Ionising Radiation Physics
Detectors II
Semiconductor and Scintillation Detectors

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Overview

- 6 hours on Detectors over the next 2 weeks

  DETECTORS I

  - Detector Fundamentals
  - Group Exercise
  - Gas Detectors

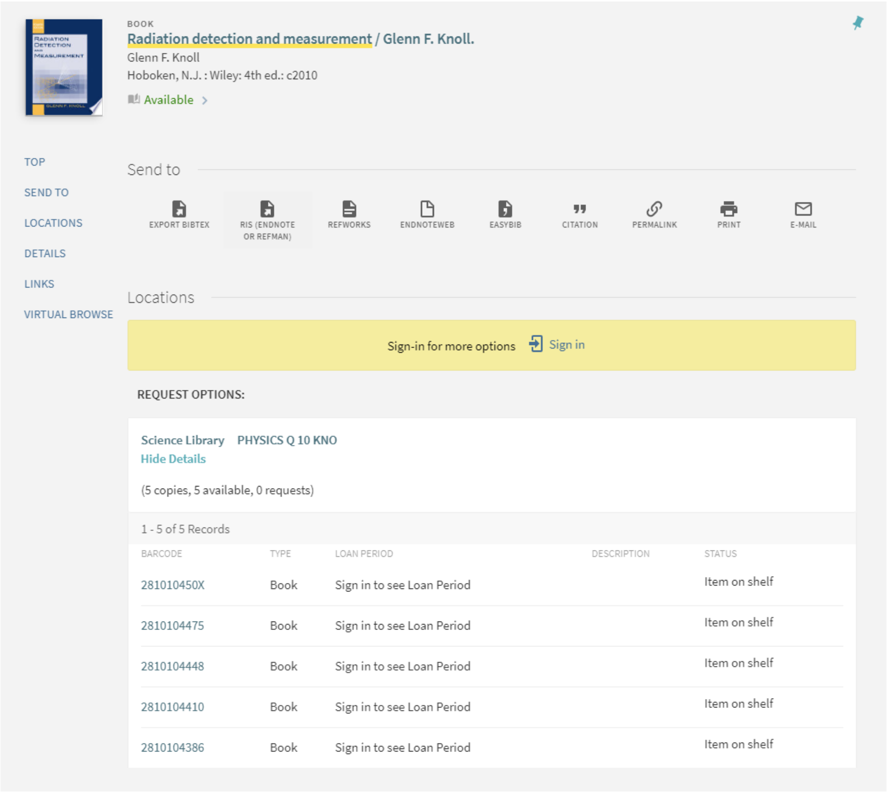
  DETECTORS II

  - Semiconductor Detectors
  - Group Exercise/Demonstration
  - Scintillation Detectors

Recommended Text

- *Radiation detection and measurement - Glen F. Knoll*

- Online (3rd Edition)
  - – http://users.lngs.infn.it/~dimarco/Radiation%20Detection%20and%20Measurement,%203rd%20ed%20-%20Glenn%20F.pdf
  - – https://phyusdb.files.wordpress.com/2013/03/radiationdetectionandmeasurementbyknoll.pdf



BOOK

Radiation detection and measurement / Glenn F. Knoll.

Glenn F. Knoll

Hoboken, N.J. : Wiley: 4th ed.: c2010

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READ IT!

Semiconductor Detectors

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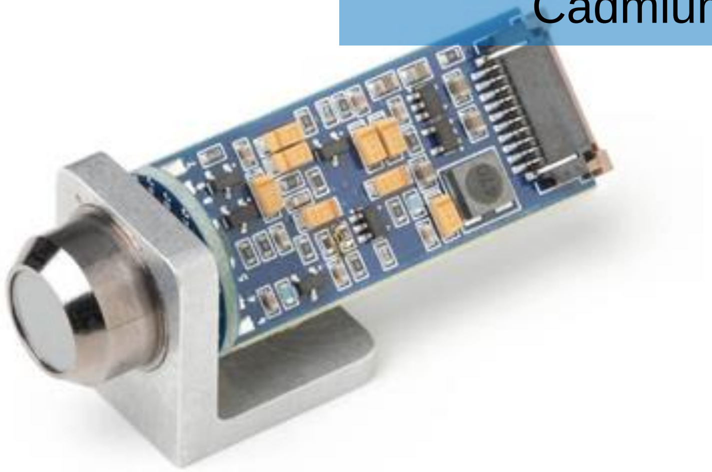
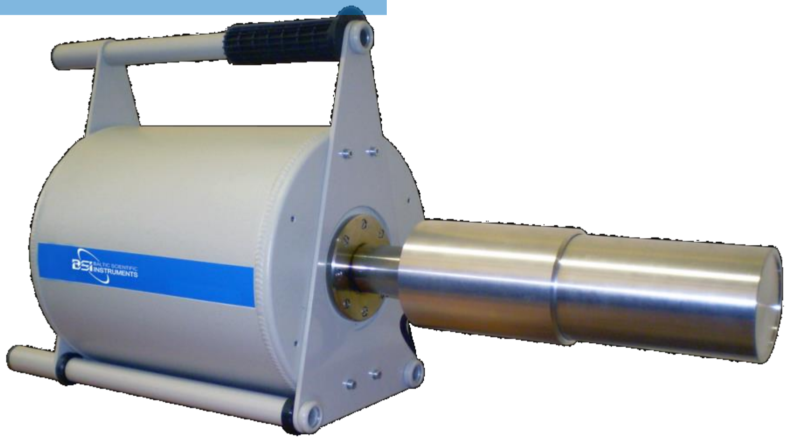
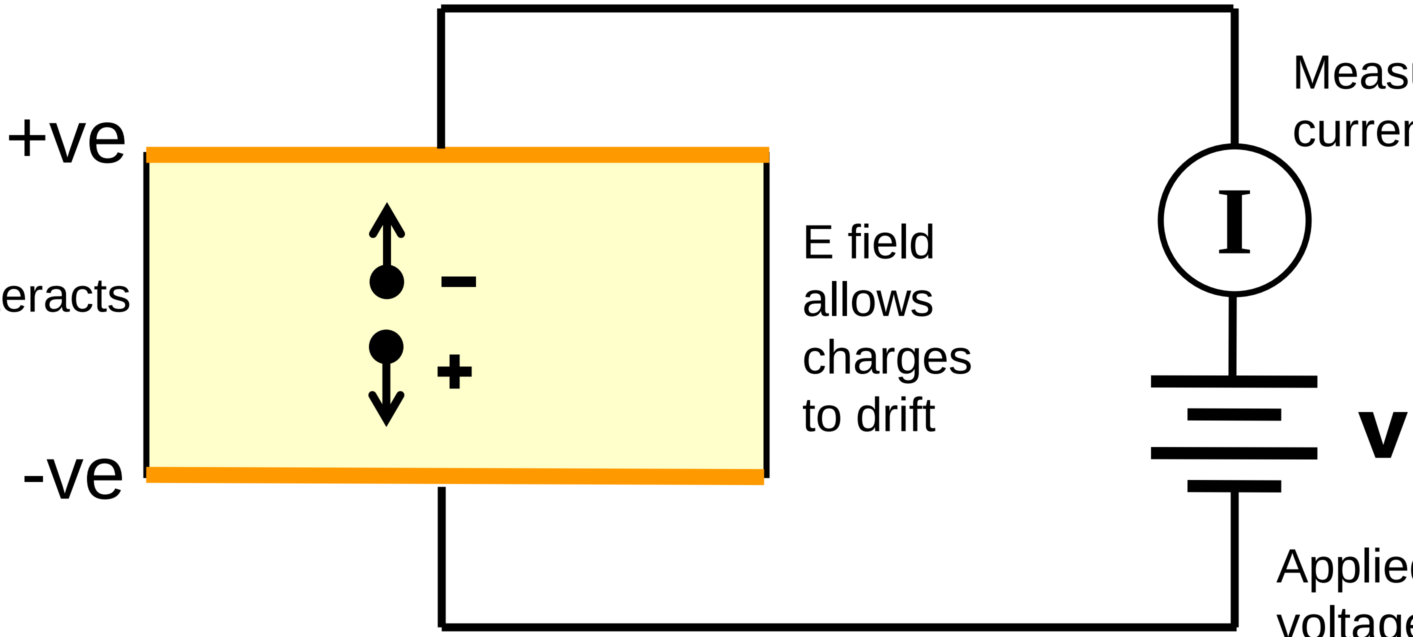
Typical semiconductor detector materials
Silicon
Germanium
Cadmium (Zinc) Telluride





Basic Detector



Radiation interacts
→ Ionisation

E field
allows
charges
to drift

Measure
current flow

Applied bias
voltage
100s-1000s V

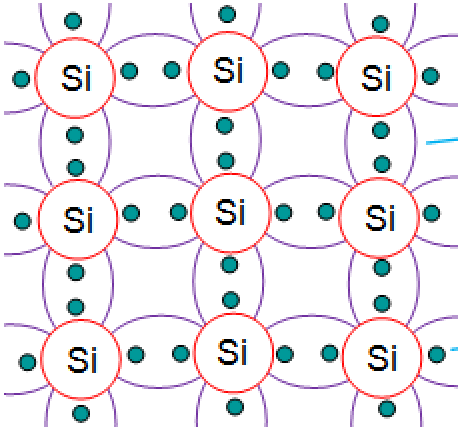
Semiconductor Detectors

- Disadvantage of gas detectors is their limited energy resolution
    - ~30 eV of energy required to produce 1 electron
    - poor statistics = limited energy resolution

- Semiconductor detectors generate a large number of charge carriers per event
    - <5 eV to produce an electron
    - good statistics = very good energy resolution

Electrons and Holes

Crystal structure of pure Si

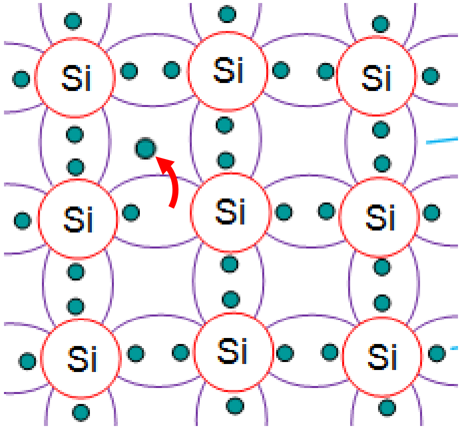


Electrons locked in covalent bonds

No electrons in partially filled shells

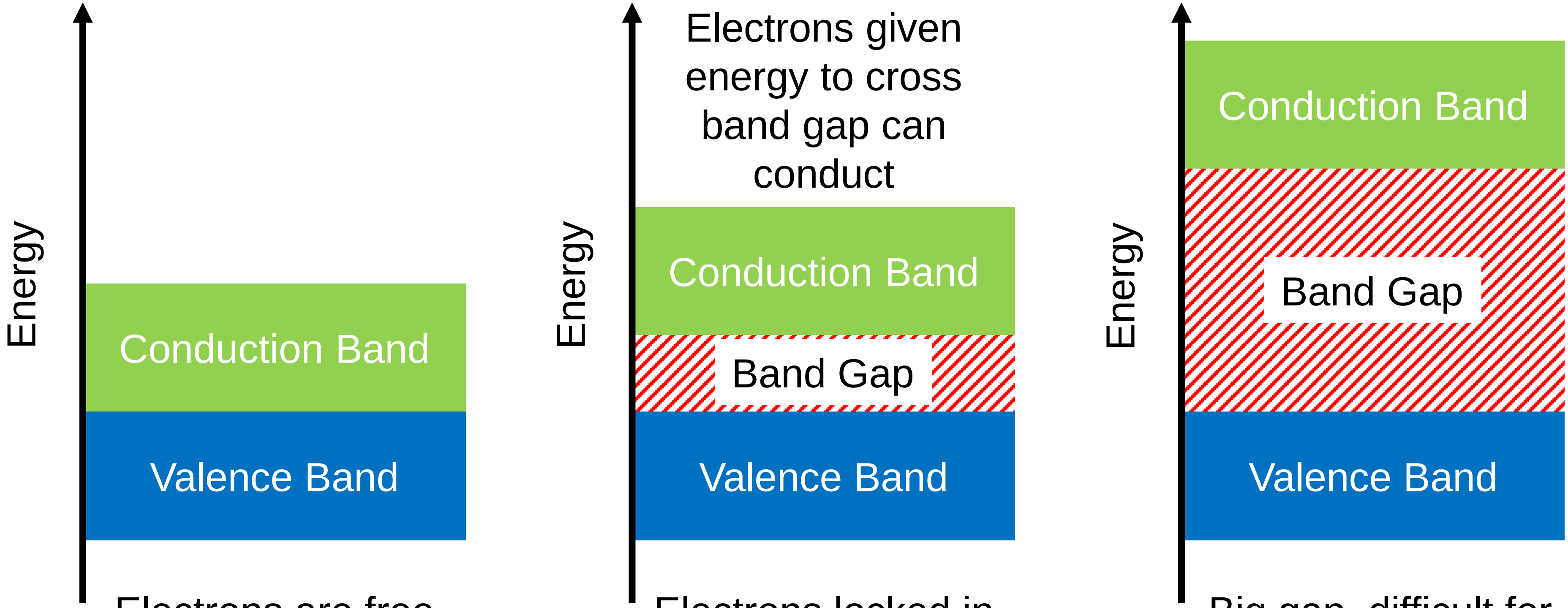
ENERGY

Electron can be promoted to a higher shell and can move between atoms



Leaves a hole in the bond

Band Model



Conductor (metal)

Energy

Conduction Band

Valence Band

Electrons are free to conduct always
$E_g = 0$ eV

Semiconductor

Energy

Electrons given energy to cross band gap can conduct

Conduction Band

Band Gap

Valence Band

Electrons locked in valence band
$E_g \approx 1$ eV

Insulator

Energy

Conduction Band

Band Gap

Valence Band

Big gap, difficult for electrons to jump
$E_g > 5$ eV

Band gaps for typical semiconductors

Material	Energy gap (eV)	
	0K	300K
Si	1.17	1.11
Ge	0.74	0.66
InSb	0.23	0.17
InAs	0.43	0.36
InP	1.42	1.27
GaP	2.32	2.25
GaAs	1.52	1.43
GaSb	0.81	0.68
CdSe	1.84	1.74
CdTe	1.61	1.44
ZnO	3.44	3.2
ZnS	3.91	3.6

Effect of Temperature

- Fully filled valence band at T = 0 K
- For T > 0 K thermal energy can promote electron to conduction band
- Probability per unit time of thermally generated electron-hole pair

$$p(T) = CT^{2/3} exp\left(-\frac{E_g}{2kT}\right)$$

T = absolute temperature
E_g = band gap energy
k = Boltzmann constant
C = constant characteristic of material

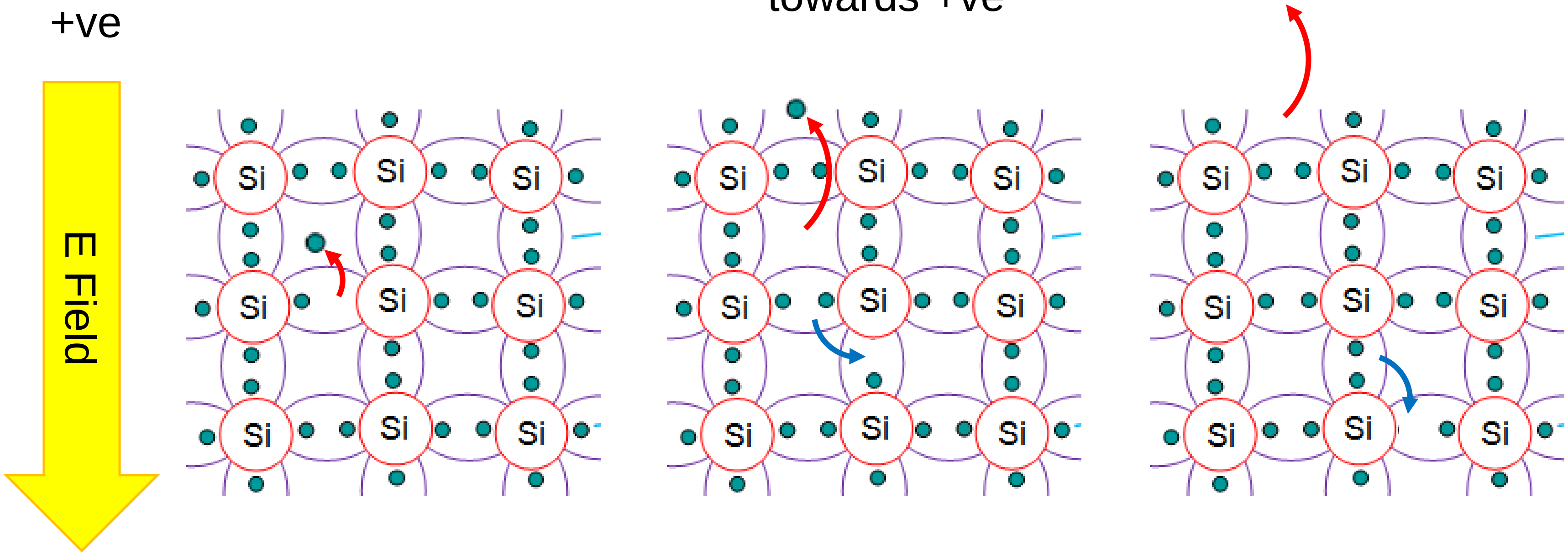
- Depending on E_g, detector might need to be cooled to be useful

Effect of Electric Field

Electron move along the field towards +ve

Electron collected at +ve contact

+ve



−ve

Electron-Hole pair created

Hole jumps between bonds towards −ve

Hole eventually replenished by electron at −ve contact

Charge Carrier Mobility

- Without E field carriers have random thermal velocity
- E field causes carriers to move with a net drift velocity parallel to the direction of the field

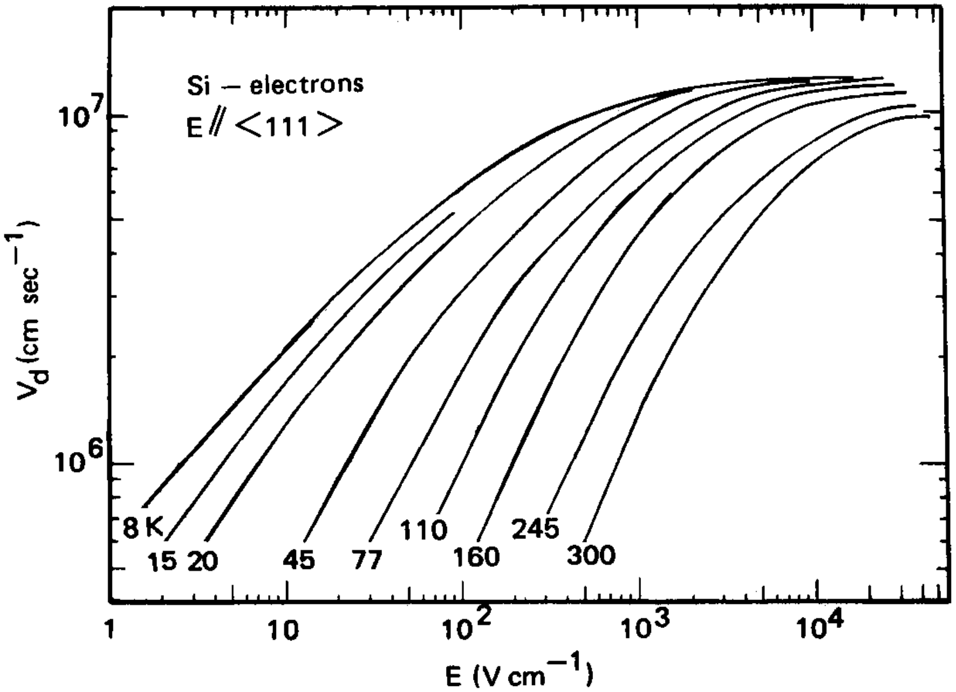
$$v_h = \mu_h E$$
$$v_e = \mu_e E$$

$v_{h/e}$ = velocity of hole/electron
$\mu_{h/e}$ = mobility of hole/electron
E = electric field magnitude

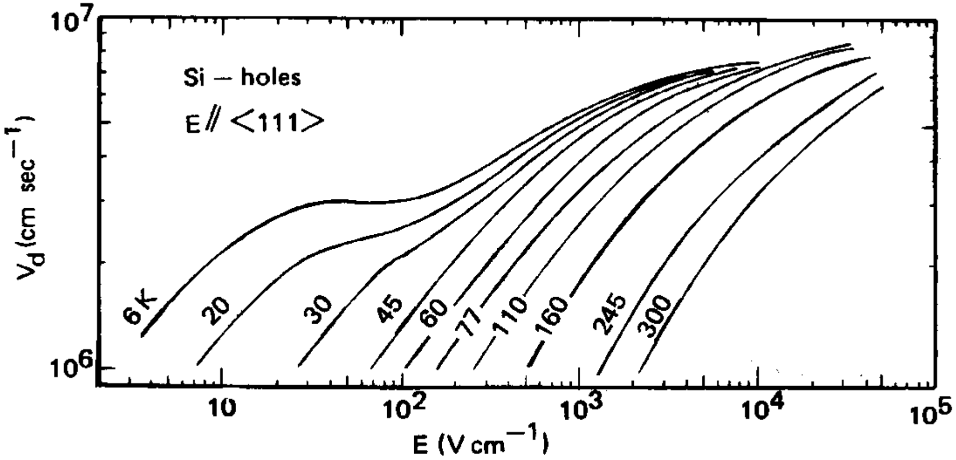
- Mobility of holes and electrons is similar
- A high E field saturation drift velocity is reached
- Total motion is a combination of thermal and drift velocities

Drift Velocity from E-field in Silicon

electrons

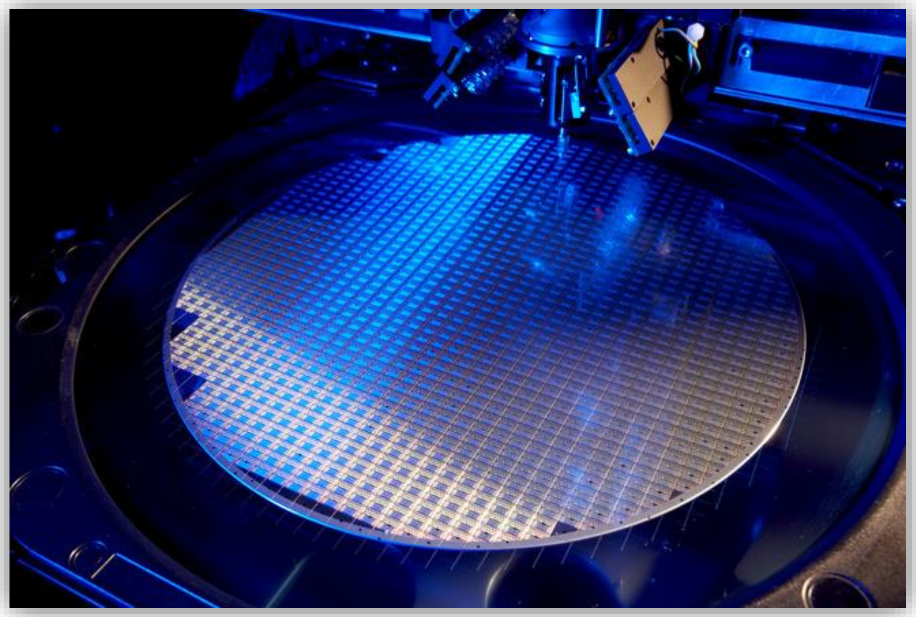


holes



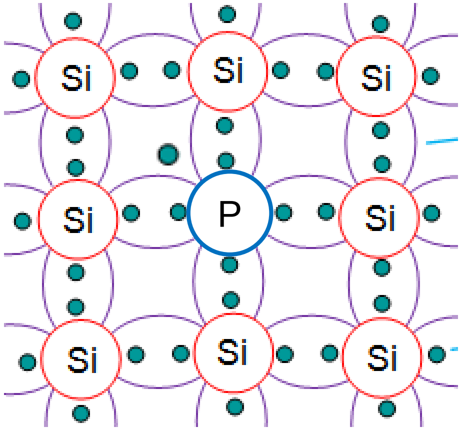
Real Semiconductors

- Intrinsic semiconductor – one electron in conduction band ≡ one hole in valence band
- ‘Impossible’ to produce in practice
- Real semiconductors have some residual impurities

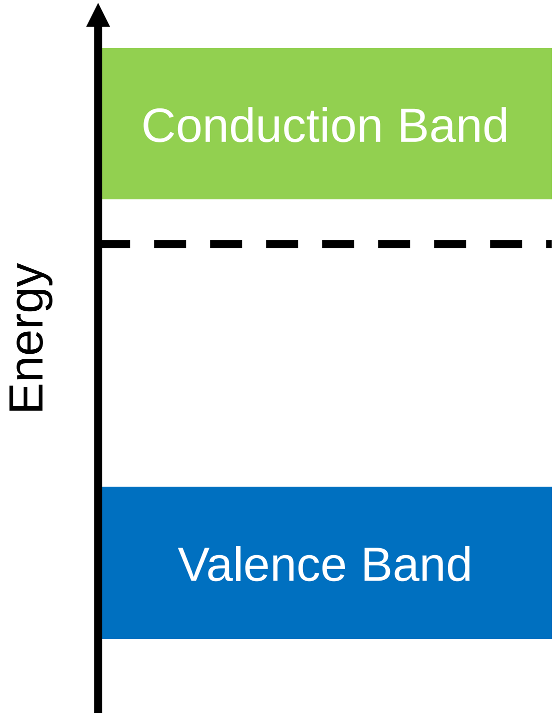


n-type Semiconductors

n-type
additional electrons



Addition of pentavalent impurity to tetravalent silicon
(phosphorus has one more outer electron than silicon – excess electron)



Conduction Band

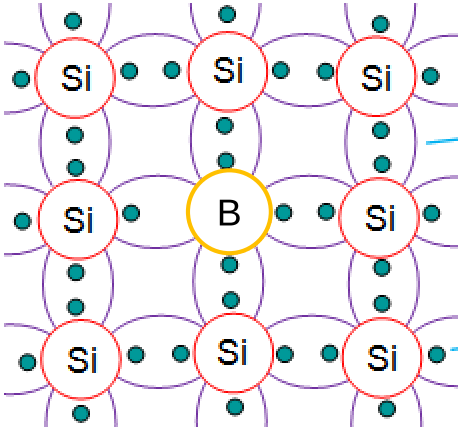
Donor levels

Energy

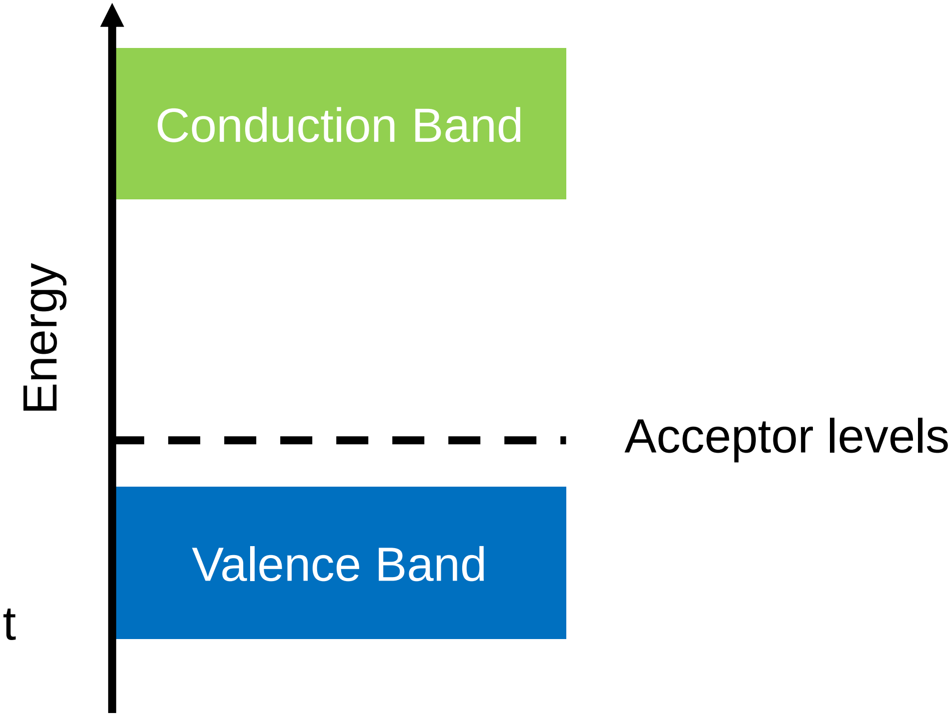
Valence Band

p-type Semiconductors

p-type
additional holes



Addition of trivalent impurity to tetravalent silicon
(boron has one less outer electrons that silicon – leaves a hole)



Energy

Conduction Band

Acceptor levels

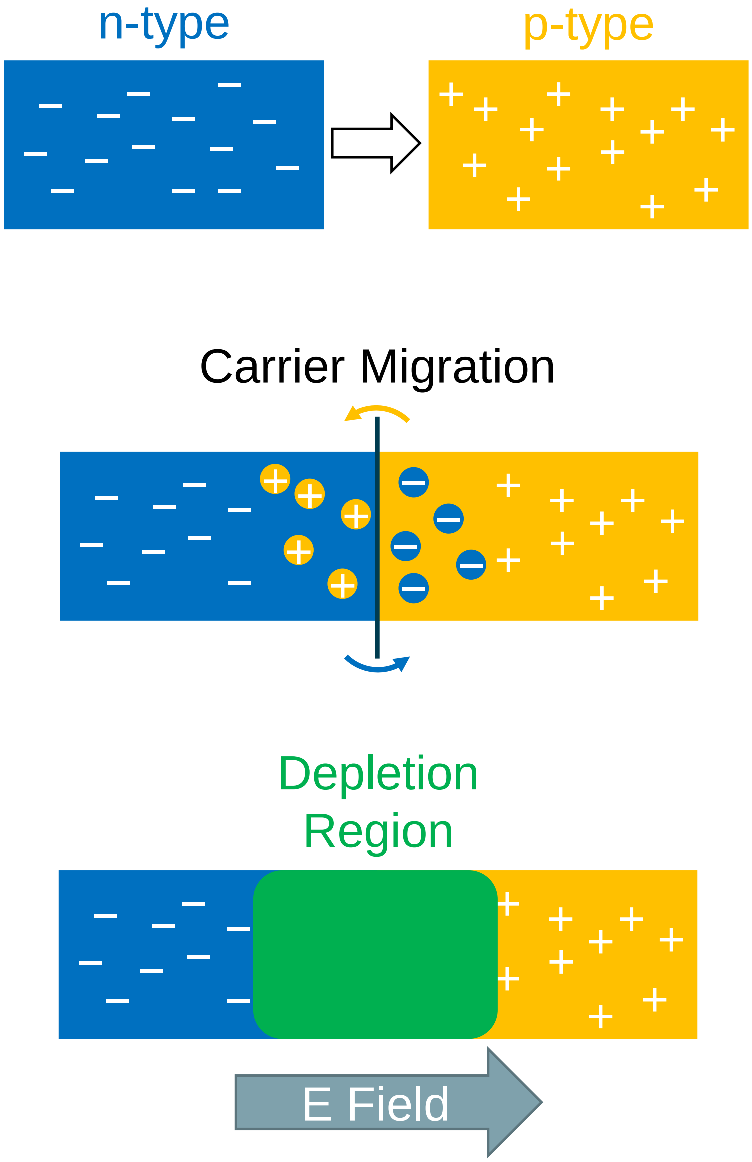
Valence Band

n-type / p-type Comparison

n-type	p-type
Extra electron bound to parent atom (due to +ve nucleus) but energy required to promote to conduction band is very small and thermal excitation means parent atom is ionised most of the time.	Holes exist without the need to promote an electron to the valence band. These are called acceptor sites.
Holes not created when extra electron goes to conduction band.	Energy required to promote an electron from the valence band to fill the extra holes is small and the acceptor sites are occupied most of the time.
When electron hole pair is produced, holes is filled quickly due to excess electrons so that conductivity is determined exclusively by flow of electrons.	Leave excess holes in valence band and recombination probability between conduction electrons and hole is increased.
Electrons are **majority carriers**.	Electrons are **minority carriers**.

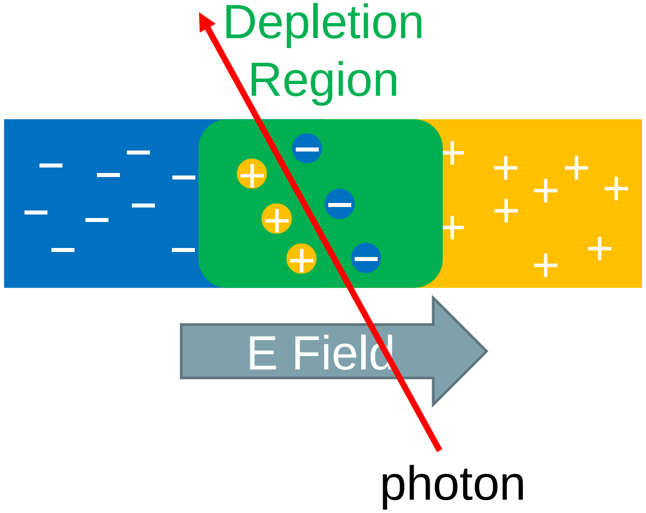
Semiconductor Junction Detector

- Both n- and p-type electrically neutral
- ‘Join’ n-type to p-type
- Charge carriers migrate → E field
- E field resists further migration
- Depletion region
  - Vacant donor sites
  - Filled acceptor sites



Semiconductor Junction Detector

- Charge carrier created by ionisation are rapidly swept out of the depletion region
- Moving charge constitutes basic electrical signal
- Poor performance due to small E field
- Apply additional (reverse) bias to increase field strength

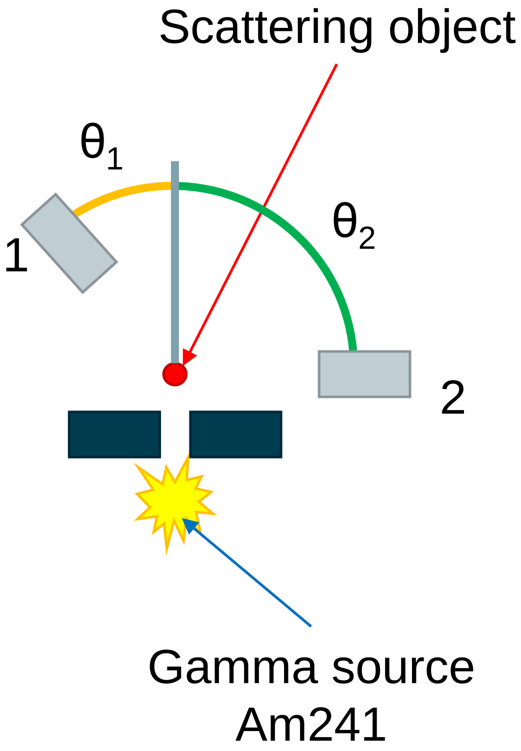


Semiconductor Detector Summary

- Many charge carrier per unit energy → good energy resolution
- Creation of charge carries depends on band structure
- ‘Impossible’ to create pure semiconductor crystal
- Energy levels modified by dopants

Group Task

- Split into groups
- Experiment setup as shown
- Use the relationships below to determine photopeak energy
- Use spectra to calculate the angles θ_1 and θ_2



HPGe: $\text{ENERGY} = 0.2895 \times \text{ADU} - 0.2346$

CdTe: $\text{ENERGY} = 0.0919 \times \text{ADU} - 0.3957$

Scintillation Detectors

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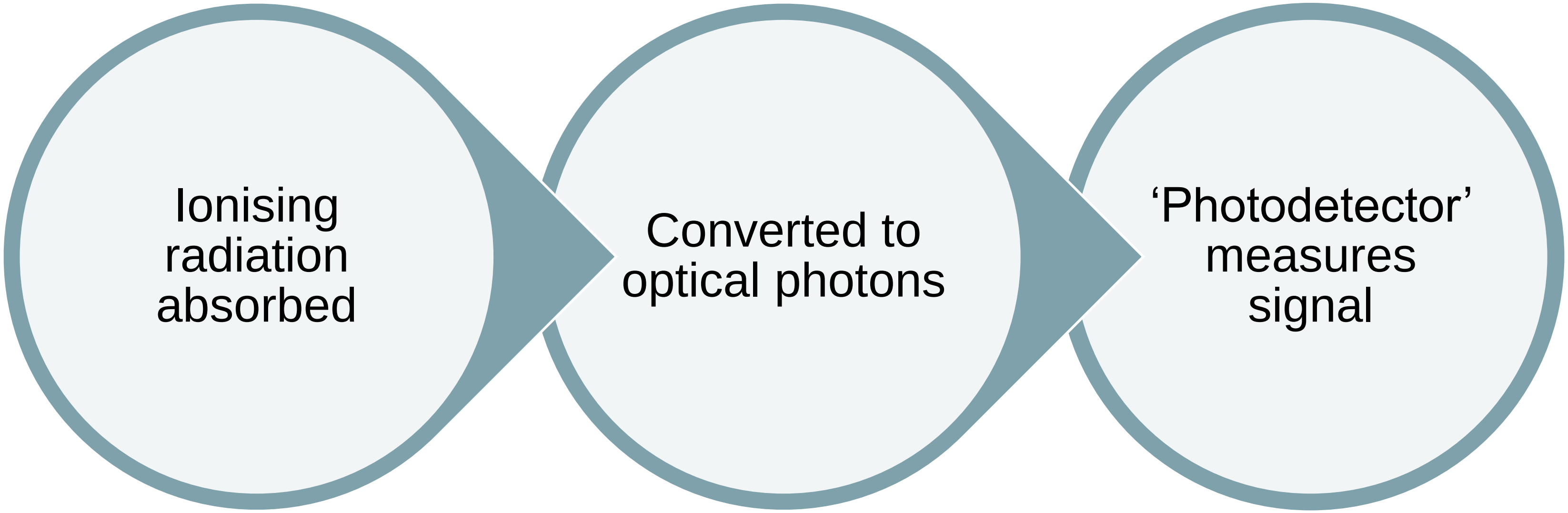
Basic Principle



Ionising radiation absorbed

Converted to optical photons

‘Photodetector’ measures signal

- Scintillator

- PMT
- Photodiode
- CMOS/CCD

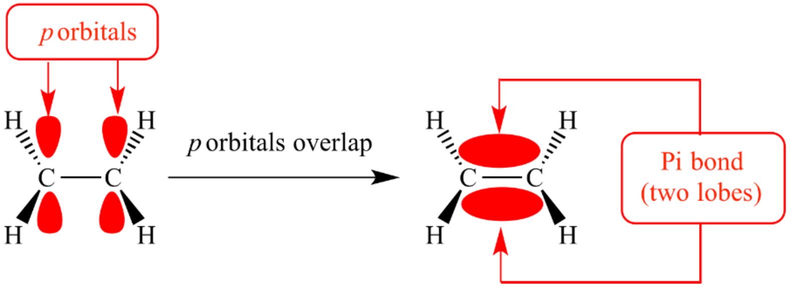
Stage I: Scintillator Materials

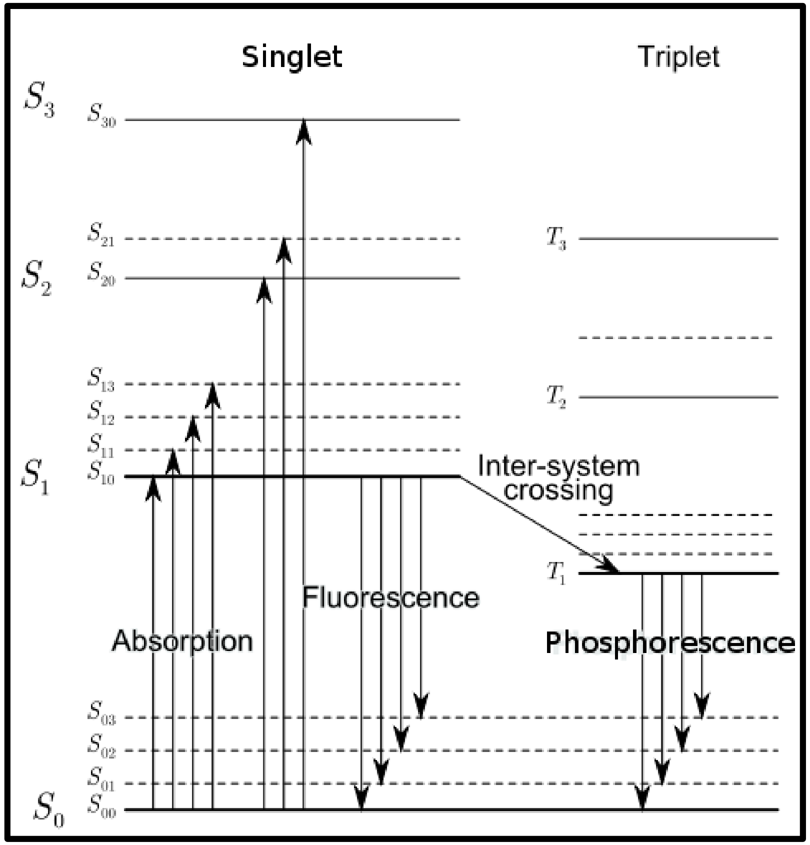
Types of Scintillators

ORGANIC	INORGANIC
Low Z and ρ	Range of Z and ρ
Inexpensive	Expensive
Fast	Good light output

Organics

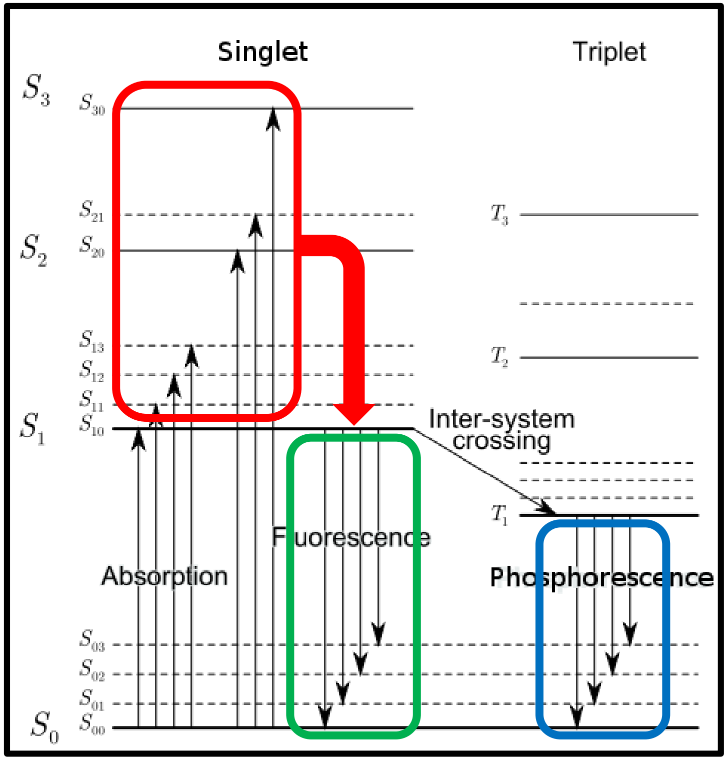
- ‘Free’ valence electrons form ‘molecular orbitals’ – π electronic structure
- Excitation due to absorption of KE of nearby charged particle
- Raised to S_{1x}, S_{2x}, S_{3x}, etc.





Relaxation Processes

- Non-radiative
  - – Excited molecules relax to S_{10}
  - – Almost instantaneous (ps)
- Fluorescence
  - – Transition back to S_{0x} states
  - – Fast (ns)
- Phosphorescence
  - – Inter-system crossing ($S_1 \rightarrow T_1$)
  - – Slow since T_1 more long-lived (up to ms)
  - – Transition of T_1 back to S_{0x}



Phases

Solid

- (Poly)crystalline
- Fragile
- Directional efficiency

Liquid

- Dissolve scintillator in solvent
- Large volume possible
- Intimate contact with target

Plastic

- Polymerise solvent – ‘solid liquid’
- Robust
- Machineable

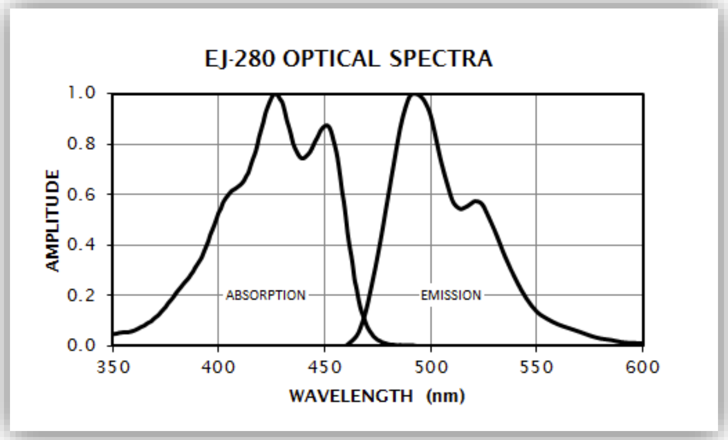
Gas

- Anthracene
- Possible – maybe not so useful

Waveshifter

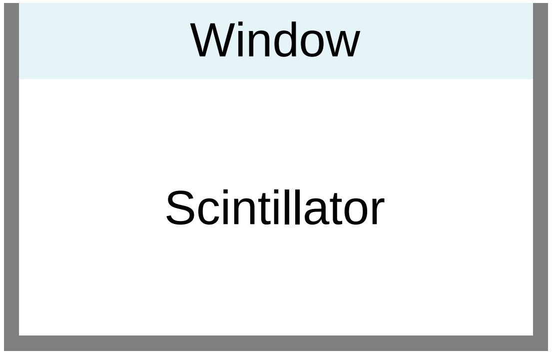
- Function
  - Absorbs primary scintillant and reradiates at longer wavelength
  - Added to liquid and plastic (prior to polymerisation)

- Purpose
  - To more closely match emission to sensitivity of photodetector



Inorganics

- Crystalline atomic structure
- Powder or bulk solid
- Encapsulation
  - – Environmental protection
  - – Containment (health hazard)
  - – Light tight
- Scintillation depends on electronic band structure

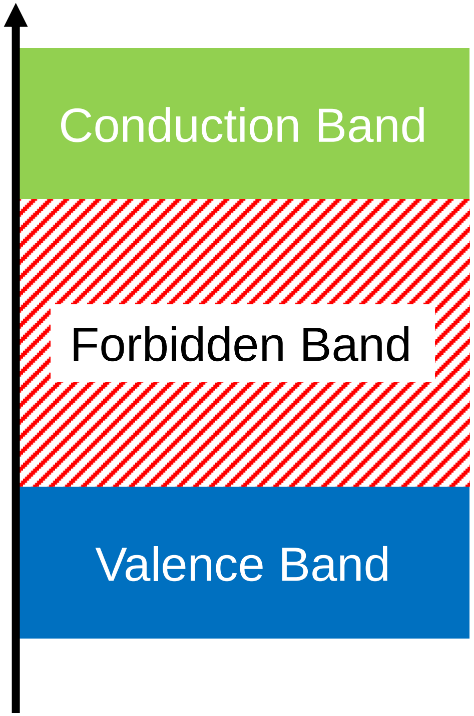


Aluminium/steel can with diffuse reflective inner surface

Examples

Scintillator	Light yield (photons/keV)	Light ouput(%) of NaI(Tl) bialkali pmt	Temperature coefficient of light output(%/C) 25°C to 50°C	1/e Decay time(ns)	Wavelength of max emission lm(nm)	Refractive index at lm	Thickness to stop 50% of 662 keV photons (cm)	Thermal expansion (/C)x10^{-6}	Density g/cm^3	Hygroscopic	Comments
$LaBr_3$(Ce+Sr)	73	190	0	25	385	~2.0	1.8	8	5.08	yes	Ultimate energy resolution (2.2% @ 662keV)
$LaBr_3$(Ce) BrilLanCe™ 380	63	165	0	16	380	~1.9	1.8	8	5.08	yes	General purpose, excellent energy resolution
CLLB $Cs_2LiLaBr_6$(Ce)	43	115		180 1080	420	~1.85	2.2	--	4.2	yes	Dual Gamma-Neutron detection, excellent
NaI(Tl)	38	100	-0.3	250	415	1.85	2.5	47.4	3.67	yes	General purpose, good energy resolution
NaI(Tl+Li)	35	100	-0.3	230. 1.1µs 240, 1.4µs	419	1.85	2.5	47.4	3.67	yes	Neutron-Gamma Scintillator
$LaCl_3$(Ce) BrilLanCe™ 350	49	70-90	0.7*	28	350	~1.9	2.3	11	3.85	yes	General purpose, good energy resolution
CsI(Na)	41	85	-0.05	630	420	1.84	2	54	4.51	yes	High Z, rugged
LYSO $Lu_{1.8}Y_{.2}SiO_5$(Ce)	33	87	-0.28	36	420	1.81	1.1	--	7.1	no	Bright, high Z, fast, dense, background from ^{176}Lu activity
CdWO4	12-15	30-50	-0.1	14000	475	~2.3	1	10.2	7.9	no	Low afterglow, for use with photodioides
CaF2(Eu)	19	50	-0.33	940	435	1.47	2.9	19.5	3.18	no	Low Z, α & β detection
CsI(Tl)	54	45	0.01	1000	550	1.79	2	54	4.51	slightly	High Z, rugged, good match to photodiodes
BGO	8 - 10	20	-1.2	300	480	2.15	1	7	7.13	no	High Z, compact detector, low afterglow
YAG(Ce)	8	15	--	70	550	1.82	2	~8	4.55	no	β-ray, X-ray counting, electron microscopy
CsI(Pure)	2	4-6	-0.3	16	315	1.95	2	54	4.51	slightly	High Z, fast emission
BaF2	1.8	3	0	0.6-0.8	220(195)	1.54	1.9	18.4	4.88	slightly	Fast component (subnanosecond)
	10	16	-1.1	630	310	1.50	1.9	18.4	4.88	slightly	Slow component
ZnS(Ag)	~50	130	-0.6	110	450	2.36	--	--	4.09	no	Coated on BC-400 or acrylic for α detection

Band Structure - Reminder



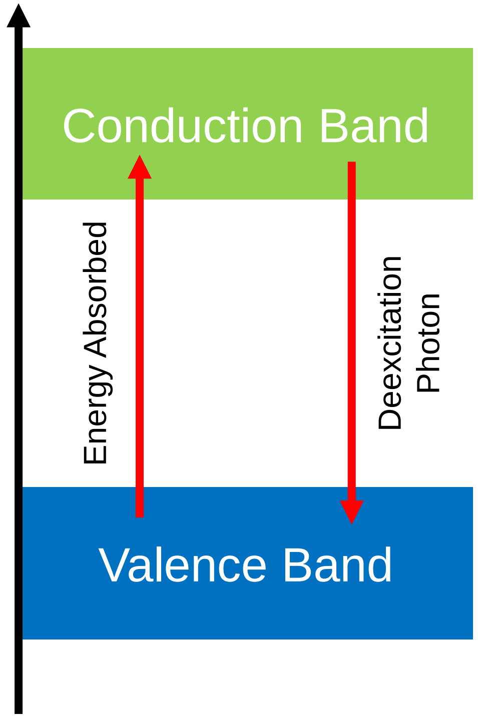
Electrons allowed to move through lattice

Electrons not permitted here in pure crystal

Electrons bound at lattice sites

Scintillation Process

- Absorption → elections excited to conduction band
- Scintillation → emission following relaxation
- Direct relaxation (CB to VB) → inefficient, wrong energy (not visible)

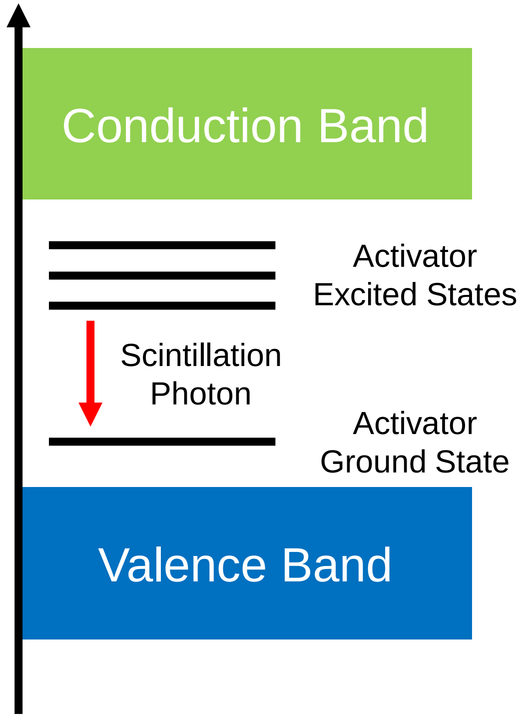


PROBLEM: WHAT DO WE DO?

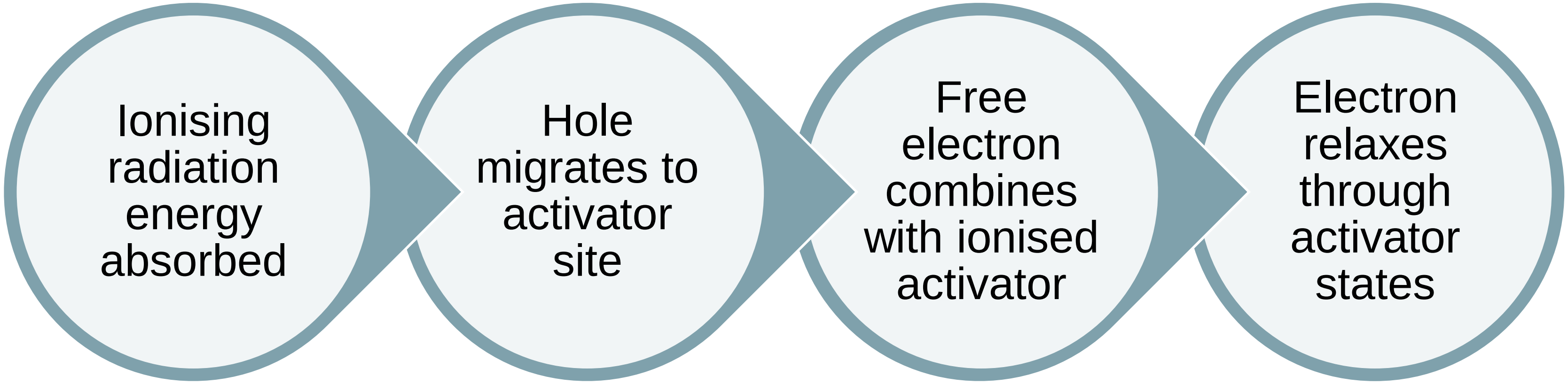
Scintillation Process

- Add small amount of impurity called ACTIVATOR

- Creates special sites in the lattice with modified band structure
- New states within the forbidden band for relaxation path
- Smaller transitions → optical photons



Scintillation Process



Ionising radiation energy absorbed

- Electron promoted to conduction band and leaves hole in valence band

Hole migrates to activator site

- Quickly ionises activator because ionisation energy is lower than normal lattice site

Free electron combines with ionised activator

- Electron move through lattice in conduction band until it encounters an ionised activator

Electron relaxes through activator states

- Emits optical photon during deexcitation back to valence band

A single ionising radiation (photon or particle) event creates many electron-hole pairs. The mean life-time of the activator excited sates is ~10^{-7} s. Electron migration is much faster so all excited impurity sites are essentially created at once. Deexcitation occurs on the time scale of the mean life-time.

Competing Processes - Phosphorescence

- Electron captured in activator excited state whose transition to the ground is forbidden
- Energy is required to move electron to an excited state with permitted route to ground
- One source of energy is thermal
- Optical photon is then released but is delayed compared to ‘normal’ emission.
- This SLOW component is phosphorescence, sometimes called “afterglow”

Competing Processes – Quenching

- Electron captured at an activator site which has non-radiative dexciation pathway
- Energy lost by vibration, etc.
- No optical photon is generated
- Not useful!

Stage II: Photodetectors

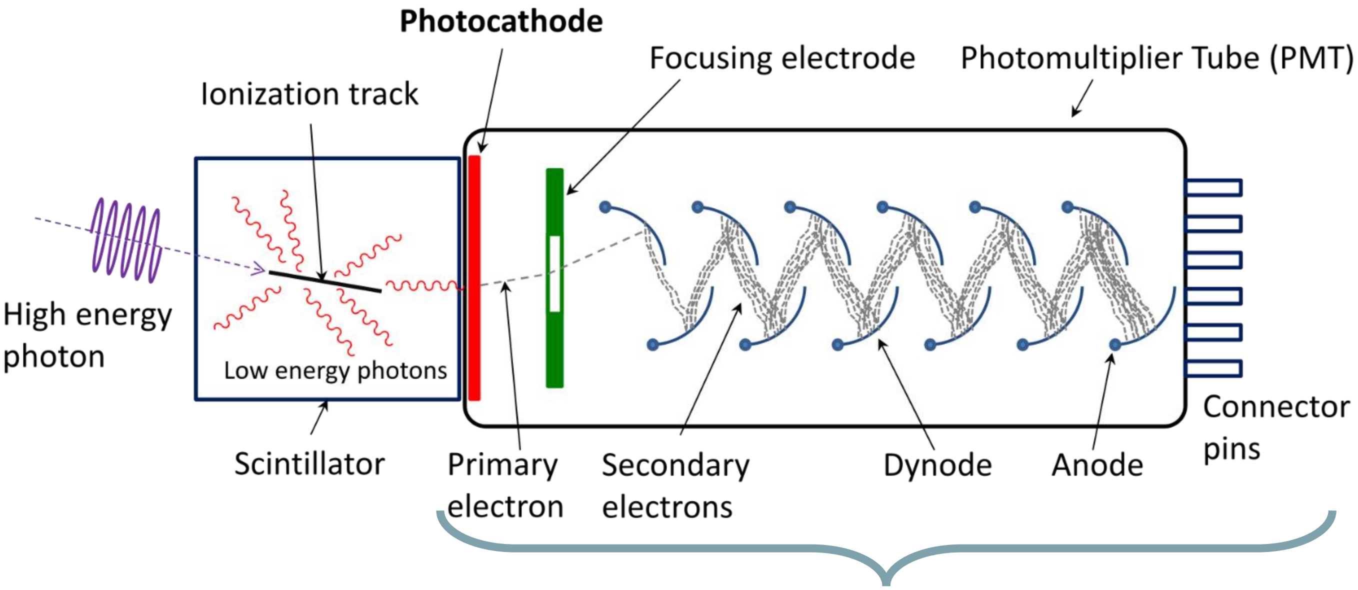
Types of Photodetectors

- Need some way of ‘recording’ the optical light output from scintillator

Photomultiplier Tubes	Solid State
• Very sensitive • Well understood • Fragile	• Mass produced • Scalable • Robust

Photomultiplier Tube (PMT)

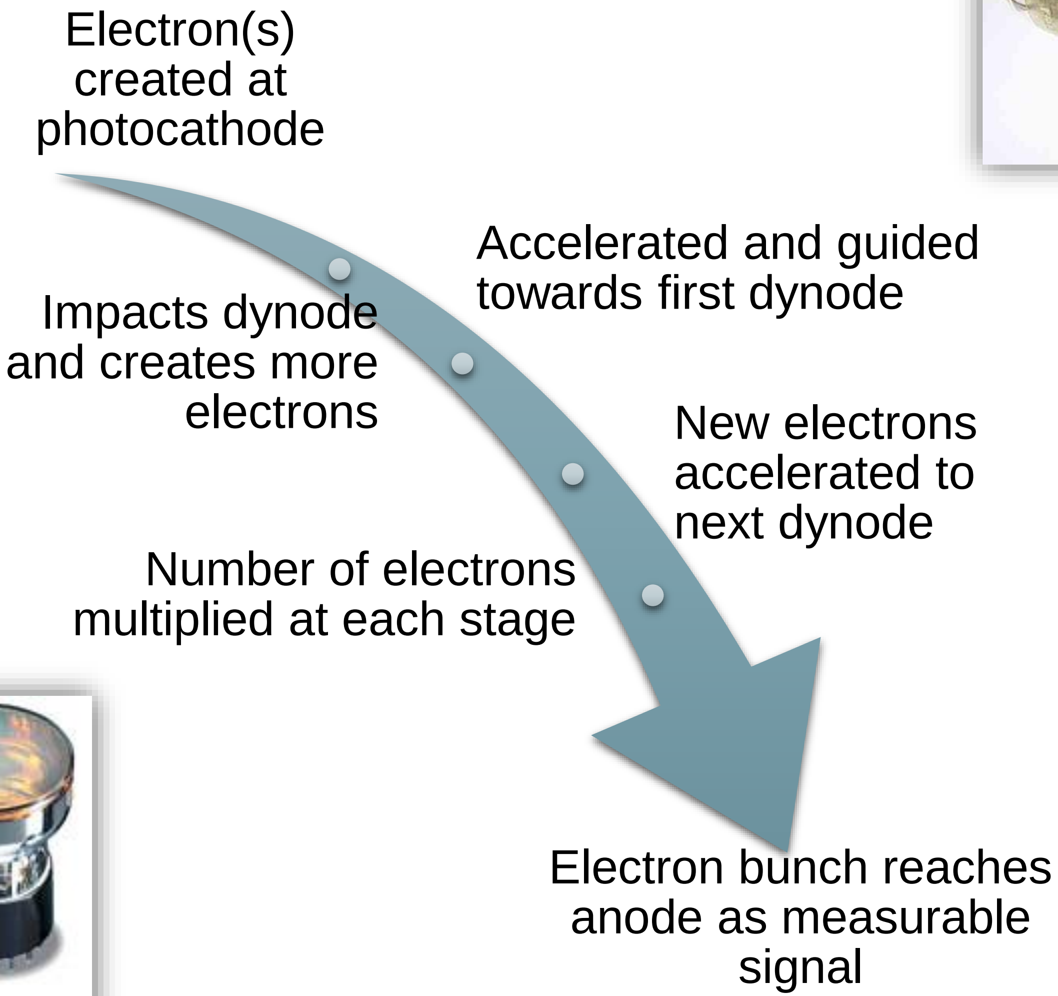
- Sensitive optical photon measurement device



PMT

- High voltage between anode and cathode, divided between dynodes

PMT Process



Electron(s) created at photocathode

Accelerated and guided towards first dynode

Impacts dynode and creates more electrons

New electrons accelerated to next dynode

Number of electrons multiplied at each stage

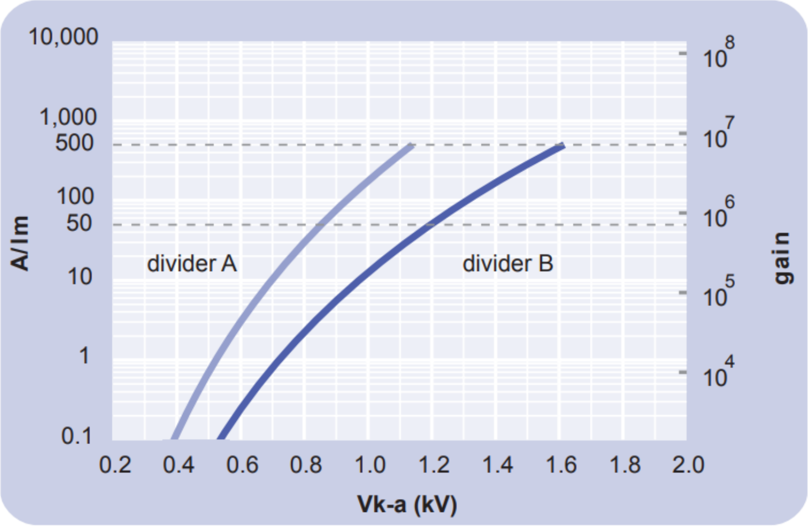
Electron bunch reaches anode as measurable signal

Coupling

- Maximise efficiency of optical photon transfer (scintillator → photocathode)
- Changes in refractive index along photon path must be minimised
- Typically use coupling compound to ‘mount’ the scintillator
- Common to use ‘light guide’ where scintillator and PMT cannot be co-located

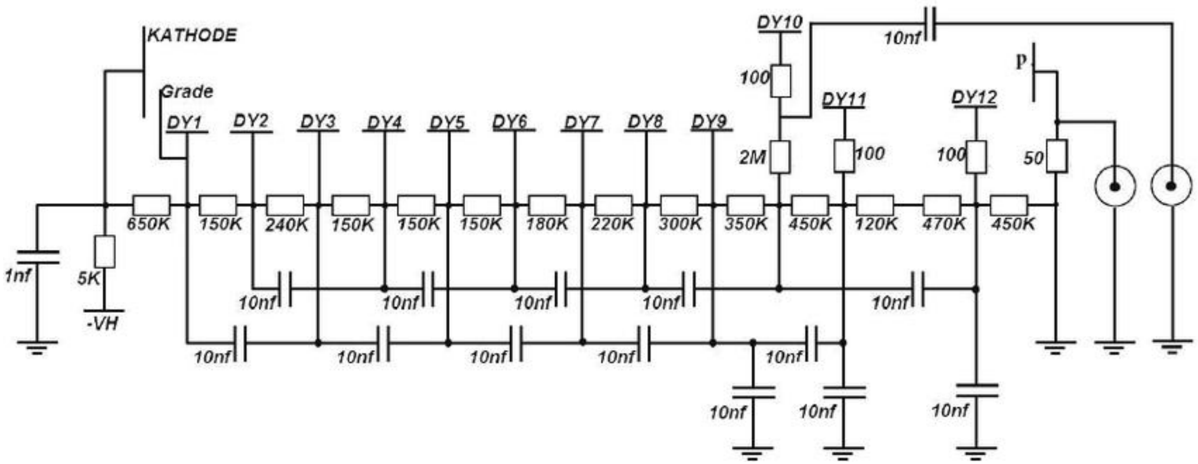
Gain

- Amount of multiplication is controlled by the HV
- Almost any voltage can be used but PMTs for this application typically designed for few 100 to few 1000 V
- Alter to match application and hardware – that's another story!



Divider

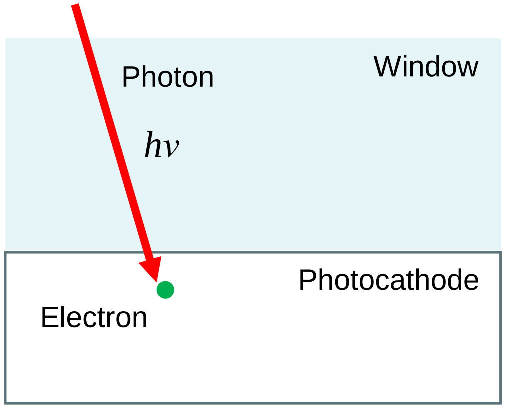
- HV is split between the dynodes to form multiplication chain
- Essentially a large potential divider
- Change resistor values to alter behaviour (e.g. make k-d1 voltage bigger to help charge collection)



Photocathode

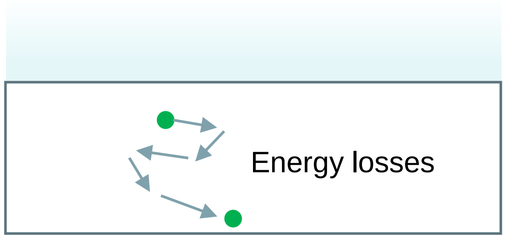
Absorption of scintillation photon

Initial electron energy equal to photon energy



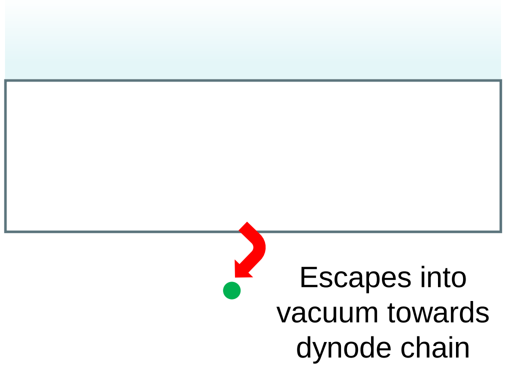
Migration through the photocathode

Energy lost dues to electron-electron interactions



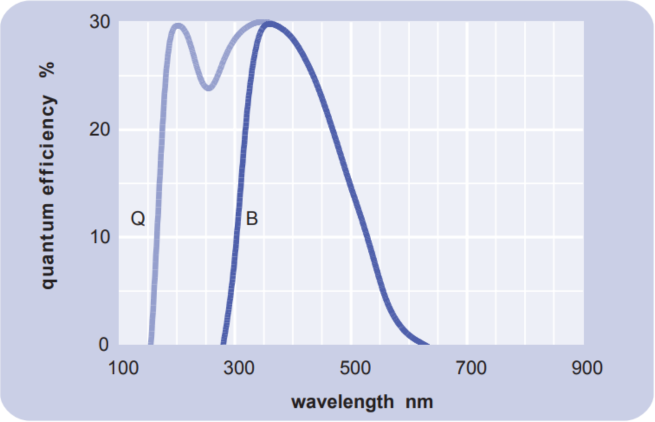
Electron escape from surface

Must have energy at least equal to work function of photocathode



Photocathode

- Thin layer on inside of PMT window
- Photocathode materials
  - Bialkali (Sb-Rb-Cs), multialkali (Na-K-Sb-Cs), GaAs, Ag-O-Cs, Sb-Cs, InGaAs, Cs-Te, Cs-I
- Window-photocathode combination
  - Bialkali on borosilicate: 300-600 nm
  - Bialkali on quartz: 150-600 nm (good for UV emitters)



Solid State Photodetectors

- Semiconductors pn junctions
- Band structure – AGAIN!
- Two main types
  - Conventional photodiode – no internal gain, simple electron-hole pair collection
  - Avalanche photodiode – internal gain due to applied electric field

Scintillator Detectors Summary

- Two stage process
  - Radiation converted to light
  - Light collected by photodetector
- Two scintillators
  - Organic
  - Inorganic
- Readout sensor must be match to scintillator output