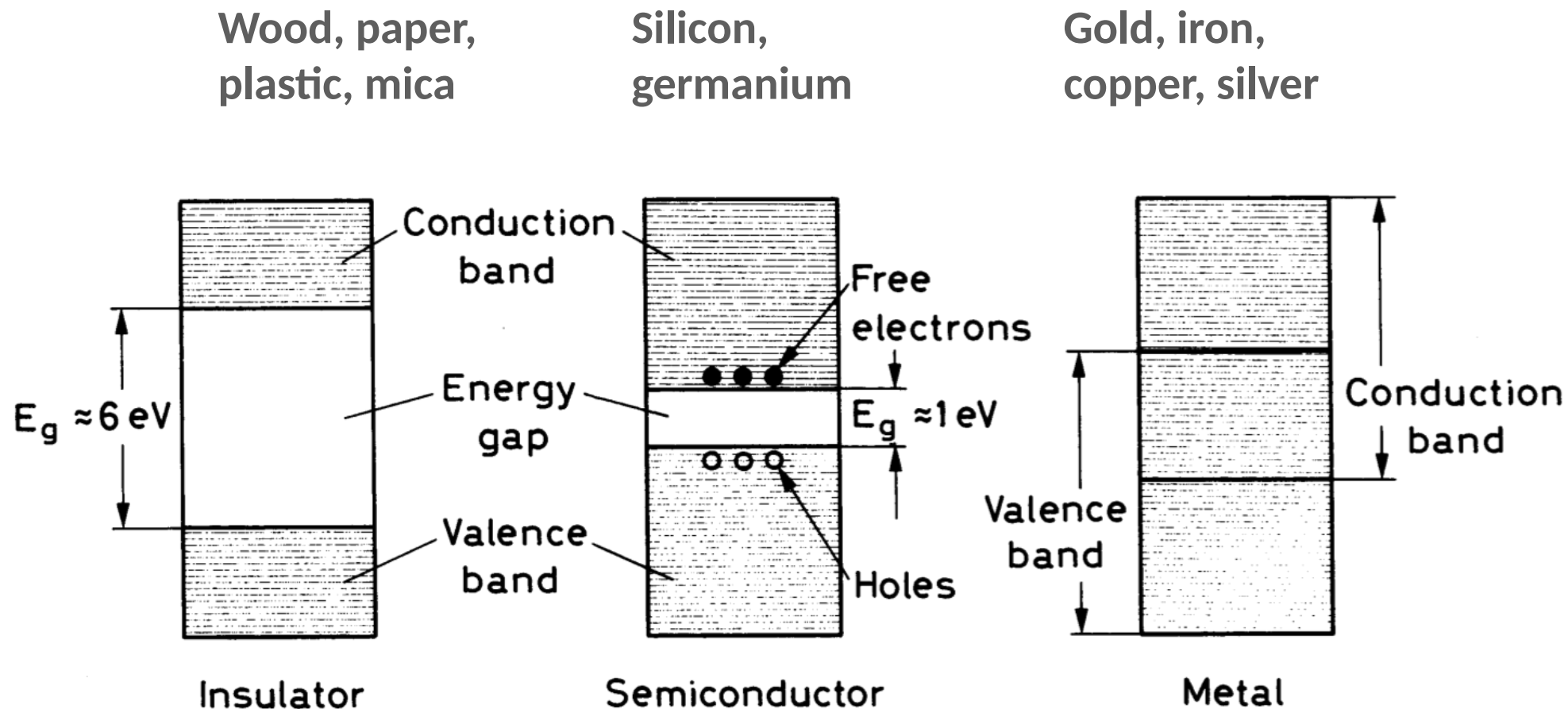


<https://www.khanacademy.org/science/in-in-class-12th-physics-india/in-in-semiconductors/in-in-band-theory-of-solids/v/band-theory-of-solids-class-12-india-physics-khan-academy>

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

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

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



Semiconductors in room temperature:

Thermal energy may excite electrons to the conduction band

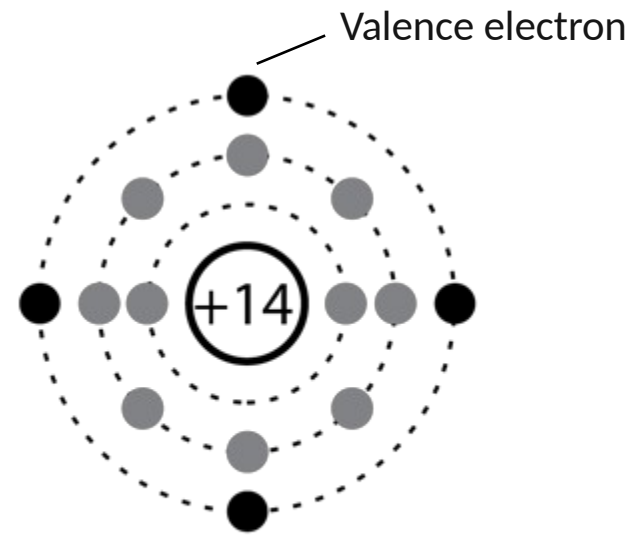
Applied electric field will cause a small current signal at the output

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.

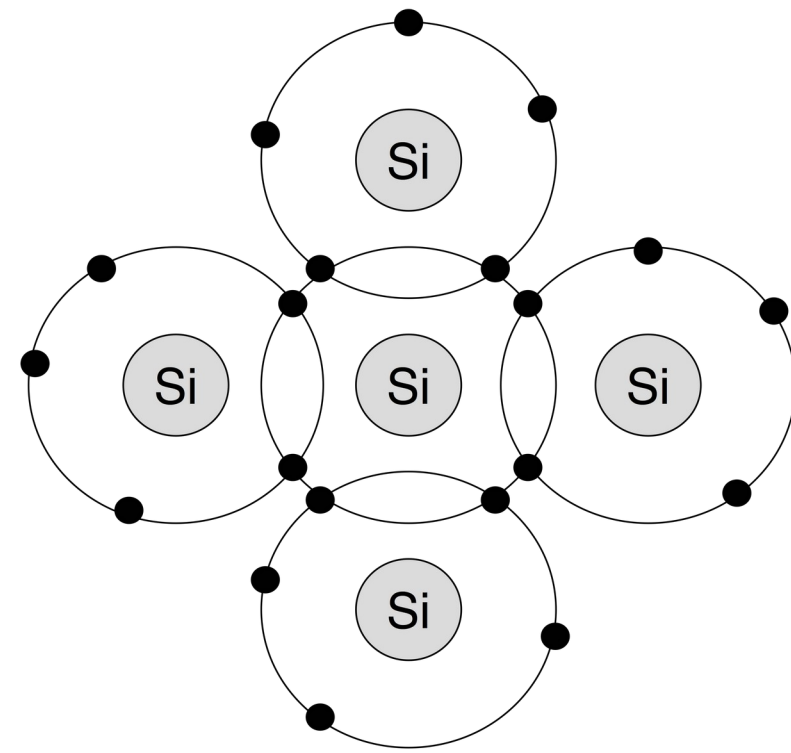
“Intrinsic” semiconductors

- ❑ intrinsic semiconductors
- ❑ Internal impurities
- ❑ the number of excited electrons is equal to the number of holes and denoted with $n_i = n_e = n_h$

2,8,4



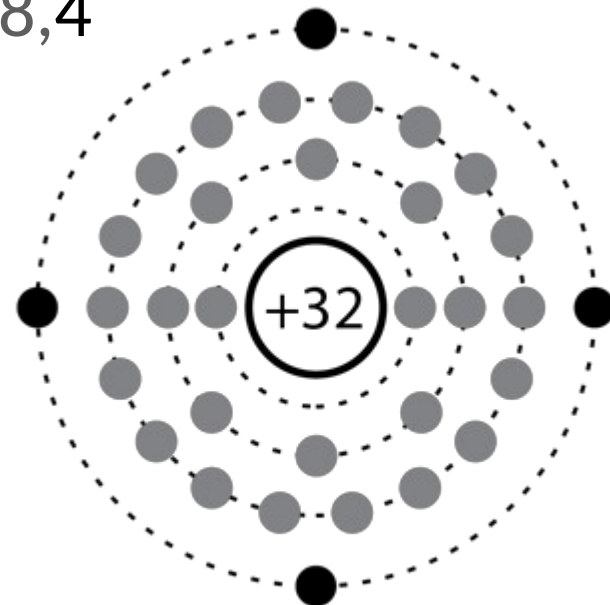
Silicon (Z=14)



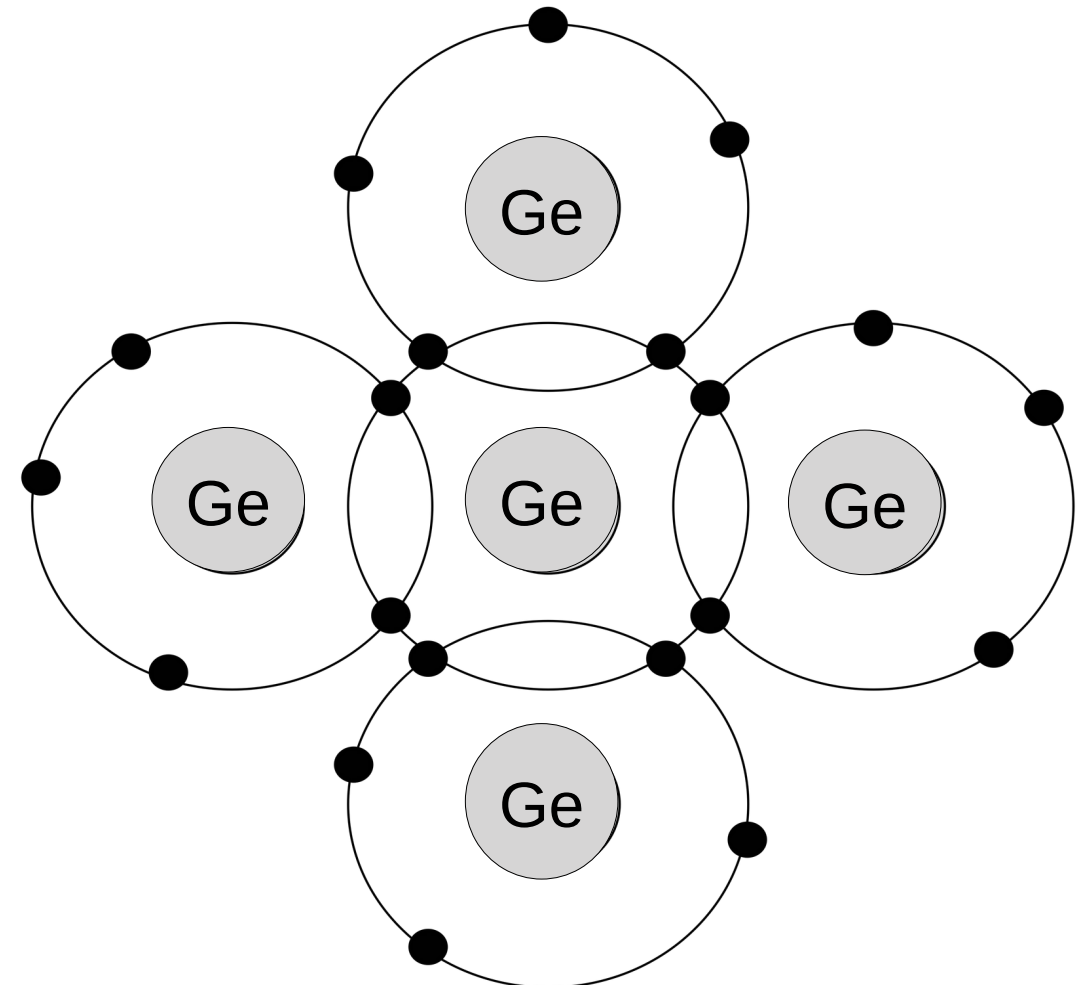
Si, Ge (Group IV), 4 valence electrons are “shared” between atoms in their chemical bonding (covalent*).

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

2,8,18,4



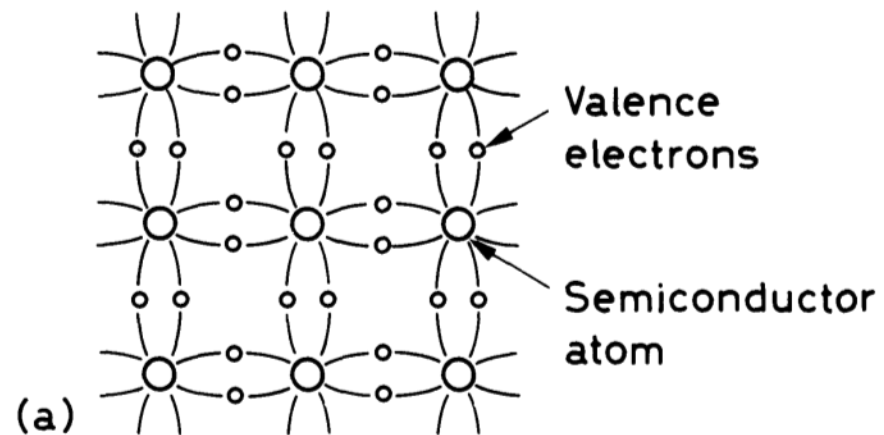
Germanium (Z=32)



General characteristics of Ge and Si materials

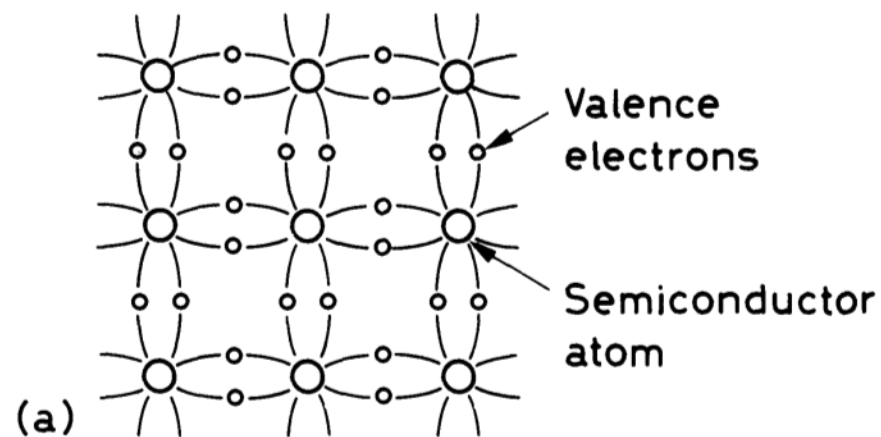
- **charge carriers**
- intrinsic charge carrier concentration
- mobility
- Internal impurities: recombination and trapping

Charge carriers

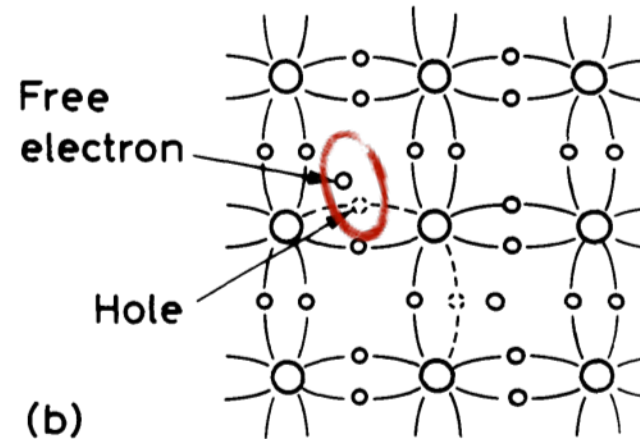
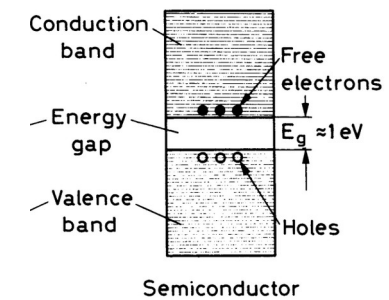


(a) at 0 K ($=-273.15^{\circ}\text{C}$), all electrons are in their place participating in bonding

What happens if we increase the temperature?



Electron leaving the bound =
electron excited to the
conduction band



(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, $\sim 300 \text{ K}$)
Some electrons might leave their covalent bounding 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)

General characteristics of Ge and Si materials

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

Intrinsic charge carrier concentration

Fermi-Dirac statistics

$$n_i = \sqrt{N_c N_v} \exp\left(\frac{-E_g}{2kT}\right) = A T^{3/2} \exp\left(\frac{-E_g}{2kT}\right)$$

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

N_c : number of states in the conduction band

N_v : number of states in the valence band

E_g : Energy gap at 0K (= -273.15 °C)

T : Temperature

k : Boltzmann constant

A : another constant (independent of temperature)

$n_i = 2.5 \times 10^{13} \text{ cm}^{-3}$ for Ge and $1.5 \times 10^{10} \text{ cm}^{-3}$ for Si at $T = 300 \text{ K}$ (room temperature).

Concentration of total
Ge/Si atoms $\sim 10^{22}$
atoms/cm³

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. Now it is a solid material.

μ : mobility

u : drift velocity

E : electric field

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

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

$$\mu_e = \frac{u_e}{E} \sim \frac{kT}{e}$$

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

1. Ge is more conductive or metallic than Si

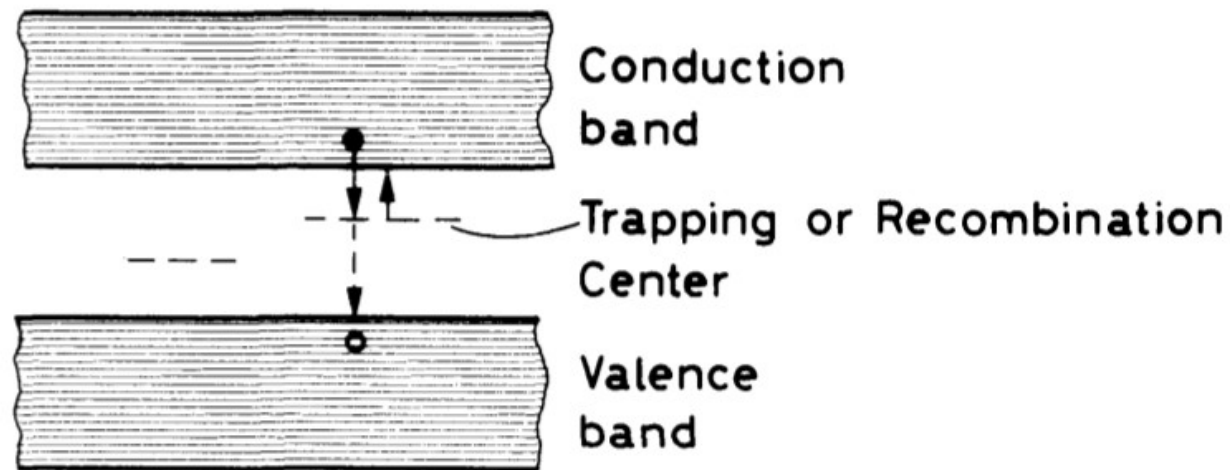
2. Ge needs cooling because of its smaller energy gap

Mobilities determine the current in the semiconductor detectors

General characteristics of Ge and Si materials

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

Recombination & 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

t_c : charge collection time

2-Recombination center due to impurities:

Deep levels: Keep charge for long time

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

If $t_r \gg t_c$, **signal is lost!!**

B-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 due to impurities:

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!!**

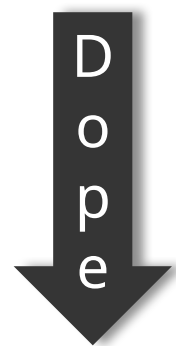
One center causes many recombination or trapping

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 make a detector with putting them together!!

a "pure"
semiconductor

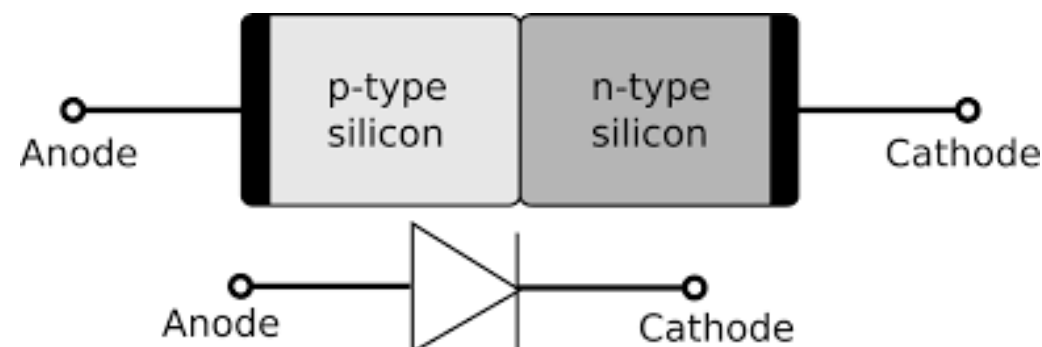


P-type
semiconductor

a "pure"
semiconductor



N-type
semiconductor



Doped Semiconductors

Recombination and trapping occur because of the “internal” impurities of the crystal. They ruin the performance of the detectors.

Doping: “External” impurities are added intentionally into the crystal in order to produce an intrinsic region in which free charge carriers of one would be able to reach the contacts and produce a signal. "

In other words, external impurities will enhance the characteristics of the material, i.e. **conductivity of the the material**. (The electrical conductivity of a doped semiconductor is always much larger than that of the corresponding pure material)

After doping, the semiconductor will have either more electrons (n-type) or more holes (p-type)

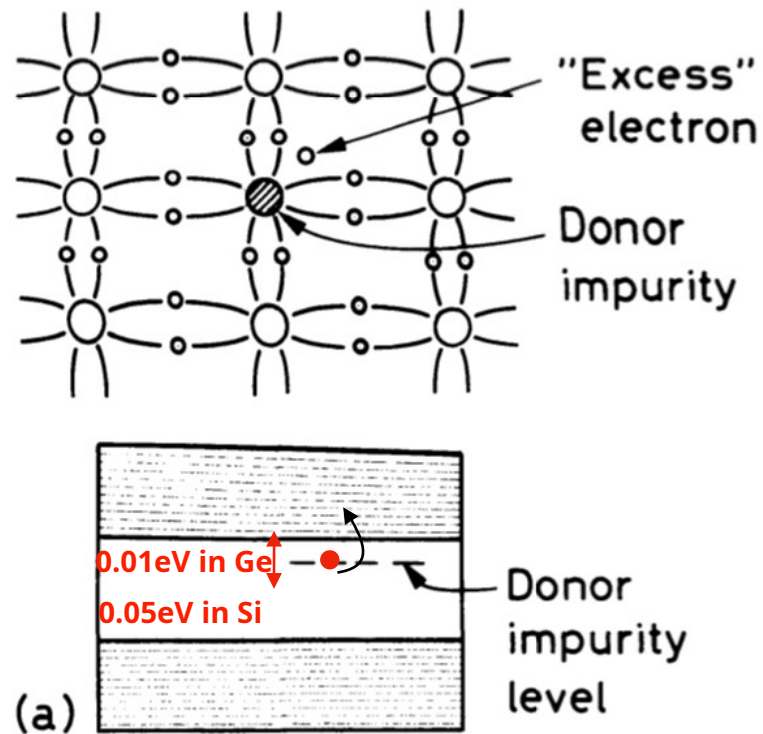
These are the desired impurities forming "**shallow traps**" that retain the electrons or holes for **short periods of time**.

Semiconductors are found in columns II-VI of the periodic table.

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

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

Knoll

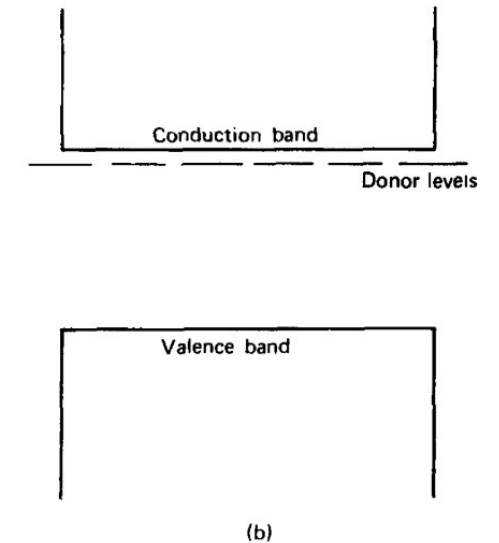
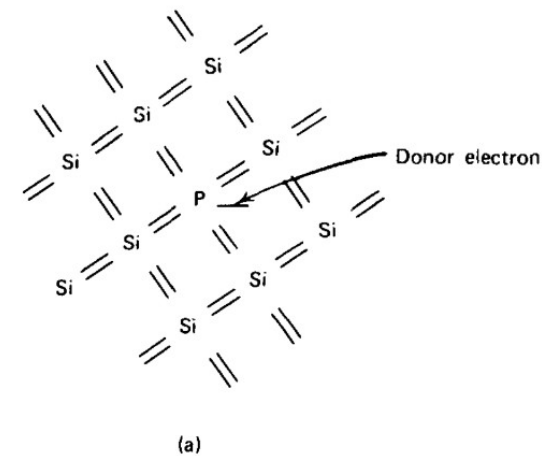


Figure 11.3 (a) Representation of a donor impurity (phosphorus) occupying a substitutional site in a silicon crystal. (b) Corresponding donor levels created in the silicon bandgap.

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

0 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

0 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^+

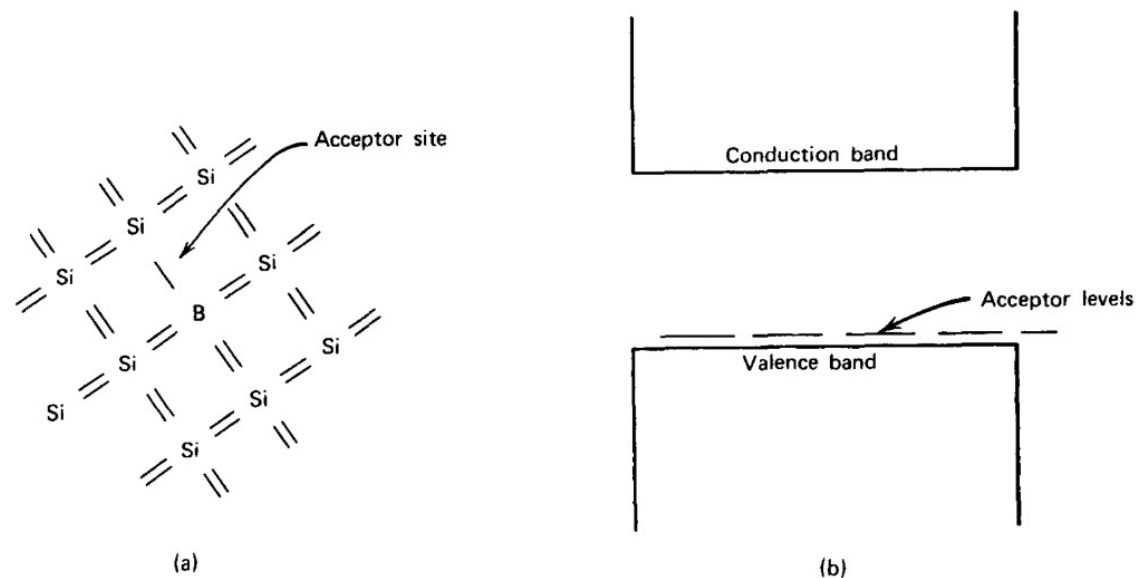
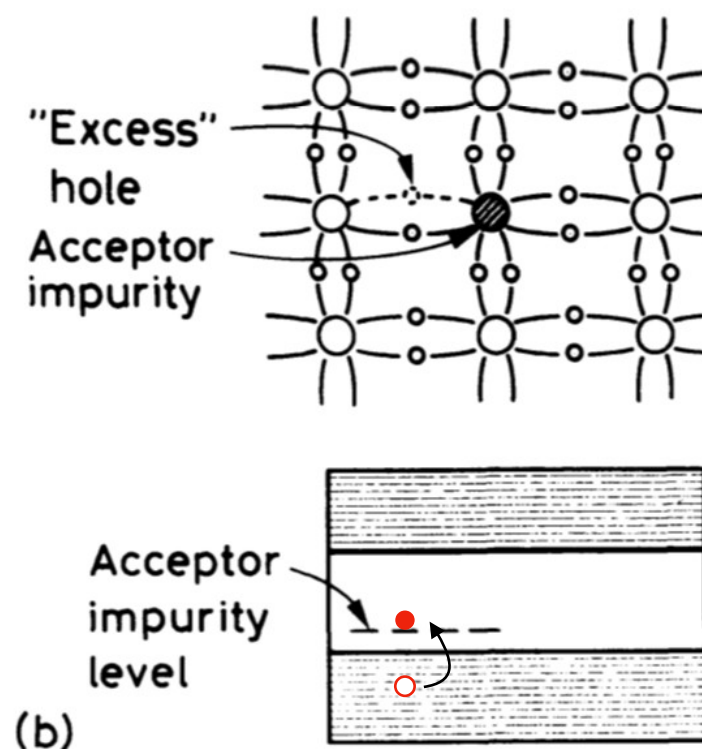


Figure 11.4 (a) Representation of an acceptor impurity (boron) occupying a substitutional site in a silicon crystal. (b) Corresponding acceptor levels created in the silicon bandgap.

Knoll

Acceptor (trivalent: 3 valence electrons)



electrons —> minority charge carriers
holes —> majority charge carriers
p-type

Read Leo page#221

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

lithium ion drifting process

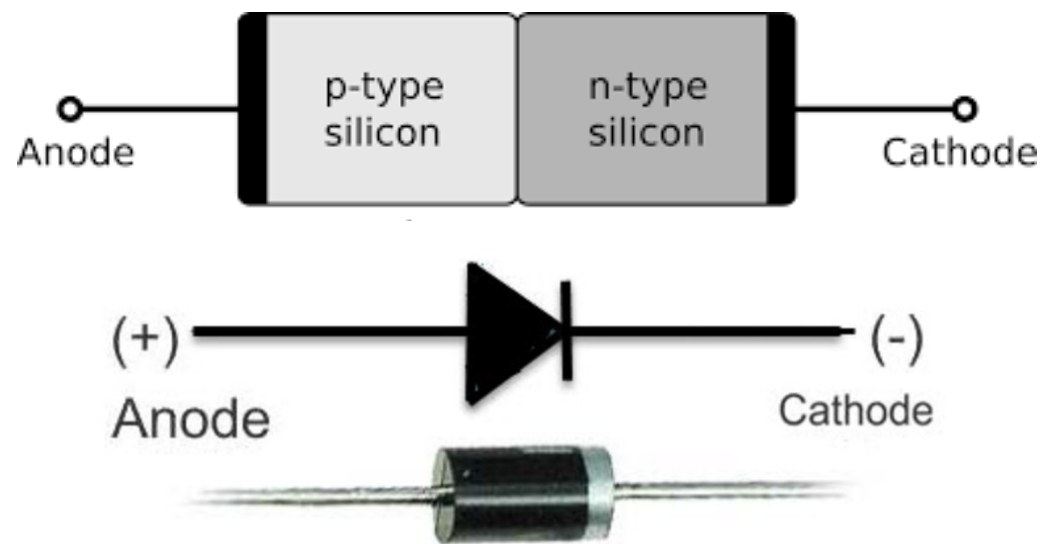
- In order to increase the conductivity, one could add equal amount of donor and acceptor impurities but this is a very difficult process to manage.
- Instead, in 1960 Pelle developed the lithium drifting method for compensating p-type silicon and germanium:

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.

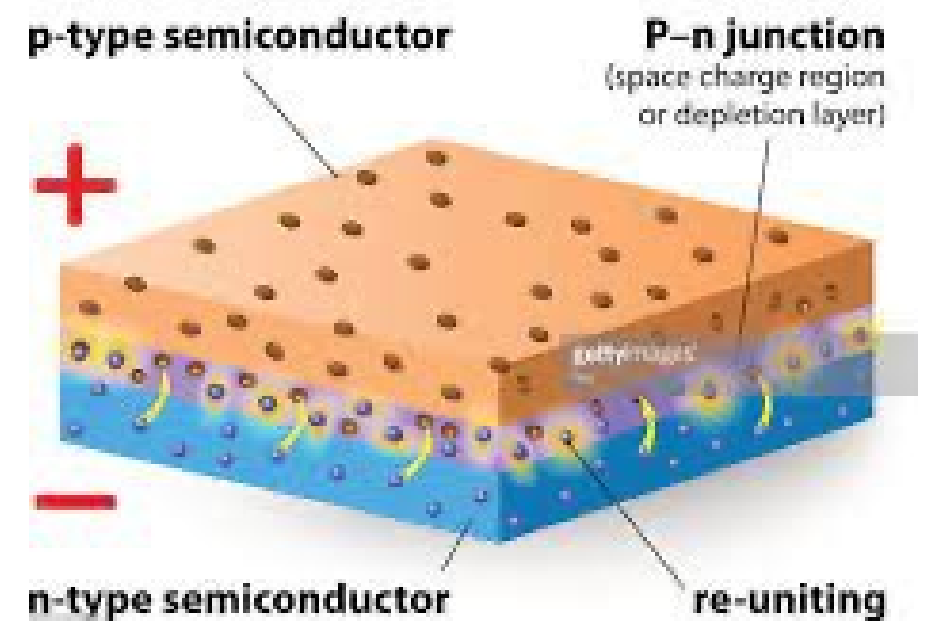
Semiconductor junction

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

Junction provides a good depletion layer/zone/depth for the purpose of radiation detection

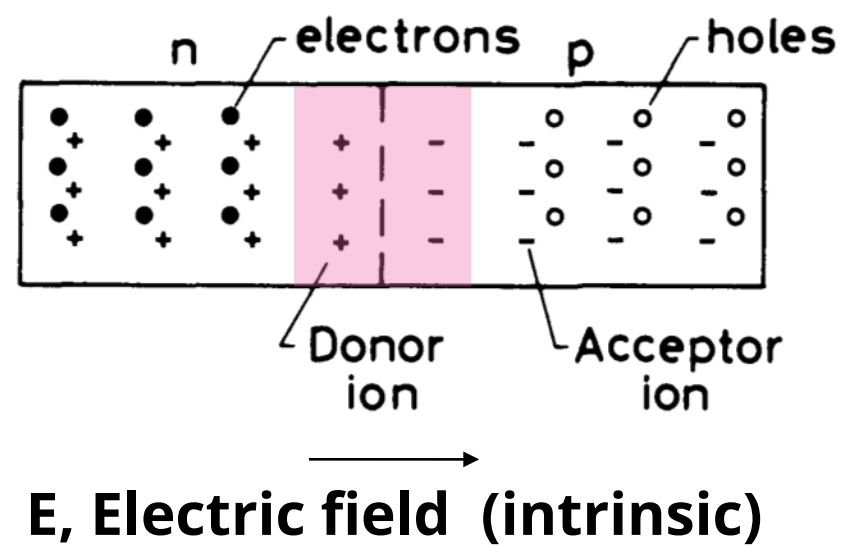


P-N JUNCTION

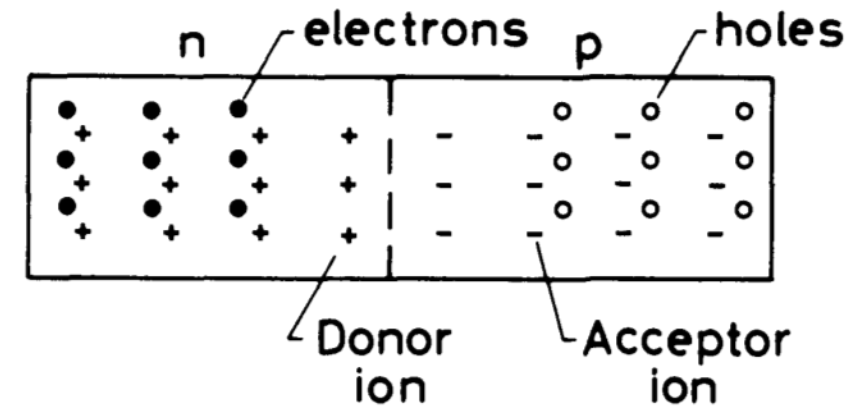


pn junction

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



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!!**

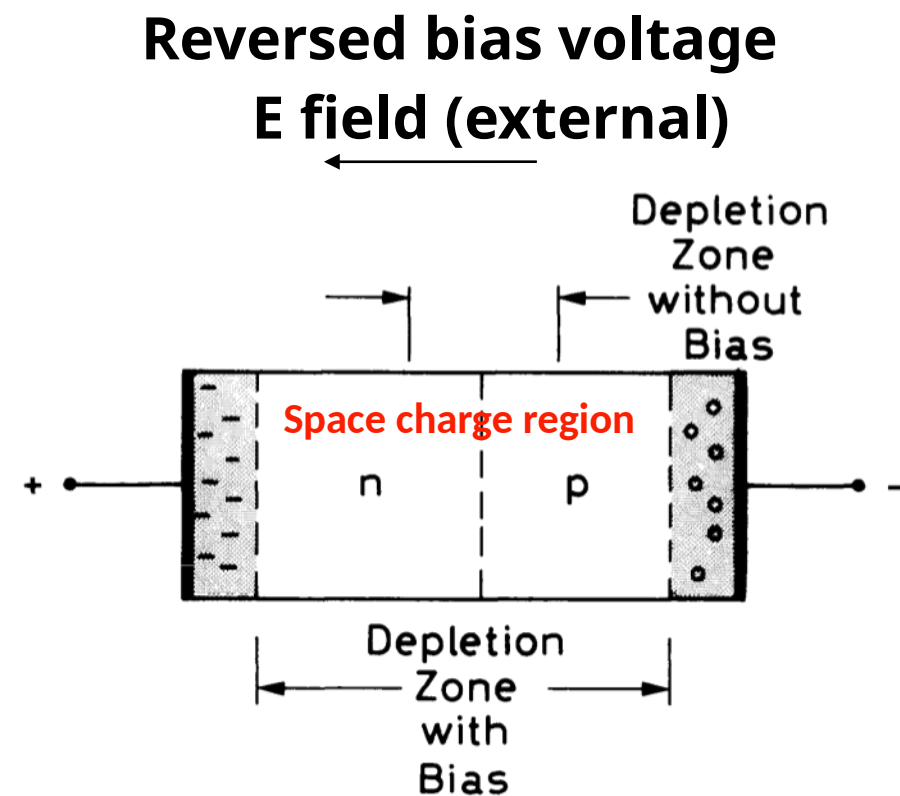
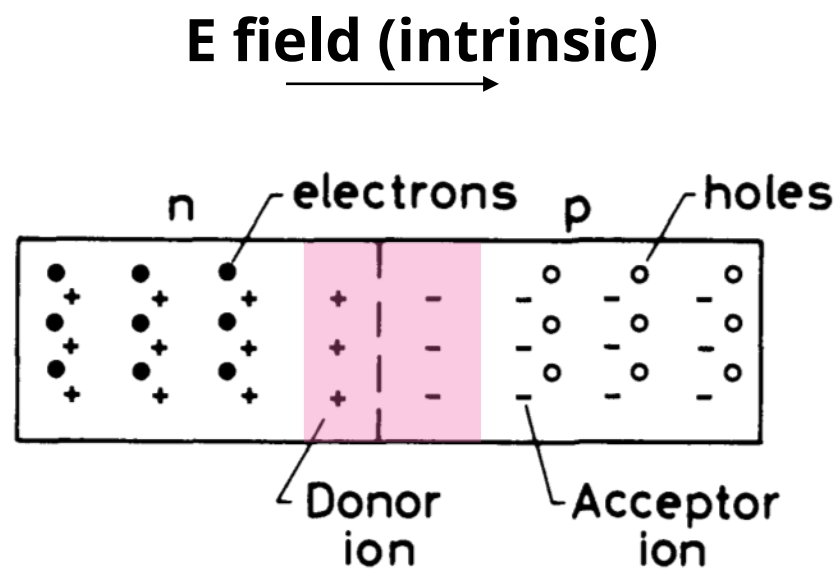
Reversed Bias Voltage:

RB voltage is a negative voltage to the p-side

Main purpose: to increase the depletion zone

Voltage value: 4000-5000 V for germanium (less for silicon)

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



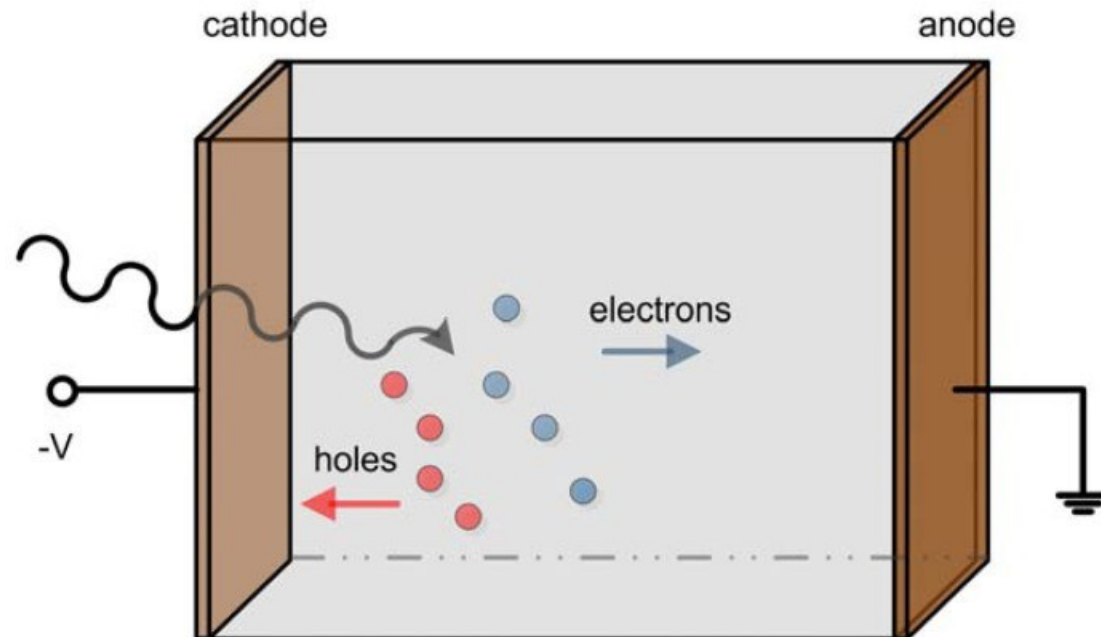
Reversed Bias Voltage:

RB voltage is a negative voltage to the p-side

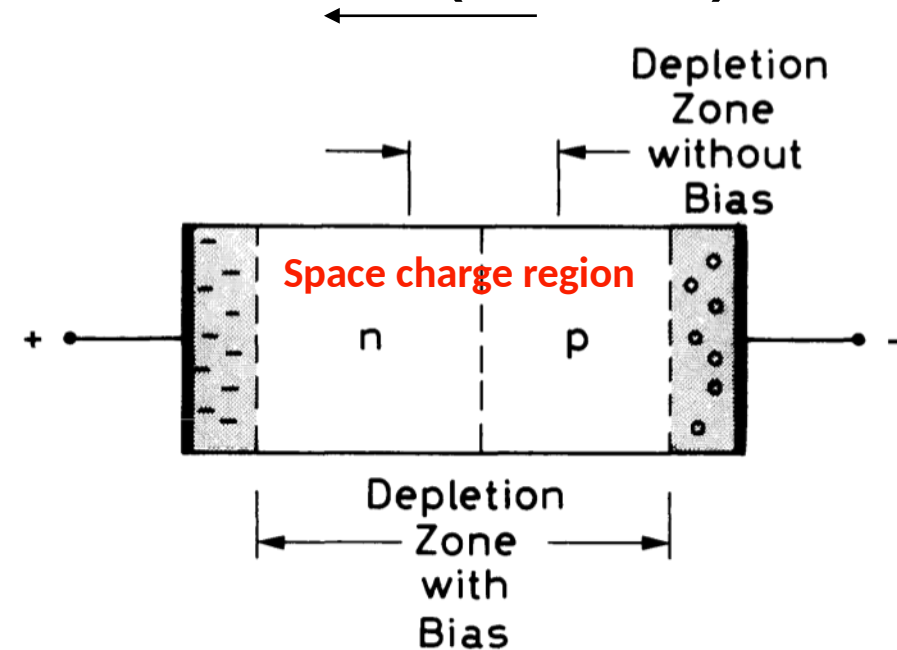
Main purpose: to increase the depletion zone

Voltage value: 4000-5000 V for germanium (less for silicon)

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



Reversed bias voltage E field (external)



Characteristics of SC detectors:

1- Average energy per e-hole pair

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

3- Resolution + Fano factor

$F \sim 0.12$

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

2- Linearity

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

n : charge collection efficiency (charge collection on the electrodes)

depletion layer has to be large enough to keep linearity, i.e. should not be smaller than the range of the radiation.

4- cooling

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

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

5- Operating voltage

HV: 4000-5000 V



germanium detector + dewar filled with a liquid hydrogen

Please read and go through material below:

Leakage current & Efficiency: Leo pp: 229-230

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

Types:

Germanium detectors —> gamma-ray detection

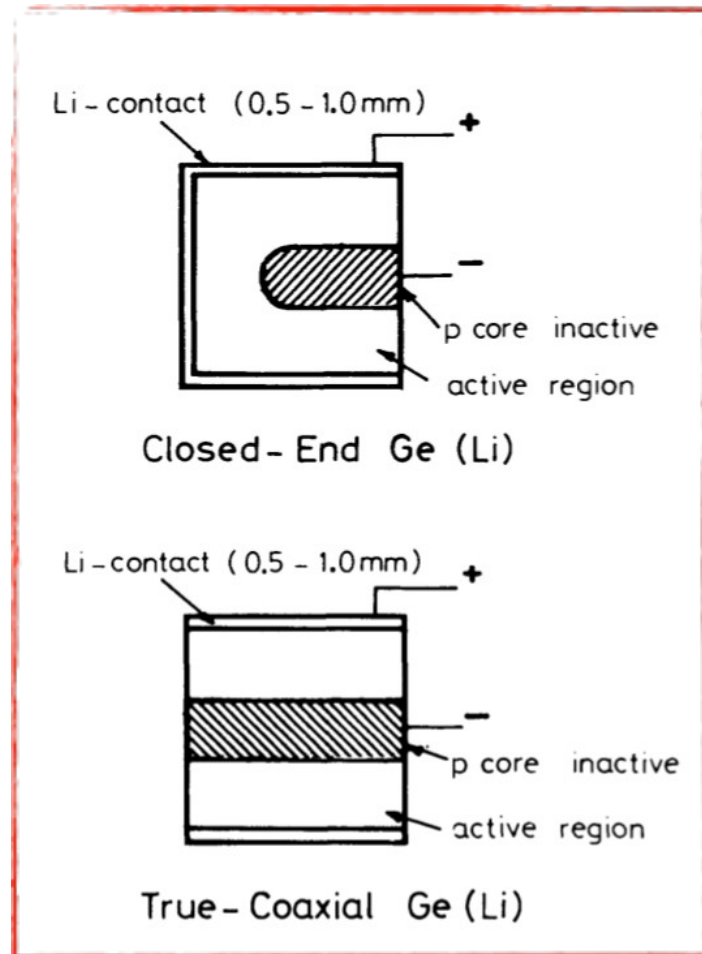
Silicon Diode Detectors —> charged particle detection

Germanium detectors

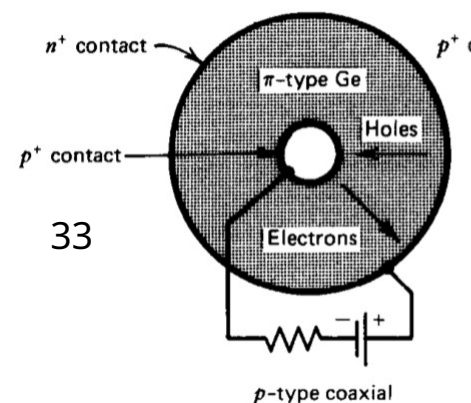
- 0 GeLi Detectors
- 0 HPGe Detectors
 - 1. Planar
 - 2. Coaxial

Ge(Li) detectors

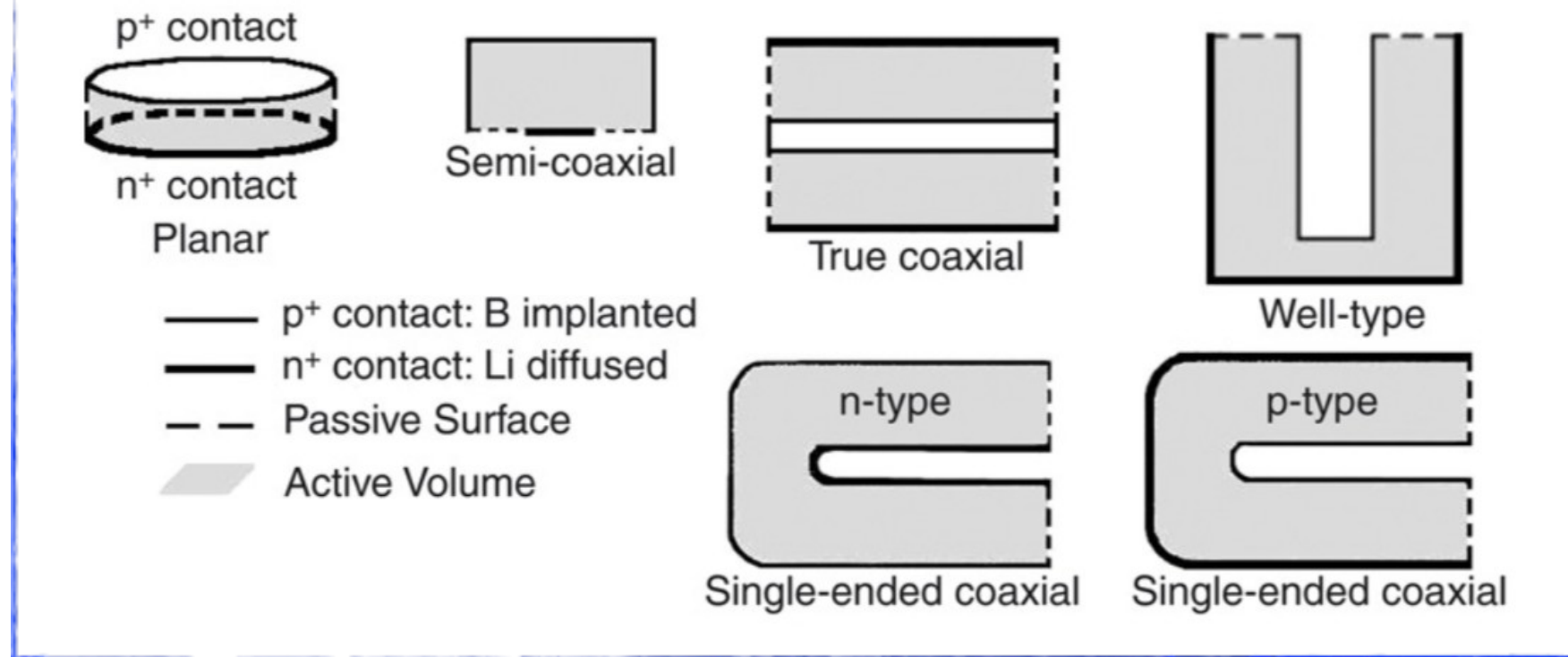
pronounced as “jelly”



- 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



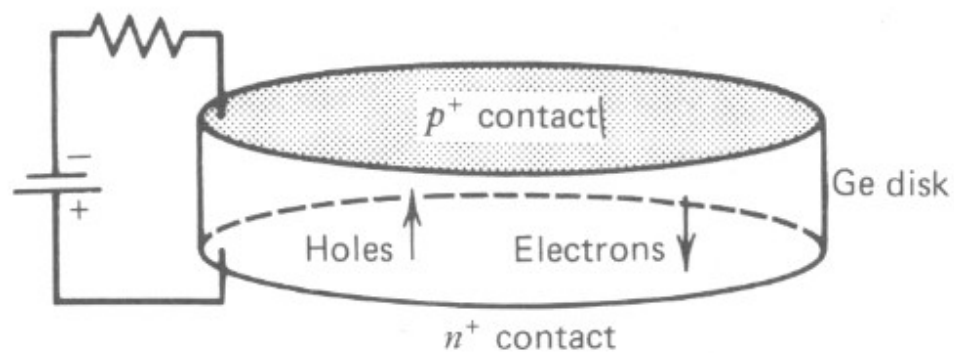
- In the late 1970s
- Pure samples of the detector material could be prepared only for germanium material
- The production process of a detector is much faster since no time-consuming drifting process is needed.
- The commercial production of Ge(Li) detectors was given up around 1980 when the volume of HPGe detectors became competitive with the volume of Ge(Li) detectors
- The size of pure crystals is limited to approximately 5 cm in diameter by 1 cm thick
- Quite expensive

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

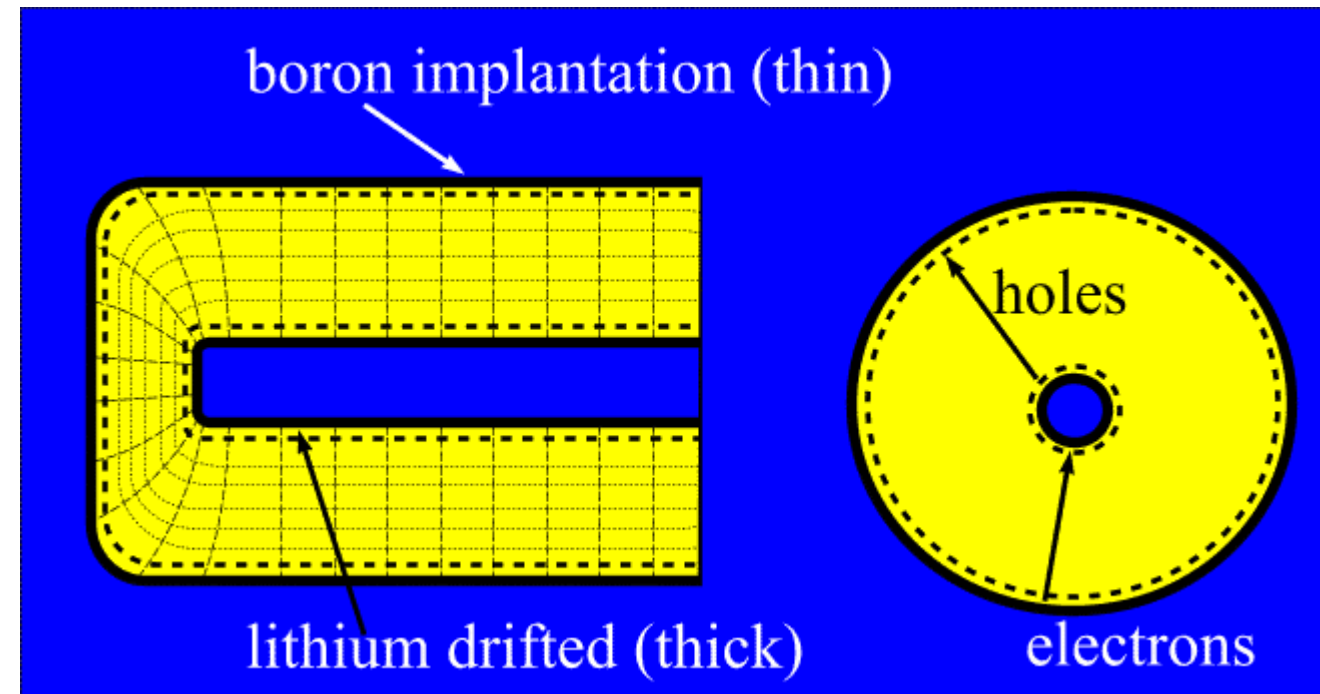
For a typical intrinsic germanium material,
 $N=10^{13}$ atoms/cm³
For HpGe $N=10^{10}$ atoms/cm³

Operated at 77 Kelvin using liquid nitrogen.

Planar



Coaxial



In Coaxial crystals:

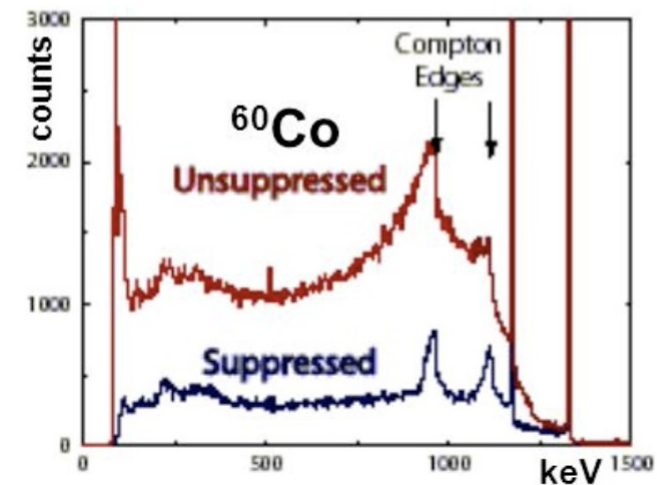
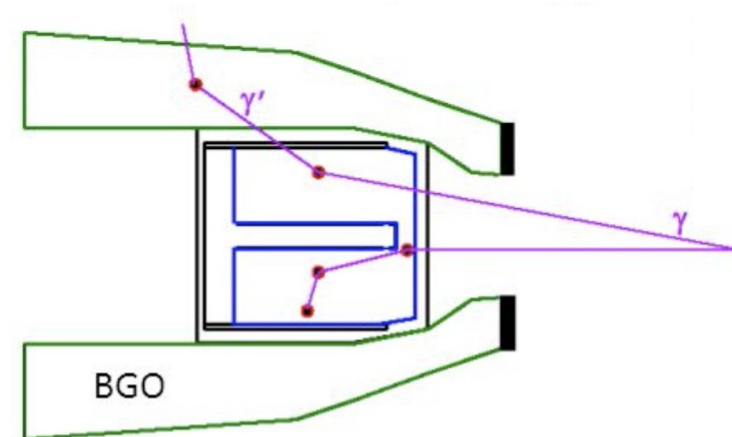
	Outer Contact	Inner
Contact		
p-type	n(Li)	p(B)
n-type	p(B)	n(Li)

The n $\sim$ 600 μm - 1 mm, p contact is very thin $\sim$ 0.3 μm .

BGO Compton suppression



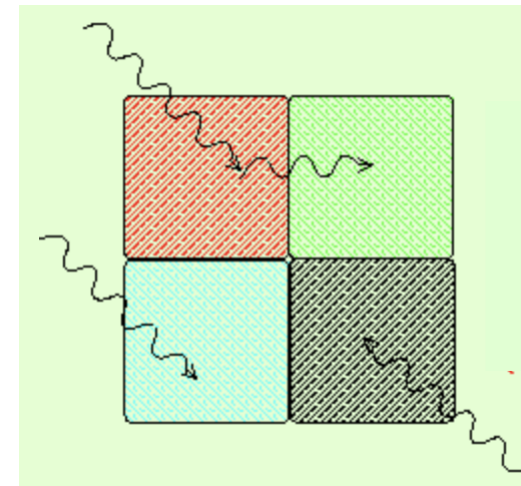
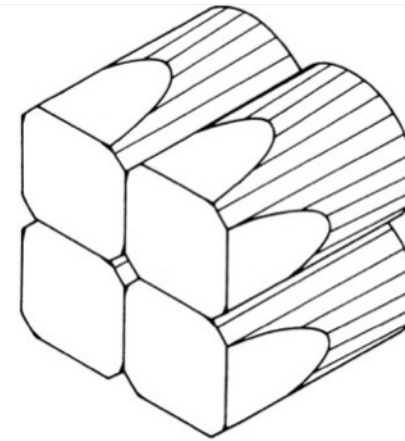
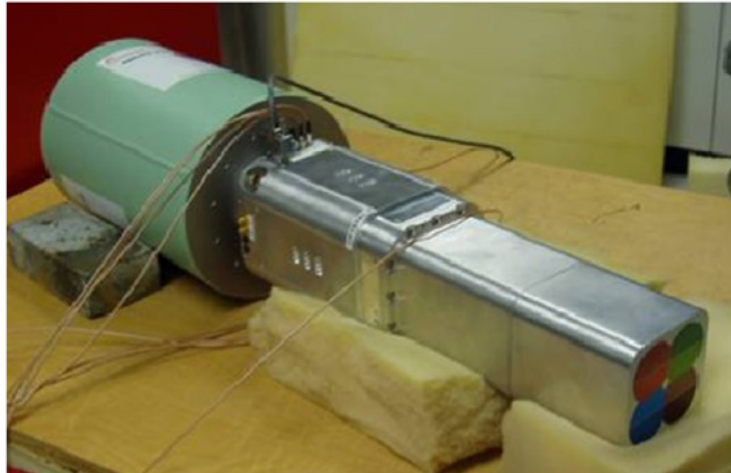
ROSPHERE at Bucharest, Romania



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

4π -Ge Arrays: Segmented crystals

Clover (4-fold segmentation)



Addback

Fig. 15. Eurogam II at IReS Strasbourg.

MINIBALL at CERN/ISOLDE

6-fold segmentation

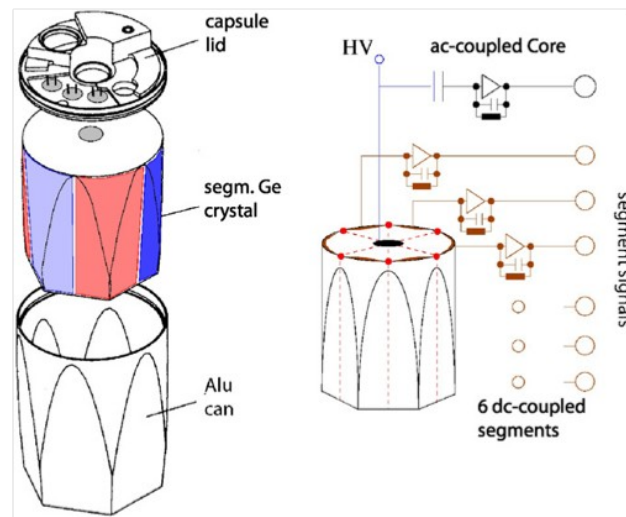
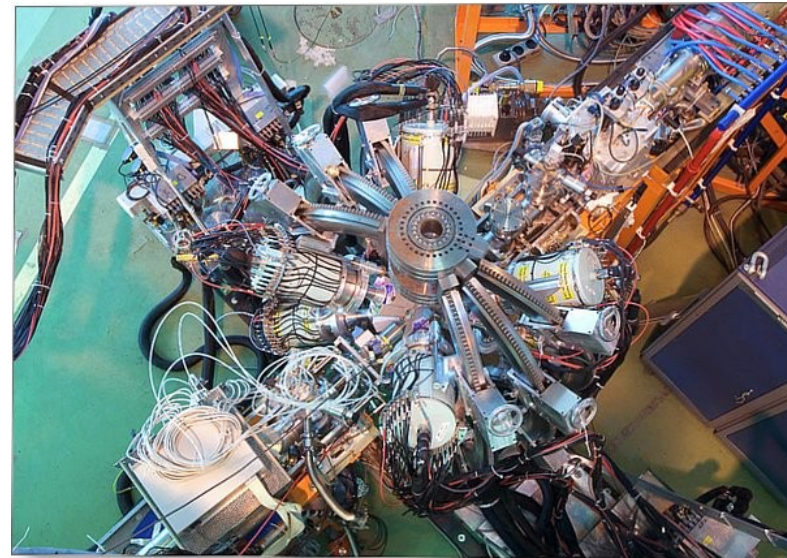
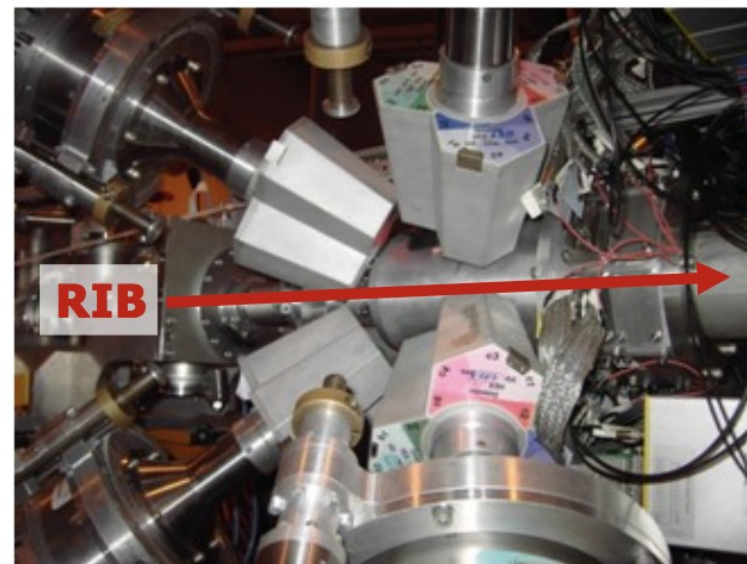
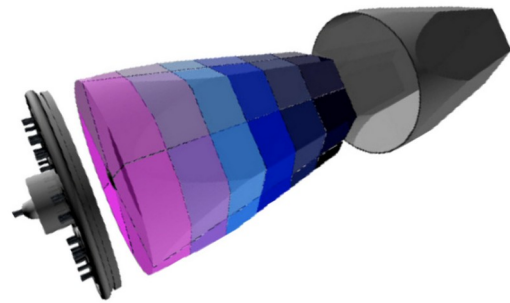


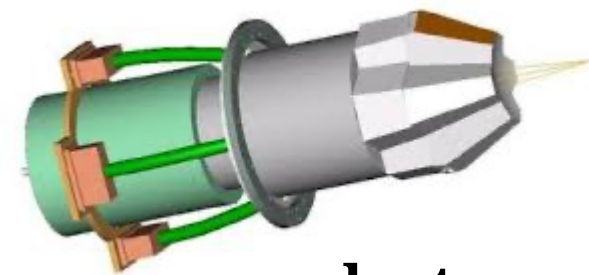
Fig. 23. The segmented MINIBALL detector.



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



triple clusters



seven clusters

36-fold segmentation

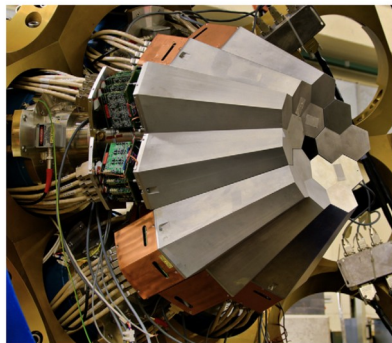
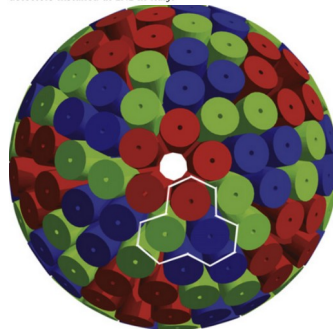
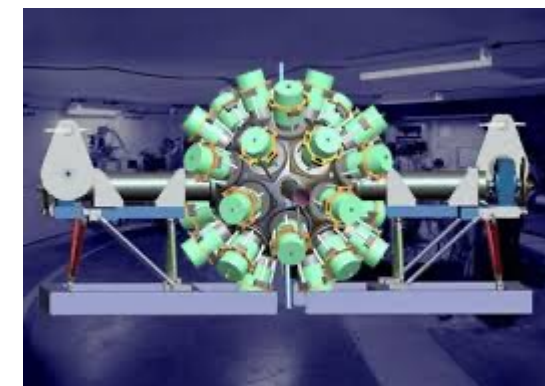
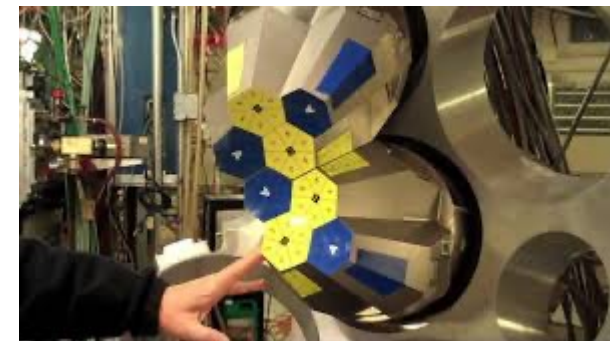


Fig. 6. (Colour online) Photograph of the setup with five AGATA triple cluster detectors installed at LNL in Italy.

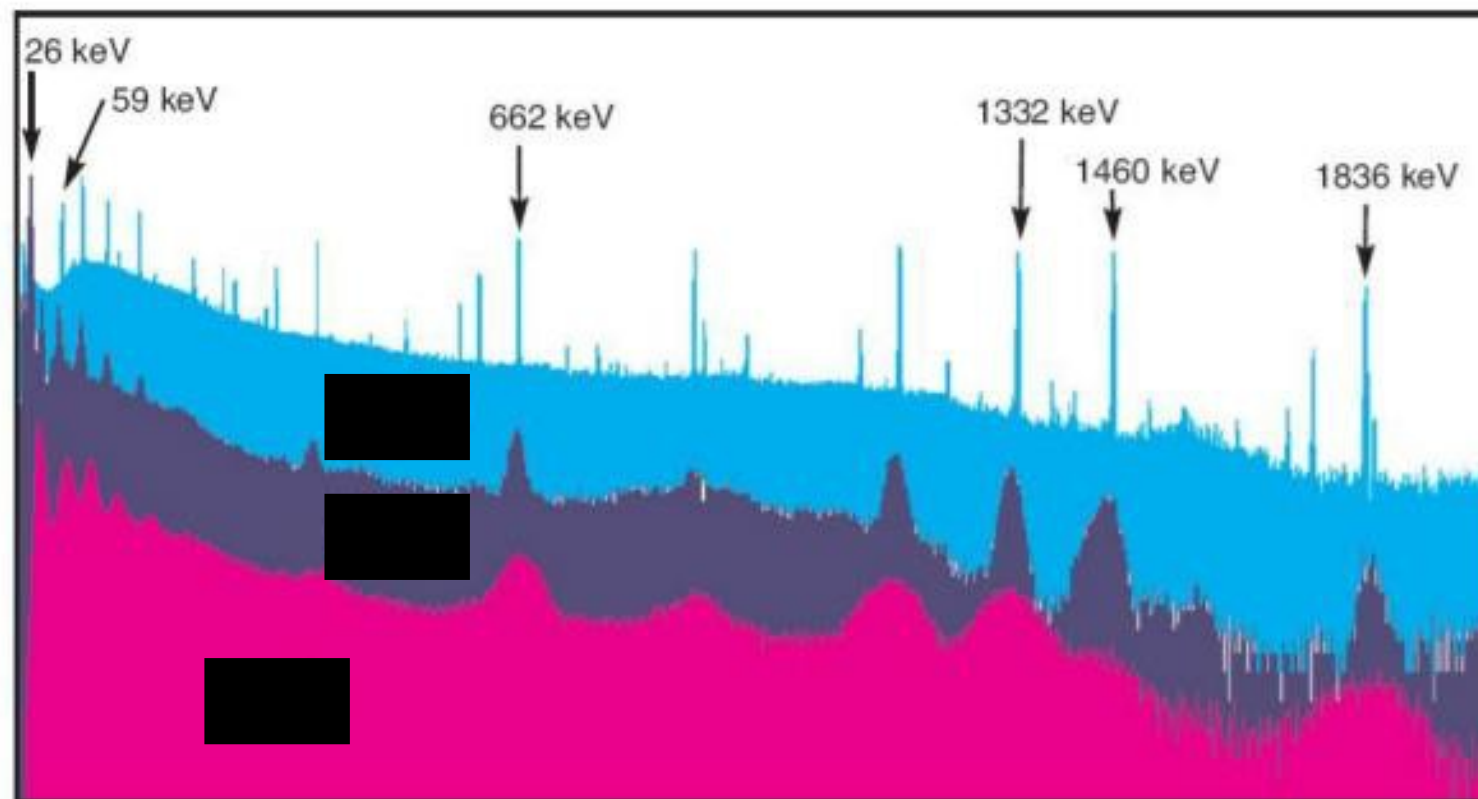


AGATA, Europe



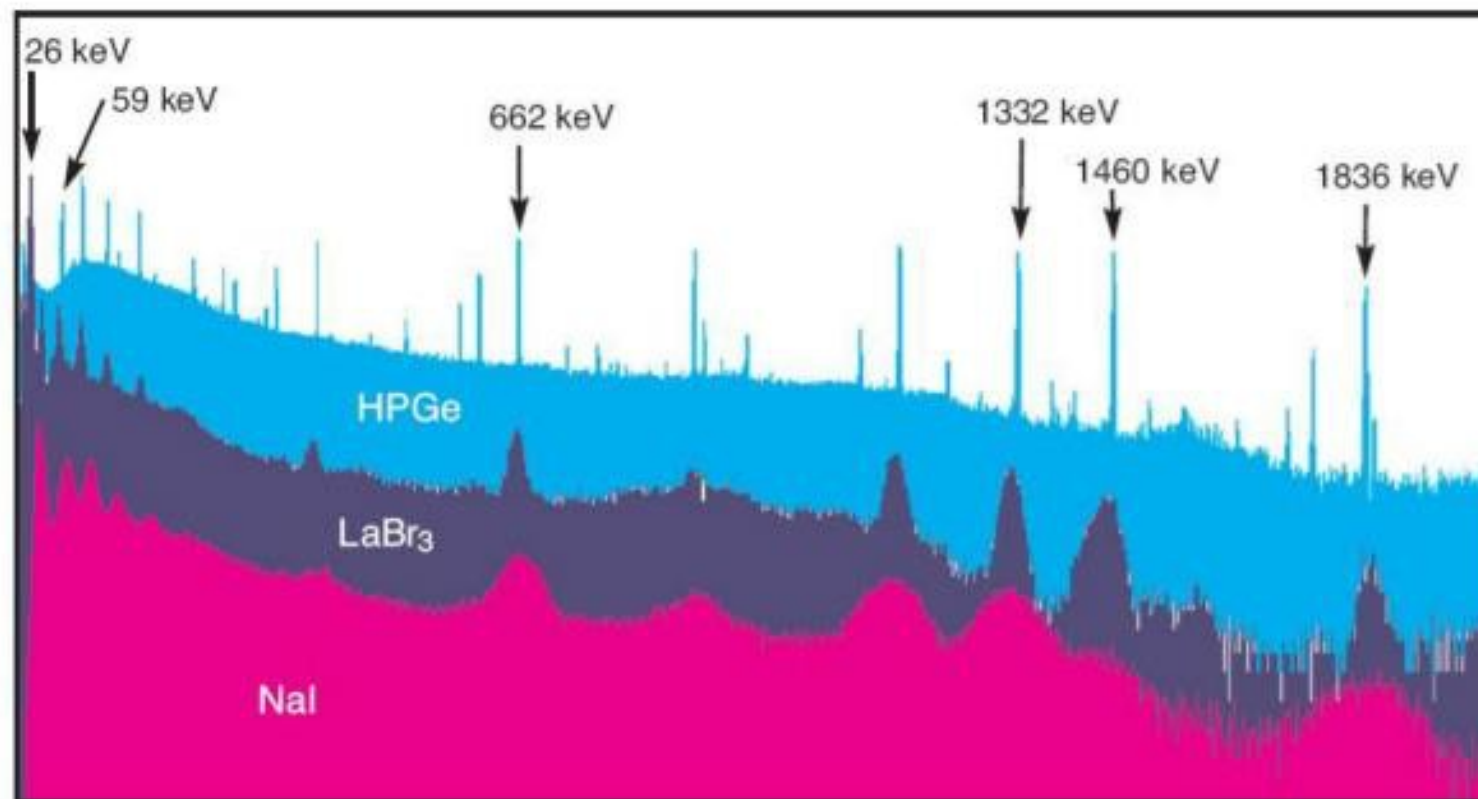
GRETA, USA

Comparison of HPGe, NaI, and LaBr



Match colours to each detector type!!

Comparison of HPGe, NaI, and LaBr



High Count Rate Compatibility

Lanthanum bromide detectors can operate over wide dynamic ranges of count rate with little variation in energy resolution.

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

Questions to you

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

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**

Semiconductor

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

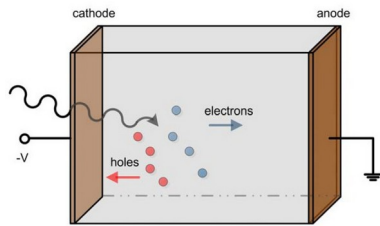
Advantages

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

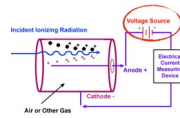
Detection mechanism: electron-hole (e-h) pair creation in solid-state material



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.

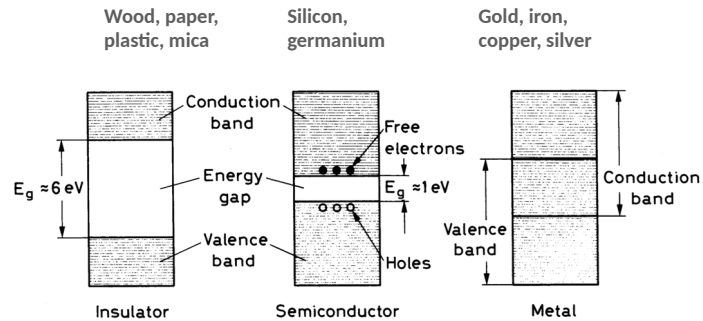
Figure: <https://www.mdpi.com/1424-8220/13/2/2447>

gas detectors: e-ion creation in gas



Solid equivalent of an ionization chamber

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



Insulator in room temperature:

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

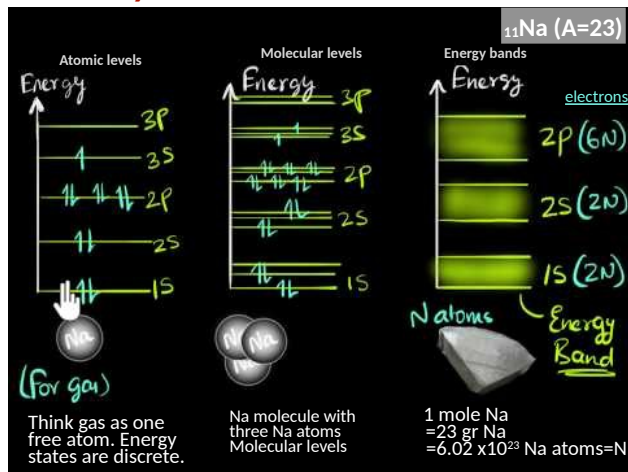
Applied electric field will not cause any current signal at the output.

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

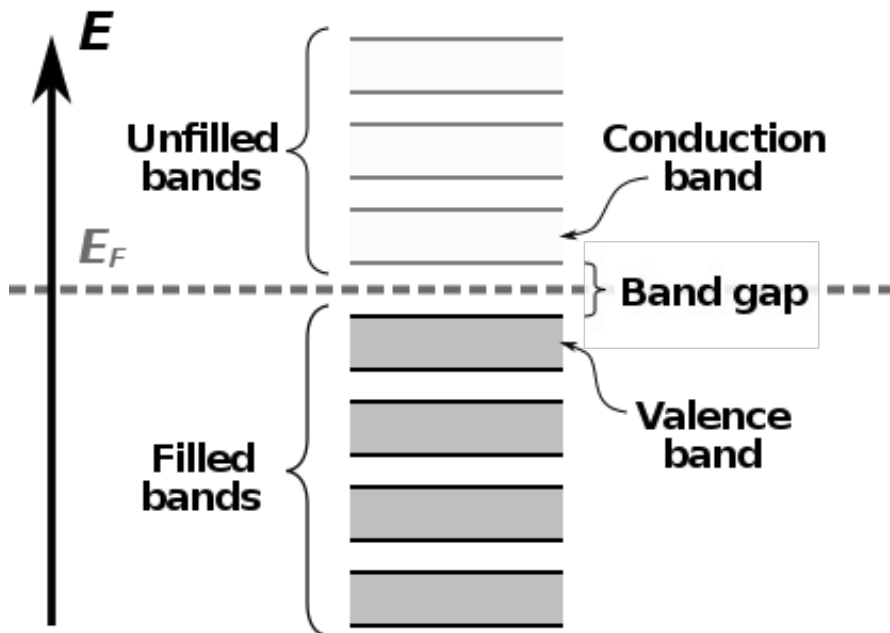


<https://www.khanacademy.org/science/in-in-class-12th-physics-india/in-in-semiconductors/in-in-band-theory-of-solids/v/band-theory-of-solids-class-12-india-physics-khan-academy>

5

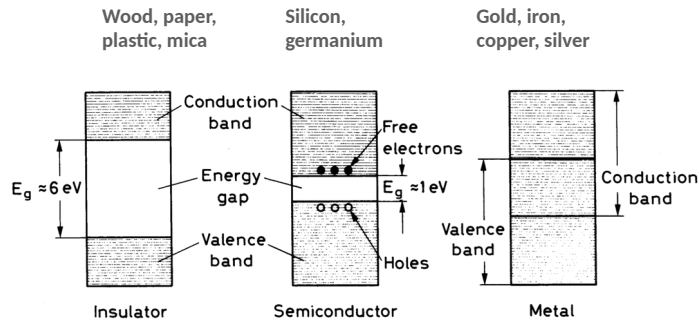
Watch the video for a great explanation of the band structure of solid materials!!!

Exciting electrons from the valence band means exciting them above the fermi level resides in the forbidden gap.



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

Q: what was the band gap value 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.

“Intrinsic” semiconductors

- ❑ intrinsic semiconductors
- ❑ Internal impurities
- ❑ the number of excited electrons is equal to the number of holes and denoted with $n_i = n_e = n_h$

7

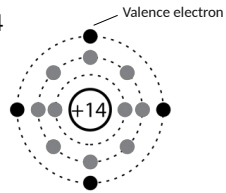
Semiconductors that are chemically pure, in other words, free from impurities are termed as intrinsic semiconductors.

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

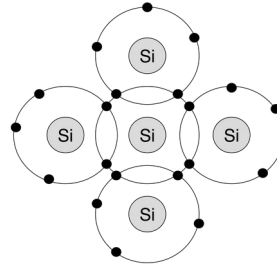
Semiconductor with their own internal impurities are called intrinsic semiconductors.

In intrinsic semiconductors, the number of excited electrons is equal to the number of holes and denoted with $n_i = n_e = n_h$

2,8,4



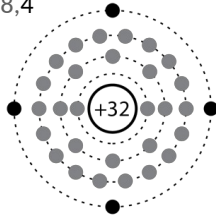
Silicon (Z=14)



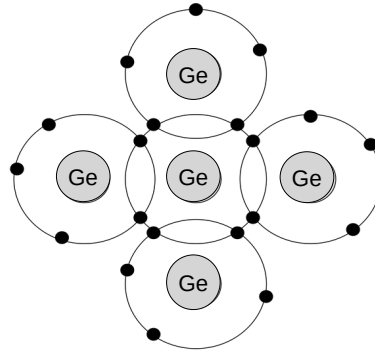
Si, Ge (Group IV), 4 valence electrons are "shared" between atoms in their chemical bonding (covalent*).

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

2,8,18,4



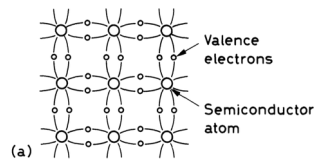
Germanium (Z=32)



General characteristics of Ge and Si materials

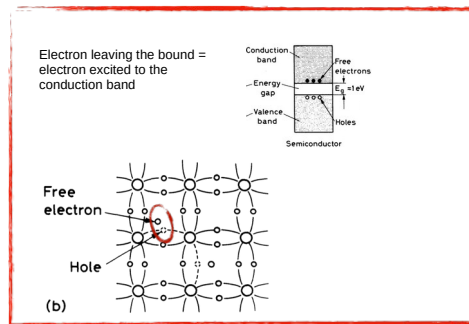
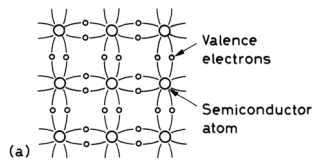
- **charge carriers**
- intrinsic charge carrier concentration
- mobility
- Internal impurities: recombination and trapping

Charge carriers



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

What happens if we increase the temperature?



(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, $\sim 300 \text{ K}$) 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)

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- electron of the bond is free in the crystal (precisely in the conduction band)
- leaves a hole in its original position (in the valence band)
- neighbouring valence electron will fill this hole and then leaves a hole in its original place
- Now the next neighbouring valence electron will fill this new hole, and this will continue so.
- If you watch the whole process from outside you will see a moving hole through the crystal.
- hole then acts like a positive charge relative to the negative sea of electrons.
- Result: in a semiconductor, the electric current arises from two sources: the movement of free electrons in the conduction band and the movement of holes in the valence band.

General characteristics of Ge and Si materials

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

Intrinsic charge carrier concentration

Fermi-Dirac statistics

$$n_i = \sqrt{N_c N_v} \exp\left(\frac{-E_g}{2kT}\right) = A T^{3/2} \exp\left(\frac{-E_g}{2kT}\right)$$

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

N_c : number of states in the conduction band

N_v : number of states in the valence band

E_g : Energy gap at 0K (=273.15 °C)

T : Temperature

k : Boltzmann constant

A : another constant (independent of temperature)

$n_i = 2.5 \times 10^{13} \text{ cm}^{-3}$ for Ge and $1.5 \times 10^{10} \text{ cm}^{-3}$ for Si at $T = 300 \text{ K}$ (room temperature).

Concentration of total
Ge/Si atoms $\sim 10^{22}$
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.

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In a semiconductor, electron-hole pairs are constantly being generated by thermal energy. At the same time, there are also a certain number of electrons and holes which recombine. Under stable conditions, an equilibrium concentration of electron-hole pairs is established.

n_i : the concentration of electrons (or equally holes)

From the equation above it is clear that the charge carrier concentration will be higher for germanium than silicon since germanium has smaller band gap.

In a metallic conductor, only the flow of negatively charged electrons contributes to its electrical conductivity.

In contrast, the flow of **both negatively charged electrons and positively charged holes** contribute to the conductivity of an intrinsic semiconductor.

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. Now it is a solid material.

μ : mobility

u : drift velocity

E : electric field

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

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

$$\mu_e = \frac{u_e}{E} \sim \frac{kT}{e}$$

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

1. Ge is more conductive or metallic than Si
2. Ge needs cooling because of its smaller energy gap

Mobilities determine the current in the semiconductor detectors

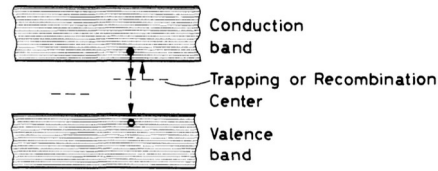
15

Once electron-hole pairs are created (by the incoming radiation), electric field, E , is externally applied for charge collection. Consequently, electron and holes drift with drift velocities.

General characteristics of Ge and Si materials

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

Recombination & 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

t_c : charge collection time

2-Recombination center due to impurities:
Deep levels: Keep charge for long time

A- After a certain holding time, electron might be released back to the conduction band
If $t_c \gg t_r$, **signal is lost!!**

B-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 due to impurities:

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 $t_c \gg t_t$, **signal is lost!!**

One center causes many recombination or trapping

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These impurities create additional electronics levels in the forbidden band and charge carriers (both electrons and holes) created by the incoming radiation can be trapped or recombined in these acceptor (donor) states. As a result, the trapped electron (hole) will not contribute to the pulse signal.

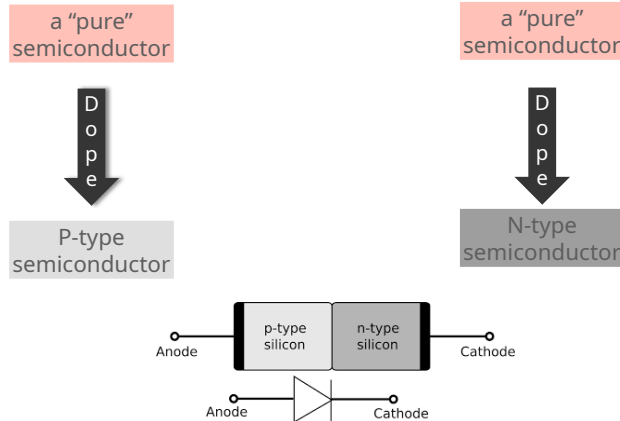
For this to happen, the electron (the hole) has to remain at the impurity until the pulse signal has been collected.

If the trapping time is in the order of charge (pulse signal) collection time, this event will be definitely lost, thus the energy resolution will be interfered.

Trapping and recombination centers are “deep trapping centers” so that electrons or holes are trapped for long time.

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 make a detector with putting them together!!



Doped Semiconductors

Recombination and trapping occur because of the "internal" impurities of the crystal. They ruin the performance of the detectors.

Doping: "External" impurities are added intentionally into the crystal in order to produce an intrinsic region in which free charge carriers of one would be able to reach the contacts and produce a signal. "

In other words, external impurities will enhance the characteristics of the material, i.e. **conductivity of the the material**. (The electrical conductivity of a doped semiconductor is always much larger than that of the corresponding pure material)

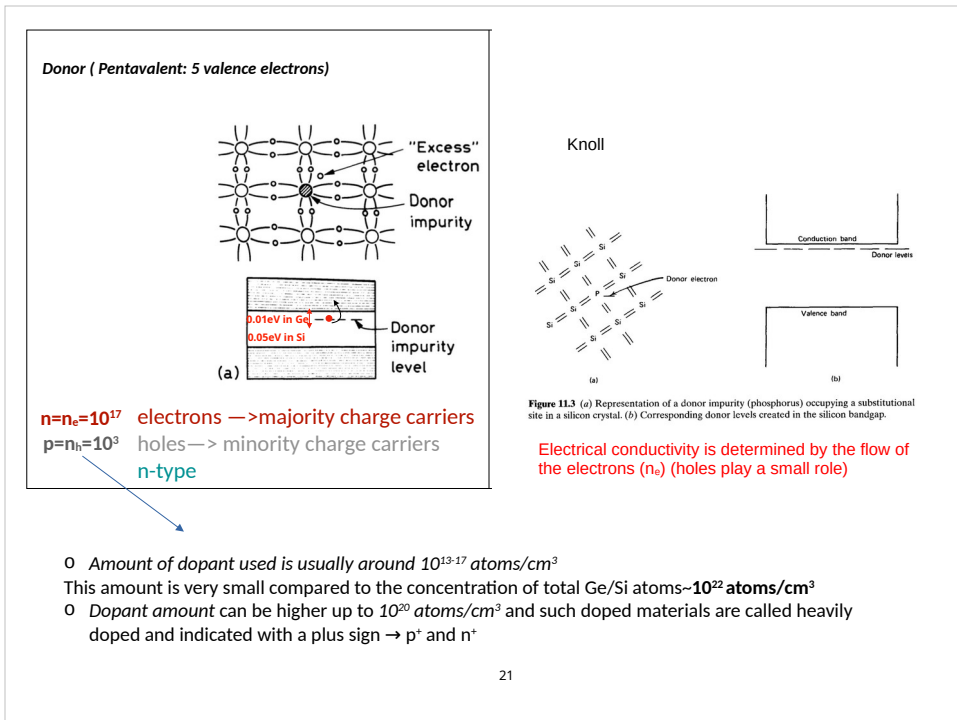
After doping, the semiconductor will have either more electrons (n-type) or more holes (p-type)

These are the desired impurities forming "**shallow traps**" that retain the electrons or holes for **short periods of time**.

Semiconductors are found in columns II-VI of the periodic table.

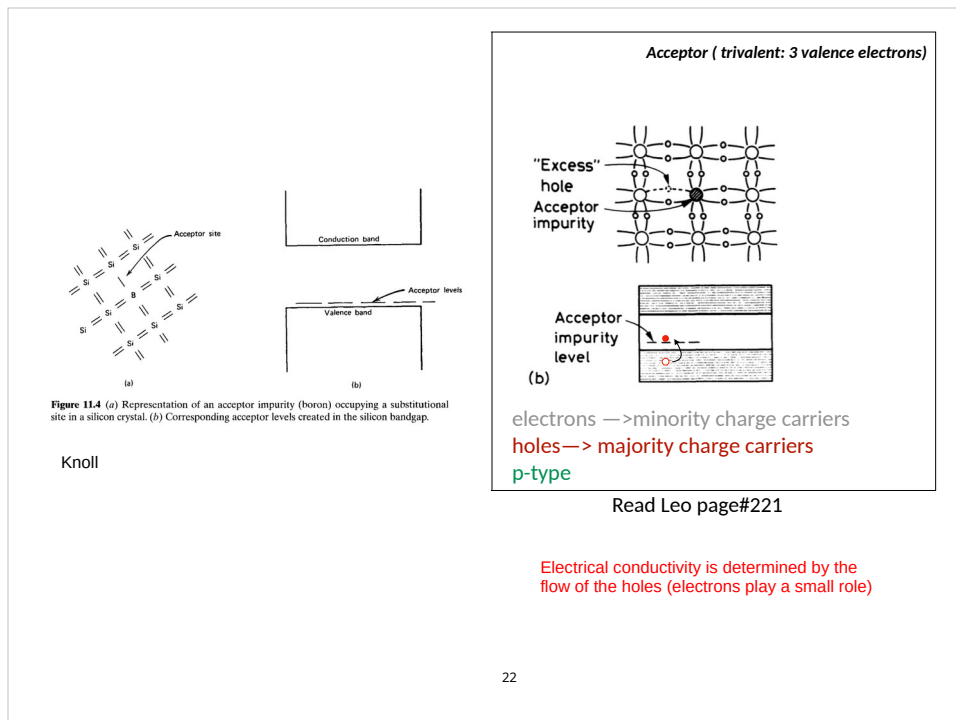
		Acceptors		Donors	
		⁵ B	⁶ C		
12 Mg	13 Al	14 Si	15 P	16 S	
30 Zn	31 Ga	32 Ge	33 As	34 Se	
48 Cd	49 In	50 Sn	51 Sb	52 Te	
II		III		IV	
				V	
				VI	

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



At normal temperatures, therefore, the extra electron is easily excited into the conduction band where it will enhance the conductivity of the semiconductor.

If the concentration of the impurity atom is N_D (D: donor), the extra atom of each impurity atom will be excited to the conduction band, becoming a conduction electron. That also means that $N_D \cong n$!!



Donor case:

Even though conduction electrons greatly outnumber the holes, charge neutrality is maintained because of the presence of ionized donor impurities. These sites represent net positive charges that exactly balance the excess electron charges.

They are not, however, to be confused with holes because the ionized donors are fixed in the lattice and cannot migrate.

Acceptor case:

The same applies here. The charge neutrality is maintained because of the presence of ionized acceptors (negatively ionized, -1). These sites represent net negative charge which compensates the positive charge of the acceptor holes.

lithium ion drifting process

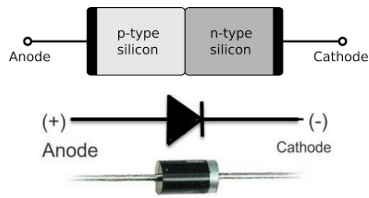
- In order to increase the conductivity, one could add equal amount of donor and acceptor impurities but this is a very difficult process to manage.
- Instead, in 1960 Pelle developed the lithium drifting method for compensating p-type silicon and germanium:

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.

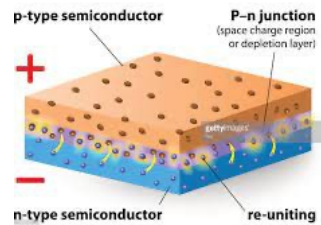
Semiconductor junction

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

Junction provides a good depletion layer/zone/depth for the purpose of radiation detection

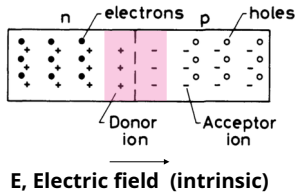


P-N JUNCTION



pn junction

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



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1- Diffusion

holes will diffuse towards n-region
electrons will towards p-region

2- Formation of depletion

Diffusing holes will recombine with electrons in n-region

Diffusing electrons will recombine with holes in p-region

n-type end will become positively charged

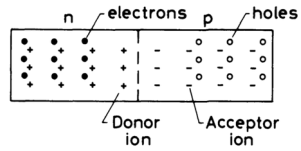
p-type end will become negatively charged

this will create a zone of electric field & contact potential usually around 1 V and called **depletion region (with no charge carriers and no current flowing through it)**. It is pure silicon (or germanium) material suitable for incoming radiations!!

3- Drift, space charge region

When the diffusion is exactly equal and opposite to the drift current (due to the electric field) this will now halt the diffusion and creates a **steady space charge 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!!**

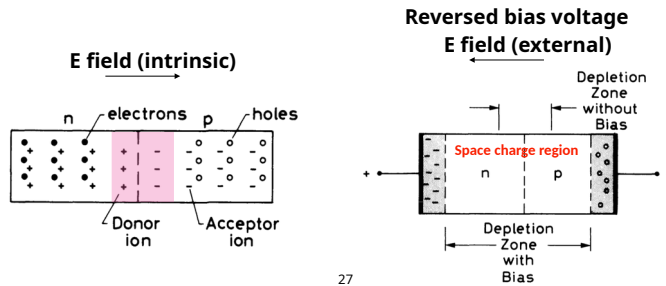
Reversed Bias Voltage:

RB voltage is a negative voltage to the p-side

Main purpose: to increase the depletion zone

Voltage value: 4000-5000 V for germanium (less for silicon)

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



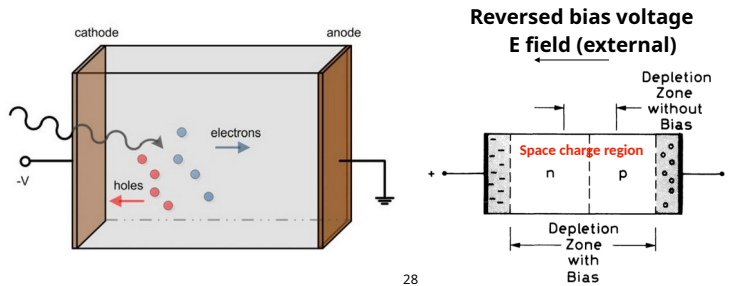
Reversed Bias Voltage:

RB voltage is a negative voltage to the p-side

Main purpose: to increase the depletion zone

Voltage value: 4000-5000 V for germanium (less for silicon)

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



Now we have built our detector with a sensitive volume, i.e. depletion layer!

What happens next?

1-Ionizing radiation entering this zone will liberate electron-hole pairs

2-The pairs will be swept out by the electric field.

3-If electrical contacts (cathode and anode) are placed on either end of the junction device, a current signal proportional to the ionization will then be detected. Energy information of the incoming radiation will be obtained!

Characteristics of SC detectors:

1- Average energy per e-hole pair

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

3- Resolution + Fano factor

$F \sim 0.12$

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

2- Linearity

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

n : charge collection efficiency (charge collection on the electrodes)

depletion layer has to be large enough to keep linearity, i.e. should not be smaller than the range of the radiation.

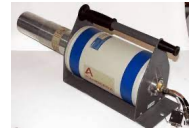
4- cooling

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

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

5- Operating voltage

HV: 4000-5000 V



germanium detector + dewar filled with a liquid hydrogen

Please read and go through material below:

Leakage current & Efficiency: Leo pp: 229-230

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

Types:

Germanium detectors —> gamma-ray detection

Silicon Diode Detectors —> charged particle detection

Germanium detectors

- 0 GeLi Detectors

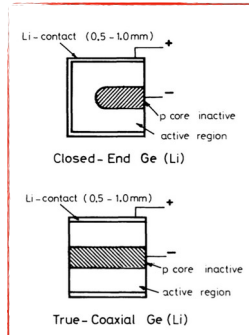
- 0 HPGe Detectors

 - 1. Planar

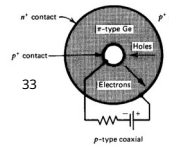
 - 2. Coaxial

Ge(Li) detectors

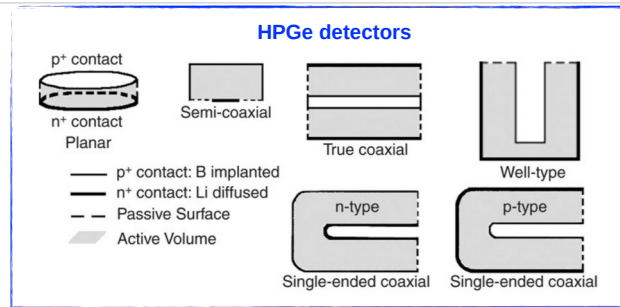
pronounced as "jelly"



- 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.



obtain figures of Ge(Li) detectors



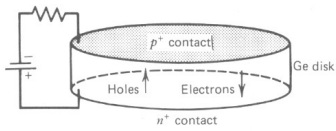
- In the late 1970s
- Pure samples of the detector material could be prepared only for germanium material
- The production process of a detector is much faster since no time-consuming drifting process is needed.
- The commercial production of Ge(Li) detectors was given up around 1980 when the volume of HPGe detectors became competitive with the volume of Ge(Li) detectors
- The size of pure crystals is limited to approximately 5 cm in diameter by 1 cm thick
- Quite expensive

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

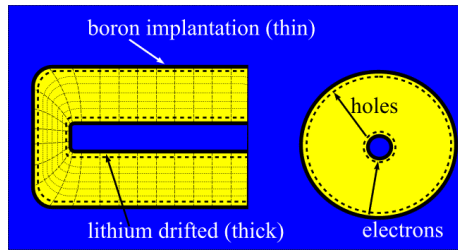
For a typical intrinsic germanium material,
 $N = 10^{13} \text{ atoms/cm}^3$
 For HpGe $N = 10^{10} \text{ atoms/cm}^3$

Operated at 77 Kelvin using liquid nitrogen.

Planar



Coaxial



In Coaxial crystals:

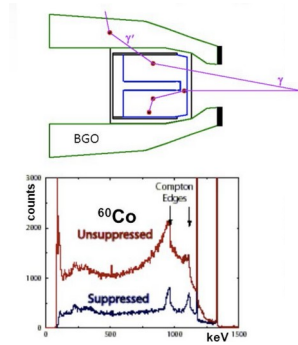
	Outer Contact	Inner
Contact		
p-type	n(Li)	p(B)
n-type	p(B)	n(Li)

The n $\sim$ 600 μm - 1 mm, p contact is very thin $\sim$ 0.3 μm .

BGO Compton suppression



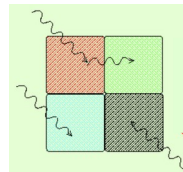
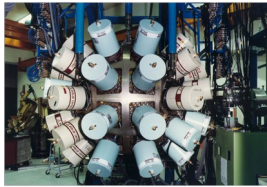
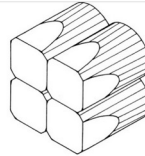
ROSPHERE at Bucharest, Romania



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

4 π -Ge Arrays: Segmented crystals

Clover (4-fold segmentation)



Addback

Fig. 15. Eurogam II at IReS Strasbourg.

MINIBALL at CERN/ISOLDE

6-fold segmentation

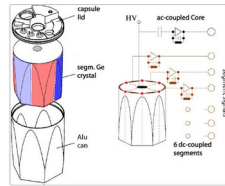
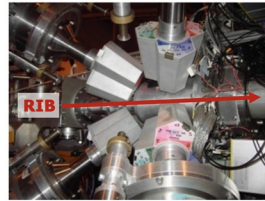
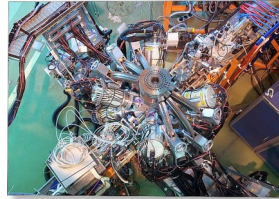
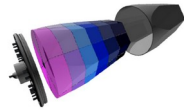


Fig. 23. The segmented MINIBALL detector.



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



triple clusters

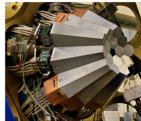
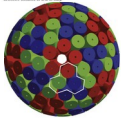


Fig. 4. 36-fold segmented HPGe array of the array with four 40% light yield.

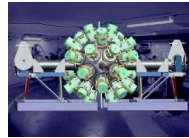
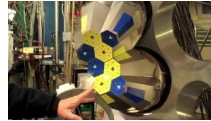


AGATA, Europe

36-fold segmentation

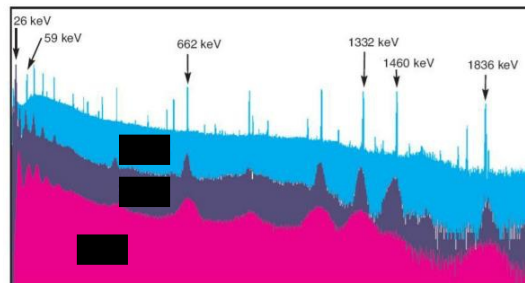


seven clusters



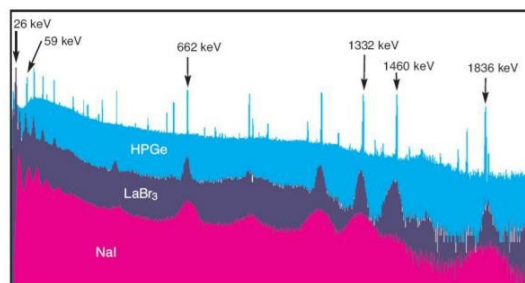
GRETA, USA

Comparison of HPGe, NaI, and LaBr



Match colours to each detector type!!

Comparison of HPGe, NaI, and LaBr



High Count Rate Compatibility

Lanthanum bromide detectors can operate over wide dynamic ranges of count rate with little variation in energy resolution.

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

Questions to you

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