530192 “Photonics in semiconductors”, (5 op / 3 ov), period III and IV – Spring 2017

**Lecturer:** Docent Ivan Kassamakov,

**Assistant:** Risto Montonen and Anton Nolvi, Doctoral students

<table>
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Photonics course exam

Friday May 19th at 10:00-14:00 in D116 (Physicum).
The diode is now forward biased with an applied voltage \( V \) greater than the bandgap voltage: \( eV > E_g \).
This applied voltage separates \( E_{Fn} \) and \( E_{Fp} \) by the applied voltage \( eV \). Since the diode is forward biased, the potential barrier is reduced to almost zero.
The electron majority carriers are injected through the depletion region and become minority carriers in the \( p^+ \)-side of the diode.
For the holes we have a similar result. Thus we have a diode current due to the movement of both charge carriers.

(b) Band diagram with a sufficiently large forward bias to cause population inversion and hence stimulated emission.
At low temperatures \((T \approx 0 \text{ K})\), the states between \(E_c\) and \(E_F^n\) are filled with electrons and those between \(E_F^p\) and \(E_v\) are empty. Photons with energy between \(E_g\) and \(E_F^n - E_F^p\) cause stimulated emissions. Photons with energy greater than \(E_F^n - E_F^p\) are absorbed since there are no available states in the system in the energy range. For \(T > 0 \text{ K}\) the Fermi-Dirac function spreads the energy distributions of electrons in the CB to above \(E_F^n\) and holes below \(E_F^p\) in the VB. The result is a reduction in optical gain. The population inversion between energies near \(E_c\) and those near \(E_v\) is achieved by the injection of carriers across the junction under a sufficiently large forward bias. The pumping mechanism is the forward diode current and the pumping energy is supplied by the external voltage. This is called injection pumping.
In addition to population inversion we also need to have an optical cavity to implement laser oscillation.
Homojunction Laser Diodes

The ends of the crystal are cleaved to be flat and to provide reflection and hence form an optical cavity. For example, the refractive index for GaAs is about 3.6 so the reflectance is

\[ R = \left( \frac{n_1 - n_2}{n_1 + n_2} \right)^2 = \left( \frac{3.6 - 1}{3.6 + 1} \right)^2 = \left( \frac{2.6}{4.6} \right)^2 = 0.31947 \]

The required threshold gain is

\[ g_{th} = \gamma + \frac{1}{2L} \ln \left( \frac{1}{R_1 R_2} \right) = \gamma + \frac{1}{2L} \ln \left( \frac{1}{0.1021} \right) = \gamma + \frac{1}{2L} (2.282) \]

For the gas laser with mirror reflectances of 100% and 90% we had

\[ g_{th} = \gamma + \frac{1}{2L} \ln \left( \frac{1}{R_1 R_2} \right) = \gamma + \frac{1}{2L} \ln \left( \frac{1}{0.9} \right) = \gamma + \frac{1}{2L} (0.1054) \]

Thus the semiconductor diode requires a considerable gain through pumping to achieve threshold.
Homojunction Laser Diodes

Slightly different refractive index <1%

Anode

Resonant cavity

\[ R = \left( \frac{n_1 - n_2}{n_1 + n_2} \right)^2 \]

Modes

\[ m \frac{\lambda_{\text{semiconductor}}}{2} = L \]
Principle of the Laser Diodes

- Typical output optical power vs. diode current ($I$) characteristics and the corresponding output spectrum of a laser diode.
- LED like below $I_{th}$, then after threshold a Laser.

The output frequency spectrum may depend on the diode current.

The main problem with the homojunction laser diode is that the required threshold current is very large. The current density $J_{th}$ is too high for practical purposes (low life of the device, high heat, low efficiencies...).
The carriers in the active region increases refractive index of GaAs
The refractive index increment is only \(~0.02\), hence is not a good dielectric waveguide
The beam therefore can be spread out to the surrounding region – mode volume
Vigorous pumping is therefore needed to enhance lasing
The threshold current for the pumping action exceeds \(~400\text{Amm}^{-2}\) at \(T \approx 300\text{ K}\),
The reduction of the threshold current $I_{th}$ to a practical value (i.e. those not needing cryogenic cooling) requires improving the rate of stimulated emission and improving the efficiency of the optical cavity.

The reduction of the threshold current $I_{th}$ can be achieved by confining the injected electrons and holes to a narrow region around the junction.

Confining the carriers to a small region means that less current is needed to establish the necessary concentration of carriers for population inversion.

We can build a dielectric waveguide around the optical guide region to increase the photon concentration and hence the probability of stimulated emissions.

Thus we need both carrier confinement and photon confinement.

In the case of LD, there is an additional requirement: for maintaining a good optical cavity that will increase stimulated emissions over spontaneous emissions.
The p-GaAs region is a thin layer, typically 0.1 – 0.2 μm. It is the active layer in which lasing recombination takes place.

Both p-GaAs and p-AlGaAs regions are heavily p-type doped and are degenerate with $E_F$ in the valence band.

When a sufficiently large forward bias is applied, $E_c$ on n-AlGaAs moves above $E_c$ of p-GaAs which leads to a large injection of electrons in the CB of n-AlGaAs into p-GaAs.
Heterostructure Laser Diodes

(a) A double heterostructure diode has two junctions which are between two different bandgap semiconductors (GaAs and AlGaAs).

(b) Simplified energy band diagram under a large forward bias. Lasing recombination takes place in the $p$-GaAs layer, the active layer.

(c) Higher bandgap materials have a lower refractive index.

(d) AlGaAs layers provide lateral optical confinement.
Double Heterostructure Laser Diodes

Electrode

n-GaAs (1.4eV)

N - AlGaAs (2eV)

p-GaAs

SiO₂

“stripe” (gain-guided)

P - AlGaAs (2eV)
The previous double-heterostructure device did little to channel the photons laterally down the slab waveguide.

A modified device is called the buried double-heterostructure. The “sides” of the active area are also doped to reduce the index of refraction so the photons are now guided down a “box” rather than a slab.

Since the optical power is confined to the waveguide defined by the refractive index variation, these diodes are called *index guided*.

1. Carrier Recombination Confinement (full cross section control)
2. Photon Confinement (full cross section control) (“index guided”)
3. Carrier Injection Current Confinement (full cross section control)
Buried Double Heterostructure LD

Electrode

SiO₂

P - AlGaAs (2eV)

n- GaAs (1.4eV)

N - AlGaAs (2eV)

Electrode

“stripe” (index-guided)

N- AlGaAs

n- GaAs
Laser Diode Characteristics

- The length $L$ determines the **longitudinal mode-separation**.
- The width $W$ and height $H$ determine the **transverse modes**, or **lateral modes**.
- If the **transverse dimensions** ($W$ and $H$) are sufficiently small, only the **lowest transverse mode TEM$_{00}$ mode**, will exist. This TEM$_{00}$ mode however will have **longitudinal modes** whose separation depends on $L$.
- The emerging laser beam exhibits **divergence**. This is due to **diffraction** of the waves at the **cavity ends**. The **smallest aperture** ($H$ in this figure) causes the greatest diffraction.

![Diagram of laser diode characteristics]
The laser diode’s output characteristics also tend to be temperature sensitive.

As the temperature increases, the threshold current increases steeply, typically as the exponential of the absolute temperature.

The threshold current shifts to higher temperatures.

\[ I_{th} = A \exp\left(\frac{T}{T_o}\right) \]

Output optical power vs. diode current at three different temperatures.

*The threshold current shifts to higher temperatures.*
The output spectrum also changes with temperature. In the case of a single-mode laser diode, the peak emission wavelength $\lambda_0$ exhibits ‘jumps’ at certain temperatures.

A jump corresponds to a mode hop in the output. That is, at the new operating temperature, another mode fulfils the laser oscillation conditions and a discrete change in the wavelength.

Peak wavelength vs. case temperature characteristics. (a) Mode hops in the output spectrum of a single mode LD. (b) Restricted mode hops and none over the temperature range of interest (20 - 40 °C). (c) Output spectrum from a multimode LD.
Laser Diode Characteristics

- Between mode hops, wavelength $\lambda_0$ increase slowly with the temperature due to the slight increase in the refractive index $n$ and the cavity length with temperature.
- Highly stabilized laser diodes are usually marketed with thermoelectric coolers integrated into the diode package to control temperature.

Figure 4
Semiconductor Laser Diodes

**Top left:** High power (0.5 – 7 W) CW laser diodes with emission at 805 nm and a spectral width of 2.5 nm. Applications include medical systems, diode pumped lasers, analytical equipment, illuminators, reprographics, laser initiated ordnance *etc.*

**Top right:** Typical pigtailed laser diodes for telecom. These are Fabry-Perot laser diodes operating at peak wavelengths of 1310 and 1550 nm with spectral widths of 2 and 1.3 nm respectively. The threshold currents are 6 mA and 10 mA, and they can deliver 2 mW of optical power into a single mode fiber.

**Lower left:** High power 850 and 905 nm pulsed laser diodes for use in range finders, ceilometers, weapon simulation, optical fuses, surveying equipment *etc.* (Courtesy of OSI Laser Diode Inc.)
Over filled launch; All modes excited.

Restricted Launch; A few modes excited.

A

LED

B

LASER / VCSEL

Core

Core
For long haul and/or wide bandwidth communications, laser diodes are invariably used because of their narrow line-width and high output power. Note that the laser diode has a restricted current range where the light output is linear.

![Typical optical power output vs. forward current for a LED and a laser diode.](image)
## Laser Vs LED Launch

Typical characteristics of LEDs and LDs for 1.3 μm emission

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<th>Structure Material Output radiation</th>
<th>LED</th>
<th>LD</th>
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<td>6~20 ns</td>
<td>Double heterojunction InGaAsP on InP coherent (Stimulated emission) 2<del>4 nm (multimode laser) &lt; 0.1 nm (single mode laser) 5</del>20 ns</td>
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The laser diode is the clear winner when line-width must be narrow. It is also the winner for another important parameter, rise time.

The speed response of an emitter is generally described by a rise time.

If the driving current is applied suddenly as a step input to the diode, the rise time is the time it takes for the light output to rise from 10% to 90% of the final value.

Laser diodes have shorter rise times and are used whenever wide bandwidths are required.
Ideally the output spectrum from a laser device should be as narrow as possible. The generally means that we have to allow only a single mode to exist.

One method of ensuring only a single mode of radiation is in the laser cavity is use frequency selective dielectric mirrors at the cleaved surfaces of the semiconductor.

The distributed Bragg reflector is a mirror that has been designed like a reflection type diffraction grating. It has a periodic corrugated structure.

(a) The basic principle of the Distributed Bragg Reflection (DBR) laser. (b) Partially reflected waves at the corrugations can only constitute a reflected wave when the wavelength satisfies the Bragg condition. Reflected waves $A$ and $B$ interfere constructively when $q(\frac{\lambda_B}{2n}) = \Lambda$.

(c) Output spectrum from a DFB laser has a single narrow peak with a $\delta \lambda$ typically very narrow, and much less than 0.1 nm. SMSR is the side mode suppression ratio.
In the distributed feedback (DFB) laser there is a **corrugated layer**, called the **guiding layer**, next to the **active layer**.

The cavity radiation **spreads** from the active layer to the guiding layer. These corrugations in the refractive index act as **optical feedback** over the length of the cavity by producing partial reflections.

Thus **optical feedback** is distributed over the cavity length. The optical feedback analysis requires attention to both the distributed nature of the corrugations, the phase changes at each of these corrugations, and the left and right travelling waves inside the cavity.
In the cleaved-coupled cavity device, two different laser optical cavities L and D are coupled.

The two lasers are pumped by different currents. Only those waves that can exist in both cavities are now allowed because the system has been coupled.
Quantum Well Devices

- A typical quantum well device has an ultra thin, typically less than 50 nm wide, narrow bandgap semiconductor such as GaAs, sandwiched between two wider bandgap semiconductors such as AlGaAs.
- The two semiconductors should be lattice matched in the sense that they have the same lattice parameter. This means that interface defects due to mismatch of crystal dimensions between the two semiconductor crystals are minimal.
At the interface between the semiconductors (at $d$ in the figure), $E_c$ and $E_v$ are discontinuous. This forms a potential barrier and conduction band electrons in the thin GaAs layer are confined in the $x$ direction of the figure.

This confinement $d$ is so small that we can treat the electron as in a one dimensional potential energy well in the $x$-direction which is free in the $yz$ plane.
The energy of a conduction electron in this three dimensional potential well of size $d$, $D_y$, and $D_z$ is given by

$$E = E_C + \frac{\hbar^2 n_x^2}{8m_e d^2} + \frac{\hbar^2 n_y^2}{8m_e D_y^2} + \frac{\hbar^2 n_z^2}{8m_e D_z^2}$$

Where $n_x$, $n_y$, and $n_z$ are quantum number with values 1, 2, 3, ...

The potential barrier height is defined with respect to the arbitrary energy level $E_C$.

Since the dimensions $D_y$ and $D_z$ are so much greater than $d$, the minimum energy is almost entirely found from term with $n$ and $d$. 
The holes in the valence band are also confined by the quantum well. Thus this system can be considered as a gas of electrons in a two dimensional space (constrained in the third dimension – \( x \) in this case). Thus we have a system with a large number of states in a very small region. Under forward bias, electrons are injected in the thin GaAs region which serves as the active layer. These injected electrons readily populated the large number of available states (likewise there are a large number of available states in the valence band for the holes).
Quantum Well Devices

- Under current injection, the electron concentration at $E_1$ increases rapidly and hence population inversion occurs quickly without the need for a large current to bring in a great number of electrons.
- Stimulated transitions of electrons lead to a lasing emission.

In single quantum well (SQW) lasers electrons are injected by the forward current into the thin GaAs layer which serves as the active layer. Population inversion between $E_1$ and $E'_1$ is reached even with a small forward current which results in stimulated emissions.
There are two distinct advantages of this structure.

The threshold current for population inversion (and hence lasing emission) is markedly reduced in comparison to that for bulk semiconductors.

Secondly, since the majority of the electrons are at or very near to $E_1$, and the holes are at or near $E'_1$, the range of emitted photon energies is very close to $E_1 - E'_1$.

Consequently the spread in the wavelength, the line-width, in the output spectrum is substantially narrower than that in bulk semiconductor lasers.

(b) The electrons and holes are injected from $n$-AlGaAs and $p$-AlGaAs respectively. The refractive index variation tries to confine the radiation to GaAs but $d$ is too thin, and most of the radiation is in the AlGaAs layers rather than within $d$.

(c) The density of states $g(E)$ is a step-like function, and is finite at $E_1$ and $E'_1$. The $E_1$ sub-band for electrons and $E'_1$ sub-band for holes are also shown.

The electrons in the $E_1$ sub-band have kinetic energies in the $yz$-plane.
Quantum Well Devices

- Threshold current is 10 times lower than double heterostructure LD
- Low dependence on T
- Without "kinks" in the output-current curve
- Poor confinement

The density of states for the confined electron and that in the bulk semiconductor

Single Quantum well SQW

Energy

2eV

1,4eV

AlGaAs GaAs AlGaAs
The advantages of the single quantum well structure can be extended to a larger volume of the crystal by using multiple quantum wells.

In MQW lasers, the structure has alternating ultrathin layers of wide and narrow bandgap semiconductors.

A simplified schematic diagram of multiple quantum well (MQW) heterostructure laser diode. Electrons are injected by the forward current into quantum wells. The light intensity distribution is also shown. Most of the light is in the active region.
Multiple Quantum Well Devices

- The smaller bandgap layers are the active layers where electron confinement and lasing transition take place. The wider bandgap layers are the barrier layers.
- Though the optical gain curve is narrow, it is not necessarily single mode. The number of modes depends on the individual widths of the quantum wells.

A multiple quantum well (MQW) structure. Electrons are injected by the forward current into active layers which are quantum wells.
Multiple Quantum Well Devices

“I threshold rises

“Multiple Quantum well” MQW
A vertical cavity surface emitting laser has the optical cavity axis along the direction of current flow rather than perpendicular to current flow as in conventional laser diodes.

The active region length is very short compared with the lateral dimensions so that the radiation emerges from the surface of the cavity rather than its edge.

The reflectors at the ends of the cavity are dielectric mirrors made from alternating high and low refractive index quarterwave thick multilayers.
Since the wave is reflected because of periodic variation in the refractive index as in a grating, the dielectric mirror is essentially a distributed Bragg reflector.

High reflectance end mirrors are needed because the short cavity length $L$ reduces the optical gain.

There may be 20 – 30 layers in the dielectric mirrors to obtain the required reflectance (~99%).

Simplified schematic illustration of a vertical cavity surface emitting laser (VCSEL).
VCSEL

- Active area
  - SQW and MQW

- Dielectric mirror ($\lambda/4$) p-type
  - (reflectance $\sim 1$)

- N-type dielectric mirror
  - (reflectance $\sim 0.9$)

- Rel. low divergence 7-10°
- Low threshold current
- Narrow spectrum
Kenichi Iga, currently (2012) the President of the Tokyo Institute of Technology, was first to conceive the VCSEL, and played a pioneering role in the development of VCSELs. (Courtesy of Professor K. Iga)

Sketch of the VCSEL in Kenichi Iga's laboratory book (1997). Professor Iga was at the Tokyo Institute of Technology at the time. (See K. Iga, Jpn J. Appl. Phys., 47, 1, 2008) (Courtesy of Professor K. Iga)

This VCSEL diode provides a single transverse mode emission 795 nm. The spectral width is less than 100 MHz, and the output power is 0.15 mW at 2 mA. (Courtesy of Vixar Inc.)
## Vertical Cavity Surface Emitting Lasers (VCSELs)

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<th>δλ (nm)</th>
<th>dλ/dT (nm/K)</th>
<th>Δθ</th>
<th>I_th (mA)</th>
<th>I (mA)</th>
<th>V (V)</th>
<th>P_o (mW)</th>
<th>η_slope (mW/mA)</th>
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<td>0.4</td>
<td>MTM&lt;sup&gt;d&lt;/sup&gt;</td>
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<sup>a</sup>Vixar, 680-000-x001, single and multi mode devices; <sup>b</sup>Laser Components (ULM Photonics) ULM775-03-TN;

<sup>d</sup>Oclaro, 850 nm 8.5 Gb/s Multimode VCSEL Chip

Left: A packaged addressable VCSEL array with 8×8 individually addressable laser devices. The chip is 3 mm × 3 mm. Right: A closer view of the chip. (Courtesy of Princeton Optronics, USA)
A semiconductor laser structure can also be used as an optical amplifier that amplifies light waves passing through its active region. The wavelength of radiation to be amplified must fall within the optical gain bandwidth of the laser.
For the travelling wave amplifier, while the cavity is pumped, the mirrors have antireflection coatings so the optical cavity does not act as an efficient resonator. Light input is amplified by the stimulated emissions and leaves the optical cavity at higher intensity. Typically such amplifiers are buried heterostructure devices and have optical gains of around 20 dB.
The Fabry-Perot laser amplifier is operated below the threshold current for lasing oscillations.

The active region has an optical gain but is not sufficient to sustain a self-lasing output. The wavelengths closest to optical gain bandwidth receive the most increase in intensity but other wavelengths are amplified as well.
Constant Current Control with Temperature Control

ACC (Automatic current control)

Reference

Control

Continuous Control

Peltier

Diode Laser

Optical Fiber

Termistor

Ip

Is
Constant Power Control

APC (Automatic power control)

Reference

Control

Measuring circuit

Photodiode

Diode Laser

Optical Fiber