Lecture 1

Instructor and TA Info

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TA Office Hours: TBD

Course Info

Catalog Description:

Electrical and optical properties of semiconductor materials. Direct and indirect gap semiconductors. Luminescence. Bulk and quantum well materials. Fundamentals of optoelectronic devices. LEDs. Photoconductors. Photodiodes. Modulators. Integrated optics.

Course Prerequisites:

ECE 162A, 162B

Required Text: Course Notes

Recommended Reading:

Optical Electronics in Modern Communications, A. Yariv, ISBN 0-19-510626-1, 6th Edition, Oxford University Press, 2006.

Course Topics

1. Electronic properties of semiconductor materials for optoelectronic devices:

   Develop firm understanding of the theory and fundamental electrical characteristics of semiconductor materials relevant to optoelectronic devices.

2. Optical properties of selected semiconductor materials:

   Develop sound understanding of basic optical characteristics of some semiconductor materials.

3. P-N junction – the basic structure for optoelectronic device realization

   Gain sound understanding of the principles of operation of various junctions, including Schottky contacts and heterojunctions and their importance to optoelectronic device fabrication.

4. Light Emitting Diodes (LEDs):

   Develop good understanding of the principles of operation of LEDs, their structures and applications.

5. Semiconductor Laser Diodes

   Understand the principles of operation of semiconductor laser diodes and the role they play in modern fiber optic communication systems.

6. Photodetectors

   Understand the operation of different types of photodetectors: PIN, APD, Photoconductive and Bolometer.

7. Optoelectronic modulators.

   Understand the principles of the electro-optic effect, materials that exhibit the EO effect and how they can be fabricated into practical intensity or phase modulators.

Homework and Grading

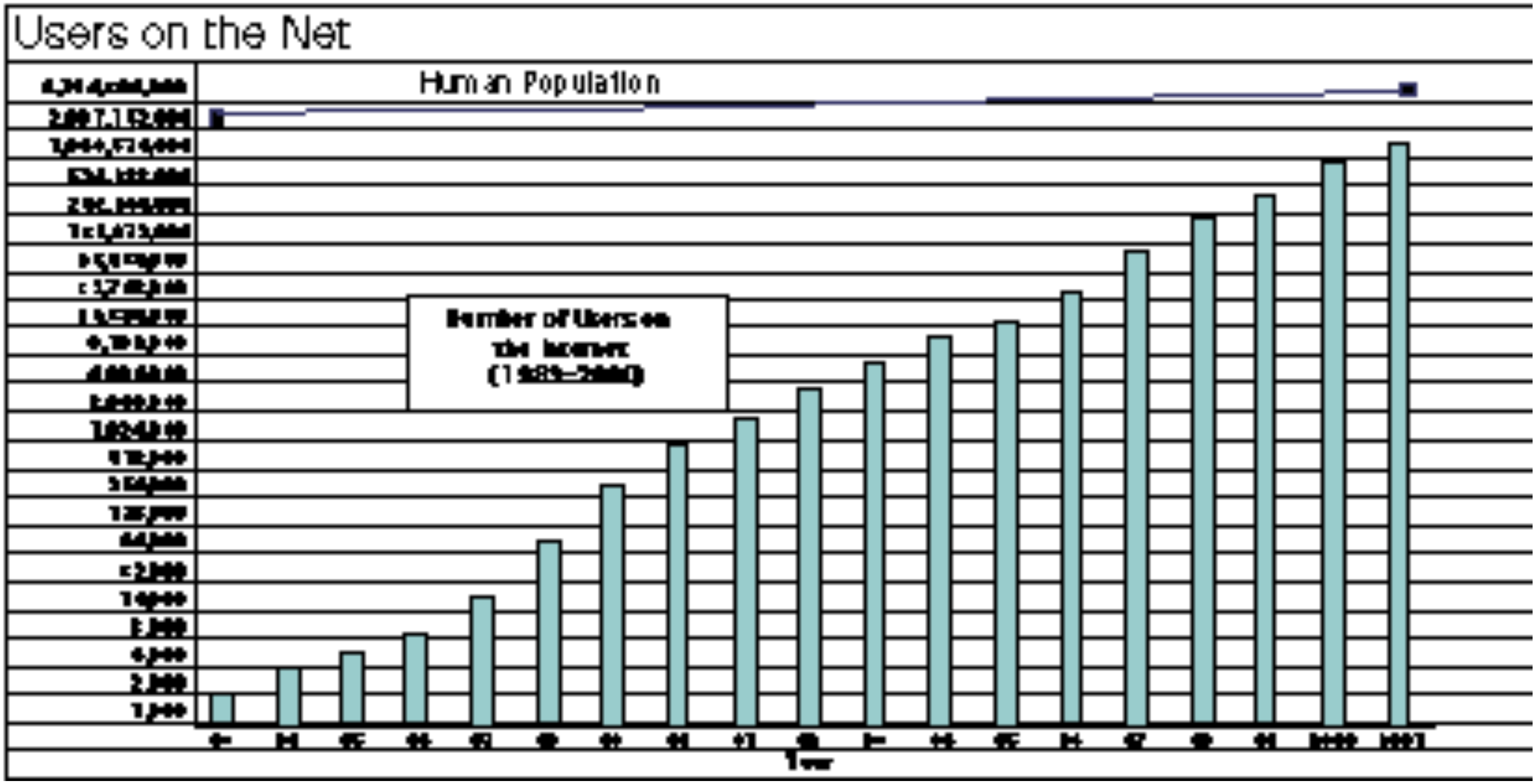
Homework:

Will be assigned each week on Tuesday and due the following Tuesday at the start of class. Late homework up to 1 day late will receive 20% reduction in grade. Assignments handed in more than 1 day after due date will not be graded.

Grading:

Homework:	30%
Midterm Exam:	30%
Final Exam:	40%

Motivation: Internet Growth



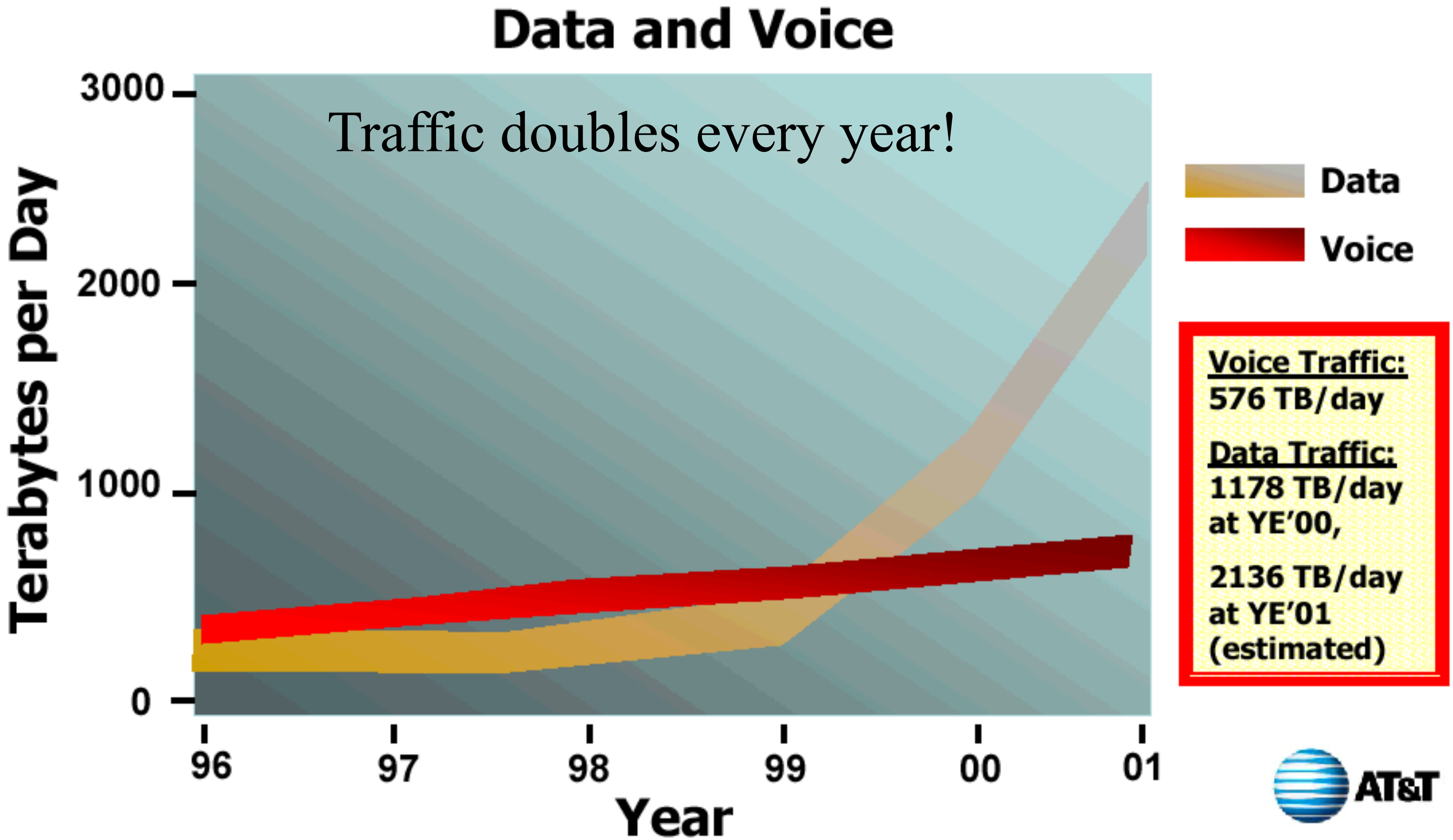
Motivation: Bandwidth

- E-mail: 10 bit/s
- World Wide Web: 1 Mbit/s
- Internet videoconferencing: 10 Mbit/s
- Video on demand, HDTV: 100 Mbit/s to 1Gbps

Motivation: Bandwidth

- More users x Higher bandwidths = More transmission capacity.
- Today: 100 million users x 50 kbit/s = 5 Tbit/s worldwide
- 2015: 5 billion users x 50 Mbit/s = 250 Pbit/s (P stands for peta =10^{15})

Growth in Network Traffic



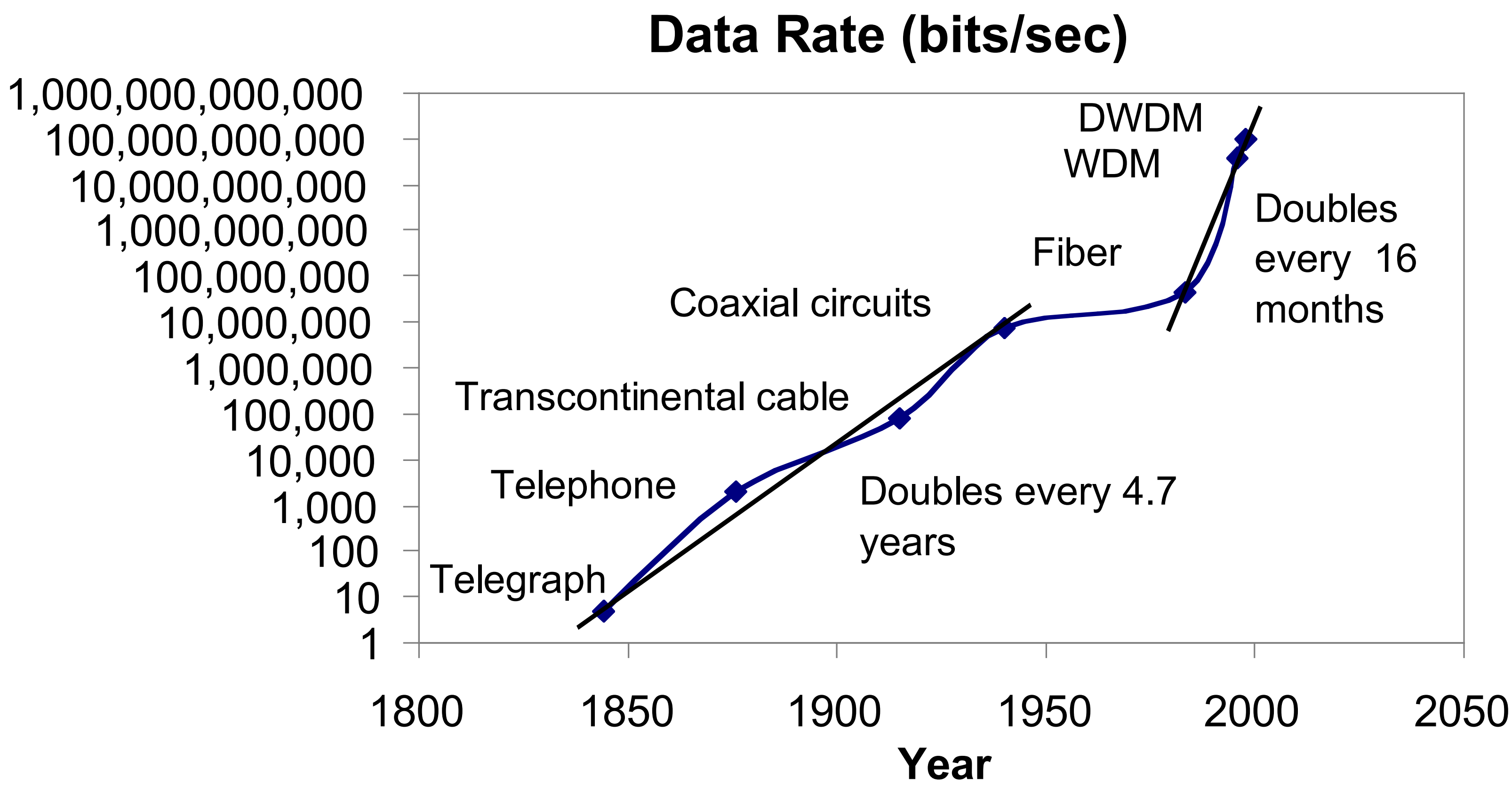
AT&T

Data Transmission

-2000	0.1 Bit/s	Smoke Signals
-300	1 Bit/s	Alphabetic signaling (Greeks)
1840	10 Bit/s	Telegraph (Morse)
1870	100 Bit/s	Time Division Multiplexing (Baudot)
1930	1 kBit/s	Teletype
1970	50 Mbit/s	Microwave transmission
1979	100 Mbit/s	LEDs/Fiber optic transmission
1985	1 Gbit/s	Lasers/Single mode fiber
1996	10 Gbit/s	WDM: Wavelength division multiplexing

Law of the Photon

Data rate doubles every 16 months



Optical Fiber: Propagation Limits

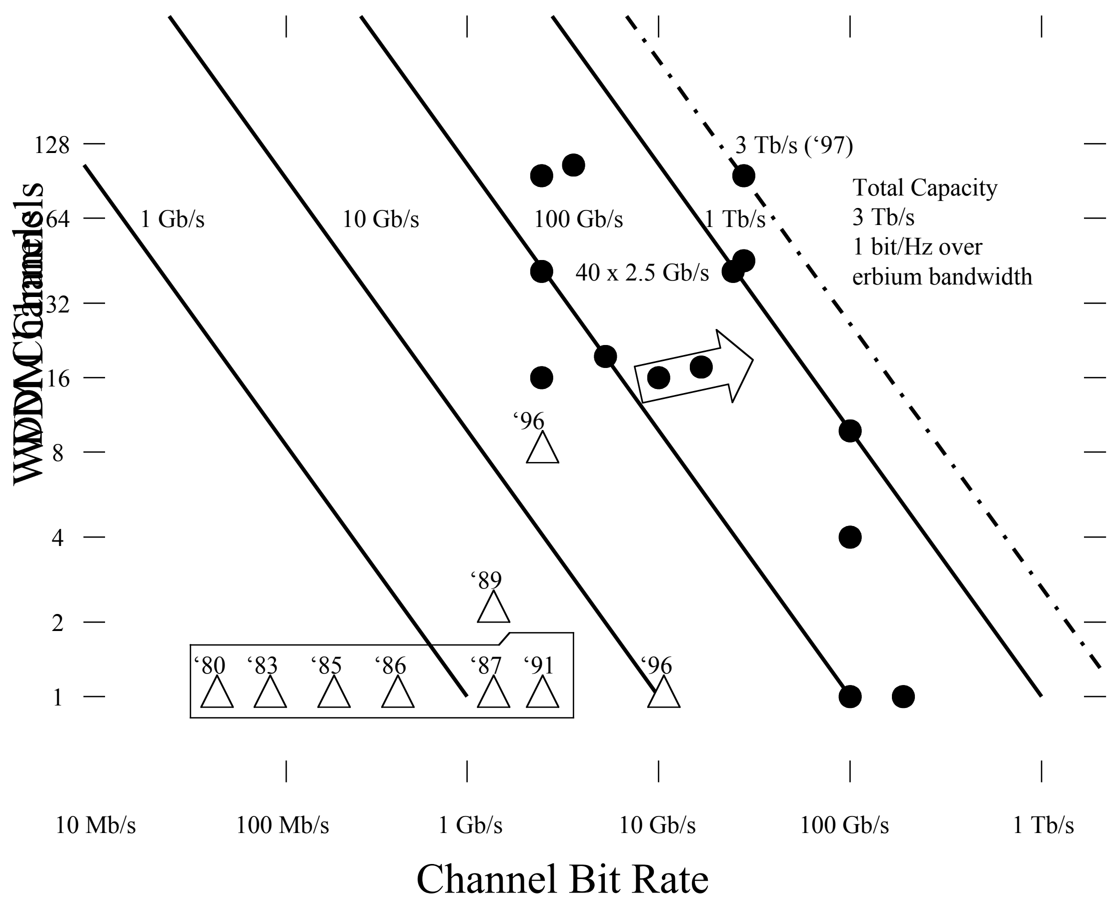
Medium	Max Bit Rate	Loss at 10 Gbit/s
Twisted pair:	100 kbit/s	
Coaxial cable:	1 Gbit/s	1 dB/m
Microwave waveguide:	1 Gbit/s	0.1 dB/m
Optical fiber (0.82 μm)	1 Gbit/s	0.001 dB/m
Optical fiber (1.55 μm)	100 Gbit/s	0.0002 dB/m

The low loss window in optical fiber is from 1.3 to 1.6 μm is 50,000 GHz wide.

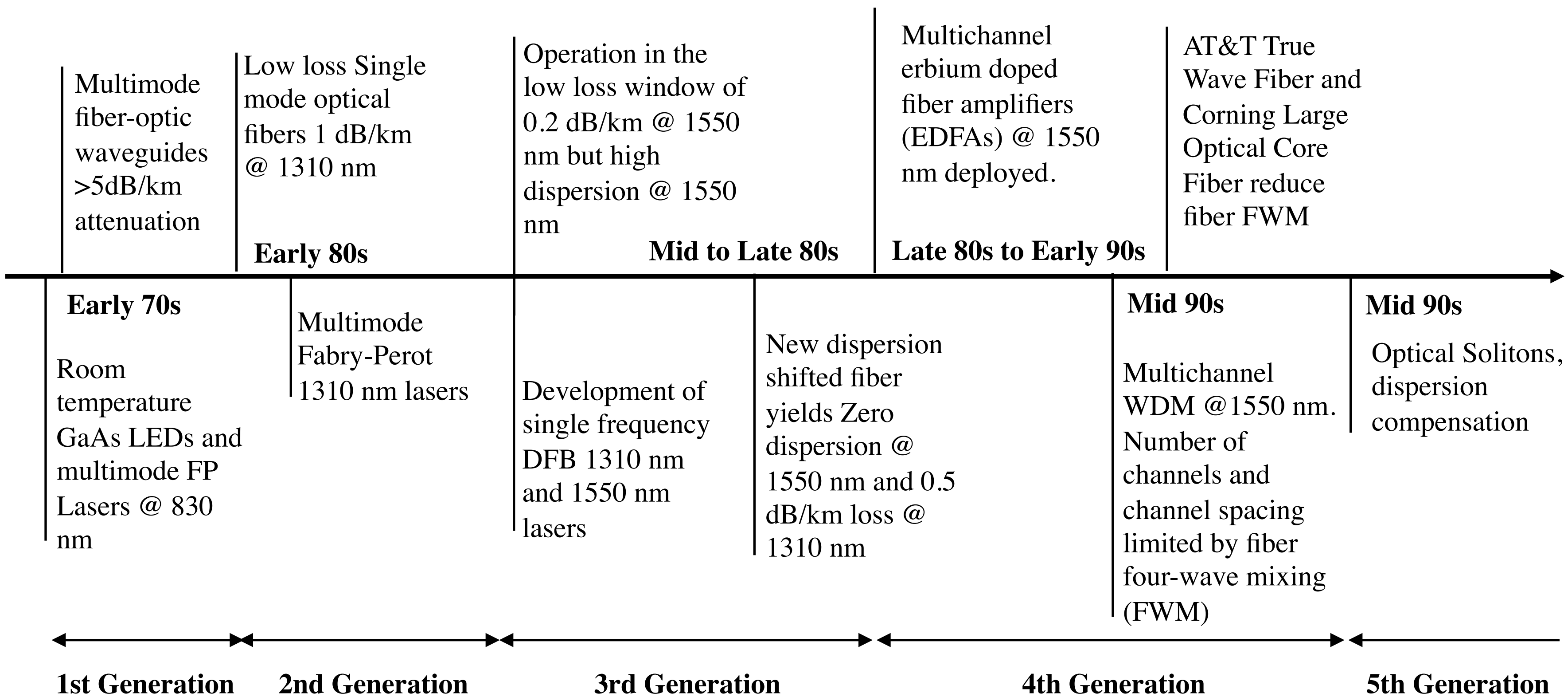
How to Achieve Higher Capacity?

- More cables
- More fibers/cables (600 fibers/cable common)
- Higher bit rates (10 Gbit/s now standard, 40Gbps being installed)
- Multiple wavelengths (WDM) (32-96 commercial)

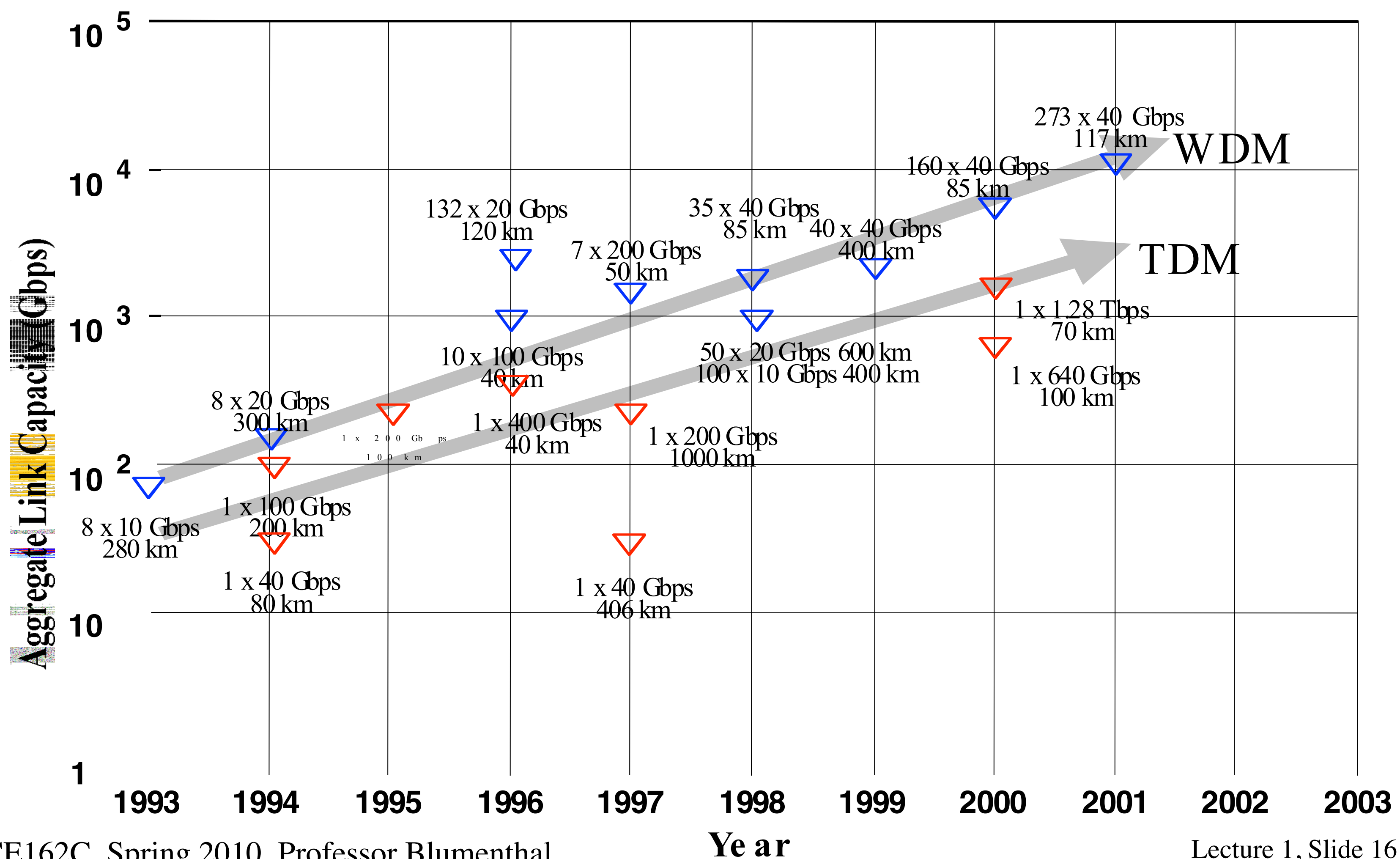
Lightwave Trends



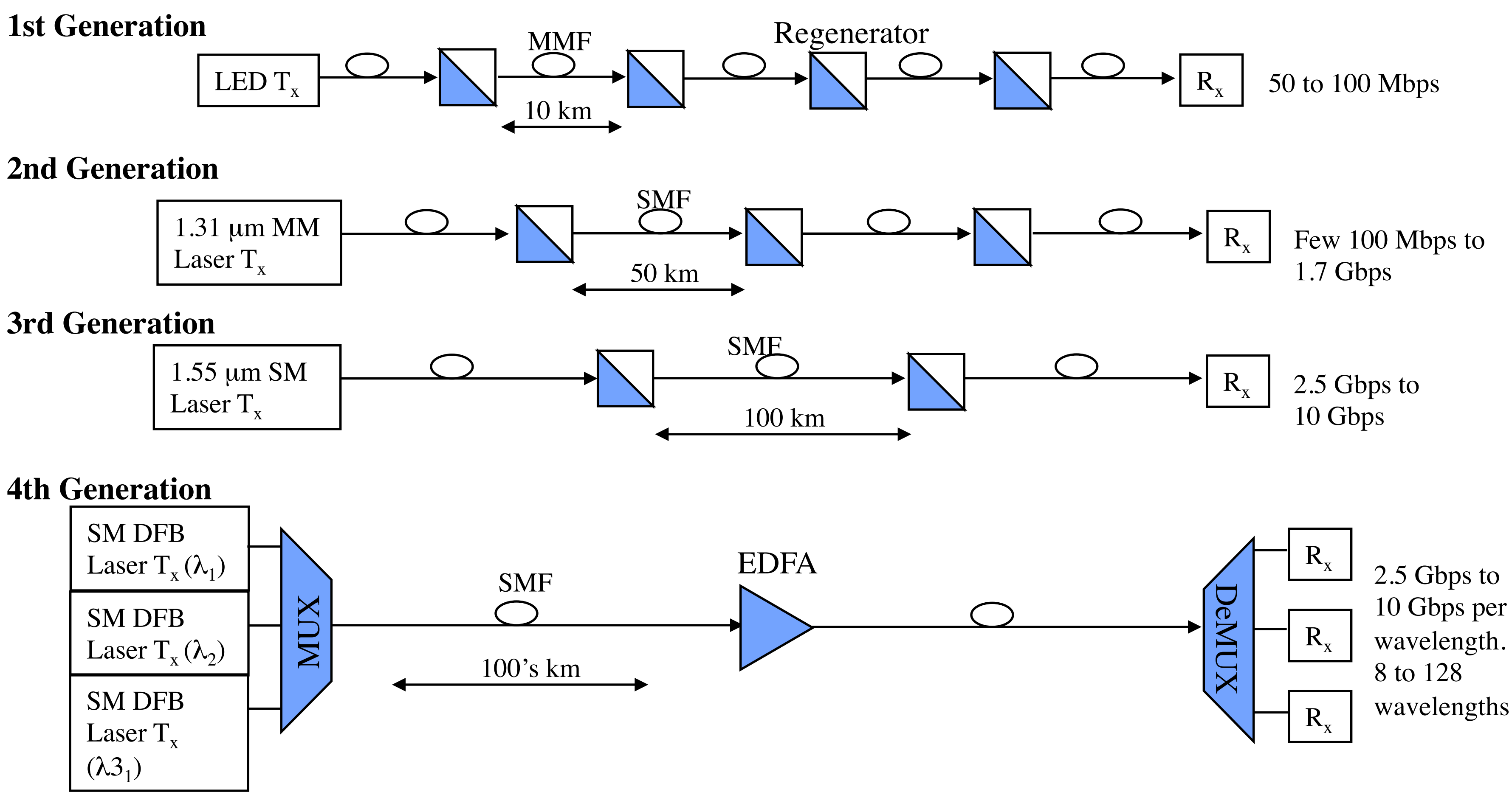
Evolution of Fiber-Optic Point-to-Point Transmission



Transmission Bandwidth Evolution



Capacity and Repeater Spacing



Evolution of Fiber-Optic Networks

Point-to-point fiber links connected to electronic switching equipment

Late 80s

First MANs. 100 Mbps FDDI and 200 Mbps ESCON for data communications. SONET and SDH for Telecommunications.

High performance data communications. Serial HIPPI standard introduced, fiber at 1.2 Gbps. Fiber Channel standard introduced at 200, 400 and 800 Mbps.

Mid to Late 90s

Layered Networking. ATM and IP over SONET.

Introduction of Optical Channel (OC) layer by the ITU. Routing in the optical layer.

Late 90s

Fixed wavelength add/drop multiplexing. Protection and survivability in the optical layer.

Early to late 2000

Reconfigurable WDM add/drop multiplexers. Optical crossconnects

Optical wavelength conversion. Optical regeneration. Optical packet switching.

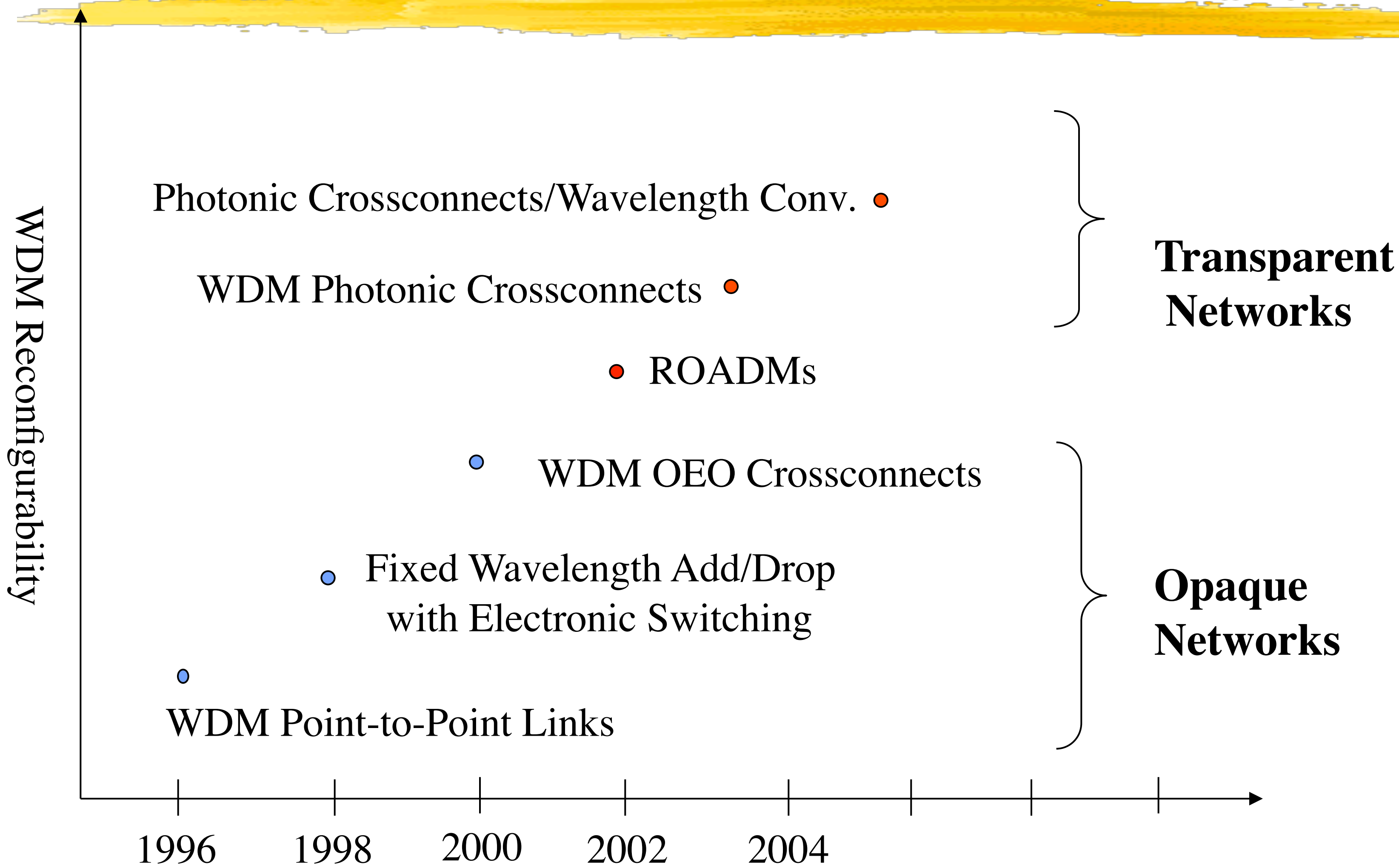
Late 00s

1st Generation

2nd Generation

3rd Generation

WDM Optical Network Evolution



High Volume:
Fiber to the Home (FTTH)

	FTTH	FTTC
Bandwidth	Huge	Large
Cost	\$1200	\$800
Labor	23%	26%
Materials	19%	23%
Fiber	8%	7%
Electronics	58%	51%
Optoelectronics	14%	2%

FTTH Initiatives announced by Verizon, Bellsouth, SBC for 2004-2010

What You Need to Know

- Modes in optical fibers (wave equation …)
- Modes in optical waveguides (lasers, modulators, …wave equation, birefringence)
- Lasers (gain, absorption, lasing,…)
- Modulators, Photodetectors, Amplifiers
- Multiplexers, Dispersion compensation

Optoelectronics

- Photodetectors:
  - Usually crystalline material (lower dark current, hence better sensitivity)
  - Bandgap smaller than required (but no more than necessary. Smaller bandgaps tend to have larger dark currents).
- Lasers
  - Always crystalline material
  - Bandgap equal to hc/λ

Growth

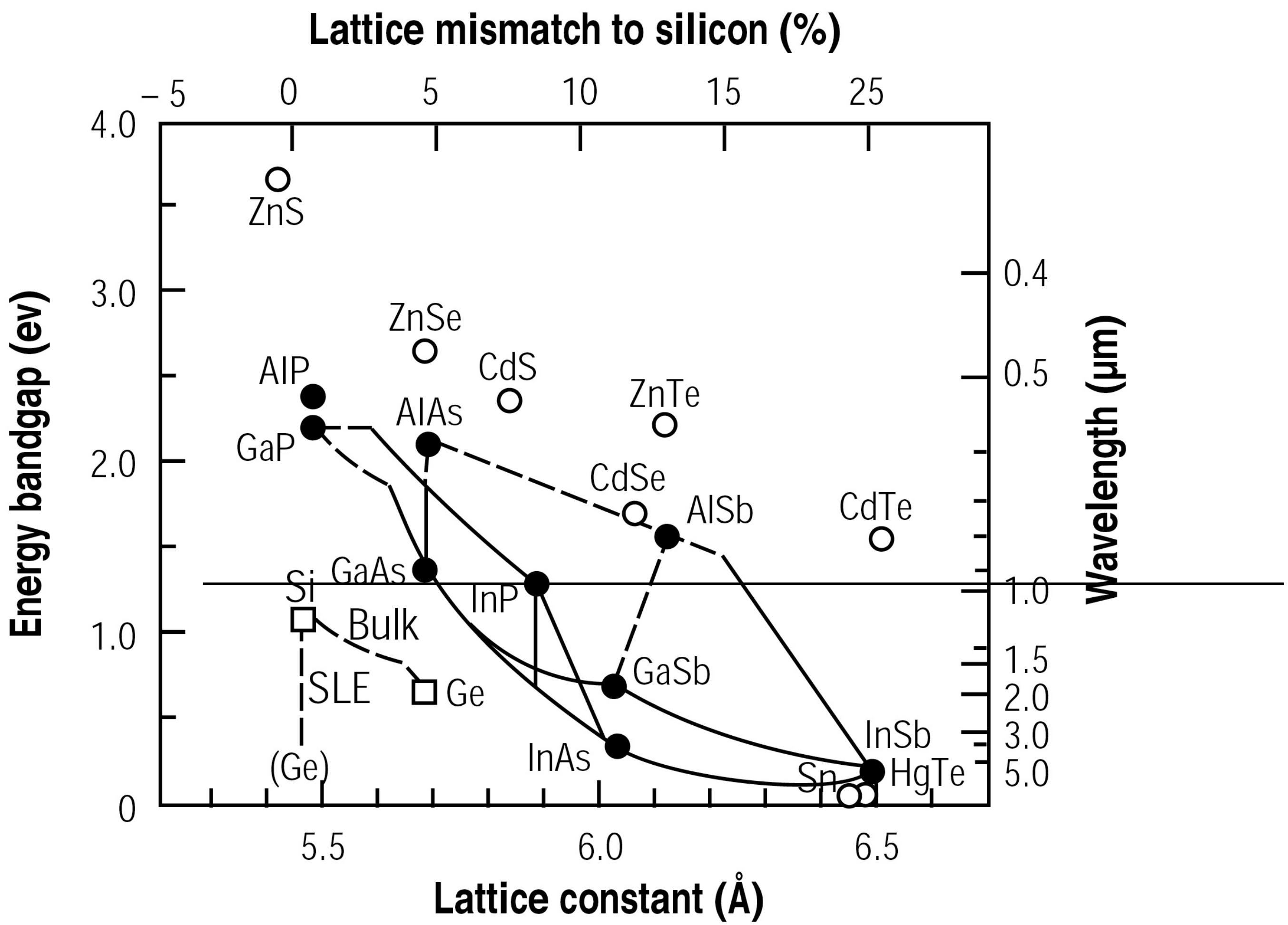
- MBE: Molecular beam epitaxy
- MOCVD: Metal organic chemical vapor deposition
- Substrate: Binary (otherwise every wafer is a little different)
- Epitaxy requires lattice constant equal to binary substrate.
- Correct lasing wavelength require correct bandgap.
- Hence, a quaternary layer is required (two degrees of freedom):
  - $In_xGa_{1-x}As_yP_{1-y}$

Ternary Materials

- Mix two binaries together. The bandgap is approximately the arithmetic average of the two (Vegard's law) e.g. $Ga_xAl_{1-x}As$
- There are two types of sites: group III and group V. (II-VI compounds also possible).
- Ternaries cannot be grown on binary substrates in general because the lattice constants don't line up and dislocations occur. Special case: $Ga_xAl_{1-x}As$ because the lattice constants of GaAs and AlAs are almost equal.

Quaternary materials

- To match bandgap and lattice constant, two degrees of freedom are required.
- Example: $Ga_xIn_{1-x}As_yP_{1-y}$
  - X is the fraction of group III sites occupied by Ga.
  - Y is the fraction of group V sites occupied by As.
- In a bandgap chart, the dots are binaries, the lines are ternaries, and the regions bounded by 4 lines are quaternaries.



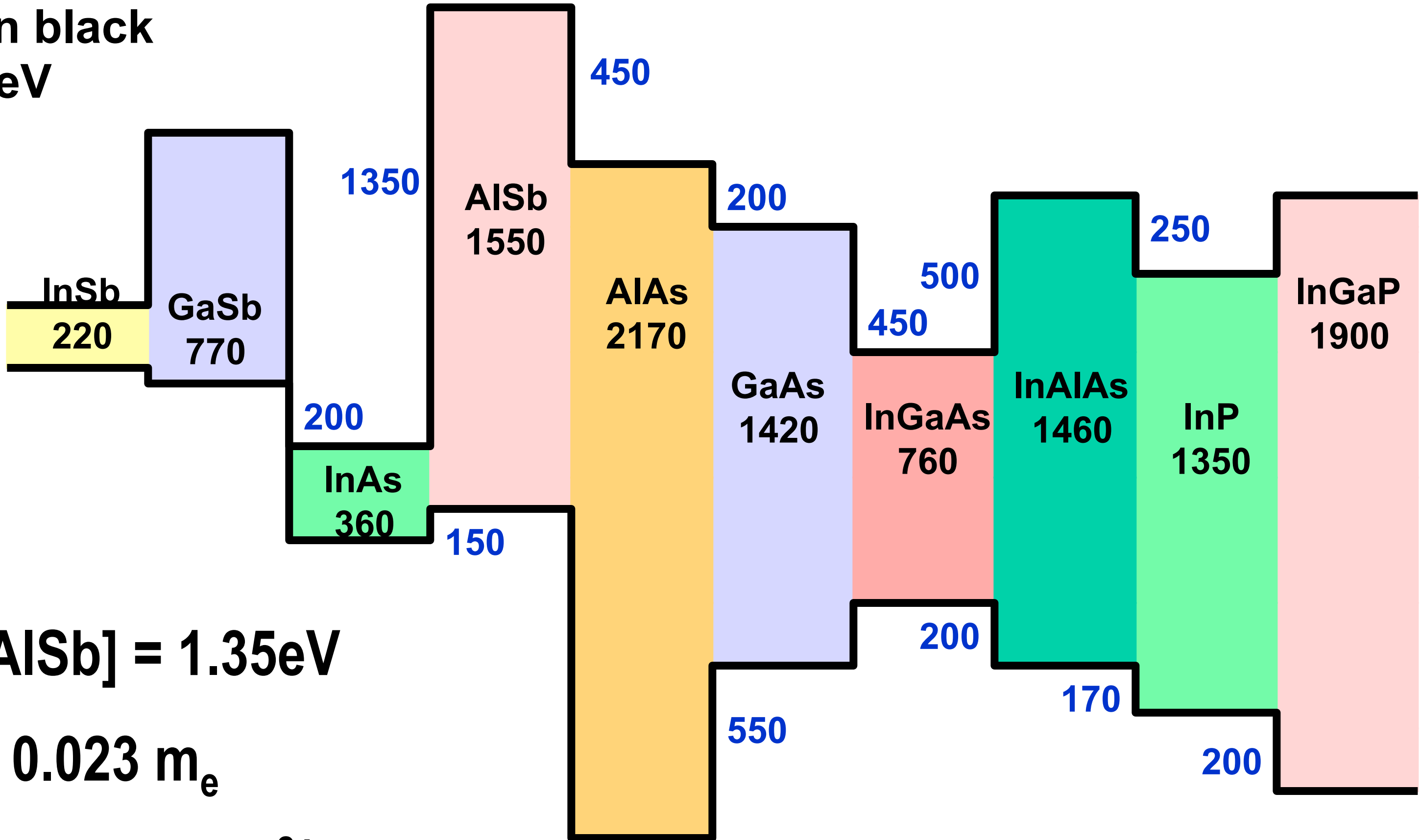
Lattice mismatch to silicon (%)
– 5
0
5
10
15
25
4.0
3.0
2.0
1.0
0
Energy bandgap (ev)
ZnS
ZnSe
CdS
ZnTe
AlP
GaP
AlAs
CdSe
AlSb
CdTe
GaAs
Si
InP
Bulk
SLE
Ge
GaSb
(Ge)
InAs
InSb
Sn
HgTe
0.4
0.5
1.0
1.5
2.0
3.0
5.0
Wavelength (μm)
5.5
6.0
6.5
Lattice constant (Å)

Epitaxial Layers

- Epitaxial layers of different compound semiconductors can be grown on top of each other.
- Small differences in lattice constants can be accommodated for thin layers (strained layers: Compressive or tensile).
- Too much accumulated strain results in dislocations.

Bandgap Heaven

- Offsets in blue #s
- Bandgaps in black
- Units are meV



ΔE_C [InAs-AlSb] = 1.35eV

m* [InAs] = 0.023 m_e

InAs RT μ > 30,000 cm^2/Vs

Guidelines

- Figure out bandgaps. (draw horizontal where there is no depletion).
- Figure out conduction band and valence band discontinuity.
- Figure out Fermi level for each material.
- Draw flat band first, then flatten out the Fermi level.
- Keep the band separation constant for any region where the bandgap is not changing.