Lecture 40: Wed, 9 Apr 2008

Reading quizzes: no talking, no looking in your books/notes

Q1. Who developed the "A and B" coefficients?

a. Avogadro and Boltzmann
b. Bohr
c. Einstein
d. Planck

Q2. Which of these processes is not one considered in the A and B coefficient analysis?

a. spontaneous absorption
b. stimulated absorption
c. spontaneous emission
d. stimulated emission

Q3. What is the relationship between B_{12} and B_{21}?

a. $B_{12} < B_{21}$
b. $B_{12} = B_{21}$
c. $B_{12} > B_{21}$

From Saleh and Teich, *Fundamentals of Photonics* (2007)

Table 15.3-1 Typical characteristics and parameters for a number of well-known lasers made of different forms of matter,[a] in order of increasing wavelength.

Laser Medium	Transition Wavelength λ_o	Single Mode (S) or Multimode (M)	CW or Pulsed[b]	Approximate Overall Efficiency η_c(%)[c]	Output Power or Energy[d]	Energy-Level Diagram
Ag^{19+} (p)	13.9 nm	M	Pulsed	0.0002	25 μJ	
C^{5+} (p)	18.2 nm	M	Pulsed	0.0005	2 mJ	Fig. 13.1-1
ArF Excimer (g)	193 nm	M	Pulsed	1.	200 mJ	
KrF Excimer (g)	248 nm	M	Pulsed	1.	500 mJ	
He–Cd (g)	442 nm	S/M	CW	0.1	100 mW	
Ar^{+} (g)	515 nm	S/M	CW	0.05	10 W	
Rhodamine-6G (l)	560–640 nm	S/M	CW	0.005	100 mW	Fig. 13.1-5
He–Ne (g)	633 nm	S/M	CW	0.05	10 mW	Fig. 13.1-2
Kr^{+} (g)	647 nm	S/M	CW	0.01	1 W	
Ruby (s)	694 nm	M	CW	0.1	5 W	Fig. 14.3-1
Alexandrite (s)	700–820 nm	M	CW	0.1	1 W	Fig. 13.1-8
Ti:Sapphire (s)	700–1050 nm	S/M	CW	0.01	5 W	Fig. 15.3-4
Yb^{3+}:YAG (s)	1030 nm	S/M	CW	5.	100 W	Fig. 15.3-3
Nd^{3+}:Glass (s)	1053 nm	M	Pulsed	1.	50 J	Fig. 14.3-3
Nd^{3+}:YAG (s)	1064 nm	S/M	CW	5.	50 W	Fig. 13.1-9
Nd^{3+}:YVO_4 (s)	1064 nm	S/M	CW	10.	30 W	Fig. 15.3-1
Yb^{3+}:Silica fiber (s)	1075 nm	S/M	CW	20.	1500 W	
Er^{3+}:Silica fiber (s)	1550 nm	S/M	CW	10.	100 W	Fig. 14.3-6
Tm^{3+}:Fluoride fiber (s)	1.8–2.1 μm	S/M	CW	5.	150 W	
He–Ne (g)	3.39 μm	S/M	CW	0.05	20 mW	Fig. 13.1-2
CO_2 (g)	10.6 μm	S/M	CW	10.	500 W	Fig. 13.1-4
H_2O (g)	28 μm	S/M	CW	0.02	100 mW	
FEL at UCSB	60 μm–2.5 mm	M	Pulsed	0.5	5 mJ	
H_2O (g)	118.7 μm	S/M	CW	0.01	50 mW	
CH_3OH (g)	118.9 μm	S/M	CW	0.02	100 mW	
HCN (g)	336.8 μm	S/M	CW	0.01	20 mW	

[a]Gas (g), solid (s), liquid (l), plasma (p).

[b]Lasers designated "CW" can, of course, be operated in a pulsed mode; lasers designated "pulsed" are usually operated in that mode.

[c]The power-conversion efficiency η_c (also called the overall efficiency and wall-plug efficiency) is the ratio of output light power to input electrical power (for pulsed lasers, the ratio of output light energy to input electrical energy). Values reported have substantial uncertainty since in some cases they include the electrical power consumed for overhead functions such as cooling and monitoring. Laser diodes exhibit the highest efficiencies, readily exceeding 50%, as discussed in Sec. 17.4C.

[d]The output power (for CW systems) and output energy per pulse (for pulsed systems) vary over a substantial range, in part because of the wide range of pulse durations; representative values are provided.

From Saleh and Teich, *Fundamentals of Photonics* (2007)

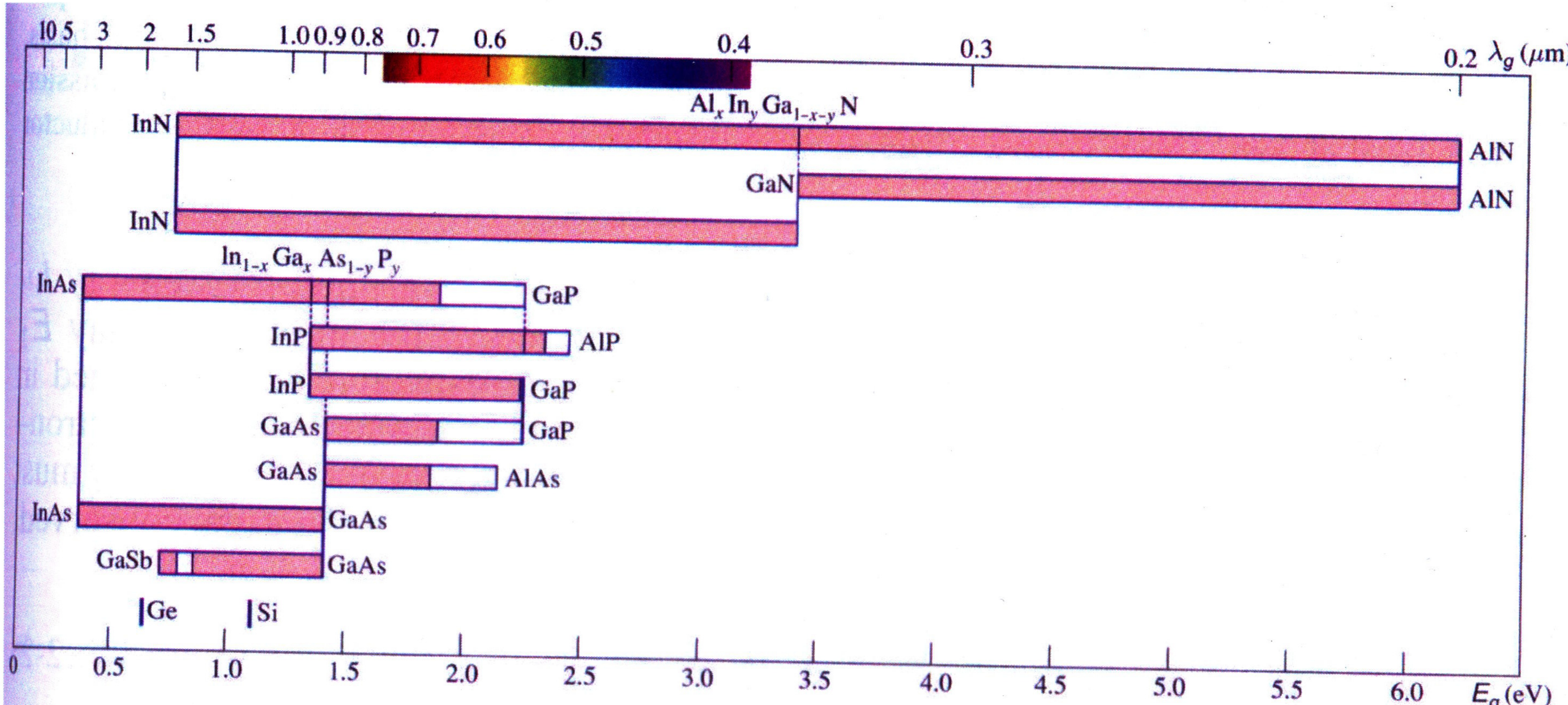
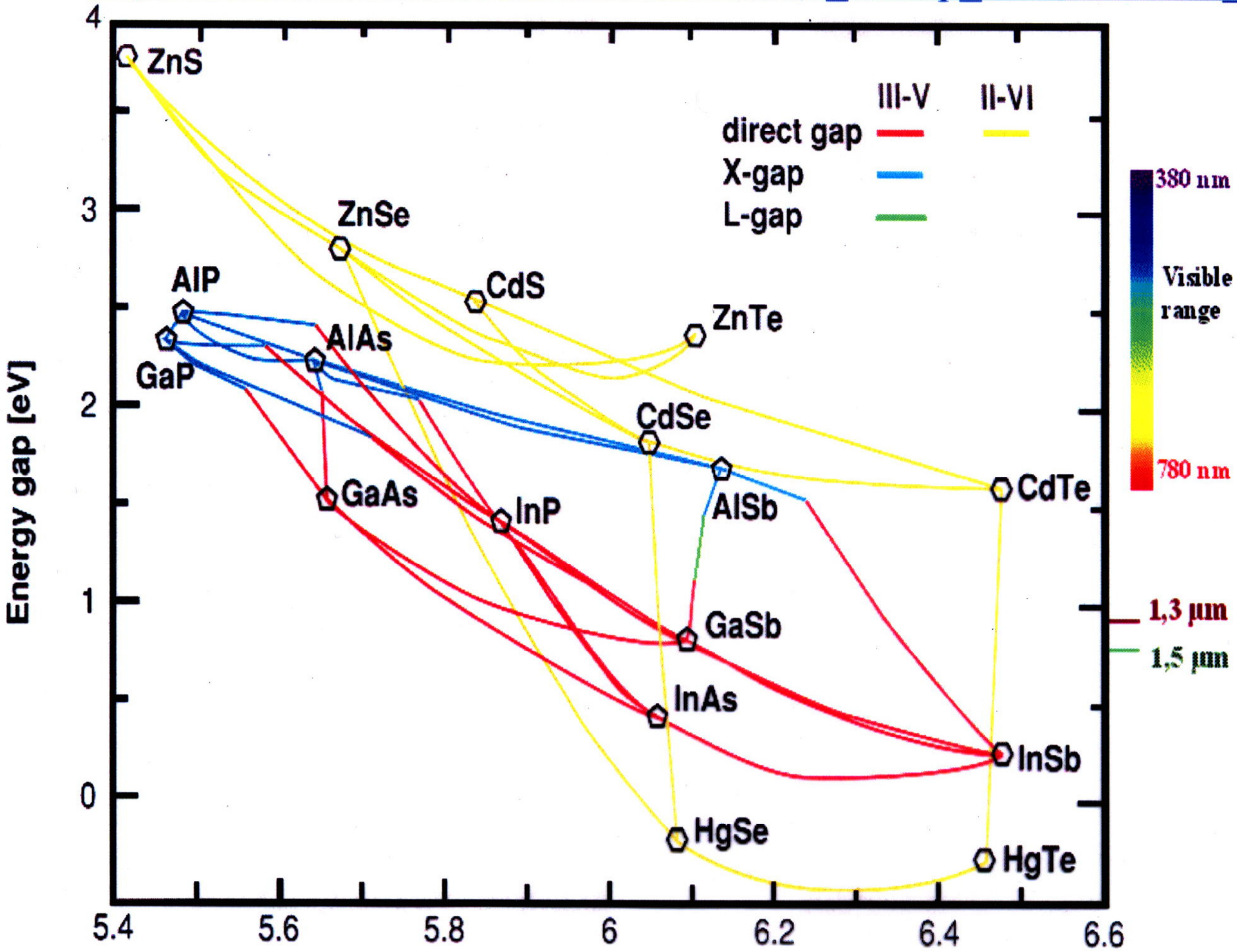
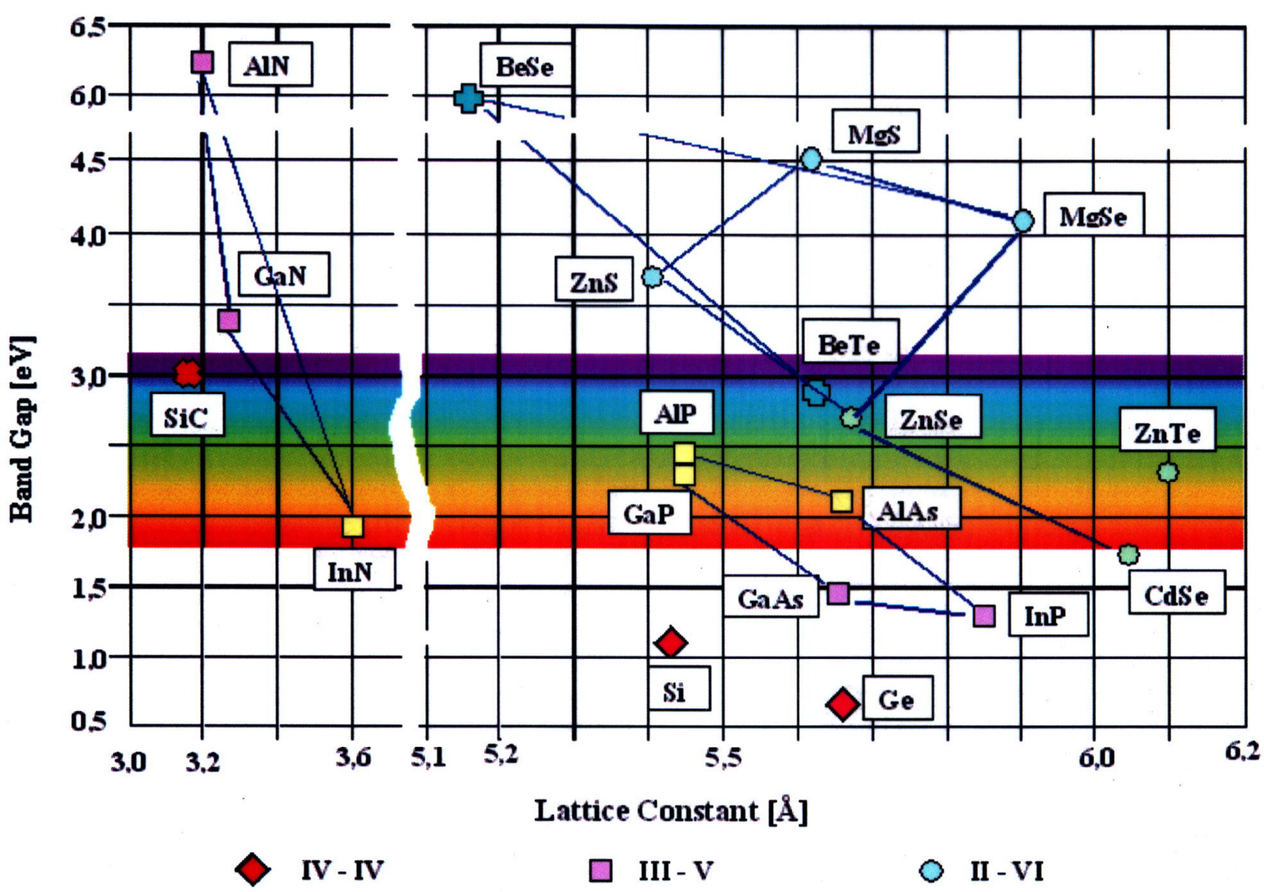


Figure 16.2-4 Bandgap wavelength λ_g, and corresponding bandgap energy E_g, for selected elemental and III–V binary, ternary, and quaternary semiconductor materials. Successive rows, starting at the top, represent AlInGaN, AlGaN, InGaN, InGaAsP, AlInGaP, InGaP, GaAsP, AlGaAs, InGaAs, and GaAsSb. The shaded regions indicate compositions for which the materials are direct-bandgap semiconductors.

From http://www.tf.uni-kiel.de/matwis/amat/semi_en/kap_5/backbone/r5_1_4.html





From http://www.tf.uni-kiel.de/matwis/amat/semi_en/kap_5/backbone/r5_1_4.html

There is a tremendous amount of information in this diagram (note that "X-gap" and L-gap" both denote indirect band gaps a the respective positions in the band diagram):

- Most III-V compounds radiate at wavelengths above the visible region, i.e. in the infrared. However, adding some Al to GaAs producing AlxGa1-xAs, will shift the wavelength into the red region of the spectrum - here are our red luminescence diodes and Lasers!
- Very fortunate: GaAs and AlAs have almost the same lattice constant; we can thus combine any combinations of these materials without encountering mechanical stress.
- Very unfortunate: There are no III-V compounds in the diagram that emit blue light - this is a severe problem for many potential applications. While SiC could be used to some extent, it was only with the recent advent of GaN that this problem was solved. SiC and GaN crystals, however, are not of the "zinc-blende" type common to all the III-Vs in the diagram but have a hexagonal unit cell. They therefore do not easily mix with the others!
- If we want to radiate at 1.3 µm or 1.5 µm - infrared wavelength of prime importance for optical communications - we should work with combinations of InAs, GaAs, and AlSb.
- Most interesting: The II-VI compounds are all direct semiconductors and span a much larger range of wavelengths than the III-V's. The fact that they are not much used for products tells us that there must be big problems in utilizing these compounds for mass products.

Obviously need lasing medium

Other laser requirement

- cavity

(curved mirrors as we discussed!)

need to trap photons long enough for them to cause stim. emission

→ partial reflector, lets photons leak out every so often

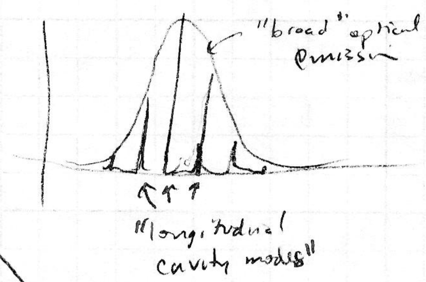
Solids: cavity can be the material itself

cavity like F-P interferometer → maxima at

$L = n\frac{\lambda}{2}$

$\lambda = \frac{2L}{n}$

↳ λ inside cavity, frequently $= \lambda_{vac}$



F.P.: $T = \frac{T_{max}}{1 + F\sin^2\frac{\Phi}{2}}$

$\Phi = 2k_2 d\cos\theta_2 + \delta_r + \delta_t$

max in T when $\sin\frac{\Phi}{2} = n\pi$

$\Phi = 2n\pi$

$2 \cdot \frac{2\pi}{\lambda} d\cos\theta + 2\pi = 2n\pi$

$\frac{4d}{\lambda} = 2n'$

$\lambda = \frac{2d}{n'}$

Yay! same answer

→ in this figure, about ~5 laser freqs possible

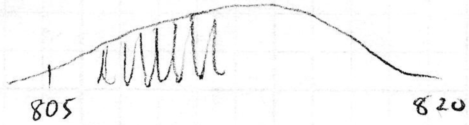
typically laser selects out one of them

→ or you can insert wavelength selecting element — like a prism

→ change the length of cavity, get different FP mode structure, and then diff output λ

Tunable lasers: very broad natural emission

my laser:



- wavelength selective device (like prism) to pick approx. λ
- mode tuning (like change cavity length) to fine-tune λ

Notes: F.P. recall large R → sharp resonances

Transverse modes already discussed (briefly) TEM_{00} gaussian normally preferred

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