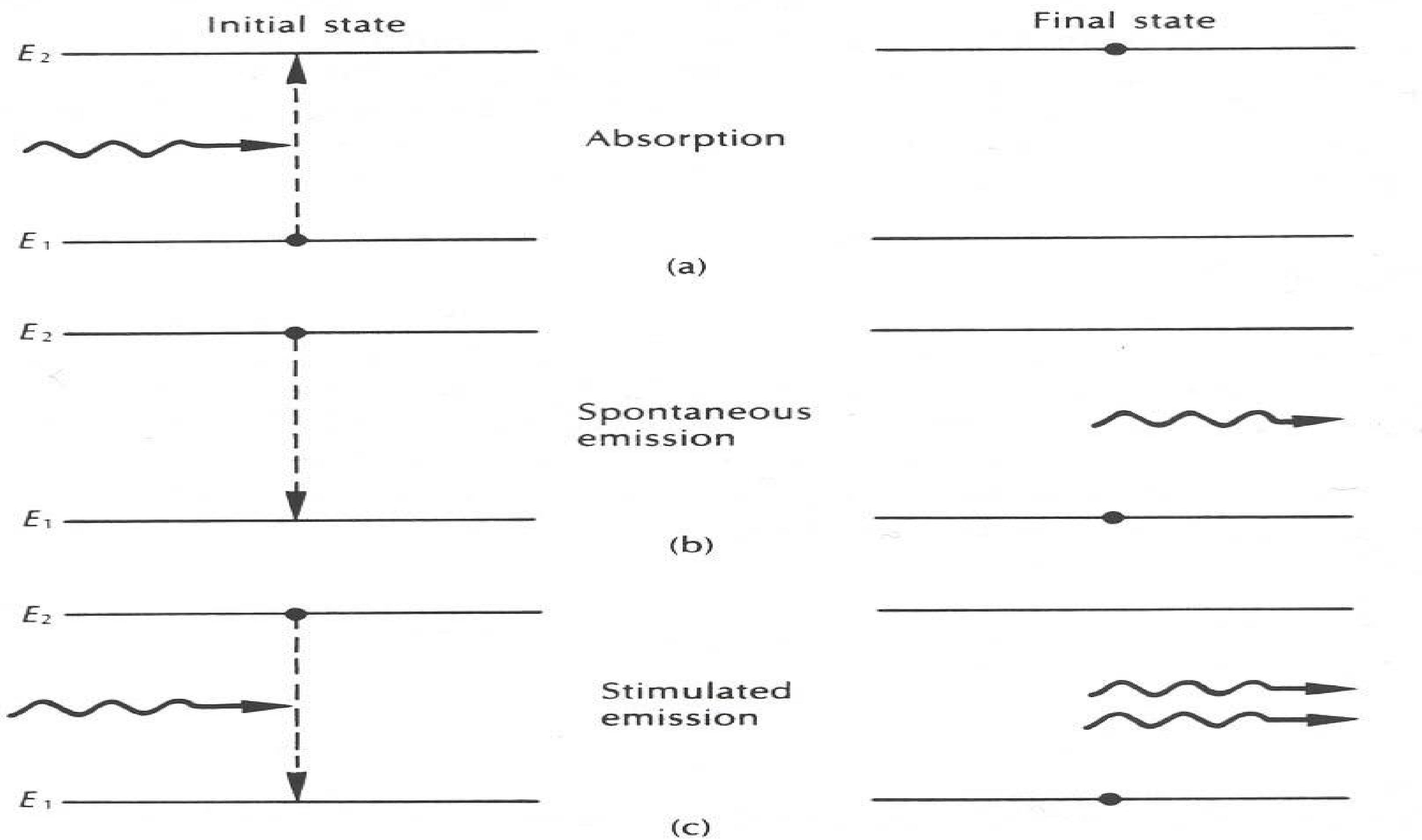
UNIT – IV
Optical Sources and Detectors

Basics of light sources

- The generation of light is caused by the transition of an electron form an energetically higher energy state to a lower energy state.
- The energy difference due to the transition of the electron leads to a **radiative** or a **non-radiative** process.
- We are of course interested in radiative processes, non-radiative processes typically lead to the creating of heat.
- The emission of light, can take place either spontaneously or it can be stimulated by the presence of another photon of the “right” energy.
- In order to understand the processes of light-generation, it is necessary to understand the energy levels in materials.

Energy state diagram showing absorption, spontaneous emission, stimulated emission



Absorption and Emission of light

- The interaction of light and matter in the form of absorption and emission requires a transition from one discrete energy level to another energy level.
- The frequency and the wavelength of the emitted or absorbed photon is related to the difference in energy E, between the two energetic states.

$$\mathbf{E = E_2 – E_1 = h\ f = h\ c/\lambda}$$

Where h is the Planck constant $h=6.626 \times 10^{-34}$ J,

f is the frequency and

λ is wavelength of the absorbed or emitted light.

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- When a photon with the energy (E_2-E_1) is incident on the material an electron may be excited from the energy state E_1 into a higher energy state E_2 through the absorption of the photon.
- Alternatively, when the electron is initially on a higher energy level it can make a transition to a energetically lower state and the provided energy loss leads to the emission of a photon. Here the transition is assumed to be a radiative transition.
- In the case of a non-radiative process the energy is dissipated as heat.
- In the case of radiative emission we can than distinguish between **spontaneous** and **stimulated emission**.

Spontaneous Emission

➢Light sources like sun, bulb photons are emitted spontaneously.

➢ In a first step an electron is elevated to an energetically higher state which is usually unstable.

➢ In the second step the electron will spontaneously return to an energetically more stable state (which is typically the energetically lower state).

➢ As a consequence spontaneously emitted photons are incoherent (very short coherence time) & emitted spectrum has broad spectral width.

➢ In the case of spontaneous emission the electron stays in the excited state usually for a shorter period of time (picoseconds).

Stimulated Emission

- If the electron which enters an energetically higher state (excited state) remains in this state until it is "stimulated" by the presence of a photon to leave this higher energetically state and return to the more stable lower energetically state (ground state).
- One of the requirements for stimulated emission is that the electron can stay in its excited state a relatively long period of time (a few microseconds) before it changes its state spontaneously.
- Stimulated emission takes place when the emitted photon has the same energy (the same wavelength), phase and direction as that of the photon which stimulated it!

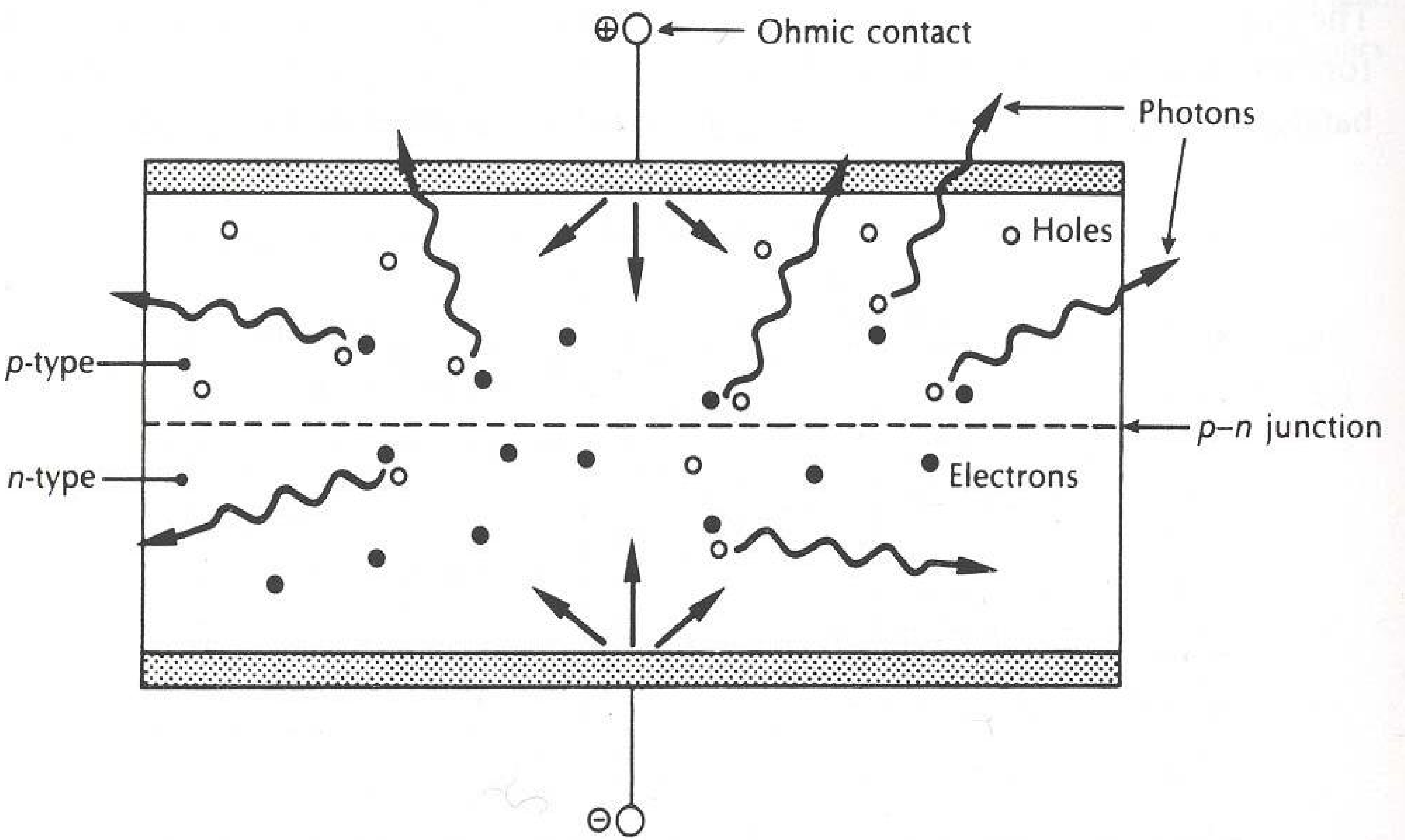
Light emitting diodes (LEDs)

- In the case of radiative recombination the wavelength of the emitted photons is given by

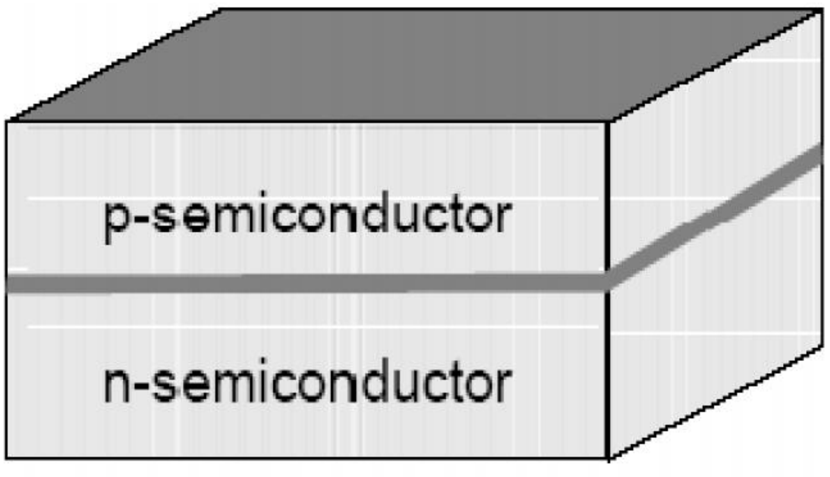
$$\lambda = \frac{c}{f} = \frac{hc}{E} = \frac{1.24}{E(eV)}\ \mu m$$

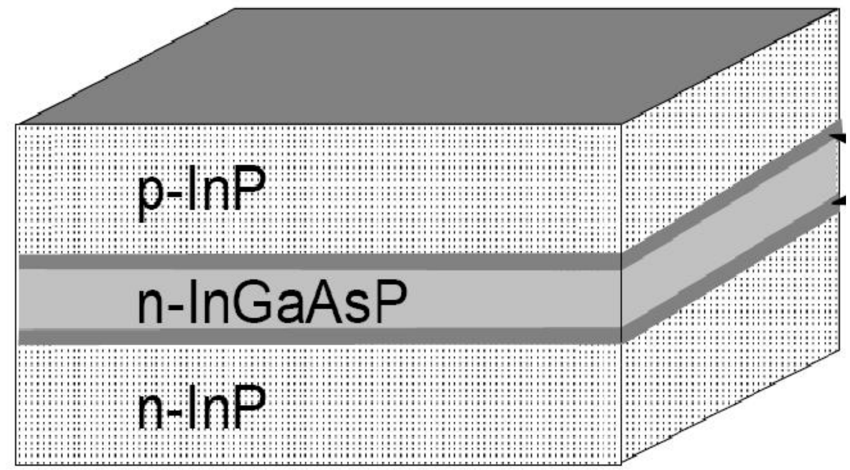
- If a material (semiconductor) emits light as a consequence of the injection of charges (current) called as electroluminescence.
- The alternative would be photoluminescence, where we shine light on a sample and the sample emits light (at a lower energy / higher wavelength).
- Emission of light depends on the semiconducting material itself, the level of impurities, the structural properties, the temperature and the device fabrication.

Carrier recombination in a PN junction



Homo junction and double Hetero junction LED





- The photons are created by the electron-hole recombination in the vicinity of the depletion region. Therefore, the emission of light occurs in this region. Such a structure is called a homo junction.
- The semiconductors in both regions of the PN diode have the same band energies so that no discontinuity occurs in the band gap.

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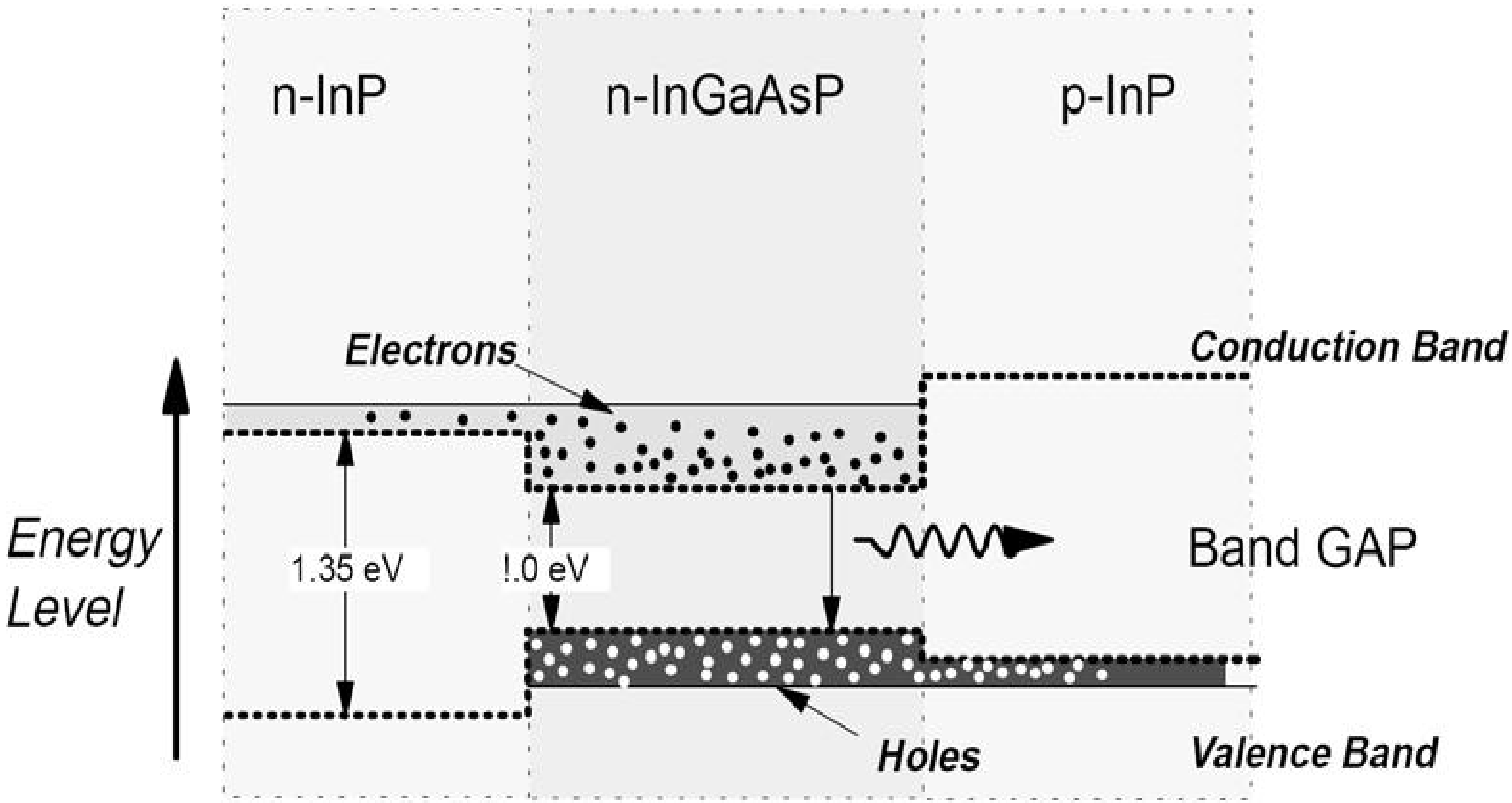
- The situation can be improved by a hetero structure.
- A hetero junction is different from an ordinary homo junction.
- In such case a discontinuity in the band diagram is observed.
- In such a configuration the charge carriers (electrons or holes) are attracted over the barrier from the material of higher band gap energy to the one of lower band gap energy.
- As a consequence most of the recombination occurs in the region of lower optical band gap.
- A double hetero junction consists of two hetero junctions. Again the recombination of carriers is restricted to the low band gap region which is called “the active region” of the diode.

Double hetero junction based on indium phosphide



Bandgap boundaries are denoted by dotted lines

LASER (Light **A**mplification by the **S**timulated **E**mission of **R**adiation**)**

- In 1927 Albert Einstein demonstrated that absorption, the spontaneous emission and the stimulated emission processes are mathematically related.
- Rate equations can be defined, which describe the probability of a transition from level 1 (lower energetic state or ground state) to level 2 (higher energetic state) and vice versa.
- For the level 1 rate equation we have to consider only the absorption, whereas for the level 2 rate equation we have to consider spontaneous and stimulated emission. This leads to the following relationship:

$$\frac{\text{Spontanious emittion rate}}{\text{Stimulated emision rate}} = \frac{1}{e^{\left(\frac{hf}{KT}\right)} - 1}$$

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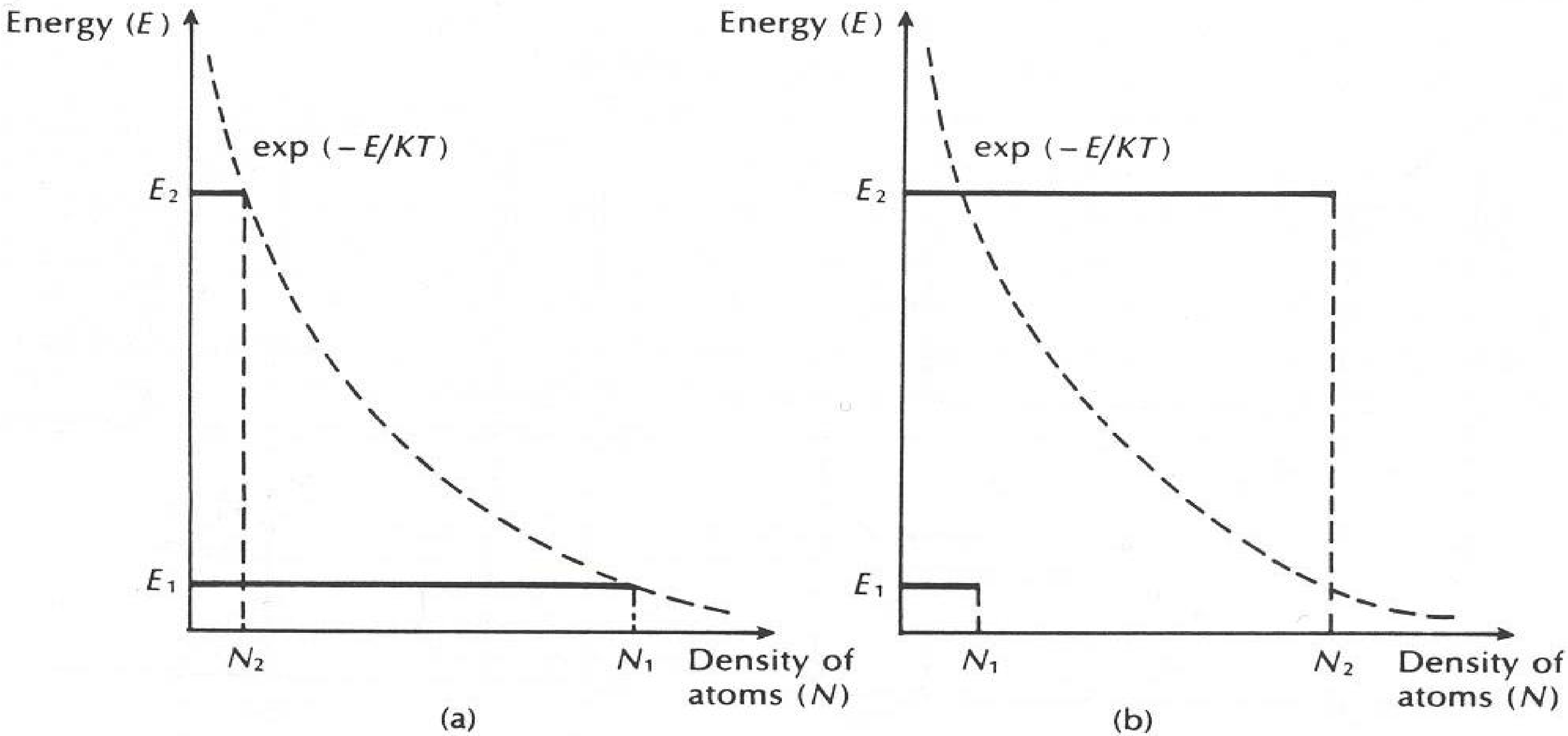
- For most of the systems in thermal equilibrium spontaneous emission is by far the dominate process.
- The spontaneous emission term of the rate equation of level 2 is much larger than the term of stimulated emission.
- In order to produce coherent light the stimulated term has to be drastically increased.

Population inversion

- In the case of a two level system in thermal equilibrium, which can be described by a Boltzmann distribution, the lower energy level E1 contains more atoms than the upper energy level.
- This situation is normal for structures at room temperature.
- To achieve optical amplification (stimulated emission) it is necessary to create a non-equilibrium distribution of atoms.
- The population of atoms in the higher energetic state has to be (significantly) higher than the population of atoms in the lower energetic state.
- This situation is called **population inversion.**

Population inversion



Population in two energy level system:

(a) Boltzmann distribution for a system in thermal equilibrium,

(b) Non-equilibrium distribution indicating the population inversion

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- In order to achieve population inversion it is necessary to excite atoms into the higher energetic state and hence achieve population inversion.
- This process is usually called “pumping”.
- We can distinguish between electrical and optical pumping. The medium is optically pumped for gas lasers (e.g. HeNe lasers) or crystal lasers (e.g. Ruby laser) where the atoms are excited by an external optical source.
- The systems are usually pumped by an intensive radiation source like a flash lamp.

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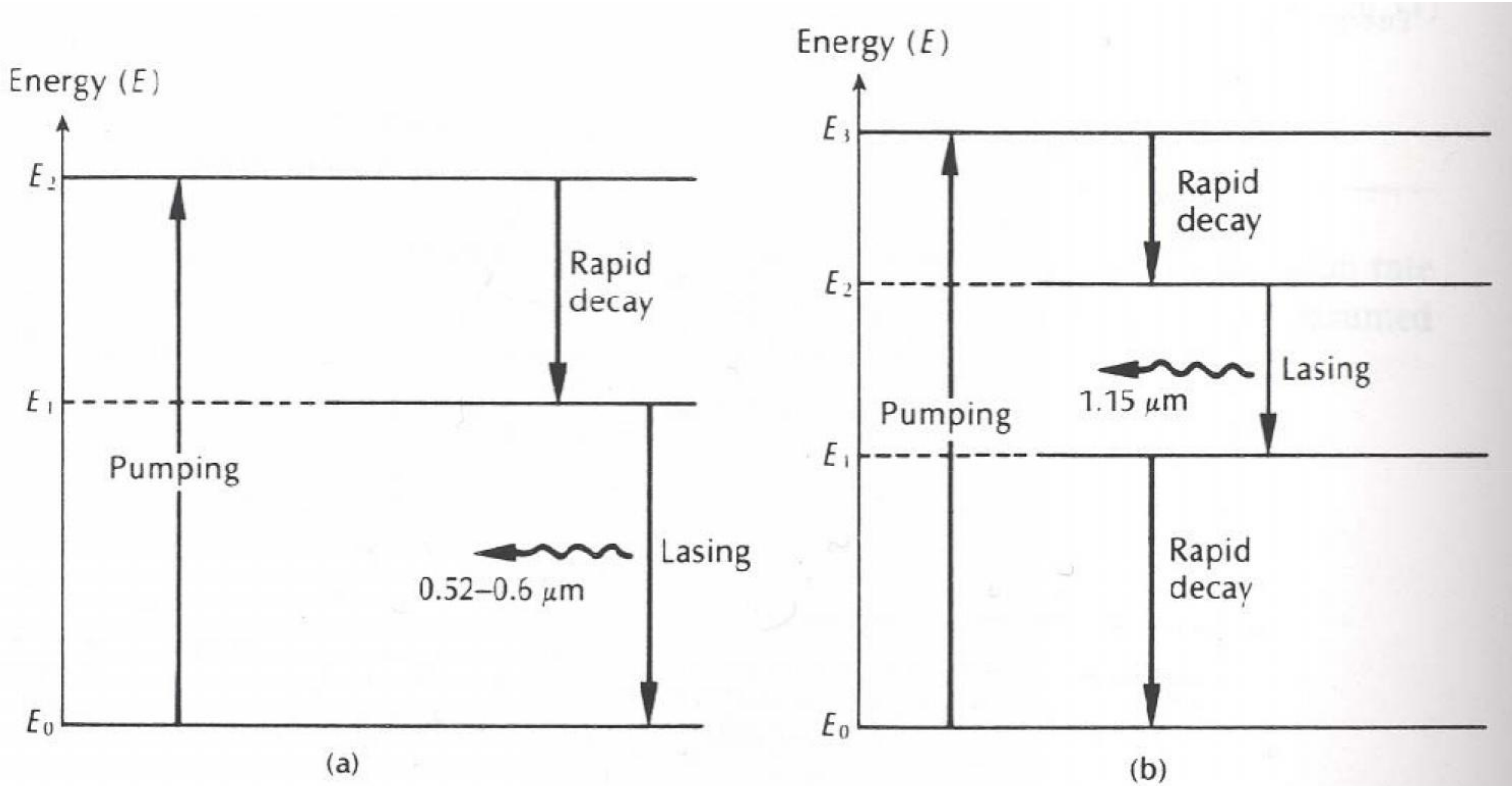
- The intense radiation leads to the transition of the atoms from the lower to the energetically higher states which we would normally be called absorption, but we can even call it “stimulated absorption”.
- The term “stimulated emission” indicate the similarities between the absorption and the stimulated emission. (The stimulated emission is the inversion of the (stimulated) absorption.) However, so far we discussed the behavior of two level systems which are not suitable for population inversion.
- Population inversion however, can be observed in certain three or four energy level systems.

Three and four energy level systems



Energy diagrams showing population inversion for
(a) Three level system (ruby crystal) (b) Four level system (ruby crystal)

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- The principle transition for a three level system is illustrated in the figure.
- The three level systems consist of a ground level E_0, a stable level E_1 and a third level E_2 which is again metastable.
- Initially (before pumping) the system is in thermal equilibrium and the atomic distribution can be described by a Boltzmann distribution.
- Due to pumping electrons get excited from the ground level to the level 2.
- The level 2 is considered to be a "normal" energy level so that the electrons rapidly decay in the lower energetic state 1

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- Of course a certain number of electrons will directly go back to the energy level 1, but most of the electrons will end up on level 1.
- As a consequence empty states will be always available on level 2. The lifetime of the electrons on level 1 is however much longer than the lifetime of the carriers on level 2, so that a large number of electrons is accumulated on level 1.
- The long lifetime of the carriers on level 1 leads to the population inversion between level 1 and the ground level.
- The stimulation of an electron on level 1 leads now to lasing. The disadvantage of a three level system is that it needs very high levels of pumping power.

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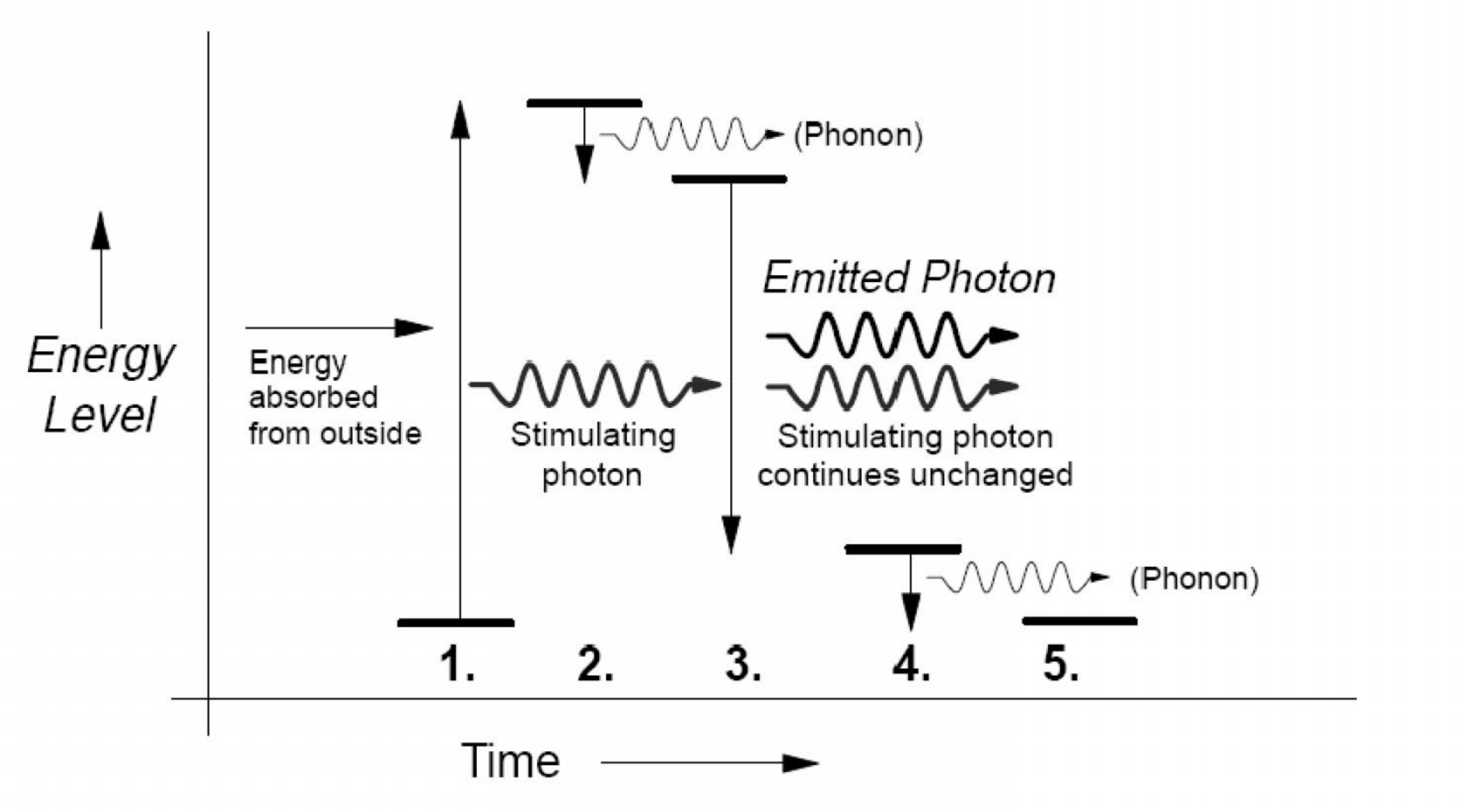
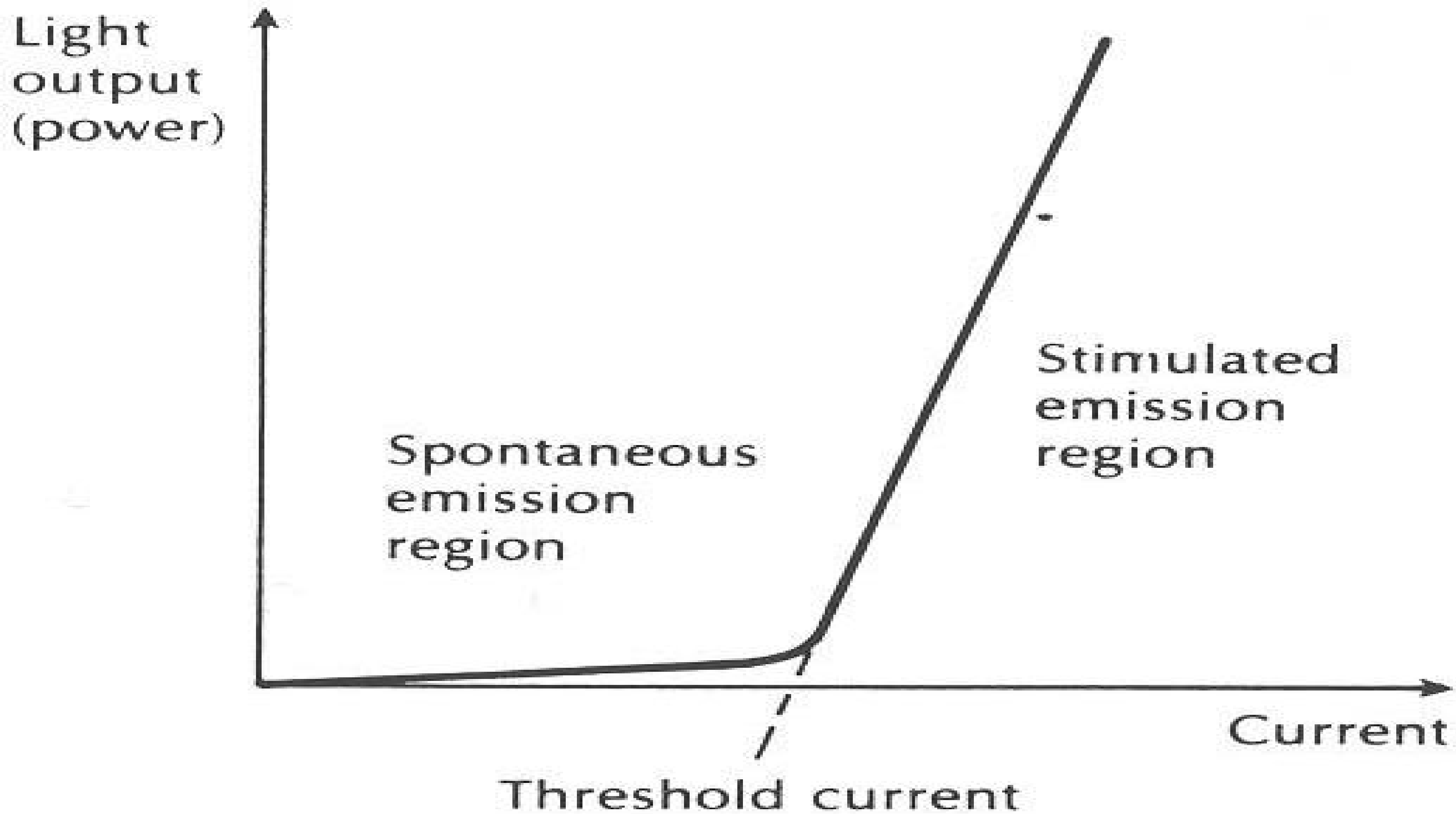
- More than half the electrons in the ground state have to pumped in order to achieve population inversion.
- A more efficient system is a four level system as it was shown for a HeNe laser system. Here much lower pumping power is needed.
- In this case an atom is pumped from the ground state into the highest energetic state on level 3. Again the transition from level 3 to level 2 is a rapid decay, because the lifetime of the carriers on level 3 is short. The lifetime of carriers on level 2 however is much longer (several orders of magnitude) so that population inversion is observed for the level 2.
- As a consequence lasing is detected between the levels 3 and 2.

Energy diagram showing population inversion for a four level system



Ideal light output curve of a laser diode against the injected current



ND:YAG LASERS

- The Nd:YAG laser is a solid-state laser. Its lasing action is developed in Yttrium Aluminium Garnet (YAG) crystal which is host to the neodyum (Nd3+) ion. It is based on a four-level system of electron energy level changes within the ion. Nd:YAG lasers are optically pumped by lamps or diode lasers mainly emitting at 810 nm. This laser can produce high power in the near infrared, at a 1064 nm wavelength.
- They are used for cutting, welding, and marking of metals and other materials. These lasers are also frequency doubled, tripled or quadrupled to produce 532 nm (green, visible), 355 nm and 266 nm (UV) beams, respectively.

Types of Optical Detectors

- Optical detectors are usually divided into two broad classes: photon detectors and thermal detectors.
- In photon detectors, quanta of light energy interact with electrons in the detector material and generate free electrons. To produce free electrons, the quanta must have sufficient energy to free an electron from its atomic binding forces.
- Thermal detectors respond to the heat energy delivered by light. These detectors use some temperature-dependent effect, like a change of electrical resistance. Because thermal detectors rely on only the total amount of heat energy reaching the detector, their response is independent of wavelength.

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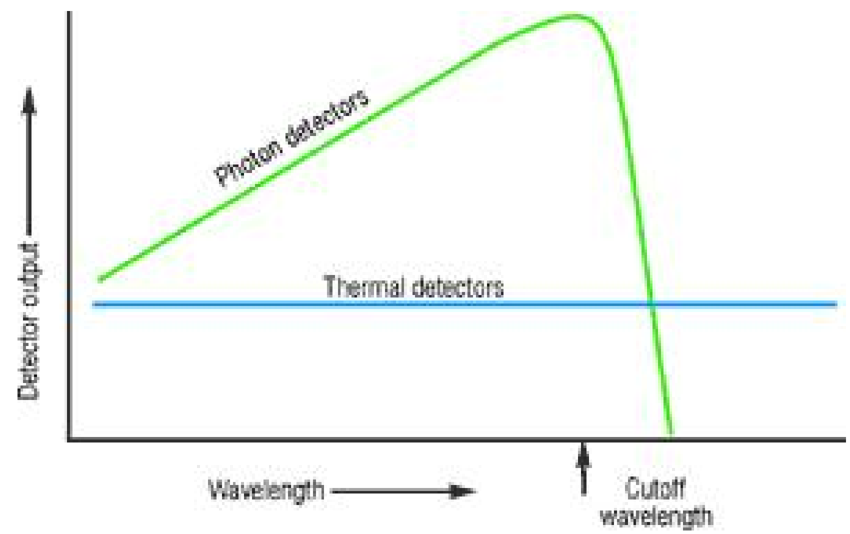
- Figure shows the typical spectral dependence of the output of photon detectors, which increases with increasing wavelength at wavelengths shorter than the cutoff wavelength. At that point, the response drops rapidly to zero.
- The figure also shows how the output of thermal detectors is independent of wavelength, and extends to longer wavelengths than the response of photon detectors.



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Some important classes of photon detectors are listed below.

Photoconductive : The incoming light produces free electrons which can carry electrical current so that the electrical conductivity of the detector material changes as a function of the intensity of the incident light.

Photovoltaic : Such a detector contains a junction in a semiconductor material between a region where the conductivity is due to electrons and a region where the conductivity is due to holes (a so-called p-n junction). A voltage is generated when optical energy strikes the device.

Photoemissive: These detectors are based on the photoelectric effect, in which incident photons release electrons from the surface of the detector material. The free electrons are then collected in an external circuit.

Detector characteristics

Responsivity :

- This is the detector output per unit of input power.
- The units of responsivity are either amperes/watt (alternatively milliamperes/milliwatt or microamperes/microwatt, which are numerically the same) or volts/watt, depending on whether the output is an electric current or a voltage.
- The responsivity is an important parameter that is usually specified by the manufacturer.
- Knowledge of the responsivity allows the user to determine how much detector signal will be available for a specific application.

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Noise Equivalent Power:

➢ A second figure of merit, which depends on noise characteristics, is the noise equivalent power (NEP). This is defined as the optical power that produces a signal voltage (or current) equal to the noise voltage (or current) of the detector.

➢ The noise is dependent on the bandwidth of the measurement, so that bandwidth must be specified. Frequently it is taken as 1 Hz. The equation defining NEP is

$$\mathbf{NEP} = \frac{\mathbf{H.\,A.\,V_N}}{\mathbf{V_s\sqrt{\Delta f}}}$$

Where H is the irradiance incident on the detector of area A, V_N is the root mean square noise voltage within the measurement bandwidth Δf, and V_S is the root mean square signal voltage.

➢The NEP has units of watts/(Hz)$^{1/2}$, usually called "watts per root hertz." From the definition, it is apparent that the lower the value of the NEP, the better is the characteristics of the detector for detecting a small signal in the presence of noise.

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Detectivity :

- The NEP of a detector is dependent on the area of the detector. To provide a figure of merit that is dependent on the intrinsic properties of the detector, not on how large it happens to be, a term called detectivity is defined.
- Detectivity is represented by the symbol D*, which is pronounced as D-star. It is defined as the square root of the detector area per unit value of NEP.

$$D^* = A^{1/2}/NEP$$

- Since many detectors have NEP proportional to the square root of their areas, D* is independent of the area of the detector.
- The detectivity thus gives a measure of the intrinsic quality of the detector material itself.

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Linearity :

- Detectors are characterized by a response in which the output is linear with incident intensity. If the output of the detector is plotted versus the input power, there should be no change in the slope of the curve. Noise will determine the lowest level of incident light that is detectable.
- The upper limit of the input/output linearity is determined by the maximum current that the detector can produce without becoming saturated. Saturation is a condition in which there is no further increase in detector response as the input light intensity is increased.
- When the detector becomes saturated, one can no longer rely on its output to represent the input faithfully. The user should ensure that the detector is operating in the range in which it is linear.

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Detector response time

- Another useful detector characteristic is the speed of the detector response to changes in light intensity.
- If a light source is instantaneously turned on and irradiates an optical detector, it takes a finite time for current to appear at the output of the device and for the current to reach a steady value.
- If the source is turned off instantaneously, it takes a finite time for the current to decay back to zero. The term response time refers to the time it takes the detector current to rise to a value equal to 63.2% of the steady-state value which is reached after a relatively long period of time. The recovery time is the time it takes for the photocurrent to fall to 36.8% of the steady-state value when the light is turned off instantaneously.

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Quantum efficiency :

- Quantum efficiency is defined as the ratio of countable events produced by photons incident on the detector to the number of incident photons.
- If the detector is a photoemissive detector that emits free electrons from its surface when light strikes it, the quantum efficiency is the number of free electrons divided by the number of incident photons.
- If the detector is a semiconductor pn-junction device, in which hole-electron pairs are produced, the quantum efficiency is the number of hole-electron pairs divided by the number of incident photons.

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- The quantum efficiency is basically another way of expressing the effectiveness of the incident optical energy for producing an output of electrical current. The quantum efficiency Q (in percent) may be related to the responsivity by the equation:

$$Q = 100\ R_d\ (1.2395/\lambda)$$

- Where R_d is the responsivity (in amperes per watt) of the detector at wavelength λ (in micrometers).

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Spectral response :

- The spectral response defines how the performance of a detector (responsivity or detectivity) varies with wavelength.
- The exact shape of the spectral response and the numerical values depend on the detector type and the material from which the detector is fabricated.
- Many different types of detectors are available, with responses maximized in the ultraviolet, visible, or infrared spectral regions.
- Again, the manufacturer usually specifies the spectral response curve. One should choose a detector that responds well in the spectral region of importance for the particular application.


Thank You