Semiconductor optoelectronics 2

Absorption and emission processes

Modern physics for engineers

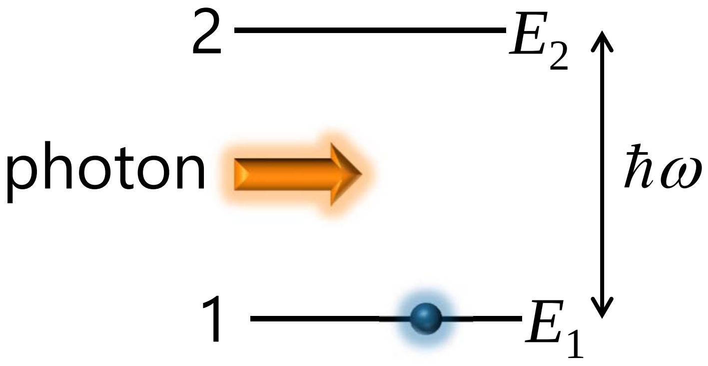
David Miller

Absorption process

We start with

one photon

and the electron in state 1



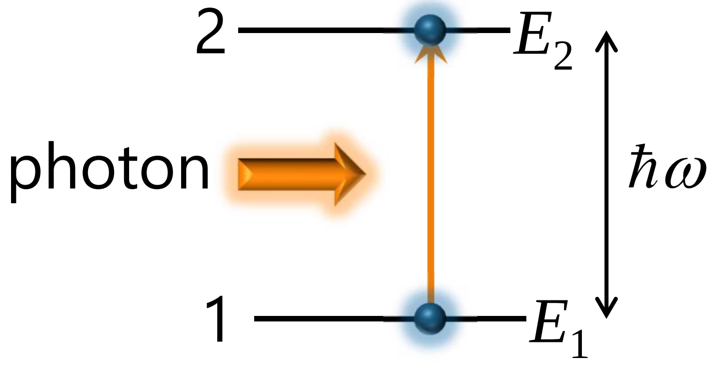
Absorption process

We start with

- one photon
  - and the electron in state 1

We finish with

- no photon
  - and the electron in state 2

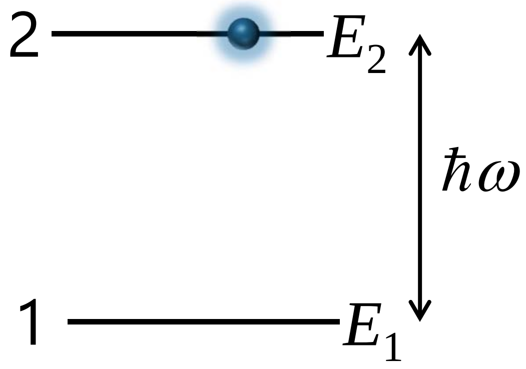


Absorption process

We start with
- one photon
  - and the electron in state 1

We finish with
- no photon
  - and the electron in state 2

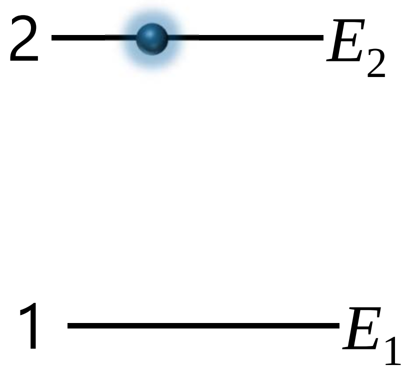
This is a normal absorption process
- requiring the destruction of the photon in the process



Spontaneous emission

Suppose

- the electron is initially in state 2
  - the upper state
- and there are no photons



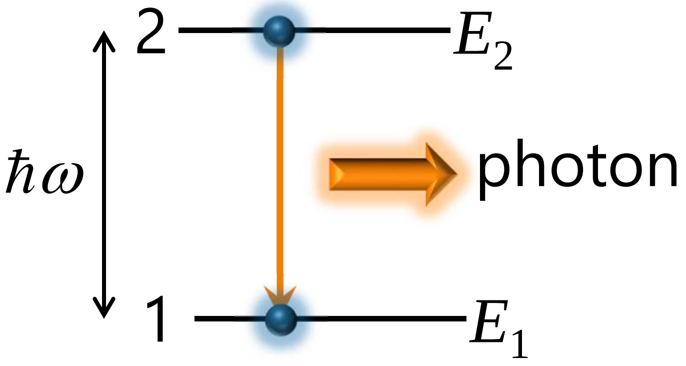
Spontaneous emission

Suppose

- the electron is initially in state 2
  - the upper state
- and there are no photons

Then a photon is spontaneously emitted

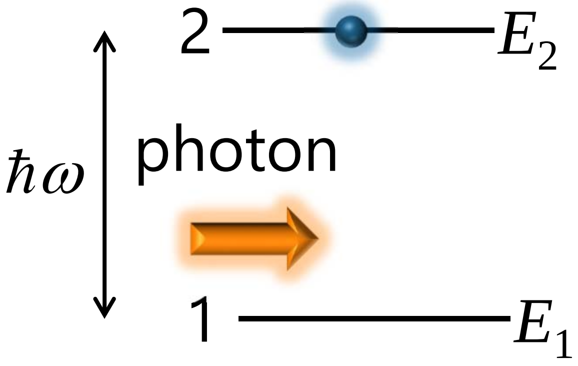
- at a random time
  - and the electron falls
    - from state 2 to state 1



Stimulated emission

Suppose now we have

- a photon and
- an electron in its upper state 2



Stimulated emission

Suppose now we have

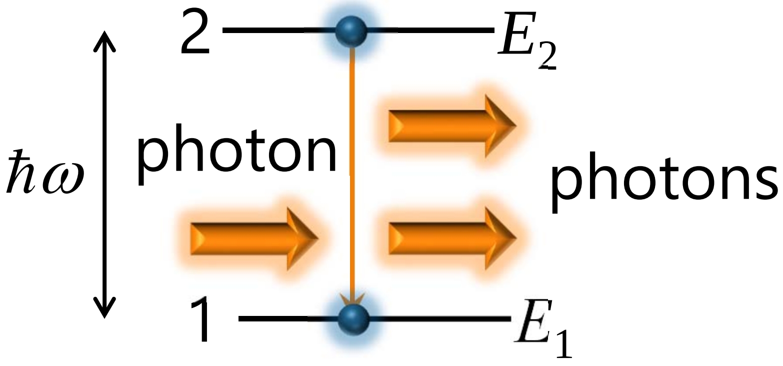
- a photon and
- an electron in its upper state 2

Then we can stimulate the emission

- of a second photon
  - while causing the electron to change from
    - state 2 to state 1

leaving 2 photons

- which are both in the same mode



Stimulated emission

We remember from Einstein's A and B coefficient argument that the

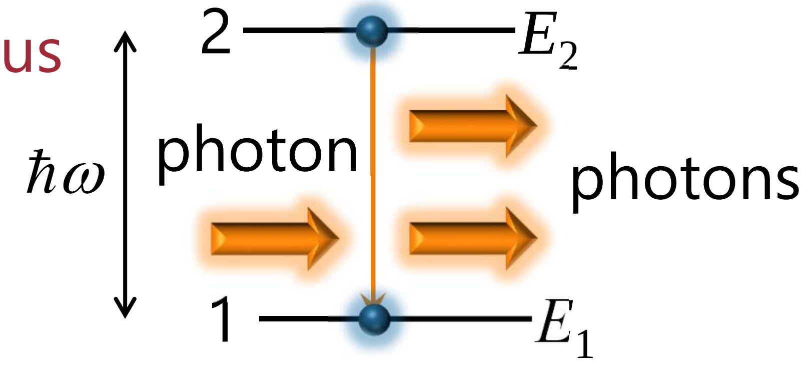
ratio of stimulated and spontaneous emission into a mode

is the number of photons n initially in the mode

So the stimulated emission rate

is proportional to

the number n of photons initially in the mode



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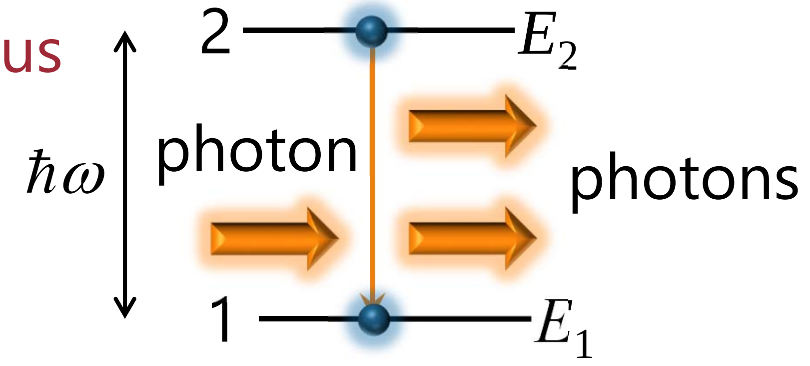

Note: adding spontaneous emission, the total emission rate into a mode is proportional to $n + 1$

Semiconductor optoelectronics 2

Lasers

Modern physics for engineers

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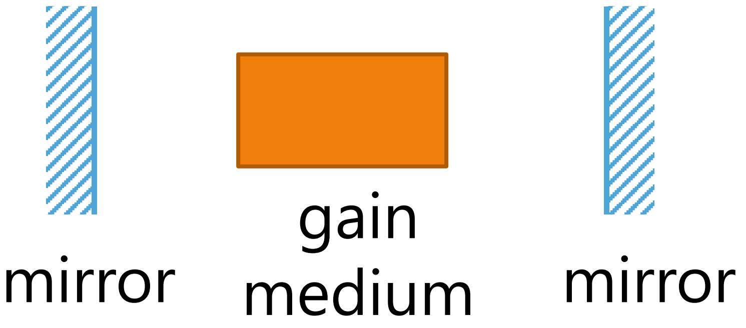
Lasers

- Lasers are light sources in which
  - the dominant emission of light is by
    - stimulated emission
- The word "laser" is an acronym
  - Light Amplification by Stimulated Emission of Radiation

How to make a laser

- We put a "gain medium"
  - in a cavity
    - e.g., between two mirrors
- Photons emitted into a cavity mode
  - tend to stay in that mode
    - if the mirrors have high enough reflectivity
- If stimulated emission dominates over absorption in a mode
  - more photons will be stimulated into that same mode



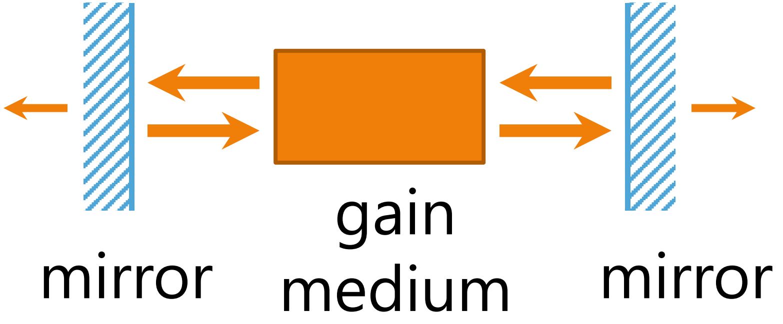
How to make a laser

To get lasing

- the overall gain for a round trip
  - has to exceed the overall loss for a round trip, e.g., including
    - mirror transmission
    - other losses such as background absorption and scattering

Generally, this gives a "threshold" amount of gain in the medium

- for lasing to occur



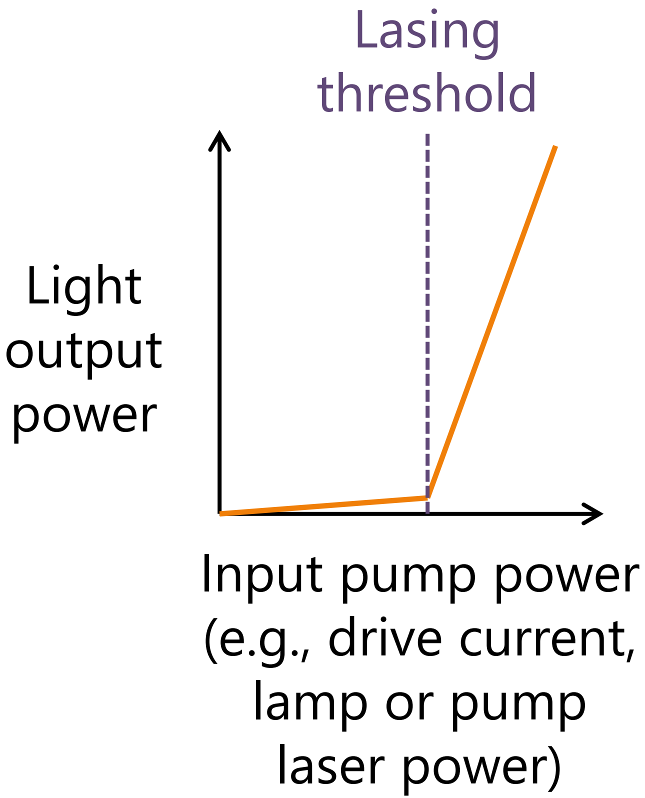
Laser light output

Below threshold

- light output is “luminescence”
  - e.g., broad spectrum spontaneous emission
  - in many directions

Above threshold

- light output is primarily in the lasing mode
  - usually a narrow spectrum
  - in well-defined beam



Optical amplifier

If we remove the mirrors

but still "pump" the gain medium strongly

we can make an optical amplifier

which is not lasing

but shows optical power gain

Optical amplifier

If we remove the mirrors

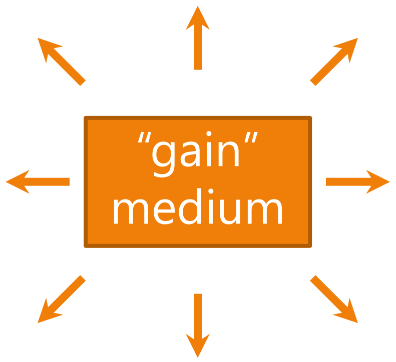
and remove the input beam

and pump the “gain” medium weakly

so there is little “gain”

we will get luminescence

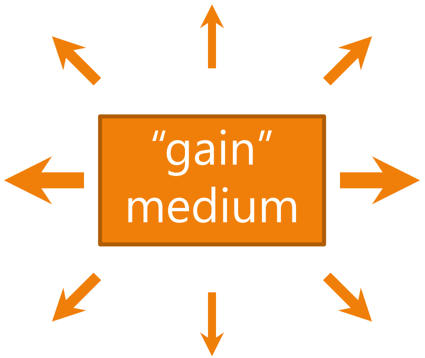
just as in a light-emitting diode



Superluminescence and "ASE"

If we remove the mirrors

- and remove the input beam
  - and pump the gain medium strongly
    - so there is significant gain at least in the "long" directions
      - luminescence in the "long" directions gets amplified
        - "Amplified Spontaneous Emission" (ASE) or superluminescence



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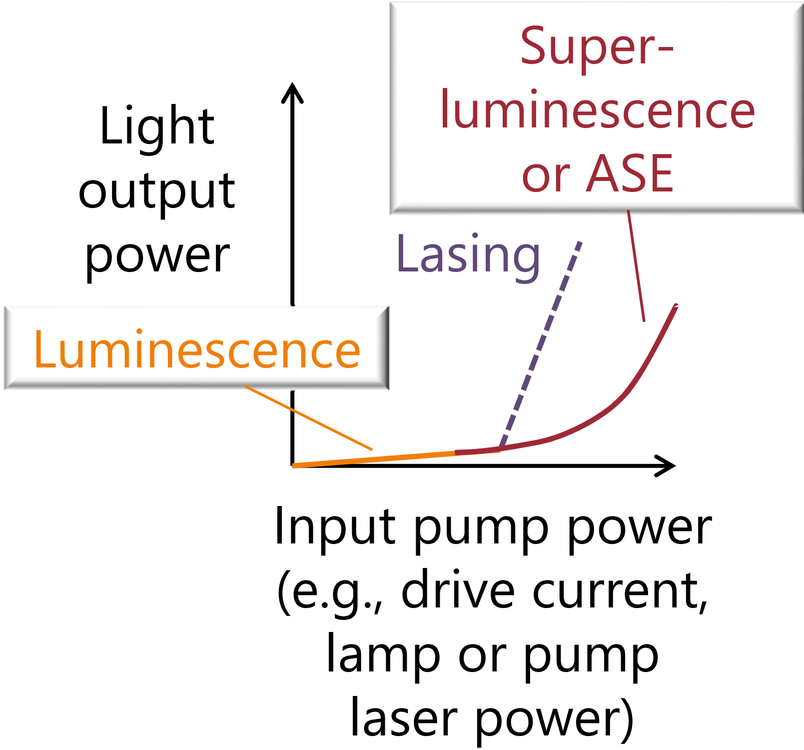


Conditions for lasing – inverted populations

A necessary condition for lasers

which use stimulated emission

is to get stimulated emission

$$B_{12}N_2\rho(\nu)$$

to dominate over ("stimulated") absorption

$$B_{12}N_1\rho(\nu)$$

which therefore requires an "inverted" population

$$N_2 > N_1$$

Conditions for lasing – inverted populations

No system in thermal equilibrium at some temperature

will give such population inversion

With an "inverted" population, though

$$N_2 > N_1$$

instead of the collection of atoms or the material

having net loss for photons

it can have net gain

Conditions for lasing – inverted populations

We could express this gain as a factor G

the ratio of photons out to photons in

or as the gain γ per unit length

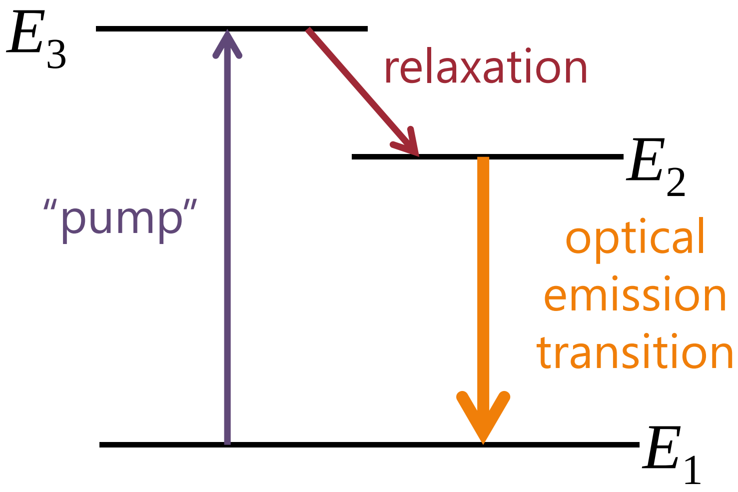
e.g., expressed in "per centimeter", cm^{-1}

with $G = \exp(\gamma L)$

for a gain region of length L

Three level lasers

- We pump somehow
  - from level 1 to level 3
    - radiatively or non-radiatively
      - Then level 3 relaxes to level 2
        - usually non-radiatively
- This gives an inverted population between level 2 and level 1
  - ideally not decaying strongly by other channels



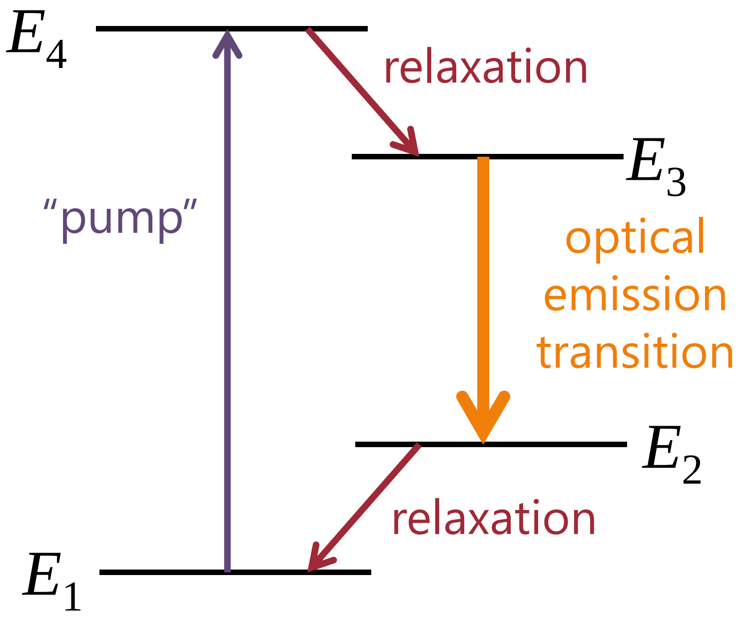
Four level lasers

We pump somehow

- from level 1 to level 4
  - radiatively or non-radiatively
    - Level 4 relaxes to level 3
      - usually non-radiatively

This gives inverted population between level 3 and level 2

- Level 2 clears out rapidly and usually non-radiatively to level 1

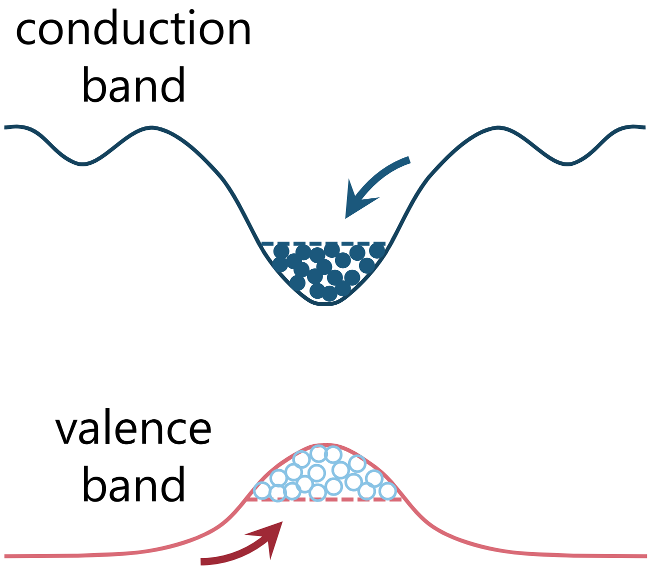


The advantage – level 2 is now usually empty

Semiconductor lasers

Semiconductor lasers are effectively four-level lasers

- We electrically pump
  - electrons into conduction band
  - and holes into valence band
- Carriers relax non-radiatively
  - to give "pools" of carriers
    - and large numbers of different possible transitions
      - all with inverted populations



Epilogue

Modern physics for engineers

David Miller

Epilogue

- We started with classical modes and eigenstates for oscillations and waves
- We used these ideas in the quantum mechanical view
  - Eigenstates become the way we look at
    - states of matter
      - including atoms and crystals
    - light and electromagnetism
      - including absorption and emission

Epilogue

We introduced the statistical view of

- the occupation of these states
  - which leads to the idea of entropy
    - Entropy then forms the core of statistical mechanics and thermodynamics
      - which then explain much macroscopic behavior
        - while also linking back to quantum mechanics

Epilogue

Putting all this together we can understand the basic physics of

electronic materials and devices

optoelectronic devices

The ideas we have covered here

do largely explain the everyday modern world around us

and give us both the concepts and vocabulary

to proceed to the next level

in science and engineering

Epilogue

You now understand a core set of concepts that is

quite finite, reliable and universally useful

and gives a solid foundation

I hope that you have found this story

at least informative

possibly interesting

and hopefully even fun!