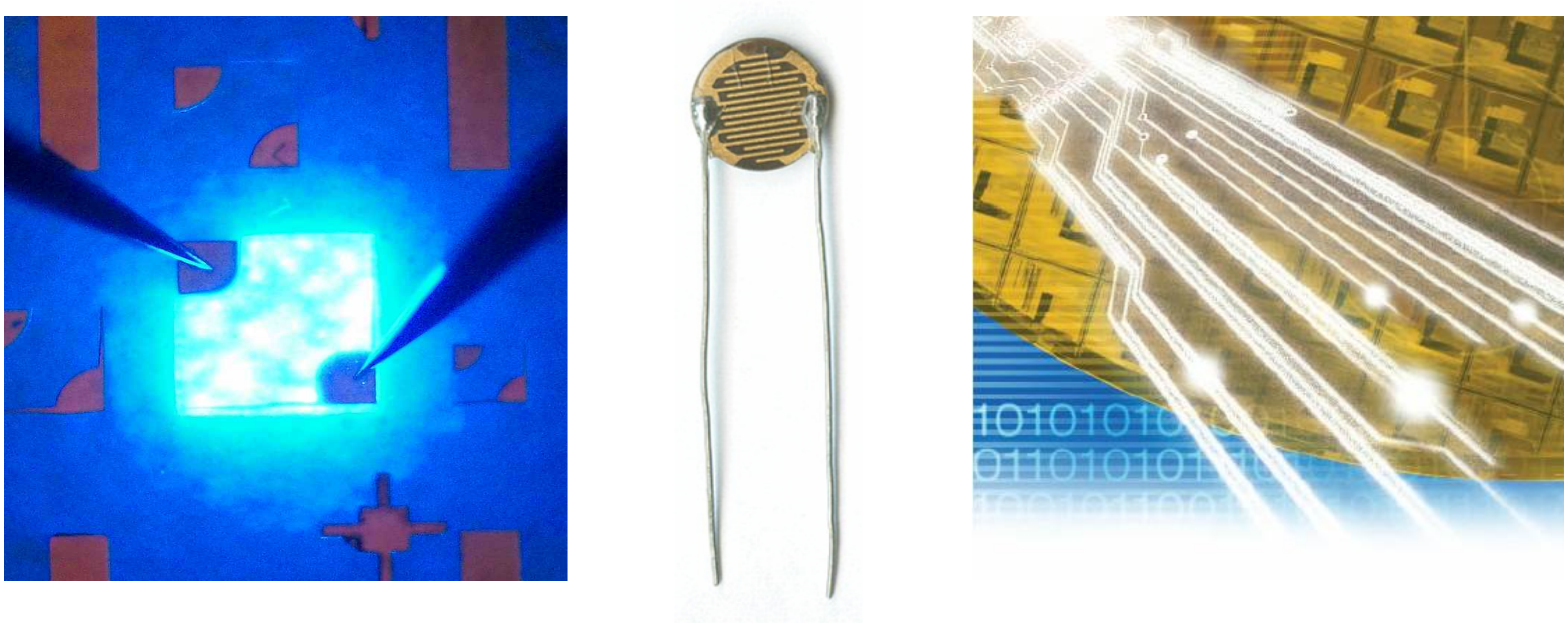
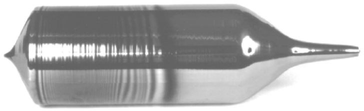
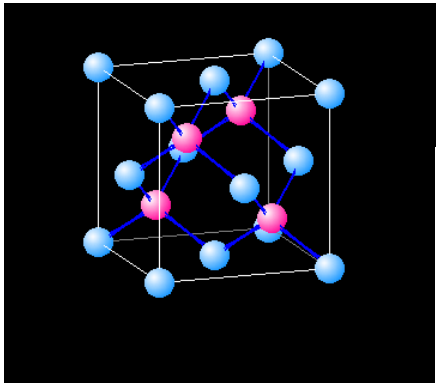
Optoelectronics
ELEC-E3210

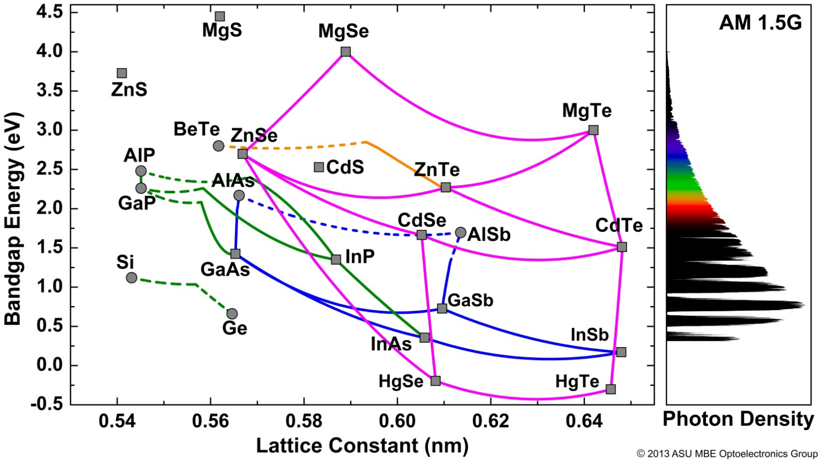


Outline



Introduction and course contents





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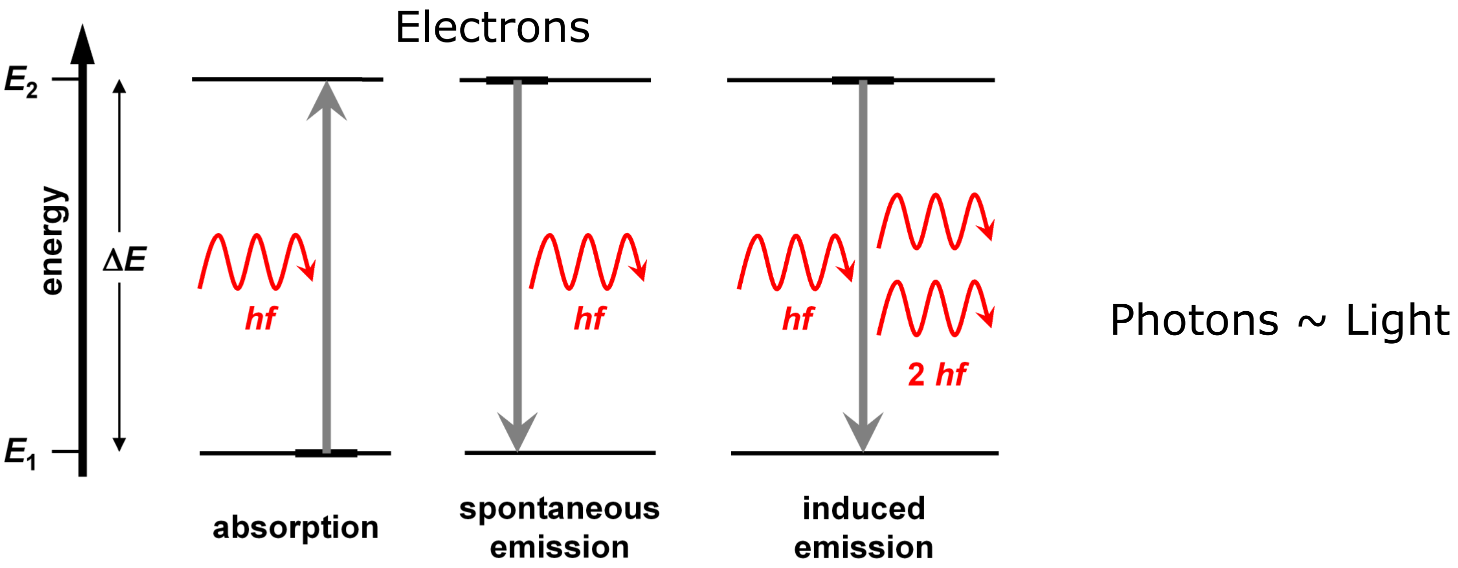
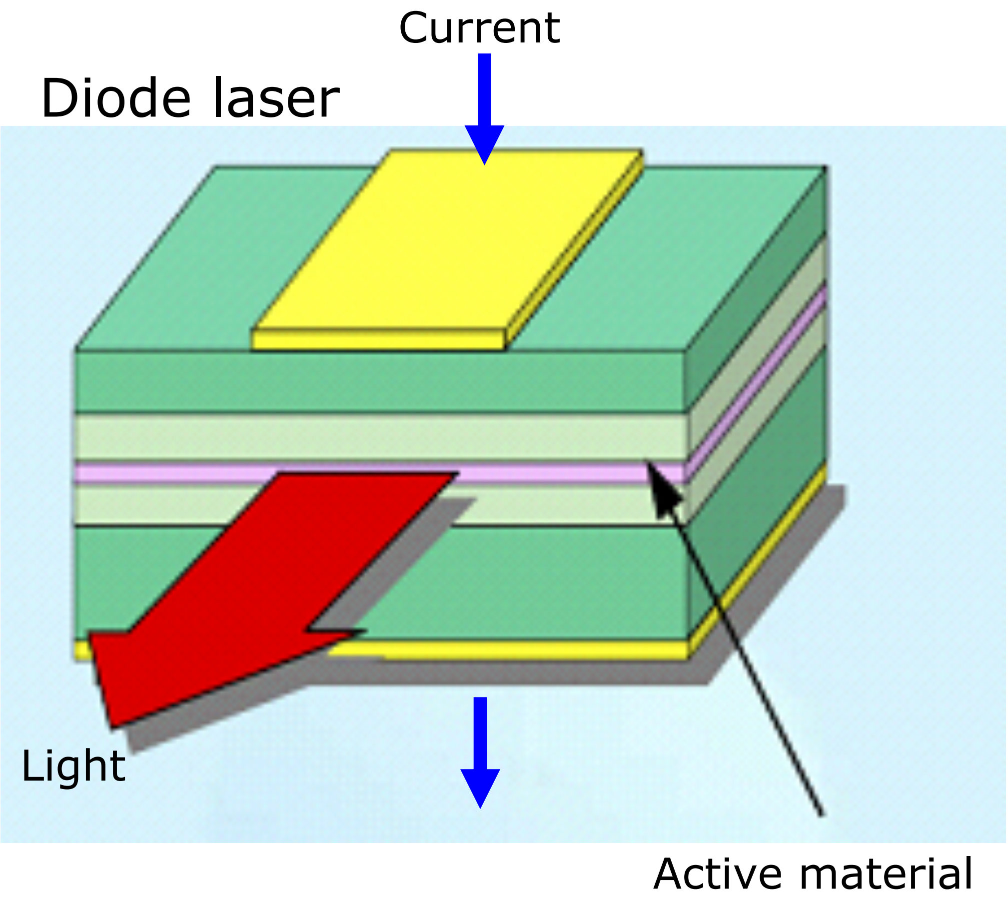
What is Optoelectronics?



- Optoelectronics is based on light-matter interaction, quantum mechanical effects of light on semiconducting materials
- Optoelectronic devices convert electrical energy to optical or optical energy to electrical
- Marriage of semiconductor electronics, solid-state sources and detectors and guided optics

Optoelectronic semiconductor devices

- LED – spontaneous emission
- Laser – stimulated emission (needs light feedback by mirrors)
- Detector and solar cell – absorption (provides electrical power from light)



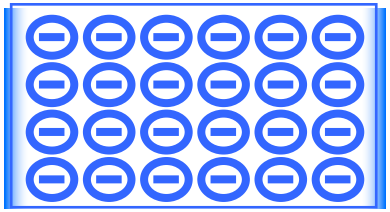
Why semiconductors?

1. Semiconductor materials contain two types of charge carriers

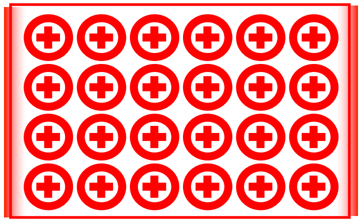
- **Negative** charge carriers (electrons)
- **Positive** charge carriers (holes)

2. By introducing **impurity atoms** (dopants) into a semiconductor it is possible to increase the concentration of either electrons or holes.

- **N-type** (or n-doped) semiconductors have a majority of electrons
- **P-type** (or p-doped) semiconductors have a majority of holes



N-type semiconductor



P-type semiconductor

3. Semiconductor’s **energy bandstructure** can be tailored by material composition, doping and by introducing quantum confinement

Materials for optoelectronics, silicon ?

Silicon is also interesting for Optoelectronics:

- **Absorbs light in the visible range**

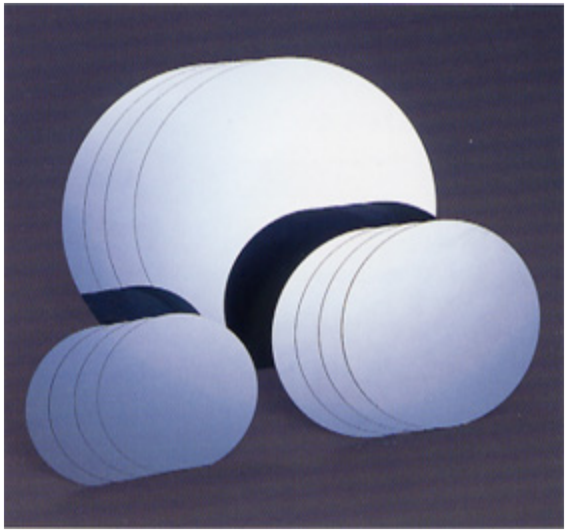
→ Solar cells, detectors

- **Transparent in near infrared (λ>1100nm)**

→ Telecommunications

- **But silicon is a poor light emitter**

→ Other materials required

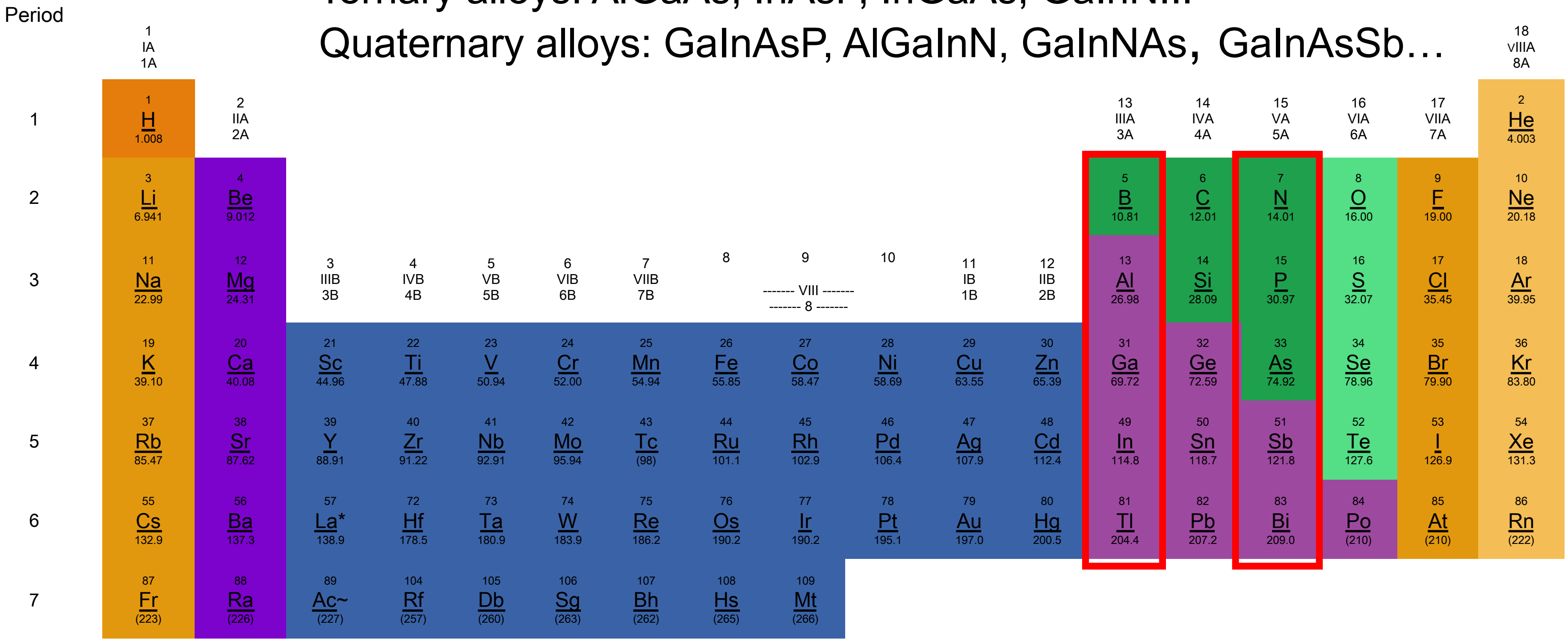


Materials for optoelectronics, III-V compounds

Example: **GaAs**, **InP**, InSb, AlAs, **GaP**, **GaN**...

Ternary alloys: AlGaAs, InAsP, InGaAs, GaInN...

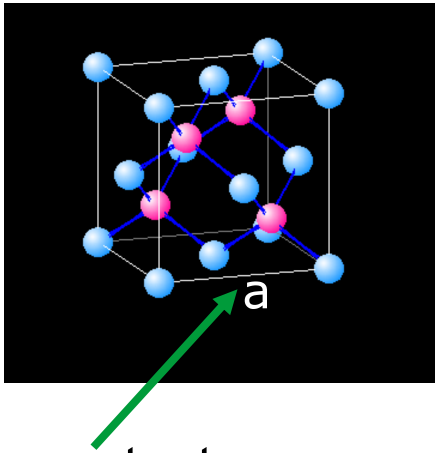
Quaternary alloys: GaInAsP, AlGaInN, GaInNAs, GaInAsSb…



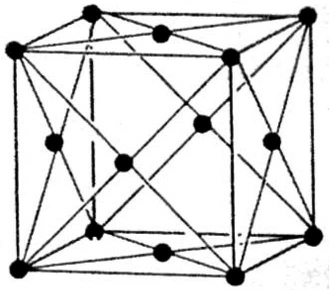
Period	1 IA 1A	2 IIA 2A	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8	9 ------- VIII ------- ------- 8 -------	10	11 IB 1B	12 IIB 2B	13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	18 VIIIA 8A
1	1 H 1.008																	2 He 4.003
2	3 Li 6.941	4 Be 9.012											5 B 10.81	6 C 12.01	7 N 14.01	8 O 16.00	9 F 19.00	10 Ne 20.18
3	11 Na 22.99	12 Mg 24.31											13 Al 26.98	14 Si 28.09	15 P 30.97	16 S 32.07	17 Cl 35.45	18 Ar 39.95
4	19 K 39.10	20 Ca 40.08	21 Sc 44.96	22 Ti 47.88	23 V 50.94	24 Cr 52.00	25 Mn 54.94	26 Fe 55.85	27 Co 58.47	28 Ni 58.69	29 Cu 63.55	30 Zn 65.39	31 Ga 69.72	32 Ge 72.59	33 As 74.92	34 Se 78.96	35 Br 79.90	36 Kr 83.80
5	37 Rb 85.47	38 Sr 87.62	39 Y 88.91	40 Zr 91.22	41 Nb 92.91	42 Mo 95.94	43 Tc (98)	44 Ru 101.1	45 Rh 102.9	46 Pd 106.4	47 Ag 107.9	48 Cd 112.4	49 In 114.8	50 Sn 118.7	51 Sb 121.8	52 Te 127.6	53 I 126.9	54 Xe 131.3
6	55 Cs 132.9	56 Ba 137.3	57 La* 138.9	72 Hf 178.5	73 Ta 180.9	74 W 183.9	75 Re 186.2	76 Os 190.2	77 Ir 190.2	78 Pt 195.1	79 Au 197.0	80 Hg 200.5	81 Tl 204.4	82 Pb 207.2	83 Bi 209.0	84 Po (210)	85 At (210)	86 Rn (222)
7	87 Fr (223)	88 Ra (226)	89 Ac~ (227)	104 Rf (257)	105 Db (260)	106 Sg (263)	107 Bh (262)	108 Hs (265)	109 Mt (266)									

Crystal structure of III-V's

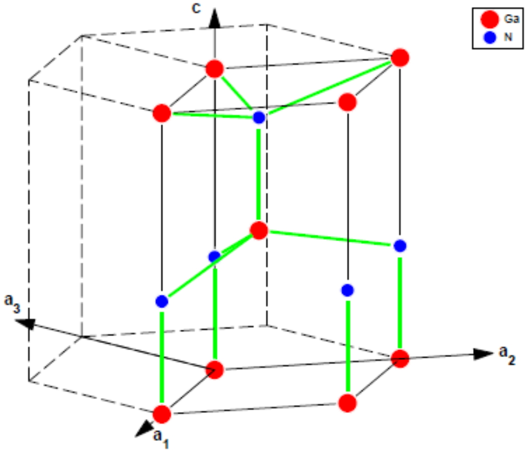
- **Zinc-blende:** two interprenating FCC sublattices shifted by ¼ of the body diagonal, examples: GaAs, InP, GaP, GaSb, InSb, ZnS, ZnSe,...
- **Wurtzite**: each of the two individual atom types forms a sublattice which is of hexagonal close-packed type, examples: GaN, SiC, ZnS, AlN and ZnO



Lattice constant
(typically 0.3–0.6 nm)

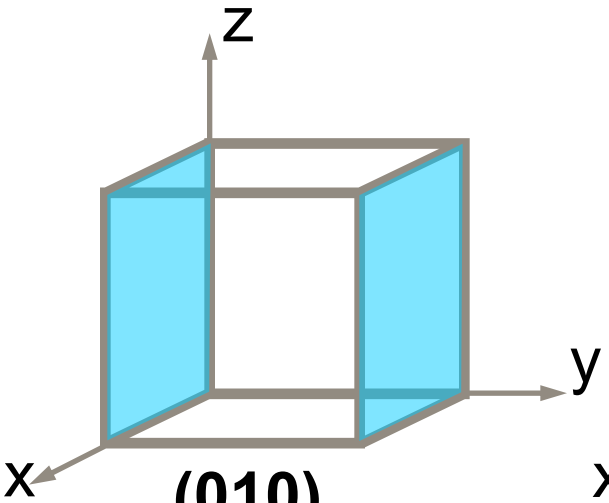


FCC lattice

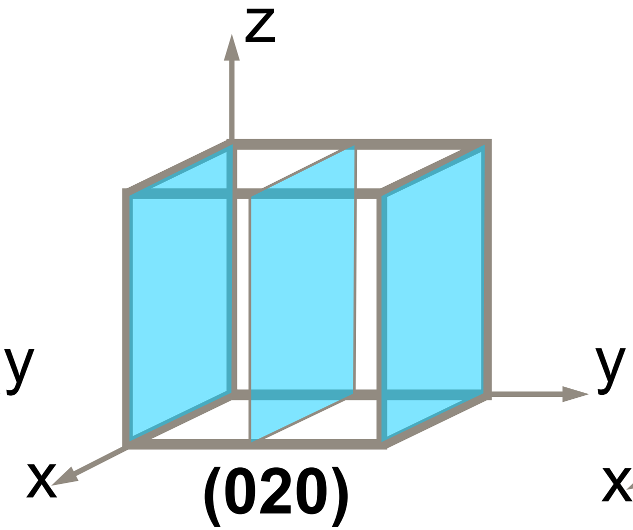


Wurtzite GaN

Crystal planes and directions



(010)



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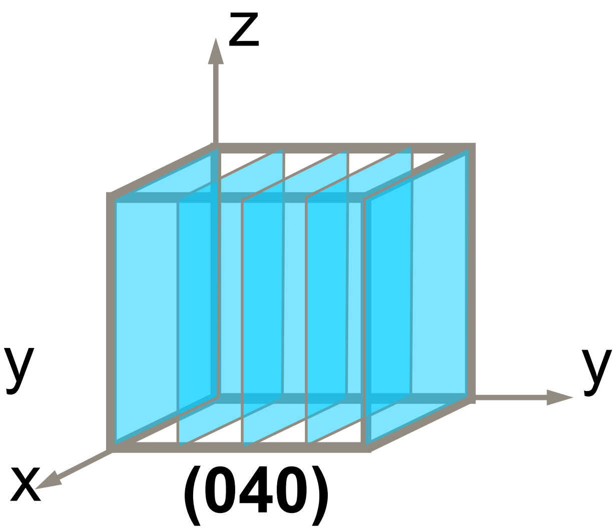


(040)

- (hkl) corresponds to a **family** of parallel planes
- **In SC, BCC and FCC lattices** [hkl] is the direction normal to the plane

$$\text{distance between planes } d_{hkl} = \frac{a}{\sqrt{h^2 + k^2 + l^2}}$$

{hkl}: Planes of equivalent symmetry $(\bar{1}00), (0\bar{1}0), (00\bar{1})$

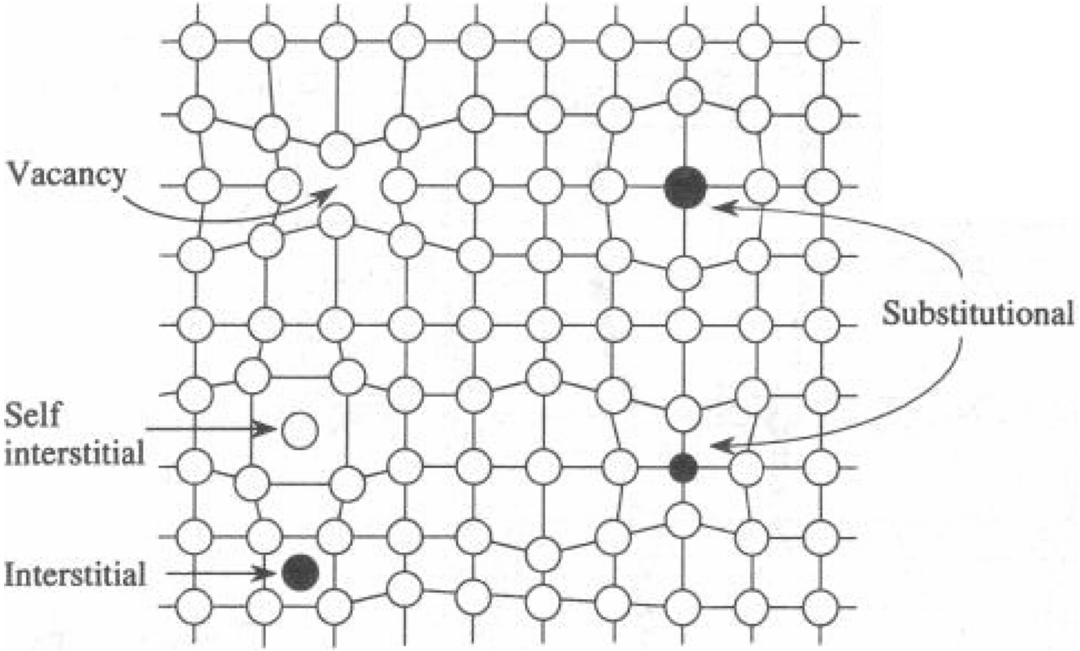
- e.g. {100} for (100), (010), (001),

<hkl>: Full set of equivalent directions

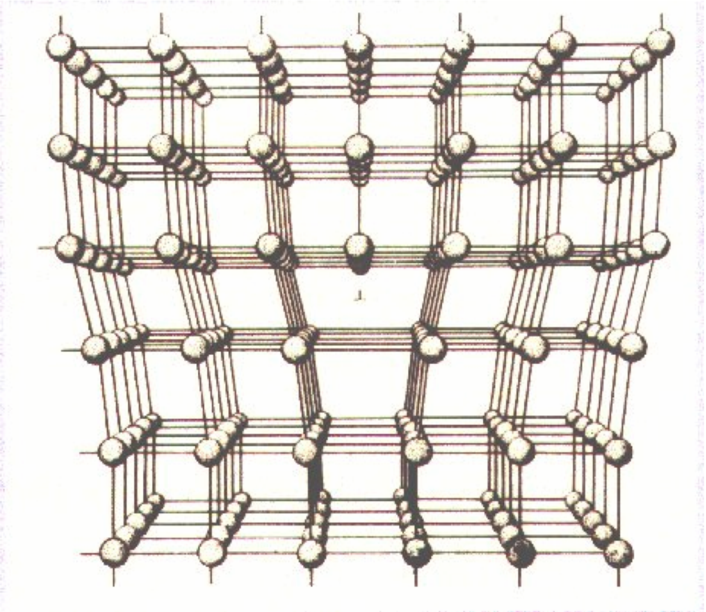
Crystal defects

Point defects

Effect is localized to a few atomic sites



Line defects = dislocations

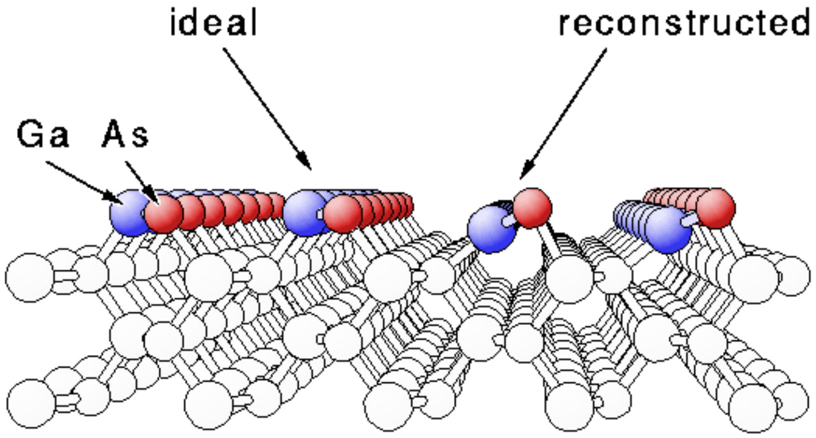


Except in doping engineering, crystal defects should be avoided!

Crystal surface: ideal versus real

At the surface, the number of neighbors is suddenly altered. Thus the lowest energy configuration at the surface may differ from that in the bulk.
→ **Reconstruction of the surface bonds**

The surface properties are determined by the number of dangling (free) bonds.

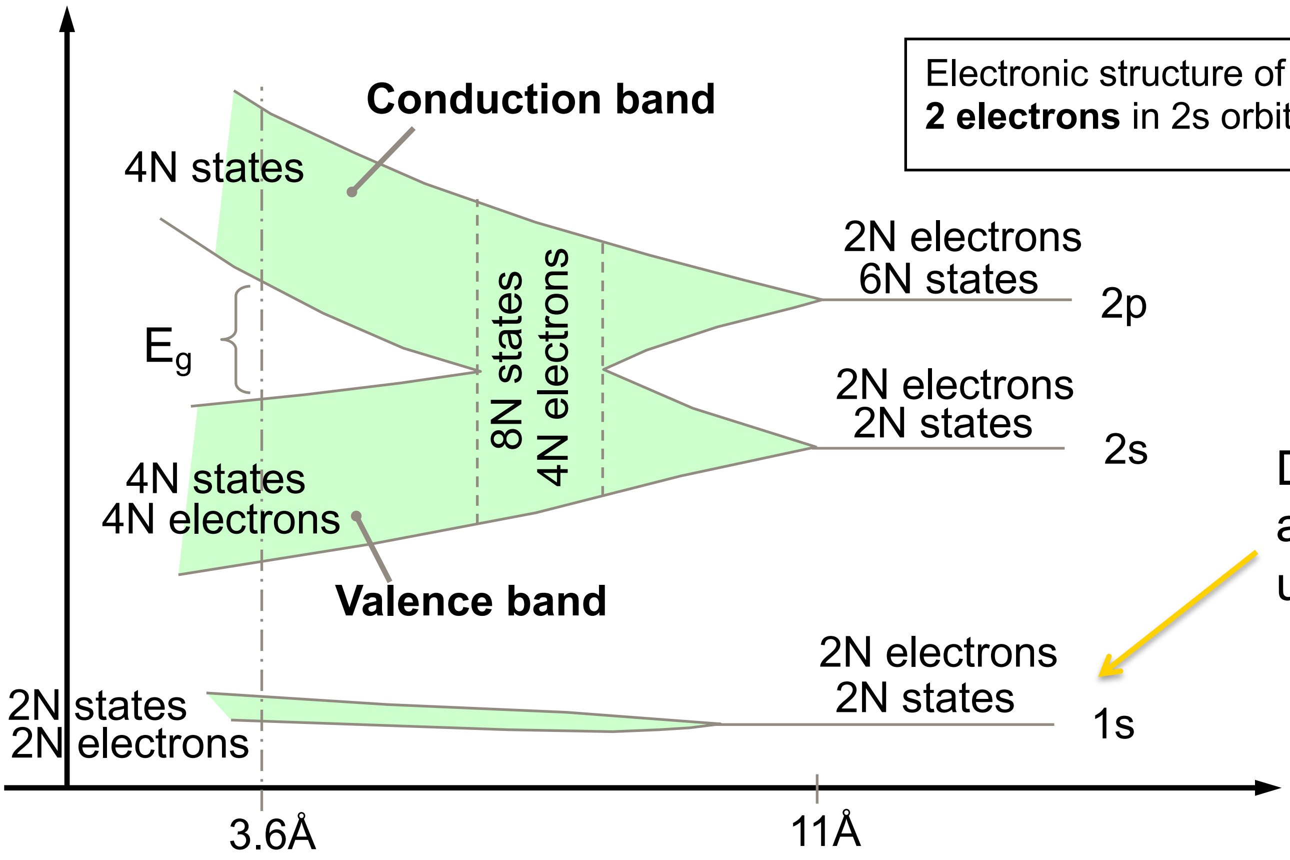


GaAs (110) ideal / reconstructed surface

Formation of energy bands

When N atoms are brought together, small energy shifts are observed in orbitals

Electronic structure of C: $1s^2 2s^2 2p^2$
2 electrons in 2s orbital, **2 electrons** in 2p orbitals

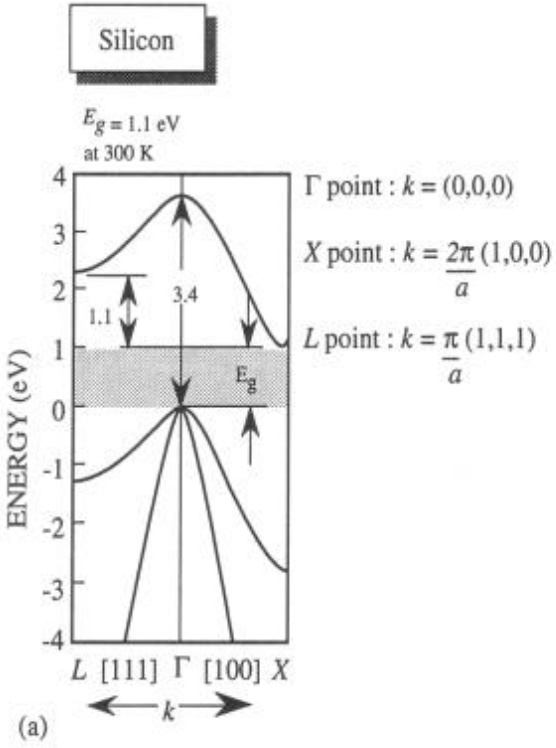


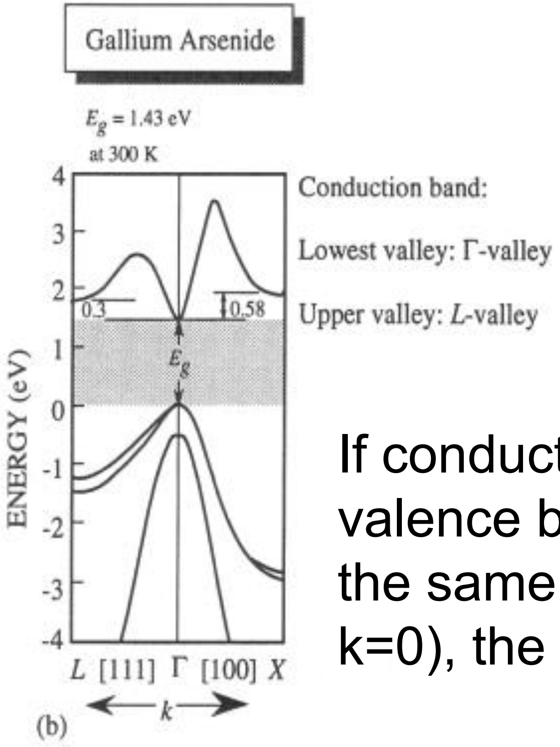
Deep core levels are relatively unaffected!

Interatomic distance

The outermost energy levels of the atoms making up semiconductors are all either s-type or p-type. Core electrons do not participate in most processes.

Direct and indirect bandgap



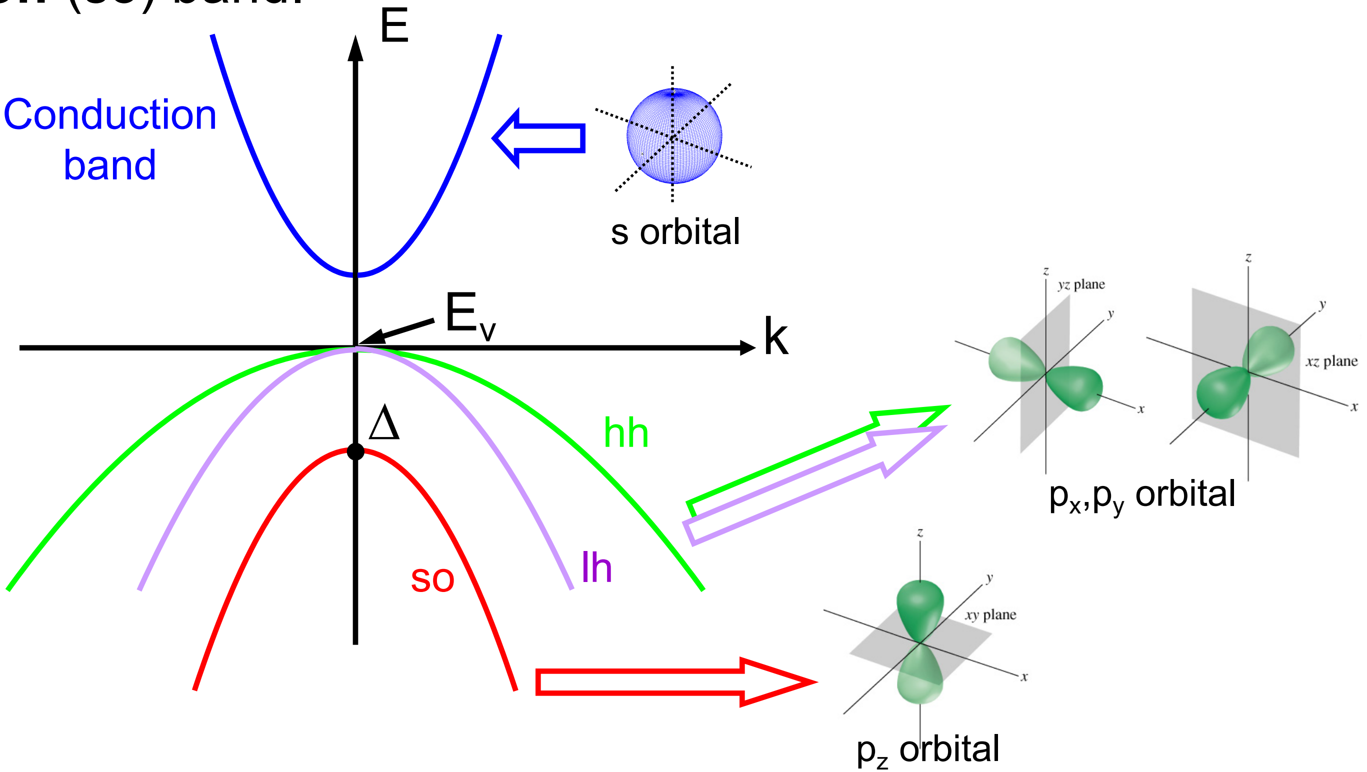


If conduction band minimum and valence band maximum occur at the same wavevector (typically k=0), the bandgap is **direct.**

- **Direct band gap**: The conduction band is formed only by overlap of s-orbitals
- **Indirect band gap**: The conduction band is a mix of p- and s-orbitals

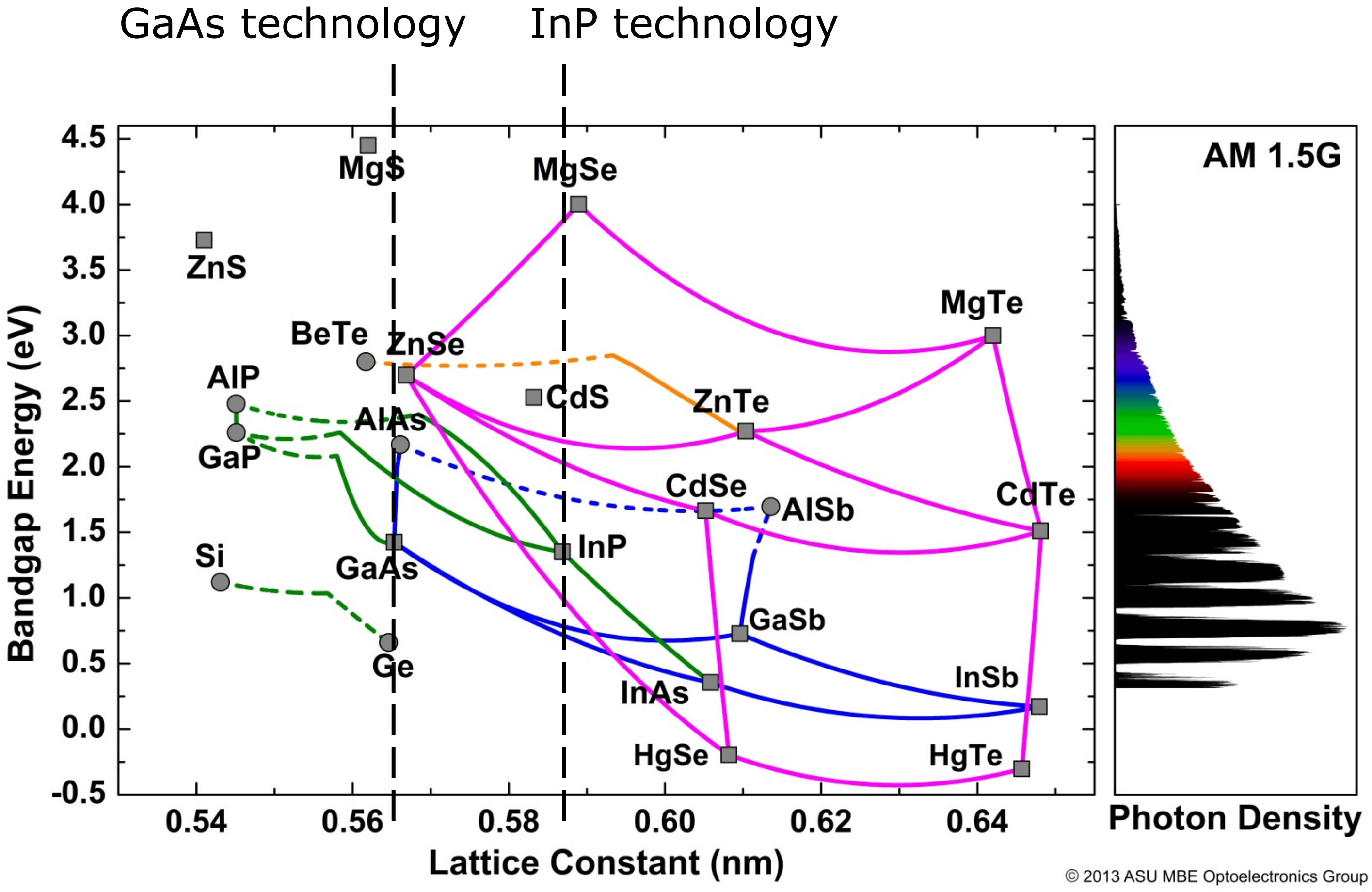
Four band theory (direct bandgap)

In **direct** semiconductors, the valence band is degenerated: it consists in fact of 3 distinct bands: the **light hole** (lh), the **heavy hole** (hh), and the **split-off** (so) band.



Bandgap energy vs. Lattice constant

GaAs technology InP technology



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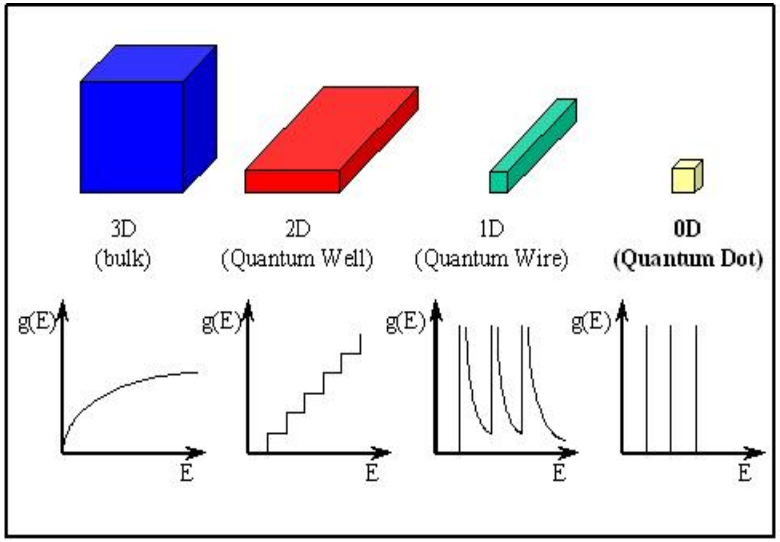
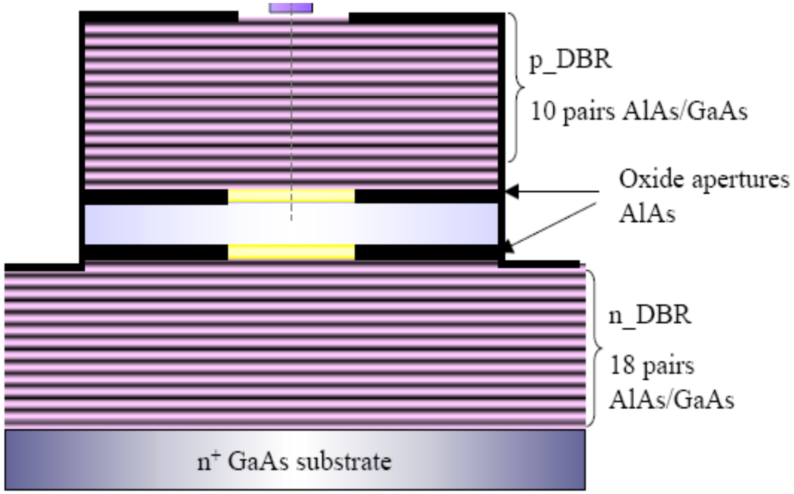
Quantum structures for optoelectronics



- Many optoelectronic devices are using **quantum structures to confine charge carriers**
- The dimension of a quantum structure does not excess a few nanometers

Vertical Cavity Surface Emitting Laser



- Advanced optoelectronic devices are made of several **crystalline layers of different composition and doping**
- Composition and doping variations can be in one, two or even three dimensions

Epitaxial growth techniques

Modern epitaxial techniques

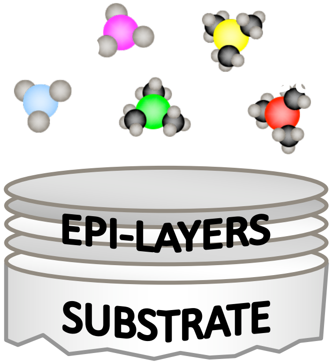
- good control of layers thickness *d* and composition needed (Δd < 1Å)

MBE (molecular beam epitaxy)

- ultra-high vacuum
- like vacuum evaporation
- often solid sources
- several systems in Tampere, one in Micronova

MOVPE or MOCVD (metalorganic vapor phase epitaxy)

- sources vapors or gases
- three systems in Micronova

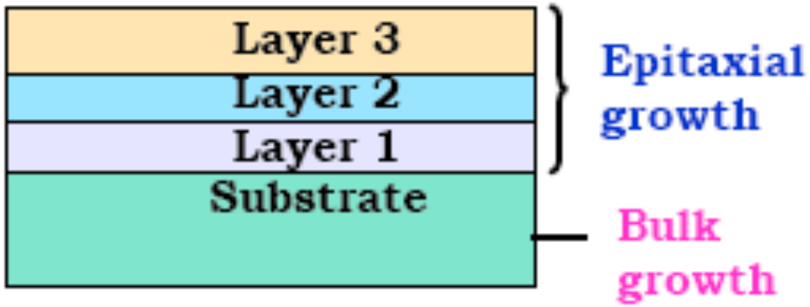


Epitaxy

NEED

- **Device structure:**

  Several epitaxial layers often with different compositions and/or doping on a substrate



- **Epitaxy (from Greek: *epi* = upon; *taxis*= ordered):**

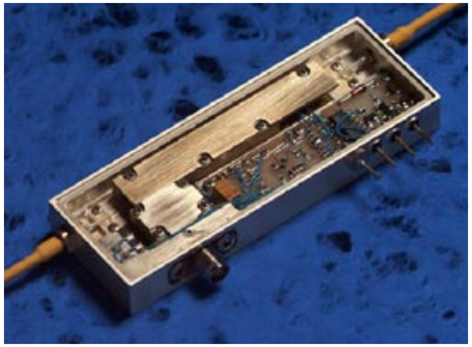
  Growth of a crystal on a substrate with the same crystallographic structure as the substrate

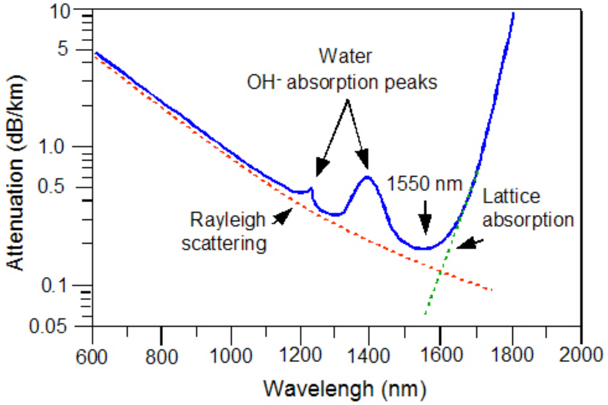
  => Monocrystalline substrate needed to grow epitaxial layers

- Homoepitaxy: e.g., InP/InP
  Heteroepitaxy: e.g., InGaAs/InP

Applications: Optical Communication

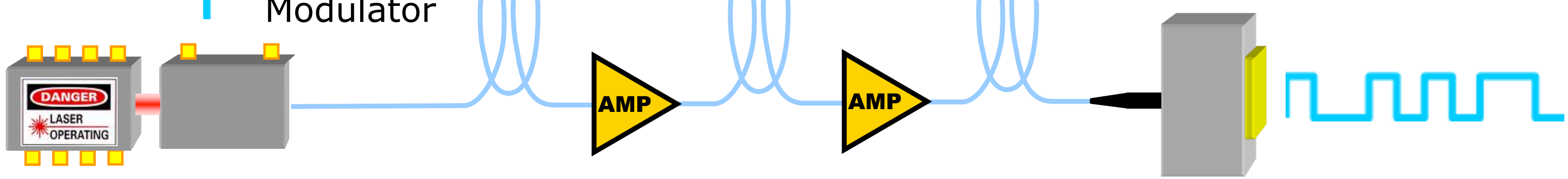
Electrical signal in





Optical fibre

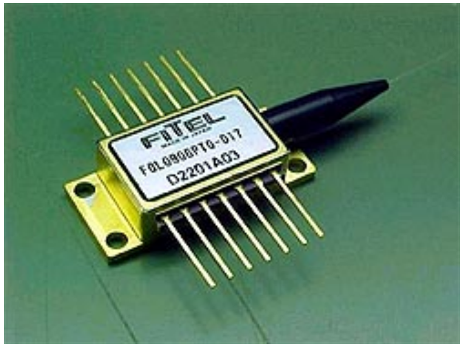
Modulator

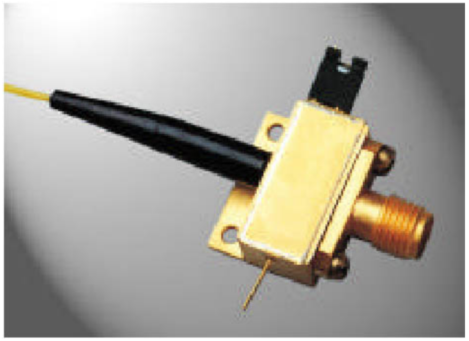


Diode laser

Optical amplifier

Photodetector

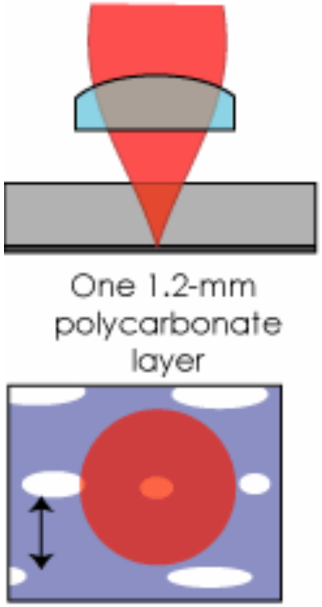




Applications: Optical Data Storage

COMPACT disc DIGITAL AUDIO

780-nm Red Laser
Lens Aperture = 0.45

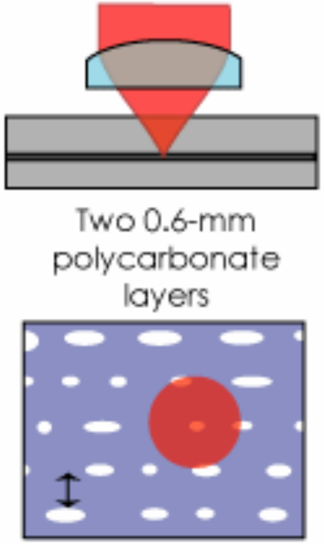


One 1.2-mm polycarbonate layer

track pitch = 1.6μm

DVD

650-nm Red Laser
Lens Aperture = 0.6

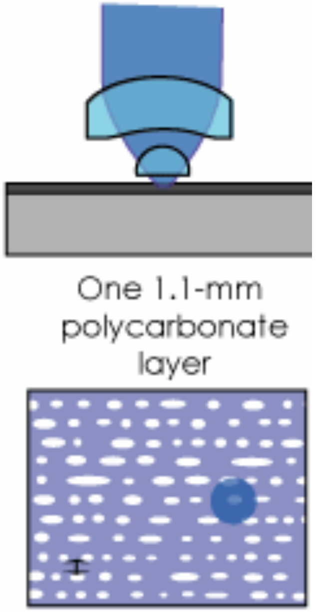


Two 0.6-mm polycarbonate layers

track pitch = .74μm

Blu-ray Disc

405-nm Blue Laser
Lens Aperture = 0.8



One 1.1-mm polycarbonate layer

track pitch = .30μm

Applications: Lighting

Cell phone backlighting

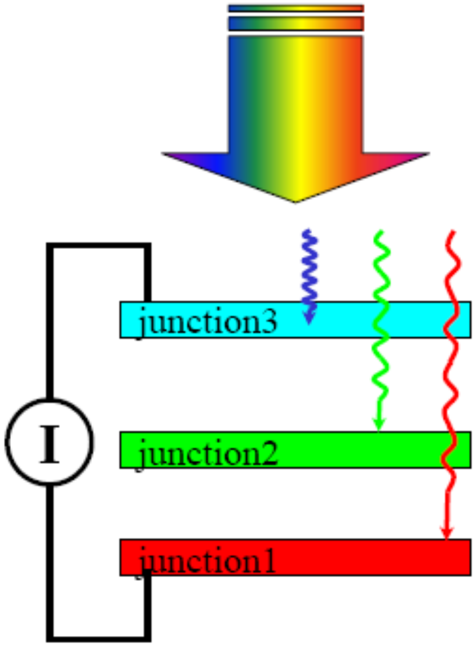
LED TVs

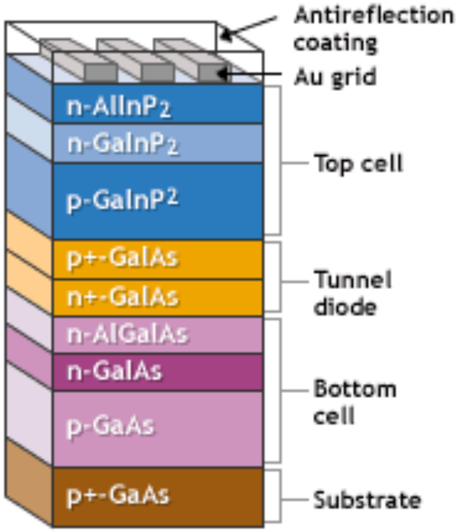
Automotive

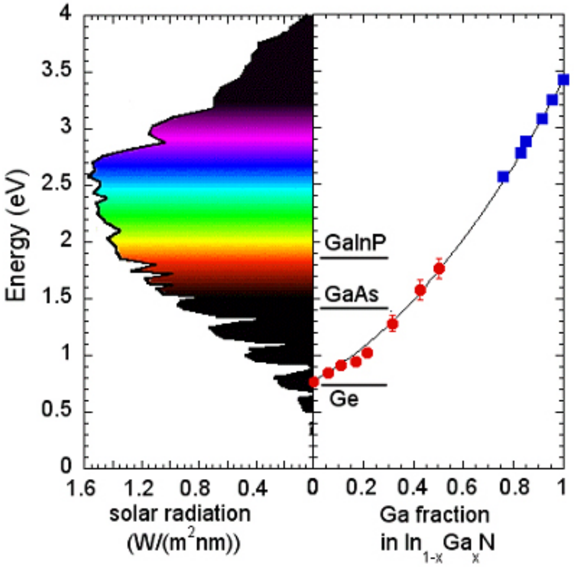
Streetlights and general lighting

Large displays

Applications: Solar Cells







World record solar cell efficiency ~ 44%