Photonic Devices

Human eye: about 400 nm to 700 nm

\[ \lambda [nm] = \frac{1240}{E [eV]} \]

S. M. Sze, "Physics of Semiconductor Devices"
Sensitivity of the human eye

Two LEDs:
- red \((\lambda = 660 \text{ nm})\)
- green \((\lambda = 560 \text{ nm})\)
emitting the same light intensity
Which one is brighter?

green LED appears 16 !!! times brighter

\(V(\lambda)\) … “standardized“ sensitivity of the human eye by day
\(V'(\lambda)\) … “standardized“ sensitivity of the human eye at night

Radiative Transitions

3 processes for interaction between a photon and an electron
- Absorption
- Spontaneous emission
  no external stimulus; quantum-electrodynamic process
- Stimulated emission
  photon interacts with excited “system“ \(
  \rightarrow \) second photon emitted with same energy and phase (coherent)

example: simple two-level system

\[ E_1 \rightarrow h\nu_{12} \rightarrow E_2 \]

\[ E_2 \rightarrow h\nu_{12} \rightarrow E_1 \] (in phase)

\[ E_2 \rightarrow h\nu_{12} \rightarrow E_4 \] (in phase)

\[ E_4 \rightarrow h\nu_{12} \rightarrow E_2 \]

Fig. 2 The three basic transition processes between two energy levels. Black dots indicate the state of the atom. The initial state is at the left, the final state, after the transition process, is at the right. (a) Absorption. (b) Spontaneous emission. (c) Stimulated emission.

S. M. Sze, “Semiconductor Devices – Physics and Technology”
Dominating processes:

**Light emitting diode (LED):** spontaneous emission

**Laser:** stimulated emission

**Photodetector and solar cell:** absorption

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**Light-emitting diode**

$p$-$n$ junction that can emit spontaneous radiation

**Visible LEDs**

![Graph showing relative eye response and wavelengths for different semiconductor materials.](image)

S. M. Sze, *Semiconductor Devices – Physics and Technology*

Fig. 6 Semiconductors of interest as visible LEDs. Figure includes relative response of the human eye.
most important SC for visible LEDs: GaAs\textsubscript{1-y}Py

\textbf{Problem:} \( y > 0.45 \) bandgap becomes indirect

\begin{itemize}
  \item replace small fraction of P by N in GaAs\textsubscript{1-y}Py
  \item isoelectric center
    \rightarrow periodicity broken
    \rightarrow localized trap level close to the bottom of the conduction band
    \rightarrow greatly enhances probability of a radiative transition
\end{itemize}

\textbf{Introduction of recombination centers}

quantum efficiency

number of photons generated per injected electron-hole pair
Consequence for GaAs$_{1-y}$P$_y$ LED

quantum efficiency  emission color

![Graphs showing quantum efficiency and emission color vs. alloy composition](image)

Fig. 9 (a) Quantum efficiency versus alloy composition, (b) Peak emission wavelength versus composition with and without isoelectronic impurity nitrogen. (After Groves, Herzog, and Craford, Ref. 31.)

graded alloy to reduce defects, which would act as nonradiative recombination centers

![Diagram showing graded alloy](image)

Fig. 10 Effects of (a) opaque substrate and (b) transparent substrate on photon emitted at the junction. (After Gage et al., Ref. 3)

S. M. Sze, "Physics of Semiconductor Devices"
Loss mechanisms:

- nonradiative recombination current
- absorption within the LED material
- reflection loss
- total internal reflection \((n = 3.66 \text{ in GaAs} \rightarrow \theta_{\text{total}} = 16^\circ \text{ at interface to air})\)

Fig. 11  Cross section of three LEDs. (a) Hemisphere, (b) Truncated sphere (Weierstrass source), (c) Paraboloid. (After Carr, Ref. 93.)

up to an order of magnitude increase in outcoupling efficiency by clever design ...

S. M. Sze, "Physics of Semiconductor Devices"

Colored plastic lens as optical filter and to enhance contrast

Fig. 10  Diagrams of two LED lamps.³

S. M. Sze, “Semiconductor Devices – Physics and Technology”
Infrared LEDs

Why?

**Opto-isolators**

electrically decouple two circuits through an IR-LED and a photodiode

![Diagram of an opto-isolator](image)

*Fig. 12* An opto-isolator in which an input signal is decoupled from the output signal.

S. M. Sze, "Semiconductor Devices – Physics and Technology"

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Optical fiber communications

![Graph of optical fiber loss](image)

*Fig. 22* Loss characteristics of a silica optical fiber. The three wavelengths of interest are also shown. (After Miya et al., Ref. 43.)

**Materials:** GaAs (0.9 µm) Ga_xIn_{1-x}As_yP_{1-y} (1.1 µm to 1.6 µm)

S. M. Sze, "Physics of Semiconductor Devices"
LEDs vs lasers for optical communications

**LEDs:**
- higher temperature operation
- smaller dependence of the emitted power on $T_{\text{simplex device structure}}$
- simpler drive circuit

**Lasers:**
- higher brightnes
- higher modulation frequency
- smaller spectral width (0.1 Å to 1 Å, compared to 100 Å to 500 Å in an LED)

Organic LEDs

Jean-Luc Brédas will talk about them …

Just a small appetizer …

Courtesy of M. Collon

Courtesy of E.J.W. List
**Semiconductor Lasers**

**Advantages** over "conventional" lasers:
small (0.1 mm), cheap, easily modulated at high frequencies by modulating the bias

**Materials** → as discussed in the heterostructures chapter...
first SC lasers: GaAs
Other materials: \( \text{Al}_{x}\text{Ga}_{1-x}\text{As}_{y}\text{Sb}_{1-y} \), \( \text{Ga}_{x}\text{In}_{1-x}\text{As}_{y}\text{P}_{1-y} \), InP, \( \text{Ga}_{x}\text{In}_{1-x}\text{As}_{y}\text{P}_{1-y} \), ...

**Requirements for laser (stimulated emission):**
gain (population inversion, optical confinement, feedback ("mirrors"))

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**Laser structures**

- homojunction laser
- double-heterojunction laser

Pair of parallel planes cleaved or polished → mirrors (Fabry-Perot cavity)

Other "vertical sides": roughened

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*Fig. 1B* Semiconductor laser structures in the Fabry Perot-Cavity configuration. (a) Homojunction laser. (b) Double heterojunction (DH) laser. (c) Stripe geometry (SCH) laser. S. M. Sze, "Semiconductor Devices – Physics and Technology"
Population inversion

Gain: probability for a stimulated emission event needs to be higher than that for an absorption event

→ high injection condition (large concentration of $e^-$ and $h^+$ injected into transition region)

"roughly" speaking: for the photon energy range of interest, more than half of the valence bend states need to be empty and more than half of the conduction band states need to be occupied

More rigorously speaking: $F_{e^-} + F_{h^+} > 1$ in the region of space, where the laser-action is supposed to occur

How can we achieve that?

Two degenerately doped semiconductors

Apply a voltage so that $E_{FC} - E_{FV} > E_g$

S. M. Sze, "Semiconductor Devices – Physics and Technology"

![Energy band diagrams](image)
Crucial parameter: Threshold current density (minimum current density required for lasing)

**homojunction laser:**
- carriers can move away from active region

**heterojunction laser:**
- carriers are confined

Also optical confinement through waveguiding
Spectral narrowing of the emission spectrum upon lasing

![Graph showing spectral narrowing upon lasing](image)

Fig. 26 Emission spectra of a laser below, just at, and above threshold, showing narrowing of the spectral distribution of the emission when lasing is initiated.

S. M. Sze, “Semiconductor Devices — Physics and Technology”

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**Photodetectors**

Convert optical signal into electrical signal

- Photon absorption
- Exciton dissociation
- Carrier transport through SC to external circuit

**Quantum efficiency**

number of electrons ( = number of holes) created (and transported out of the device) per incident photon
**Photoconductor**

slab of semiconductor with Ohmic contacts at the end

![Schematic diagram of a photoconductor](image)

Fig. 29  Schematic diagram of a photoconductor that consists of a slab of semiconductor and two ohmic contacts at the ends.

Electron-hole pairs are created by absorbed photons → increased number of free carriers → **increased conductivity**

*S. M. Sze, “Semiconductor Devices – Physics and Technology”*

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**Photodiode**

p-n junction operated under reverse bias

Electric field in the depletion region separates photogenerated e-h pair → electric current in external circuit

**Quantum-efficiency:**

depletion region very thick to absorb as many photons as possible in a region with an electric field!

**Response speed (high frequency applications):**

depletion region as thin as possible to reduce transit time!

→ **compromise depending on application**
Quantum-efficience of photodiodes

Long wavelength cutoff: bandgap

Short wavelength cutoff: very large absorption coefficient at short wavelengths → radiation absorbed near surface (short recombination time, no field)

p-i-n photodiode

deployment region thickness “artificially increased” by an additional intrinsic layer

tuning the thickness of the intrinsic region → tune quantum efficiency and response speed
Other photodetectors:

• Metal-semiconductor photodiode

• Heterojunction photodiode

• Avalanche photodiode (multiplication effect)
Solar cells

main difference to standard photodetectors:

need to efficiently detect solar radiation (created by nuclear fusion in the sun)

no external bias applied

Current use:

• remote Power Supplies
• portable Power Supplies
• replacement of Batteries

Solar Radiation

Nuclear fusion in sun:
hydrogen converted to He ⇒ mass loss ⇒ $E=mc^2$

⇒ primarily emitted as electromagnetic radiation in the UV to IR region

Projected: nearly constant radiative-energy output of over 10 billion years

solar constant (intensity of solar radiation in free space at average distance of Earth): 1353 W/m$^2$

at 0°: 925 W/m$^2$
at 45°: 844 W/m$^2$
Influence of the Atmosphere

**air mass**
(UV absorption in O₃; IR in water vapor; scattering by dust and aerosols)

AM0: outside atmosphere
(satellites ….)
AM1: at surface, when sun is overhead
AM1.5 ….. see sun at 48°

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**Power conversion efficiency**

Output electrical power (i.e. \(I \times V\)) per incident power

- theoretical limit depends on \(E_g\)
- Under AM1.5, maximum efficiency is 31% at \(E_g = 1.35\) eV
- for two band-gaps in series: max. efficiency is 50%

*Amorphous silicon 12% AM1.5*
*Single-crystal silicon 24.4%*
*GaAs (crystalline) 25.1%*
Organic solar cells have generally only a few % power conversion efficiency.

So why organic solar cells?

- cheap
- large area
- flexible
- less energy in production process …

How much light do we get into the cell?

Reflection at interfaces (refractive index contrast) ⇒ “anti-reflection” coating

More sophisticated design employing „inverted pyramids“:
Optical concentration

- reducing area needed for solar cell
- increasing efficiency!

Organic solar cells:

Absorption

Absorption of virtually all incident light desired

⇒ \( \alpha \) determines layer thickness

What determines magnitude of \( \alpha \)?

Inorganic semiconductor: direct vs. indirect band-gap

Conjugated organic molecule:
- conjugation length, side chains, texturing, ...

What is the proper energy gap (for a single-layer cell)?

\[ E_{\text{photon}} < E_{\text{gap}} \Rightarrow \text{no contribution to cell output} \]

\[ E_{\text{photon}} > E_{\text{gap}} \Rightarrow \text{excess energy wasted as heat} \]

"Ideal" single-layer cell:
maximum efficiency 31% at \( E_g = 1.35 \text{ eV} \)
\( E_g \) between 1eV and 2 eV OK
- good news for inorganic SC
- bad news for organics!


Structure of inorganic solar cells

Apart from lack of band-bending similar to inorganic solar cell, but charge separation needs to be discussed in more detail!

Charge separation in conjugated molecules

Electron-hole pairs are strongly bound in conjugated polymers!

Dissociation mediated by defect sites
- Trap sites
- Carbonyl groups (Rothberg)
- Molecular oxygen (Frankevich)
- Conformational defects
- Grain boundaries (crystals)
- Dopant sites

and high local fields (eg. Interfacial layers – in the case of the build up of space-charge regions)

(What can be detrimental for an LED can be helpful for a solar cell!)

⇒ Insert “defects” and interface sin a controlled manner!
Double-layer organic solar-cell

Charge- vs. energy transfer (simplified model)

excited state diffuses to interface

The “Tang” Cell (1986)

- Power conversion efficiency of about 1% reported
- Bilayer cell, evaporated molecules
- CuPc - Perrylene as a donor/acceptor pair
- Drawbacks: Sharp interface - fewer excitons hit the interface
- Advantages: Molecules exhibit higher mobility

30 nm copper phthalocyanine + 50 nm perylene - derivative

K. Petritsch Dissertation TUG 2000
Numerous other material combinations

Problem with solution-processing:
Polymers must not be soluble in the same solvents

Laminated devices

Each layer can be treated individually
e.g., doping, heat treatment

During lamination control of interdiffusion through
pressure
temperature,
exposure to vapor ...

K. Petritsch, Dissertation TUG 2000
Choice of materials:

- The red-shifted form (of POPT) is preferred here as it provides the best match to the solar spectrum.
- MEH-CN-PPV ... large electron affinity as a result of the electron-withdrawing cyano-groups.

• QE of 29% at peak wavelength
• Power conversion efficiency of 4.8% (at peak wavelength)
• Power conversion efficiency of 1.9% (at AM1.5)

Blend Structures

- Distribute active interfaces throughout the bulk
- Mix electron acceptor and hole acceptor together
- All excitons are within a diffusion range of an interface (10 nm)
- Electrons transferred to one component, holes to the other

For excited state charge transfer compare N.S. Sariciftci, L. Smilowitz, A.J. Heeger, and F. Wudl, Science 256, 1474 (1992)
Charges travel to respective electrodes (percolation) (11 %)

Requirement: Interpenetrating network

Problem: Phase Separation

Possible solutions:
Self-organizing structures
Link C60 covalently to conjugated backbone

Dye-sensitized solar cell

- Invented 1991 by Grätzel (best:11%)

Sponge of nano-crystalline TiO₂
Coated with dye molecules
⇒ huge effective surface area

Dye excited
⇒ e- transferred into conduction band of TiO₂
⇒ e- transmitted through semiconducting TiO₂
⇒ dye reduced by electron from redox couple

Compare e.g.: http://www.sta.com.au
Device characteristics

Equivalent circuit:

constant current source parallel to diode (p-n junction)

“ideal” current voltage characteristics:

\[ I = I_s (e^{\frac{qV}{kT}} - 1) - I_L \]

and

\[ J_s = \frac{I_s}{A} = qN_C N_V \left\{ \frac{1}{N_A} \sqrt{\frac{D_n}{\tau_n}} + \frac{1}{N_D} \sqrt{\frac{D_p}{\tau_p}} \right\} e^{-\frac{E_s}{kT}} \]

Organic SC - Device Physics/Device Parameters

- a) Reverse External Bias
- b) 0 Bias = Short Circuit Current
- c) 0 Current = Open Circuit Voltage
- d) Forward External Bias

K. Petritsch Dissertation TUG 2000
Power conversion efficiency

\[ P = I \times V \]

What is \( P_{\text{max}} \)?

Filling Factor (FF)

\[ FF = \frac{\left( I \times V \right)_{\text{max}}}{I_{\text{SC}} \times V_{\text{OC}}} \]

Power Conversion Efficiency

\[ \eta(\lambda) = \frac{\left( I \times V \right)_{\text{max}}(\lambda)}{P_{\text{light}}(\lambda)} = \frac{I_{\text{SC}}(\lambda) \times V_{\text{OC}}(\lambda) \times FF(\lambda)}{P_{\text{light}}(\lambda)} \]

External Load

\[ R_L = \frac{V_P}{I_P} \]

Examples for I-V characteristics in organic solar cells

Tang – double-layer cell

- QE of 29% at peak wavelength
- Power conversion efficiency of 4.8% (at peak wavelength)

Laminate solar cell
Concluding remarks

PV is about the 3 fundamental steps:

1. Light absorption
2. Charge separation
3. Charge collection

This can in organic Solar Cells be achieved by

1. Single layer structures
2. Blend structures
3. Hetero structures
4. Laminated hetero structures
5. Dye sensitized structures