Lecture 1 - The Compound Semiconductor Palette - Outline

- **Announcements**
  - Handouts - General Information; Syllabus; Lecture 1 Notes
- **Why are semiconductors useful to us?** (Why isn't Si enough?)
  - Review of the properties of silicon
  - Quantifying the importance of silicon to the electronics industry
  - Representative applications silicon is not suitable for (...at least not yet)
- **Which materials are semiconductors?** (What are our choices?)
  - Elemental semiconductors
  - Compound semiconductors - binaries
    - 1. III-V's; 2. II-IV's; 3. IV-VI's; 4. I-VII's
  - Alloy semiconductors
    - 1. Ternaries; 2. Quarternaries; 3. Others: a) More than 4; b) Si-Ge
- **Properties vs. composition** (Making sense of all the options)
  - Crystal structure
  - Energy band structure
  - Carrier type and transport
  - Optical properties
  - Other

Important properties of silicon

- **Physical, structural**
  - Crystal structure: diamond
  - Lattice period (Å): 5.431
- **Energy levels**
  - Energy gap (eV): 1.1
  - Band symmetry: indirect gap
  - Density of states (cm^{-3}): $N_c = 2.8 \times 10^{19}$ $N_v = 1.02 \times 10^{19}$
- **Electrical, charge carriers**

	Electrons		Holes
Low field mobility ($cm^2/V\text{-}s$)	1450		450
Critical E-field (V/cm)	10^4		5×10^4
Saturation velocity (cm/s)	10^7		10^7
Effective mass (relative)	m_l 0.98	m_{lh}	0.16
	m_t 0.19	m_{hh}	0.5

- **Optical**
  - Absorption edge (λ_{gap}): 1.1 μm
  - Radiative lifetime (s): few ms
  - Typical radiative Efficiency (%): <<1%

Things that cannot yet be made from silicon

- **Light emitters**
  - **Light emitting diodes, Laser diodes** — any wavelength
- **Mid- and far-infrared detectors ($\lambda \geq 1.1\ \mu$m)**
  - **Fiber communication wavelengths** — λ = 1.3 and 1.55 μm
  - **Atmospheric windows** — λ = 3 to 5 μm and 8 to 12 μm
  - **Infrared imaging arrays** — night vision
  - **Thermophotovoltaic cells** — responding to 500 K black bodies
- **Ultraviolet detectors ($\lambda \leq 0.5\ \mu$m)**
  - **Solar blind detectors** — no response in visible
- **Optical modulators**
  - **Amplitude modulation of light** — for fiber telecomm
- **Very-high speed electronics**
  - **Systems operating at 40 GHz and above** — for fiber telecomm
- **High temperature electronics**
  - **Operable at temperatures above 200˚C** — process monitoring
- **Cryogenic electronics**
  - **Operating at 4.2 K and below** — space instrumentation

Materials other than Si that are semiconductors:

- **Elemental semiconductors**
  - **Column IV: C (diamond), Si, Ge, Sn (grey)**
  - **All have the diamond structure:**
  - **All are indirect band gap**

(Image deleted)

See Fig 3a in: Sze, S.M. Semiconductor Devices, Physics and Technology New York, Wiley, 1985.

(Image deleted)

See Fig 1-5-6 in: Shur, M.S. Physics of Semiconductor Devices Englewood Clifs, N.J., Prentice-Hall, 1990.

Notice the trend (E_g):

Sn: ~0.08 eV
Ge: 0.67 eV
Si: 1.12 eV
C: 5.5 eV

Diamond and Ge are useful, but we will say little about them.

Materials other than Si that are semiconductors:

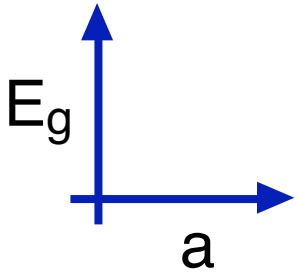
- **Binary compounds**

The choices are many-

Column III with column V (the three-fives, III-V's) : $A_{III}B_{V}$
Column II with column VI (the two-sixes, II-VI's): $A_{II}B_{VI}$
Column IV with Column VI (the four-sixes, IV-VI's): $A_{IV}B_{VI}$
Column I with Column VII: $A_{I}B_{VII}$ (these are insulators)

To help us make sense of all these options we will find that there are clear trends (a method to the madness)

The best way to start is by looking at plots of lattice period vs. energy gap...



	III	IV	V	VI
	B 5	C 6	N 7	O 8
II	Al 13	Si 14	P 15	S 16
Zn 30	Ga 31	Ge 32	As 33	Se 34
Cd 48	In 49	Sn 50	Sb 51	Te 52
Hg 80	Tl 81	Pb 82	Bi 83	Po 84

Compound Semiconductors: The zinc blende lattice

(Image deleted)

See Fig 3a in: Sze, S.M. Semiconductor Devices, Physics and Technology New York, Wiley, 1985.

Diamond lattice

(Image deleted)

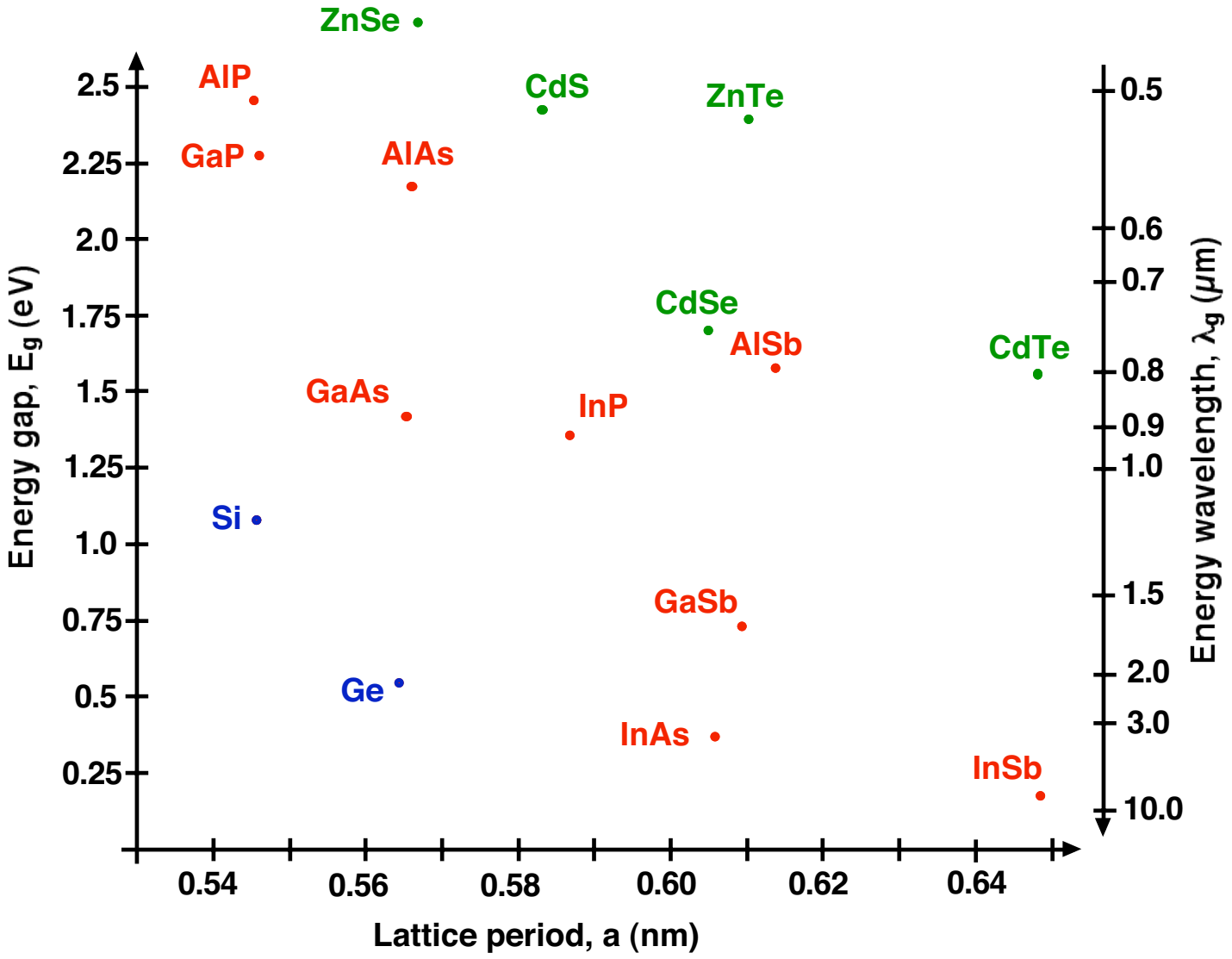
See Fig 3b in: Sze, S.M. Semiconductor Devices, Physics and Technology New York, Wiley, 1985.

Zinc blende lattice (GaAs shown)

Compound Semiconductors: Direct vs indirect bandgaps

(Image deleted)
See Fig 1-5-6 in: Shur, M.S. Physics of Semiconductor Devices
Englewood Cliffs, N.J., Prentice-Hall, 1990.

Binary Compound Semiconductors: Zinc-blende III-V's II-VI's



Binary Compound Semiconductors: Zinc-blende III-V's II-VI's

Material System	Semiconductor Name	Symbol	Crystal Lattice Structure	Period(A)	Energy Band Gap(eV)	Type
III-V	Aluminum phosphide	AlP	Z	5.4510	2.43	i
	Aluminum arsenide	AlAs	Z	5.6605	2.17	i
	Aluminum antimonide	AlSb	Z	6.1355	1.58	i
	Gallium phosphide	GaP	Z	5.4512	2.26	i
	Gallium arsenide	GaAs	Z	5.6533	1.42	d
	Gallium antimonide	GaSb	Z	6.0959	0.72	d
	Indium phosphide	InP	Z	5.8686	1.35	d
	Indium arsenide	InAs	Z	6.0584	0.36	d
	Indium antimonide	InSb	Z	6.4794	0.17	d
II-VI	Zinc sulfide	ZnS	Z	5.420	3.68	d
	Zinc selenide	ZnSe	Z	5.668	2.71	d
	Zinc telluride	ZnTe	Z	6.103	2.26	d
	Cadmium sulfide	CdS	Z	5.8320	2.42	d
	Cadmium selenide	CdSe	Z	6.050	1.70	d
	Cadmium telluride	CdTe	Z	6.482	1.56	d

Key: Z = zinc blende; i = indirect gap, d = direct gap

Additional Semiconductors: Wurzite III-V's and II-VI's
Lead Salts (IV-VI's), Column IV

Material System	Semiconductor Name	Symbol	Crystal Lattice Structure	Period(A)	Energy Band Gap(eV)	Type
III-V	Aluminum Nitride	AlN	W	a = , c =	6.2	i
(nitrides)	Gallium Nitride	GaN	W	a = 3.189, c = 5.185	3.36	d
	Indium Nitride	InN	W	a = , c =	0.7	d
II-VI	Zinc Sulfide	ZnS	W	a = 3.82, c = 6.28	3.68	d
(wurtzite)	Cadmium Sulfide	CdS	W	a = 4.16, c = 6.756	2.42	d
IV-VI	Lead Sulfide	PbS	R	5.9362	0.41	d
	Lead Selenide	PbSe	R	6.128	0.27	d
	Lead Telluride	PbTe	R	6.4620	0.31	d
IV	Diamond	C	D	3.56683	5.47	i
	Silicon	Si	D	5.43095	1.124	i
	Germanium	Ge	D	5.64613	0.66	i
	Grey Tin	Sn	D	6.48920	0.08	d
IV-IV	Silicon Carbide	SiC	W	a = 3.086, c = 15.117	2.996	i
	Silicon-Germanium	Si_xGe_{1-x}	Z	vary with x (i.e. an alloy)		i

Key: Z = zinc blende, W = wurtzite, R = rock salt; i = indirect gap, d = direct gap

Binary Compound Semiconductors: mobility trends

(Image deleted)

See Fig 1 in: Sze, S.M. ed., High Speed Semiconductor Devices
New York, Wiley, 1990.

(Image deleted)

See Fig 2 in: Sze, S.M. ed., High Speed Semiconductor Devices
New York, Wiley, 1990.

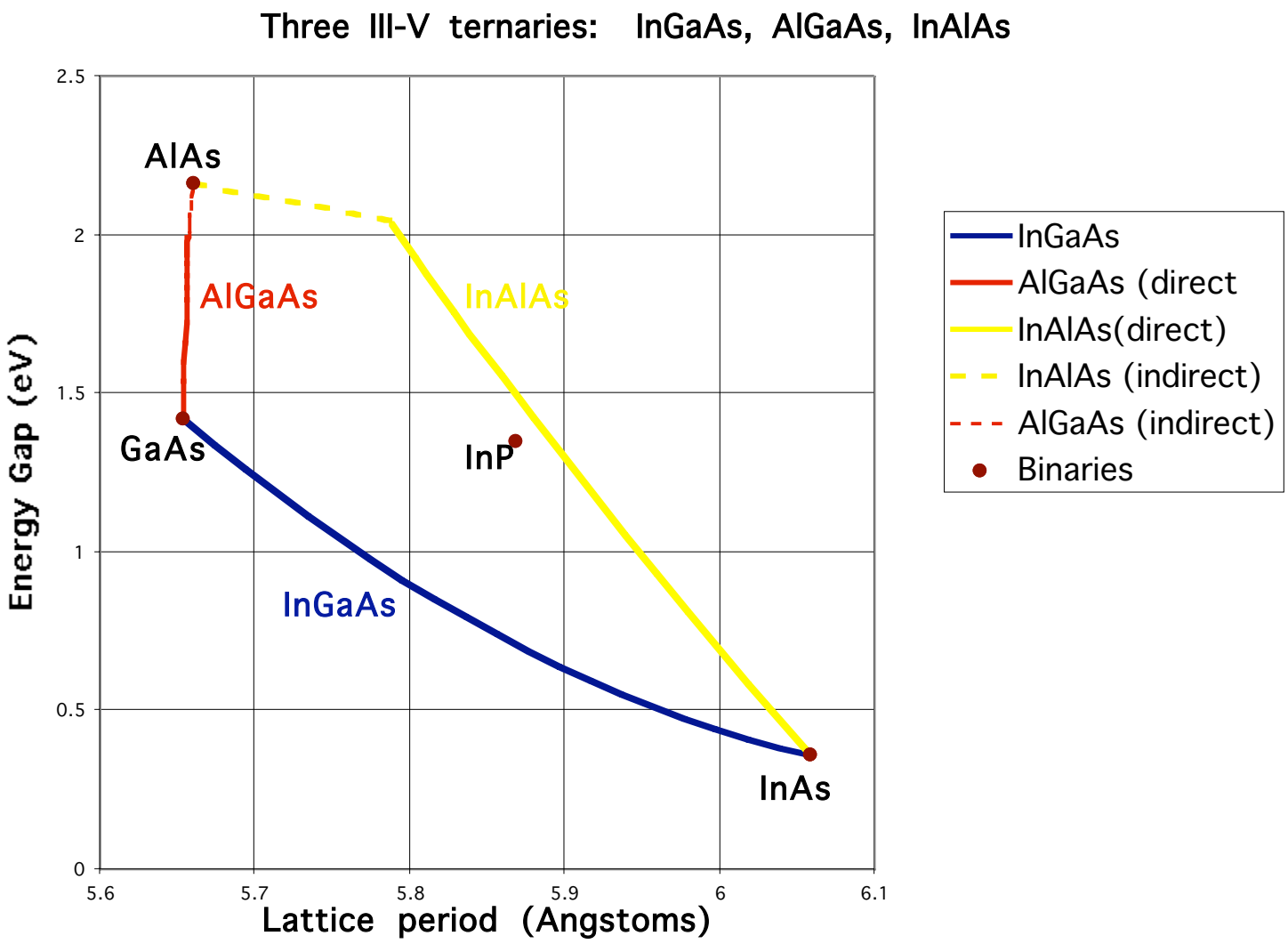
Materials other than Si that are semiconductors:

- **Binary compounds**
  - Most have direct bandgaps. (very important to optoelectronic device uses)
  - They cover a wide range of bandgaps, but only at discrete points.
  - They follow definite trends
  - They can be grown in bulk form and cut into wafers.
  - We still need more….
- **Ternary alloys**
  - Not compounds themselves, but alloys of two binary compounds with one common element. (ternary compounds are of limited interest)
  - Ternary alloys have two elements from one column, one from another and there are two options: (III-V examples)

    $A_{III(1-x)}B_{III(x)}C_V$ $\{= [A_{III}C_V]_{(1-x)} + [B_{III}C_V]_{(x)}\}$

    $A_{III}B_{V(1-y)}C_{V(y)}$ $\{= [A_{III}B_V]_{(1-y)} + [A_{III}C_V]_{(y)}\}$
  - With ternary alloys we have access to a continuous range of bandgaps

Ternary Alloy Semiconductors: 3 III-V examples, AlGaAs, InGaAs, InAlAs



Ternary trends:

Lattice period: linear with composition (Vegard's Law)

Band gaps: quadratic with composition; slope and curvature vary with band minima

Ternary trends:

↑ Most properties, such as effective mass, vary quadraticly and monotonically with alloy fraction.

Alloy scattering is largest near a 50% mix and transport properties tend to not vary monotonically. →

Materials other than Si that are semiconductors:

- **Ternary alloys**

  Give us access to continuous ranges of bandgaps,
  but as E_g varies so in general does a.

  Substrates are always binary and only come at discrete a's.

  Thus to grow heterostructures we need different E_g layers,
  all with the same a, and ternaries don't do the full job.

  (Note: AlGaAs is an important exception; since it is intrinsically lattice-matched to GaAs it was used in the first heterostructure work. However, soon more was needed...)

- **Quarternary alloys**

  Quarternaries mix 4 elements - there are 2 types: (III-V examples)

  1. 2 elements from one column, 2 from the other: (mixes of 4 binaries)

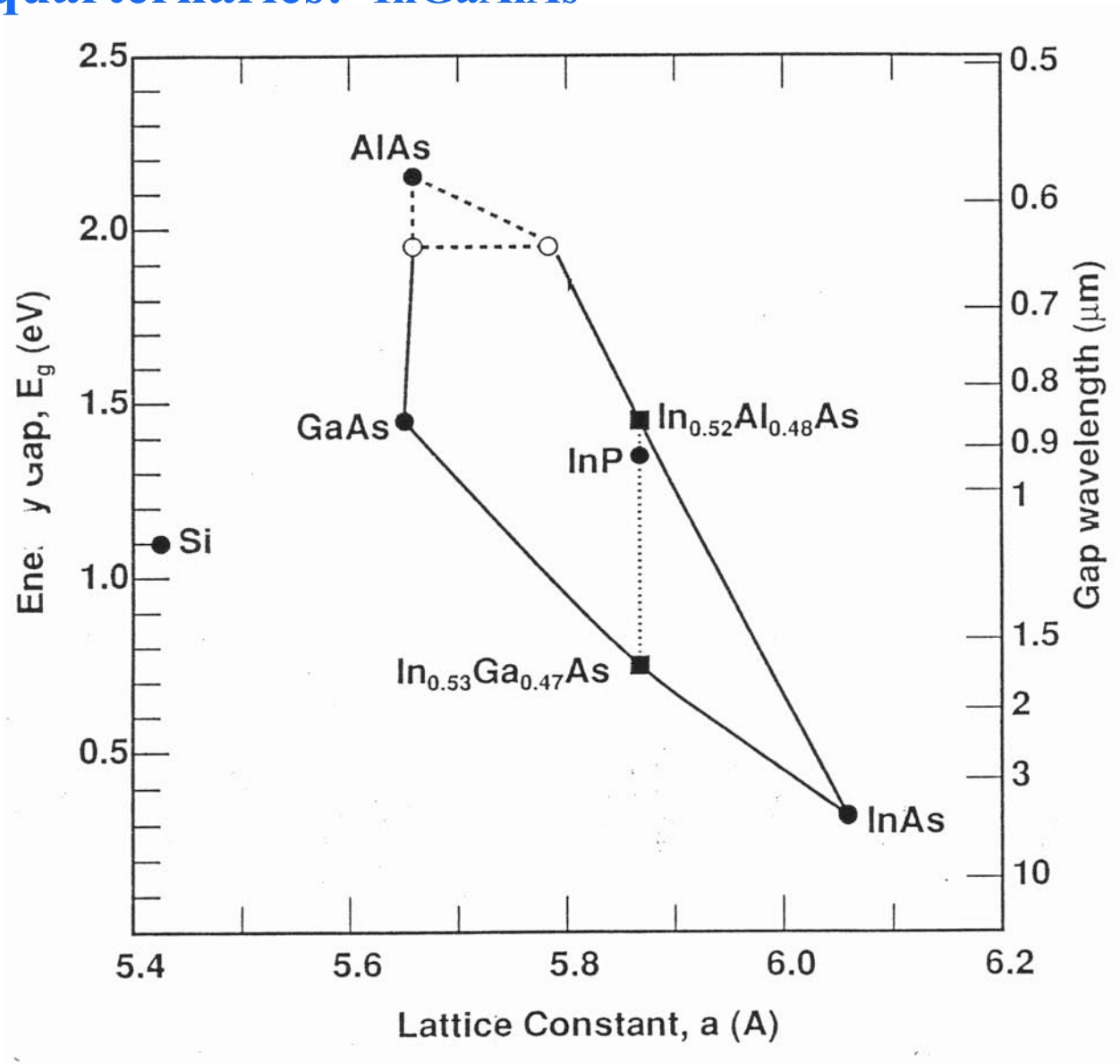
     $A_{III(1-x)}B_{III(x)}C_{V(1-y)}D_{V(y)}$ $\{= [A_{III}C_V]_{(1-x)(1-y)}+[A_{III}D_V]_{(1-x)y}$
     $+[B_{III}C_V]_{x(1-y)}+[B_{III}D_V]_{xy}\}$

  2. 3 elements from one column, 1 from the other: (3 binary mixes)

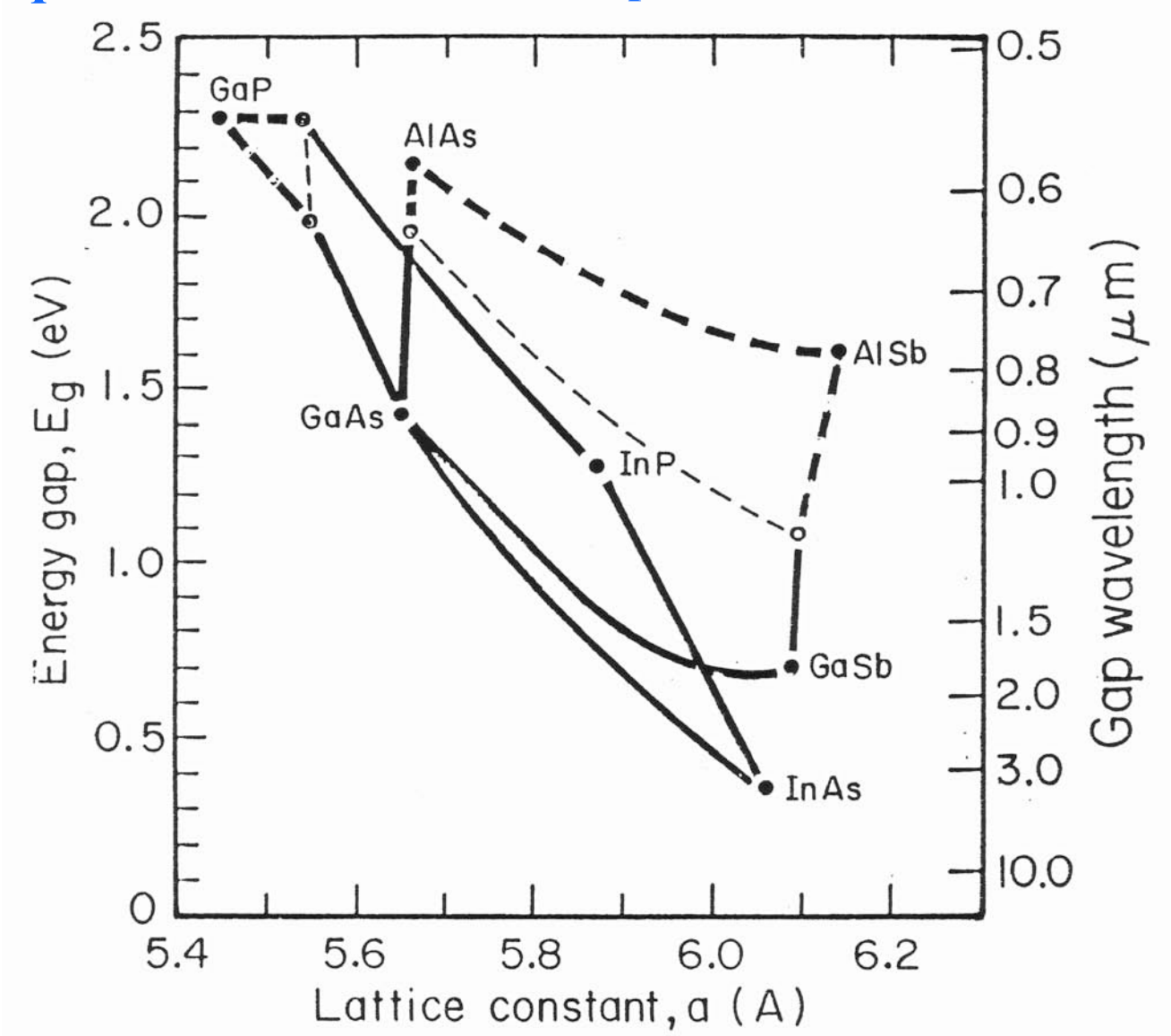
     $A_{III(1-x-y)}B_{III(x)}C_{III(y)}D_V$ $\{= [A_{III}D_V]_{(1-x-y)}+[B_{III}D_V]_{(x)}+[C_{III}D_V]_{(y)}\}$
     $A_{III}B_{V(1-x-y)}C_{V(x)}D_{V(y)}$ $\{= [A_{III}B_V]_{(1-x-y)}+[A_{III}C_V]_{(x)}+[A_{III}D_V]_{(y)}\}$

  With quarternary alloys we have access to ranges of
  in materials that are all lattice-matched to a binary substrate

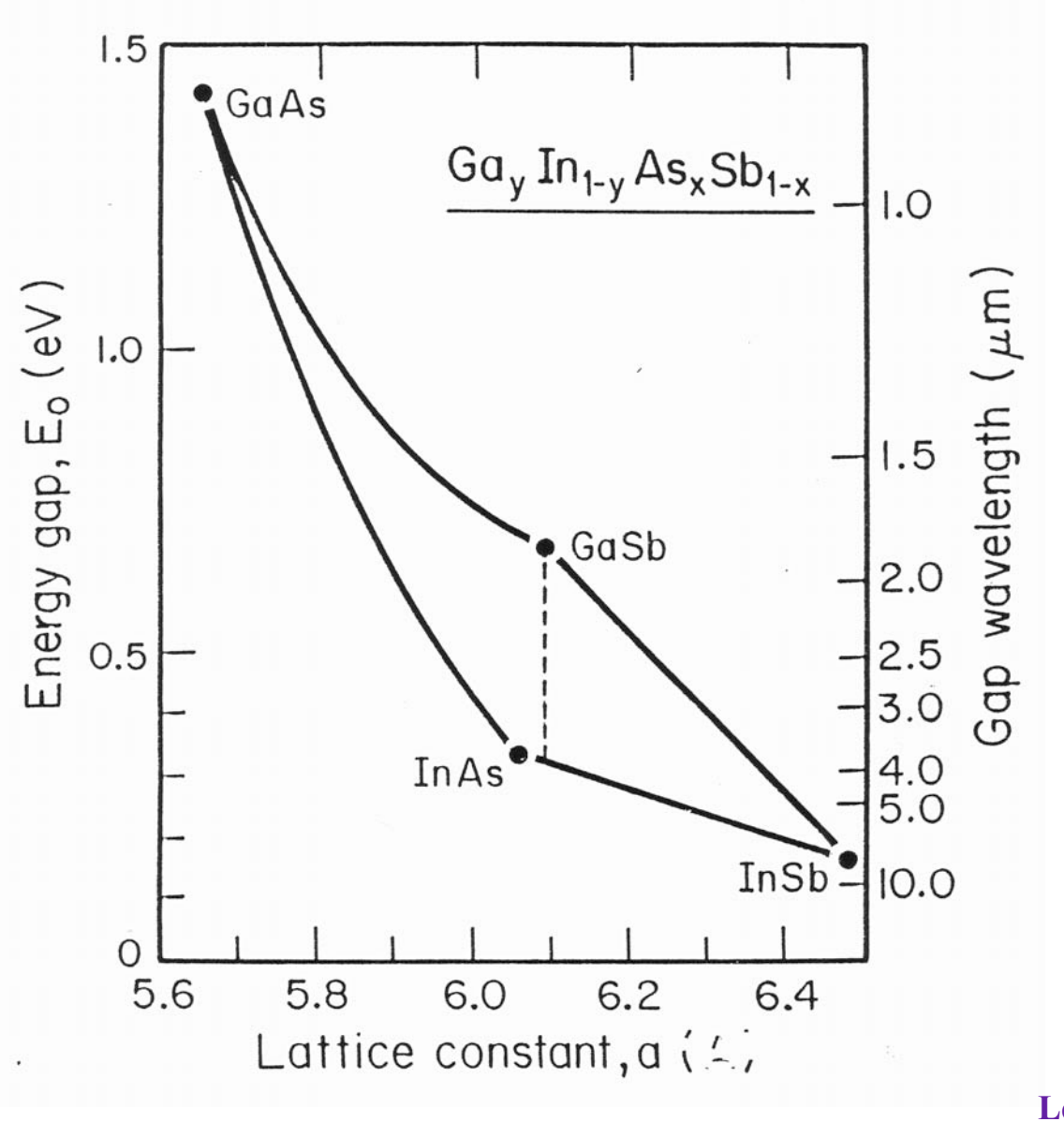
III-V quarternaries: InGaAlAs



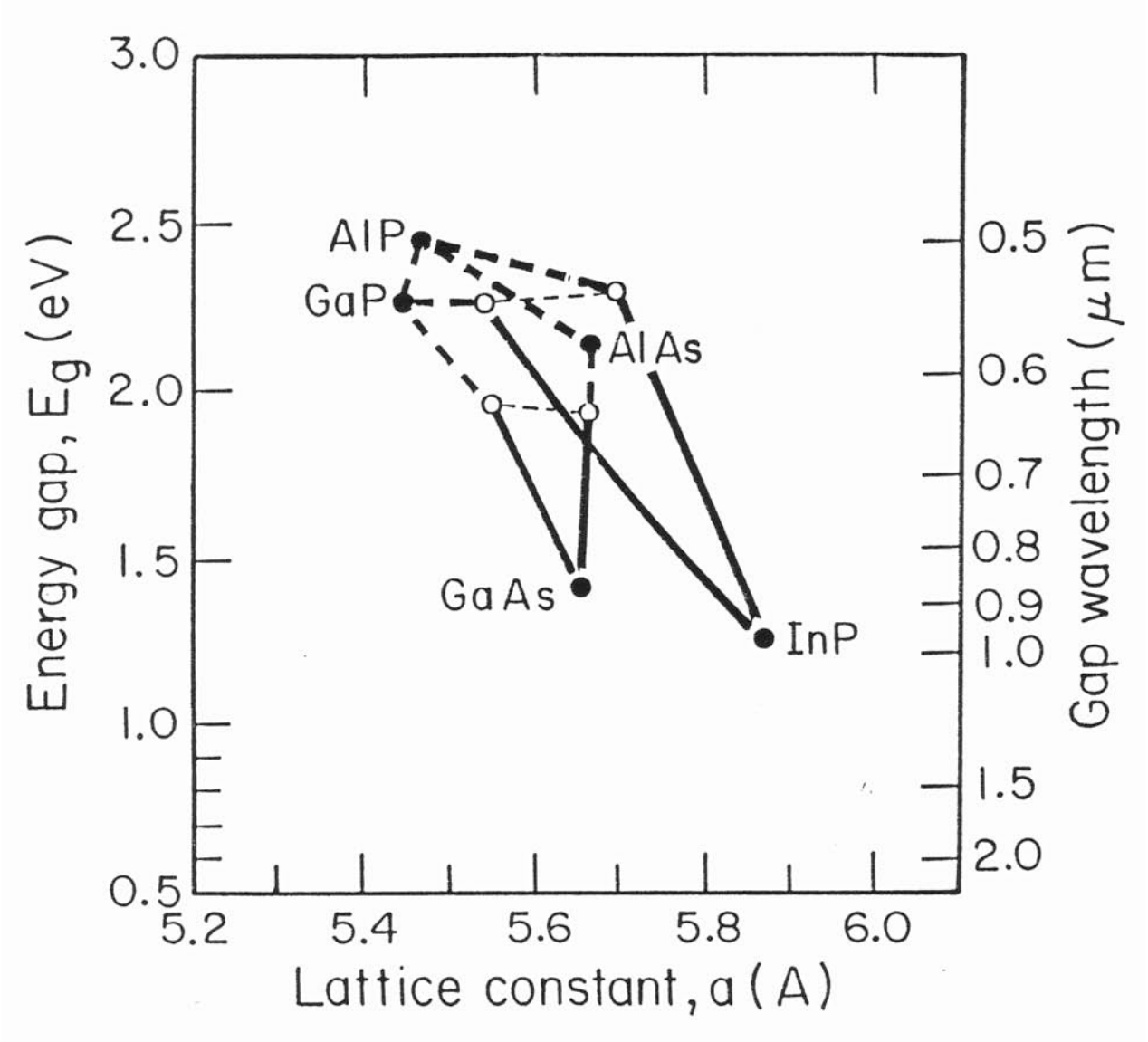
III-V quarternaries: more examples InGaAsP and AlGaAsSb



III-V quarternaries: more examples GaInAsSb

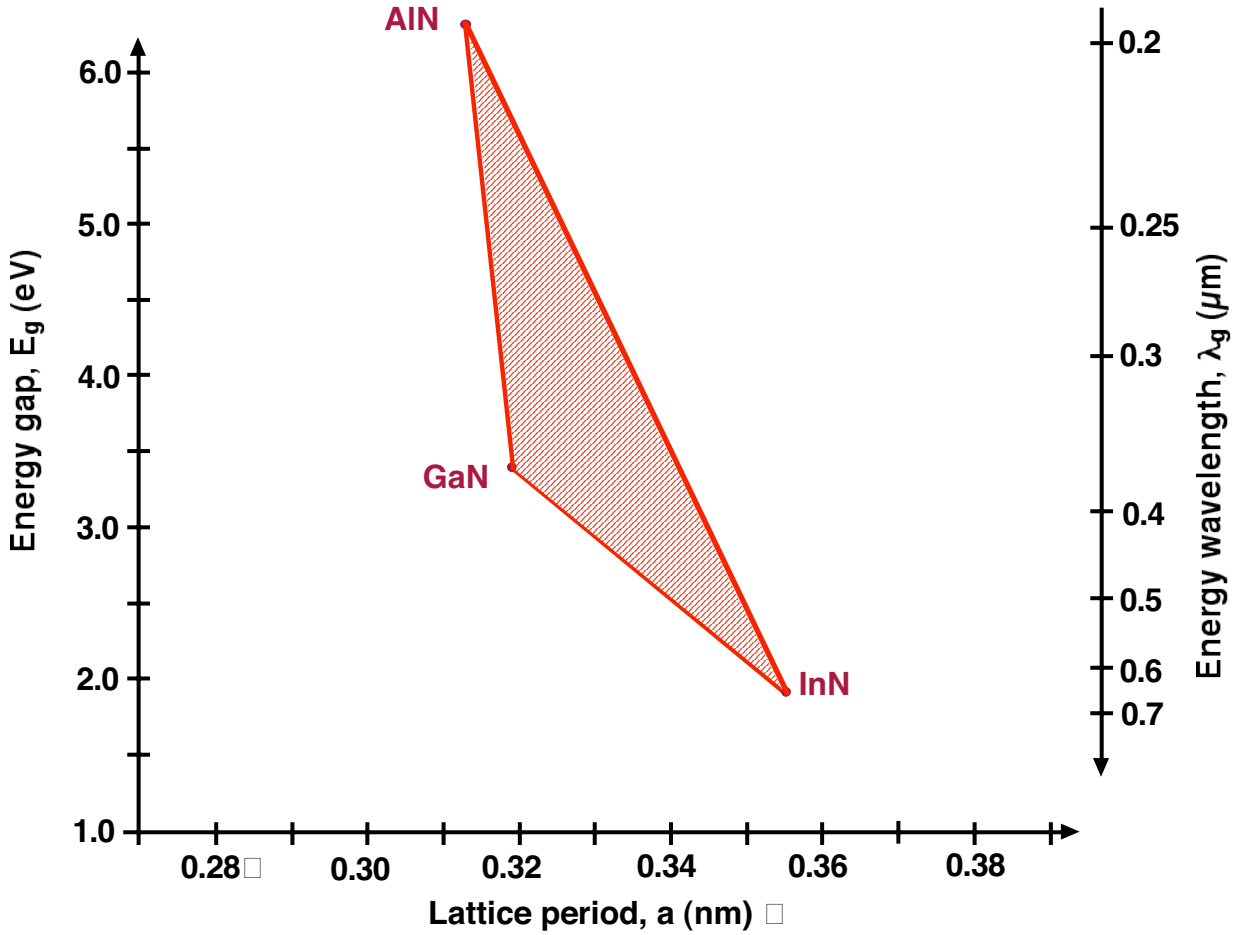


III-V quarternaries: more examples GaAlAsP and GaAlInP



The III-V wurtzite quarternary:

GaInAlN



(Image deleted)

See Fig 2a: Sze, S.M. Physics of Semiconductor Devices, 2nd ed. New York: Wiley, 1981

So…where are we?
Are all these semiconductors important?

- **All have uses, but some are more widely used than others**
  - GaAs-based heterostructures
  - InP-based heterostructures
  - Misc. II-IVs, III-Vs, and others
- **Important Binaries**

GaAs	substrates, MESFETs
InP	substrates
GaP	red, green LEDs

- **Important Ternaries and Quaternaries**

AlGaAs on GaAs	HBTs, FETs, optoelectronic (OE) devices
GaAsP on GaAs	red, amber LEDs
HgCdTe on CdTe	IR imagers
InGaAsP, InGaAlAs on InP	OEs for fiber telecomm.
InGaAlAs on InP	ditto
InGaAs on GaAs, InP	ohmic contacts, quantum wells
InGaAsP on GaAs	red and IR lasers, detectors
GaInAlN on various substrts.	green, blue, UV LEDs, lasers

Lecture 1 - The Compound Semiconductor Palette - Summary

- **Why are semiconductors useful to us?**
  - **Unique electrical and optical properties we can control**
  - **Silicon falls short in light emission and at performance extremes**
    (...at least so far)
- **Which materials are semiconductors?**
  - **Elemental semiconductors: Si, Ge, Sn**
  - **Compound semiconductors - binaries**
    - **1. III-V's; 2. II-IV's; 3. IV-VI's; 4. I-VII's**
  - **Alloy semiconductors: 1. Ternaries; 2. Quarternaries; 3. Si-Ge**
- **Properties vs. composition**
  - **General observation** - energy gap increases, lattice period decreases as move up periodic table and out from Column IV
  - **Crystal structure** - determines compatibility; heterostructure feasibility; lattice spacing varies linearly with alloy composition
  - **Energy band structure** - important for electrical and optical properties
  - **Carrier type and transport** - narrower gap implies higher electron mobility; hole mobilities change little; cannot always have p-type when gap is large
  - **Optical properties** - direct band-gaps essential for some applications; indirect band-gaps appear in wider band gap materials