Semiconductor optoelectronics 1

Optoelectronic devices and photodetectors

Modern physics for engineers

David Miller

Optoelectronic devices

Optoelectronic devices

Being able to convert

easily and efficiently between

light and electrical power and signals

has transformed what we can do with light

The devices that enable such conversions are called

optoelectronic devices

Optoelectronic devices

Viewed broadly, optoelectronics includes

- conventional incandescent and fluorescent light bulbs
- vacuum-based devices like cathode ray tube and plasma displays and some specialized photodetectors (e.g., photomultiplier tubes)
- liquid crystal display technology
- and, especially now

  semiconductor optoelectronics

  which we can now understand

Optoelectronic devices

Many optoelectronic devices use diodes, but in different ways

- collecting electrons and holes generated by absorbing photons, in, e.g.,
  - solar cells
  - photodetectors for signals on light beams

Optoelectronic devices

- injecting electrons and holes into the junction region
  - by forward biasing the diodes so they can
    - recombine by emitting photons for
      - light-emitting diodes
        e.g., illumination
      - semiconductor lasers
        e.g., fiber communications

Optoelectronic devices

- applying large electric fields inside devices without much current by reverse biasing
  - We use this for several kinds of light modulators to
    - turn light beams on and off in optical communications
  - by changing the material's optical properties, such as
    - optical absorption strength or refractive index

Optoelectronic devices

Here we will introduce especially

the use of diode structures in

detection

and

light emission

Photoconductors

Generating electron-hole pairs

Absorbing a photon in a semiconductor

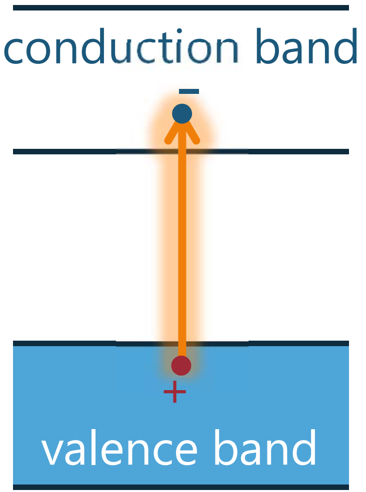
- with photon energy greater than the band gap energy can
  - take an electron from the valence band
    - and put it in the conduction band
      - leaving a hole in the valence band

We can call this process

- generation of an "electron-hole pair"

These "photogenerated" electrons and holes

- are sometimes called "photocarriers"



Photoconductors

Before the electron and hole "recombine"

with the electron falling back into the valence band

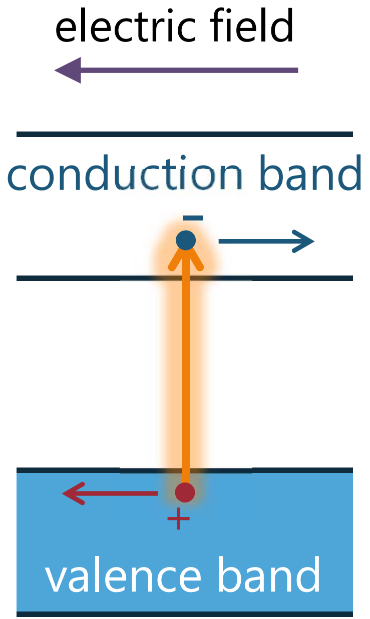
they can conduct electricity

In a piece of semiconductor

this is called photoconduction

This process is used

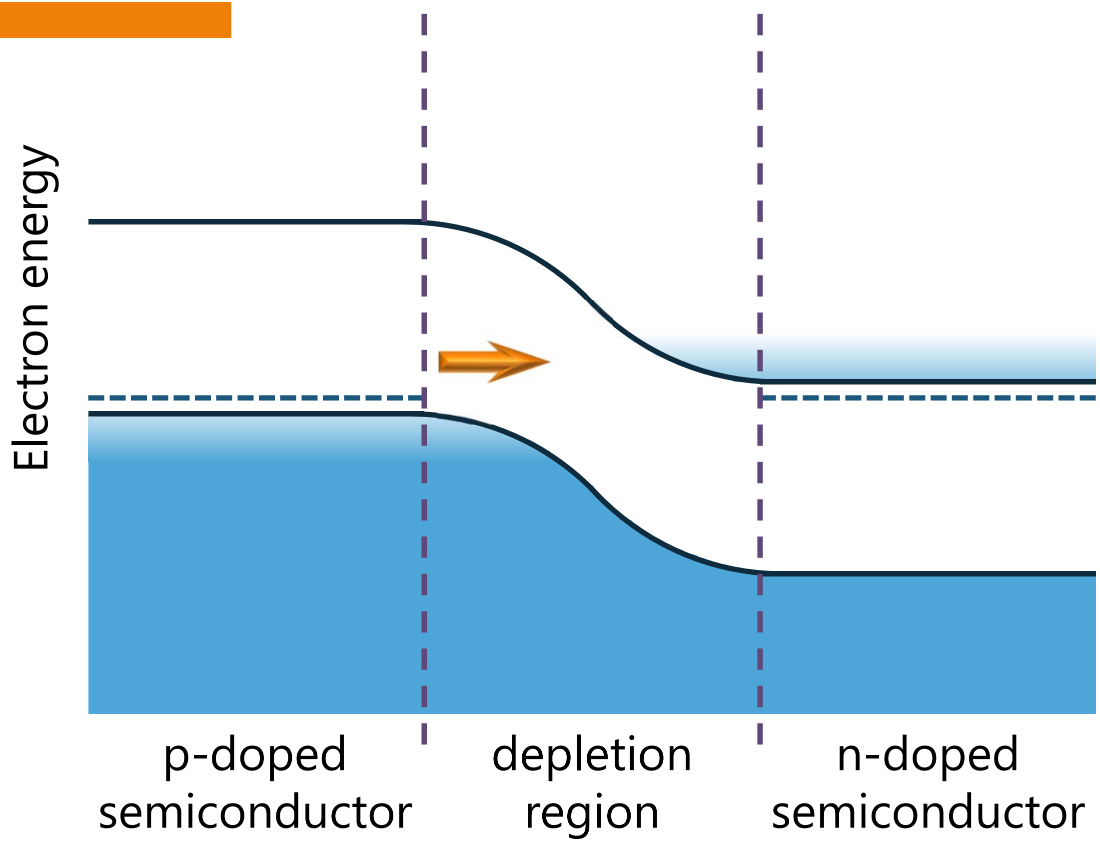
for some photodetectors



Photodiodes

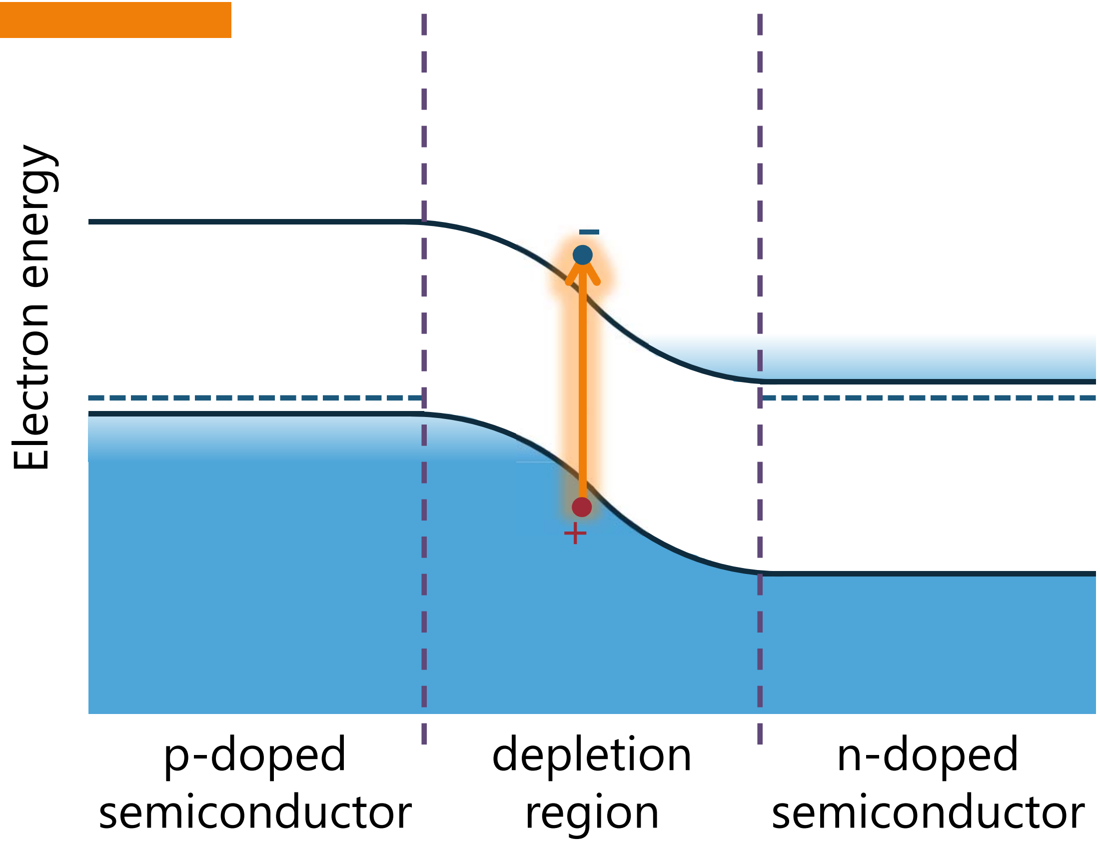
Photocarriers in diodes

Absorbing a photon in the depletion region



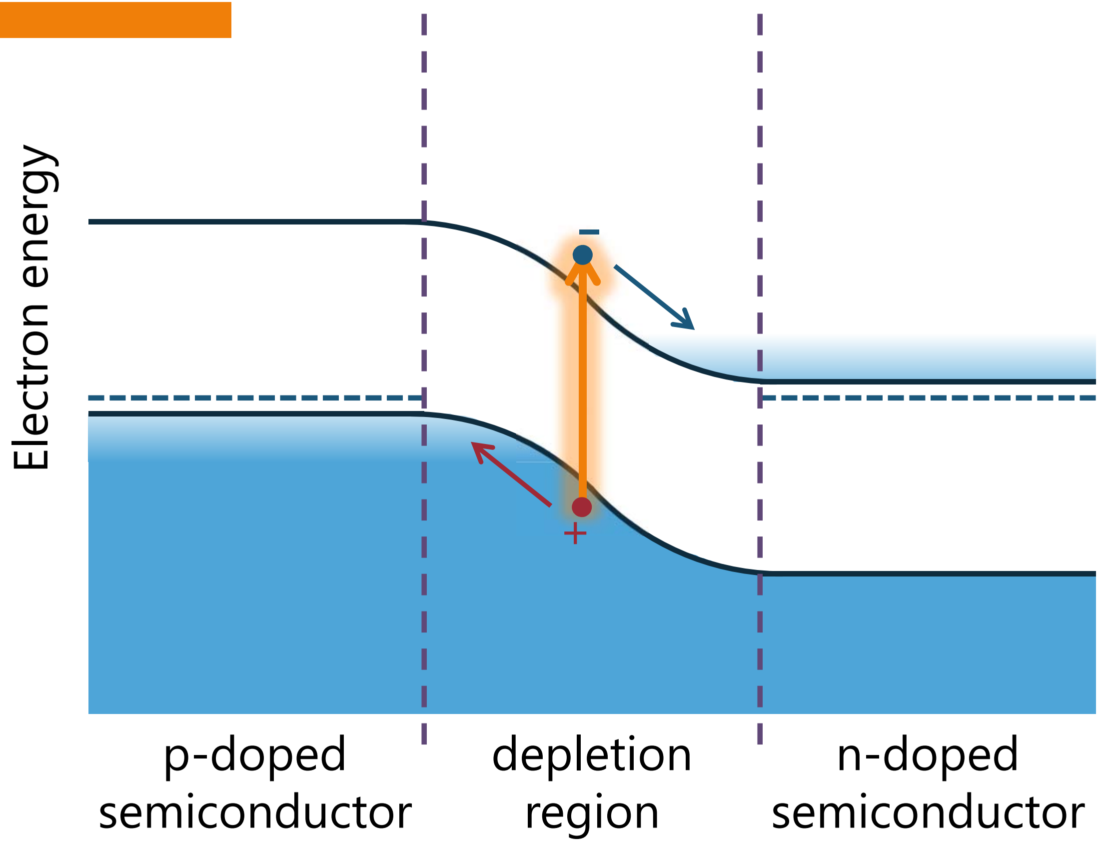
Photocarriers in diodes

Absorbing a photon in the depletion region generates an "electron-hole" pair



Photocarriers in diodes

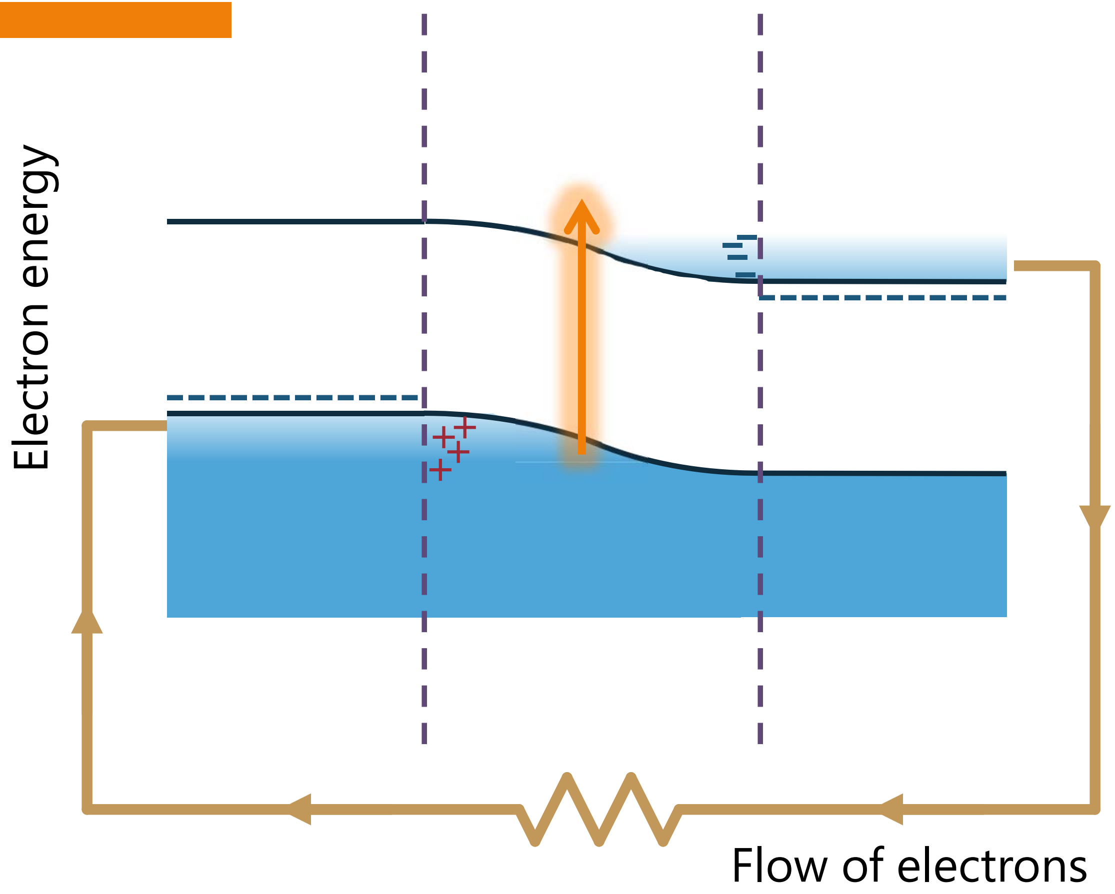
- Absorbing a photon in the depletion region
  - generates an
    - "electron-hole" pair
- The electron and hole drift "downhill" in the field



Photovoltaic diode

The charge separation

- creates a potential to resist the charge separation
  - which creates an external voltage
    - which can drive a current through a resistor



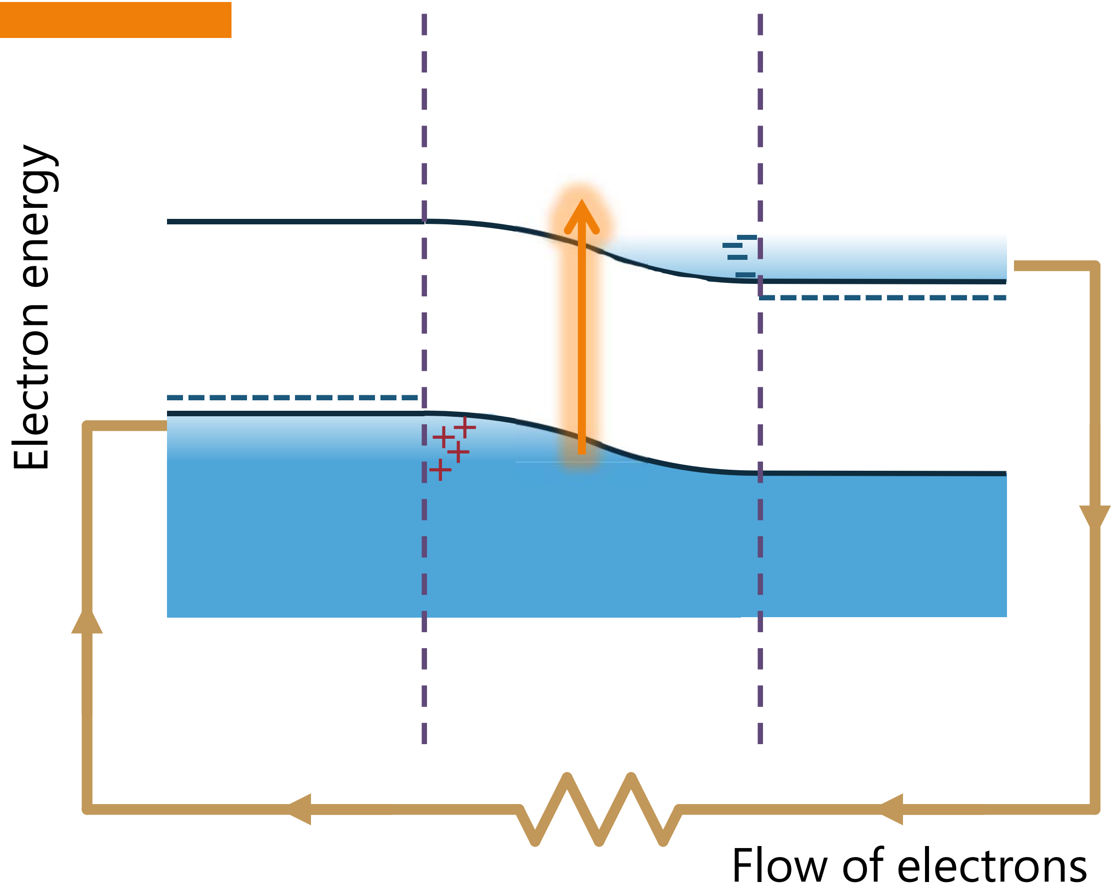
Photovoltaic diode

This generates electric power

in a solar cell

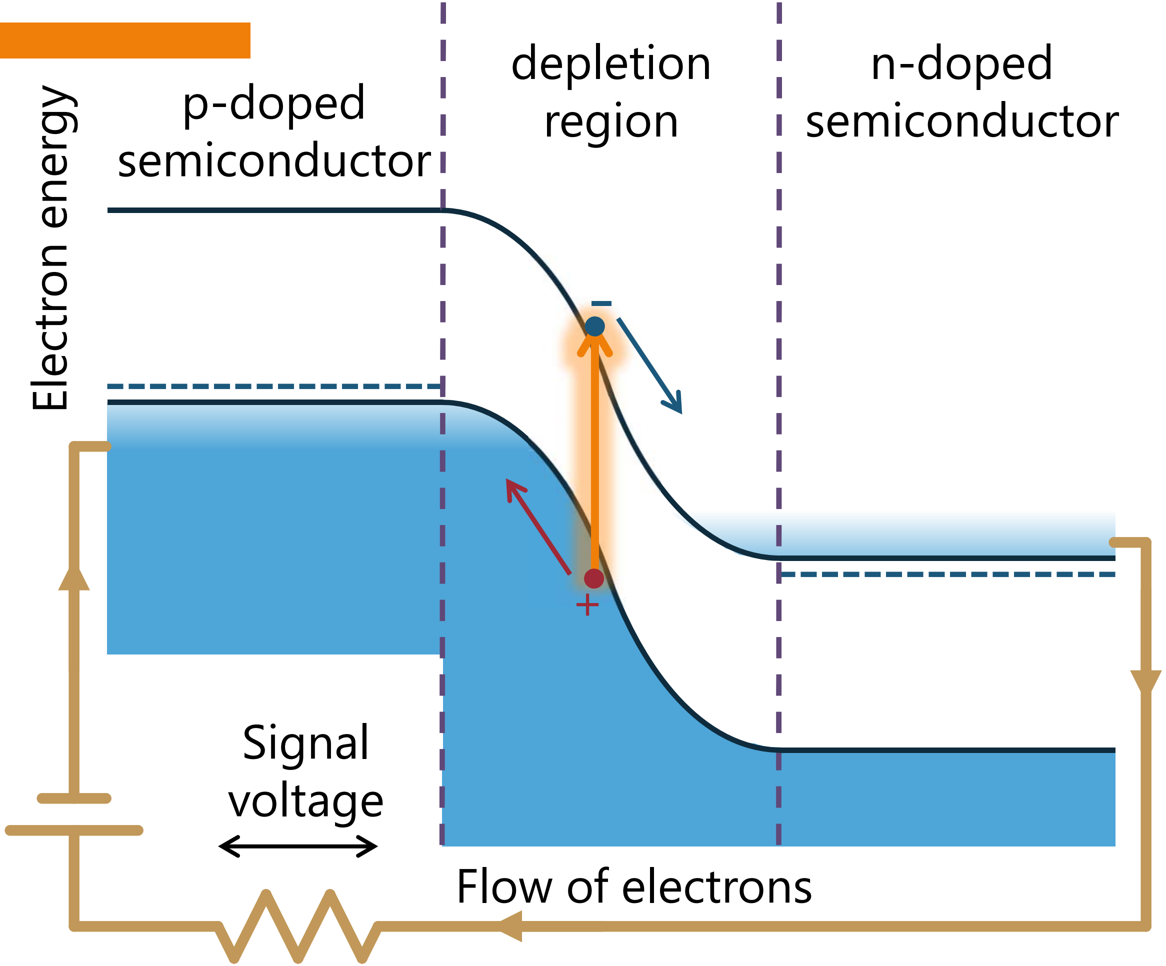
and gives an output voltage

for a photovoltaic photodetector



Reverse-biased photodiode

- In a reverse-biased photodiode
  - photogenerated electrons and holes
    - are rapidly swept out by the electric field
- This gives a photocurrent in an external circuit
  - and a signal voltage over a resistor



Diode current-voltage (I-V)

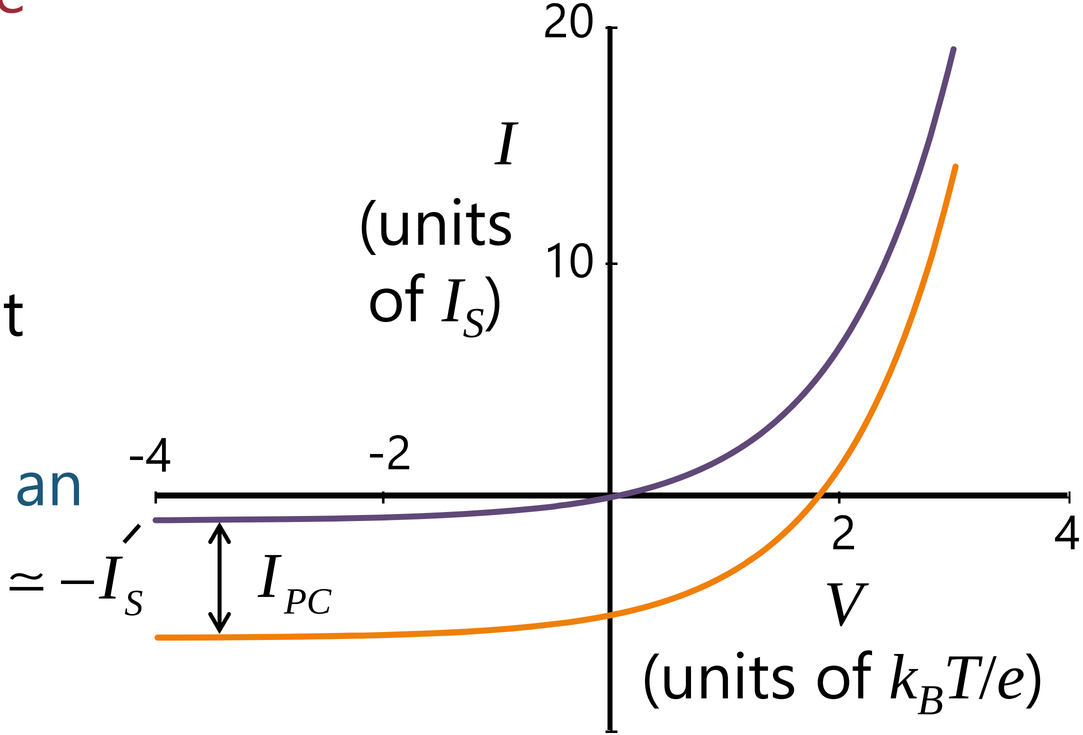
$$I = I_S\left[\exp\left(\frac{eV}{k_B T}\right) - 1\right] - I_{PC}$$

With light

- the current-voltage curve
  - is shifted down by the magnitude of the photocurrent I_{PC}

In the lower right quadrant

- power $|V \times I|$
  - would be generated in an external resistor
    - as in a solar cell



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Light emission

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Thermal and non-thermal light sources

Thermal and non-thermal light sources

From the Boltzmann factor

$$\frac{N_2}{N_1} = \exp\left(-\frac{E_2 - E_1}{k_B T}\right)$$

at any finite temperature

there are always more systems in the lower state than in the upper state

so a photon coming into the system

is more likely to be absorbed – $B_{12} N_1 \rho(\nu)$

than it is to stimulate emission – $B_{12} N_2 \rho(\nu)$

Hence photon loss exceeds photon gain for a system in thermal equilibrium

so stimulated emission does not “run away” to lasing

Thermal and non-thermal light sources

There is still emission from warm bodies

- both spontaneous $A_{21}N_2$
- and even some stimulated $B_{12}N_2\rho(\nu)$
  - though that is normally a small fraction

These are the normal processes of "thermal" emission of light from hot objects

Thermal and non-thermal light sources

- If by some non-thermal process, we can put some of the "atoms" in their upper states
  - we can get light emission without high temperatures
    - as in light emitting diodes and lasers

Direct gaps and light emission

Direct gap semiconductor

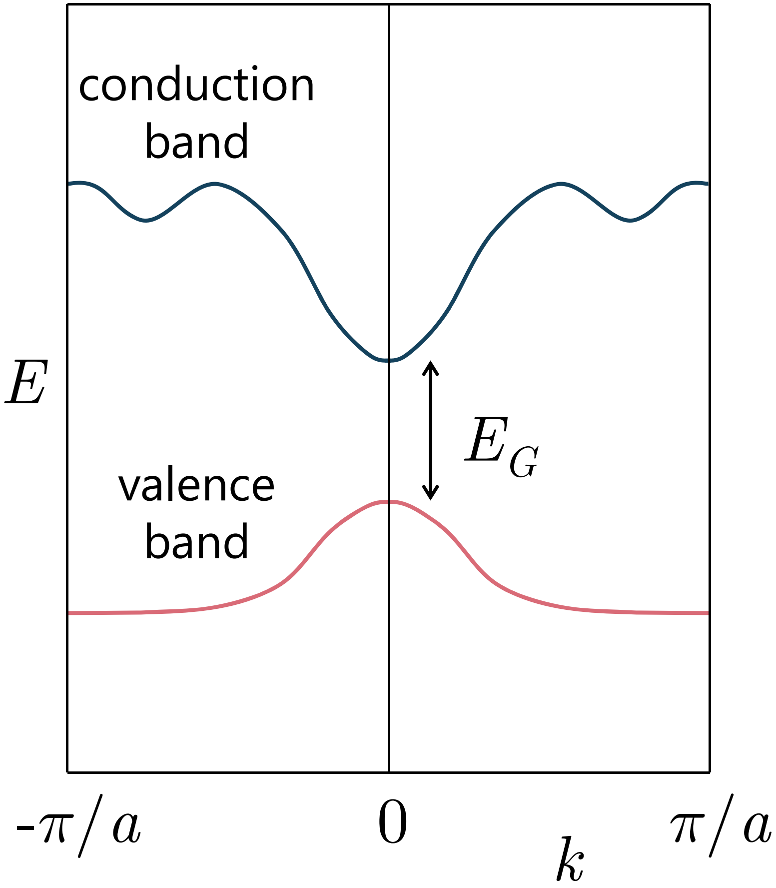
If the lowest minimum in the conduction band

lies directly above

the highest maximum in the valence band

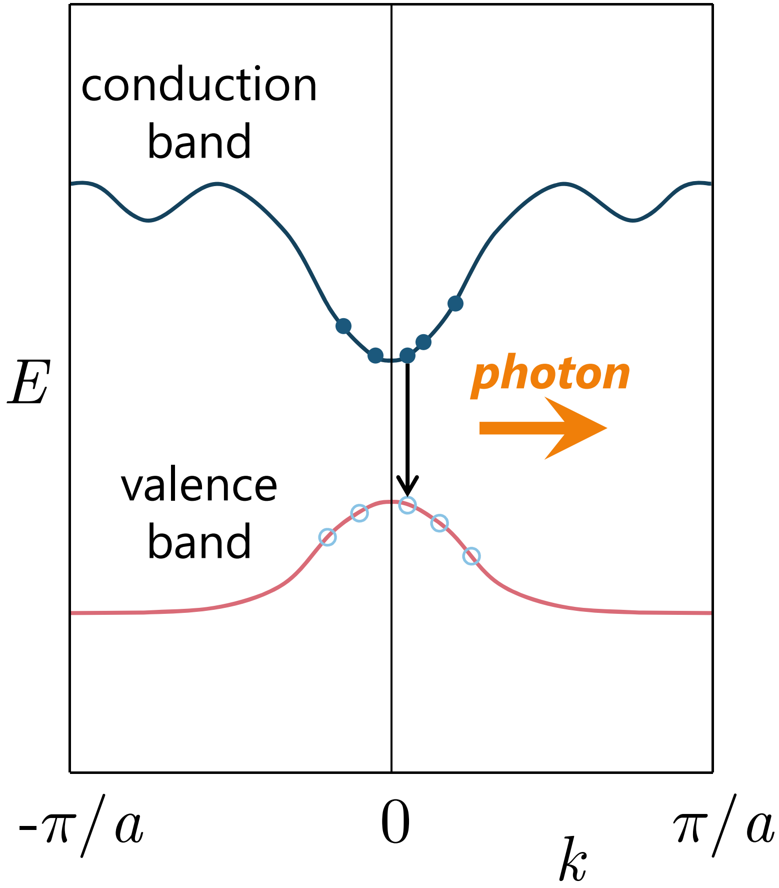
the semiconductor is said to have a

"direct gap"



Direct gap semiconductor

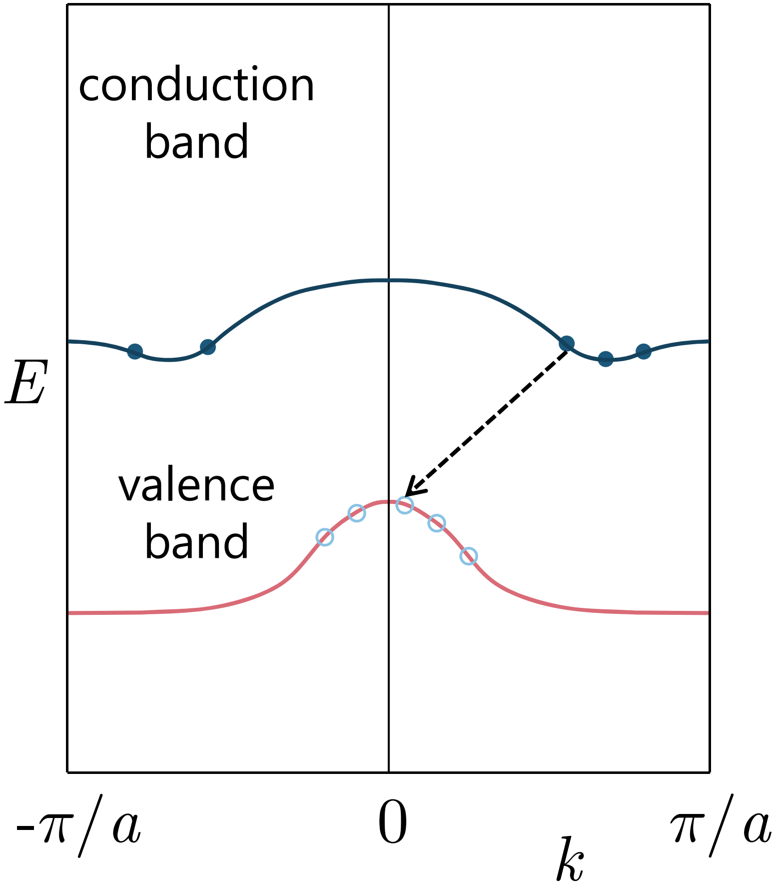
- Direct gaps are important for light emitters
  - Electrons "pumped" into the conduction band gather in the lowest minimum
  - "Holes" pumped into the valence band gather in the highest maximum
- An electron can fall "vertically" to fill in a hole beneath it
  - emitting light



Indirect gap semiconductor

In an indirect gap semiconductor
- e.g., silicon, germanium
  - the lowest conduction band minimum (or minima)
  - is (are) not directly above the highest valence band maximum

Light emission is weak
- "non-vertical" transitions by emission of photons are weak



Forward-biased diode light emitters

Forward-biased light emitter

Forward biasing the diode

injects

electrons

and

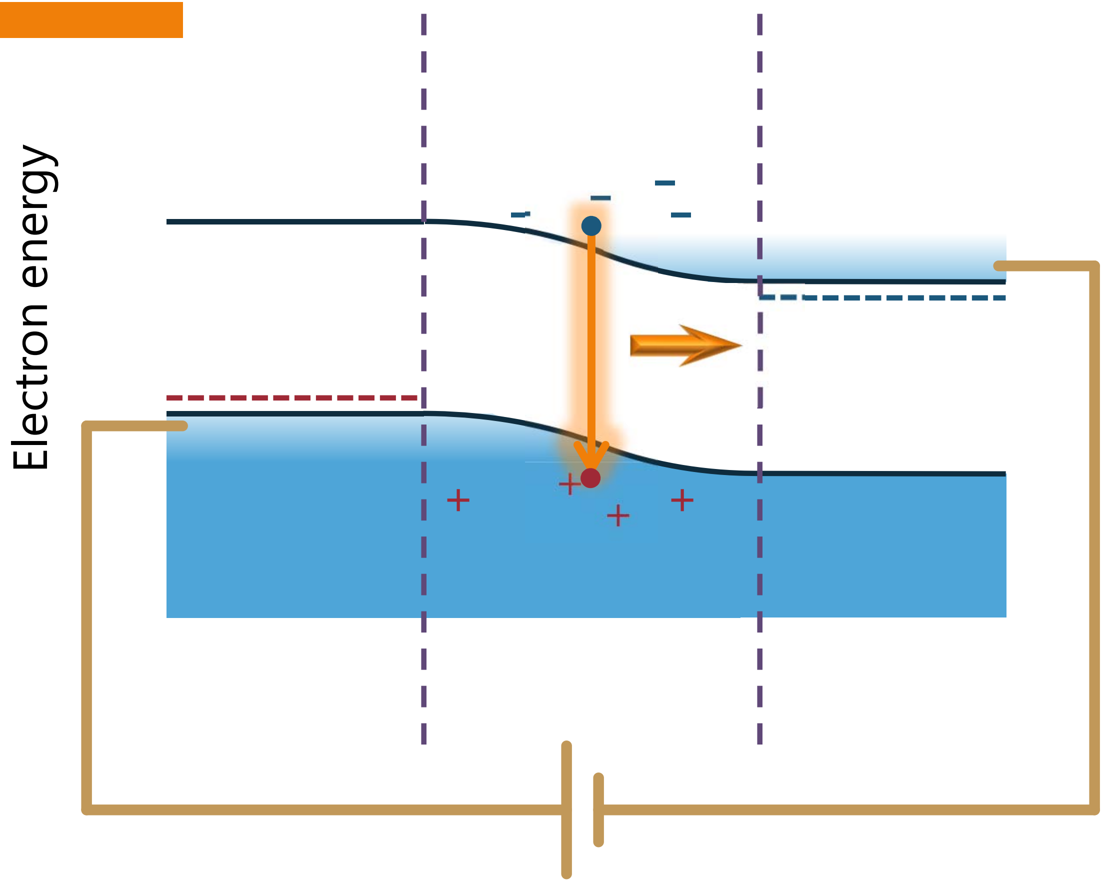
holes

into the same region

where they can

recombine

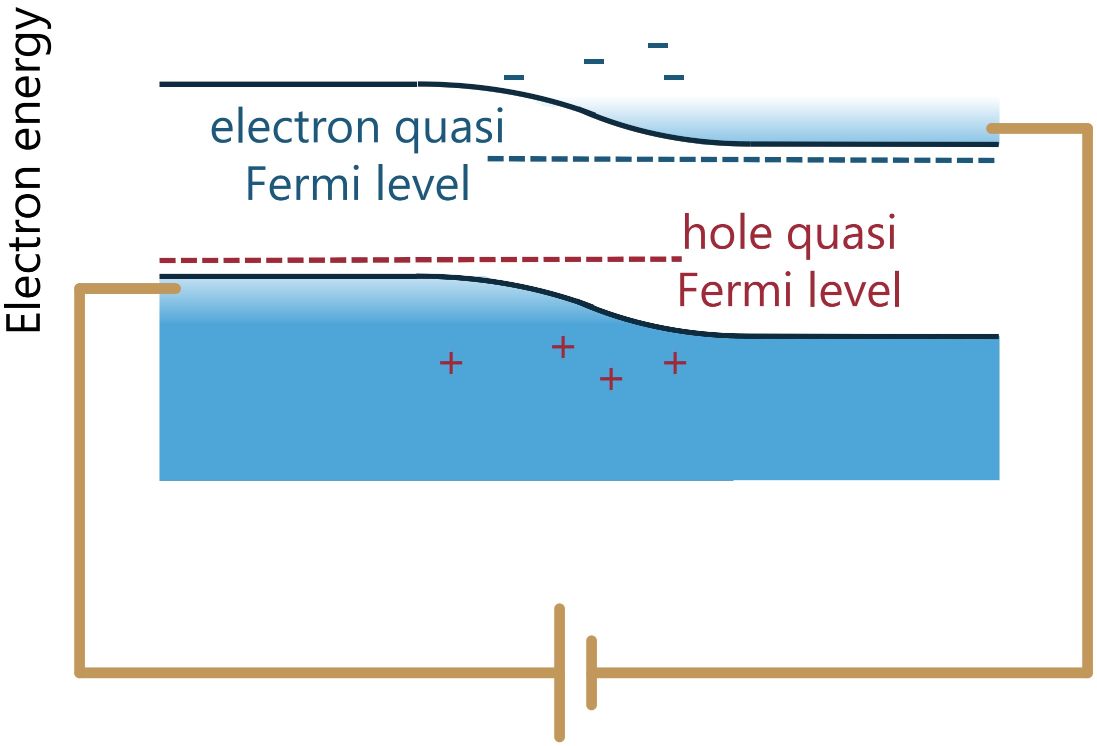
to emit light



Forward-biased light emitter

Under forward bias

- electrons and holes
  - near the junction
    - can effectively have their own Fermi levels
      - different from each other
        - known as quasi Fermi levels



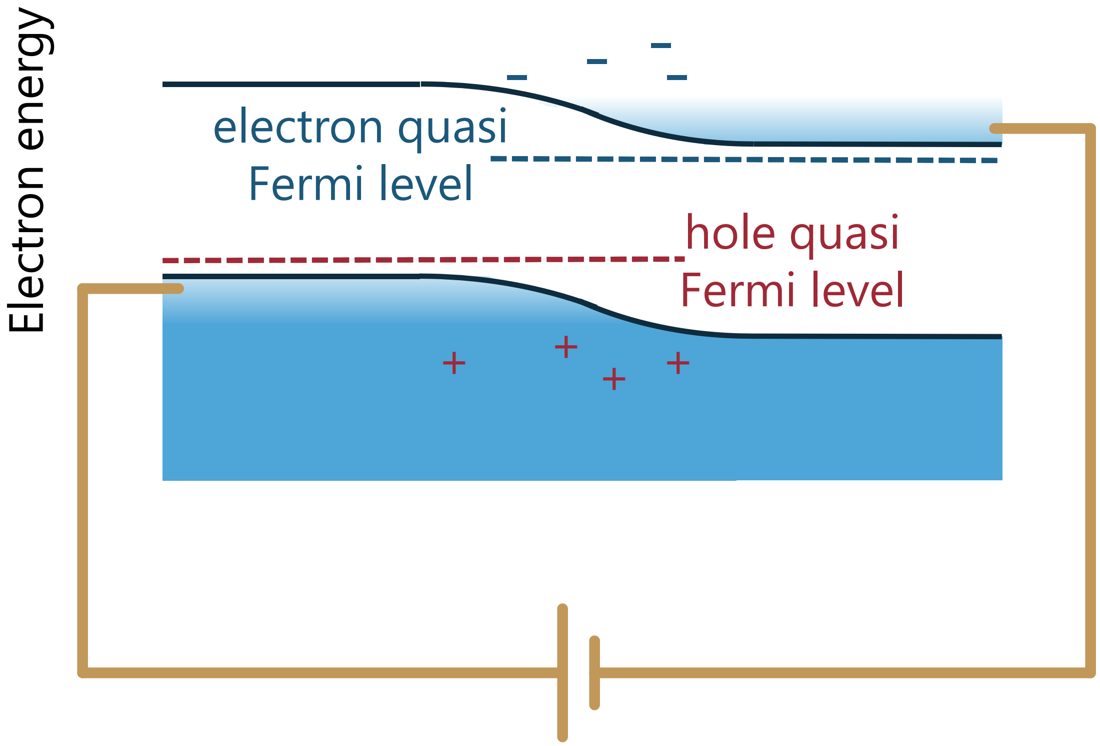
Forward-biased light emitter

The electrons can be in thermal equilibrium with each other

- and so can the holes
  - giving useful models for their distributions

This allows detailed models for

- light emission by "recombination"



Light-emitting diode emission

For light emitting diodes

- it is sufficient to get some electrons in the conduction band
- and some holes in the valence band
- Then recombination can happen
- emitting photons