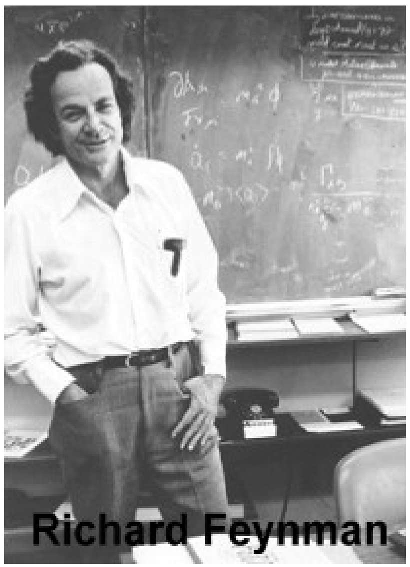
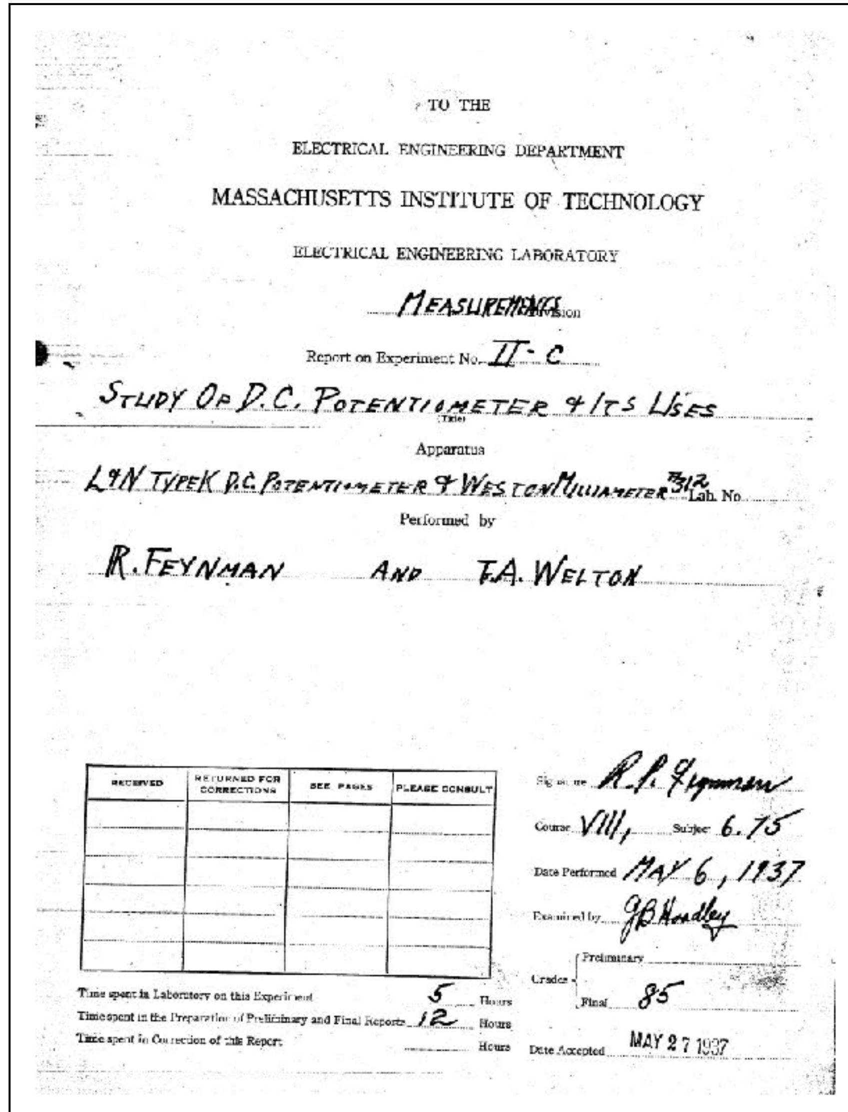
Richard Feynman, 1965 Nobel
One of the greatest physics teachers
One of the fathers of Nanoscience



[Feynman's 1937 Electronics lab report]
(85% grade)



TO THE
ELECTRICAL ENGINEERING DEPARTMENT
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
ELECTRICAL ENGINEERING LABORATORY

MEASUREMENTS Division

Report on Experiment No. II - C

STUDY OF D.C. POTENTIOMETER & ITS USES
(Title)

Apparatus

L&N TYPE K D.C. POTENTIOMETER & WESTON MILLIAMETER 312 Lab. No.

Performed by

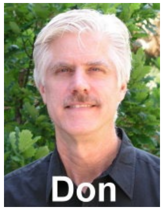
R. FEYNMAN AND T.A. WELTON

RECEIVED	RETURNED FOR CORRECTIONS	SEE PAGES	PLEASE CONSULT

Signature R. P. Feynman
Course VIII, Subject 6.75
Date Performed MAY 6, 1937
Examined by G.B. Hoadley
Grades: Preliminary .... Final 85

Time spent in Laboratory on this Experiment 5 Hours
Time spent in the Preparation of Preliminary and Final Reports 12 Hours
Time spent in Correction of this Report .... Hours

Date Accepted MAY 27 1937



Calendar of Topics Covered

Physics PHYS 2371/2372, Electronics for Scientists

Don Heiman and Hari Kumarakuru
Northeastern University, Fall 2020

Also see **Course Description** and **Syllabus**

This is a schedule of the topics covered, but it may be modified occasionally (10/22/2020).

Week #	Lectures	Weekly Topics (Chs.)	Homework (Ch-Problem)	Lab Experiments (always look for latest version)
VII Oct 19, 21-23 **MON/WED**	**MONDAY** **EXAM-I**	**Wed Lecture** Magnetoelectronics Magnetoelectronics Lecture Magnetic induction/flux Transformers (Ch-11)	11-all	**Lab-6, *Build a Magnetometer*** Lab-6 video, Lab-6 data
VIII Oct 28-30	**Wed Lecture** Optoelectronics	Photodiode, LED, laser	none	**Lab-7, *Optoelectronics*** (coupled LED-photodiode)
IX Nov 2, 4-6 **MON/WED**	**Mon/Wed Lectures** MON Digital-1 WED Digital-2	Digital Logic (Ch-19,22), Binary Numbers (Ch-54) Logical Networks (Ch-20)	19-all, 20-all	**Lab-8a, *Digital Circuits*** (truth table, 4-bit decoder)
X Nov 11-13	**Wed Lecture** Pulsed ICs	Lecture: Pulsed ICs Digital Summary	21-1/2	**Lab-8b, *Pulsed Digital*** (Flip-flops, counter, displays)
XI Nov 18-20 **WED EXAM**	**EXAM-II - Wed** Final Project	**EXAM-II: Magnetoelectronics, Optoelectronics, Digital/Pulsed**		***Final Project***
XII Nov 25-27	No Lecture	**Thanksgiving**		No Lab
XIII Dec 2	**Wed Lecture**	Future Electronics		***Project PowerPoint*** **due Monday Dec 2** (EG361 or email file)
XIV Dec 7-9	**No Classes**			

Optoelectronics

Communications
- Highspeed, femtosec pulses, GHz
- Ease of coupling to electronics
- Multichannel, indep wavelengths

Light Spectrum and Vision
- Chromaticity Diagram

Spectral Response of Semiconductors
- Semiconductor **Bandgap**
  Quantum Mechanics

Light Detectors
- Photovoltaics (solar cells)

Light Emitters
- LED, Laser Diode, Ruby Laser

Lab-7, Optoelectronics

Optoelectronics

- **Optoelectronics**
  Optical + Electronic
  O → E or E → O
- **For what?**
  - Memory (CD ROM)
  - Laser printers
  - Communications (fiber optics)
- **Optical Communications**
  – fiber optics (Verizon FiOS)
- **Light Spectrum and Vision**
  – Chromaticity Diagram
- **Spectral Response of Semiconductors**
  – Semiconductor Bandgap
- **Light Detectors** - Photovoltaics (solar cells)
- **Light Emitters** - LED, Laser Diode

Semiconductors

- **Light Emitters**
  E → O
  - *LEDs (blue, white)*
  - *laser diodes*
  - *light bulbs*
- **Light Detectors**
  O → E
  - *Si solar cells*
  - *InGaAs*

All have *pn*-junctions

Optoelectronics

- Optoelectronics
  - Optical + Electronic
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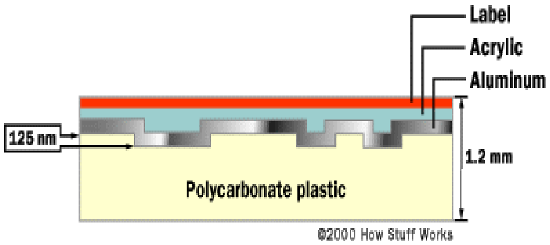

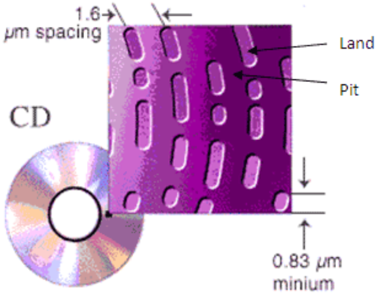

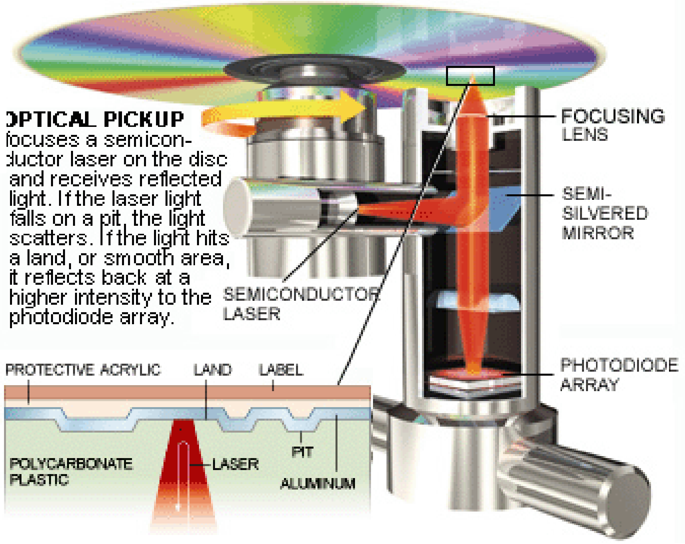

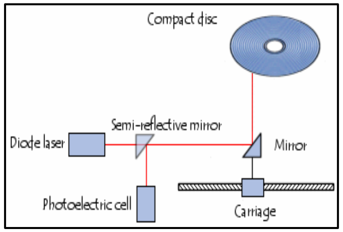

How (CD) Compact Discs Work (0:32)

Optoelectronics

- Optoelectronics
  - Optical + Electronic
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Telegraphy History

Communicating over distances

Optical Telegraphy

ancient times - smoke signals, lamps

semaphores
1684 – proposal by Robert Hooke
1767 – first implementation
1791 – 10 miles in French Revolution

Electrical Telegraph

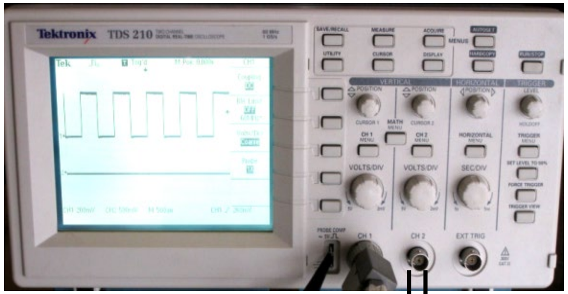
1753 – suggestion, one wire per letter
1833 – first by Gauss/Weber
1837 – Samuel Morse "code" 1:15
1837 – commercialized, 13 miles
1858 – transatlantic cable

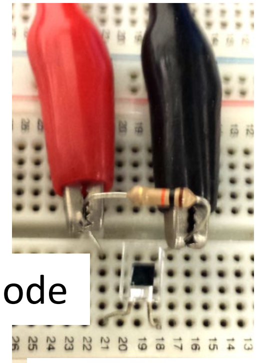
Back to Optical Pulses in Glass Fibers

1880 – Alexander Graham Bell (in air)
1962 – first diode laser (picoseconds)
1963 – glass fibers proposed
1965 – Telefunken system

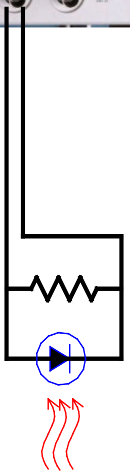
Questions ?

Example of Optical Digital Encoding
TV Remote "Clicker"

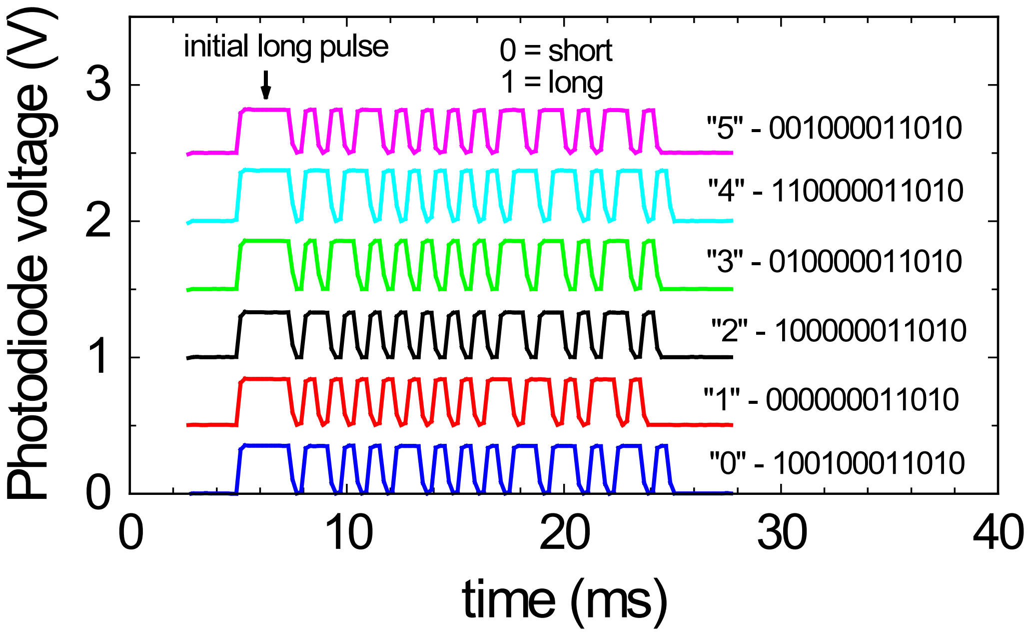




photodiode



LED



Questions ?

Optoelectronics

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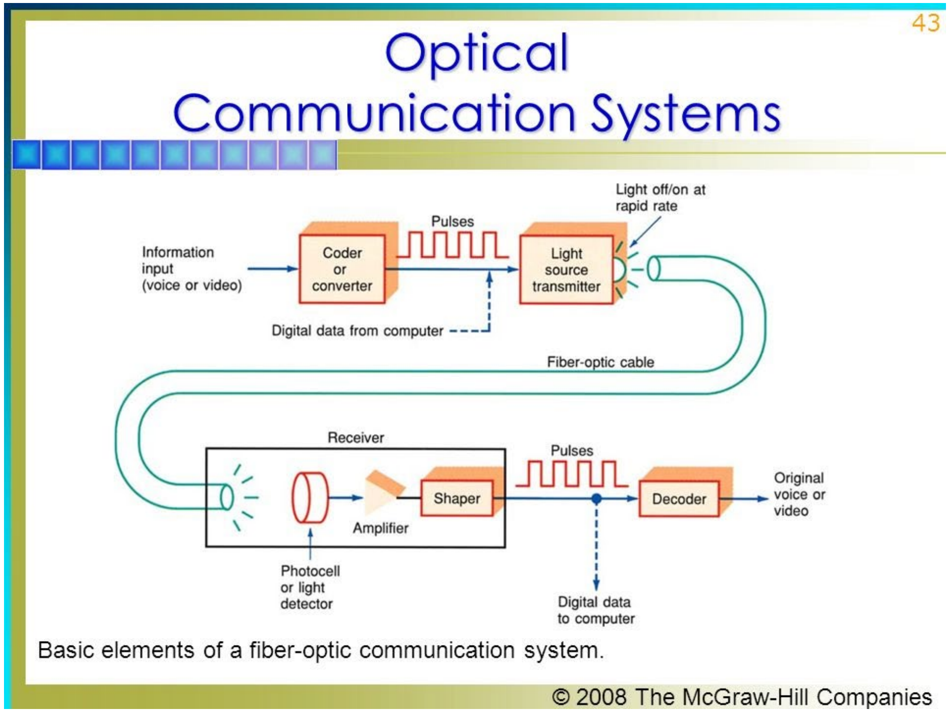
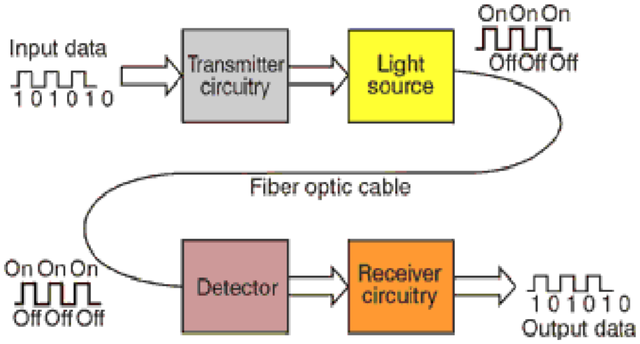
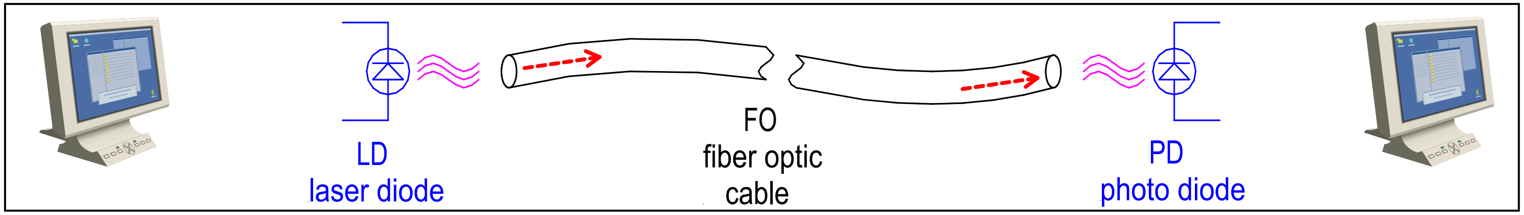


Basic elements of a fiber-optic communication system.



Fiber Optic Communication System



The illustrated Fiberoptic (FO) communication system contains:

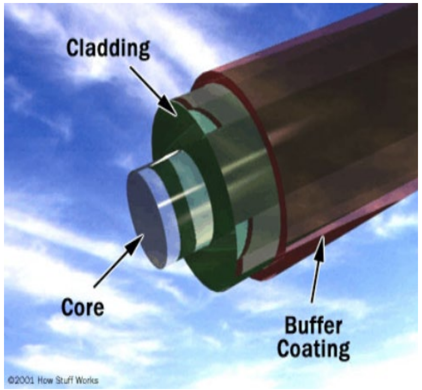
(1) laser diode (LD) is electrically modulated (on/off) with digital information;
(2) FO cable transmits the light pulses;
(3) photodiode converts the light pulses back into electrical pulses.

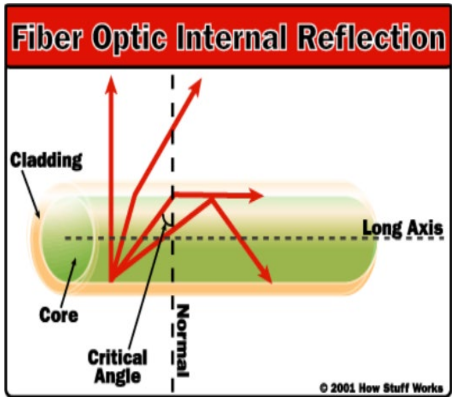
Most FO systems use light pulses generated by a **GaInAsP** semiconductor laser diode operating at **1.55 μm wavelength**, where the transmission in the glass fiber is at a minimum.

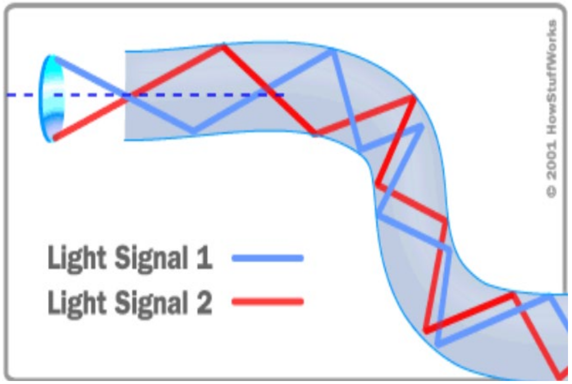
In a 10 GHz system the pulses are only a **few cm in length**. Pulses are transmitted through single-mode fibers of optical glass (SiO_2=silica=quartz) having a core diameter of about 6-8 μm.

At the receiving end of the optical fiber the pulses are detected by a high-speed **InGaAs photodiode** that converts the encoded light pulses back into electrical pulses.

Optical Fibers







FO cable where the light passes through the glass core

Internal reflection inside the glass fiber

Transmission of light inside the FO core

For light to exhibit **total internal reflection**, the cladding layer must have a smaller refractive index than the core region.

Improvements in FO Communication Systems

Transatlantic communications cable

1858 first transatlantic wire **telegraph** cable.

1988 first transatlantic glass **fiber optic** cable.

Commercial FO cables typically have four strands of fiber cost ~ $300M

Time to cross the Atlantic (NYC-London) ~60-70 ms.

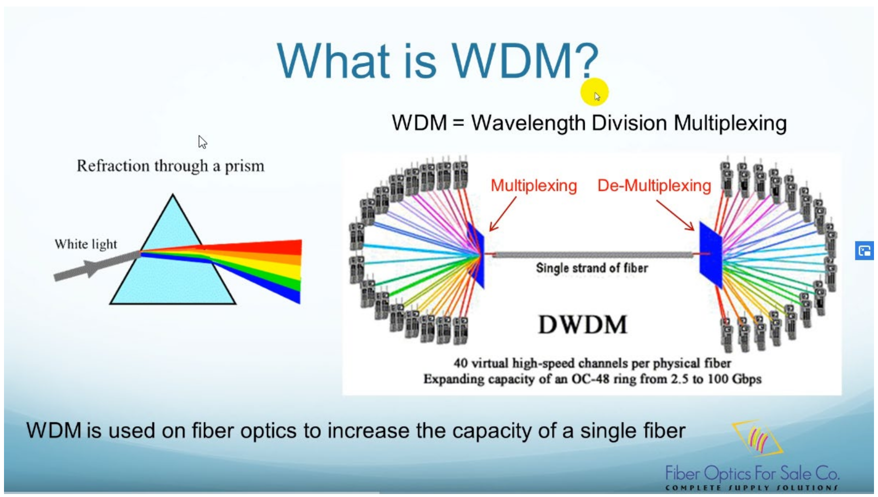
FO systems operating at **1.55 µm**
Losses are **0.2 dB/km (4% loss per mile)**

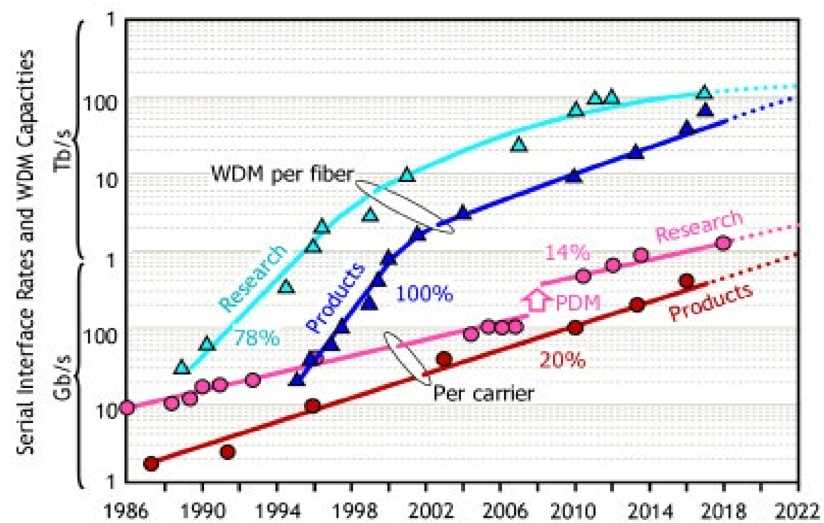
There is a need for amplifiers or repeaters, even in the Atlantic ocean.

Wavelength-Division Multiplexing

Wavelength-division multiplexing (WDM) (0-1:52)

Each fiber can carry ~**100** independent channels, each using a **different wavelength** of light.





WDM (0 - 1:52)

Product lags Research by about 8-10 years.
Now, about 100 channels or wavelengths.

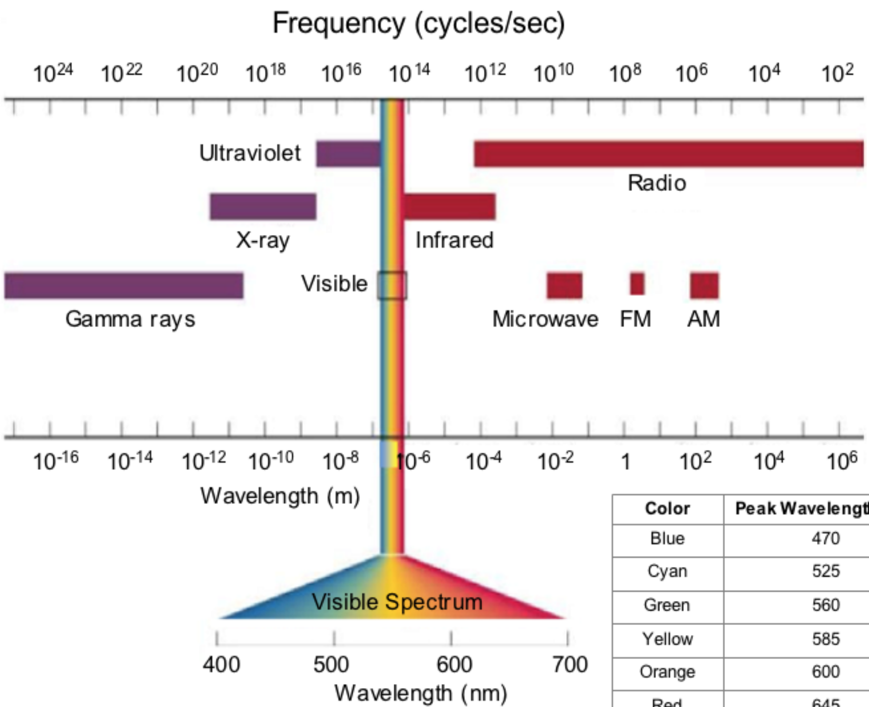
Advantages of FO Communication Systems

Advantages of Optical versus Wire Communications

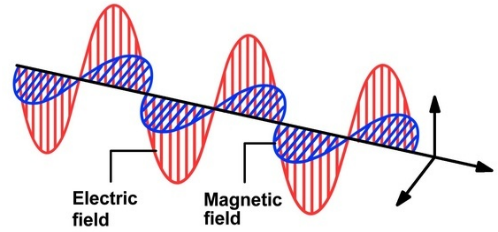
- **Higher bandwith** **(higher bits/sec)**
  multiplex many wavelengths (WDM)
- **More energy efficient**
  glass is less expensive than copper
  smaller diameter cables

Questions ?

Electromagnetic Spectrum



Color	Peak Wavelength [nm]
Blue	470
Cyan	525
Green	560
Yellow	585
Orange	600
Red	645
Deep Red	700



Units for EM radiation

- Wavelength (Å, nm, µm, m)
- **Photon energy (meV, eV)**
- Frequency (Hz)
- Color temperature (deg C, K)

Color Temperature	Source
1,700 K	Match flame
1,850 K	Candle flame, sunset/sunrise
2,700-3,300 K	Incandescent light bulb
3,350 K	Studio "CP" light
3,400 K	Studio lamps, photofloods, etc.
4,100 K	Moonlight, xenon arc lamp
5,000 K	Horizon daylight
5,500-6,000 K	Vertical daylight, electronic flash
6,500 K	Daylight, overcast
9,300 K	CRT screen

Visible Spectrum

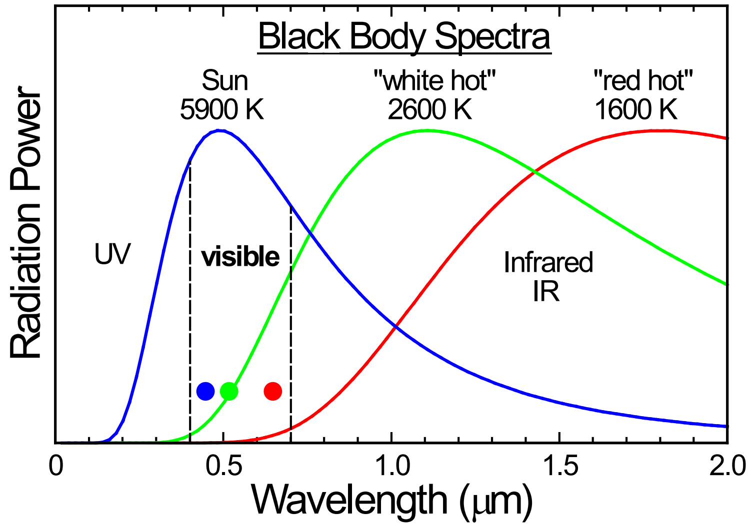
λ = 400 – 700 nm, 0.4 - 0.7 µm

$h\nu = hc/\lambda$ = 3 – 1.8 eV

T = 9,300 - 1,700 K

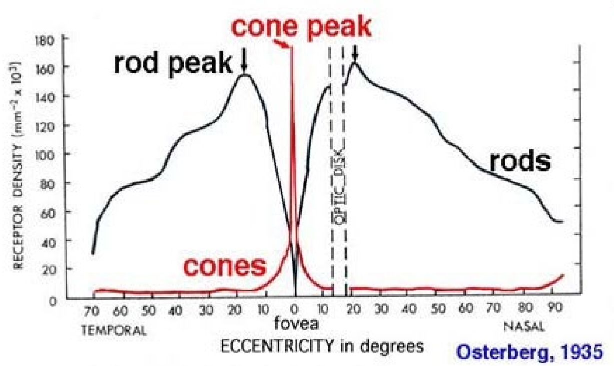
Black Body Spectra

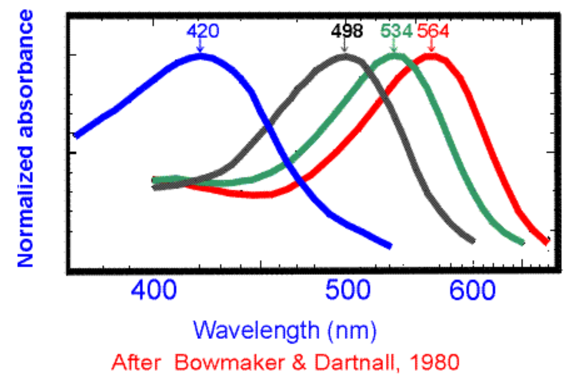
All substances emit EM radiation according to their absolute temperature.



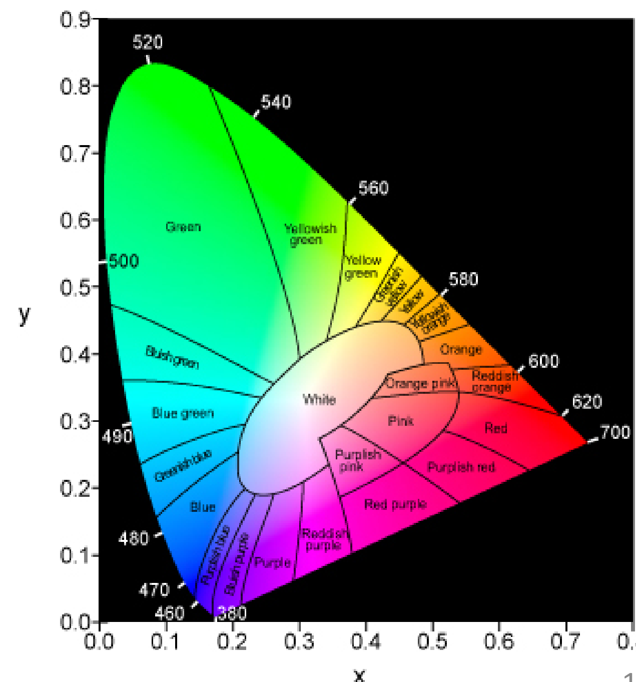
$$P(\nu) = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/kT}-1}$$ Planck's Law

Color Vision





Benham disc
See colors in black/white rotating disc



Chromaticity Diagram

Photoreceptors (rhodopsin) in the human eye (cones) can distinguish three additive ***primary*** colors: **red**, **green** and **blue** (absorbance shown on the upper right). These three colors are also used in TV and computer color monitors.

J.C. Maxwell first described a diagram, the Maxwell triangle, to quantitatively represent all possible colors using the three primary colors, which has been updated into the universally accepted CIE chromaticity diagram (shown on the lower right). The x- and y-axis are the relative amounts of red and green light, and the amount of blue is 1-x-y.

Semiconductor Electron Energy States (Bands)

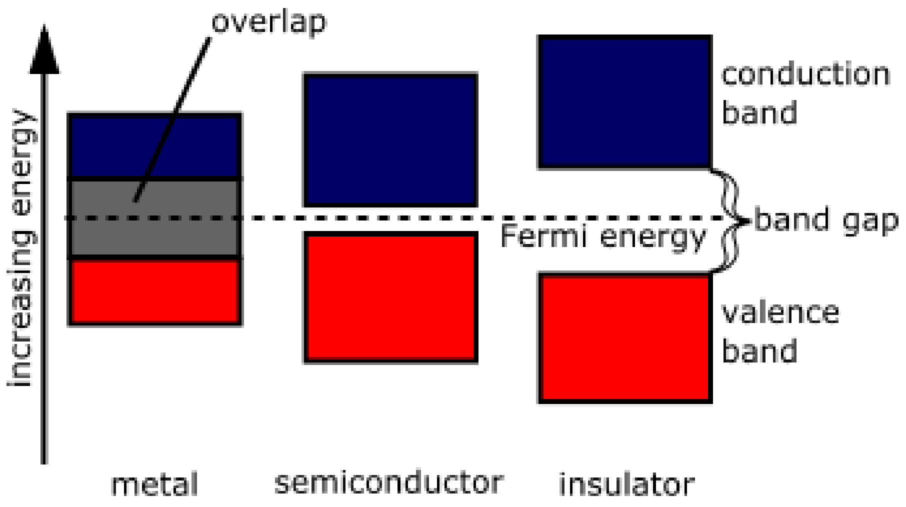
In all materials,
especially semiconductors,
you have the following concepts
for the states of electrons.

- **Conduction Band**
- **Valence Band**

Quantum Mechanics
provides the Energy Gap

Below are the possible energy levels for electrons in a metal, semiconductor and insulator.

Only electrons in the **conduction band** can **move**, or **conduct** electricity.



Introduction to "Energy Gap"

Bohr Model of H-atom

Semiclassical model of the hydrogen atom

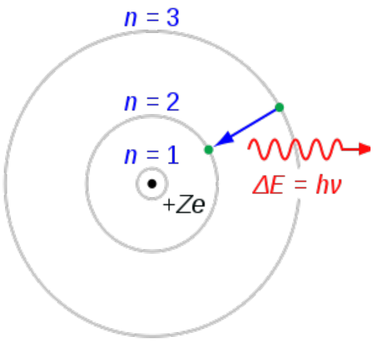
The angular momentum of the orbiting electron is quantized → **$mvr = n\hbar$**, where r=orbit radius, n=orbital quantum number.

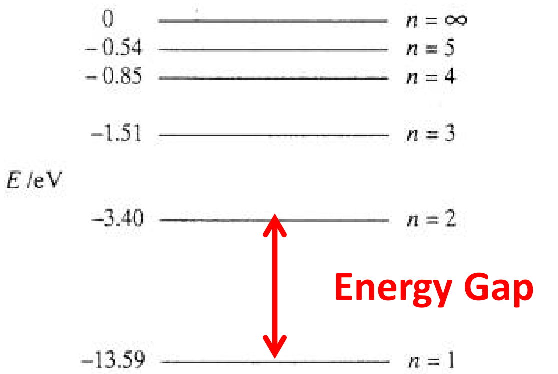
$r=an^2$ where the Bohr radius $a=0.526$ A
$E=R/n^2$ where the Rydberg $R= -13.6$ eV

For n=1	r= 0.53 A	and	E= -13.6 eV
For n=2	r= 2.1 A	and	E= - 3.4 eV
For n=3	r= 4.7 A	and	E= - 1.5 eV

…

Energy levels for the ground state (n=1) and excited states (n=2,3).





Quantum mechanics provides discrete **quantized** energy levels.

Thus, there are gaps in energy or **Energy Gaps**

Valence Band, Conduction Band and Forbidden Energy Gap 1:40

Semiconductor Conduction and Valence Bands

How are the conduction and valence bands created?

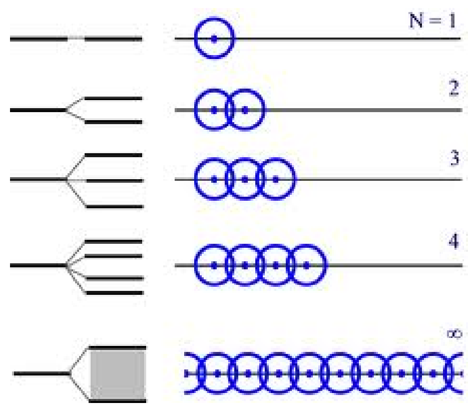
When N atoms overlap, each energy state splits into N states. So the ground and excited states each split into N states.

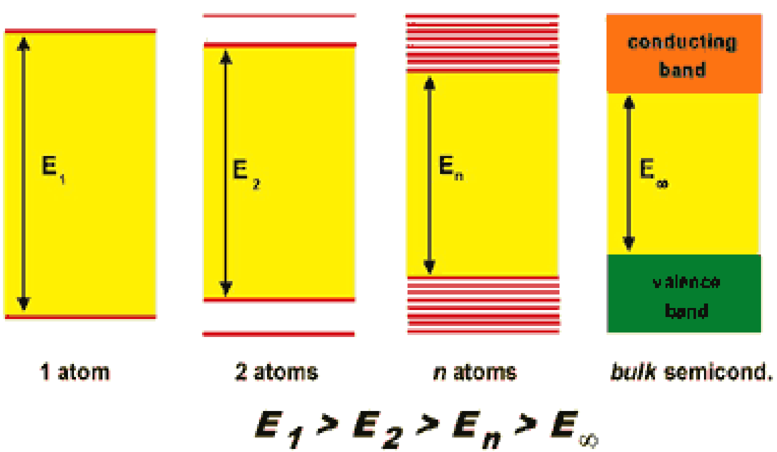
The more atoms you have with overlapping electron orbitals, the larger the number of accessible energy states.

With a very large number of atoms (~10^{20}) you can have a continuum of states, hence "bands."

Energy levels for the **ground state** with different number of overlapping electron states.

Similar splitting occurs for the **excited states**.





Semiconductor Energy "Bands"

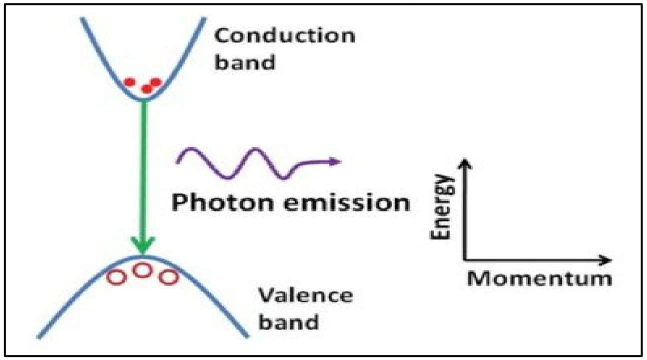
Skip

Why do they call the energy states "bands"?

The more atoms you have with overlapping electron orbitals, the larger the number of accessible energy states.

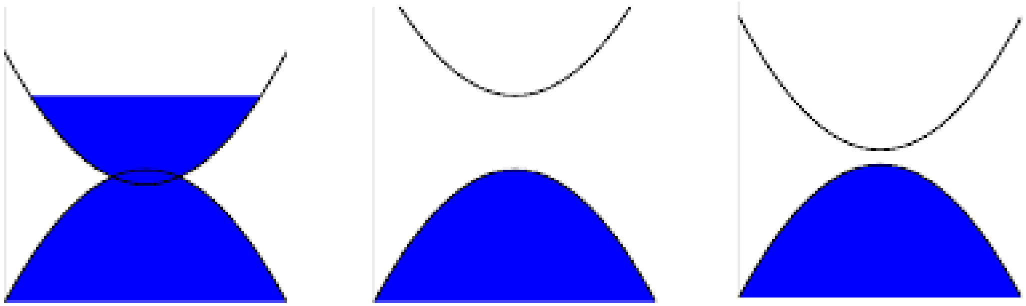
Since an electron can move from atom to atom, it has a parabolic **Energy** that depends on **Momentum**,

$E(k) = p^2/2m = \hbar^2k^2/2m$ (parabola).



Conduction Band →

Valence Band →



conductor insulator semiconductor

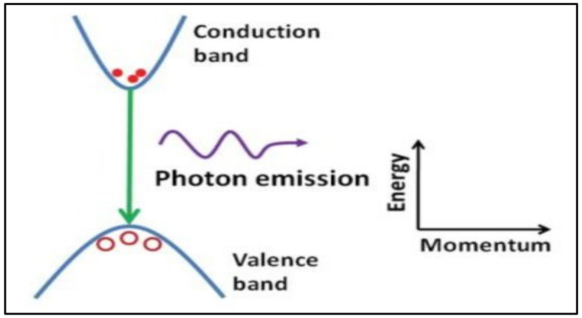
Note: electrons can only lie on the parabola

For more details, check out
Energy Bands and Semiconductors (22:01)
Electron Band Structure (10:00)

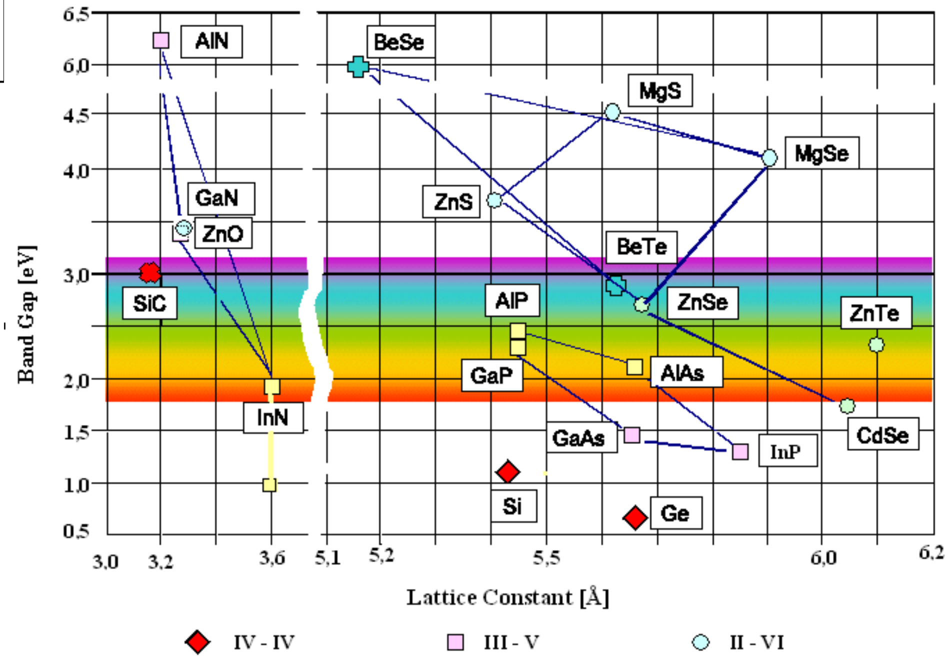
Spectral Response of Semiconductors

Moving the electrons between valence and conduction bands

Photons need to bridge the **bandgap** of the semiconductor to create *e-h* pairs, $hc/\lambda > E_g$



Material	E_g (eV)	λ (µm)	Color
HgCdTe	0.12 eV	10.6	IR
InSb	0.25	5	IR
Ge	0.7	1.8	IR
Si	1.12	1.1	near-IR
GaAsP	1.42	0.7	red
GaP	2.3	0.5	green
ZnSe	2.8	0.44	violet
GaN	3.4	0.36	UV

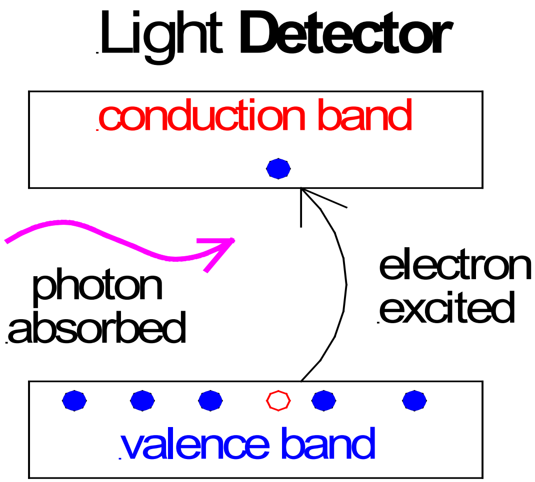


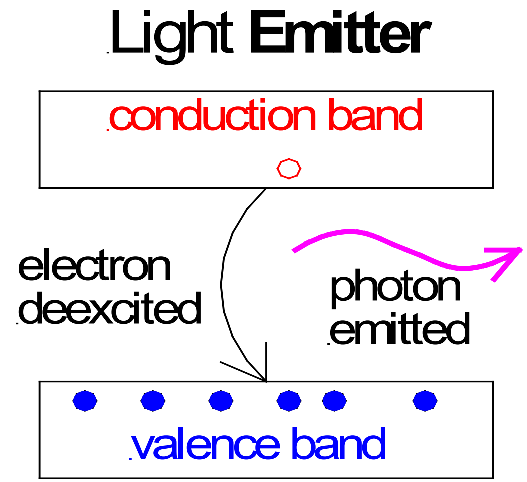
[Optical band gaps and absorption](#) 3:00-6:00

Questions ?

Semiconductor Photodiodes (PD) and Light Sources (LED,LD)

Bandgaps are very important for light **detectors** and light **emitters**





Light in – Current out

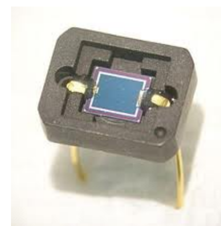
An absorbed photon makes a free electron available for current

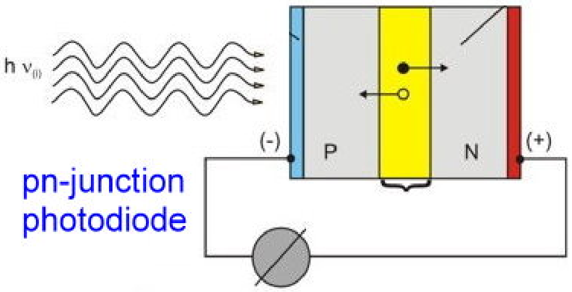
Current in – Light out

Current excites an electron, then a photon is emitted as the electron falls down

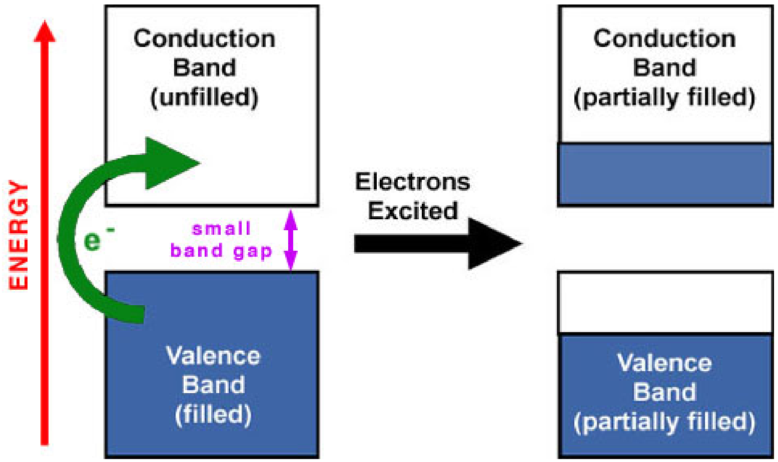
Light Detectors

- Photon is absorbed
- Lifts an electron from the valence to the conduction band
- Creates a free electron and hole





pn-junction photodiode

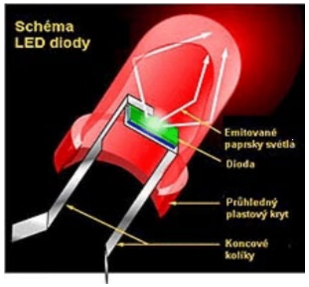


Silicon photovoltaic (solar cell)

- *pn*-junction semiconductor diode
- Absorbs all light with E=hc/λ > Eg, **photon energy must exceed Eg**
- Light generates electron-hole pairs, thus is a **photocurrent** device
- Current proportional to number of photons per second (Response is rated in amps/watt)
- **Electric field in depletion region separates the *electrons* from *holes***

Semiconductor Light Sources

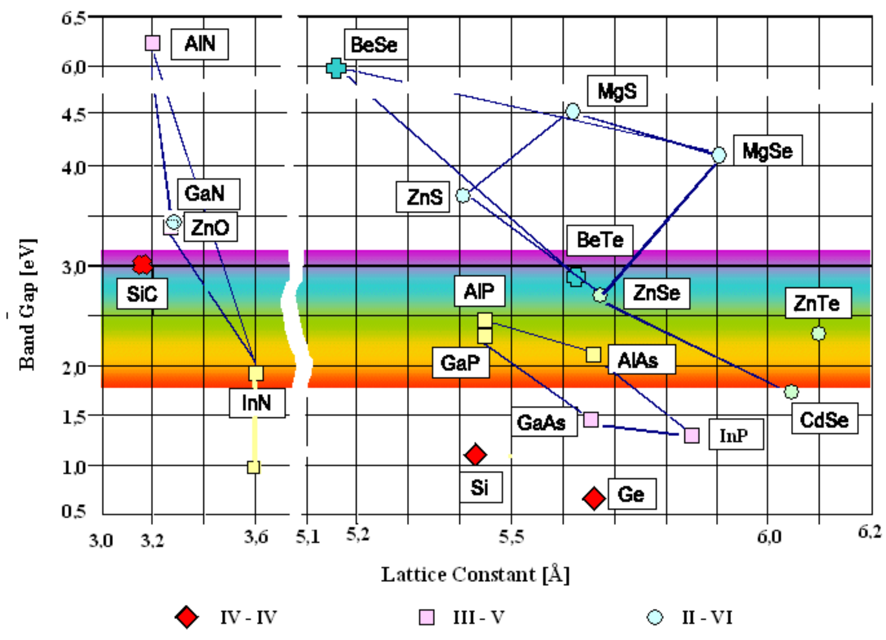
LED – Light Emitting Diode



***pn*-junction diode** produces light of a single wavelength, but broad Δλ ~ 30-40 nm

Emitted Wavelength

The photon energy is approximately equal to the “bandgap” of the semiconductor.



Change Color of Semiconductor Light Sources

Change LED Color (wavelength) by changing the bandgap energy

Vary the composition by **alloying** the elements in the semiconductor

For example:
$GaAs_{1-x}P_x$
$Ga_{1-x}Al_xAs$

Change wavelength from infrared to green

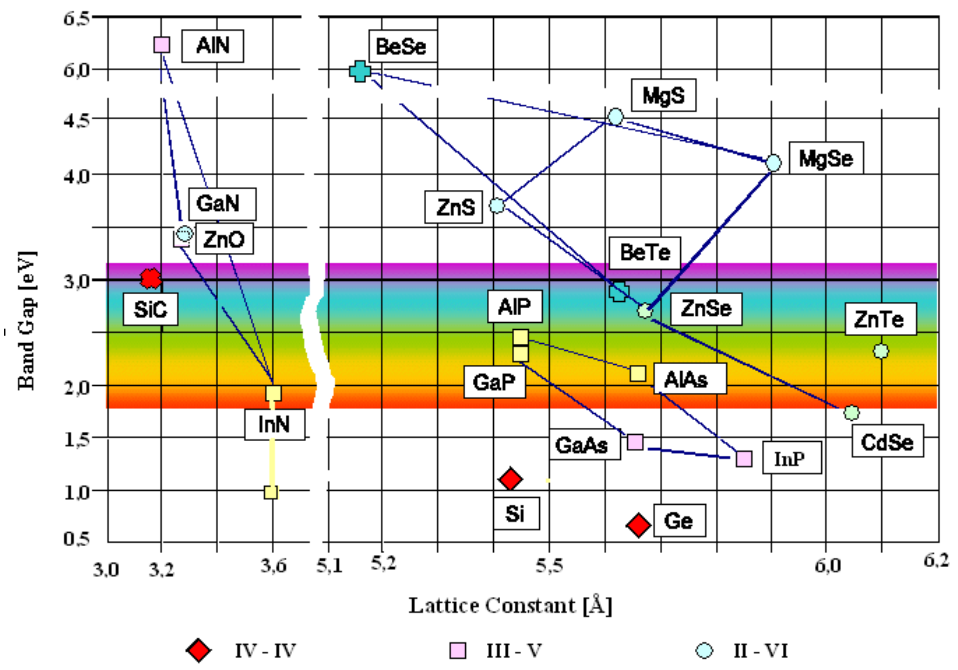
$GaAs_{1-x}P_x$ (IR to green)

$E_g = E_g^{GaAs} + x(E_g^{GaP} - E_g^{GaAs})$

$E_g^{GaAs} = 1.42$ eV

$E_g^{GaP} = 2.26$ eV

E_g (eV) = 1.42 + 0.84x



Questions ?

World’s First Laser: The Ruby Laser

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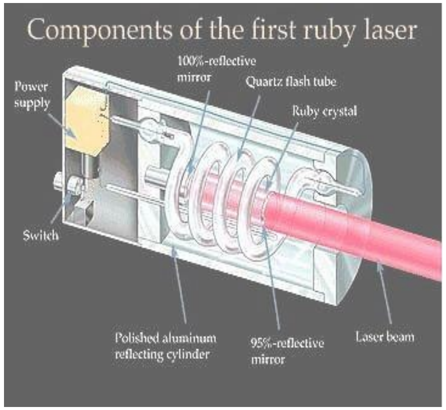
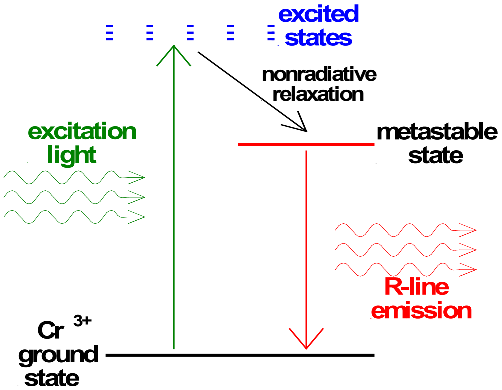




The laser was invented in 1960 by Theodor Maiman. This first laser was constructed of a cylindrical ruby crystal (Al_2O_3:Cr) surrounded by a photographic flash lamp, all contained in a polished aluminum cylinder (on left). The flash lamp was used to excite the chromium ions in the sapphire host crystal. As the excited Cr(3+) ions de-excite they emit light as individual photons. Then as these photons travel back and forth in the **optical cavity** between the mirror-coated ends on the crystal, they induce other excited Cr ions to de-excite causing “stimulated emission.” Rapidly, all of the ions become de-excited and generate a lasing light pulse. The light beam is *coherent* in the sense that the photons all travel in the same direction and have the same *phase*.

LASER is an acronym for **Light Amplification by Stimulated Emission of Radiation**.

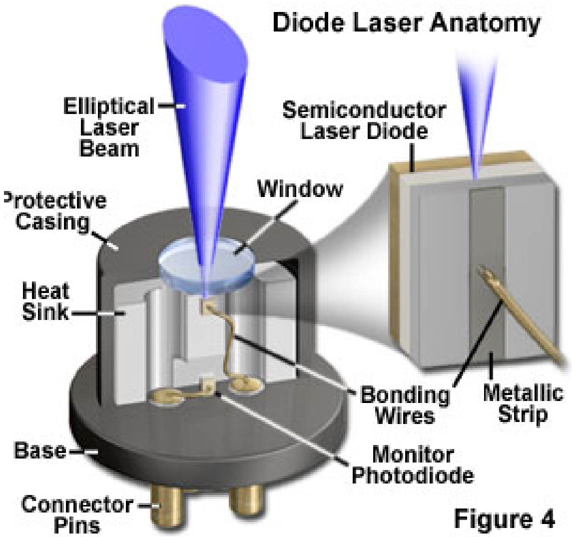
How lasers work (in theory) 1:41 How a Ruby Laser Works 1:10

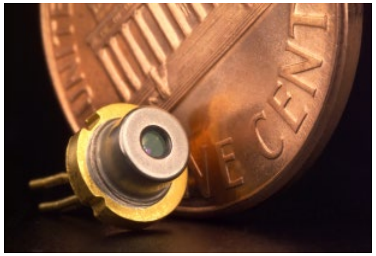
Laser Diode (LD): GaAs Semiconductor

A Laser Diode is an LED in a Resonant Cavity

1970 - first CW IR LD

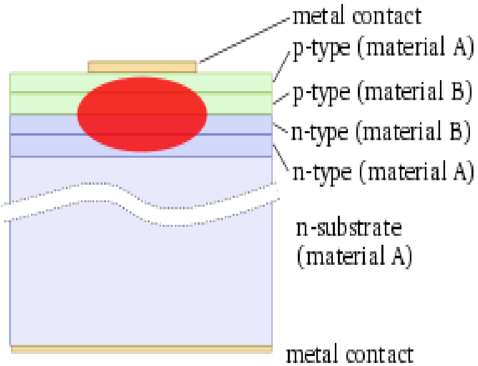
Later - Visible LD Al-Ga-In-P





Visible Red Laser diode

AlGaInP



[How a Laser Diode Works]() 1:14

"Blu Ray" Laser for DVD ROM

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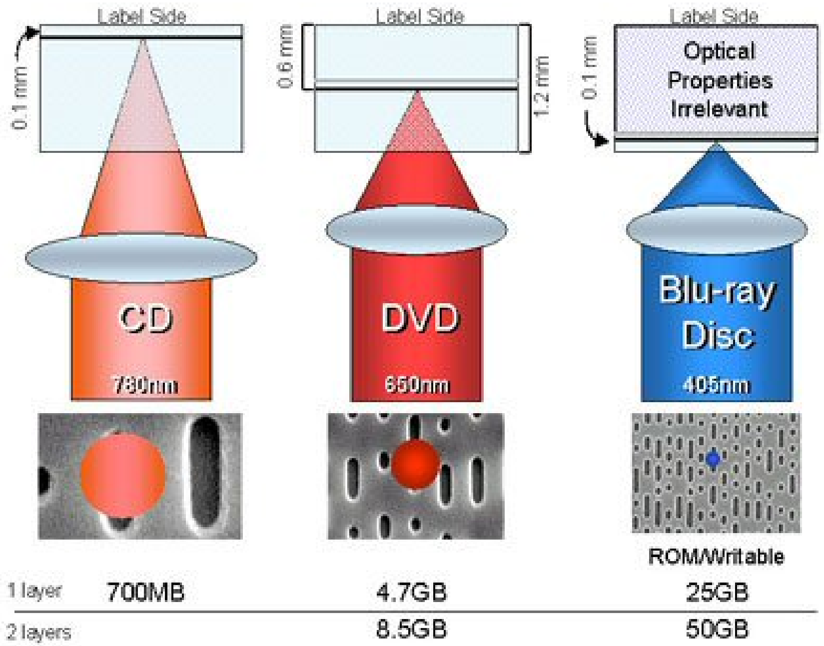
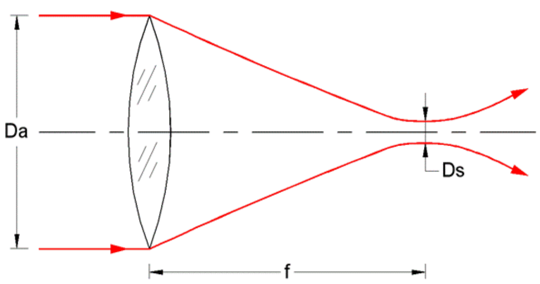
Advances for Optical Storage ROM
CD → DVD → Blu-ray

Reducing the wavelength to $\lambda/2$
Increases the bit density by 4X





Diffraction Limited Focal Spot Diameter

$$Ds = 2.44\,\lambda\,(f / Da)$$

Area ~ λ^2
Data density ~ $1/\lambda^2$

The Blue LED for White Lighting

The Blue LED

- Need blue for white lighting
- LEDs are more efficient
- LEDs last longer

White light requires

1962 Red LED
1967 Green LED
1991 Blue LED

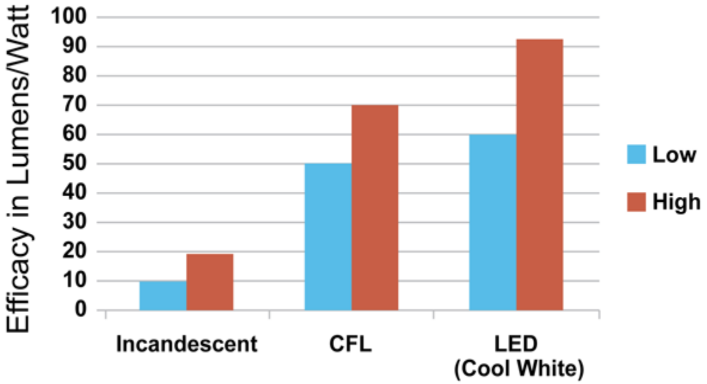


Figure 1. The Efficiency of Traditional Light Sources Compared to Solid-State Lighting Shows the Significant Benefit of LED-based SSL. (Source: Department of Energy (DOE) Energy Savers)

Nobel Prize Rewards
Crucial Blue LED Invention 1:51

Questions ?

Lab-7 - Optoelectronics

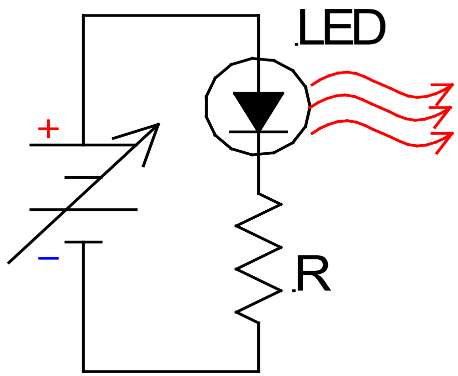
I. LED I(V) –

Measure electric and optical properties of a red and a blue LED.

Plot IV curves for both red and blue LEDs

Use current a limiting resistor in series.

Explain the difference in the I(V) curves for the two colors?



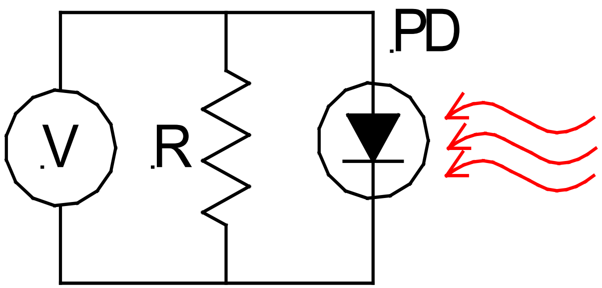
Lab-7 - Optoelectronics

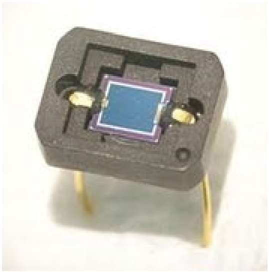
II. Silicon Photodiode –

Connect an R=100 kΩ to 1 MΩ resistor in **parallel** with the PD.
Choose a resistor that produces a voltage of 300-400 mV.

Measure V_{PD} as you place small squares of the neutral-density (ND) filters to cover the PD.
Plot V_{PD} versus the number, N, of ND filters on a log scale.

Determine V_{PD}^{max} where the response is linear.





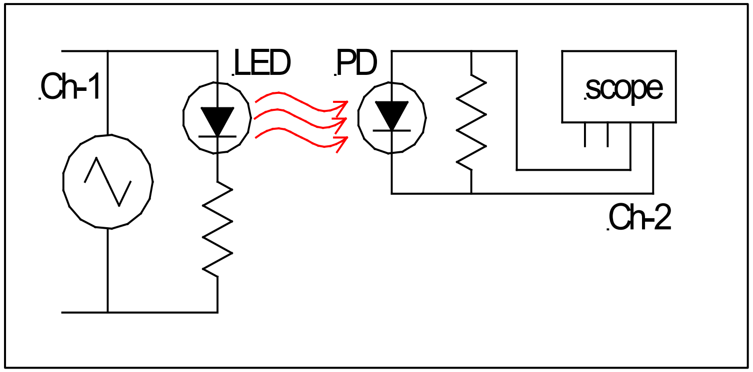
Lab-7 - Optoelectronics

III. PD Frequency Response –

Configure the LED so that it shines directly on the PD.

Apply a saw tooth wave to the current limiting resistor and LED.
Adjust the PD resistor or add ND filters to keep V_{PD} below $\mathbf{V_{PD}^{max}}$.

Plot $G=V_{PD}/V_{FG}$ as a function of f (log scale) for f=10 to 10^6 Hz.



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