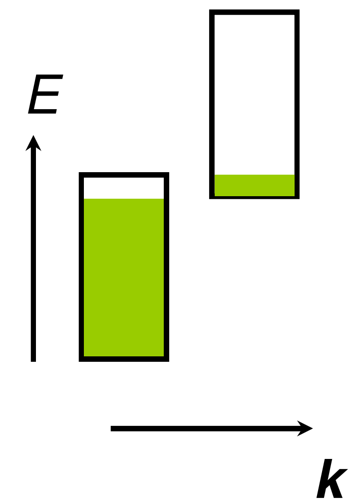
In This Lecture:

- Introduction to Semiconductors

Classification of Electronic Materials

METALS	SEMICONDUCTORS	INSULATORS
• Have very low resistivities (~10^{-6} Ωcm). • Resistance is difficult to alter or tailor.	Have resistivities that can be altered by up to 10 orders of magnitude by doping or external biases.	Have extremely high resistivities. It is difficult to alter the resistivity through doping or external fields.
⇕ because	⇕ because	⇕ because
Highest occupied energy band is partially filled with electrons.	Highest occupied energy band (valence band) is completely filled with electrons at low temperature. Next band (conduction band) is empty.	High bandgap between valence band (filled) and conduction band (empty) is large ($\gtrsim$4 eV).

Semimetals



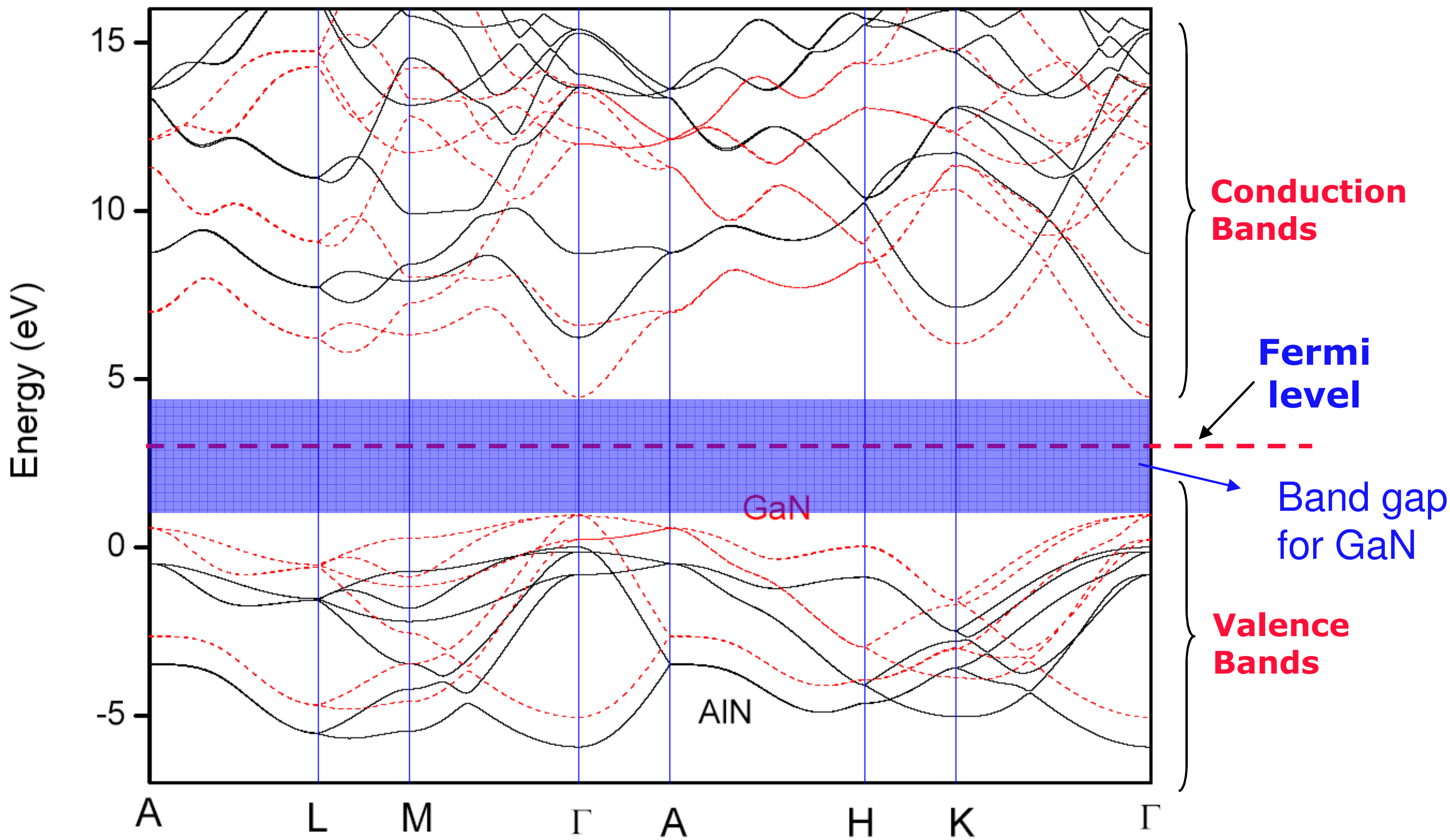
e.g., Bi, Sb, As, HgTe, HgSe

SEMICONDUCTORS: • Conductivity of the material can be altered (in times as fast as 1 ps).
• Optical properties (absorption coefficient, refractive index) can be altered.

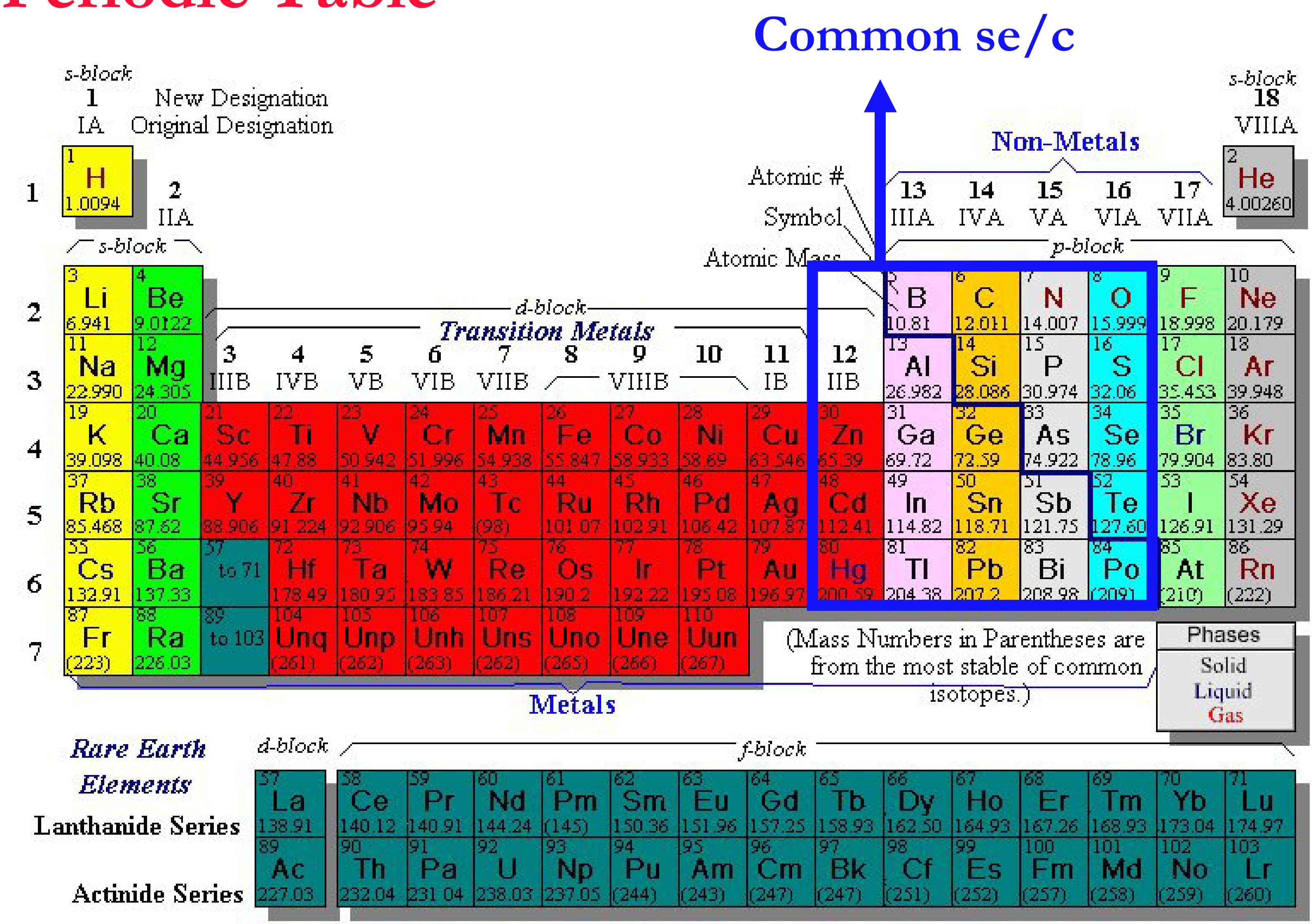
USEFUL IN:	Electronic devices:	ON/OFF switches, high gain amplifiers...
	Optoelectronic devices:	Detectors, modulators, lasers, light emitting diodes.

Source: J. Singh

A typical se/c (EPM) bandstructure: GaN & AlN



Periodic Table



A Classification of Se/c's

Elemental Semiconductors

- Group-IV: Si, Ge; Diamond structure, tetrahedrally coordinated
- Group-V, VI: P, S, Se, Te are also se/c's with several different crystal structures. Good glass formers

Binary Semiconductors

- III-V compounds are similiar to group IV
- IV → III-V ionicity increases. Electronic charge transfer from III to V atom: Coulomb interaction, changes in electronic band structure
- II-VI (ZnS): more ionic. Mostly large bandgaps → displays and lasers. Exception: HgTe zero bandgap → IR detectors.
- I-VII (CuCl): have larger bandgaps. Some are regarded as insulators. Increased cohesive energy. Rock salt struc.
- IV-VI (PbS, PbTe, SnS): semiconductors. Large ionicity. 6-fold coordination. Very small gaps. → IR detectors

Ref: Yu-Cardona

A Classification of Se/c's (Cont'd)

Oxides

- CuO, CuO_2:semiconductors ZnO →transducer
- High T_c SC: Copper oxides: La_2CuO_4 → bandgap 2 eV.Dope with Ba or Sr. P-type.

Layered Semiconductors

- PbI_2, MoS_2, GaSe, GaS: Intraleyer bonding covalent, interlayer bonding van de Waals.
- **2D Materials:** MoS_2, $MoSe_2$, WSe_2, … (Currently very hot in research)

Organic Semiconductors

- Polyacetylene [$(CH_2)_n$], polydiacetylene
- LEDs, lasers? Displays. Cheap. Slow. Bandgap manipulation is easier.

Magnetic Semiconductors (gained further importance with spintronics)

- Magnetic ions: Mn, Eu etc. EuS, $Cd_{1-x}Mn_xTe$: ferromag, antiferromag possible. Dilute mag se/c's. Large Faraday rotation → optical modulators.

Others

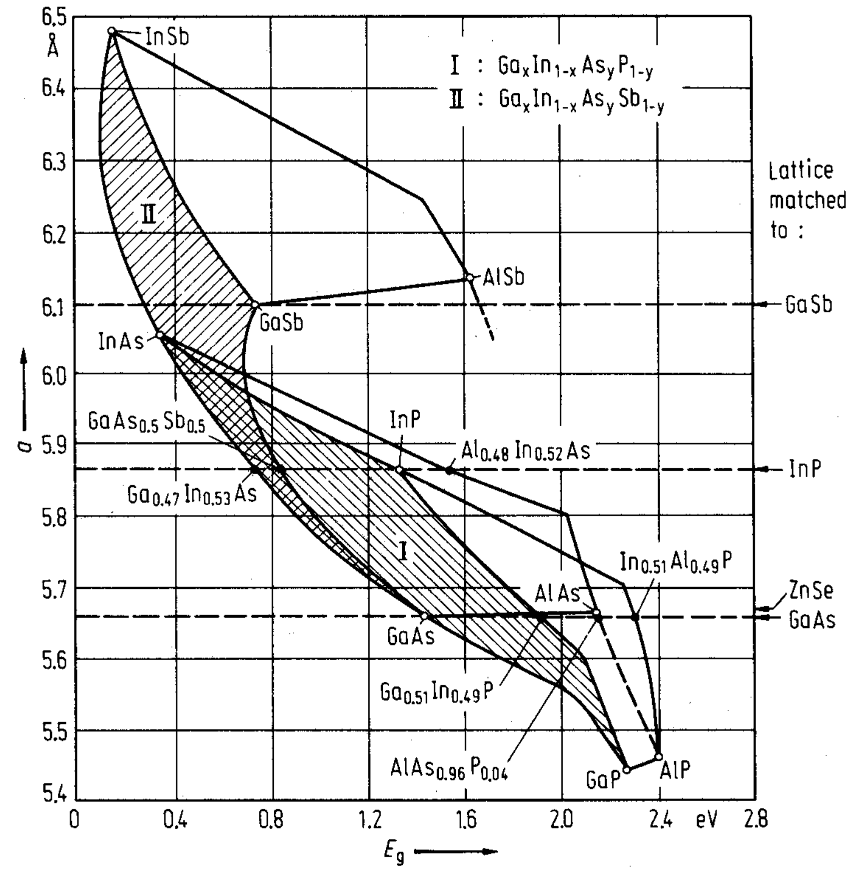
- SbSI: Ferroelectricy at low T,
- I-III-VI_2, II-IV-V_2: $AgGaS_2$ and $ZnSiP_2$ → chalcopyrite struc. Tetrahedral bonding. Analog to III-V and II-VI.
- IV-VI with formula such as As_2Se_3: se/c's in crystalline or glassy states

Ref: Yu-Cardona

A Classification of Se/c's (Cont'd)

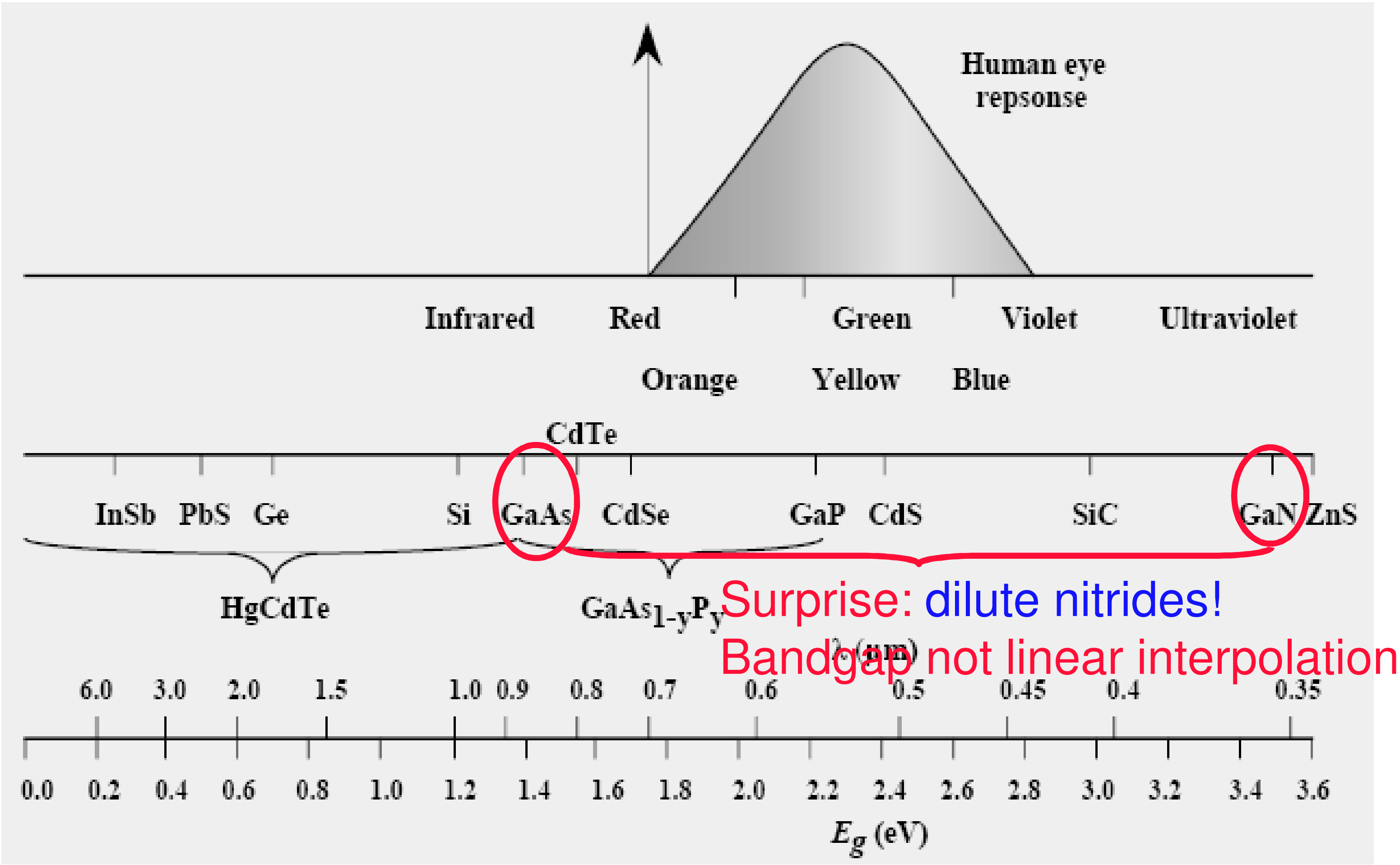
Ternary and Quaternary Se/c's

- III_x-III_{1-x}-V type ternaries:
  - $Al_xGa_{1-x}N$, $Al_xGa_{1-x}As$, $Al_xIn_{1-x}P$, $Al_xIn_{1-x}Sb$, etc.
- III-V_{1-x}-V_x type ternaries:
  - $AlAs_{1-x}P_x$, $GaAs_{1-x}P_x$, $InSb_{1-x}As_x$, $InSb_{1-x}Bi_x$, etc.
- III_x-III_{1-x}-V_y-V_{1-y}, type Quaternaries:
  - $Ga_xIn_{1-x}As_yP_{1-y}$, $Ga_xIn_{1-x}As_ySb_{1-y}$, etc.
- III_{1-x-y} III_x- III_y-V type Quaternaries:
  - $In_{1-x-y}Al_xGa_yP$, $In_{1-x-y}Al_xGa_yAs$, etc.



Band gap vs. Photon Wavelength

SEMICONDUCTOR BANDGAPS (WAVELENGTHS) AND HUMAN EYE RESPONSE



Source: J. Singh

Comparison of se/s

High speed ⟹ low effective mass, superior mobility.
High power applications ⟹ large bandgap.
High temperature applications ⟹ large bandgap.

	ADVANTAGES	DISADVANTAGES
Silicon (Si):	The most important semiconductor system. MOSFETs, bipolar devices based on Si form over 90% of the electronic market.	Not as "fast" as other semiconductors. Not good for high power, high temperature operation. Cannot emit light, since it is an indirect gap material.
Silicon-Germanium (Si-Ge):	Can be grown on Si substrates and processed using Si technology. Bipolar divices have performance rivaling GaAs technology.	Strained system. Needs great care in crystal growth conditions.
GaAs; GaAs/ AlGaAs:	High speed devices for digital/microwave applications. Performance is superior to silicon.	More expensive than Si technology.
InP; InGaAs/ InP:	High speed performance is superior to GaAs based technology. Can be combined with longhaul optoelectronic communication technology.	Expensive.
GaN/ AlGaN	High power/high temperature applications.	Not as reliable yet; high cost.
SiC:	High power/high temperature applications.	Reliability; cost.

Source: J. Singh

Why insist on se/c ?

- Physical properties of se/c can be altered drastically by
  - ✓ Doping
  - ✓ Pressure
  - ✓ Electric or magnetic field
  - ✓ Light
  - ✓ Temperature

- Response of se/c to external inputs can be tailored in a manner that allows the devices to implement all necessary information processing operations
  - ✓ Digital & analog signal processing
  - ✓ Oscillators
  - ✓ Detectors
  - ✓ Memories
  - ✓ …
- Industrial conservatism; huge investments and acquired knowledge

Why insist on se/c ?

- **Electrons** have:

charge → interact strongly

Good for information processing/computation (digital/analog)

But they interact strongly among themselves and the environment, hence they are prone to noise

mass → they suffer from propagation delays (drift velocity in se/c ~ 10^7 cm/s)

spin → a gateway to spintronics & quantum technologies **(inc. nuclear spins)**

- **Photons** have:

no mass, no charge → very weak interaction

Ideal for signal transmission as they are fast and hardly interact with each other

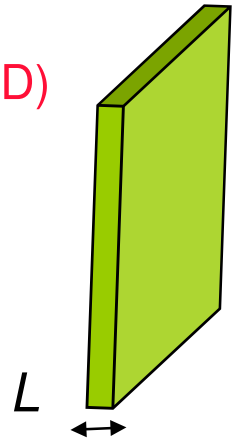
But, it is also harder to operate on them as in the case of electrons

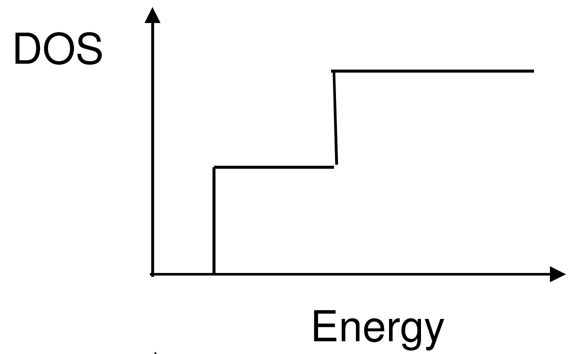
- Semiconductors are ideal for hosting both electrons & photons!

Low-dimensional structures

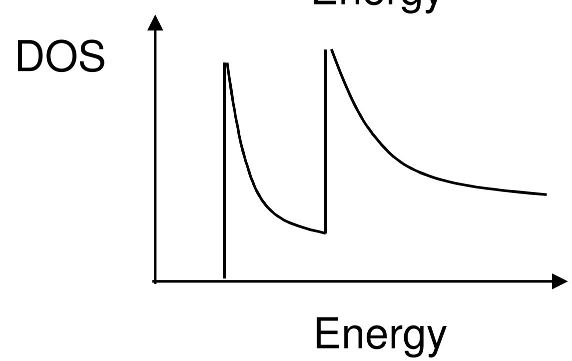
Spatial confinement length scale (*L*) comparable with de Broglie wavelength

- Quantum Well (2D)





- Quantum Wire (1D)



- Quantum Dot (0D)