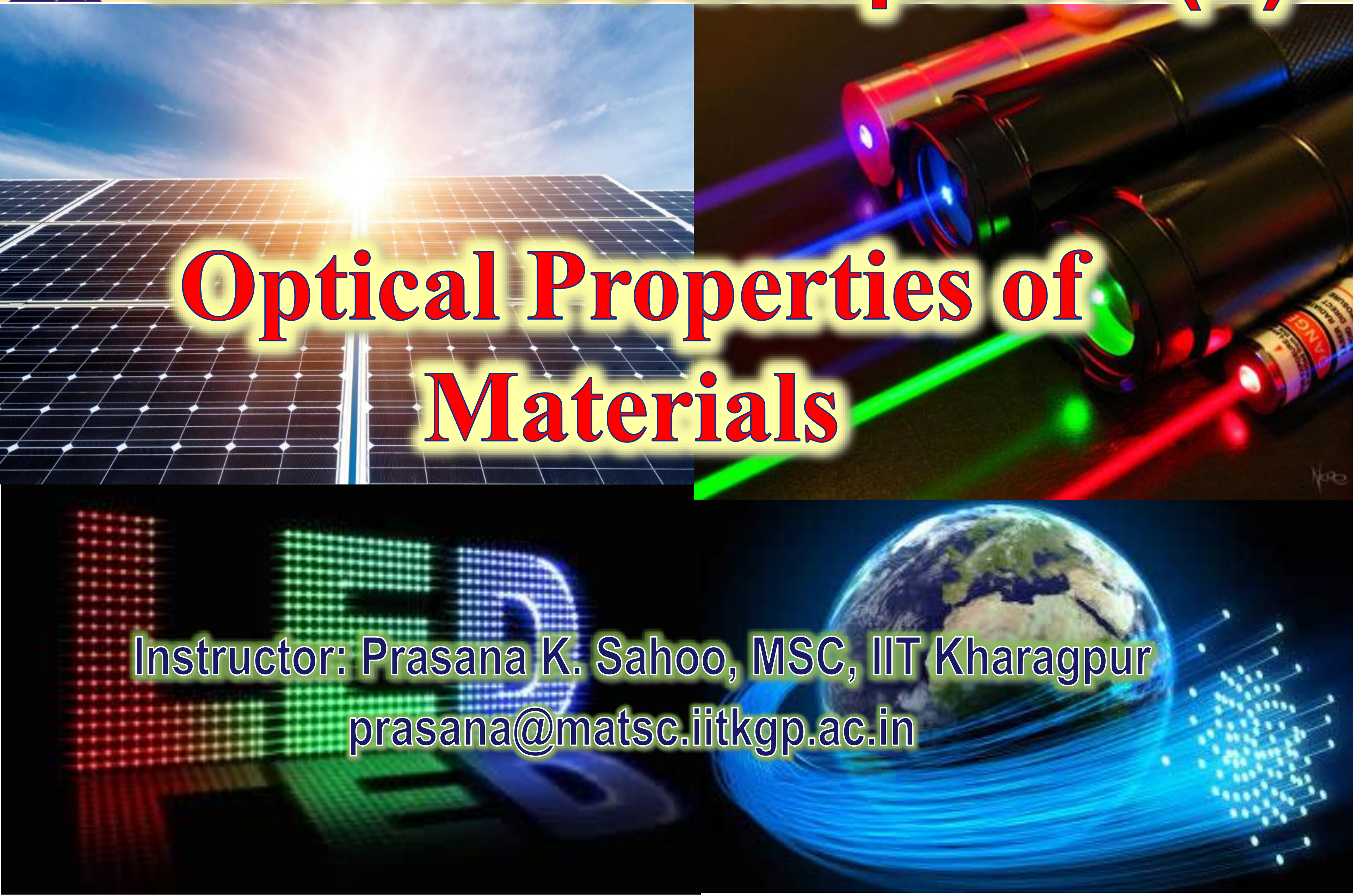
MS31007 : Chapter 9 (II)



Optical Properties of Materials

Instructor: Prasana K. Sahoo, MSC, IIT Kharagpur
prasana@matsc.iitkgp.ac.in

ISSUES TO ADDRESS...

- What phenomena occur when light is shined on a material?
- What determines the characteristic colors of materials?
- Why are some materials transparent and others are translucent or opaque?
- Optical applications:
  -- luminescence
  -- photoconductivity
  -- solar cell
  -- optical communications fibers

- How does a solar cell operate?
- How does a LED operate?
- How does a laser operate?
- Why Optical Fiber are necessary for communication?

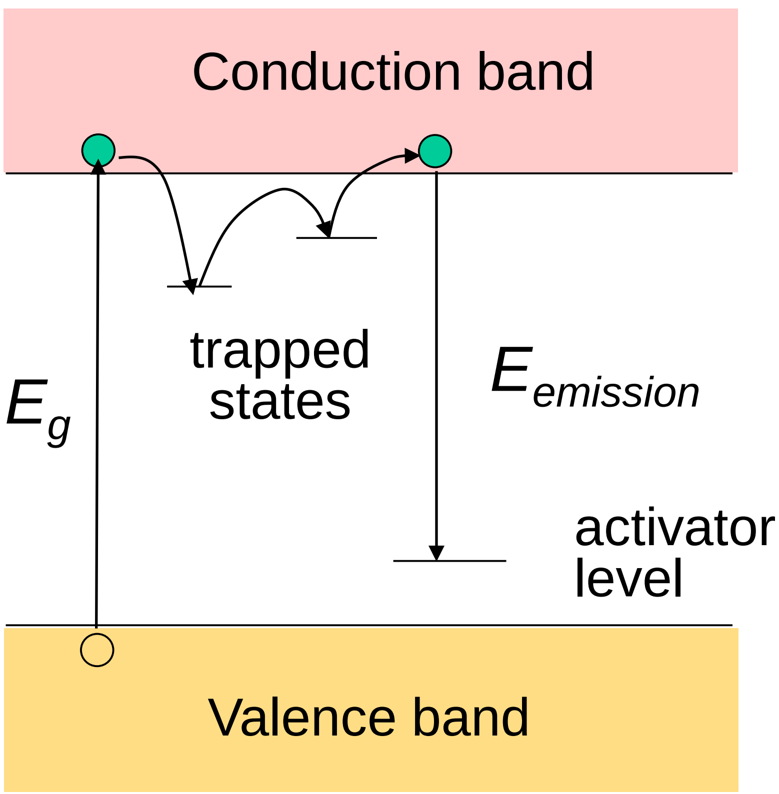
Applications of Optical Phenomena: **Luminescence**

Luminescence – re-emission of light by a material

Type	Source of energy
Photoluminescence	Photons, mainly ultraviolet
Triboluminescence	Mechanical bond-breaking, fracture or friction
Chemiluminescence	Chemical reactions
Cathodoluminescence	Electron bombardment
Thermoluminescence	Increase of temperature
Electroluminescence	Applied electric field
Bioluminescence	Life processes
Radioluminescence	Radioactive decay
Sonoluminescence	Ultrasonic waves

Luminescence

- Luminescence – reemission of light by a material
  - Material absorbs light at one frequency and reemits it at another (lower) frequency.
  - Trapped (donor/acceptor) states introduced by impurities/defects



- If residence time in trapped state is relatively long (> 10^{-8} s) -- phosphorescence

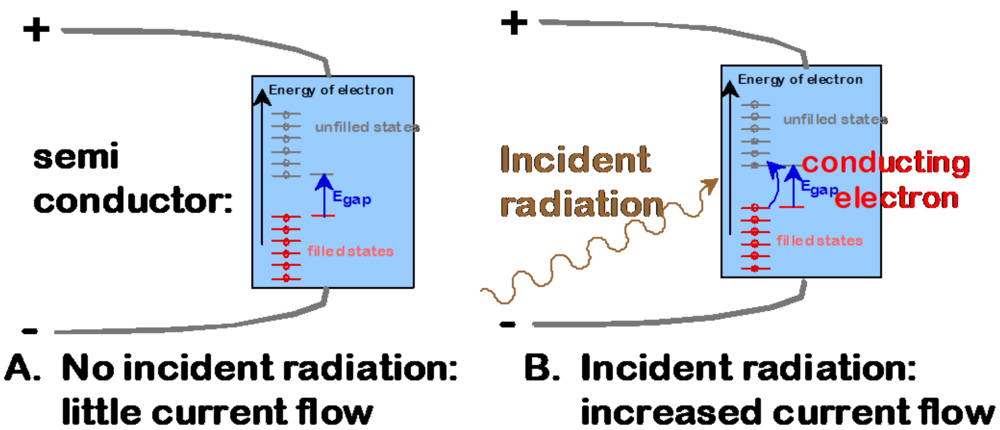
Reemission of light over time—phosphorescence

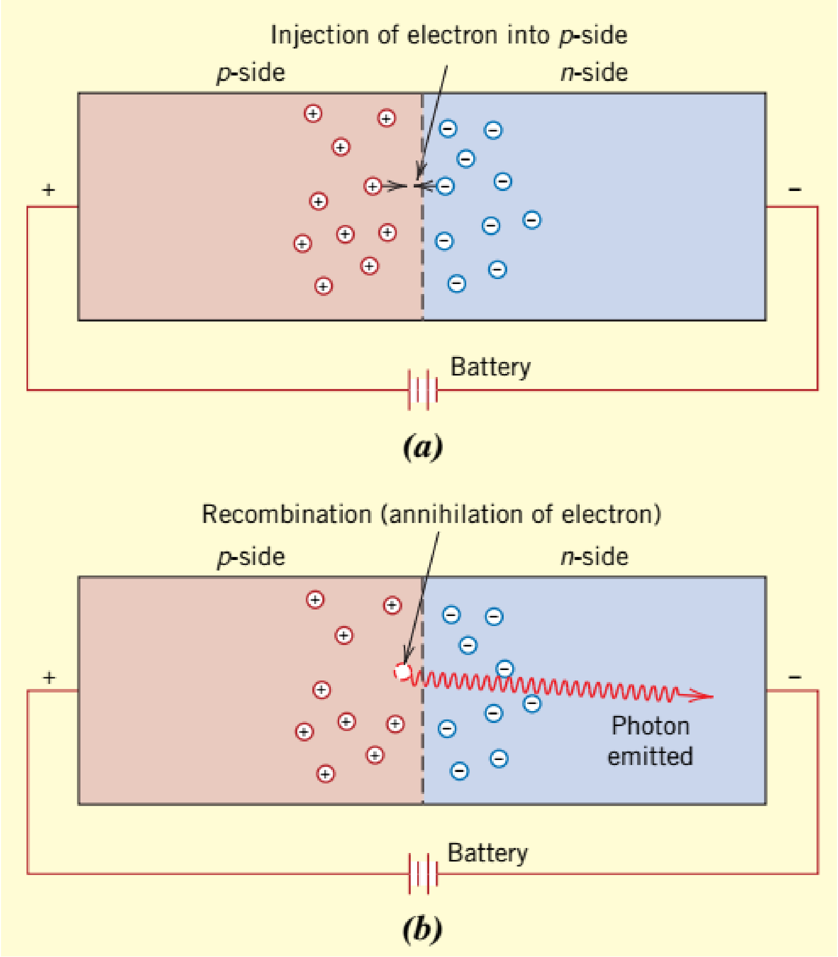
- **For short residence times (< 10^{-8} s)** -- fluorescence

Example: Toys that glow in the dark. Charge toys by exposing them to light.

PHOTOCONDUCTIVITY

Photoconductivity is an optical and electrical phenomenon in which a material becomes more electrically conductive due to the absorption of electromagnetic radiation





Examples:

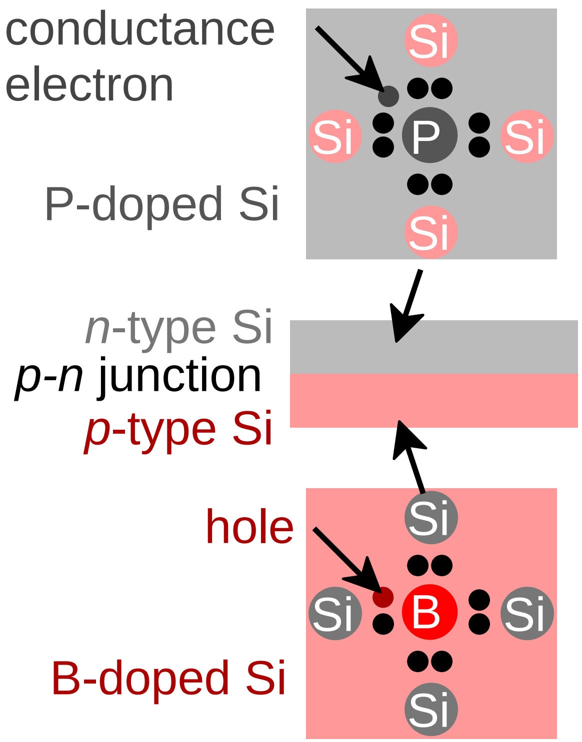
1) Photodetector/Photosensor
2) **Light Emitting Diode**
3) Solar Cells

When a forward-biased potential of relatively high magnitude is applied across a *p–n* junction diode, visible light (or infrared radiation) is emitted. This conversion of electrical energy into light energy is termed **electroluminescence,** and the device that produces it is termed a **light-emitting diode (LED)**

Schematic diagram of a forward-biased semiconductor p–n junction showing (a) the injection of an electron from the n-side into the p-side, and (b) the emission of a photon of light as this electron recombines with a hole.

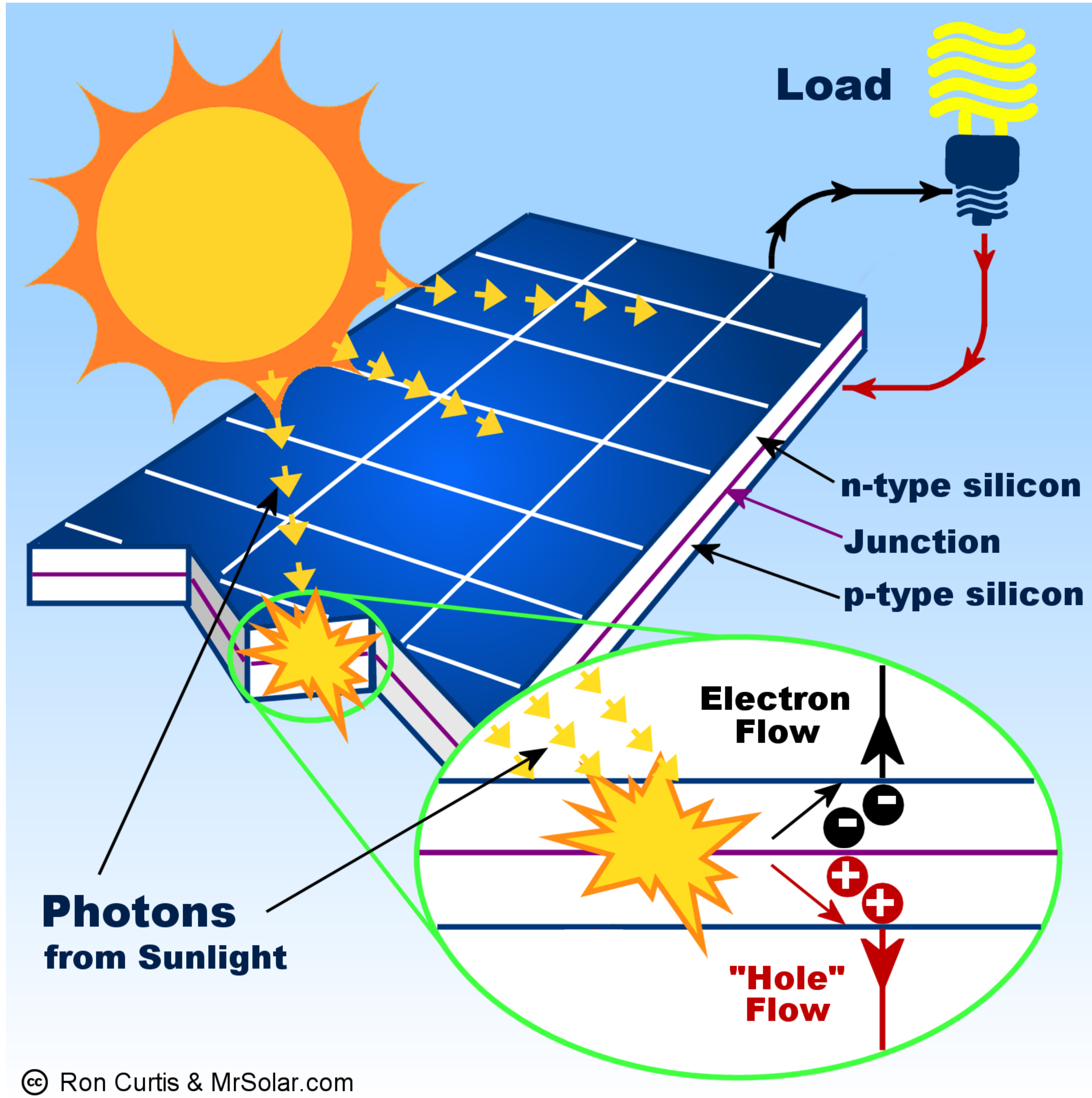
Solar Cells

***p-n* junction:**



Solar Cells Operation:

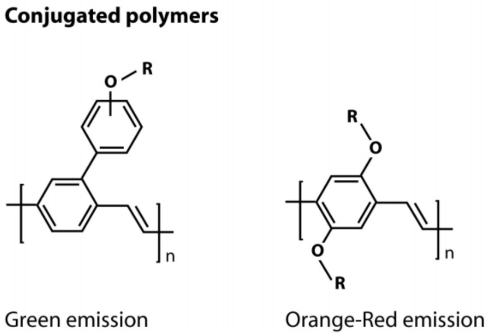
- incident photon of light produces electron-hole pair.
- typical potential of 0.5 V produced across junction
- current increases with light intensity.

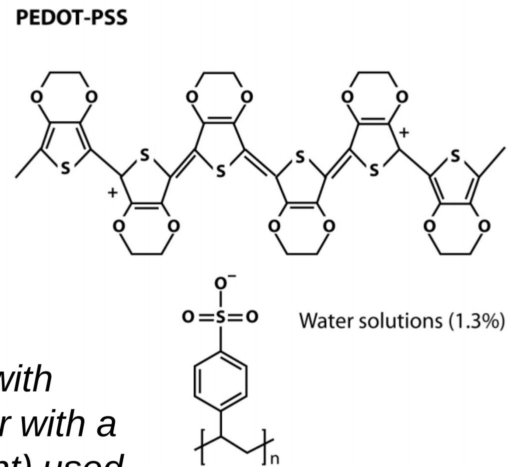


Electrical Conduction in Polymers : Doping

Doping with electron acceptors such as halogens (chlorine, iodine, etc.) oxidise the polymer, in this process, electrons are taken from the filled lower band and used to form halide ions, leaving holes, which result in a **p-type** material.

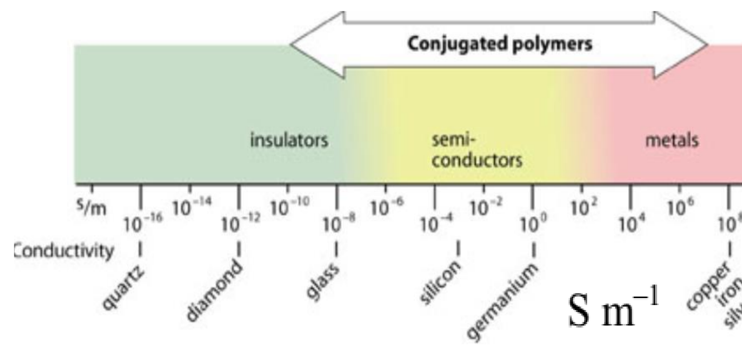
The Nobel Prize in Chemistry, 2000: Conductive polymers

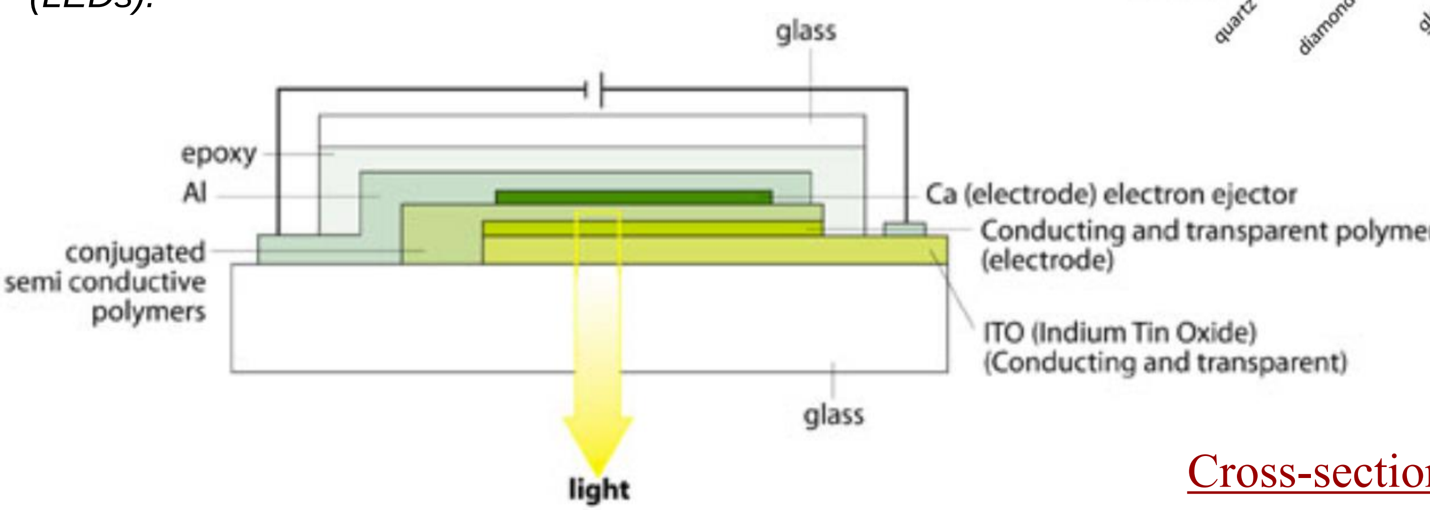




a. Semiconductor polymers (left) with different emission colours together with a conductive electrode polymer (right) used for fabrication of light-emitting diodes (LEDs).

Doping with alkali metals, (lithium, sodium, etc), reduces the polymer. In this process, the alkali metal donates electrons to the empty band, forming an alkali metal ion and transforming the polymer into an **n-type** material.

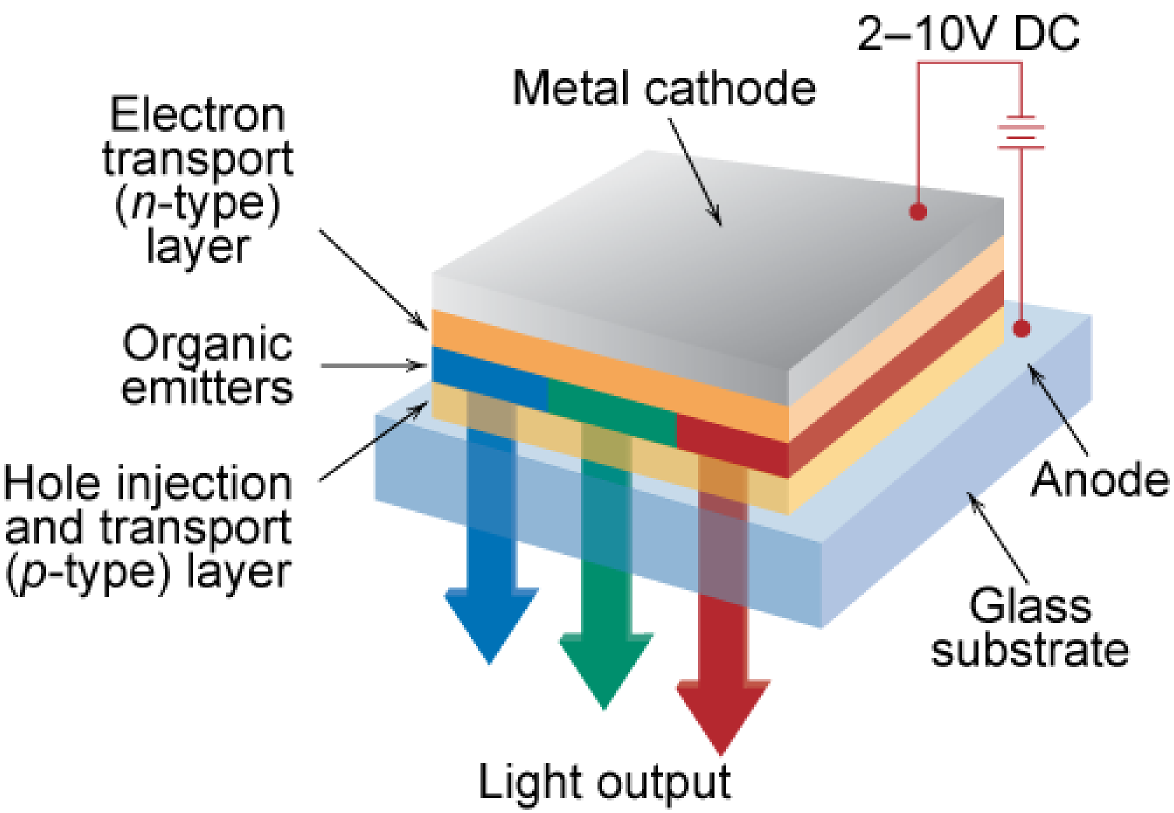




Cross-section of a polymer LED

Light Emitting Diodes

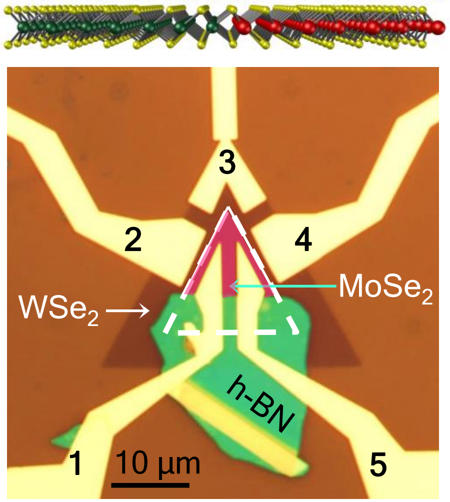
- New materials must be developed to make new & improved optical devices.
  - Organic Light Emitting Diodes (OLEDs)
    - More than one color available from a single diode
    - Also sources of white light (multicolor)



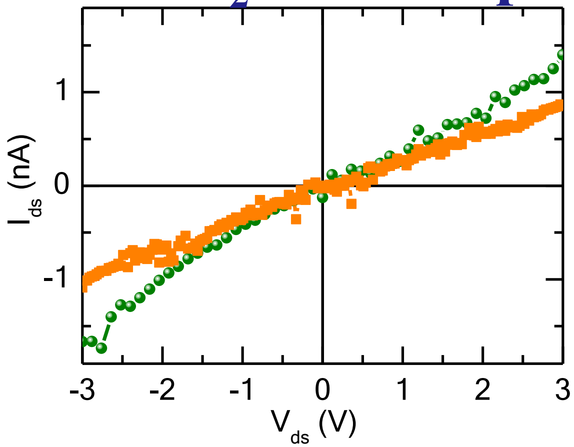
Electrical Transport Measurement: 2D p-n junction

P. Sahoo et al. Nature 2018

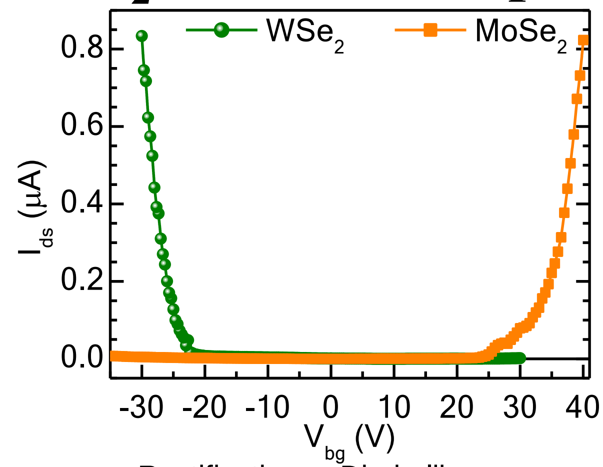
$MoSe_2$@ WSe_2



WSe_2 : hole doped; $MoSe_2$: electron doped



I_{ds} ~V_{ds} is nearly **linear** [V_{bg}=0V] indicating thermionic emission of charge carriers across the Schottky barriers



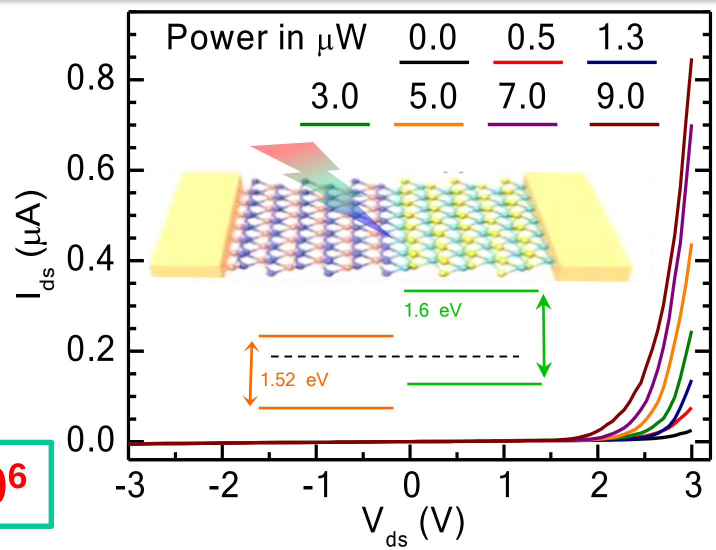
Rectification or Diode-like response indicating PN junction formation

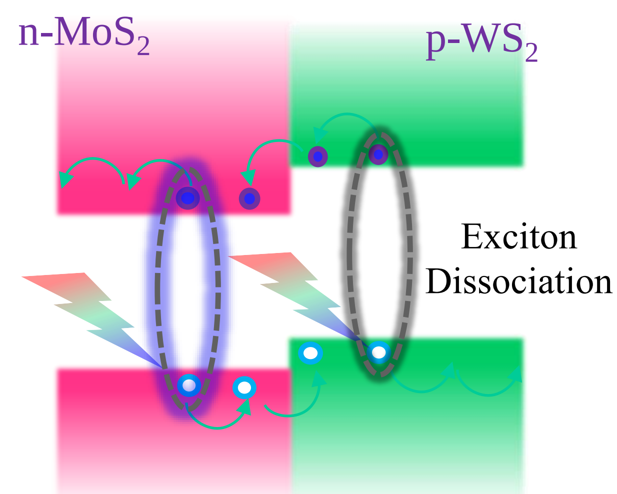
Two Terminal I-V Characteristics : Diode-like response and more prominent under illumination

λ = 532 nm
Mode filed diameter: 10 µm

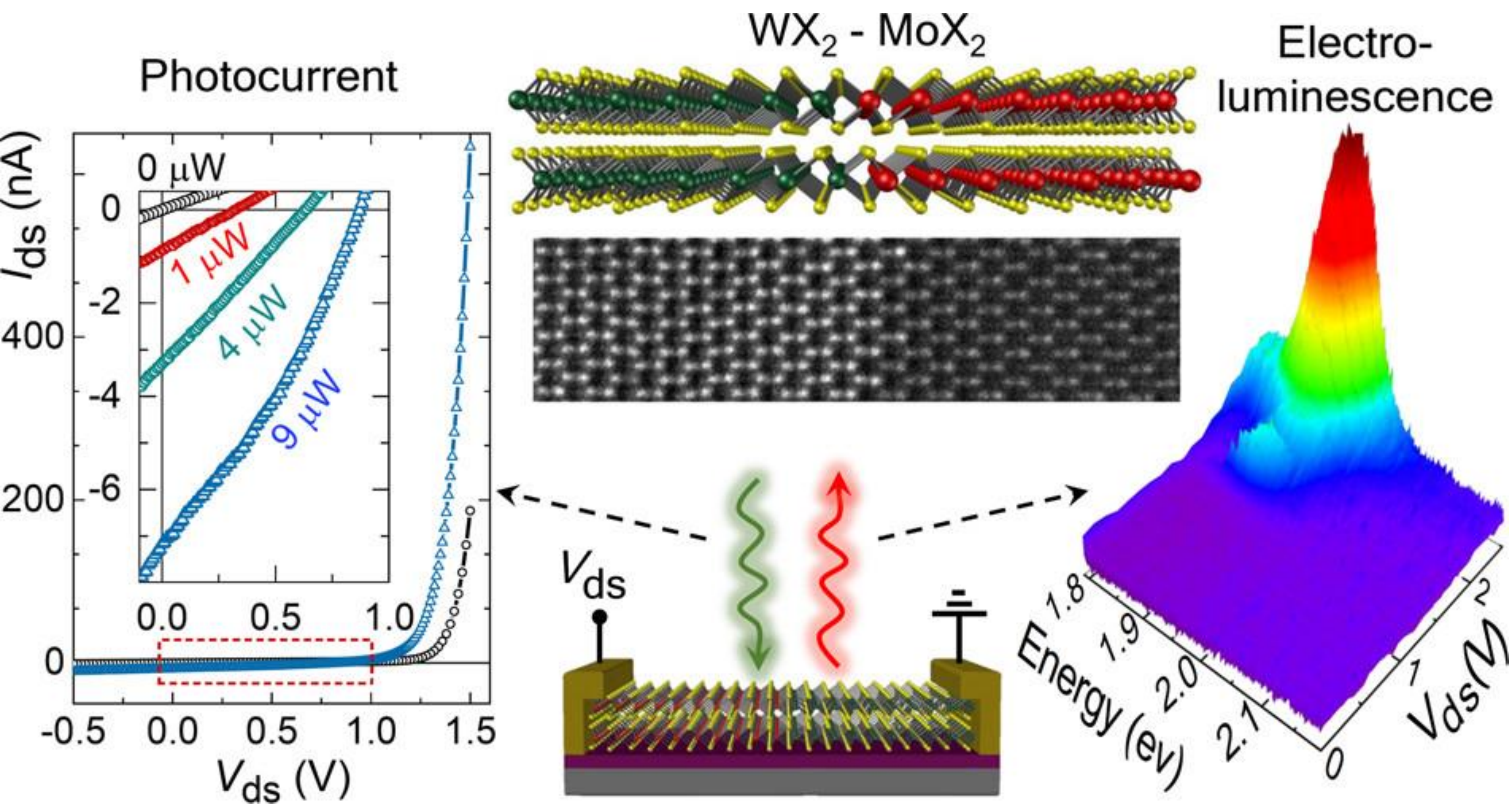
Photo current
$I_{ph}=I_{ds}-I_{dark}$ at $V_{bg}=0$

I_{on}/I_{off} = ~ 10^5 to 10^6





Atomically thin LED: Two-dimensional Lateral p-n junction



P. K. Sahoo et al. ACS Nano 2019, 13, 11, 12372-12384

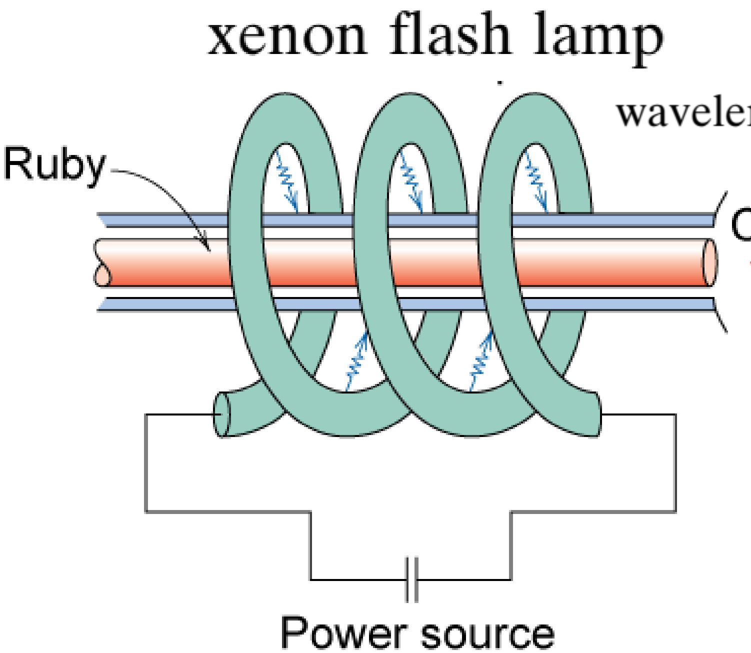
The LASER

The laser generates light waves that are in phase (coherent) and that travel parallel to one another

- LASER : Light *A*mplification by *S*timulated *E*mission of *R*adiation
- Operation of laser involves a population inversion of energy states process

Operation of the Ruby Laser

Ruby (red color) is a single crystal of Al_2O_3 (sapphire) with 0.05% Cr^{3+} ions
Both ends are silvered such that one is totally reflecting and the other partially transmitting.



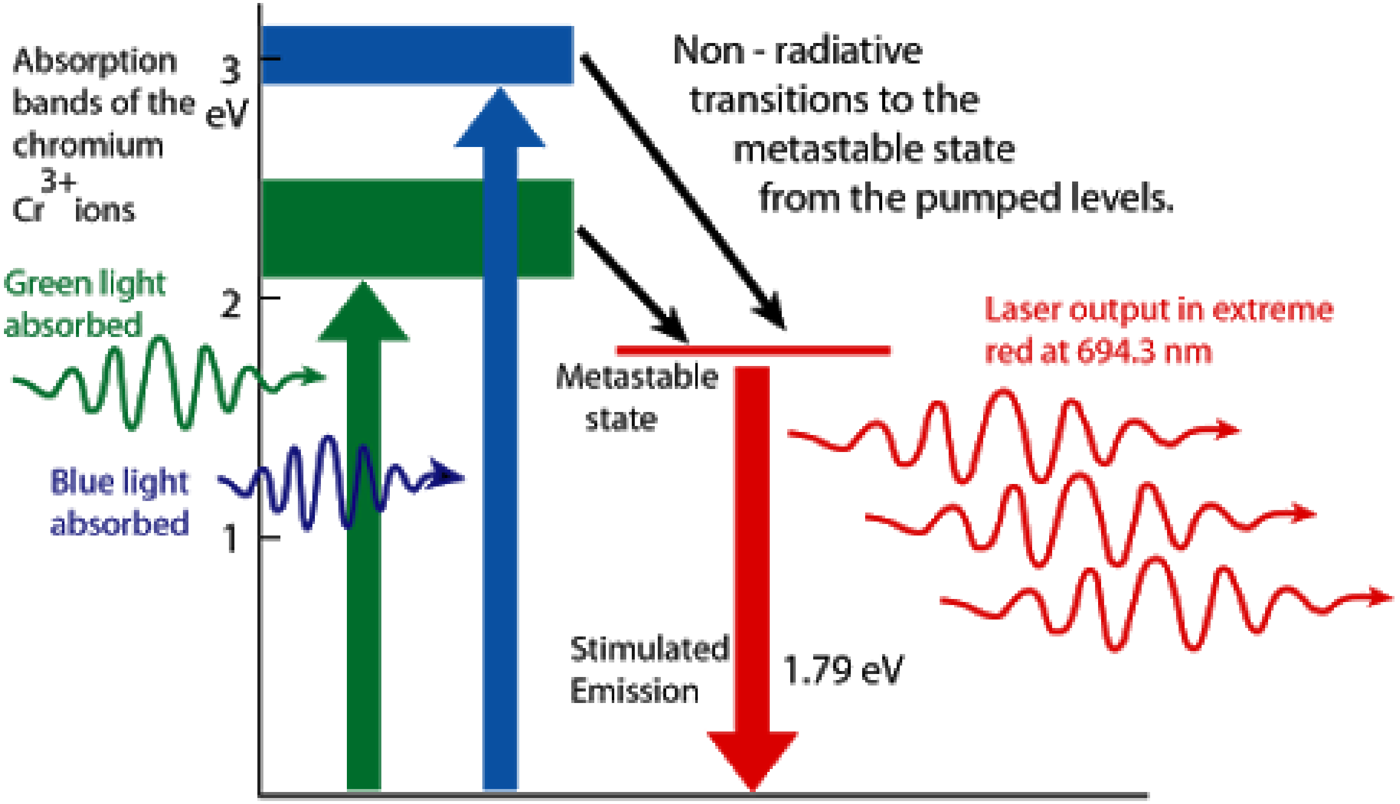
"pump" electrons in the lasing material to excited states

– e.g., by flash lamp (incoherent light).

– Direct electron decay transitions — produce incoherent light

Population Inversion

More electrons in excited energy states than in ground states



- Excited state electron decay into a metastable intermediate state, where they may **reside for up to 3 ms before spontaneous emission.**
- In terms of electronic processes, **3 ms is a relatively long time**, which means that a large number of these metastable states may become occupied.

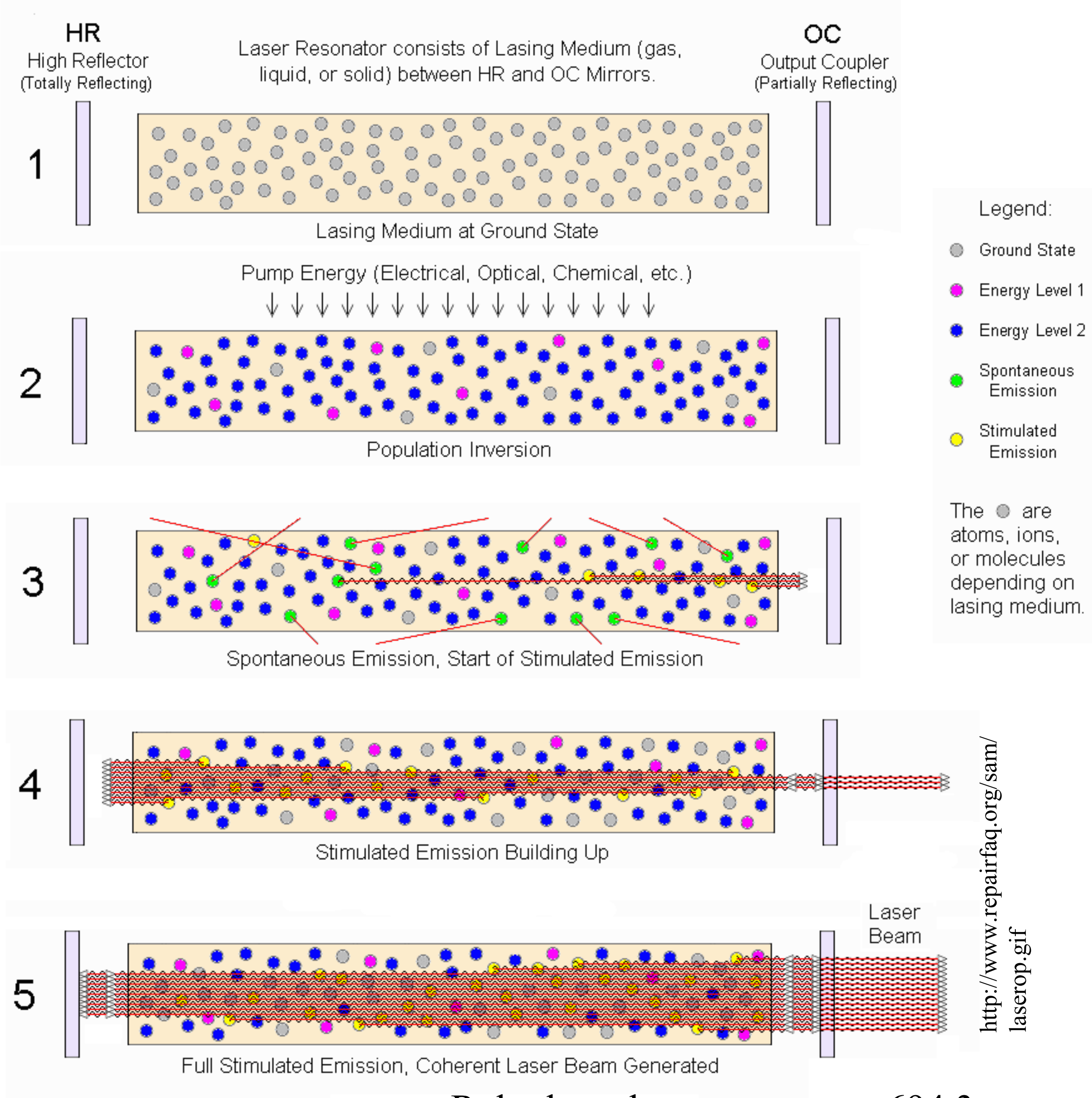
Operation of Laser

So all we need to make a laser is to achieve

(i) **population inversion**

(ii) **enough photons to stimulate emission**

- The first is achieved by filling the metastable states with electrons generated by light from a xenon flash lamp
- The second condition is achieved by confining the photons to travel back and forth along the rod of ruby using mirrored ends
- In order to keep the coherent emission, we must ensure that the light which completes the round trip between the mirrors returns in phase with itself.
- Hence the distance between the mirrors should obey $2L = N\lambda$. where N is an integer, λ is the laser wavelength and L is the cavity length



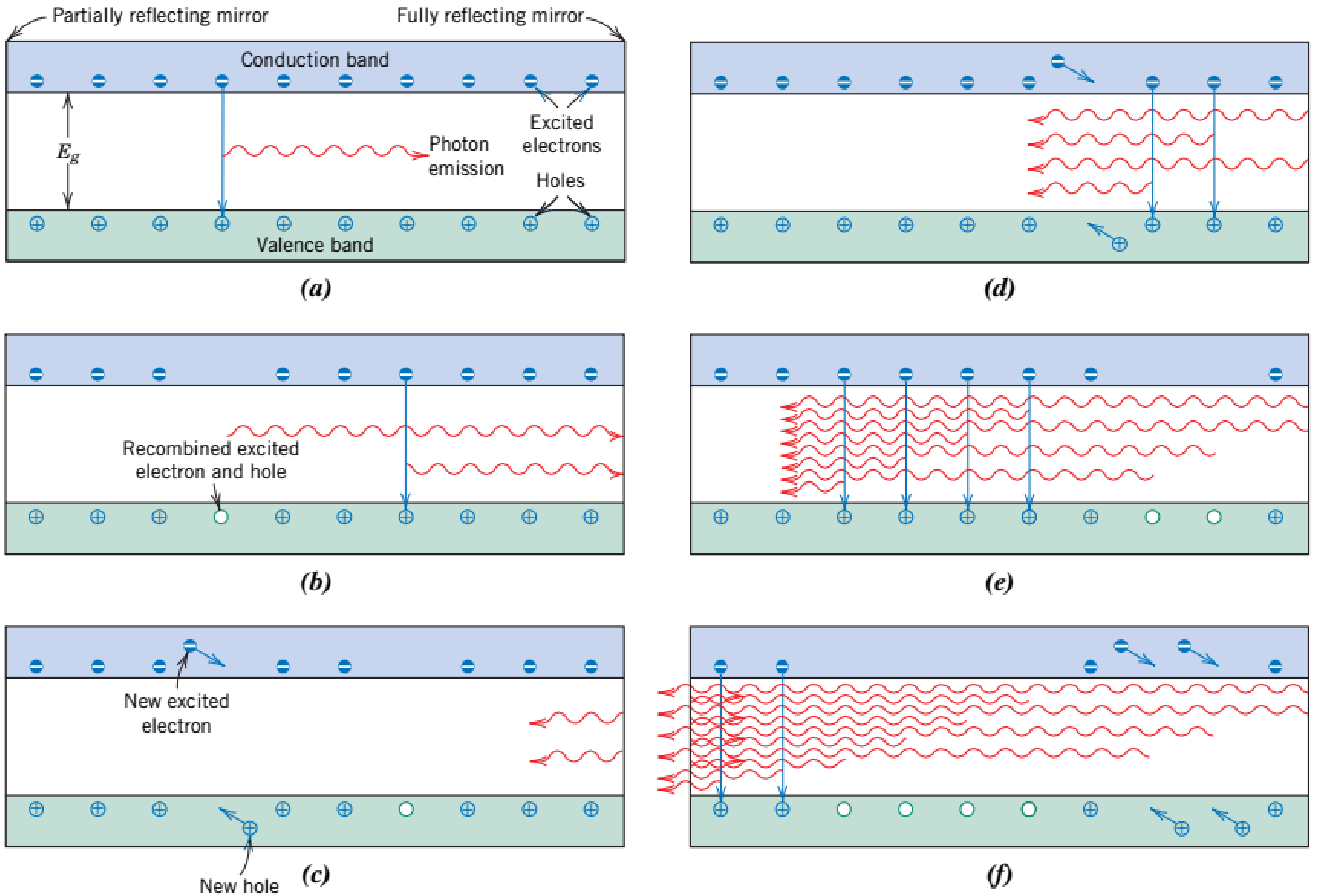
Ruby laser has an output at 694.3 nm

Semiconductor Laser

Semiconducting materials (GaAs) used as laser in compact disc players and in the modern telecom. industry.

Requirement E_g: Visible light

Stimulated recombination of excited electrons in the conduction band with holes in the valence band that gives rise to a laser beam.



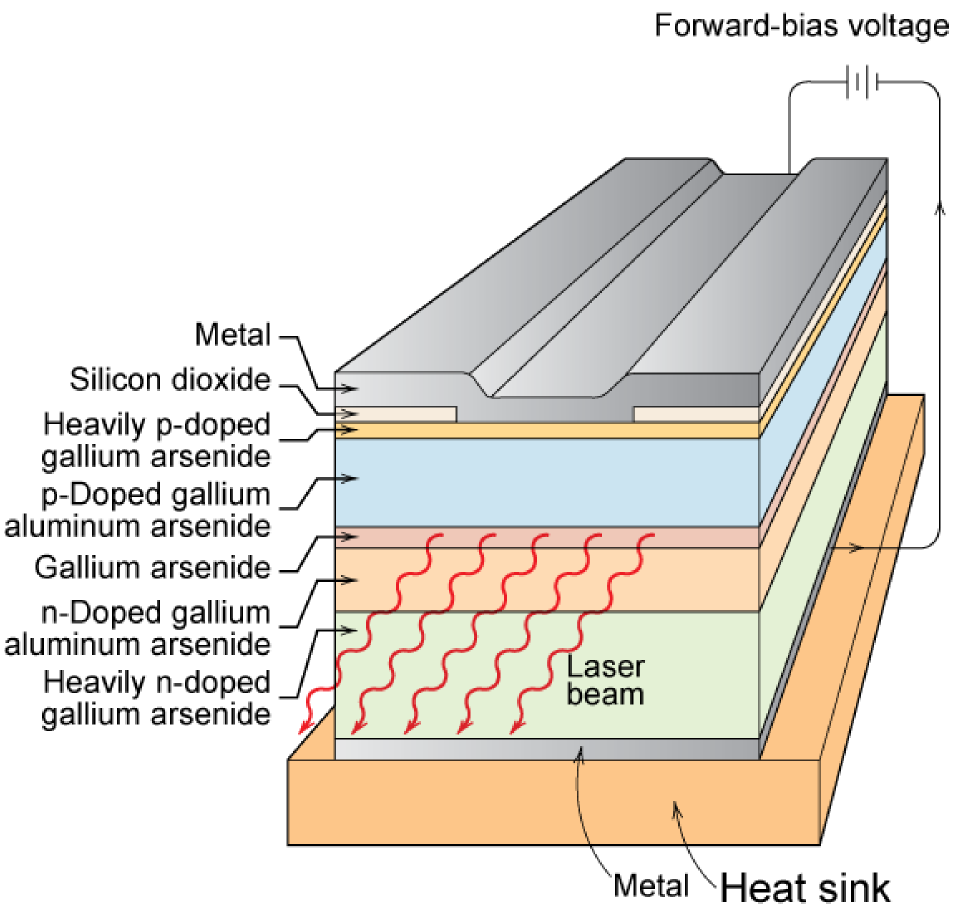
(*a*) One excited electron recombines with a hole; the energy associated with this recombination is emitted as a photon of light. (*b*) The photon emitted in (*a*) stimulates the recombination of another excited electron and hole, resulting in the emission of another photon of light. (*c*) The two photons emitted in (*a*) and (*b*), having the same wavelength and being in phase with one another, are reflected by the fully reflecting mirror back into the laser semiconductor. In addition, new excited electrons and new holes are generated by a current that passes through the semiconductor. (*d*) and (*e*) In proceeding through the semiconductor, more excited electron–hole recombinations are stimulated, which give rise to additional photons of light that also become part of the monochromatic and coherent laser beam. (*f*) Some portion of this laser beam escapes through the partially reflecting mirror at one end of the semiconducting material.

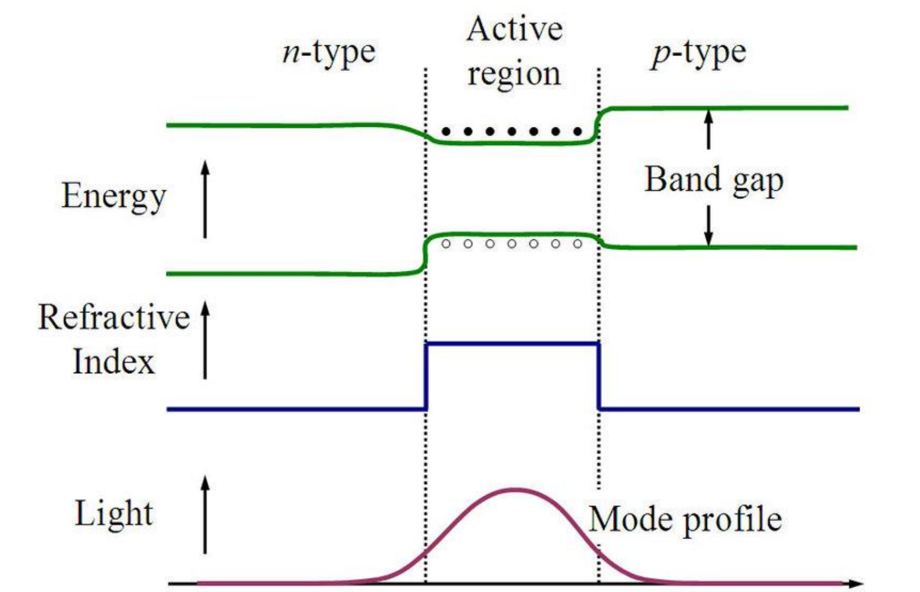
Semiconductor Laser

- Apply strong forward bias across semiconductor layers, metal, and heat sink.
- Electron-hole pairs generated by electrons that are excited across band gap.
- Recombination of an electron-hole pair generates a photon of laser light

$$\underbrace{\text{electron} + \text{hole}}_{\text{recombination}} \rightarrow \underbrace{\text{neutral}}_{\text{ground state}} + h\nu$$

photon of light

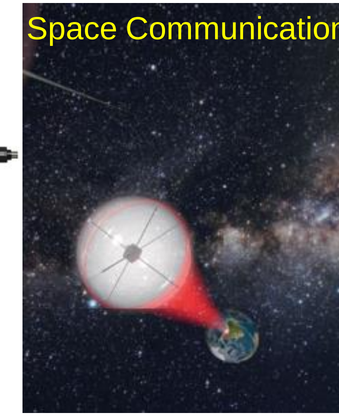




Continuous Wave Lasers

- Continuous wave (CW) lasers generate a continuous light
- Materials for CW lasers include semiconductors (e.g., GaAs), gases (e.g., CO_2), and yttrium-aluminum-garnet (YAG)
- Uses of CW lasers : Welding, Drilling, Cutting – laser carved wood, eye surgery, Surface treatment, Scribing – ceramics, etc. Photolithography – Excimer laser

Thin Film Growth PLD : Laser

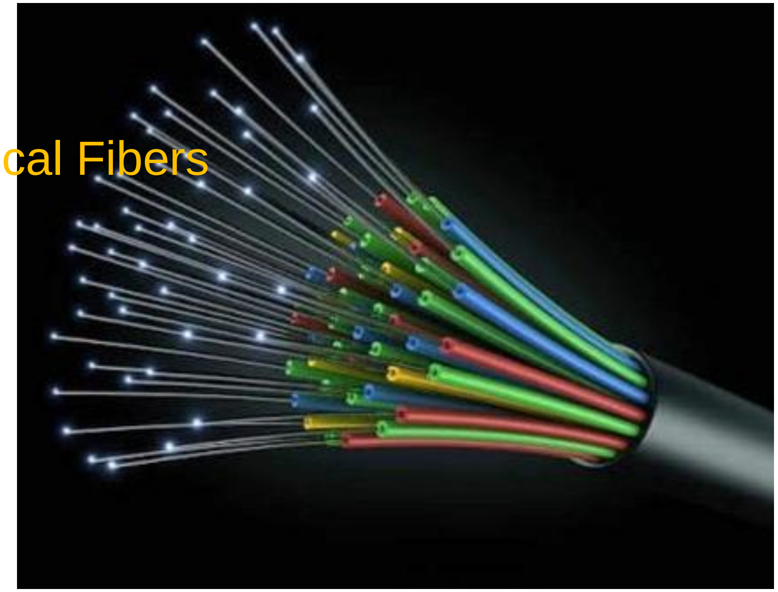


Laser	*Wavelength (μm)*	*Average Power Range*	*Applications*
Carbon dioxide	10.6	Milliwatts to tens of kilowatts	Heat treating, welding, cutting, scribing, marking
Nd:YAG	1.06 0.532	Milliwatts to hundreds of watts Milliwatts to watts	Welding, hole piercing, cutting
Nd:glass	1.05	Watts[a]	Pulse welding, hole piercing
Diodes	Visible and infrared	Milliwatts to kilowatts	Bar-code reading, CDs and DVDs, optical communications
Argon-ion	0.5415 0.488	Milliwatts to tens of watts Milliwatts to watts	Surgery, distance measurements, holography
Fiber	Infrared	Watts to kilowatts	Telecommunications, spectroscopy, directed energy weapons
Excimer	Ultraviolet	Watts to hundreds of watts[b]	Eye surgery, micromachining, microlithography

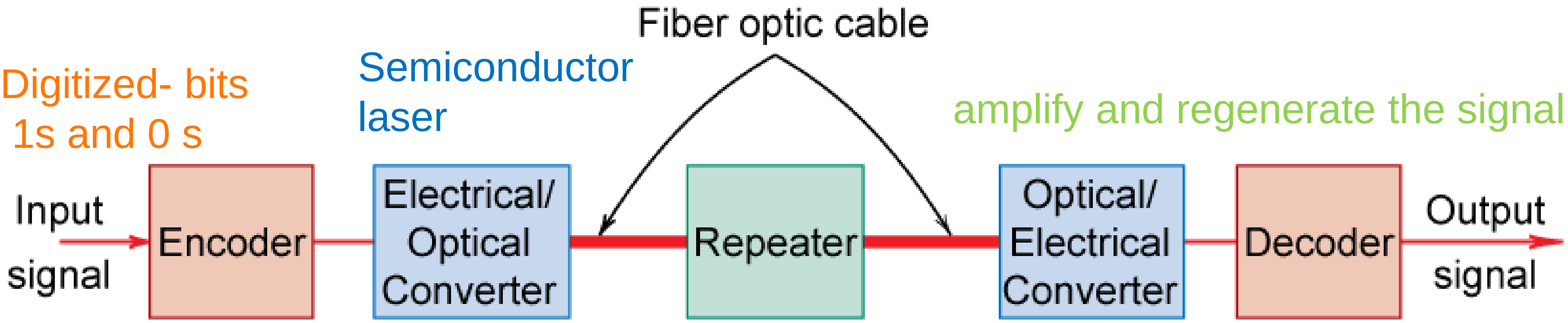
Optical Fibers

Fibre-optic technology has revolutionised telecommunications owing to the speed of data transmission:

- equivalent to >3 hrs of TV per second
- 24,000 simultaneous phone calls / 2 Optical Fibers
- 0.1kg of fibre carries same information of copper cable ~30,000 kg (33 tons)



Owing to attenuation in the cable, transmission is usually digital and the system requires several sections:

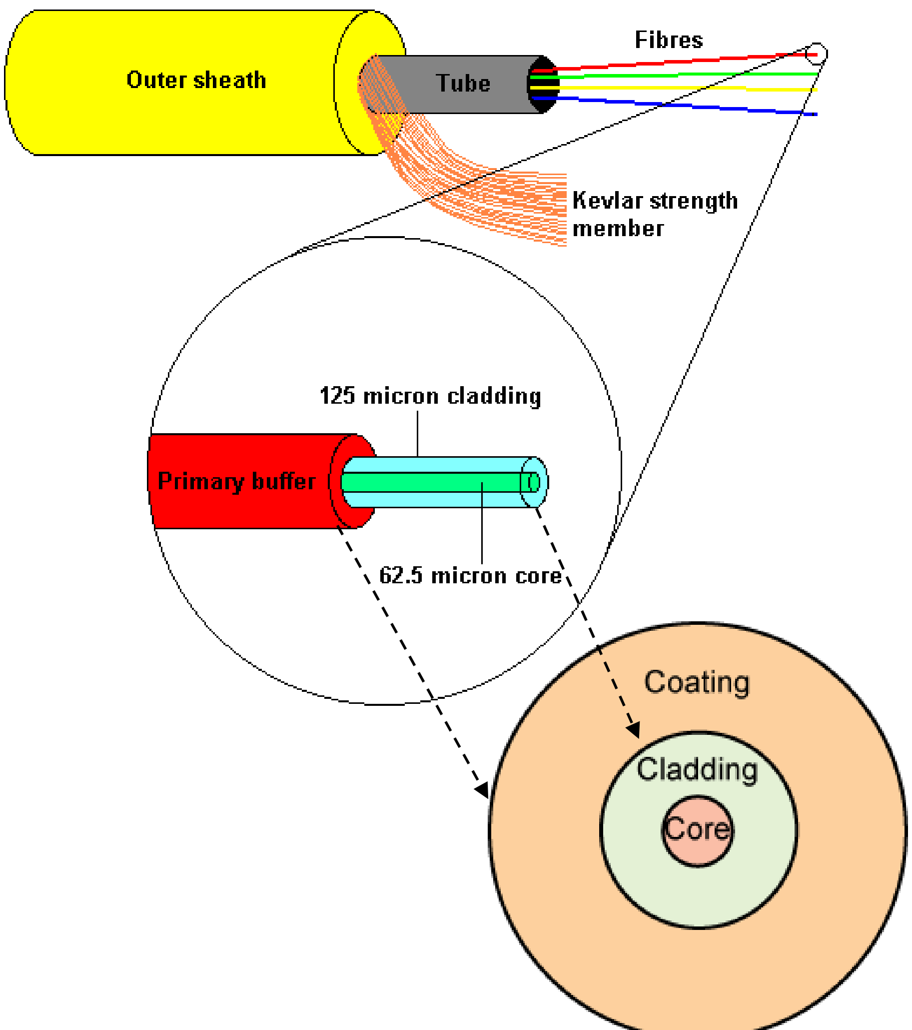


0.78 and 1.6 μm
(heart of this communication system)

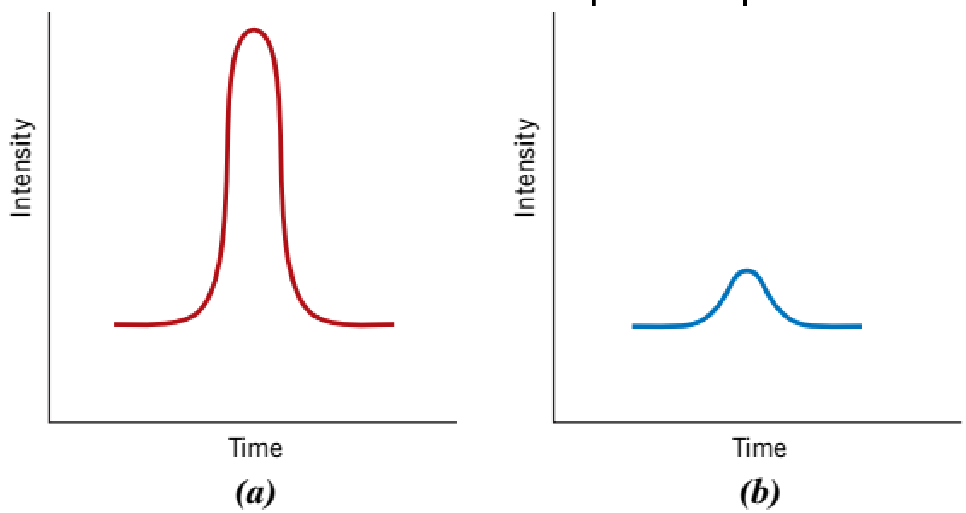
Optical Fibers

Fiber components are the core, cladding, and coating

- fibers materials have diameters 5 to 100 μm
- plastic cladding 60 μm thick is applied to fibers



Digital encoding scheme for optical communications. (*a*) A high-power pulse of photons corresponds to a 1 in the binary format. (*b*) A low-power photon pulse represents a 0.



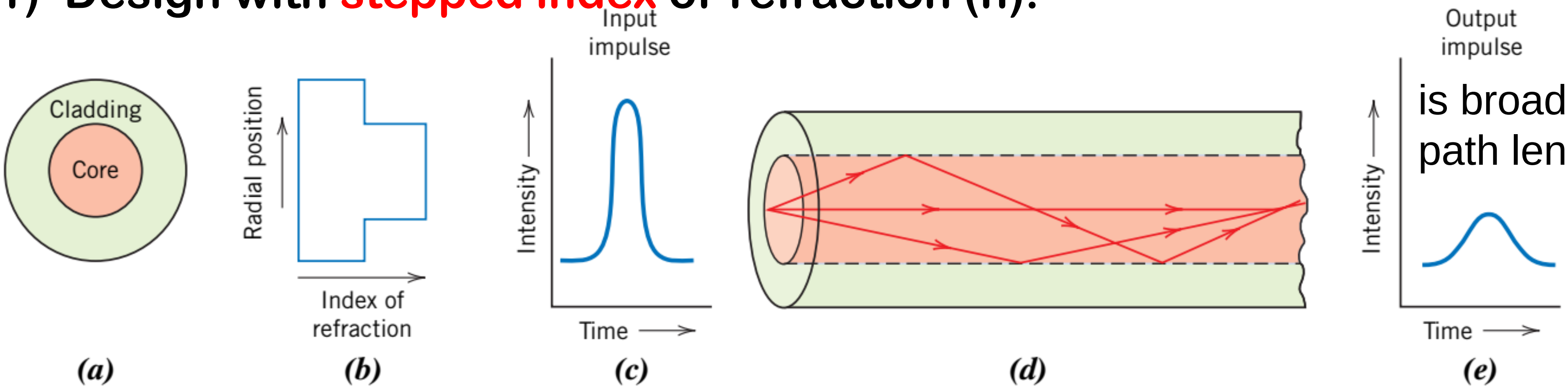
High-purity silica glass is used as the fiber material

FIBER OPTICS

Containment of the light to within the fiber core is made possible by total internal reflection

Two design types are used

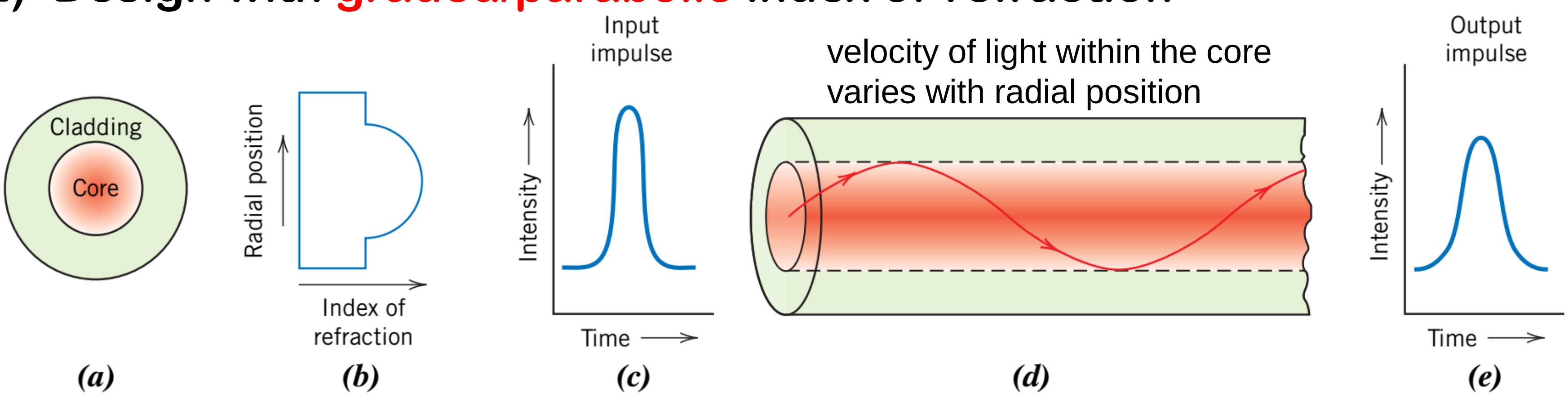
1) Design with stepped index of refraction (n):



is broader; path lengths

2) Design with graded/parabolic index of refraction

velocity of light within the core varies with radial position



Impurities such as boron oxide (B_2O_3) or germanium dioxide (GeO_2) are added to the silica glass

- **Parabolic = less broadening = improvement!**

SUMMARY

- Light radiation impinging on a material may be reflected from, absorbed within, and/or transmitted through
- Light transmission characteristics:

  -- transparent, translucent, opaque
- Optical properties of metals:

  -- opaque and highly reflective due to electron energy band structure.

- Optical properties of non-Metals:

  -- for $E_{gap} < 1.8$ eV, absorption of all wavelengths of light radiation

  -- for $E_{gap} > 3.1$ eV, no absorption of visible light radiation

  -- for 1.8 eV $< E_{gap} <$ 3.1 eV, absorption of some range of light radiation wavelengths

  -- color determined by wavelength distribution of transmitted light

- Other important optical applications/devices:

  -- luminescence, photoconductivity, light-emitting diodes, solar cells, lasers, and optical fibers

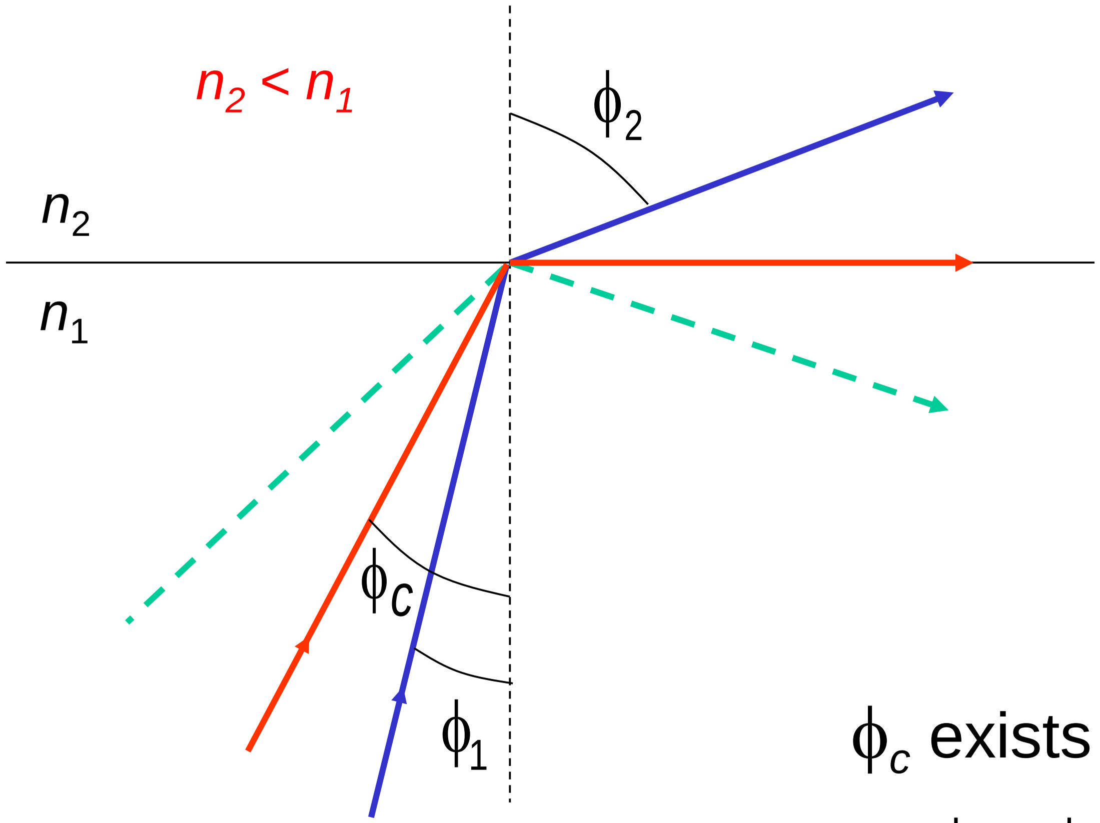
Practice Questions

Q 13. 1 The fraction of nonreflected light that is transmitted through a 250-mm thickness of glass is 0.98. Calculate the absorption coefficient of this material.

Q 13.2 Are the elemental semiconductors silicon and germanium transparent to visible light? Why or why not?

Q 13. 3 Is the semiconductor Gallium Nitride (GaN), which has a band gap of 3.4 eV, photoconductive when exposed to visible light radiation? Why or why not?

Total Internal Reflectance



$$\frac{n_1}{n_2} = \frac{\sin\phi_2}{\sin\phi_1}$$

ϕ_1 = incident angle

ϕ_2 = refracted angle

ϕ_c = critical angle

Total Internal Reflectance

ϕ_c exists when $\phi_2 = 90^\circ$

For $\phi_1 > \phi_c$ light is internally reflected

- Fiber optic cables are clad in low *n* material so that light will experience total internal reflectance and not escape from the optical fiber.

Computations of Minimum Wavelength Absorbed

(a) What is the minimum wavelength absorbed by Ge, for which $E_g = 0.67$ eV?

Solution:

$$\lambda_{\mathrm{Ge}}(\mathrm{min}) = \frac{hc}{E_g(\mathrm{Ge})} = \frac{(6.63 \times 10^{-34}\ \mathrm{J \cdot s})(3 \times 10^{8}\ \mathrm{m/s})}{(0.67\ \mathrm{eV})(1.60 \times 10^{-19}\ \mathrm{J/eV})}$$

$$\lambda_{\mathrm{Ge}}(\mathrm{min}) = 1.86 \times 10^{-6}\ \mathrm{m} = 1.86\ \mu m$$

(b) Redoing this computation for Si which has a band gap of 1.1 eV

$$\lambda_{\mathrm{Si}}(\mathrm{min}) = 1.13\ \mu m$$

Note: the presence of donor and/or acceptor states allows for light absorption at other wavelengths.

Example: Diamond in air

- What is the critical angle ϕ_c for light passing from diamond (n_1 = 2.41) into air (n_2 = 1)?
- Solution: At the critical angle, $\phi_1 = \phi_c$ and $\phi_2 = 90°$

Rearranging the equation $$\frac{n_1}{n_2} = \frac{\sin\phi_2}{\sin\phi_1}$$

$$\sin\phi_1 = \sin\phi_c = \frac{n_2}{n_1}\sin(90°) = \frac{n_2}{n_1}$$

Substitution gives

$$\sin\phi_c = \frac{1}{2.41}$$

$$\phi_c = 24.5°$$