Semiconductor Detectors

Band Theory of Solids

Band Theory of Solids

General

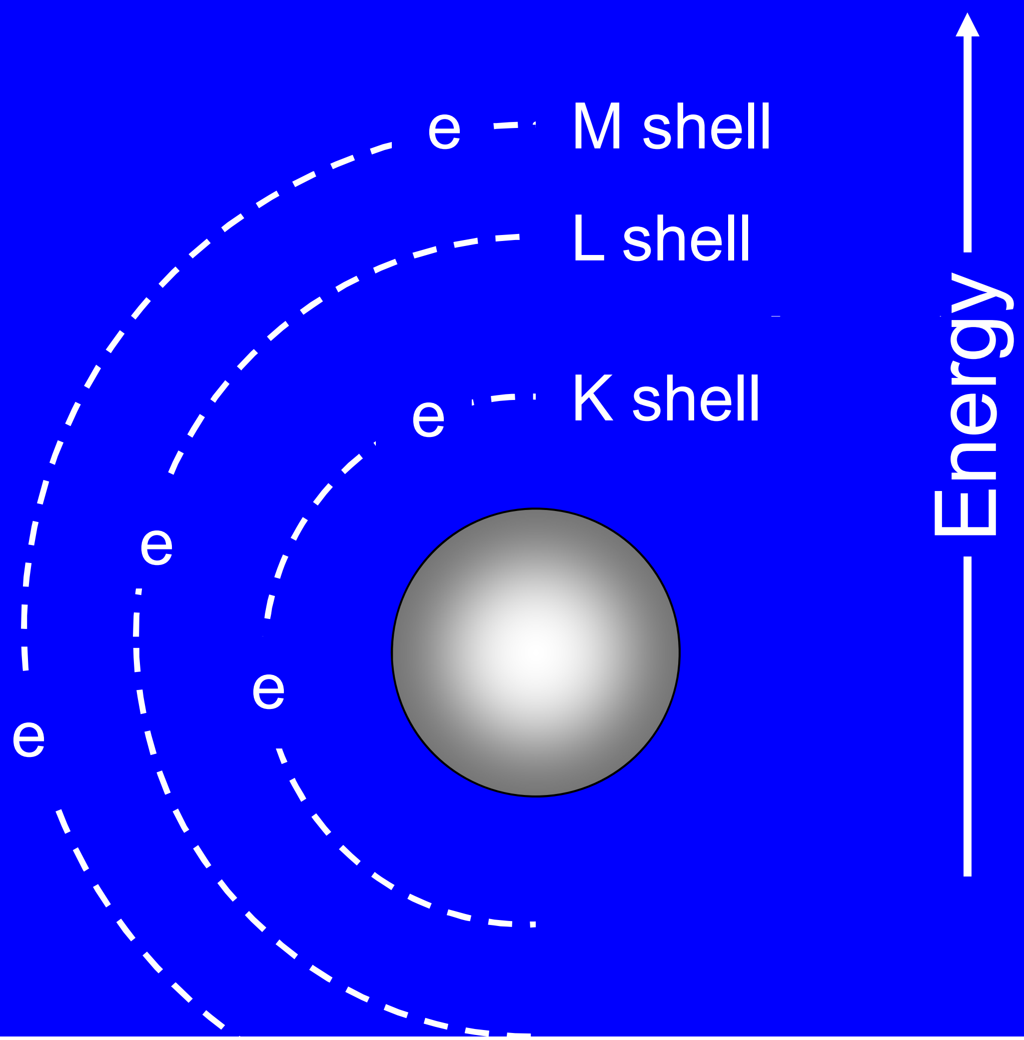
When radiation energy is deposited in a semiconductor detector, electron-hole pairs are created.

Under the influence of an applied electric field, the holes and the electrons move to the cathode and anode respectively. The result is an electronic pulse.

The process is analogous to the formation and collection of ion pairs in the gas of an ionization detector. Indeed, semiconductor detectors are the solid equivalent of an ionization chamber.

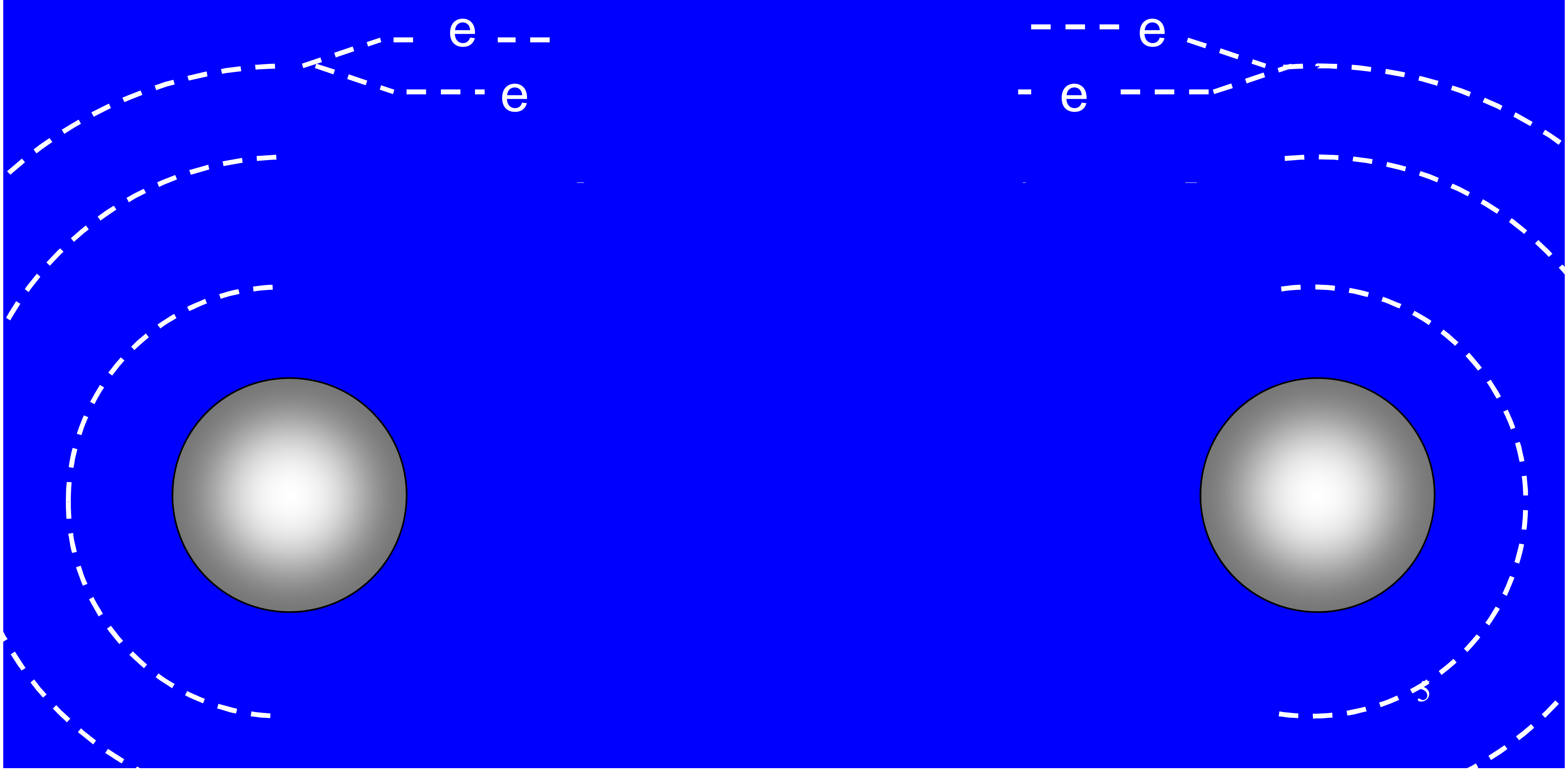
Band Theory of Solids

The energy levels of electrons in an atom are referred to as shells.



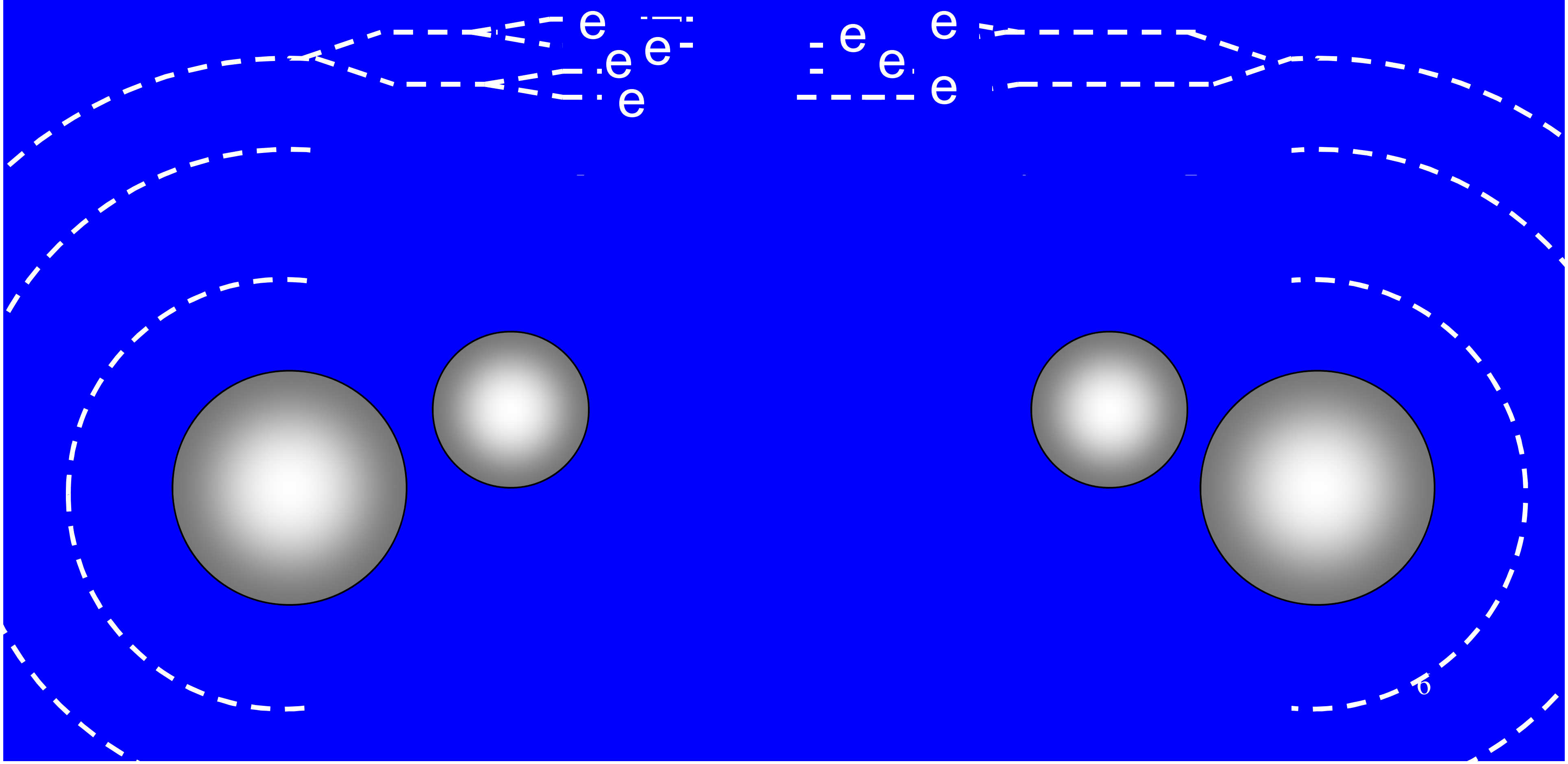
Band Theory of Solids

When atoms are brought close to each other, the highest shell occupied by electrons, the valence shell, splits.



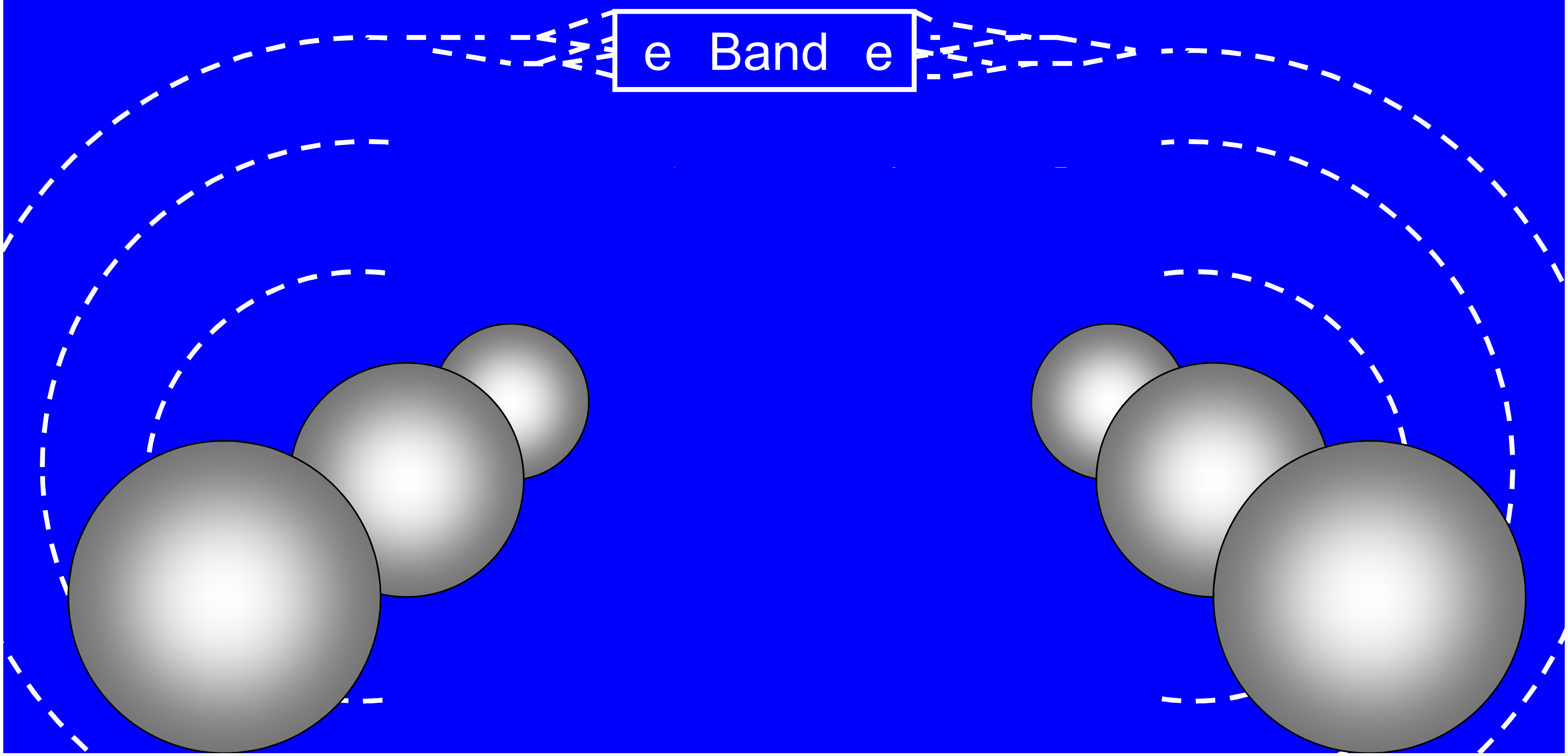
Band Theory of Solids

The greater the number of atoms, the greater the splitting.



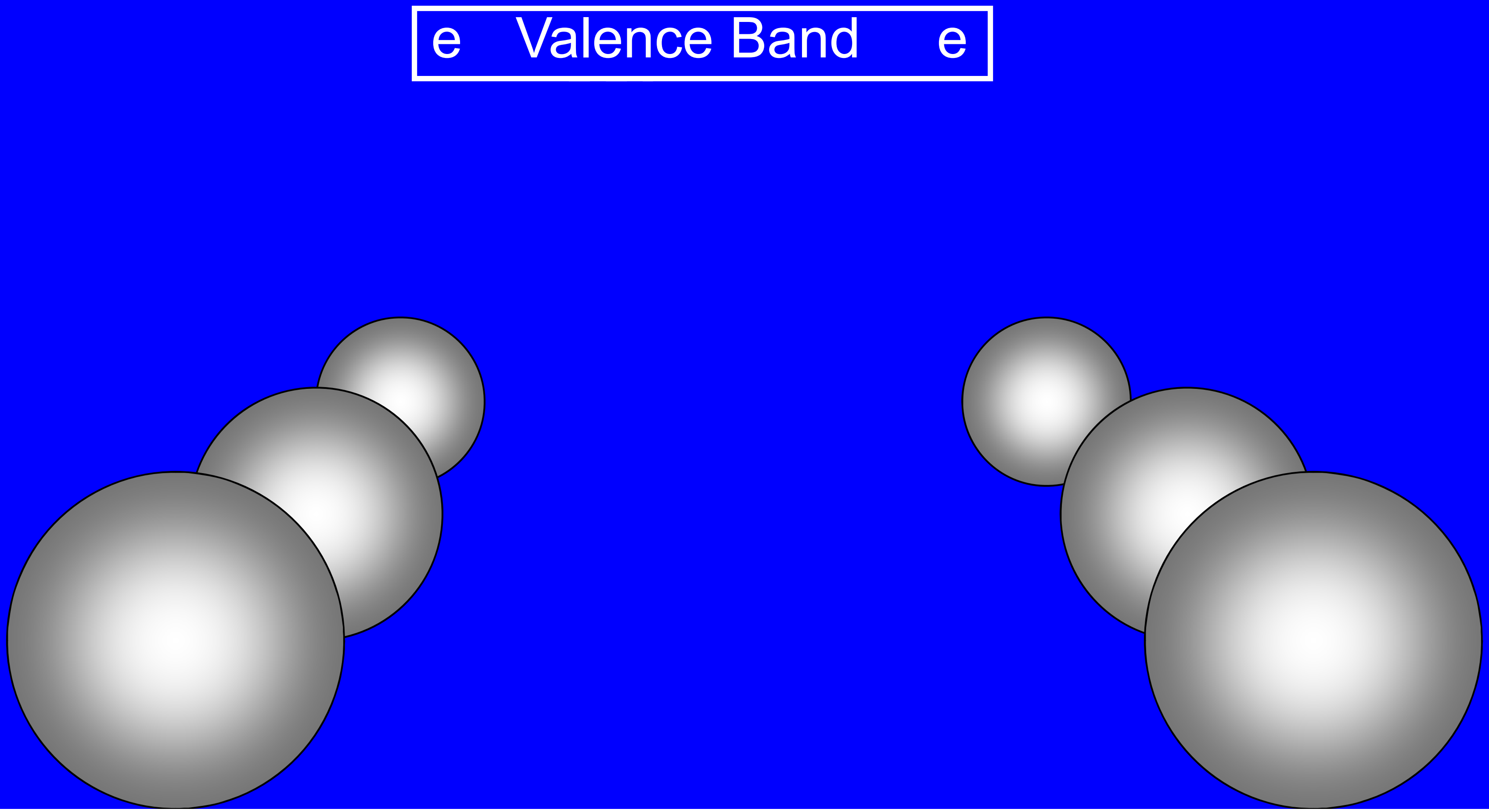
Band Theory of Solids

When many atoms combine to form a solid, the valence shell has split so many times that it forms a continuum of energies, i.e., a band.



Band Theory of Solids

The highest energy band occupied by electrons is the valence band.

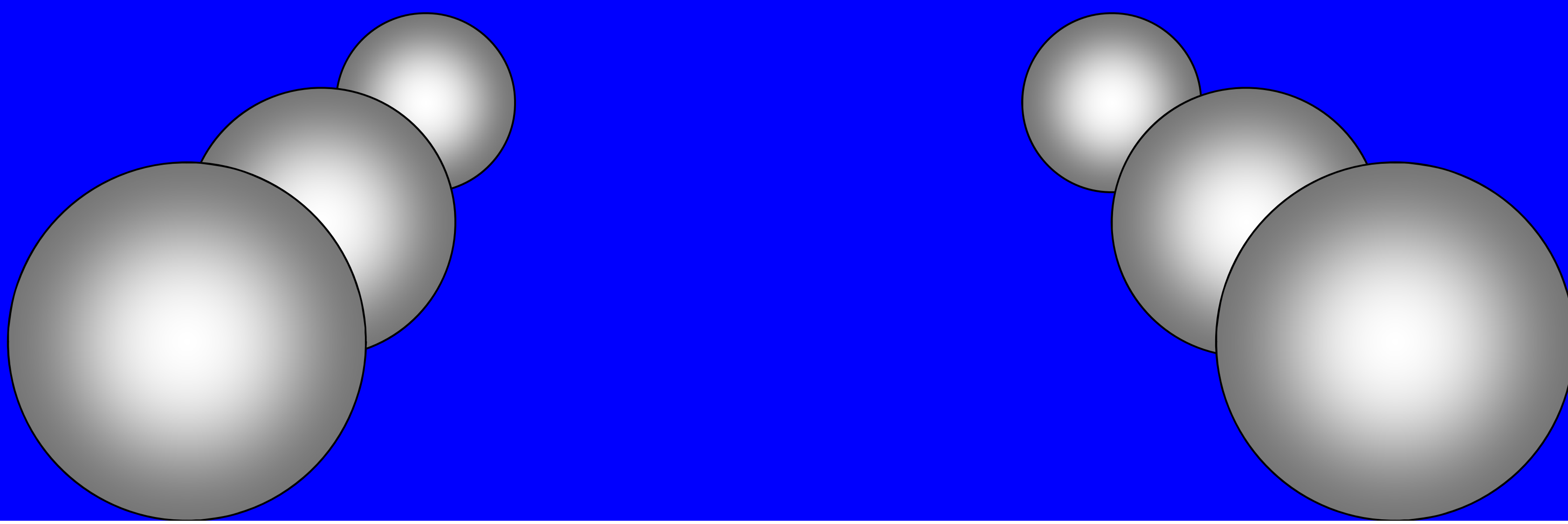


Band Theory of Solids

The empty energy band above the valence band is the conduction band.

Conduction Band

e Valence Band e



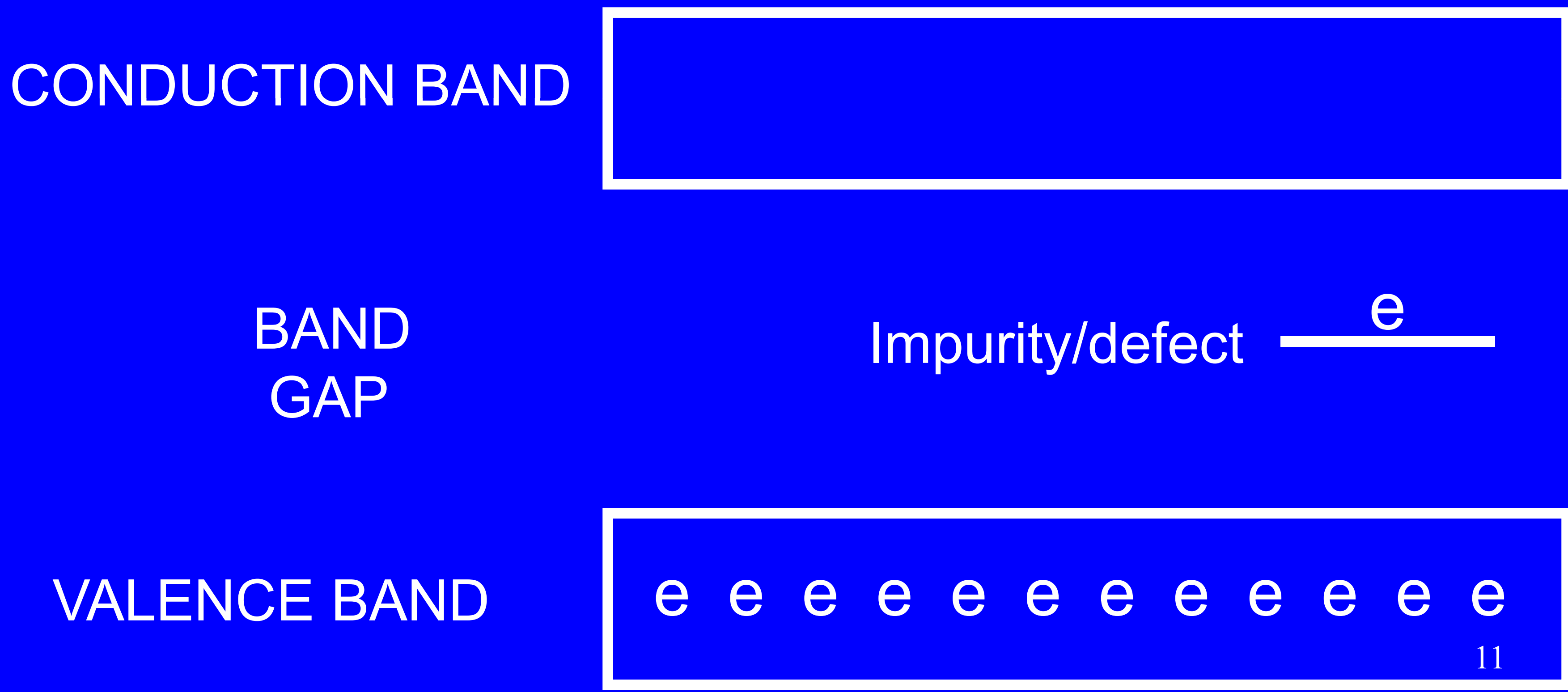
Band Theory of Solids

The range of energies between the valence band and the conduction band is called the band gap or forbidden band.

Band Theory of Solids

In a pure material, electrons cannot possess energies in the band gap.

However, if there are impurities or defects, electrons at these locations can possess energies in the band gap.



Band Theory of Solids

Insulator

The valence band is full. As such, the electrons are immobile and the material does not conduct electricity.

Conductor

The valence band is not full. As such, the electrons are mobile and the material conducts electricity.

Semiconductor

The valence band is full. As such, the electrons are immobile and the material does not conduct electricity.

Band Theory of Solids

The difference between a semiconductor and an insulator is the width of the band gap:

Semiconductor

Band gap < 5 electron volts

Band gap of 1 to 2 eV is typical

Insulator

Band gap > 5 electron volts

Silicon and Germanium Crystal Structure

Silicon and Germanium Crystal Structure

General

Carbon, silicon and germanium are group IV elements.

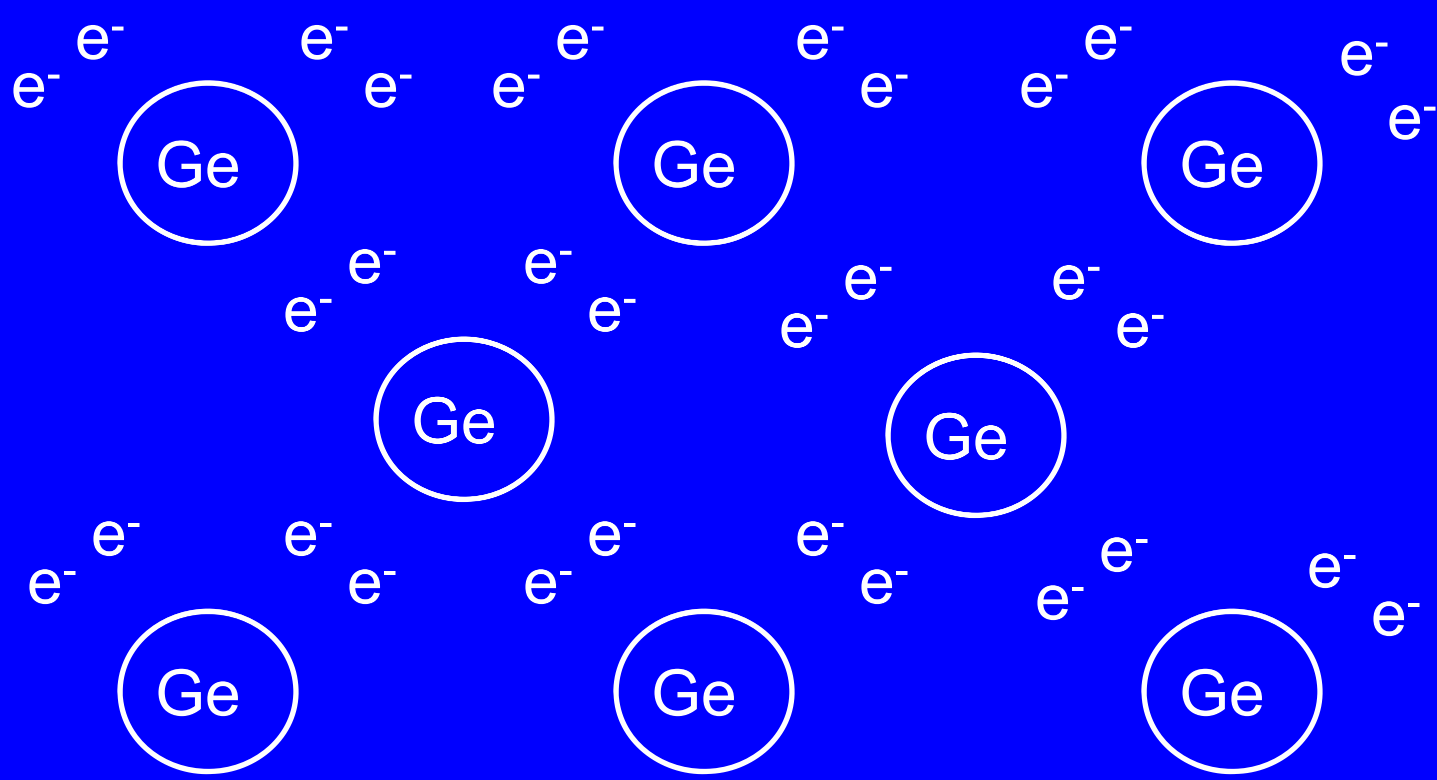
They have four unpaired electrons that can participate in covalent bonds. As such, the atoms in a silicon or germanium crystal are arranged in a diamond-shaped lattice.

The figure on the next slide shows the arrangement of atoms in a germanium crystal.

Each germanium atom participates in four covalent bonds and each bond is represented by a pair of electrons.

Silicon and Germanium Crystal Structure

General



These electrons have energies in the valence band.

Silicon and Germanium Crystal Structure

General

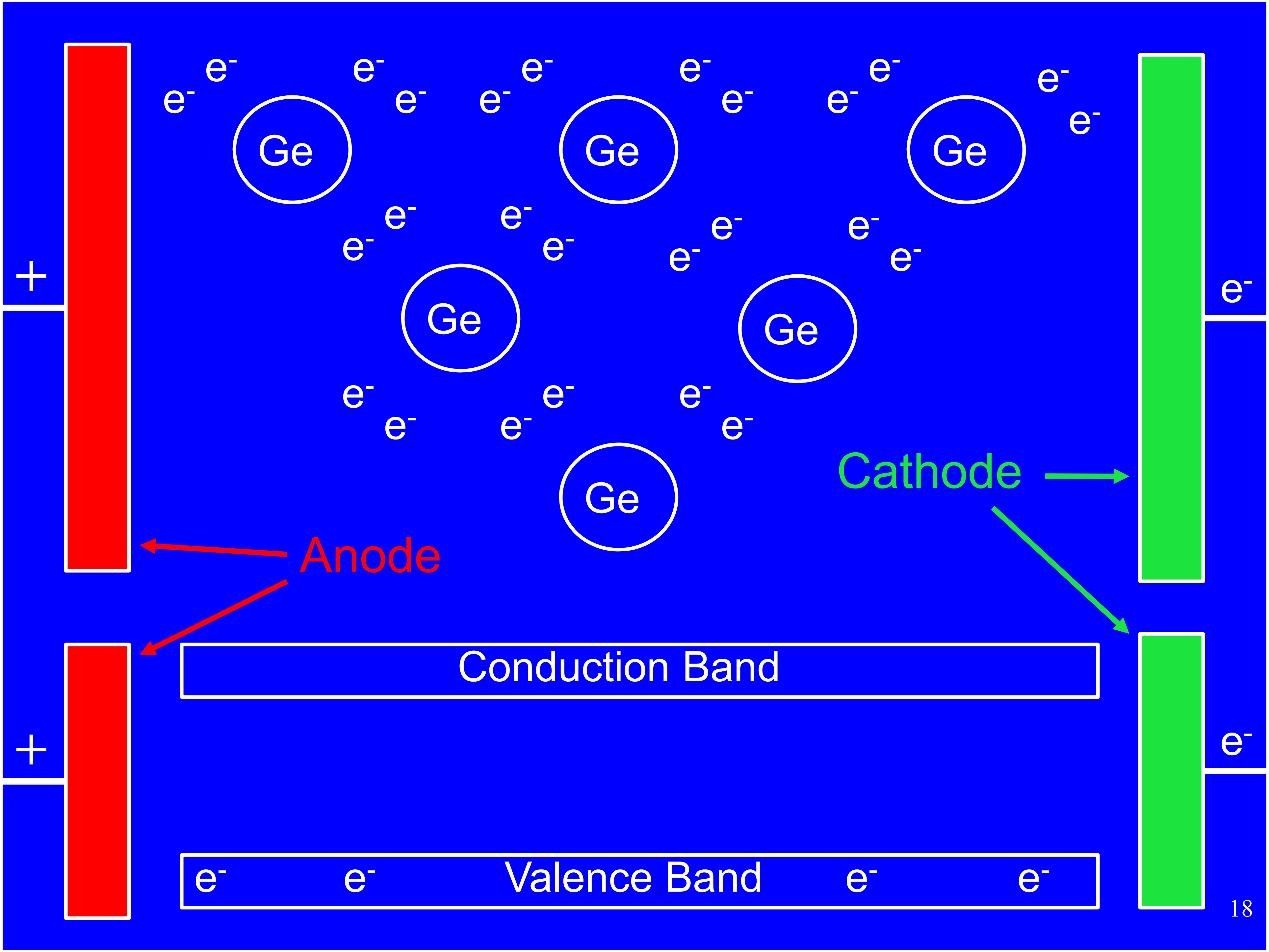
In the next slide, two electrodes applied to opposite sides of the crystal:

a positively charged anode on the left

a negatively charged cathode on the right

The bottom half of the slide illustrates the distribution of the electrons in the valence and conduction bands.

All the electrons are attracted towards the anode because of the electric potential, but they cannot move because the valence band is full.


Ge
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Ge
Ge
Ge
Ge
+
+
Anode
Cathode
Conduction Band
Valence Band
e⁻

Pulse Formation

Pulse Formation

The following sequence of slides illustrates the formation of a pulse in a semiconductor detector.

The first slide shows the initial position of the electrons.

The second slide shows an electron being promoted to the conduction band because of the absorption of radiation energy. This creates a “hole” or vacancy in the valence band.

In the third slide, the promoted and now mobile electron moves to the anode.

The electrons in the valence band are now mobile because it is no longer full.

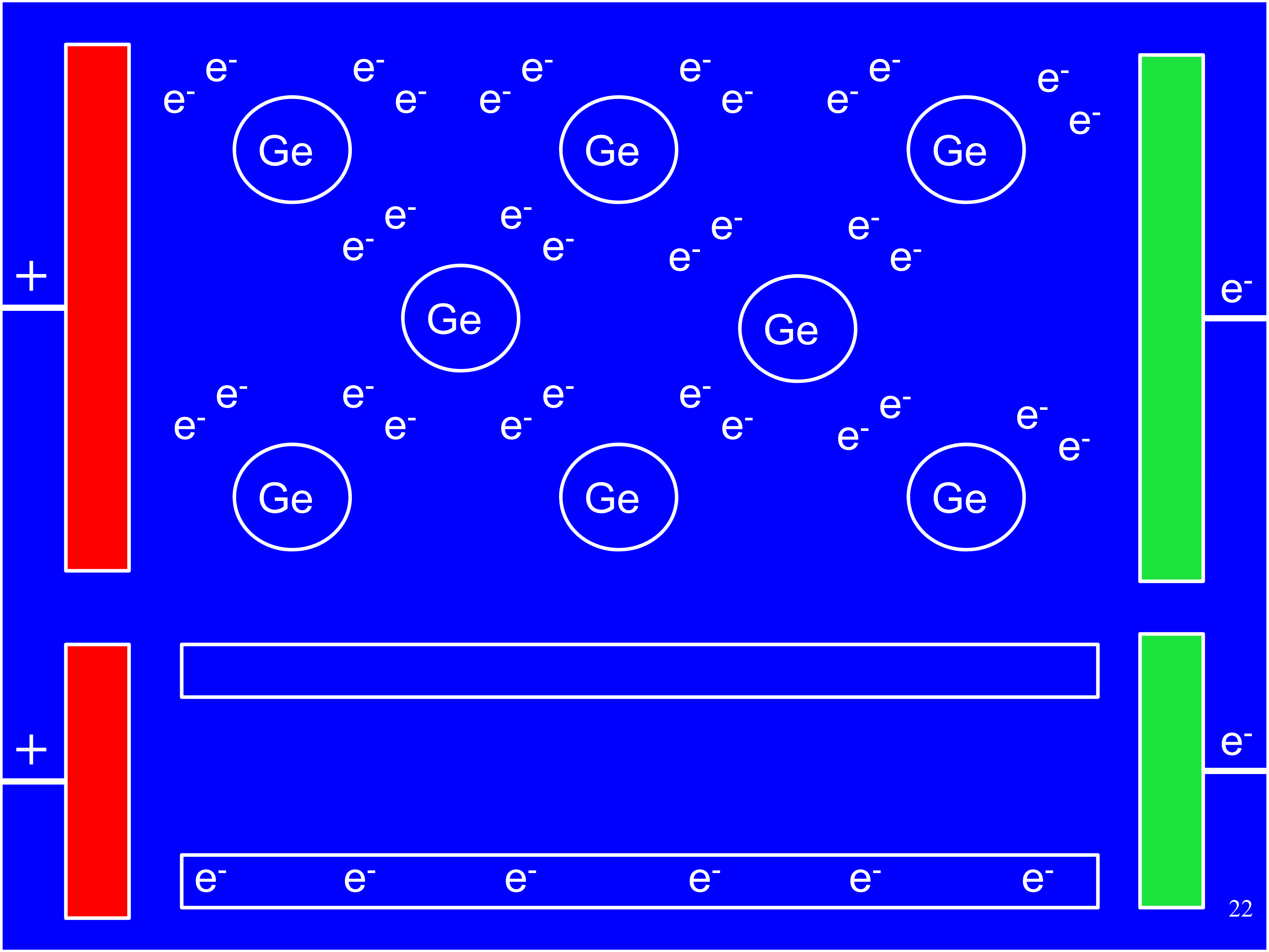
Pulse Formation

Drawn by the electric field between the anode and cathode, one of the electrons moves towards the left to fill the hole.

This creates a hole at the at the original site of the electron that moved to the left.

The net effect is that the “hole” moves to the cathode.

The subsequent series of slides show this process repeating itself until the hole reaches the cathode.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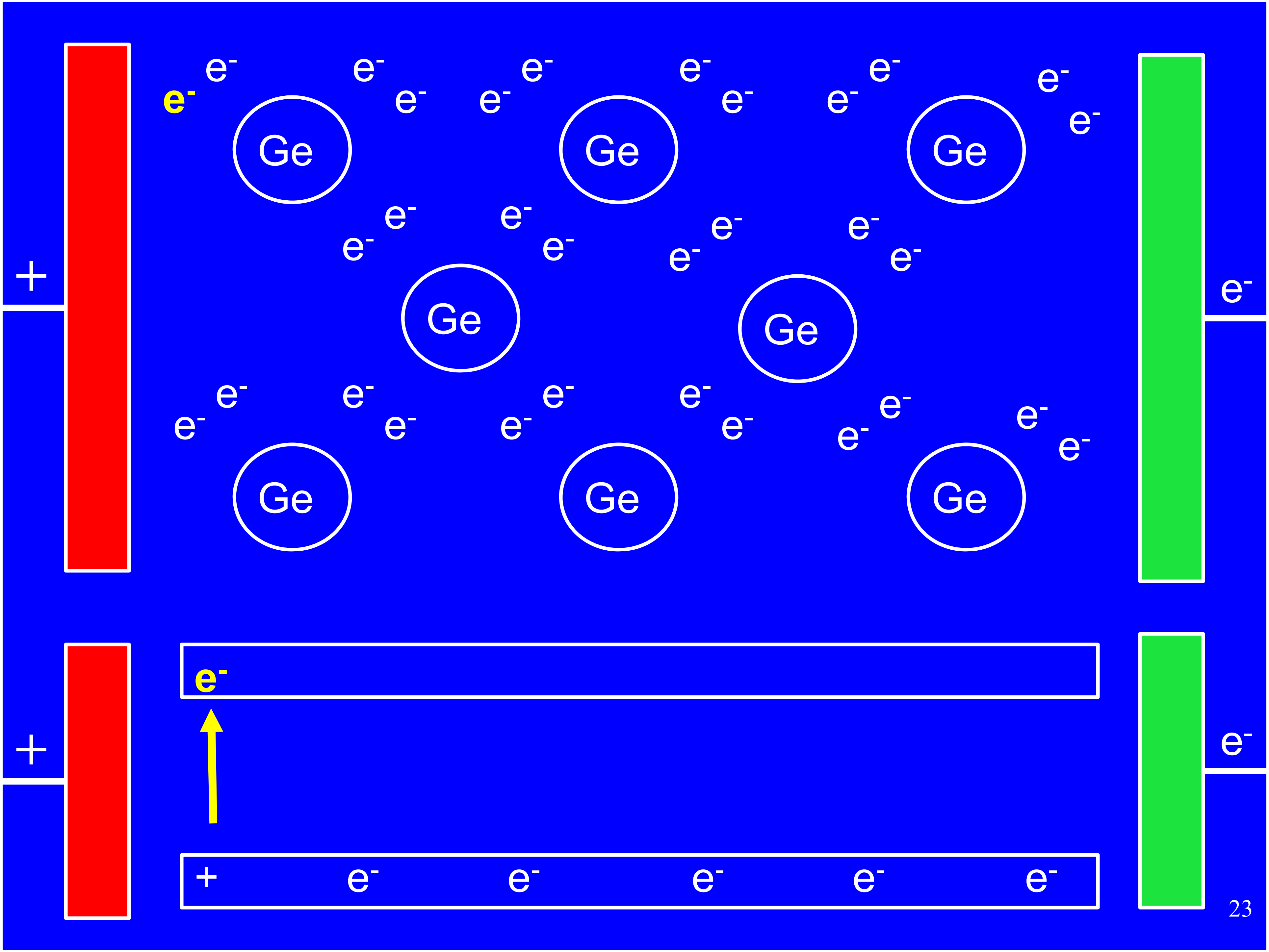
e-



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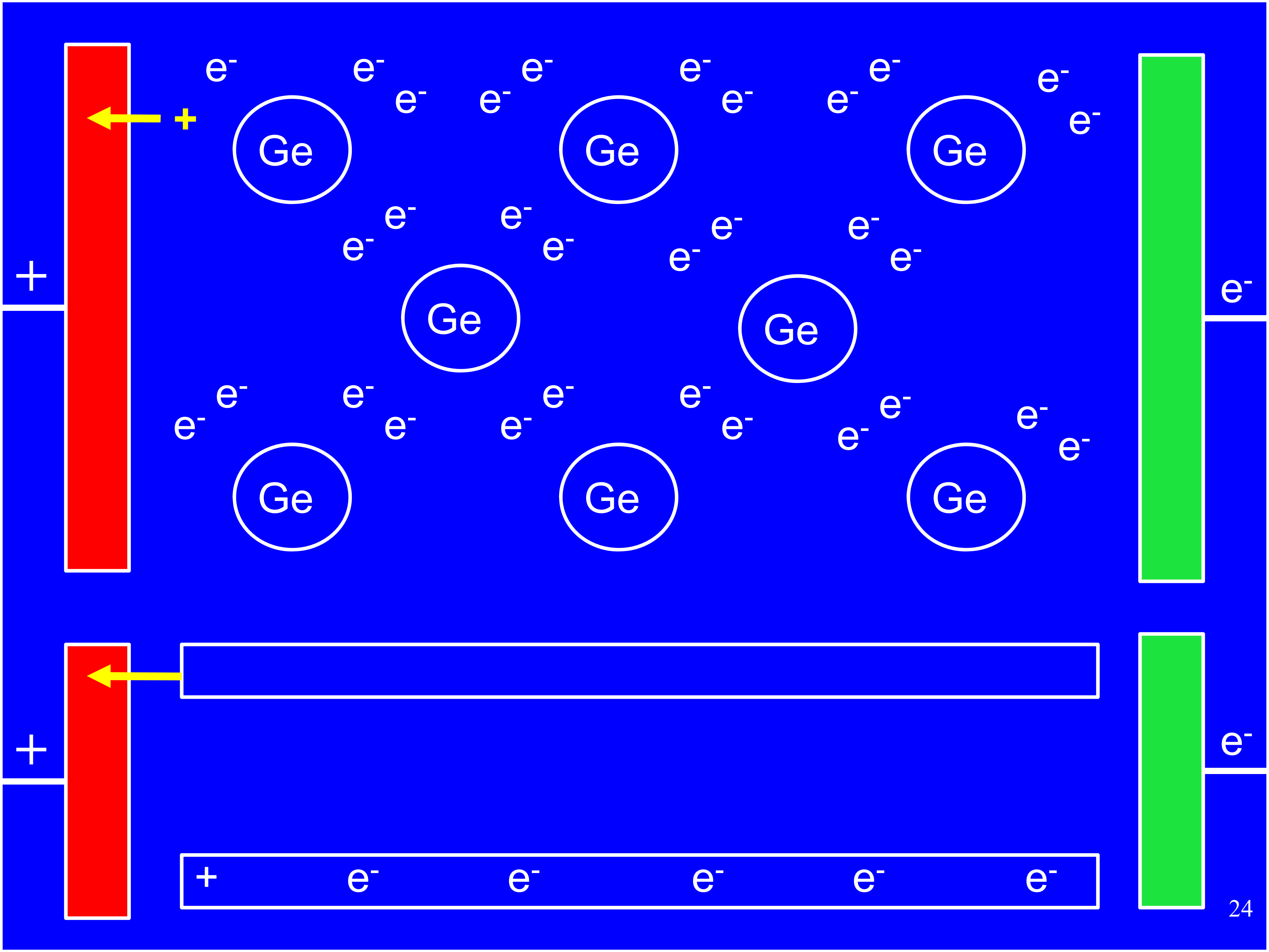

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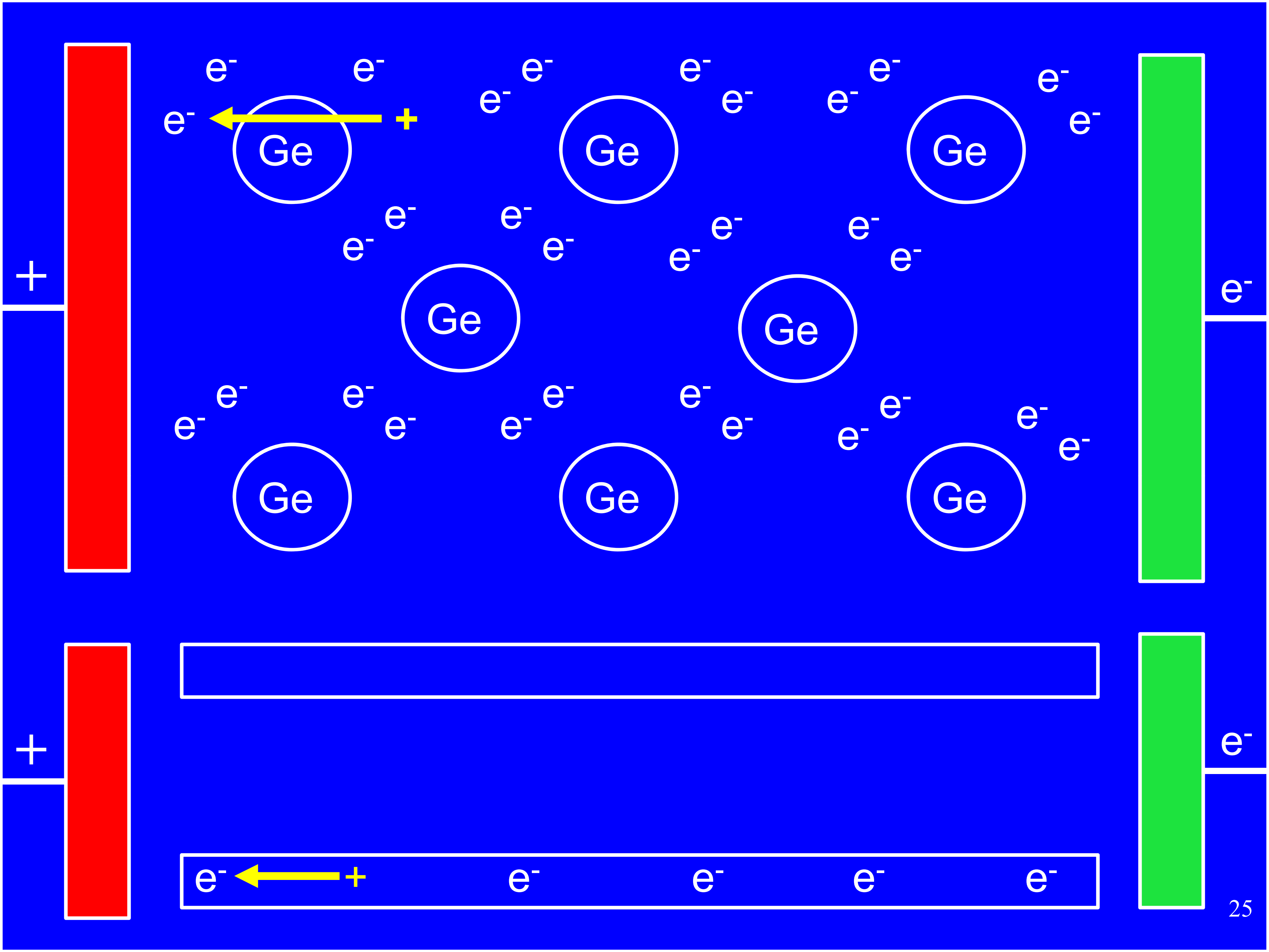

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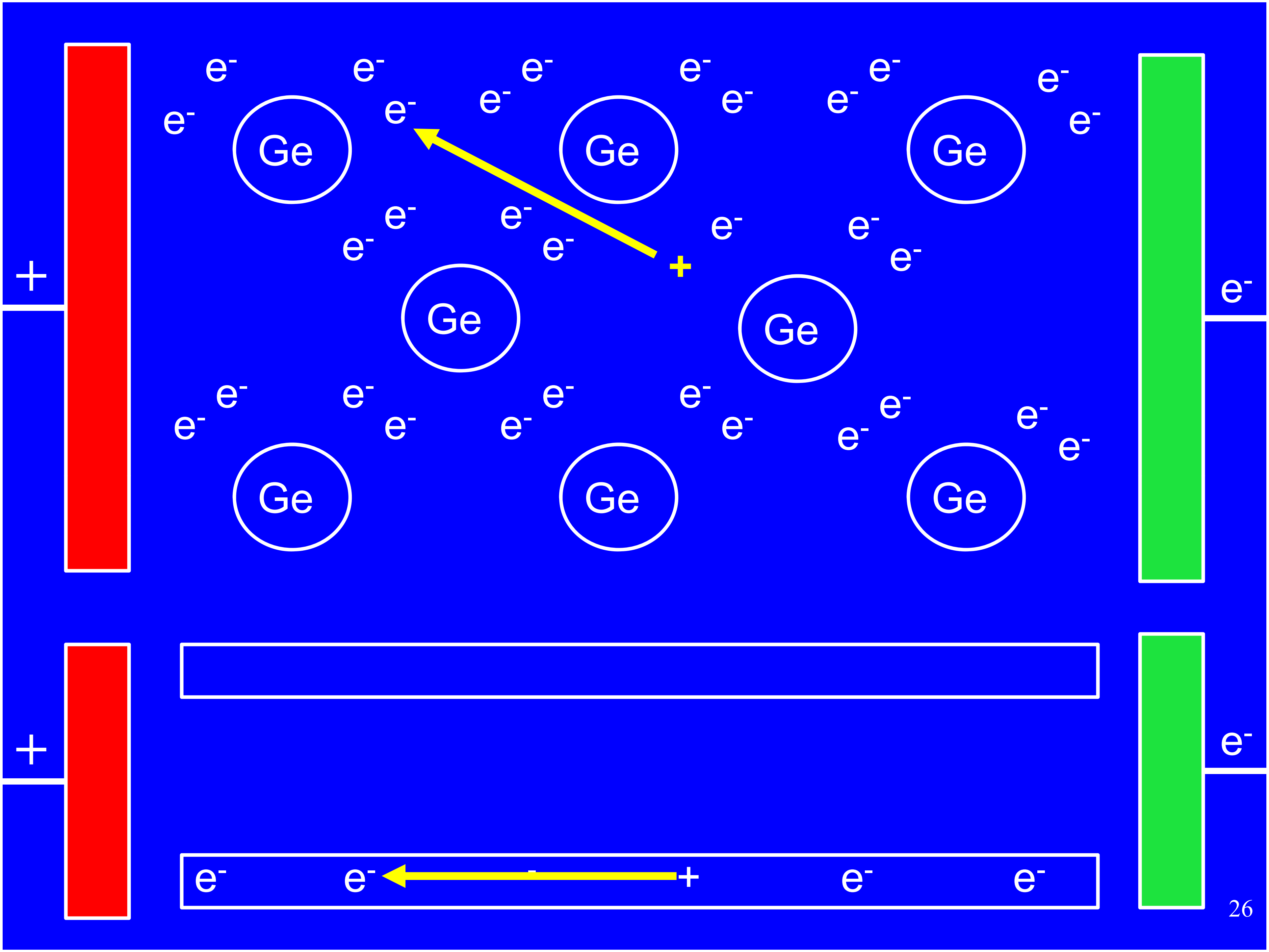
e^-



+
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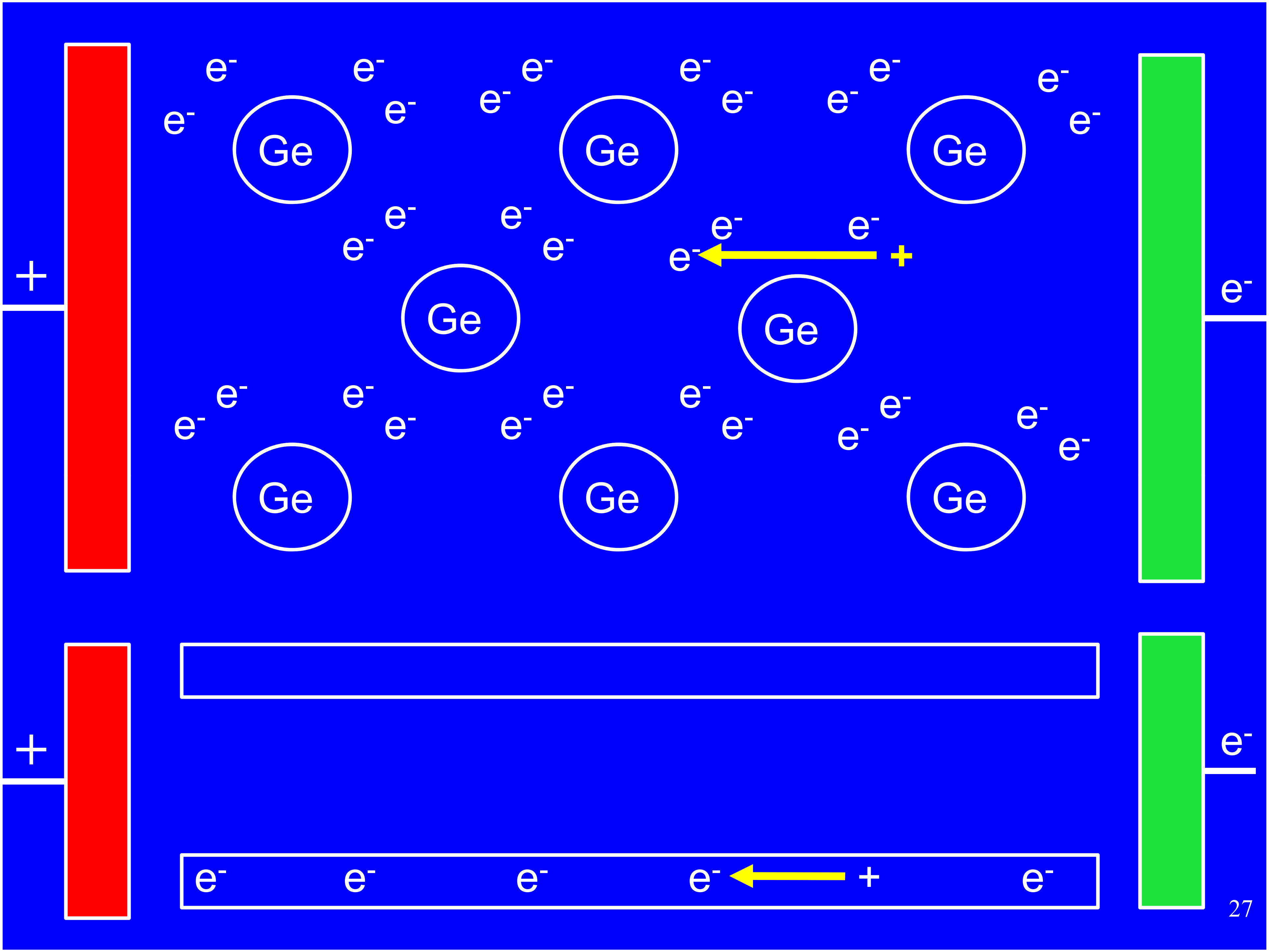
e⁻
+
-
+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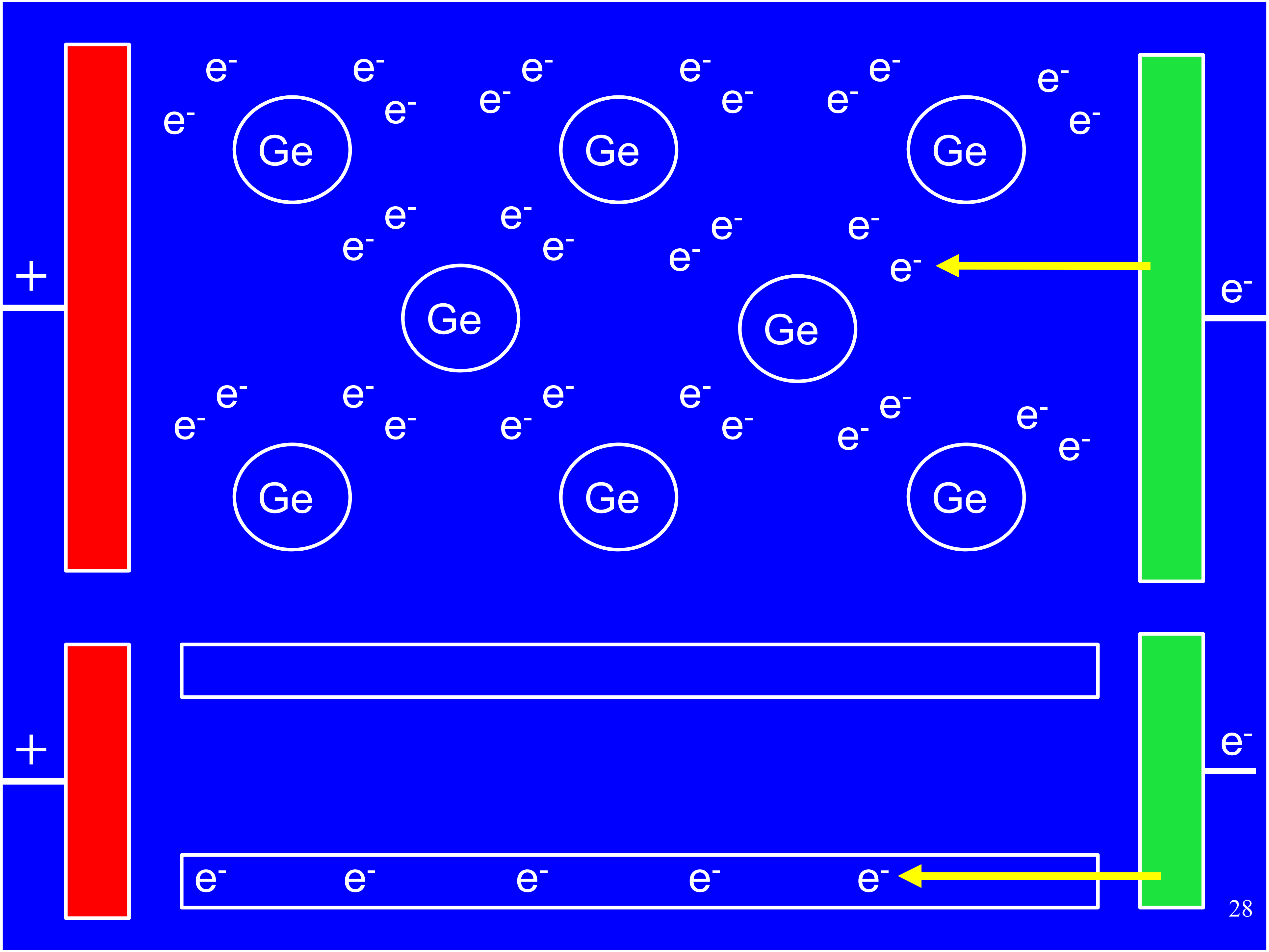
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Pulse Formation

Energy Required to Produce Electron-Hole Pairs

The average energy absorbed by the detector for each electron-hole pair created is approximately three times the width of the band gap. This depends on the material the detector is made of. Typical values are as follows.

Detector	Temperature	Average energy to produce an electron-hole pair
Germanium detector	80 ^oK	2.95 eV
Silicon detector	295 ^oK	3.62 eV
Silicon detector	80 ^oK	3.72 eV

Types of Semiconductor Material

Types of Semiconductor Material

General

Even the purest crystal of silicon of germanium contains some impurities.

Germanium and silicon are classified according to the predominant type of impurity that they possess.

They are classified as either: n-type

p-type

Types of Semiconductor Material

N-type

N–type germanium or silicon has an excess of donor impurities (more donor impurities than acceptor impurities).

Donor impurities are usually group V elements such as phosphorous.

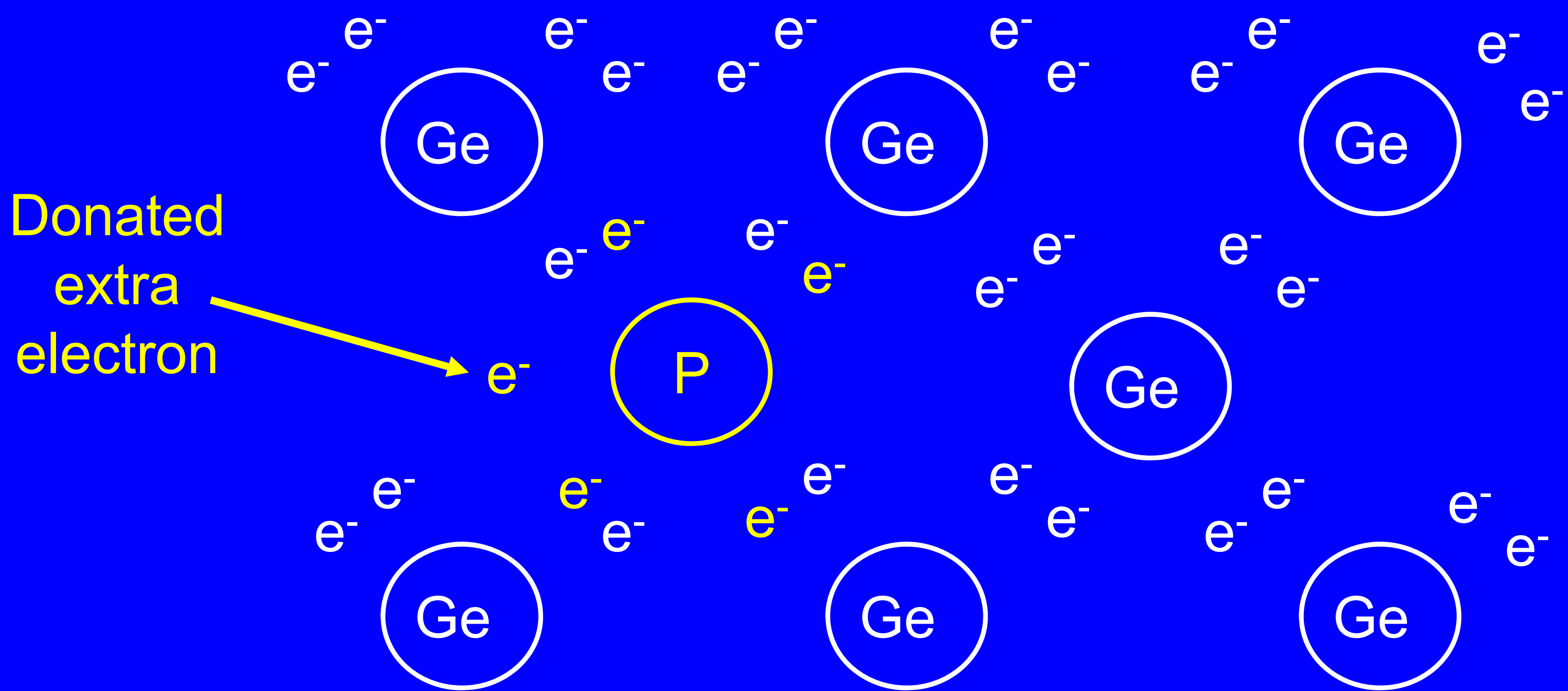
Being group V elements they have five unpaired valence electrons.

Positioned in the lattice of a germanium or silicon crystal, only four of these electrons can participate in covalent bands.

The impurity thereby "donates" an extra electron thus leaving the material with an extra negative charge.

Types of Semiconductor Material

N-type



Types of Semiconductor Material

P-type

P–type germanium or silicon has an excess of acceptor impurities.

Acceptor impurities are usually group III elements, e.g., boron.

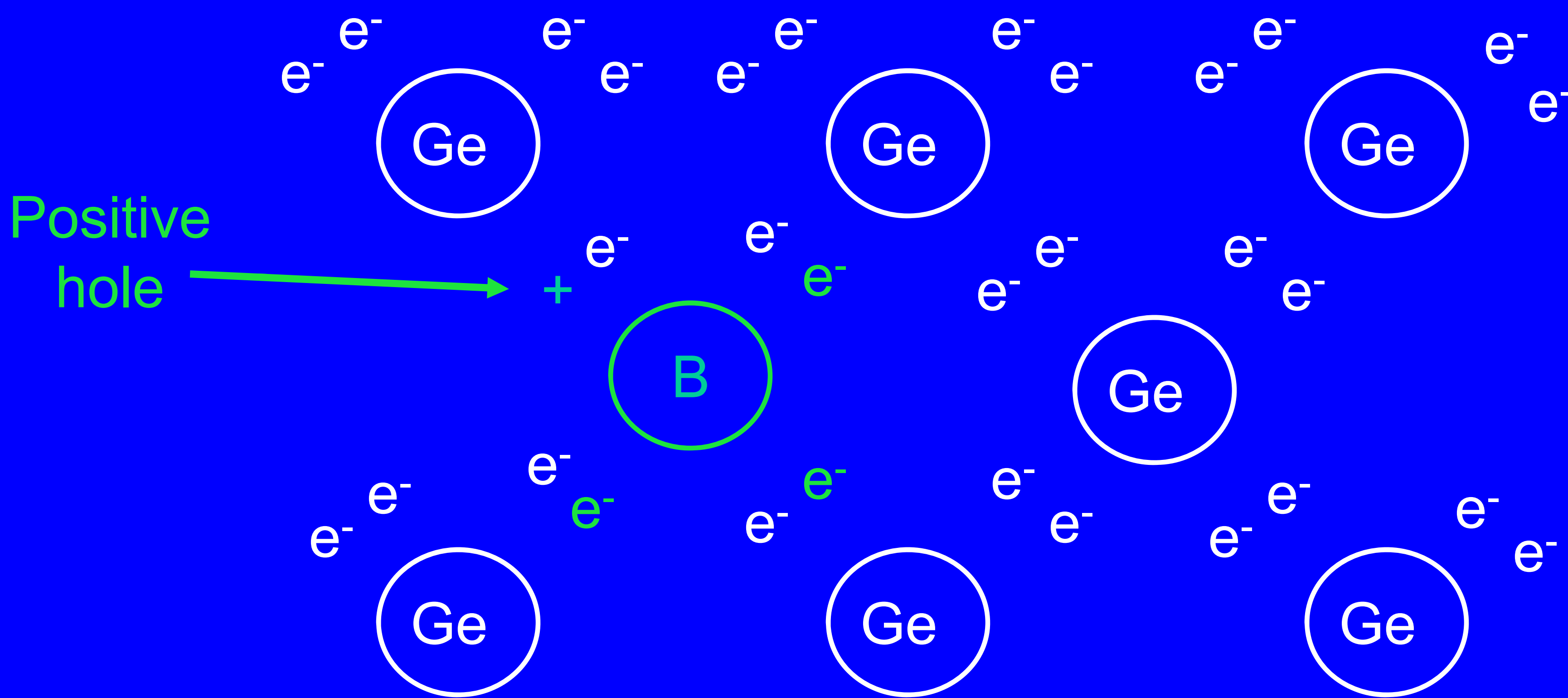
Being group III elements they have three unpaired valence electrons.

Positioned in the lattice of a germanium or silicon crystal, their electrons can only complete three covalent bands.

The impurity thereby adds a hole/vacancy thus leaving the material with an extra positive charge.

Types of Semiconductor Material

P-type



Effect of Impurities on Pulse Formation

Effect of Impurities on Pulse Formation

General

Impurities interfere in the charge collection process.

If an electron moving through the conduction band towards the anode becomes trapped at an acceptor impurity, it will not contribute to the pulse. For this to happen, the electron only has to remain at the impurity until the pulse has been collected (which only takes 0.1 usec or so).

The same thing applies to the trapping of holes by donor impurities.

The result is a deterioration of detector resolution.

Effect of Impurities on Pulse Formation

General

It is preferable that the impurities form "shallow traps" that retain the electrons or holes for short periods of time.

Commonly encountered impurities such as boron and phosphorous produce this sort of "innocuous" shallow trap.

Overall, the charge collection process in a semiconductor is extremely efficient, only one in one thousand charge carriers is lost because of trapping.

Nevertheless, the active volume of a semiconductor detector should be effectively free of impurities.

Detector Resolution

Detector Resolution

General

The resolution of a detector refers to the width of the peaks on the spectrum. The narrower the peaks, the better the resolution.

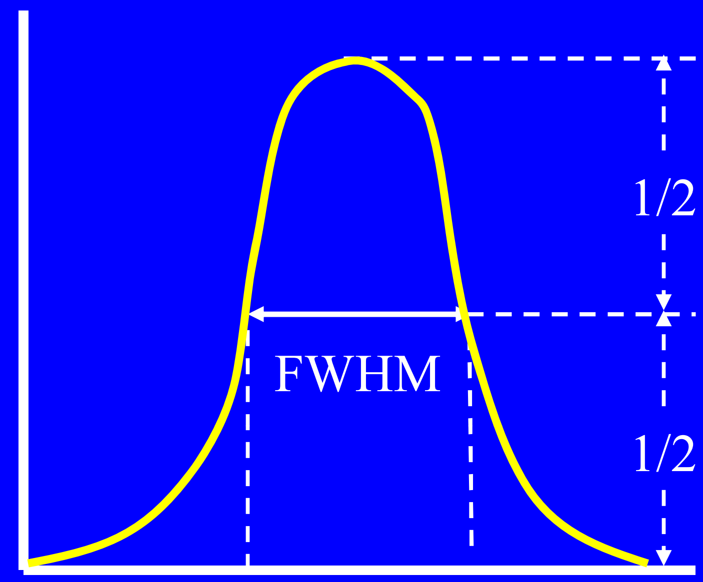
A detector with good resolution will generate two peaks for radiations of similar, but different, energies (e.g., 511 and 514 keV gamma rays). A detector with poor resolution will be unable to resolve the two radiations and only produce one peak instead of two.

Detector resolution depends on the energy of the radiation as well as the type of detector. The lower the radiation energy, the narrower the peaks.

Detector Resolution

Full Width Half Maximum

The conventional way to describe the resolution of a semiconductor detector is to specify the full width of a peak in keV at one-half its maximum height (FWHM).



For alpha detectors, the FWHM of the Am-241 peak is usually specified.

For high purity germanium detectors, the FWHM of the 1332 keV peak of Co-60 is used.

Detector Resolution

Resolution and the Number of Charge Carriers

The greater the number of charge carriers produced per unit energy deposited in a detector, the better the resolution.

In a semiconductor detector, the charge carriers are the electron-hole pairs.

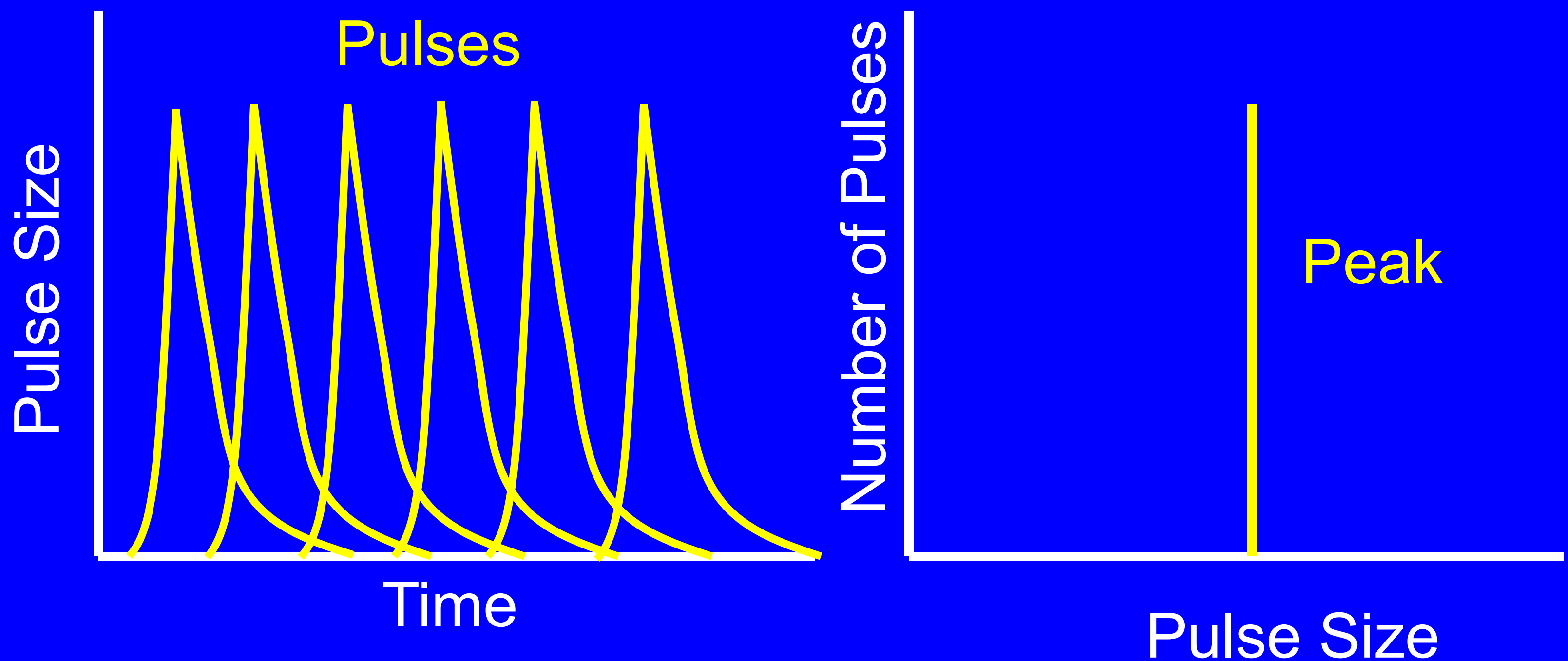
The relevant charge carriers in a scintillator are the photoelectrons ejected from the photocathode of the PMT (not the electron hole pairs in the scintillator).

Charge carriers are also referred to as information carriers because their number carries information about the radiation energy.

Detector Resolution

Resolution and the Number of Charge Carriers

Imagine six particles of radiation deposit exactly the same amount of energy in the detector (e.g., 1 MeV). Also imagine exactly the same number of charge carriers are produced and collected. Six pulses of the same size are produced.



Detector Resolution

Resolution and the Number of Charge Carriers

Since the six pulses were exactly the same size, they are sorted into the same channel by the ADC. The peak is as narrow as possible.

This doesn't occur in the real world. The major reason is the statistical nature of the processes by which the radiation absorbed energy produces the charge carriers.

Even if exactly the same energy were deposited in the detector six times, the number of charge carriers and the pulse sizes would vary.

This variation is proportional to the square root of the average number of charge carriers.

Detector Resolution

Resolution and the Number of Charge Carriers

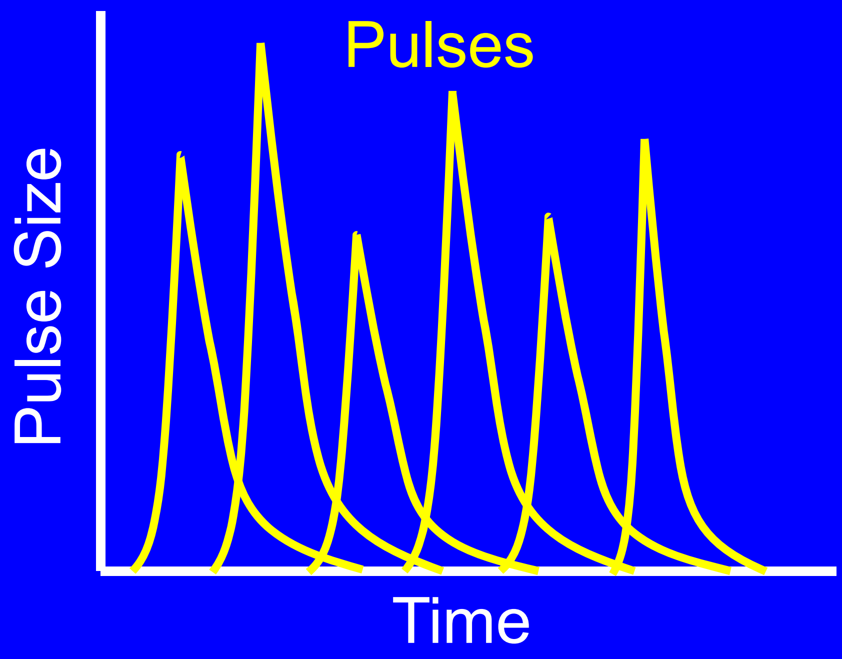
If N is the average number of charge carriers per pulse, the statistical nature of the process is such that 68% of the pulses are produced by:

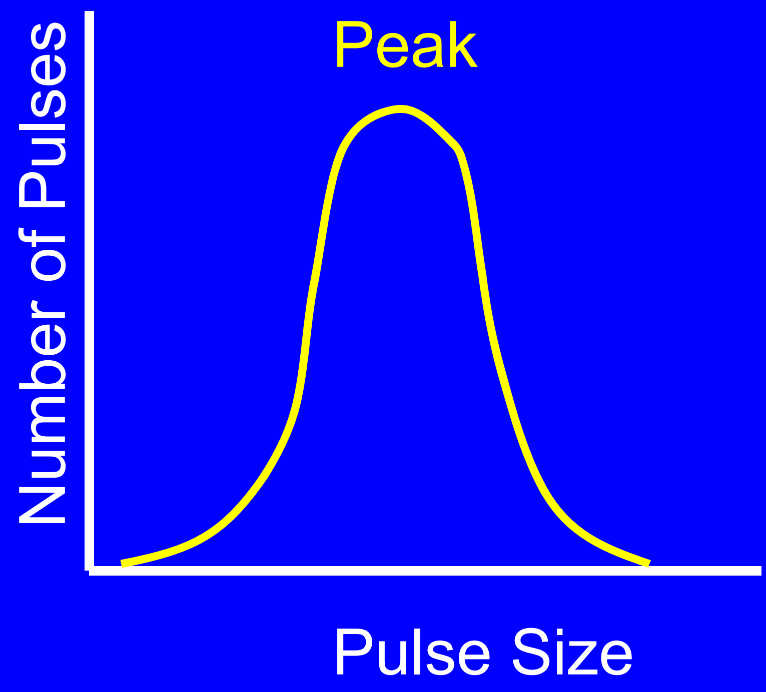
$$N \pm \sqrt{N}$$

Detector Resolution

Resolution and the Number of Charge Carriers

If the average number of charge carriers per pulse is 100, 68% of the pulses are produced by 100 ± 10 charge carriers. There is a large fluctuation in pulse size, i.e., ± 10%. The peak on the spectrum is wide:

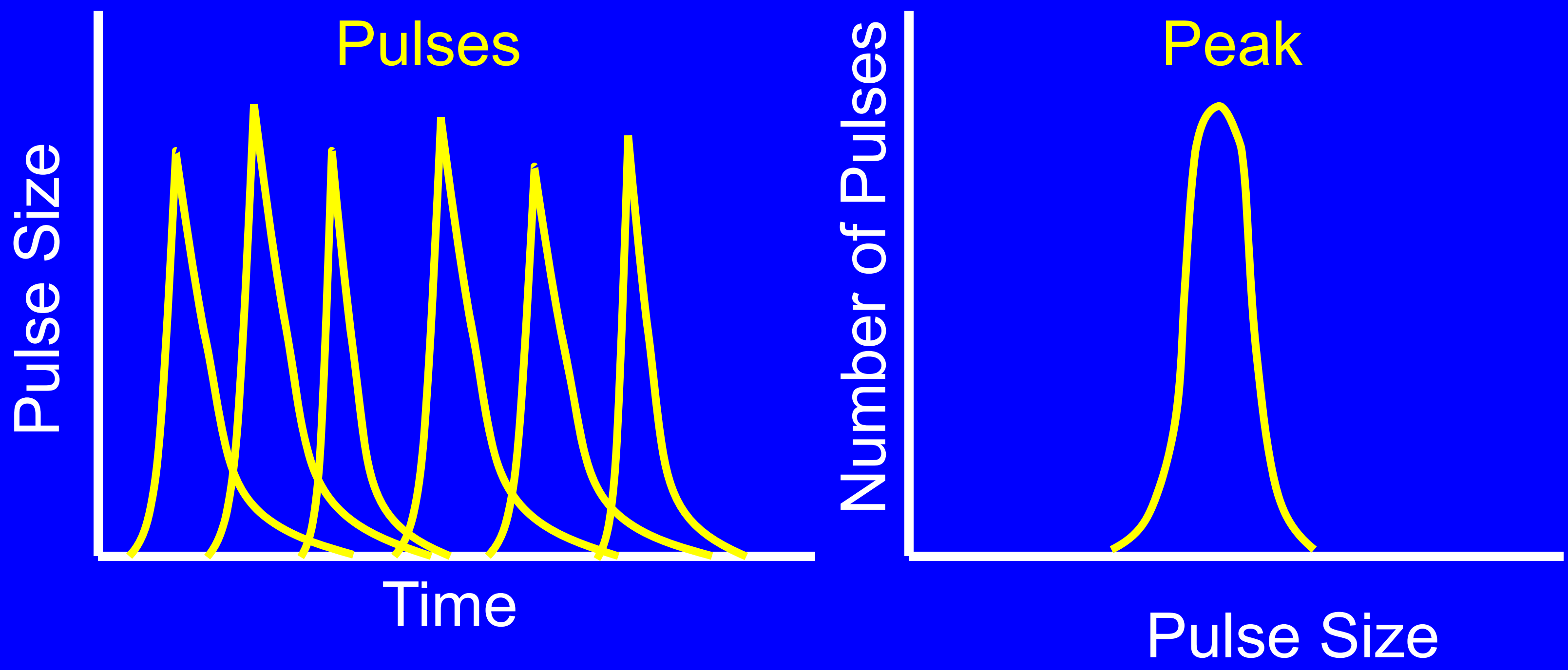




Detector Resolution

Resolution and the Number of Charge Carriers

However, if the average number of charge carriers per pulse is 10,000, 68% of the pulses are produced by 10,000 ± 100 charge carriers. There is a smaller relative fluctuation in pulse size, i.e., ± 1%. The peak on the spectrum is narrow:



Detector Resolution

Resolution and the Number of Charge Carriers

In a NaI detector system, the variation in pulse size is primarily due to the statistical variation in the number of photoelectrons produced at the photocathode of the PMT.

To free one photoelectron from the PMT's photocathode, 1000 to 2000 eV of gamma ray energy must be absorbed by the NaI crystal.

As such, the deposition of 1 MeV of gamma ray energy in a NaI detector would produce 750 or so charge carriers.

Detector Resolution

Resolution and the Number of Charge Carriers

In a germanium semiconductor detector, the average energy to produce a charge carrier (electron-hole pair) is approximately 3 eV. The deposition of 1 MeV in a germanium detector produces approximately 300,000 charge carriers.

As such the relative peak width for NaI and germanium detectors is:

$$\frac{NaI\ \ FWHM}{Germanium\ FWHM} \approx \frac{\frac{1}{\sqrt{750}}}{\frac{1}{\sqrt{300{,}000}}} \approx 20$$

NaI peaks are approximately twenty times the width of the peaks obtained with a germanium detector.

Detector Resolution

Resolution and the Reproducible Collection of Charge Carriers

The more reproducible the collection of the charge carriers, the better the system's resolution.

You can't collect 90% of the charge carriers one time, 99% the next, and get two pulses of identical size.

Reproducible collection of the charge carriers requires a uniform distribution within the detector volume of the impurities that trap the holes and electrons.

Detector Resolution

Resolution and the Reproducible Collection of Charge Carriers

Reproducible collection of the charge carriers also requires that the strength of the electric field be as uniform as possible throughout the volume of the detector.

For this reason, large detector crystals often have their edges rounded off (bulletized). In the old days, detector crystals were usually right angle cylinders and the electric field would be distorted near the corners.

Detector Resolution

The Fano Factor and Detector Resolution

If, as we have implied, the uncertainty in the number of charge carriers produced in a germanium detector simply depends on Poisson statistics, the following equation would give the smallest peak width (FWHM) possible for a gamma ray of energy E (in keV):

$$\text{FWHM (keV)} = 0.128 \sqrt{E}$$

This would mean that the best peak width for the Co-60 1332 keV gamma would be:

$$\text{FWHM (keV)} = 0.128 \sqrt{1332} = 4.67 \text{ keV}$$

In reality, the FWHM is much smaller! As a rule, they range from 1.6 to 2.0 keV or so.

Detector Resolution

The Fano Factor and Detector Resolution

The fact that reality is better than predicted by theory is quantified by the Fano factor (F).

The Fano factor is the observed real world variation in the number of charge carriers divided by that predicted by Poisson statistics.

The smaller the Fano factor, the better the real world resolution, i.e., the narrower the peaks.

Published Fano factors for germanium detector often range from 0.058 to 0.108.

$$\text{Real World FWHM (keV)} = 0.128\sqrt{(E \times F)}$$

Semiconductor Temperature of Operation

Temperature of Operation

General

At room temperature, large numbers of electrons in a semiconductor might have sufficient thermal energy to climb into the conduction band and generate thermionic noise. This deteriorates the detector resolution.

Operating the detector at reduced temperatures (e.g. that of liquid nitrogen) prevents this, but it places limitations on the design and operation of the system.

Temperature of Operation

General

The greater the width of the band gap, the more suitable a semiconductor material is for operation at room temperature. For this reason, silicon is better suited to room temperature operation than germanium. The tradeoff with a larger band gap is that fewer charge carriers are produced per unit energy deposited - this means poorer resolution.

Reducing a detector's physical size also improves its performance at room temperature because the detector will contain fewer electrons. Fewer electrons means less thermionic noise.

Temperature of Operation

General

Room temperature detectors are most suitable for:

- applications where physically small detectors are required (e.g., wound probe)
- alpha particle detection and spectroscopy
- beta particle detection and spectroscopy
- low energy photon (e.g., x-ray) spectroscopy when high efficiency is not required

In general, they are unsuitable for spectroscopy involving high energy photons since this application requires physically large detectors.

Temperature of Operation

General

Various semiconductor materials have been investigated that are better suited than silicon and germanium for room temperature spectroscopy of photons.

	Z	Density (g/cm^3)	Band Gap (eV)	Energy per electron-hole pair	Temp. (°K)	Photons FWHM (keV)
Silicon	14	2.33	1.12	3.61	300	
Germanium	32	5.32	0.74	2.98	80	0.42 (100 keV) 0.92 (662 keV) 1.3 (1332 keV)
CdTe	48, 52	6.06	1.47	4.43	300	3.5 (122 keV) 8.0 (662 keV)
CZT	48, 30, 52	5.86	1.57	4.6	300	3.2 (122 keV) 10.8 (662 keV)
HgI_2	80, 53	6.30	2.13	4.22	300	0.65 (5.9 keV) 2.5 (122 keV)

Temperature of Operation

CdTe and CdZnTe (CZT) Detectors

CZT and CdTe are the most important room temperature semiconductors for the gamma/x-ray detection and spectroscopy.

Typical detector crystals range from 1 - 10 mm in size which limits their detection efficiency, especially for high energy photons. Larger sizes aren't employed because hole trapping in these materials is so significant that a complete collection of charge carriers can only be accomplished over a few mm.

CZT crystals tend to be larger than CdTe crystals and better suited to spectroscopy (as opposed to simple detection).

Temperature of Operation

CdTe and CdZnTe (CZT) Detectors

With regard to detection efficiency, their high atomic numbers compensate to some extent for the their small size.

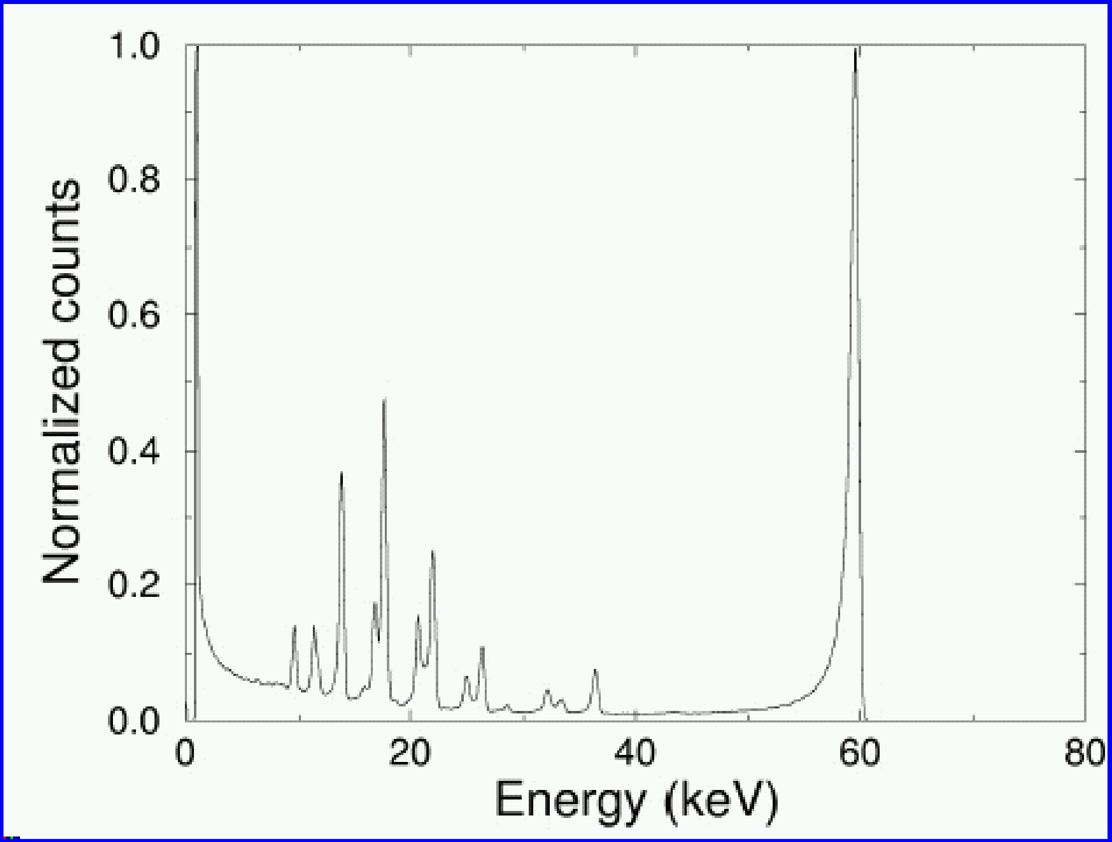
CdTe detectors are best suited to the detection low energy photons (e.g., x-rays) and applications where pulse height analysis is not required.

One common application of CZT and CdTe detectors is the medical imaging of low energy gamma rays and x-rays. Other applications include astrophysics and homeland security.

Temperature of Operation

CdTe and CdZnTe (CZT) Detectors

Below is a CZT spectrum of Am-241. CdTe spectra tend to have more pronounced tails on the low energy side of the peaks.



Three Types of Semiconductor Detectors

Types of Semiconductor Detectors

Three Types of Semiconductor Detectors

1. Diode Detectors
   - P-N Junction detectors
   - PIN Detectors

2. Lithium Drifted Detectors
   - SiLi
   - GeLi

3. High Purity Germanium Detectors

Types of Semiconductor Detectors

1. Diode Detectors

Diode detectors for alpha or beta spectroscopy are thin silicon wafers (sometimes germanium). The active volume of the detector, a region of relative purity, is variously known as the depletion region.

The thickness of the depletion region is so small that only charged particles (e.g., alpha particles) can deposit a significant fraction of their energy in the detector.

When operated in the pulse mode, diode detectors are only suitable for use with charged particles. When they are operated in the current mode, they can be used to estimate the dose due to x-rays and gamma rays as well as charged particles.

Types of Semiconductor Detectors

1. Diode Detectors

The major types of diode detectors include:

- P-N junction Diode Detectors
  - surface barrier detectors
  - passivated ion implanted planar (PIP) detectors
- PIN Diode Detectors

Types of Semiconductor Detectors

2. Lithium Drifted Detectors

Lithium drifted detectors are made from p-type silicon or germanium in which the acceptor impurities are compensated for by lithium atoms.

The active volume of these detectors is large enough for them to be suitable for x-ray and/or gamma ray spectroscopy.

Two types of lithium drifted detectors:

- lithium drifted silicon (SiLi, pronounced “silly”)
- lithium drifted germanium (GeLi, pronounced “jelly”)

Types of Semiconductor Detectors

3. High Purity Germanium Detectors

High purity germanium detectors (HPGe) are made from extremely pure p-type or n–type germanium.

The impurities, although present, have been reduced to such a low a concentration that their presence is inconsequential.

The active volume of these detectors is large enough for them to be suitable for gamma ray spectroscopy.

Types of Semiconductor Detectors

4. Primary Applications of Semiconductor Detectors

Diode Detectors

P-N Junction detectors - alpha and/or beta detection
- alpha spectroscopy

PIN detectors - photon dosimetry

Lithium Drifted Detectors

GeLi detectors - gamma spectroscopy

SiLi detectors - x-ray spectroscopy

High Purity Germanium Detectors - gamma spectroscopy

Diode Semiconductor Detectors

Diode Semiconductor Detectors

General

Diodes only permit current to flow in one direction.

They are almost always made of silicon.

One region of the diode consists of p-type silicon and the other region consists of n-type silicon.

Even though they might have an extra hole or unpaired electron, the atoms of the impurities in p-type and n-type materials are electrically neutral.

Diode Semiconductor Detectors

General

There are two general types of diode detectors:

P-N diodes

For charged particle detection and spectroscopy

PIN diodes

For gamma/x-ray detection or spectroscopy

P-N Junction
Diode Detectors

P-N Junction Diode Detectors

General

P-n junction diodes are primarily used for charged particle detection and spectroscopy.

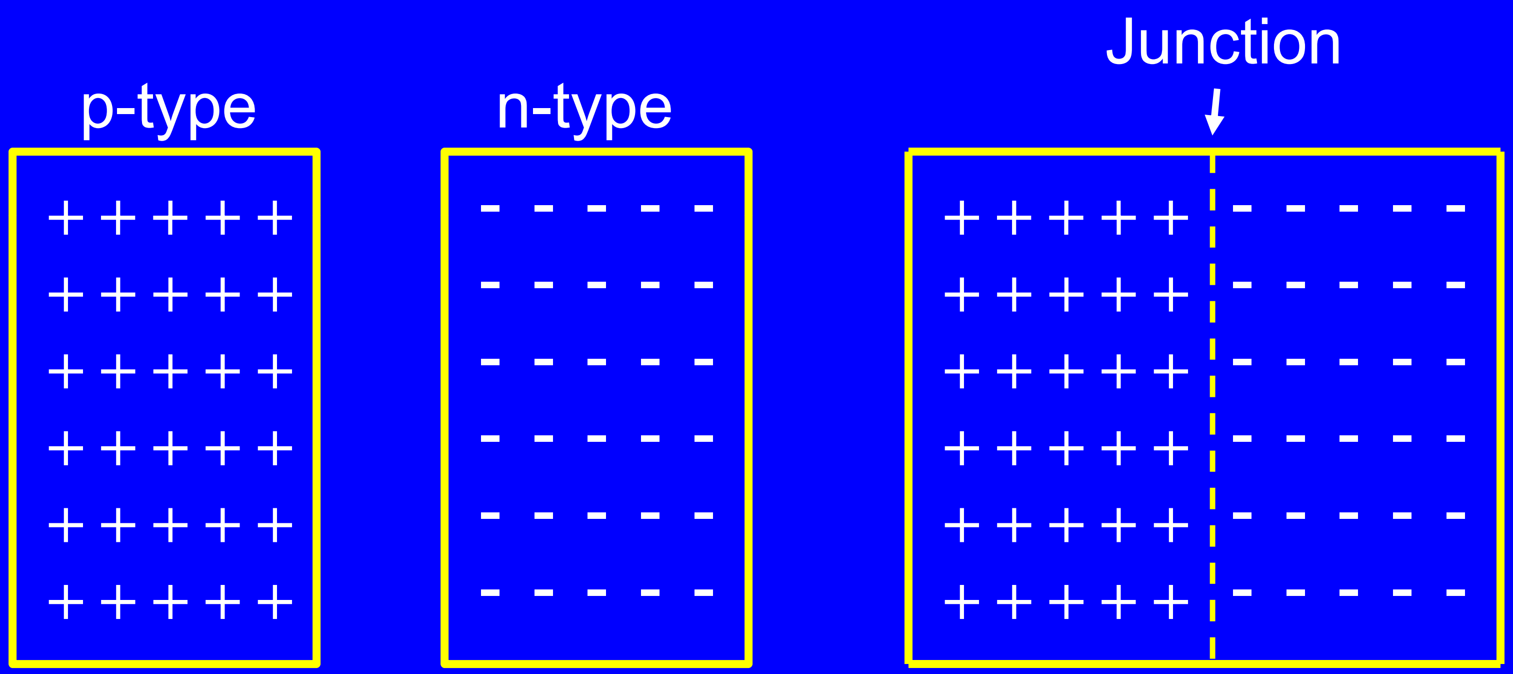
They are more commonly employed for detecting and measuring alpha particles than beta particles.

They are also used as dosimeters for photons in therapeutic radiology,

P-N Junction Diode Detectors

Diode Junction

The junction is the region where n–type and p-type materials meet. It is often referred to as an p-n junction.



Despite the implication of the positive and negative signs, p-type and n-type silicon consist of electrically neutral atoms.

P-N Junction Diode Detectors

Diode Junction

The junction is created by doping one side of the silicon with acceptor impurities and the other side with donor impurities.

Diffusion causes some of the unpaired electrons of the donor impurities in the n-type silicon to move across the junction into the p-type material and combine with the holes. The donor impurities that those electrons came from are no longer electrically neutral – they now have a positive charge.

Similarly, holes from some of the acceptor impurities in the p-type material "diffuse" across the junction to combine with donor electrons on the n-type side of the junction. This leaves those acceptor impurities with a negative charge.

P-N Junction Diode Detectors

Diode Junction

The combination of electrons and holes near the junction creates a non-conductive region almost devoid of free charge carriers. This is known as the depletion region. It serves as the active volume of the detector.

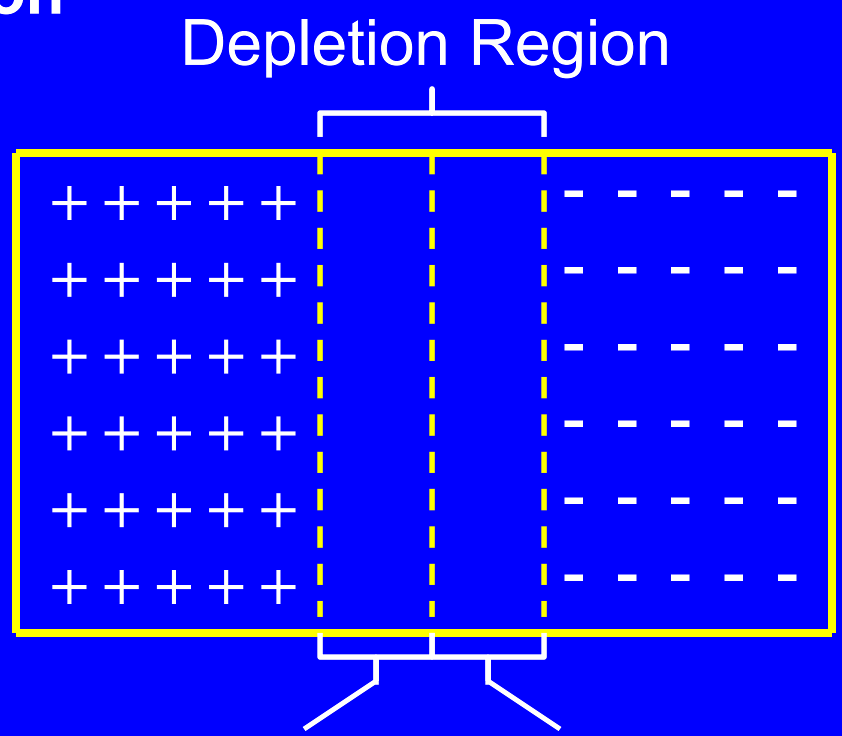
There is a positive charge associated with the n-type silicon side of the depletion region and a negative charge in the p-type silicon side of the depletion region.

This creates a “natural” electric potential across the depletion region of approximately one volt.

In the following figure, any electron flow in the depletion region (current) would be from left to right.

P-N Junction Diode Detectors

Diode Junction

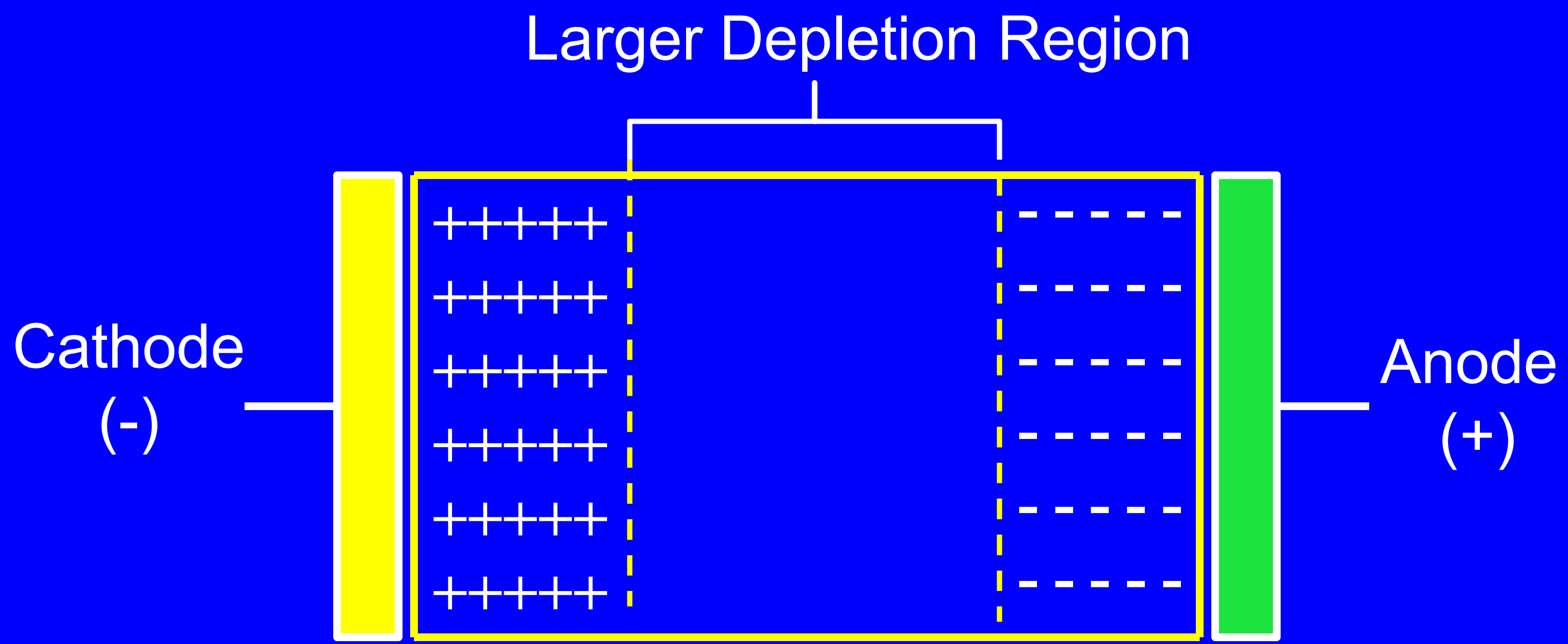


This side of the depletion region has a negative charge because electrons moved here from the right side of the junction to fill the holes.

This side of the depletion region has a positive charge because electrons moved from here to the left side of the junction to fill the holes.

P-N Junction Diode Detectors

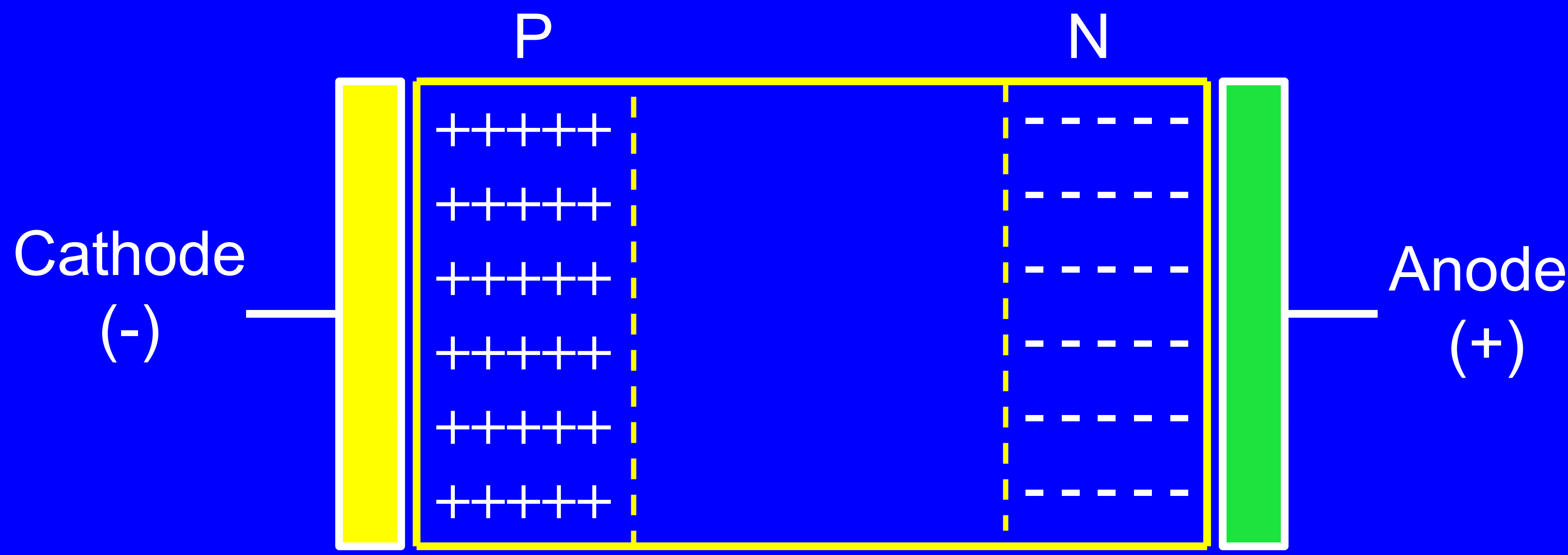
Reverse Bias



Applying a “reverse bias” increases the size of the depletion region. This means that the electrical contact on the n–type material is given a positive potential (anode) with respect to the potential on the p-type material (cathode.

P-N Junction Diode Detectors

Reverse Bias



A reverse bias can be imagined to "pull" the holes and electrons associated with the impurities closer to the cathode and anode respectively - this increases the width of the depletion region. P-N diode detectors are unique in the dependence of the active detector volume on the applied voltage.

P-N Junction Diode Detectors

Reverse Bias

The electric field strength across the depletion layer can be as high as 10^7 V/m!

This produces a rapid collection of charge carriers which, in turn, permits the detector to operate at very high count rates.

Increasing the applied high voltage increases the thickness of the depletion region. A thicker depletion (insulating) layer reduces the detector capacitance and a lower capacitance means less noise.

However, increasing the operating voltage beyond a certain point can cause a breakdown of the detector.

P-N Junction Diode Detectors

Depletion Depths

Depletion depths of 50 - 100 μm are common in diode detectors designed for alpha detection.

Most beta particles would only deposit a small fraction of their total energy in such a small depletion depth. Junction detectors capable of beta spectroscopy require depletion depths on the order of 1000 μm.

P-N Junction Diode Detectors

Detector Materials and Construction

Diode detectors are usually made of silicon. The low atomic number of silicon (compared with germanium) reduces the response to background gamma rays. An advantage for a charged particle detector.

The detector electrodes are usually thin deposits of aluminum.

Gold is sometimes used for the facing electrode because it can be deposited in extremely thin layers, an advantage for alpha particle detection. However, a gold electrode can be so thin that cleaning the detector face is impossible - a single touch can effectively destroy a $2000 investment. Detectors with thin gold electrodes can be light sensitive.

P-N Junction Diode Detectors

Detector Materials and Construction

Typical detector areas range from 50 mm^2 to 2000 mm^2.

The larger the surface area, the higher the counting efficiency.

However, the larger the surface area, the greater the detector capacitance and electronic noise. The greater the noise, the poorer the resolution.

P-N Junction Diode Detectors

Operating Conditions

Diode detectors are usually operated at room temperature. Reducing the temperature can reduce noise and produce some improvement in resolution, but it is the detector's capacitance that ultimately determines resolution.

For alpha spectroscopy, it is preferable, but not always possible, to operate in a vacuum.

If the alpha particles lose some of their energy in air before reaching the detector, the alpha peaks become wider and are shifted to the left on the spectrum.

Alpha spectroscopy system should develop a reproducible vacuum each time a sample is counted.

P-N Junction Diode Detectors

Leakage Current

Even in the absence of ionizing radiation, a small current will flow across a semiconductor when a high voltage is applied. Minimizing this “leakage current” improves detector resolution.

Leakage current involves either: bulk flow through the material

leakage across the surface

Bulk flow of current through the material can be reduced by the use of blocking (non-injecting) contacts which do not serve as a source of charge carriers to replace those collected at the opposite electrode when the high voltage is initially applied.

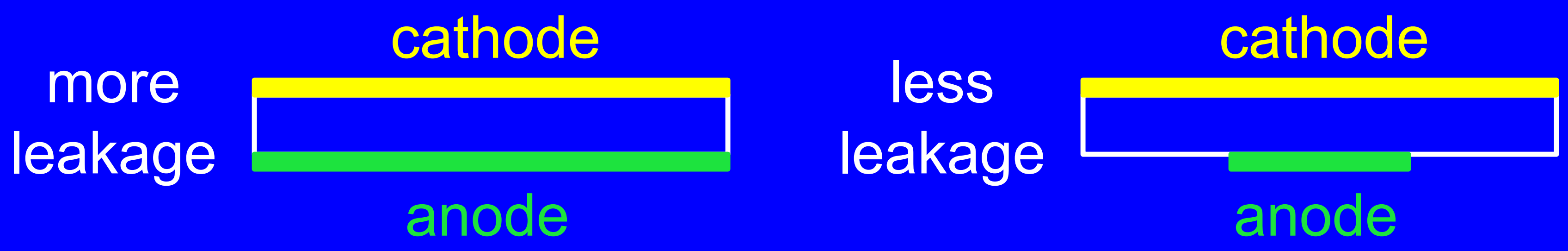
P-N Junction Diode Detectors

Leakage Current

Leakage current across the detector surface can be reduced by manufacturing techniques that ensure clean surfaces.

Leakage current is a particular problem when the anode and cathode are in close proximity, e.g., the edges of diode detectors.

Modifying the manner in which the electrodes are deposited on the silicon/germanium can affect the leakage current.



P-N Junction Diode Detectors

Efficiency and Resolution

The intrinsic efficiency for charged particles is 100%. Every particle incident upon the detector window produces a pulse.

The absolute efficiency (the fraction of the emitted alpha particles that are detected) is lower.

The absolute efficiency depends on:

- detector (window) area
- the detector-source distance

P-N Junction Diode Detectors

Efficiency and Resolution

There is a trade-off between efficiency and resolution:

- Larger detector areas increase the absolute efficiency, but the resolution is worse because of the noise caused by the larger detector capacitance.

- Smaller detector-source distances increase the efficiency but decrease the resolution.

  At large source-detector distances, all the alphas strike the detector at close to 90^o. This means that they all traverse the same amount of dead layer on the detector surface and have the same energy when they reach the detector sensitive volume. The peak on the alpha spectrum will be narrow.

P-N Junction Diode Detectors

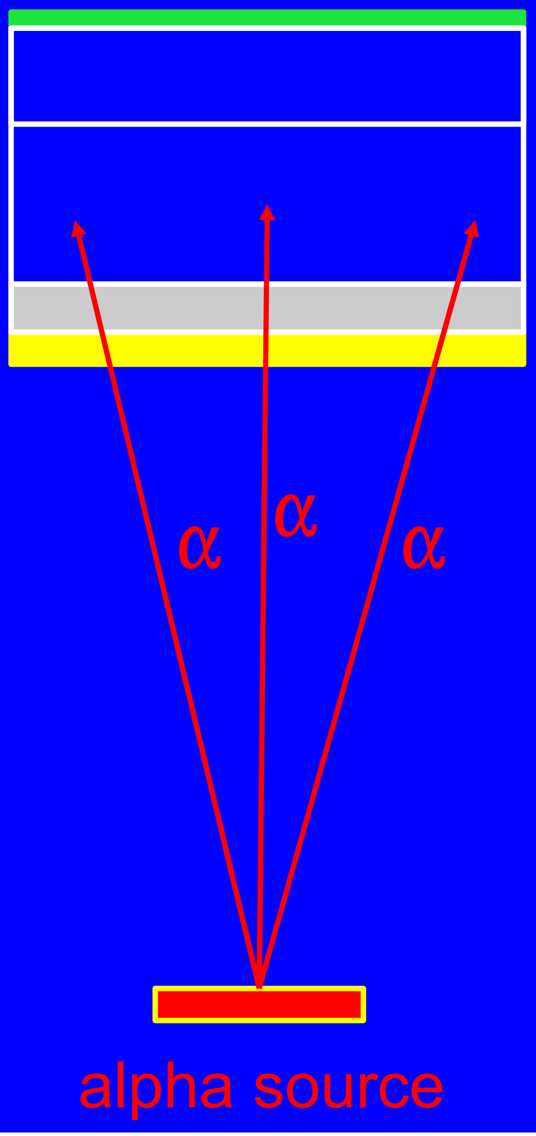
Efficiency and Resolution

On the other hand, if the detector-source distance is small, the alphas are incident upon the detector at a wide range of angles: from 90^o to nearly 180^o. This means that they traverse different thicknesses of the inert layer on the detector surface.

As a result, the alphas will have a wide range of energies when they enter the detector sensitive volume (depletion layer) and the alpha peak on the spectrum will be broad.

P-N Junction Diode Detectors

Efficiency and Resolution



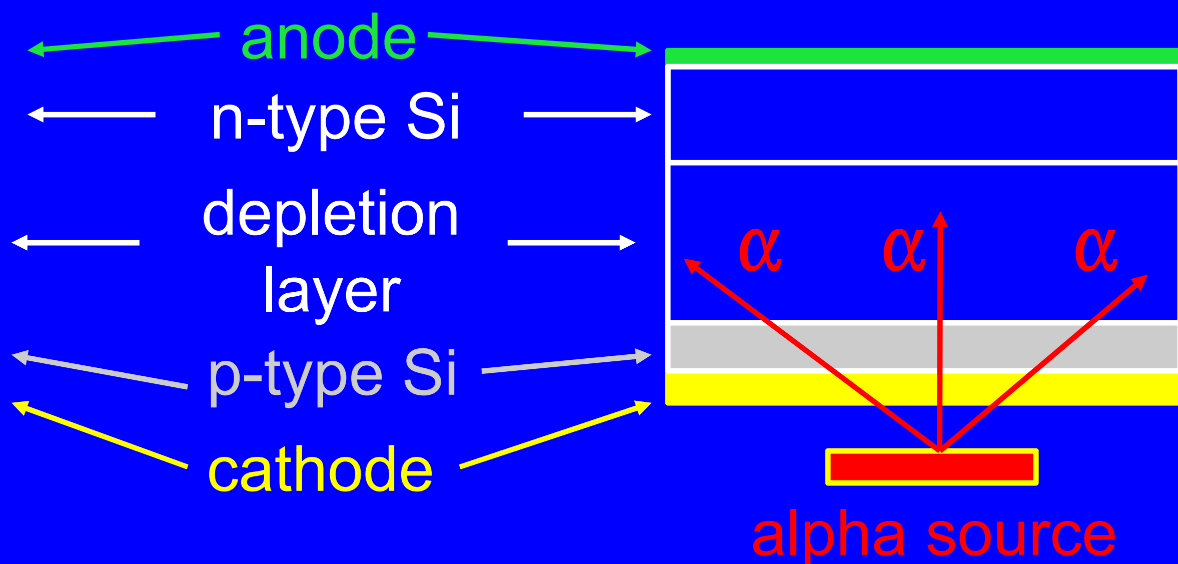


Figure on left: large detector-source distance means poor efficiency but good resolution.

Figure on right: small detector-source distance means good efficiency but poor resolution.

P-N Junction Diode Detectors

Resolution

Alpha detector resolutions are usually described by the FWHM (full width of half the maximum peak height) for the Am-241 5.486 MeV peak. Typical values range from 15-50 keV.

The actual resolution is often poorer than that stated by the manufacturer. One reason might be that the source being counted consists of a thick deposit and the alphas experience significant self-absorption.

Resolutions for monoenergetic electrons (e.g., conversion electrons) are superior to those for alpha particles since less energy is lost in the detector dead layer. The beta resolution is usually measured with a pulser rather than a radioactive source. Typical values are between 5 and 20 keV.

P-N Junction Diode Detectors

Alpha Contamination Problems

Alpha counters of any type are prone to becoming contaminated for several reasons:

- Alpha sources are unsealed
- The decay products of alpha decay can have sufficient recoil energy to escape the source and strike the detector or the walls of the counting chamber. These alpha decay products are often radioactive alpha emitters.
- The emission of alpha particles can damage the source and small bits of the source can be carried off with the alpha particles (alpha creep).

P-N Junction Diode Detectors

Alpha Contamination Problems

To reduce the potential of contamination:

- Leave alpha sources in counter no longer than necessary
- Fill the chamber with helium instead of using a vacuum. Helium's low density allows the alphas to reach the detector with little energy loss. However, helium is dense enough to reduce the number of recoil nuclei striking the detector.
- An alternative to helium is the use of a controlled air leak. The resolution is not as good as if no air were present, but the residual air in the chamber reduces contamination.
- Apply a negative potential (e.g., 6 V) on the source support to reduce the emission of the positively charged recoil nuclei from the sample surface.

P-N Junction Diode Detectors

Detector Background

As a detector is used, it inevitably becomes more and more contaminated. The result is an increase in the detector background which can make the detector unsuitable for low level counting applications.

Many labs operate with two sets of detectors. New detectors (those with a low background) are used to count low activity samples. The older detectors (with the higher backgrounds) are used to count the hotter samples.

If a very low background detector is required, the manufacturer can be requested to forgo the usual QA checks that involve exposing the detector to an alpha source. The phrase “see no alpha’ (or SNA) is sometimes used to specify such detectors.

P-N Junction Diode Detectors

Surface Barrier Detectors

Manner of fabrication:

A thin wafer (disk) of n–type silicon is etched with an acid vapor under conditions that promote oxidation.

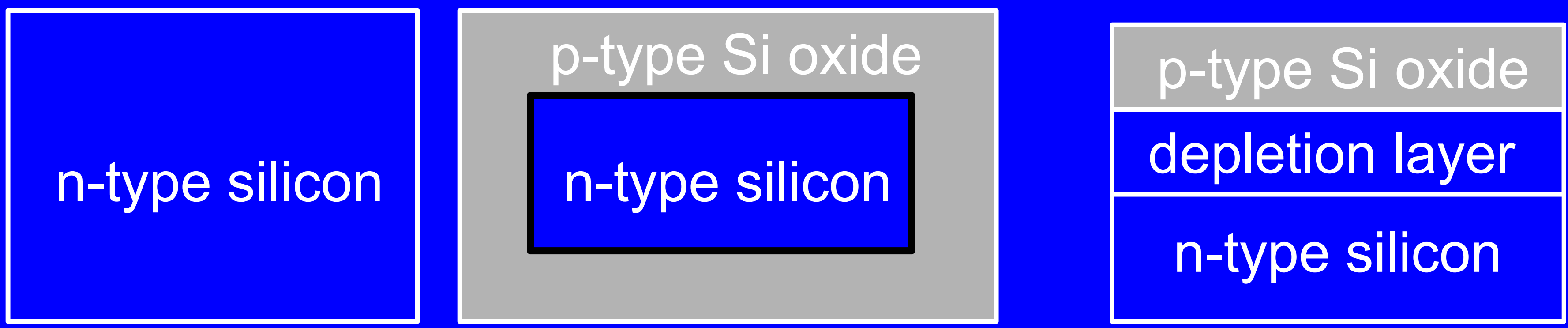
The resulting thin layer of silicon oxide on the surface has the properties of p-type material.

After the oxide is removed from all but one surface, the surface with the p-type oxide layer is coated with a thin layer of gold to serve as the cathode.

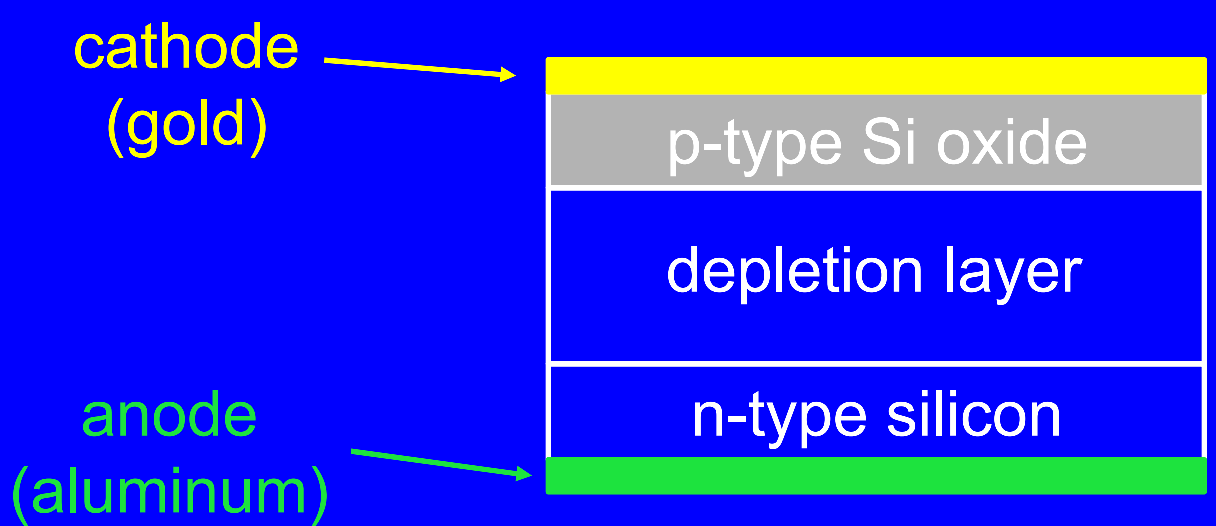
The other side of the detector is coated with aluminum to serve as the anode.

P-N Junction Diode Detectors

Surface Barrier Detectors



1. silicon wafer
2. Surface etched in oxidizing atmosphere
3. p-type oxide removed from all but one surface



4. Electrodes deposited

P-N Junction Diode Detectors

Passivated Ion-implanted Planar (PIP) Detectors

The process of manufacturing a PIP detector begins with a large area high-purity n–type silicon wafer. Several detectors can be produced from each wafer.

Manner of fabrication:

The wafer is passivated by creating a p-type surface oxide layer.

The oxide is removed on the backside of the detector, and on the front where the detector windows will be located.

The back side of the detector is doped with arsenic, a donor impurity, while the front side is doped with boron, an acceptor impurity.

P-N Junction Diode Detectors

Passivated Ion-implanted Planar (PIP) Detectors

Damage caused by the implantation process is repaired by annealing the wafer at 600 degrees centigrade.

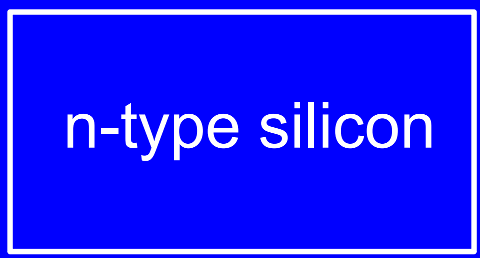
Aluminum is deposited on the front and back surfaces.

The aluminum is selectively removed to create the front and rear electrical contacts. This is done so as to create a relatively large distance between the front and rear electrical contacts (electrodes). The result is that the leakage current between the electrodes is smaller than that of a surface barrier detector where the front and rear electrodes extend to the very edges of the wafer. The aluminum electrode is also more rugged than the gold electrode of a surface barrier detector.

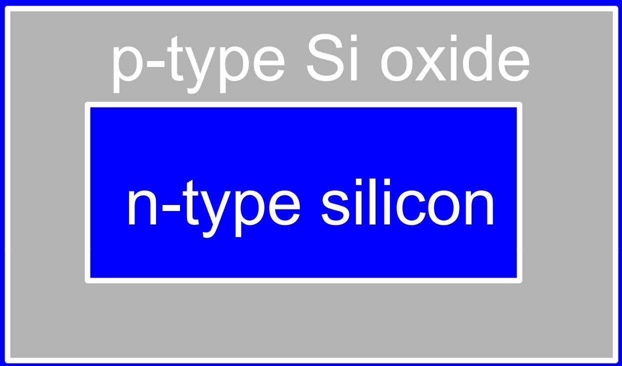
P-N Junction Diode Detectors

Passivated Ion-implanted Planar (PIP) Detectors

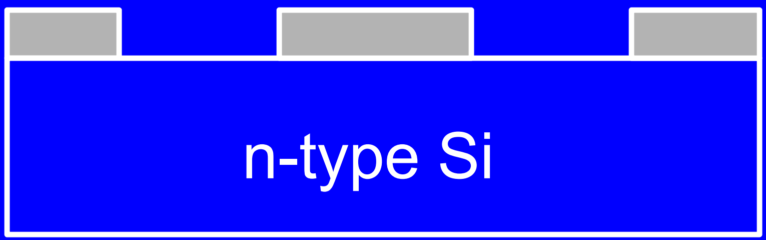
1. silicon wafer



2. Surface etched in oxidizing atmosphere



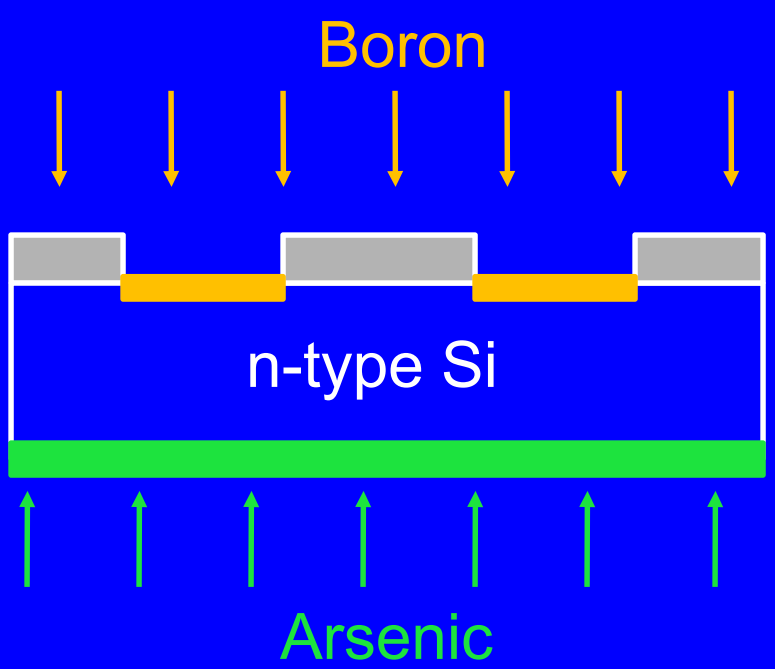
3. Selective removal of p-type Si oxide layer.



P-N Junction Diode Detectors

Passivated Ion-implanted Planar (PIP) Detectors

4. Ion implantation of boron (acceptor) and arsenic (donor)

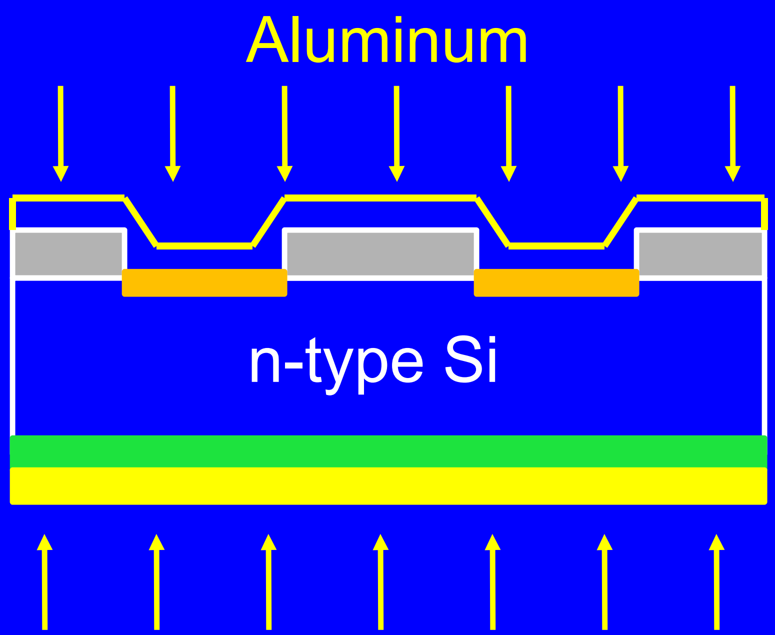


5. Annealing and partial removal of oxide layer

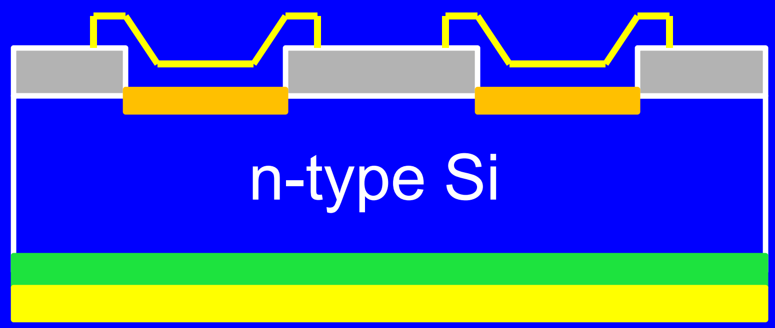
P-N Junction Diode Detectors

Passivated Ion-implanted Planar (PIP) Detectors

6. Aluminum metalization



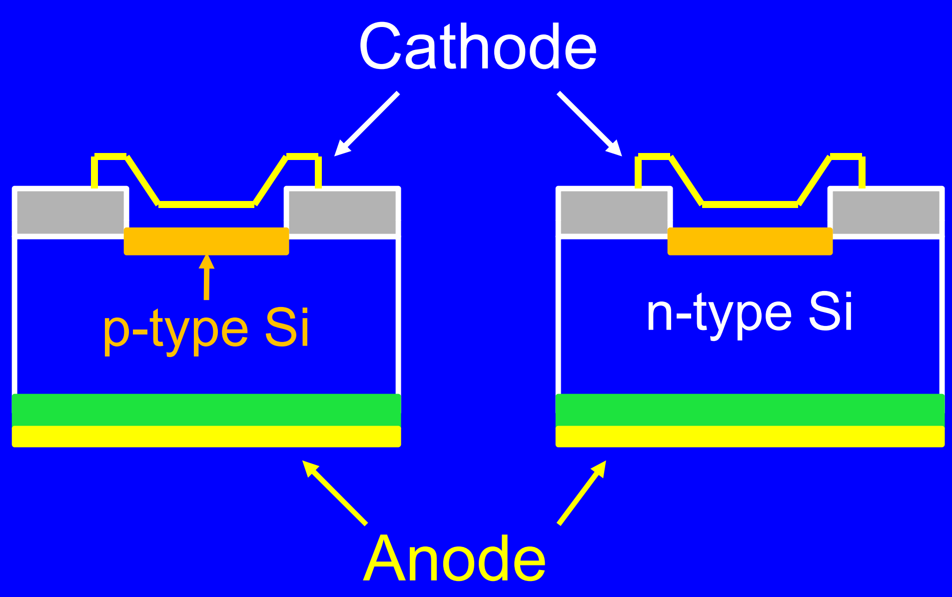
7. Aluminum patterning on front



P-N Junction Diode Detectors

Passivated Ion-implanted Planar (PIP) Detectors

8. Division into multiple detectors



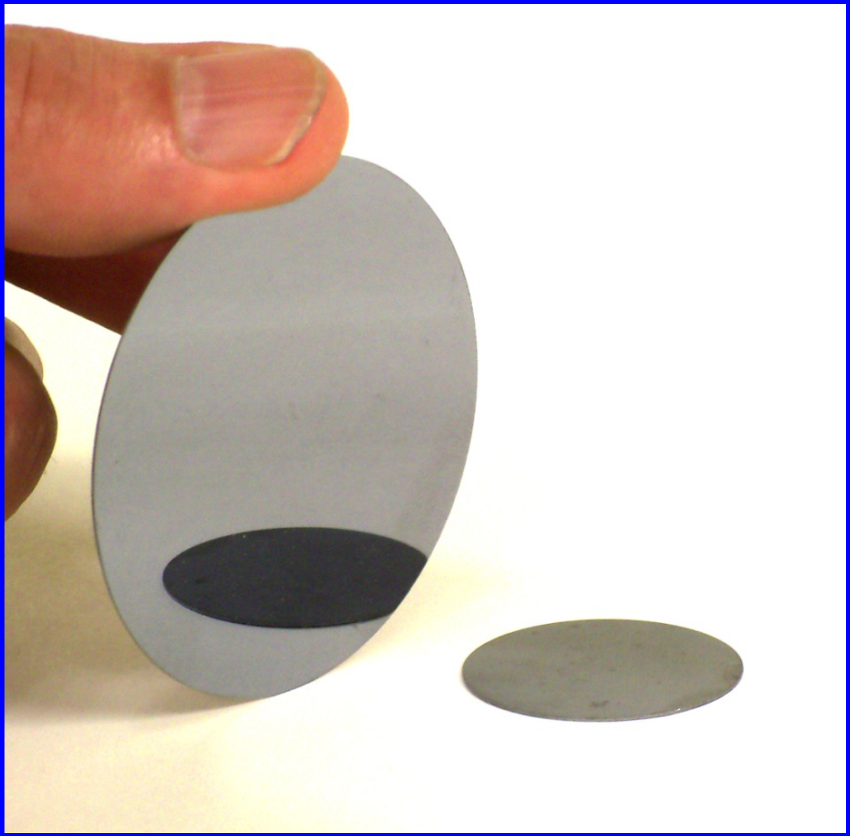
P-N Junction Diode Detectors

Passivated Ion-implanted Planar (PIP) Detectors

PIP detectors are very popular because of their excellent resolution and their ruggedness.

The aluminum electrode facing the source is thick enough to permit cleaning (unlike the gold electrode of a surface barrier detector).

P-N Junction Diode Detectors



Silicon wafers. Smaller horizontal wafer has oxide layer on surface.

Three alpha P-N diode detectors.

P-N Junction Diode Detectors

PIP detector.

P-N Junction Diode Detectors

Advantages of Silicon Diode Detectors as Dosimeters

- Their small size (compared to gas detectors or scintillators) makes them excellent for measurements in small beams, and in steep dose gradients.
- The atomic number of silicon is closer to that of human tissue than is the atomic number of germanium. Silicon's larger band gap means less noise at room temperature than with germanium.
- Unlike TLDs, OSL or film, diodes can provide real time measurements as well as measure an integrated dose.

P-N Junction Diode Detectors

Disadvantages of Silicon Diode Detectors as Dosimeters

- They can be directionally dependent.
- Silicon's high atomic number relative to air or tissue means that silicon dosimeters are energy dependent, i.e., they over-respond at low energies.
- Their response can be affected by temperature (possibly an issue if they are in contact with a body). N–type silicon detectors are more sensitive to temperature than p-type.
- The dose-rate can affect their response, especially n–type silicon detectors.

P-N Junction Diode Detectors

Disadvantages of Silicon Diode Detectors as Dosimeters

- Their sensitivity can decrease over time due to the accumulation of radiation damage in the crystal. This reduction in sensitivity might be as much as 10% per kGy or so. The result is that it can be necessary to perform frequent verifications of the calibration, especially in high dose applications, e.g., therapeutic radiology.

- They can be subject to magnetic and rf interference.

P-N Junction Diode Detectors

Dosimeters Used in Radiology

Silicon diode dosimeters are primarily used for in-vivo measurements.

They are more commonly employed in therapeutic, as opposed to diagnostic, radiology because of the requirements for dose verification.

Detectors take various configurations including linear arrays.

P-N Junction Diode Detectors

Dosimeters Used in Radiology

The intrinsic potential at the p-n junction of a diode is approximately 0.7 volts and the depletion layer is a few tens of micrometers. Although a bias would increase sensitivity (intrinsic region volume) and reduce leakage current, the signal to noise ratio is superior with no bias. For this reason, diode dosimeters are usually operated (in the current mode) with no bias applied. Sensitivity is not a major concern here because of the relatively high dose rates involved.

However, due to the high exposures employed in therapy, the gradual decrease in sensitivity brought about by radiation damage to the crystal is of particular concern. This can necessitate the use of regular calibrations.

P-N Junction Diode Detectors

Dosimeters Used in Radiology

Since silicon diodes are energy dependent, it is desirable for the calibration energies to be as close as possible to the energy of the radiation that will be measured. Unfortunately, the energy spectrum depends on a variety of factors such as field size, focus to detector (surface) distance, and the thickness of the phantom or patient.

Often designed for a specific type of radiation (e.g., they might incorporate a particular thickness of metal to generate the appropriate buildup) and corrections might have to be performed when used for other types of radiation.

P-N Junction Diode Detectors

Dosimeters Used in Radiology

Because of their planar construction and encapsulation, diode detectors can experience considerable angular dependence. As such, it is important that the diodes' orientation during calibration is the same as that during measurements.

Diode detectors are somewhat temperature dependent and it can be necessary to calibrate at the same temperatures at which the measurements are performed, e.g., skin temperature.

PIN Diode Detectors

PIN Diode Detectors

General

PIN diodes consist of a large relatively pure “intrinsic region” that is sandwiched between a heavily doped p-type region and a heavily doped n-type region.

PIN Diode Detectors

General

The depletion region extends almost completely across the intrinsic region. When reversed biased, the volume of the depletion layer is not affected by the applied voltage.

PIN Diode Detectors

General

The large depletion region gives the PIN detector a much larger sensitive volume than the P-N detector.

This makes it more suitable for x-ray of gamma ray detection/spectroscopy.

For photons above 60 keV, the predominant interaction with the detector is Compton scattering and the efficiency is more or less independent of the photon energy. Typical intrinsic efficiencies are on the order of 1 – 2%

PIN Diode Detectors

Electronic Personnel Dosimeters

Electronic personnel dosimeters (EPDs or EDs) have come into widespread use, especially in the nuclear power industry where they have almost completely eliminated the use of direct reading pocket dosimeters.

They are used to keep exposures ALARA, control access to work areas and provide a backup for the information provided by the TLD or film.

In the U.S., EDs cannot be used to determine the dose of record. At least some nuclear power plants in Great Britain use EDs for the dose of record however.

PIN Diode Detectors

Electronic Personnel Dosimeters

They indicate the dose rate (e.g., 0.1 to 1000 mrem/hr) as well as accumulated dose (e.g., 0.1 mrem to 1000 rem).

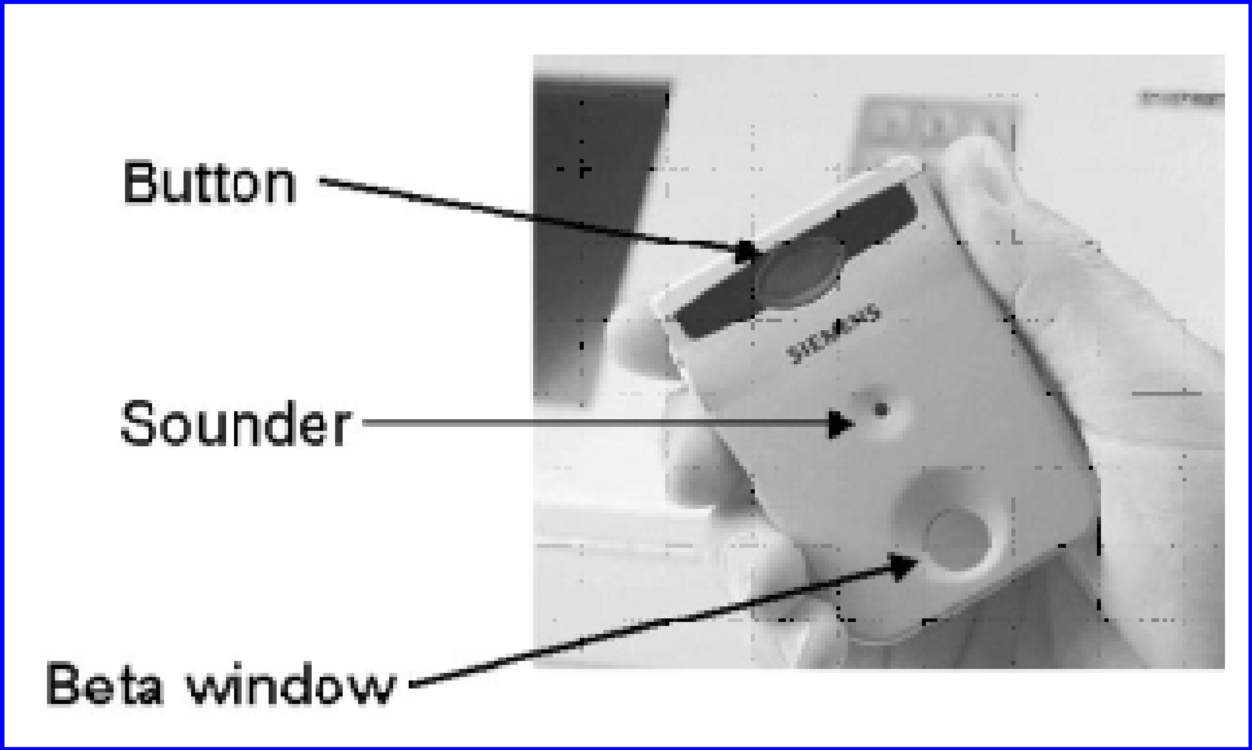
Their alarms can be set to sound (or vibrate) when a specified dose or dose rate is exceeded.

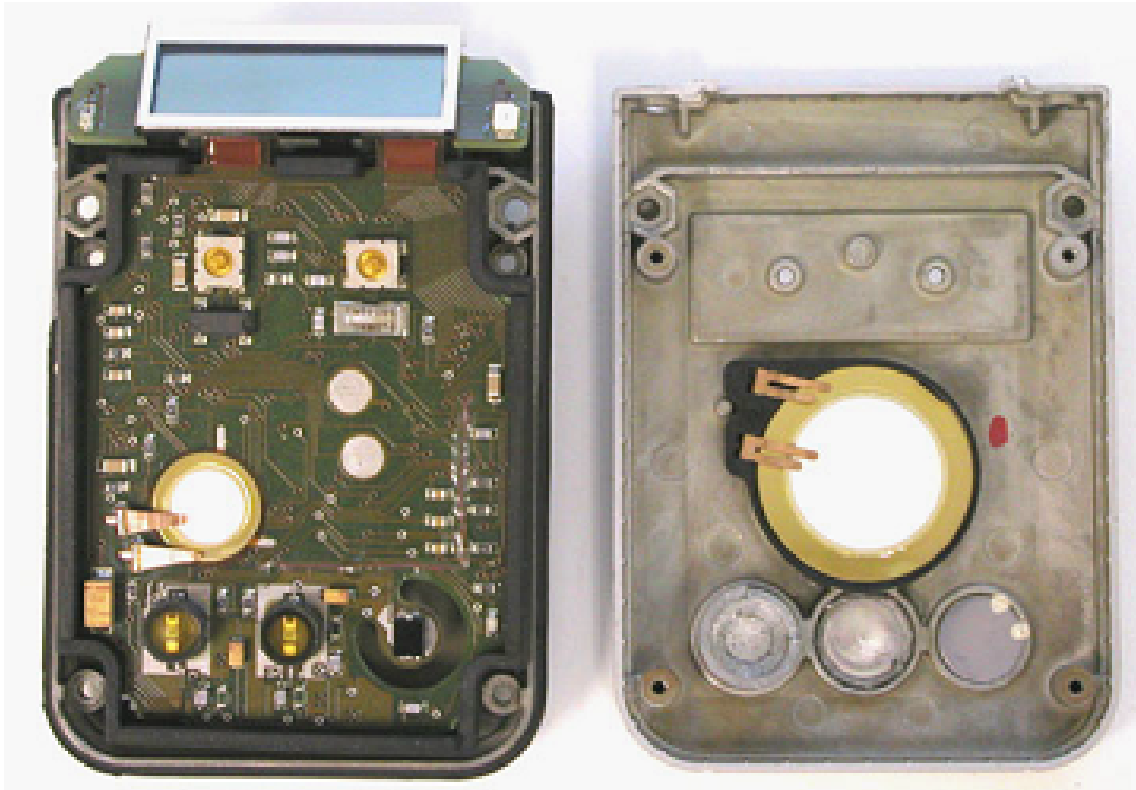
Their output can be transmitted via radio to a base station where the worker's exposures are continuously monitored.

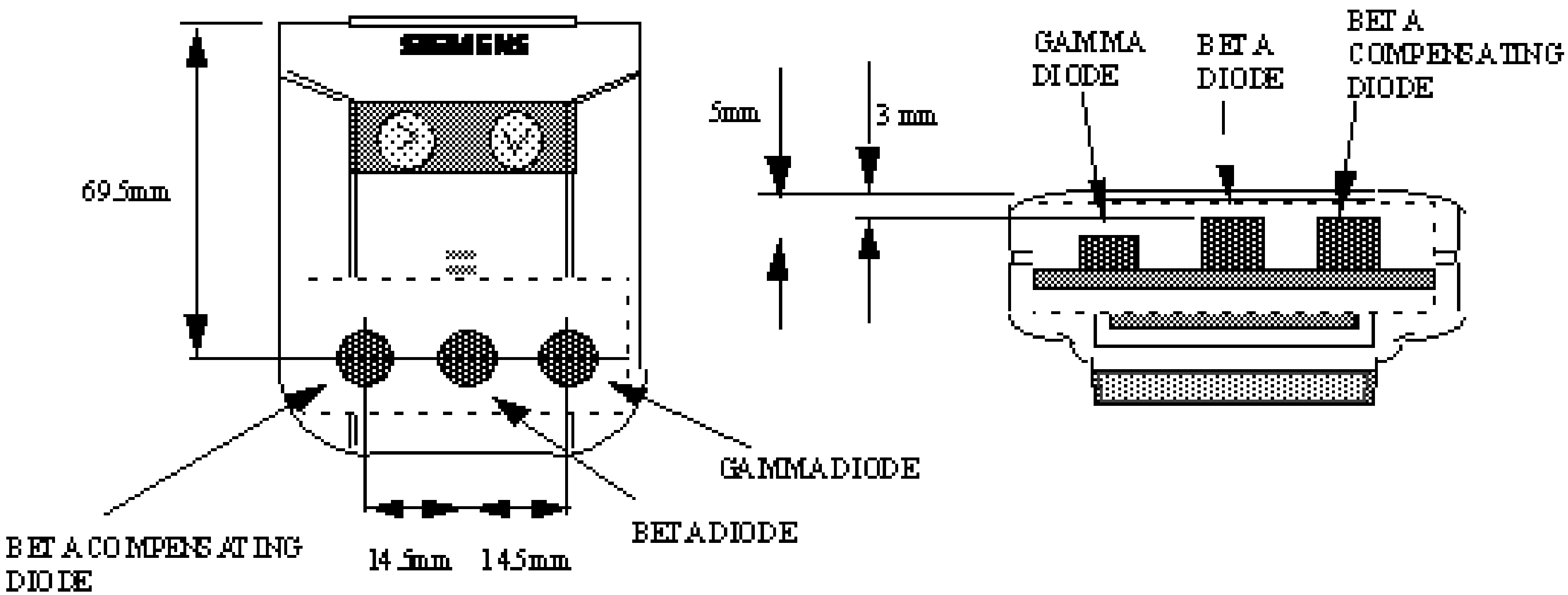
Depending on the design, EPDs might respond to gammas, betas, and/or neutrons. Being energy dependent, a typical EPD contains several diodes each of which has a unique filter. The relative responses of the different detector elements is used to estimate and correct for the energy of the radiation.

PIN Diode Detectors

Electronic Personnel Dosimeters






SIEMENS
69.5mm
14.5mm
14.5mm
BETA COMPENSATING DIODE
BETA DIODE
GAMMA DIODE
5mm
3 mm
GAMMA DIODE
BETA DIODE
BETA COMPENSATING DIODE

PIN Diode Detectors

RTI Electronics' BARRACUDA

The Barracuda is a multimeter that is used for X-ray QA.

A somewhat unique feature is its use of a hand-held graphical interface (Palm). With a single multipurpose PIN diode detector, it can measure kVp, irradiation time, dose, dose rate, dose per pulse, pulse rate, waveforms and half-value layer.

The use of additional detectors make it possible to also measure mA, mAs, light and CT dose.

PIN Diode Detectors

RTI Electronics' BARRACUDA

The small sensitive area of the detector (3 x 21.1 mm) makes it ideal for measurements of narrow x-ray beams.

Since silicon detectors over-respond at low energies, the MPD is energy compensated. This is accomplished with a metal filter that preferentially attenuates the low energy photons to which the detector would otherwise over-respond.

Since diode detectors are directionally dependent, the Barracuda incorporates a built-in position check feature.

Lithium Drifted Detectors

Lithium Drifted Detectors

General

There are two types of lithium drifted detectors:

- Lithium drifted silicon (SiLi) detectors
- Lithium drifted germanium (GeLi) detectors

Unlike diode semiconductor detectors, lithium drifted detectors can be manufactured in very large sizes (many cubic centimeters).

As such, lithium drifted detectors are primarily designed for gamma ray or x-ray spectroscopy.

Lithium Drifted Detectors

The Lithium Drifting Process

Lithium drifting is a method employed with p-type silicon or germanium to "compensate" for the acceptor impurities.

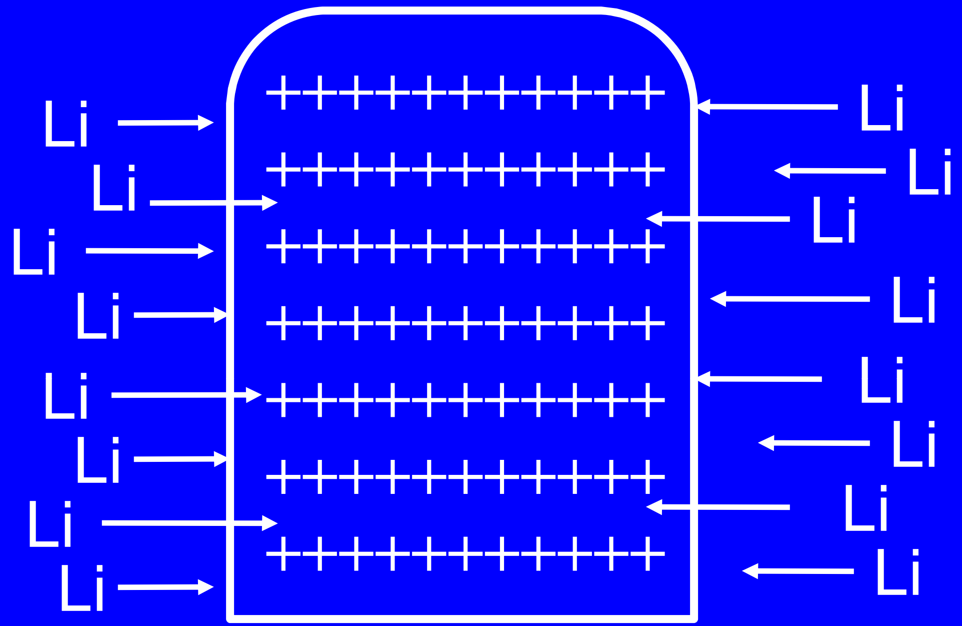
The entire process might take two weeks or so.

A silicon or germanium crystal is exposed to a lithium vapor at 60 ^{o}C (lithium atoms are very small atom and possess one unpaired electron).

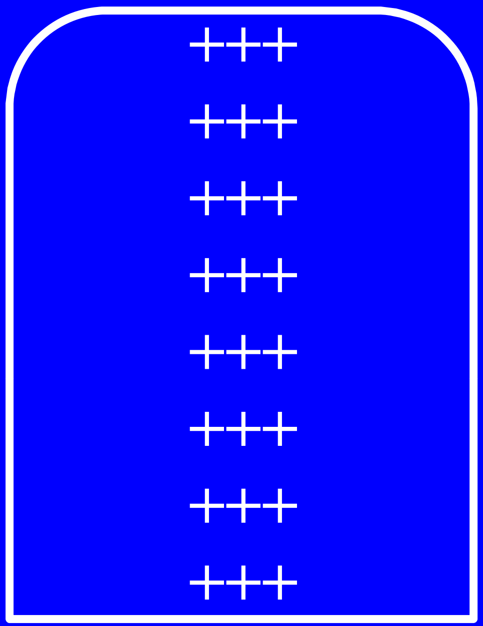
With a reverse bias applied, the lithium atoms migrate (drift) through the crystal.

Lithium Drifted Detectors

The Lithium Drifting Process



Lithium drifting into
silicon or germanium crystal



Compensation complete
except for central p-type
core which will serve as
the central electrode

Lithium Drifted Detectors

The Lithium Drifting Process

The lithium atoms "locate" and pair up with the acceptor impurities in the crystal - the lithium atom's unpaired electrons "fill" the positively charged holes associated with the impurities. This is referred to as compensation.

The compensation process is stopped before the entire crystal is compensated. The central core is left as p-type material.

The compensated region of the crystal, which behaves as if it were pure material, serves as the sensitive volume of the detector.

Lithium Drifted Detectors

SiLi Detectors

- referred to as "silly" detectors
- primarily used for x-ray spectroscopy
- must be operated cold (e.g., liquid nitrogen temperatures)
- can come up to room temperature during storage
- less efficient than GeLi detectors for high energy photons due to lower Z

Lithium Drifted Detectors

GeLi Detectors

- referred to as “jelly" detectors
- primarily used for gamma-ray spectroscopy
- must be kept cold at all times (e.g., during operation and storage) or will have to be re-drifted
- not produced anymore - have been replaced by high purity germanium detectors

Lithium Drifted Detectors

Why GeLi Detectors Must be Kept Cold

If a GeLi detector comes up to room temperature, the lithium atoms will have sufficient thermal energy to migrate away from the impurity sites.

This is not an issue with SiLi detectors since the atoms of a silicon crystal have a relatively close spacing. The lithium atoms are relatively immobile in a SiLi crystal.

However, the atoms in a germanium crystal are more widely separated and the lithium atoms can move more freely. It thus become necessary to maintain GeLi detectors at liquid nitrogen temperatures to fix the lithium at the impurity sites.

Lithium Drifted Detectors

Why GeLi Detectors Must be Kept Cold

If the detector warms up and compensation is lost, the detector can be “redrifted” but this process is expensive and the detector performance may not be quite as good as it was.

The detector might warm up because of a failure of the cryostat (the insulating jacket used to keep the detector cold) seals. If a seal fails, the vacuum in the cryostat is lost and the liquid nitrogen in the dewar will be rapidly used up.

Although all lithium drifted and high purity detectors must be operated at low (e.g., liquid nitrogen) temperatures to reduce noise, only the GeLi must always be kept at such temperatures, even during storage.

Lithium Drifted Detectors

GeLi Detectors

High Purity Germanium Detectors

High Purity Germanium Detectors

General

High purity germanium (HPGe) detectors have two advantages over GeLi detectors:

- they can be allowed to warm up to room temperature during storage
- they can be produced more quickly than GeLi detectors

HPGe systems deal with the problem of impurities by reducing these impurities to an inconsequential level. Only one impurity will be found for every 10^{12} atoms of germanium.

Despite the low levels of impurities, high purity germanium will still be classified as either n–type or p-type.

High Purity Germanium Detectors

HPGe Production

A bar of germanium is placed in a quartz trough maintained on a slight incline.

The bottom end of the germanium is heated to the melting point using an induction heater. The latter is slowly moved up the germanium causing the molten region (glowing red) to move with it.

Impurities in the germanium preferentially migrate to the molten region. As the induction heater moves along the germanium, the impurities in the germanium move with it.

When the process is complete, the impurities are concentrated at the upper end of the germanium bar.

High Purity Germanium Detectors

HPGe Production cont.

The end containing the impurities is removed leaving behind a bar of high purity germanium.

Next, the high purity germanium is melted in a quartz chamber. A rod with a seed crystal of germanium at the end is lowered into the molten germanium. As the germanium crystallizes about the seed, the rod is turned and pulled out of the molten material. The rate at which this is done controls the size of the crystal. The result is a cylindrical crystal with the shape of a small loaf of French bread.

Finally, the crystal is cut into sections which are shaped and polished.

High Purity Germanium Detectors

Detector Construction

HPGe and SiLi detectors are either: planar
coaxial

Planar Detectors

Planar detectors are primarily intended for low energy gamma or x-ray spectroscopy in the 1 to several hundred keV range.

Planar detectors generally have better resolution than coaxial detectors below 100 keV or so. They also often have superior count rate capabilities.

They consist of disks of high purity (usually n–type) germanium or silicon, approximately 1-5 cm in diameter and 0.5- 2.0 cm thick.

High Purity Germanium Detectors

Planar Detectors cont.

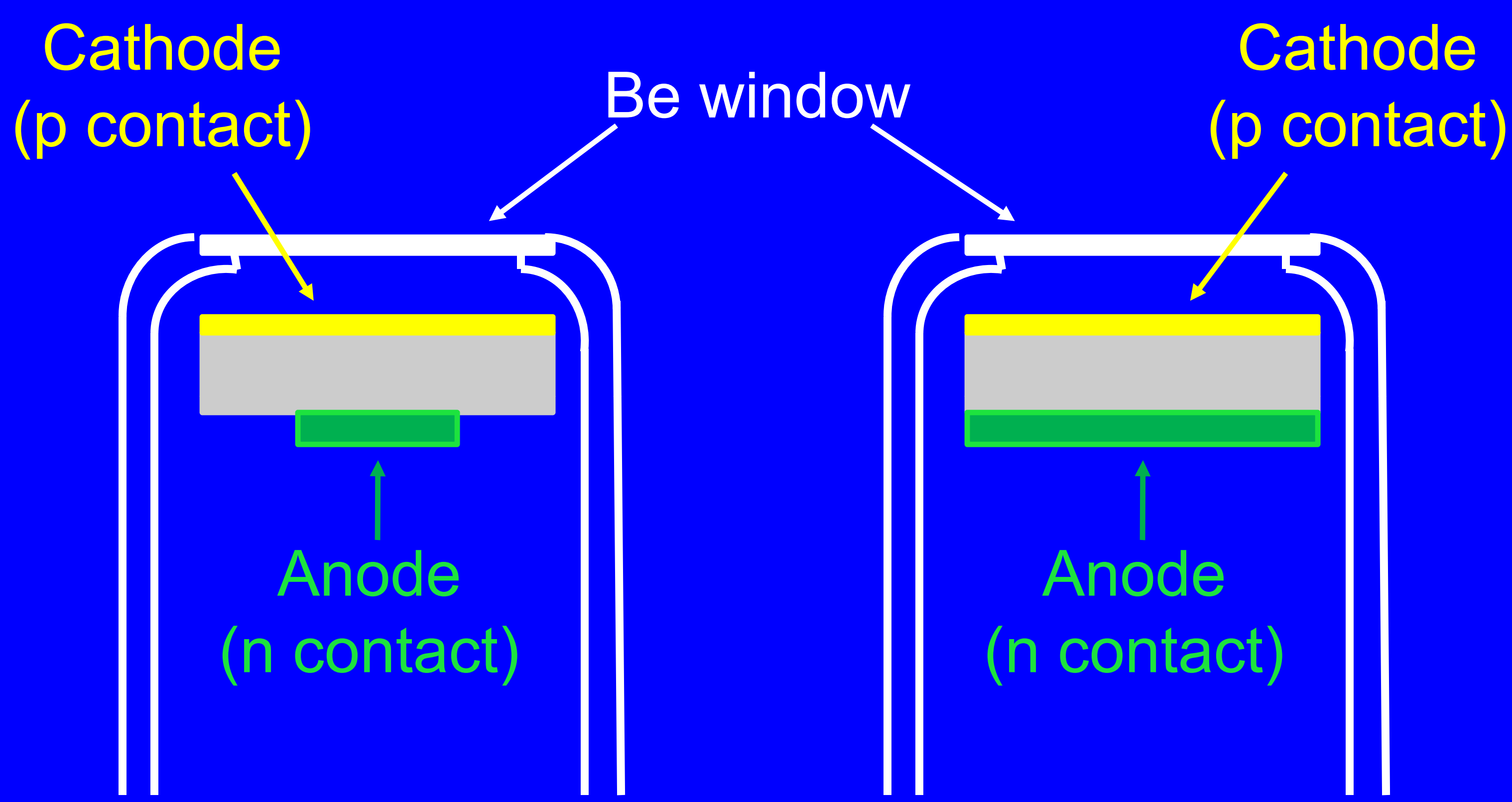
A very thin (<0.3 micron) ion-implanted electrical contact of boron (Z = 5) is deposited on the front surface to serve as the cathode.

A thicker (500 - 1000 micron) lithium diffused contact is deposited on the back side of the detector. This serves as the anode.

To improve transmission of low energy photons, the detector housing (cryostat) has a thin (ca. 0.02 - 0.03”) beryllium window. In some systems plastic/carbon fiber windows are used instead of beryllium.

High Purity Germanium Detectors

Planar Detectors cont.



Electrode configuration on left has reduced leakage current, lower capacitance and improved resolution,

High Purity Germanium Detectors

Planar Detectors cont.

Early version of planar GeLi detector. End cap with beryllium window on right.

High Purity Germanium Detectors

Coaxial Detectors

The two electrodes of a coaxial detector share the same axis.

In a "true" coaxial detector (standard configuration for GeLi detectors) the central electrode runs the length of the crystal.

Most HPGe detectors are "closed end" systems in which the central electrode extends only part way into the crystal. The closed end coaxial detector has a higher counting efficiency than a true coaxial detector since there is more active germanium close to the source.

Coaxial detectors are usually 4 - 7 cm in diameter and 4 - 7 cm in height. A hole is "drilled" into one end of the crystal to form the surface for the central electrode while the outside of the cylinder serves as the surface for the other contact.

High Purity Germanium Detectors

Coaxial Detectors

Closed end coaxial HPGe detector crystal on left.
True coaxial GeLi detector crystal on right.

High Purity Germanium Detectors

P-type Coaxial Detectors

In a “conventional” detector of p-type germanium, the outer electrode is a 500 - 1000 micron thick deposit of lithium. It is given a positive bias and serves as the anode for the collection of the electrons.

The inner contact, the cathode, is ion implanted boron or evaporated gold (<0.3 microns thick). It serves as the cathode for the collection of the holes.

Since most photon interactions occur closer to the anode than the cathode, the charge collection time is primarily determined by the time it takes for the holes to be collected.

These types of detectors are useful from 50 keV to more than 10 MeV.

High Purity Germanium Detectors

N-type Coaxial Detectors

With n–type germanium the position of the electrodes are reversed. In fact, n–type HPGe coaxial detectors are sometimes referred to as reverse electrode detectors.

Since the outer electrode is thinner than that of a "conventional" p-type coaxial detector, an n–type detector is more suitable for low energy work. As such, the end cap of an n–type coaxial detector will have the same type of window as that found in a planar detector.

High Purity Germanium Detectors

N-type vs. P-type Coaxial Detectors

P-type detectors are useful from 50 keV to more than 10 MeV whereas n-type detectors are useful from 10 keV to more than 10 MeV.

N-type detectors are more expensive.

P-type detectors have slightly better resolution.

N-type detectors are more resistant to neutron damage, which can result in low energy tails on the peaks, than p-type detectors. Fast neutrons create hole trapping centers but electrons are the primary charge carrier with n-type detectors.

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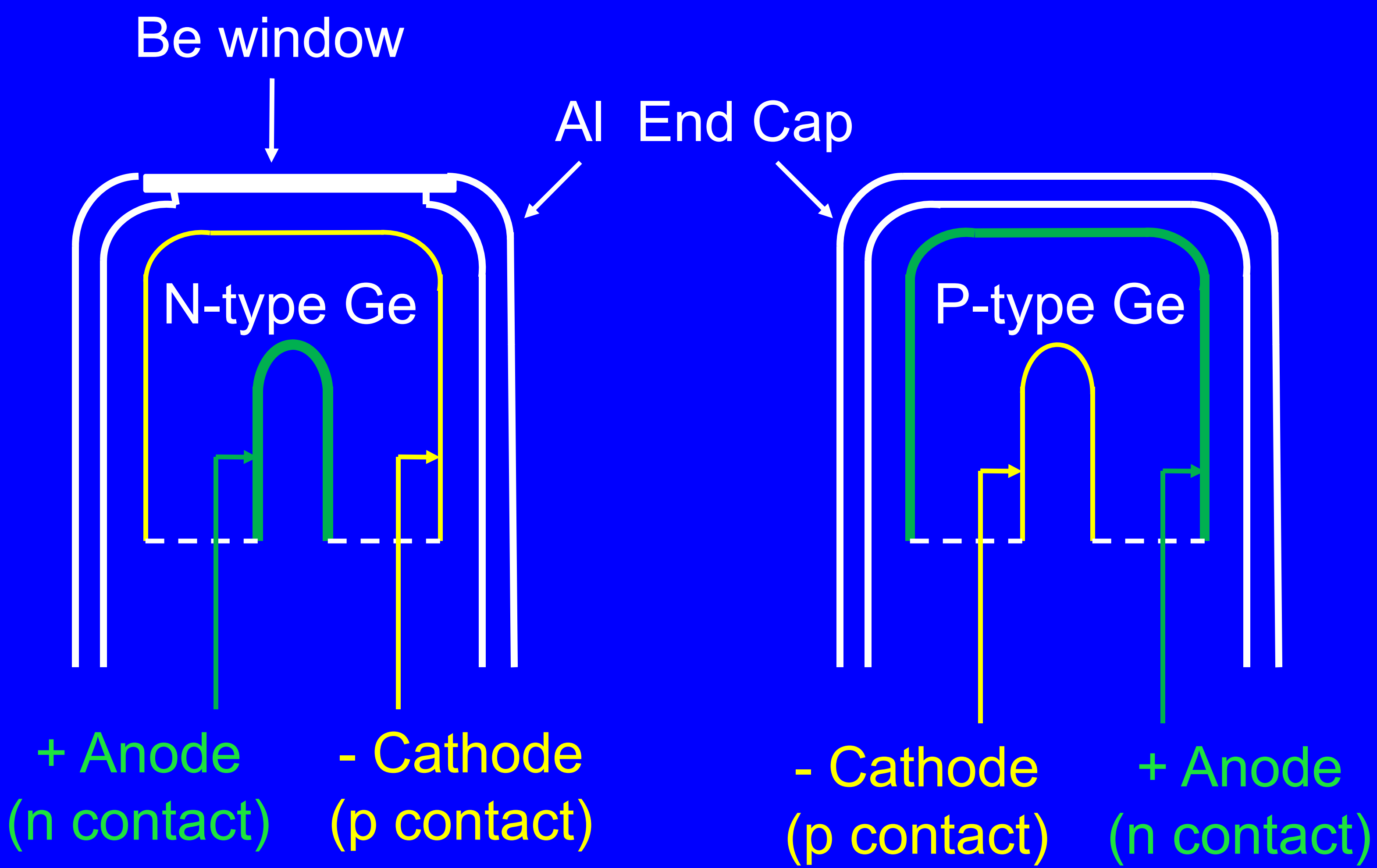
N-type vs. P-type Coaxial Detectors



High Purity Germanium Detectors

End Cap Windows

Detectors capable of low energy spectroscopy (e.g., planar, SiLi , and n-type coaxial HPGe detectors) have a thin entrance window on the cryostat end cap just above the detector crystal.

These windows are usually made of beryllium and are 0.02 to 0.03” thick. Carbon composite windows are also common.

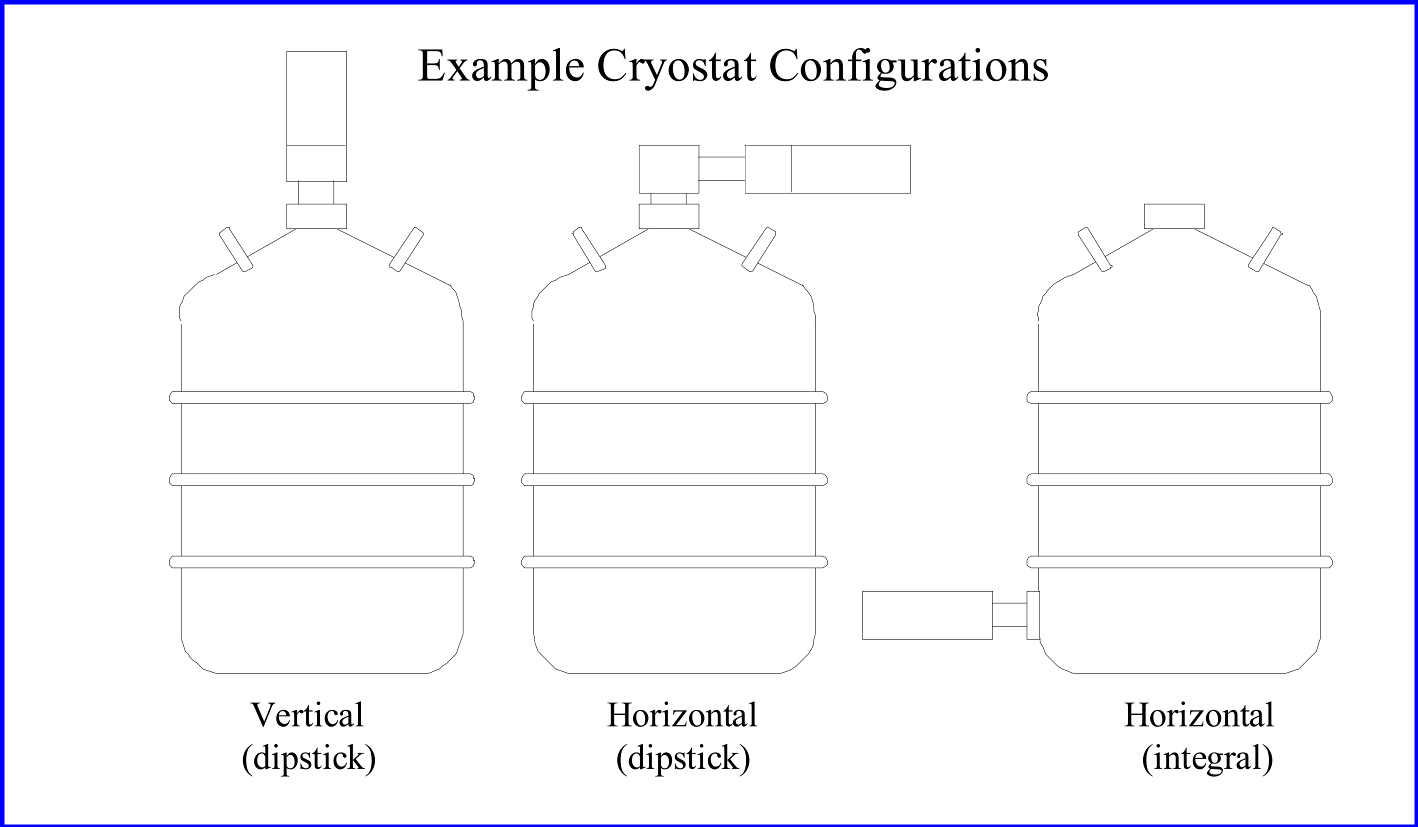
The windows are easily broken. When the low energy portion of the spectrum is not being analyzed, the window should be protected with a cap.

Increased efficiency for low energy photons increases the potential for coincidence losses since x-rays will be detected that would not normally reach the detector.

High Purity Germanium Detectors

Detector Cryostat

The cryostat is the insulating jacket that keeps the detector cold. If a dewar is employed to hold liquid nitrogen to cool the detector, the dewar might be considered part of the cryostat.



High Purity Germanium Detectors

Detector Cryostat

The end cap, usually 1mm thick aluminum, is that part of the cryostat surrounding the detector.

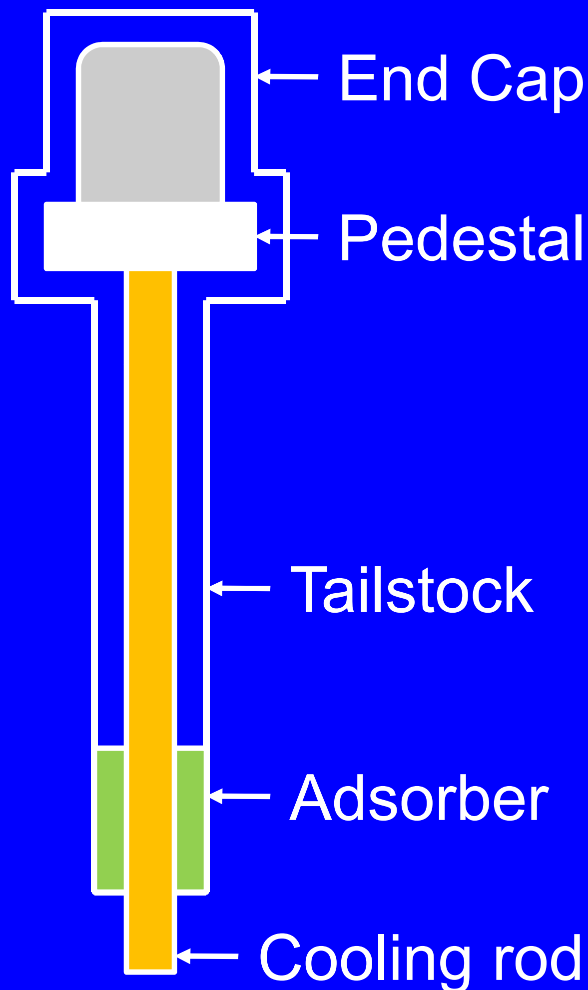
The tailstock is the dipstick-like tail of the cryostat that is inserted into the neck of the dewar.

The tailstock almost completely encloses a copper rod (aka, the cold finger) that thermally connects the detector crystal to the liquid nitrogen. Only the last inch or so of the cooling rod extends outside the tailstock.

Heat is drawn from the detector crystal, through the pedestal (a magnesium or copper block) to the copper cooling rod and finally to the liquid nitrogen.

High Purity Germanium Detectors

Detector Cryostat



The vacuum in the cryostat is necessary to minimize conductive heat transfer. A loss of vacuum (e.g., due to a failure of the cryostat seals) would result in rapid loss of the liquid nitrogen.

Since a good vacuum is necessary, the tailstock contains a granular adsorber (molecular sieve or activated charcoal) as a "getter" to collect any residual gas.

High Purity Germanium Detectors

Detector Cryostat

Loss of vacuum is a common problem. One reason this might happen is that the cryostat seals deteriorate over time.

Components of the gas in the cryostat might then plate out on the surface of the detector crystal. This could lead to a leakage current across the detector surface which would impair the detector resolution.

The resolution might be improved by re-evacuating the cryostat (possibly a 1-2 day process).

In some cases it might be necessary to “bake off” the impurities by heating the cryostat to 100 C (or so) as the latter is being pumped down.

High Purity Germanium Detectors

Detector Cryostat

The cryostat also encloses various electronic components including the high voltage filter, the high voltage shutdown, and part (the FET) or all of the preamplifier.

Cryostats completely enclosing the entire preamplifier are sometimes said to have “slim” or streamed designs.

An advantage of the slimline (or streamlined) systems is the smaller size of the hole required in the shield for the cryostat. This helps reduce background.

High Purity Germanium Detectors

Low Background Detectors

Most cryostat jackets are made of aluminum which can contain residual traces of Ra-226. Low background systems might replace aluminum with magnesium.

The end caps might be made from carbon fiber material or oxygen-free high conductivity (OFHC) copper. Other detector components might be made from high purity aluminum.

Since the electronic components inside the cryostat contain naturally occurring radionuclides (e.g., uranium series), they might be shielded from the detector (e.g., with old lead).

Activated charcoal might be used as the adsorber in the tailstock instead of molecular sieve.

High Purity Germanium Detectors

Detector Resolution

The resolution of a detector describes the width of the photopeaks. The narrower the peak, the greater the ability of the system to distinguish different gamma rays of similar energies.

The resolution depends on the photon energy: the lower gamma ray energy, the narrower the peak.

The resolution of a HPGe detector is usually expressed as the Full Width at Half Maximum (FWHM) for the 1332.5 keV peak of Co-60. It is expressed in keV. This contrasts with the resolution for a scintillation detector which is usually described as a percent relative efficiency for the Cs-137 peak.

High Purity Germanium Detectors

Detector Resolution cont.

HPGe detector resolutions at 1332.5 keV are usually in the 1.6 - 2.0 keV range.

It is also common to specify the resolution at 122 keV (Co-57). If the detector is capable of low energy spectroscopy, its resolution will also be specified at 5.9 keV (Mn x-ray).

All other things being equal, a p-type germanium detector has better resolution than an n–type detector.

The higher the detector efficiency (i.e., the larger it is), the poorer the resolution.

High Purity Germanium Detectors

Detector Resolution cont.

The FWHM of a Gaussian shaped peak, the best that is theoretically possible, completely describes its shape.

In the real world where perfection is not achieved, it is useful to provide additional parameters regarding peak shape, e.g.:

- full width at one tenth the maximum height (FWTM)
- full width at one fiftieth the maximum height (FWFM)

For a perfect Gaussian shape, the FWTM/FWHM ratio would be 1.83 and the FWFM/FWHM ratio would be 2.83.

High Purity Germanium Detectors

Detector Resolution cont.

Detector resolution should be monitored on a daily basis by recording the FWHM of the Co-60 1332.5 keV peak.

If a deterioration in the detector resolution is observed, it might be due to any number of causes. The most common might be a bad preamplifier or, as discussed earlier, a loss of vacuum in the cryostat.

To minimize the chance of this happening, the detector should be sent back to the manufacturer for maintenance every ten years or so.

Another possible reason for poor resolution is that the detector bias is too high. Dropping the voltage by 100 or 200 volts might be all that is necessary.

High Purity Germanium Detectors

Detector Efficiency

A germanium detector has a lower efficiency than a sodium iodide detector of equal size because the effective atomic number of NaI is higher than that of germanium.

However, this does not necessarily mean that the sensitivity of the NaI detector is better. The peaks in a HPGe spectrum might have fewer counts than those in a NaI spectrum, but they might be more easily detected because the counts are distributed in far fewer channels.

High Purity Germanium Detectors

Detector Efficiency

The most common way to describe an HPGE detector's efficiency is to specify its efficiency relative to that of a 3" x 3" NaI detector:

$$Relative\ efficiency = 100\ x\ \frac{Efficiency\ of\ HPGe\ detector}{Efficiency\ of\ 3''\, x\, 3''\ NaI\ \ detector}$$

The HPGe and NaI efficiencies are for the 1332.5 keV peak of a Co-60 point source 25 cm away from the detector.

The most common detector efficiency currently being manufactured is 50%.

High Purity Germanium Detectors

Detector Efficiency

Relative efficiency is used to compare one detector with another, not to quantify radioactive material.

The efficiency usually employed to quantify a gamma emitting radionuclide indicates the fraction of the gammas emitted by the source that produce a count in the photopeak.

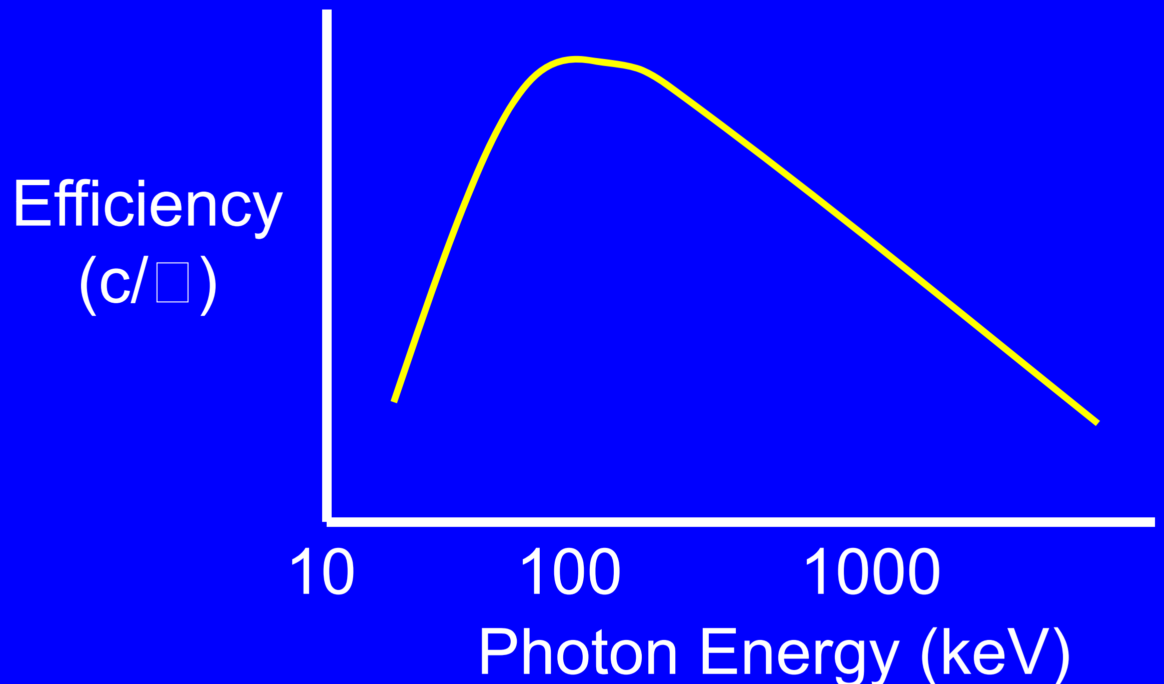
This efficiency depends on the:

- size and shape of the source
- source-detector distance
- source matrix which affects self absorption
- photon energy

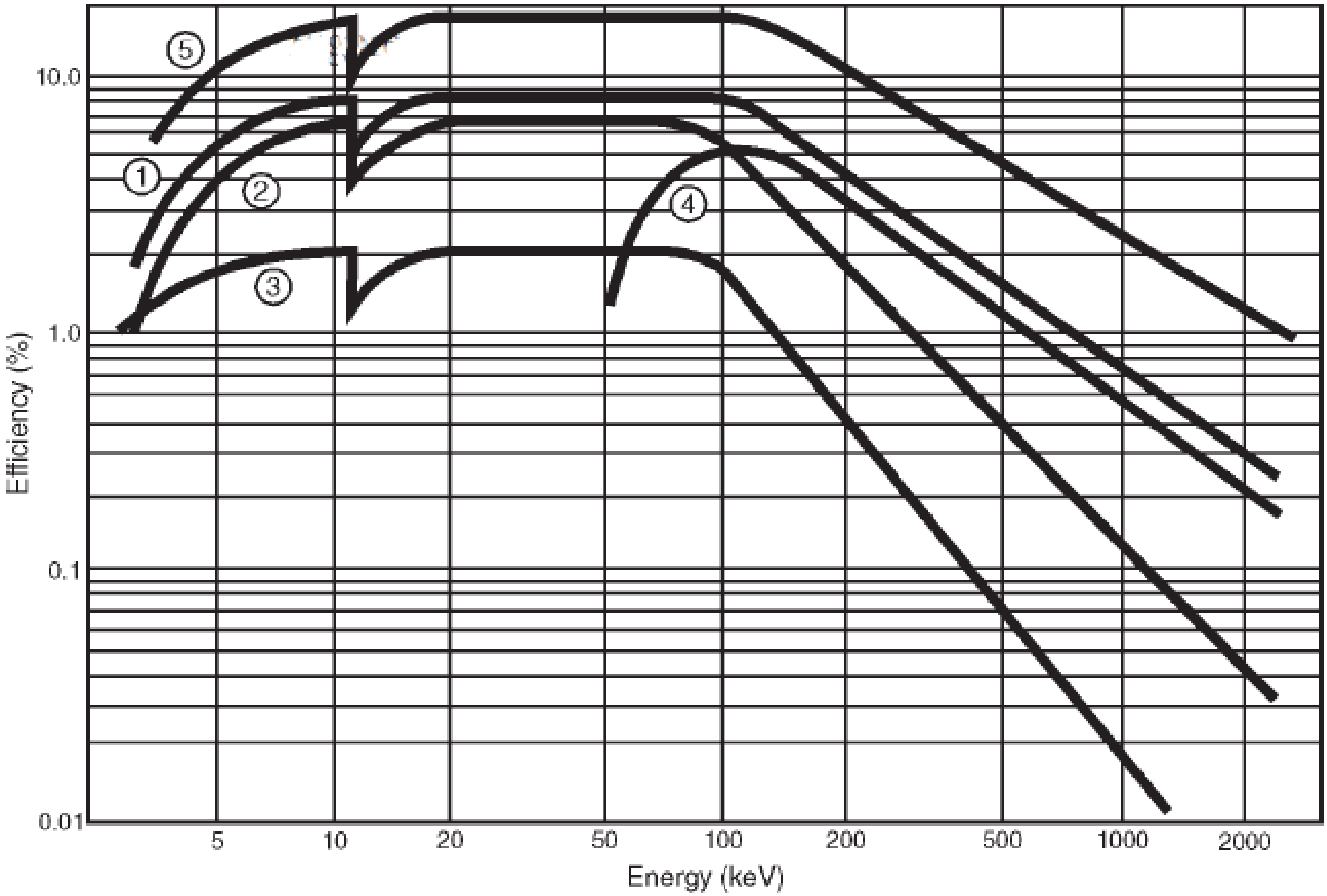
High Purity Germanium Detectors

Detector Efficiency

This curve shows the efficiency (counts per gamma) as a function of energy for a typical p-type coaxial detector.



The curves on the next page show efficiency as a function of energy for a number of different detectors.



Typical absolute efficiency curves for various Ge detectors
with 2.5 cm source to end-cap spacing

Code:

1. REGe, 15% Relative Efficiency
   XtRa, 15% Relative Efficiency
2. LEGe, 10 cm^2 x 15 mm thick
3. LEGe, 200 mm^2 x 10 mm thick
4. Coaxial Ge, 10% Relative Efficiency
5. BEGe, 5000 mm^2 x 30 mm thick

High Purity Germanium Detectors

Peak to Compton Ratio

Each photopeak on a spectrum has an associated Compton continuum. The latter increases the background at the lower energies and this results in poorer counting statistics and minimum detectable activities (MDAs).

To reflect the "size" of the Compton continuum associated with a given detector, manufacturers specify the peak to Compton ratio: ratio of the count at the center of the Co-60 1332 keV photopeak divided by the average counts per channel at the Compton edge between 1040 and 1100 keV.

The larger the peak to Compton ratio, the better. Bigger more efficient detectors have higher ratios than smaller detectors.

Example Specifications for HPGe Detector