Optical Properties of III-V Nanowire/Nanopillar lasers grown on Si

Juan Salvador Dominguez Morales
Department of Physical Sciences, Cork Institute of Technology, Cork, Ireland, j.dominguez-morales@mycit.ie

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Optical properties of III-V Nanowire/Nanopillar lasers grown on Si

Juan Salvador Dominguez Morales

Thesis submitted for the degree of

Doctor of Philosophy

Thesis Advisor: Dr. Tomasz Ochalski

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Tyndall National Institute

Submitted to Cork Institute of Technology

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Declaration

This thesis is entirely the candidate's own work, except where otherwise credited.

This thesis has not been submitted for an award in any other institution.

Author's signature: __________________________
Juan Salvador Dominguez Morales

Supervisor's signature: __________________________
Tomasz Ochalski
Nanowires (NW) /nanopillars (NP) offer the possibility of reducing the mismatch of III-V semiconductor materials grown on different substrates such as Si, SiN, SiO$_2$ and are hence being considered potential candidates for coherent light sources in optoelectronics technologies. The difference between NPs and NWs lies in the growth process. The NPs are site-controlled using a patterned mask, while the NWs use a self-catalysed such as gold or Ga-droplet.

In this dissertation, the emission properties of GaAs/AlGaAs (core-shell and core-multishell) and InGaAs (unpassivated and passivated with InGaP) nanolasers have been studied with excitation powers above and below the lasing threshold at different temperatures. Both nanolasers showed a reduction of carrier decay time with excitation power. On the other hand, the spectral intensity increased with the excitation power, suggesting transition from spontaneous to stimulated emission. In particular, time-resolved photoluminescence spectra for GaAs/AlGaAs NWs reported a shift towards longer wavelength of the longitudinal modes for temperatures below 225 K. This phenomenon is caused by the increment of the material refractive index during the recombination process. Finally, the physical properties of the lasing modes have also been analysed for both samples. Helical modes are propagating inside InGaAs NPs, while multiple longitudinal and transverse modes are resonating inside the GaAs/AlGaAs NWs. Helically propagating modes allow high refractive index between interface with low refractive contrast due to the near-90 degree angle of the incident light at the interface NP-Si.
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In 1915, Albert Einstein introduced the stimulated emission concept for the first time in science history\(^1\). This concept was essential to develop laser devices, where the word LASER is an acronym of light amplification by stimulated emission of radiation. The stimulated emission is the process by which an incoming photon interacts with an excited electronic state producing another photon with identical characteristics that of the incident photon (frequency, direction of travel, polarisation, and phase). This is only possible if the incident photon has the same energy as the difference between the electronic states. The stimulated mechanism competes directly with the spontaneous process. In spontaneous emission, the electron is recombined in the electronic states, generating light without any interaction with another photon. In 1928, Rudolf Ladenburg and co-workers\(^2\) found experimental evidence of stimulated emission for the first time. However, the scientific community had to wait until the 1950 when laser operation was proposed by Prokhorov\(^3\) and the group of Schawlow and Townes\(^4\). Finally, it was experimentally observed by Maiman\(^5\) in a ruby crystal in 1960. Two years later, Hall et al. reported the first coherent light emitted from a semiconductor device\(^6\) in a biased GaAs p-n junction.

Nowadays, the applications of lasers are numerous and extremely varied. It is easy to find coherent light emitters in medicine, manufacturing companies, military sector and research. Telecommunications is one of the industries where it has generated most impact. Since the first commercial installation of a fibre optic in 1977, the electrical links have been replaced by optical links to send and receive information at long distances. The electrical interconnection presents higher bandwidth limitation, losses, cost, and susceptibility to interference and environmental conditions in comparison with optical interconnections. The increment in information processing, transmission and reception evidences the electrical links limitations also for chip to chip and on-chip
Chapter 1 Introduction and background

communications\textsuperscript{7,8}. In order to solve this problem, numerous authors suggest replacing the electrical by optical interconnections for short-distance communications\textsuperscript{8–10}.

In the past decade, investigations in Si-based photonics have promised to obtain CMOS compatible technology (mass-produced photonics) and multiple data channels in a single I/O port (high bandwidth density)\textsuperscript{8,11,12}. The combination of silicon photonics with III-V materials is currently the most viable option for the next generation of interconnectors (although other options, such as SiGe-based systems, are being actively explored\textsuperscript{13,14}). III-V materials possess high gain value, direct band gap, and easy band gap tunability by varying the alloy component. The major problem of III-V materials growth in silicon is the lattice mismatch in the interface, which produces dislocation and poor performance. In III-V semiconductor nanowires (NWs) and nanopillars (NPs), the lattice mismatch can be fully relaxed over a small number of monolayers because of its small footprint. Moreover, NWs/NPs offer significant potential for nanoscale laser source due to the quasi-one-dimensional structure, which facilitates a natural Fabry-Perot resonator cavity and optical gain medium simultaneously\textsuperscript{15–18}.

1.1 Theoretical background

1.1.1 Electronic band structure

In order to understand the concept of energy band, it is essential to explain the idea of periodic crystalline solids (full details on crystal structure and bands can be found in a number of textbooks\textsuperscript{19–21}). The crystals are formed by an orderly and periodically arrangement group of atoms. The unit cell is the minimum number and arrangement of atoms that, when repeat creates the full crystal structure. And, the lattice constant is the distance between the atoms in the unit cell. Any lattice point (\(\mathbf{R}'\)) can be described by one lattice vector (\(\mathbf{R}\)) plus integer lattice translation vectors (\(\mathbf{r}_j\)): \[
\mathbf{R}' = \mathbf{R} + \mathbf{r}_j \]

where,
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\[ \vec{r}_s = m_1 \vec{a}_1 + m_2 \vec{a}_2 + m_3 \vec{a}_3 \]  
Equation 1.2

vectors \( \vec{a}_1, \vec{a}_2 \) and \( \vec{a}_3 \) are the three primitive basis vectors in the crystalline solid and \( m_1, m_2 \) and \( m_3 \) are integers. According with equation 1.2, the crystal lattice possible in 3 dimensions are: cubic (simple, body-centered, face-centered), tetragonal (simple, centered), orthorhombic (simple, base centered, body-centered, face-centered), monoclinic (simple, centered), triclinic, trigonal, Hexagonal, figure 1.1.

![Bravais lattice in three-dimensions](image)

Figure 1.1. Bravais lattice in three-dimensions

For a given set of three primitives vector, there is a set of three reciprocal lattice vectors define by:

\[ \vec{a}_1^* = 2\pi \frac{\vec{a}_3 \times \vec{a}_2}{\vec{a}_1 \cdot \vec{a}_2 \times \vec{a}_3} \quad \vec{a}_2^* = 2\pi \frac{\vec{a}_3 \times \vec{a}_1}{\vec{a}_1 \cdot \vec{a}_2 \times \vec{a}_3} \quad \vec{a}_3^* = 2\pi \frac{\vec{a}_1 \times \vec{a}_2}{\vec{a}_1 \cdot \vec{a}_2 \times \vec{a}_3} \]  
Equation 1.3

the general reciprocal lattice vector is given by:

\[ \vec{G} = p_1 \vec{a}_1^* + p_2 \vec{a}_2^* + p_3 \vec{a}_3^* \]  
Equation 1.4
where \( p_1, p_2 \) and \( p_3 \) are integers. The scalar product of the reciprocal lattice vector with the direct lattice vector is equal to \( 2\pi \times \) integer. Therefore, each vector of the reciprocal lattice is normal to a set of planes in the lattice.

The unit cell of a reciprocal lattice can be represented by a Wigner-Seitz cell, and the Brillouin zone is defined as a Wigner-Seitz cell of the reciprocal lattice. The Wigner-Seitz cell of a lattice point is defined as the volume that encloses all points in space which is closer to this particular lattice point than to any other. Figure 1.2 shows the first Brillouin zone for a face-centered cubic lattice.

![Figure 1.2](image)

Figure 1.2. The first Brillouin zone for a face-centered cubic lattice.

After this brief introduction of periodic crystalline solids, the semiconductor theory can be expounded. The relation between the energy and momentum of a crystal is obtained by solving the time-independent Schrödinger equation for an electron in the crystalline solid:

\[
-\frac{\hbar^2}{2m_e} \nabla^2 \Psi(\vec{r}) + V(\vec{r}) \Psi(\vec{r}) = E \Psi(\vec{r})
\]

Equation 1.5

where \( \Psi(\vec{r}) \) are the electron stationary states or waves functions, \( -\frac{\hbar^2}{2m} \nabla^2 \) is the kinetic energy operator, \( V(\vec{r}) \) is the potential energy operator, \( E \) are the eigenvalues that gives the energy of the states \( \Psi(\vec{r}) \), and \( m_e \) is the electron’s mass. However, the motion of an electron in a crystalline solid can be reduced to the problem of an electron in a
Chapter 1 Introduction and background

periodic potential, due to the repetitive structure of the crystalline solid. And hence, the Bloch’s theorem can be applied and the wave function can be expressed as Bloch functions $\phi_{\mathbf{k}}(\mathbf{r})$:

$$\frac{-\hbar^2}{2m^*_e} \nabla^2 \phi_{\mathbf{k}}(\mathbf{r}) V(\mathbf{r}) \phi_{\mathbf{k}}(\mathbf{r}) = E_{\mathbf{k}} \phi_{\mathbf{k}}(\mathbf{r}) \quad \text{Equation 1.6}$$

with,

$$\phi_{\mathbf{k}}(\mathbf{r}) = e^{-i\mathbf{k} \cdot \mathbf{r}} u_{n,\mathbf{k}}(\mathbf{r}) \quad \text{Equation 1.7}$$

where $m^*_e$ is the electron effective mass, $n$ is the band index, $\mathbf{k}$ is the wavevector and $u_{n,\mathbf{k}}(\mathbf{r})$ is a periodic function in $\mathbf{r}$ with the periodicity of the direct lattice:

$$u_{n,\mathbf{k}}(\mathbf{r} + n\mathbf{\Gamma}) = u_{n,\mathbf{k}}(\mathbf{r}) \quad \text{Equation 1.8}$$

Equation 1.7 describes the periodicity of the wavevector, as a consequence the energy $E_{\mathbf{k}}$ is periodic in the reciprocal lattice, $E_{\mathbf{k}} = E_{\mathbf{k} + \mathbf{\Gamma}}$. Then, the wave vector $\mathbf{k}$ can always be reduced to a value residing in the first Brillouin zone for a given band index.

The energy band structure of a crystalline solid describes the possible energy of an electron according to its wavevector, figure 1.3. There are numerous numerical methods to calculate the band structure of a solid such as; nearly free electron energy band, pseudopotential, $\mathbf{k} \cdot \mathbf{p}$, tight-binding, Density Functional Theory (DFT) and Green’s function methods.

Every method solves the equation 1.6 considering different assumptions.

Analysing the band diagram in figure 1.3, we may be distinguished the conduction band, $E_c$, and the valence band, $E_v$. The valence band refers to the highest energy band that is fully occupied by electrons at zero absolute (0K) and no external excitation. On the other hand, the conduction band is the lowest energy band empty of electrons at the same conditions. The energy separation between these two bands is called the energy bandgap, $E_g$. 
In zincblende structure (face-centered cubic), the valence band is formed by four subbands. Each subband is doubled with the introduction of the spin interaction in the Schrodinger equation, equation 1.6. The three subbands with the highest energy in the valence band are degenerated at $\vec{k} = 0$ (Γ point at the energy band structure) and they split with the introduction of the spin-orbit interaction, figure 1.3b and figure 1.4. In particular, the two subbands of the valence band with the highest energy can be approximated to two parabolic functions with different curvature. The heavy-hole band is name to the subband of the valence band with the wider band and smaller $\frac{\partial^2 E}{\partial k^2}$ (larger effective mass), and the light-hole band refers to the narrower band with larger $\frac{\partial^2 E}{\partial k^2}$ (smaller effective mass). The effective mass is defined as the tensor with the following components:

$$\frac{1}{m_{ij}} = \frac{1}{\hbar^2} \frac{\partial^2 E(\vec{k})}{\partial k_i \partial k_j}$$

Equation 1.9
1.1.2 Type of crystalline solid

The crystalline solid can be classified into insulator, semiconductor and conductor, figure 1.3. Some solid sates textbooks describe a semiconductor as a material with electrical resistivity within the range of $10^{-3} \, \Omega \cdot \text{cm}^{-1}$ to $10^9 \, \Omega \cdot \text{cm}^{-1}$ at room temperature, a conductor below $10^{-3} \, \Omega \cdot \text{cm}^{-1}$ and an insulator above $10^9 \, \Omega \cdot \text{cm}^{-1}$. Others define metals as material with zero bandgap, insulator with larger bandgap than 3 eV and semiconductor in between. However, GaN is considered a semiconductor material and its bandgap is 3.5 eV. Another definition refers to the occupation of electrons in the conduction energy band at room temperature. Before introducing this definition, the carrier density calculation in the conduction and valence band will be discussed. The occupational probability, $f(E)$, with energy $E$, for a system of identical fermions in thermodynamic equilibrium, is given by the Fermi–Dirac distribution:

$$f(E) = \frac{1}{e^{(E-E_F)/kT} + 1}$$

where $E_F$ is the Fermi energy, $k$ is the Boltzmann constant and $T$ is the temperature. At temperature close to zero, the Fermi–Dirac distribution can be approximated to the step function with the transition between one and zero at energies equal to the Fermi energy. The fermions occupy the energy levels from the lowest to the higher according to the
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Pauli Exclusion Principle. The energy difference between the highest and the lowest occupied level is the Fermi energy. At energies equal to the Fermi energy and temperatures far from zero, the function is one-half and decreases exponentially for higher energies, figure 1.5a.

Having introduced the Fermi-Dirac distribution, the carrier and hole density can be determined as the integral over the energy of filled states in the conduction and valence band, respectively:

\[ N = \int_{E_c}^{\infty} \rho_c(E)f(E)dE \quad \text{Equation 1.11} \]

\[ P = \int_{-\infty}^{E_v} \rho_v(E)f(E)dE \quad \text{Equation 1.12} \]

were \( \rho_c(E) \) and \( \rho_v(E) \) are the density of states in the conduction and valence band. And, it can be described for bulk material following:

\[ \rho(E) = \frac{\sqrt{E}}{2\pi^2} \left[ \frac{2m^*}{\hbar^2} \right]^{3/2} \quad \text{Equation 1.13} \]

where \( m^* \) is the effective mass and \( \hbar \) the reduced Planck constant.

Figure 1.5. a, semiconductor energy band diagram at zero absolute and room temperature with the Fermi-Dirac distribution inset. b, insulator energy band diagram at room temperature. c, conductor energy band diagram.

In semiconductor materials, the conduction band is not occupied by electrons at zero absolute, however it is slightly populated at room temperature, figure 1.5a. On the other
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hand, the conduction band is partially populated by electrons in metals or conductor materials at any temperature, deriving in high electrical conductivity, figure 1.5c. In contrast, insulator materials show poor electrical conductivity and the conduction band is not thermally occupied by electrons at room temperature, figure 1.5b.

1.1.3 Light interaction with semiconductor materials

This section will describe the electronic transition and its interaction with the light in semiconductor materials. The electronic transitions between the conduction and valence band must fulfil the conservation of momentum and are illustrated in figure 1.6.

![Figure 1.6. Electronic transitions in a semiconductor material. a, photon emission in radiative recombination transitions. b, photon absorption in radiative recombination transitions. c, coherent photon emission in radiative recombination transitions. d, two examples of non-radiative recombination transitions.]

The generation and recombination of electrons can be classified into radiative (figure 1.6a, b, c) and non-radiative (figure 1.6d) electronic transitions. The spontaneous emission is a radiative recombination process which implicates the annihilation of an electron-hole pair, and it is the primary mechanism of the Light-Emitting Diode (LED), figure 1.6a. The absorption is the process in which an electron is promoted from the valence to the conduction band by the assimilation of a photon. This mechanism generates a hole in the valence band, and an electron in the conduction band, figure 1.6b. The energy of the incident photon must be the same or superior to the energy difference between the conduction and valence band. The principle of coherent light emission is given by the stimulated recombination process, figure 1.6c. In this electronic transition, the photon generated has the same energy, phase, and direction as the incident photon. Population inversion is required to obtain coherent light emission. During population inversion, a high concentration of carriers populates the excited electronic levels.
Finally, figure 1.6d illustrates some example of non-radiative processes. In this type of transition, the light is not generated in the relaxation of the carriers. The energy released is dissipated non-radiatively via the lattice vibrations or electronic excitations. Defects in the crystal such as point defects, linear defects or dislocations, planar, interface and surface states, create recombination centres between the energy bands. These processes are usually a two-step transition. The electron falls into the energy trap (non-radiative centres) by the exchange of momentum with the lattice before it recombines. Near zero absolute, the electron cannot exchange momentum with the lattice because of the low lattice vibration energy. However, the rise of temperature creates an increase of the vibrational energy of the lattice and consequently the activation of this non-radiative recombination process. This mechanism is called the thermal activation of non-radiative recombination. Another mechanism of non-radiative process is Auger recombination, in which the energy released in an electronic transition is absorbed by a third particle with energy necessary to ionise.

1.1.4 Semiconductor lasers

Semiconductor laser diodes generate coherent light using semiconductor materials as a gain medium. In laser diodes, the structure can be divided into the optical gain medium and the resonant optical cavity, figure 1.7. The gain medium consists of a semiconductor material with a certain band gap. Two mirrors separated by a distance $L$ build the resonance cavity, contributing to the light recirculation along the gain medium. The optical or electrical excitation of the semiconductor gain medium creates electron-hole pairs which drive the emission of light during the recombination process. The light travels along the resonance cavity, forcing it to circulate in the semiconductor gain media. Part of this light is absorbed by the gain medium and the mirrors (optical losses) and part of the light is emitted. The semiconductor gain medium achieves population inversion when the majority of the carriers (created during the excitation process) populate the upper electronic levels. At this status, stimulated recombination process dominates over the spontaneous, and the optical losses are compensated with the photon emission. The lasing threshold is defined as the excitation power at which the optical gain equals the losses in one round trip.
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Figure 1.7. Diagram of laser diode. The optical cavity is defined by the distance between the mirrors.

In Fabry-Perot resonators, longitudinal modes are originated by the interferences of the light circulating in the optical gain medium, following:

$$ l = m \left( \frac{\lambda}{2n} \right) $$

Equation 1.14

$\lambda$ is the longitudinal mode wavelength, $m$ the order of the mode and $n$ the refractive index of the cavity. The distance between two consecutive modes is inversely proportional to the resonance cavity length. Therefore, short cavity length shows large distance between the modes, and vice versa for long cavity, figure 1.8. Single mode emission is obtained when the optical length is equal to half wavelength, figure 1.8. The optical length is the product of the refractive index and the mode wavelength.

Figure 1.8. Dependency of the resonance cavity length on the distance between lasing modes. From left to right, single mode laser, quasi-single mode laser and multi-mode laser.
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1.1.4.1 Optical gain media

The optical gain medium is the medium where the power of light is amplified in coherent light emitters. In diode lasers, the gain medium is a semiconductor structure with a certain band-gap. The material gain per unit length is the proportional photon density amplified in the gain media. The gain spectrum can be determined following by

\[
g(\hbar \omega) = \frac{\pi e^2}{n_re_0m_0^*\omega} |M|^2 \int \rho(E)(f_c(E) - f_v(E))\ell(E)
\]

\[-\hbar \omega) dE
\]

Equation 1.15

where \(e, n_r, c, e_0, m_0, \hbar, \omega\) and \(|M|^2\) are the electron charge, material refractive index, speed of light, vacuum permittivity, electron mass, reduced Planck constant, angular frequency of light, and the momentum matrix element, respectively. Moreover, \(\rho(E)\) is the density of states function, \(f_c(E)\) and \(f_v(E)\) are the Fermi-Dirac distribution in the conduction and balance band respectively, and \(\ell(E - \hbar \omega)\) is the lineshape broadening function. During the gain spectrum calculation, the Fermi energy levels for the conduction and valence band must be firstly calculated for a given injected carrier density, equation 1.11 and equation 1.12. In this estimation, the contributions of the light-hole and heavy-hole subbands might be included in the calculation of the Fermi level for the valence band, for a given injected carrier density.

The lineshape function determines the probable energy distribution of the electron-hole pair annihilation, taking into consideration the uncertainty of the carrier potential energy. There are multiple functions which can be used to describe the energy broadening, Gaussian, Lorentzian, hyperbolic secant. In this work, the function used is the hyperbolic secant to avoid unphysical absorption below the band gap:

\[
\ell(E - \hbar \omega) = \frac{\hbar}{\pi \tau_{in}} sech \left( \frac{E - \hbar \omega}{\hbar / \tau_{in}} \right)
\]

Equation 1.16

\(\tau_{in}\) is the intraband relaxation time, it is a time constant related with the exponential decay of the electron. The intraband relaxation time is calculated by fitting the analytical spontaneous emission spectra equation with the spectra emission of the
sample measured. The analytical spontaneous emission spectra equation is derived from the gain spectrum and it is defined as:

\[
r_{sp}(\hbar \omega) = \frac{2n_r \omega e^2}{\hbar c^3 e_0 m_0^2 \omega} |M|^2 \int \rho_r(E) f_r(E) (1 - f_v(E)) \ell(E - \hbar \omega) dE
\]

Equation 1.17

Figure 1.9 illustrates the GaAs gain spectra for different carrier concentration and the gain maximum as a function of the carrier density at 300K. The material parameters are listed in section 3.2.1. The GaAs becomes transparent (material gain equal to zero) for carrier injected below \(4.7 \times 10^{17} \text{cm}^{-1}\) and the maximum gain as a function of the carrier density increase logarithmically\(^\text{28}\). The estimation of the gain peak is fundamental to compute the laser rate equations, and hence study the dynamics of the laser.

![Material gain spectra for bulk GaAs at 300 K. a, gain spectra for different carrier density. b, maximum gain with carrier density.](image)

1.1.4.2 Carrier and photon density rate equation

The carrier and photon density rate equations describe the dynamic of carriers and photons in light emitters. In particular, equation 1.18 and equation 1.19 represent the dynamic of carriers (N) and photon (S) density in a diode laser with an injected current (I)\(^\text{28}\),

\[
\frac{dN}{dt} = \frac{\eta_l I}{qV} - \frac{N}{\tau} - \nu_g S(N)S
\]

Equation 1.18
Chapter 1 Introduction and background

\[
\frac{dS}{dt} = \Gamma v_g g(N)S + \Gamma \beta \frac{N}{\tau_{sp}} - \frac{S}{\tau_p}
\]

Equation 1.19

where \( q, V, \tau_{sp}, \tau_c, \tau_p, g \) and \( v_g \) are the elementary charge, the volume of the active region in the diode laser, the spontaneous carrier lifetime, the carrier lifetime, the photon decay rate, the material gain and the group velocity of the light traveling inside the laser cavity, respectively. The active volume in a laser is the region where the recombination process contribute to amplify the light emitted. \( \eta_i \) is the internal efficiency and it is the fraction of the current that generates carrier in the gain medium. It shows the fraction of current that contributes in the recombination process. \( \Gamma \) is the confinement factor. It indicates the ratio between the volume of the active region and the volume occupied by the optical mode\(^{28}\). \( \beta \)-factor or spontaneous emission factor describes the coupling quality of the spontaneous light into the laser. A laser with \( \beta \)-factor equal to one will show perfect coupling of the spontaneous light and the lowest noise possible of the coherent light emitted. For instance, figure 1.10a illustrates the modelling of carrier and photon density rate equation for a typical coherent light emitter at different \( \beta \)-factor. The amplified spontaneous emission regime profile is altered with the value of \( \beta \)-factor. For \( \beta \)-factor near to the unity, the transition between spontaneous to stimulated emission is smooth. On the other hand, values closer to cero drive in an abrupt transition and more pronounced S-like feature, figure 1.10a. Finally, \( \tau_p \) or photon lifetime quantifies the photon loss along the laser cavity.

\( g_{th} \) or gain threshold is the minimum gain to obtain stimulated light emission and fulfil:

\[
\Gamma g_{th} = \alpha_i + \alpha_m
\]

Equation 1.20

where \( \alpha_i \) and \( \alpha_m \) are the losses due to the absorption in the cavity and mirror respectively. The photon decay rate is\(^{28}\):

\[
\frac{1}{\tau_p} = \frac{1}{\tau_i} + \frac{1}{\tau_m} = v_g (\alpha_i + \alpha_m)
\]

Equation 1.21

Therefore, the gain threshold can be express with the following equation:

\[
\Gamma g_{th} = \frac{1}{v_g \tau_p}
\]

Equation 1.22
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The minimum current to obtain stimulated light emission is called the current lasing threshold. Above this current injected, the stimulated process dominates over the spontaneous during the recombination mechanism. Under steady state conditions \( \frac{dN}{dt} = 0 \), the optical gain is equal to the gain threshold at any injected current above the lasing current threshold \( (g(I \geq I_{th}) = g_{th}) \), figure 1.10b. Otherwise, the intensity of the coherent light emitted would continue to rise and this cannot occur in steady state conditions. Indeed, the increment of current in an amount above the lasing threshold creates a rise of the material gain and carrier density \( ^{28} \). Then, the term in equation 1.18 related with the stimulate recombination \( (\nu_{gs}(N)S) \) also increases, reducing the optical gain media and the carrier to the threshold value.

![Figure 1.10](image)

Figure 1.10. Modelling of carrier and photon density rate equation for a typical coherent light emitter. a, \( \beta \)-factor dependency. The grey area ephasises the amplified spontenous emission regime. It divides the curve between the spontenous emission regime (power below grey area) and stimulated emission (power above grey area). b, gain threshold dependency.

The steady-state threshold current injected can be determined as \( ^{28} \):

\[
I_{th} = \frac{qV}{\eta_i} \left( R_{sp}(N_{th}) + R_{nr}(N_{th}) \right) = \frac{qVN_{th}}{\eta_i \tau} \quad \text{Equation 1.23}
\]

where \( R_{sp} \) is the spontaneous recombination rate, and \( R_{nr} \) is the nonradiative recombination rate. Therefore, a reduction of the lasing threshold can be achieved by:
Chapter 1 Introduction and background

- The decrease in the active gain media volume
- The increase of the internal efficiency
- Minimising the carrier density at the threshold \((N_{th})\)

1.2 Review of nanowires and nanopillars nanolasers

Nanowires/Nanopillars are a one-dimensional nanostructure with a diameter in the order of 100s nanometers and length of micrometres. Their small diameter or footprint permits the high-quality growth of these nanostructures on substrates with large lattice mismatch\(^{15,17}\), figure 1.11. The material composition determines the growth mechanism, the geometry limitations, the spectral emission and the refractive index contrast. For instance, a high refractive index contrast leads to elevating light confinement, forming a strong resonance cavity defined by the NWs/NPs facets. This characteristic facilitates the circulation of the light inside the gain media, and hence the generation of coherent light. The difference between NPs and NWs lies in the position of the NW with the substrate. NWs are lying on the substrates and the facets interface is air-Gain media. While, one of the facets is attached to the substrate in NPs and the facets interfaces are air-gain media and gain media-substrate.

Nanowires nanolasers were first demonstrated by Huang et al.\(^{29}\), in 2001. It was reported ultraviolet coherent light emission from ZnO NW arrays at room temperature. The nanostructure was synthesised with vapour phase transport process, using Au as the catalyst in a sapphire substrate. Since then, stimulated light has been observed in numerous NWs/NPs with different material composition, spectral wavelength and structure. For instance, it has been studied laser emission in GaN\(^{30}\), CdSe\(^{31}\), GaAs\(^{17,32}\), InP\(^{33}\), GaSb\(^{34,35}\) as a gain media in NWs/NPs with spectral wavelengths in the range of ultraviolet\(^{29,30}\), visible\(^{31}\) and near-infrared\(^{17,32-35}\), figure 1.12. Highlight the work of Liu, Z. et al.\(^{36}\), where they reported room temperature simultaneous red and green spectral lasing in single NW by varying the composition of one of the alloys along the NW.
III-V semiconductor materials are important for the development of optoelectronics devices. Most of these materials offer direct bandgap and bandgap engineering by changing one of the alloy compounds. The major disadvantage is the substantial lattice mismatch between III-V semiconductor materials and Si, complicating the epitaxial growth process. Other disadvantages are the differences in crystal structure and thermal expansion coefficient. NPs/NWs provide a small footprint and hence they can be direct epitaxial grown on Si substrate. The first III-V NW nanolaser on Si was published by the group of Chen et al. They demonstrated lasing in a single InGaAs NP optically excited, and at 4 K. Following this article, more publication have shown lasing in NWs/NPs grown on Si platform, GaAs/AlGaAs, InP, GaAs-(InGaAs/AlGaAs).

NWs/NPs also provide a platform to grow different quantum confinement nanostructures such as quantum wells (QWs) and quantum dots (QDs). The first to obtain lasing for an NW with quantum confinement structures insets was Qian et al., using III-nitride materials. On the other hand, Stettner et al. demonstrated coherent light emission in a GaAs/AlGaAs core-shell NWs growth in Si platform in 2016. And, Tatebayashi et al. demonstrated lasing in GaAs/AlGaAs NWs with GaAs QDs insets. NWs/NPs with quantum confinement structures inset acting as gain media have reported lower lasing threshold and greater temperature stability in comparison with the bulk materials.
The majority of the NWs/NPs lasers have revealed coherent light emission with the nanostructure laid down the substrate. In this horizontal position, the NW/NP acts as a Fabry-Perot laser with the active gain media defined by the facet. This configuration facilitates coherent light emission reducing the lasing threshold and simplifies the output light coupling into waveguides. However, the NW/NP is usually grown in a vertical position and transferred into other substrates. The relocation of the NW/NP with precise control is exceptionally challenging.  

On the other hand, it has also found laser emission in vertical NWs/NPs using different techniques. The disadvantage of vertical configuration is the low refractive index contrast between the substrate and the NWs/NPs. The similar refractive index complicates the light feedback, and hence the generation of coherent light. However, some authors have resolved this problem by using different approaches. Heo J. group embedded a GaN NW in a 2D photonic crystal, achieving coherent light emission optically pumped at room temperature. The NW served as an active gain media and the 2D photonic crystal as a resonance cavity. Chen et al. described lasing in a standing InGaAs NP on Si produced by the resonance of helical modes. Helically propagating modes facilitate total internal reflection at the interface due to the near-90 degree angle of the incident light at the interface NP-Si. Another solution is used a silicon oxide layer between substrate and NW/NP, creating high contrast and optical feedback.
Polarisation and directionality of the light emitted by NWs/NPs are essential for the integration of these nanostructures into optoelectronic devices. A extend numbers of authors have studied the possibility to control the modes resonating along NWs/NPs\textsuperscript{15,17,36,48–57}. For instance, the diameter and length of NWs/NPs profoundly influence the modes appearing along the resonance cavity. In particular, Saxena \textit{et al.}\textsuperscript{17,49,58} published the relation between GaAs/AlGaAs core-shell and core-multishell NWs diameter and the transversal mode emitted. Chen \textit{et al.}\textsuperscript{15} also reported a direct connection between the InGaAs NPs helical lasing modes type and the NP diameter. Regarding NW/NP length, Liu X.\textsuperscript{55} work described a new optical self-feedback mechanism, using self-absorption at the Urbach tail states of semiconducting nanostructures. They were able to tune the CdS NW emission by 30 nm, increasing the NW length. Other publications suggested manipulating the cross section shape (rectangular\textsuperscript{53}, conical\textsuperscript{51}, or annular\textsuperscript{52}), growing loop NW\textsuperscript{36}, coupling two NWs\textsuperscript{48,56,57}, or placing the NW in a metal\textsuperscript{50} or grating substrate\textsuperscript{54}, to control the mode selection in NWs/NPs coherent light emitters.

The majority of the NWs/NPs emit coherent light using an optical coherent light source as an excitation power\textsuperscript{15,17,53–57,59–62,32,36,40,48–52}. Thus far, few publications have demonstrated coherent light emission in NWs/NPs with electrical pumping\textsuperscript{44,63,64}. For instance, Duan \textit{et al.} described lasing in a single CdS NW electrically driven\textsuperscript{44}. Most recently, Li \textit{et al.} showed lasing in electrically injected AlGaN NWs grown on Si. However, the design of NWs/NPs as a monolithic coherent light source electrically pumped is the challenge of this nanostructure\textsuperscript{65}.

1.3 Thesis outline

This thesis describes the optical properties of III-V semiconductor NWs and NPs. Four samples are studied, two GaAs NWs and two InGaAs free standing NPs. The GaAs NWs measured are GaAs/AlGaAs core-shell, and GaAs/AlGaAs core-multishell. The core-multishell NW contains seven concentric GaAs quantum wells as an active gain media. On the other hand, the emission feature of InGaAs passivated and unpassivated standing NPs has also been explored. The Time-resolved photoluminescence (TRPL) and photoluminescence (PL) spectroscopy techniques are performed for a better
Chapter 1 Introduction and background

understanding of the light emitted by these nanostructures. PL and TRPL measurements are carried out for a set of temperatures and excitation power. The dissertation is structured in the following manner.

Chapter 2 will describe the spectroscopy techniques and the set-up used to analyse the NWs and NPs samples. The key fundamentals of time-resolved photoluminescence and photoluminescence is illustrated, likewise the set-up necessary to carry out the experiments.

Chapter 3 will show the emission properties of GaAs/AlGaAs core-shell and core-multishell NWs. The emission temporal evolution reveals a shift towards longer wavelength (redshift) of the longitudinal modes with time in both samples. The redshift disappears at temperatures above 225 K. This phenomenon is the result of the refractive index variation caused by the decrease of carriers along the recombination process. PL measurements for a set of excitation power contribute to estimate the lasing threshold and study the light-input light-output curve. Finally, the refractive index change is estimated experimentally from TRPL spectra for both samples.

Chapter 4 will analyse the output light features of InGaAs NPs passivated and unpassivated. Power dependence PL determines the excitation power at which the NPs begin to radiate coherent light. TRPL and PL measurements are carried out at low temperature to minimise non-radiative processes. InGaAs passivated in comparison with unpassivated NPs shows longer carrier lifetime and a single emission peak due to the reduction of non-radiative processes on the NP surface. Two lasing modes also appear in passivated NPs with spectral separation of 100 nm, and a single mode for the passivated sample.

Finally, chapter 5 will conclude and summarise the work done in NPs and NWs nanolasers. It will also suggest the future work necessary to develop a monolithic coherent light source based in this nanotechnology.
Chapter 2 Experimental techniques

Optical spectroscopy studies the interaction between matter and light. An incident electromagnetic wave can be reflected, absorbed, transmitted or scattered, figure 2.1. The wavelength of the incident light is not altered in reflected or transmitted photons. However, other properties such as phase and polarisation can be modified. For instance, the photo-reflectance technique analyses the features of the light reflected in response to a modulated light. This technique determines the electron mobility characteristics by varying the material reflectance with a modulated beam. Fourier-transform infrared spectroscopy (FTIR) uses the light absorbed to obtain information about the gas, liquid or solid measured. It has numerous applications in agriculture, food processing, medical and in pharmaceutical applications, polymer and plastics processing, and in satellites or aircraft for remote sensing\textsuperscript{66}.

In Raman and Photoluminescence (PL) spectroscopy, the spectral wavelength of the output light differs with the incident light. Raman is a spectroscopy technique that examines the light scattered in the material. It provides information about molecular vibration, and it can be used for sample identification and quantitation\textsuperscript{67}. On the other hand, PL studies the light emitted from the material. The photons absorbed by the material create electron-hole pairs. During radiative recombination processes, the pairs are annihilated, generating photon with the same energy that the difference between the energy of the electron and hole. The dynamic of this process is described in Time-resolved PL spectroscopy.
Chapter 2 Experimental techniques

Figure 2.1. Light interaction with matter diagram.

2.1 Experimental set-up

Figure 2.3 shows the experimental photo-luminescence set-up to characterise the GaAs NWs and InGaAs NPs. The excitation source is a pulsed Ti-Saphire laser. The wavelength can be tuned from 690 nm to 1000 nm, and the pulse width is approximately 300 fs. The laser beam is guided to a neutral-density filter to have control of the excitation power amount. Confocal mode is the configuration used for μ-PL or μ-TRPL in this dissertation. A set of beamsplitters drives the laser beam into the microscope lens. The microscope lens is a 50x Olympus silicone achromatic with numerical aperture of 0.65. In chapter 3, a cylindrical lens is introduced in the experimental set-up to change typical Gaussian profile of the laser beam focused in the sample to elliptical shape, figure 2.3. The elliptical profile of the laser beam focused achieves the excitation of the entire NW, see chapter 3.
Chapter 2 Experimental techniques

Figure 2.2. Transmittance spectrum for the 50x Olympus silicone achromatic microscope lens (https://www.olympus-ims.com/en/microscope/lmlcpln-ir/#!cms[tab]=%2Fmicroscope%2Flmlcpln-ir%2F50x).

In order to visualise the sample and the laser beam location, a 660 nm LED source and CMOS camera is placed in the set-up. The sample emission is guided with beamsplitters to the lens that focuses it on the monochromator. The monochromator filters the light and sends it to the femtowatt photodetector, or the streak camera. The photoreceiver is connected with a lock-in amplifier to reduce the signal noise and enhance the PL spectrum of the sample. On the other hand, the monochromator might focus the light into the streak camera to measure the TRPL spectra of the sample. The time resolution is controlled with the slits size located in the streak camera.

The sample is placed in a Helium closed-cycle or a continuous flow liquid Helium cryostat if vibration must be avoided. The Helium closed-cycle cryostat can achieve temperature from 7 K to 300 K while continuous flow liquid Helium from 3.6 K to 300 K.
Chapter 2 Experimental techniques

2.2 Photoluminescence measurements

Photoluminescence is light emitted by a material or a molecule in a recombination process due to the excitation of carriers by incident light and the subsequent decay to inferior energy level. The wavelength emitted is equivalent to the energy difference between the initial and final energy state. This spectroscopy technique is being used in biology, geology, material science, food science... It is a non-destructive technique and can be combined with external factors (excitation power, material temperature) to obtain a better knowledge of the sample. In particular, PL is a fundamental technique to study...
and characterise novel semiconductor material. It can determine the crystal quality, impurities in the crystal growth, exciton properties, material bandgap…

![Diagram showing PL diagram and spectra](image)

Figure 2.4. a. PL diagram in a semiconductor bulk material. b, PL spectra for a GaAs/AlGaAs NW at 4 K.

Chapter 1 describes the interaction of light with a semiconductor material. When an incident light hits a semiconductor material, the light can be absorbed and create an electron-hole pair with the same energy as the incident light. Alternatively, it can pass through the material without any interaction, in the case of the photon energy is below the semiconductor bandgap. The electron-hole pair relaxes to the minimum energy state by thermal processes and the material reaches quasi-thermal equilibrium, figure 2.4. The carriers distribution is ruled by the Fermi-Dirac distribution. Finally, the photocarrier recombines emitting a photon with energy similar to the energy band gap in bulk materials and radiative process.

In this work, PL measurements have mostly been carried out using a monochromator and an InGaAs or Si femtowatt photoreceiver connected with the lock-in amplifier. However, the light-input light-output curves described in chapter 3 and chapter 4 are obtained with an Ocean Optic spectrometer. A typical PL spectrum is shown in figure 2.4, where the x-axis represents the wavelength in nanometers and the y-axis the intensity in arbitrary units.
2.3 Time-resolved photoluminescence

TRPL measurements provide the emission dynamic of an excited material by a short pulse source. For instance, carrier excitation and relaxation timescale are in the range of a few femtoseconds to picosecond, radiative recombination process between tens of picoseconds to hundreds of microseconds, auger recombination between a few picoseconds to tens of nanoseconds\textsuperscript{68}. Therefore, the dynamic emission study let us determine the process involved in the light emitted by a material. Multiple techniques allow us to obtained TRPL spectra. Fast photodiode connected with an oscilloscope and a modulated light source can obtain resolution in the order of microseconds. Other techniques can achieve resolution in the order of the femtoseconds or picoseconds such as time-correlated single photon counting, photoluminescence upconversion, optical Kerr gating and streak camera\textsuperscript{69}.

In this thesis, the streak camera is the instrument used to measure the temporal evolution of the light emitted for the sample study. The light filtered and spectrally dispersed by the monochromator is focused into the streak camera, figure 2.6. The light is first guided through the streak camera slit and photocathode. The slit selects the temporal resolution, and the photocathode converts the photons sequentially in electrons via the photoelectric effect. The numbers of electrons are proportional to the intensity of the light focused on the photocathode. The photocathode is the Si infrared-enhanced TO-chilled, see spectral response in figure 2.5. The working process of the following step is similar to the cathode-ray tube television technology. The electrons are conducted towards the sweep high voltage electrodes. The excitation source triggers the sweep circuit unit, and it also defines the temporal resolution. The electrons are deflected to the micro-channel plate (MCP) from left to right and from top to bottom corresponding with the spectral position and time, respectively. The MCP multiplies the electrons, and these are bombarded against the phosphor screen converting it back to light. The brightness of the fluorescence image is proportional to the intensity of the incident light. For instance, the yellow peak in figure 2.6 appears at the top and right because it is the first incident pulse and with the longest wavelength, while brown peak
Chapter 2 Experimental techniques

is at the bottom and left. Finally, the fluorescence image is captured with a CCD camera.

Figure 2.5. Spectral response of the different photocathode used by Hamamatsu streak camera. The photocathode used in this dissertation is the S-1.

The lowest temporal resolution of the streak camera is 3 ps, and it is acquired with the synchroscan unit M5675. However, the temporal resolution of the experiment is also determined by the optics geometry and the slit aperture shown in figure 2.6. The temporal resolution of the experiment is estimated measuring the Ti:Saphire laser pulse lifetime. The laser pulse is under the temporal resolution of the streak camera and hence the lifetime of the laser pulsed measured in the streak camera corresponds with the temporal resolution of the experiment. For instance, the laser lifetime measured in figure 2.7 is 10ps, and also it is the temporal resolution of the experiment.
Figure 2.6. Operating principle of the streak camera. The picture was taken from Hamamatsu streak camera datasheet (https://www.hamamatsu.com/).

The typical streak camera image or TRPL spectra is shown in figure 2.7. Figure 2.7 describes the temporal evolution of the InGaAs NPs emission and the laser pulse. The warmest colour represents the highest intensity incident light and the coldest the lowest. In this figure, we can observe how the excitation source (laser pulse, right image) triggers the NPs emission (left image).

The streak camera software is supplied by Hamamatsu (HPD-TA). The system can control and integrate the multiple hardware devices for the acquisition and processing of the TRPL spectrum. For instance, the software synchronise the image grabbing with the streak camera and the excitation source (laser pulsed). And also, it provides different data correction and pre-processing function such as background, shading, curvature and jitter correction.
Chapter 2 Experimental techniques

Figure 2.7. TRPL spectra of the laser pulse (left-side) and InGaAs NPs (right-side). White line inset, laser pulse decay curve normalised. Black line, InGaAs NP decay curve normalised.
Chapter 3.

Emission properties of GaAs/AlGaAs core-shell nanowire lasers on Si

The number of cores inside a microprocessor has increased since the first multicore processor (IBM POWER 4) began to commercialise in 2001. Nowadays, AMD Naples includes 32 cores in a CPU with a memory bandwidth requirement of 170.7 GB/s. In the tera-era (near future) the microprocessor will demand 1 TB/s of bandwidth. Therefore, the circuit complexity, cost, and energy consumption must increase to satisfy TB/s bandwidth, or the interconnection technology must improve. Optical links offer the opportunity to raise the bandwidth and reduce material costs, power consumption, and crosstalk. However, it is necessary to have a CMOS compatible technology to replace electrical with optical interconnections. Si-based photonics combined with III-V semiconductor material is currently the most viable option for optical interconnects.

III-V materials possess direct bandgap, high gain value, and bandgap tunability by varying the alloy component. The major problem of III-V materials growth on silicon is the lattice mismatch between the substrate and material growth interfaces, which produces dislocations and poor performance.

The nanoscale interface between Si substrate and III-V semiconductor NWs reduces the lattice mismatch, and hence achieves monolithic integration of high-quality III–V semiconductors on silicon. III-V NWs also offer great potential for coherent light sources at the nanoscale. Because of their quasi-one-dimensional structure and high refractive index they provide: a natural Fabry-Perot resonator cavity defined by the end facets, optical gain medium simultaneously with the resonator cavity, low loss optical waveguiding, and strong optical confinement, figure 3.1. Since Yang group first observed coherent light emission in zinc oxide NWs optically pumped, a number of publications have accomplished NWs lasing emission in different materials (e.g., ZnO, GaN, CdSe, GaAs, InP, GaSb) and range of wavelength (ultraviolet, visible and near-infrared).
Coaxial GaAs-AlGaAs core-shell NW has emerged as one of the most promising NWs structure for monolithic coherent light sources on Si\textsuperscript{17,42,47,58,59,61,62,76–79}. The work published by Saxena\textsuperscript{17} and Mayer\textsuperscript{61} showed stimulated emission under fs pulsed optical excitation from 10 K to room temperature. The NWs were grown with the optimal dimensions to reduce the threshold gain and improve the quantum efficiency. Finite-difference time-domain (FDTD) simulations determined that NWs with a few tens of μm length and 200-400 nm of diameter minimise the threshold gain for lasing in TE01 (Transverse Electric mode) and TM01 (Transverse Magnetic mode) optical modes\textsuperscript{61}. Mayer \textit{et al.} \textsuperscript{59} also observed lasing from a single GaAs-AlGaAs core-shell NW under continuous wave excitation power at room temperature. This publication caused a high impact because continuous wave nanolasers are essential for the integration of optoelectronic technologies in chip-scale interconnectors\textsuperscript{80}. Stettner \textit{et al.} \textsuperscript{42} explored the substitution of bulk GaAs for radial layers of GaAs multi-quantum well (MQW) passivated with AlGaAs as gain media to control the lasing threshold and bandwidth. This work reported the expected reduction in lasing threshold and modes blueshifted (shift of the NW modes emission towards shorter wavelength) due to the quantum confinement. Recently, Mayer \textit{et al.} demonstrated the phase-locked coherent light emission (on the order of ps) with a repetition rate up to 200 GHz.

![Figure 3.1. Nanowire nanolaser diagram](image)

The following sections will contribute to a better understanding of GaAs/AlGaAs core-shell and core-multishell NWs with an analysis of the spectral emission dynamic for excitation power above, during and below the lasing threshold, and temperatures between 3.6 K to room temperature. The longitudinal modes will show a shift towards
longer wavelength (redshift) in the spectral position along the recombination process at 3.6 K, for both nanostructures. This phenomenon will be undetectable by the streak camera at temperatures near room temperature. The longitudinal modes redshift is a result of the change in the material refractive index caused by the decrease in carrier concentration during the recombination process. It disappears above 200 K and 225 K for core-shell and core-multishell NWs respectively due to the thermal activation of non-radiative recombination channels. The thermal activation generates a carrier lifetime reduction, which leads to a change in the material refractive index below the time resolution of the streak camera. Finally, the refractive index change with the increase of excitation power will be quantified.

3.1 Growth process and structure description

GaAs-AlGaAs core-shell NWs structures on a [111] orientated Si substrate were grown by Thomas Stettner at the Walter Schottky Institut & Physik Department inside the group led by Prof. Jonathan J Finley. The NWs was grown using solid source molecular beam epitaxy (MBE). The substrates were thermally oxidised and chemically treated to produce a ~2 nm thick SiO$_2$ mask layer with ~5–10 nm wide pinholes that act as nucleation sites for the self-catalysed MBE growth. Then, a GaAs seed is synthesised by self-catalysed vapour–liquid–solid technique (figure 3.2a). The axial and radial growth rate along [111] orientation was obtained by setting the MBE reactor with a temperature of 630 °C, Ga flux of 0.03 nm·s$^{-1}$ and As of 0.32 nm·s$^{-1}$. This procedure finished once the NWs height achieved a length between 11 to 16 μm. The diameter measured after the axial and radial growth mechanism was 80±5 nm. However, the NW diameter must be larger than 300 nm in order to obtain, single-mode transverse, optical confinement and low-loss waveguiding. The optimal NW diameter was accomplished by changing the conditions in the MBE reactor. The temperature was reduced to 490 °C, and the As flux was increased to 1.89 nm·s$^{-1}$, achieving an overgrowth in the radial growth along the six equivalent {110}-oriented sidewall facets (figure 3.2c).
Chapter 3 Emission properties of GaAs/AlGaAs core-shell nanowire lasers on Si

To avoid non-radiative recombination in the surface and improve the optical properties\textsuperscript{81}, the radial growth process for bulk GaAs-AlGaAs core-shell NWs ended with Al\textsubscript{0.3}Ga\textsubscript{0.7}As passivation of 5 nm thickness (figure 3.2c). On the other hand, the radial growth of MQW or core-multishell NWs was combined with passivation procedures to create multi-layers of GaAs QW passivated with Al\textsubscript{0.3}Ga\textsubscript{0.7}As. The core-multishell nanolaser nanostructure consists in 7 QW of 8 nm thick. Each QW was passivated with a 10 nm thick of Al\textsubscript{0.3}Ga\textsubscript{0.7}As to avoid QW coupling. Moreover, 20 nm wide of Al\textsubscript{0.3}Ga\textsubscript{0.7}As was grown between the NW core and QW to prevent charge tunnelling from the NW core to the QWs. The implementation of multiple quantum confined structures as an active gain media reduces the lasing threshold, increases the bandwidth, and enhances the gain and temperature stability\textsuperscript{42}. Finally, the passivation layer was capped with GaAs to prevent oxidation, mechanically removed from the growth substrate, and spatially dispersed onto a sapphire substrate (figure 3.2d,e). Note that in the following sections the NW with a bulk GaAs gain media will be named as core-shell NW and MQW NWs core-multishell NWs.

![Figure 3.2](image)

Figure 3.2. Growth process. a, Si substrate [111] on SiO\textsubscript{2} mask layer with ~5–10nm wide pinholes and GaAs Seed. b, GaAs axial and radial growth along the [111] orientation. c, radial growth along the six equivalent {110}-oriented sidewall facets, Al\textsubscript{0.3}Ga\textsubscript{0.7}As passivation and capped with GaAs. d and e, bulk and MQW NWs respectively mechanically removed from the growth substrate and spatially dispersed onto a sapphire substrate. d, the inner circle represent the GaAs core growth in the first stage. f, layers in core-multishell NWs (green and white correspond with GaAs and AlGaAs respectively.)
3.2 GaAs-AlGaAs core-shell NWs optical properties

The section below will describe the emission properties of GaAs-AlGaAs core-shell NWs. μ-PL and μ-TRPL measurements will be carried out at different optical excitation powers and temperatures. The lasing threshold will be estimated by measuring the spectral intensity in PL emission at different pump powers and 3.6 K. The experimental results will contribute to calculating the carrier density generated along the recombination process, using numerical simulations of the carrier and photon density rate equations. The emission dynamics will also be analysed with TRPL measurements.

The NW emission shows different resonance mode in PL and TRPL measurements. The spectral position of the longitudinal modes illustrates a shift towards longer wavelength (redshift) along the emission decay time due to the change of the material refractive index. The variation of carrier concentration during the recombination process induces a reduction in the material refractive index. The refractive index change will be analysed by fitting the Fabry-Perot resonance relations into the longitudinal modes. This section will finish with the study of the temporal evolution in the emission spectra with an increase of temperature. The redshift phenomenon will not be visible above 225 K, because of the thermal activation of non-radiative recombination.

μ-PL and μ-TRPL spectrum at 3.6K below the lasing threshold for a single NW of 10 μm length is shown in figure 3.3. The emission at 820nm corresponds with the emission of GaAs at 3.6 K. And, the multiple peaks observed in figure 3.3a are Fabry-Perot resonances inside the NW. The longitudinal modes are also visible in TRPL spectrum, figure 3.3c. Each constructive interferences show different carrier lifetime, figure 3.3c.

For instance, 491 ps, 620 ps and 2000 ps are the decay time for the peaks, P1, P2 and P3. Johnson et al. measured a carrier lifetime for GaAs at 5 K similar as the longitudinal mode P3 emission decay time. The constructive interferences of P1 and P2 occur below the bandgap, causing a reduction in the emission decay time of P1 and P2 in comparison with P3. On the other hand, the longitudinal modes with a longer wavelength (above P4) experience an increase in emission lifetime because the Fabry-Perot interferences take place in a transparent media. Note that the measurement of
longer decay time must be done with the single unit in the streak camera and low frequency optical pump source (less than 80 MHz).

Figure 3.3. Emission properties of a single GaAs core-shell NW of 10 μm length with an excitation power below the lasing threshold and 3.6 K of temperature. The multiple peaks observed in μ-PL and μ-TRPL spectra are Fabry-Perot resonances inside the NW. a, μ-PL spectrum. The fitted curve correspond with the optical gain spectrum of GaAs. b, NW emission picture. c, μ-TRPL spectrum. d, decay time curves for each longitudinal modes.

Non-radiative recombination centres are activated with the temperature due to the exchange of momentum between the lattice and the carriers, section 1.1.3. In order to understand the thermal activation of non-radiative recombination mechanism, μ-TRPL measurements below the lasing threshold for a set of temperature is illustrated in figure 3.4 and figure 3.5a. The measurements correspond with the emission of a single GaAs/AlGaAs core-shell NW with a length of 12 μm and diameter of 340 nm. The temperature evolution in carrier lifetime shows a reduction of one order of magnitude

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Chapter 3 Emission properties of GaAs/AlGaAs core-shell nanowire lasers on Si

from 3.6 K to 150 K, and near two orders of magnitude up to room temperature, figure 3.4 and figure 3.5a. The decrease in the emission decay time is due to the thermal activation of non-radiative recombination. The non-radiative recombination starts to dominate at temperatures above 100 K. At this temperature, the declining tendency begins to be stronger, measuring a reduction in the emission decay time by two from 100 K to 125 K.

PL spectra with temperatures reveal a redshift and a broadening in the spectral emission, figure 3.5b. The spectral emission redshift is caused by the energy bandgap shrinks with an increase of temperature$^{82}$. And, the energy bandgap shrink is the result of the the interatomic spacing increase with temperature. On the other hand, the PL emission of the core-shell NW also reports a spectral broadening. Thermal broadening of states is
owed to the temperature dependence of the probability of filling the energy levels. At 0 K, the density of filled states in the conduction and valence band is limited by the Fermi energy levels. The increase of temperature derives in a distribution of the filled states at higher energy levels. Therefore, the PL emission of the material gets broader with the temperature, as it is predicted by the Fermi-Dirac distribution.

Figure 3.5. a, spontaneous emission decay time for a single GaAs/AlGaAs NW with a length of 12 μm and diameter of 340 nm at different temperatures. Inset, linear scale. b, temperature evolution of PL spectra.

3.2.1 Pump power dependence in μ-PL measurements at 3.6 K

Lasing occurs when stimulated recombination process dominates over the spontaneous, i.e. the excitation power reaches the lasing threshold. μ-PL spectra for a set of different excitation powers were carried out for a NW with 12 μm length and 340 nm width at 3.6 K. Therefore, the light input-light output curve (L-L curve) is obtained, and the lasing threshold is estimated. The L-L experimental curve is fitted with the rate equations to calculate fundamental laser parameters such as threshold gain and β factor, equation 3.4 and equation 3.5. However, the rate equation requires the optical gain calculus for bulk GaAs.

The material gain spectra for undoped bulk GaAs at 3.6 K has been calculated using the parameters shown in the work of Saxena et al.\textsuperscript{17}, and Vurgaftman et al.\textsuperscript{84}, table 3.1. The gain model includes the contribution from the conduction band to light-hole subband and conduction to heavy-hole, equation 1.15. The lineshape used in the optical gain
estimation is a hyperbolic secant to avoid unphysical absorption below the band gap\(^1\), equation 1.16. The photoluminescence spectra of a NW with a length of 12 µm and diameter of 340 nm at 3.6 K and 17 W/cm\(^2\) (average optical pumped power) is fitted with the analytical spontaneous emission spectrum to obtain the intraband scattering lifetime (290fs), figure 3.6. This parameter must be calculated to estimate the gain spectrum, see equation 1.17. Notice that figure 3.6 shows two emission peaks resulting from the Fabry-Perot interference of the light inside the NW, figure 3.8c.

Figure 3.6. PL spectra of a NW with a length of 12 µm and a diameter of 340 nm at 3.6 K and 17 W/cm\(^2\). Blue curve, analytical spontaneous emission spectrum fitted with the experimental curve; the intraband scattering lifetime of carriers estimated from the fit is 290fs.

Figure 3.7a illustrates the optical gain spectrum at different carrier density, and figure 3.7b the peak gain variation with carrier density. The peak gain as a function of the carrier density can be fitted with the following logarithmic equation\(^2\):

\[
g = g_0 \ln \left[ \frac{N + N_S}{N_{tr} + N_S} \right]
\]

Equation 3.1
where $g$ is the optical gain, $N$ the carrier density generated during the excitation mechanism, $N_t$ the transparency carrier density, and $g_0$ and $N_s$ are parameters obtained by fitting the curve with a logarithmic function.

<table>
<thead>
<tr>
<th>Effective electron mass</th>
<th>$m_e^*$</th>
<th>0.063 $m_0$ kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective light hole mass</td>
<td>$m_{lh}$</td>
<td>0.082 $m_0$ kg</td>
</tr>
<tr>
<td>Effective heavy hole mass</td>
<td>$m_{hh}$</td>
<td>0.51 $m_0$ kg</td>
</tr>
<tr>
<td>Interband matrix element</td>
<td>$E_p = \frac{2m_0}{\hbar^2}</td>
<td>M</td>
</tr>
<tr>
<td>Energy band gap</td>
<td>$E_g$</td>
<td>$1.519 - 5.405 \cdot 10^{-4} \cdot \frac{T^2}{T + 204}$ eV</td>
</tr>
<tr>
<td>Material refractive index</td>
<td>$n_r$</td>
<td>3.6</td>
</tr>
<tr>
<td>Spin-orbit bandgap</td>
<td>$\Delta_{SO}$</td>
<td>0.341 eV</td>
</tr>
</tbody>
</table>

Table 3.1. Parameter used to calculate the optical gain of a bulk GaAs NW obtained from the work of Saxena et al.\textsuperscript{17} and Vurgaftman et al.\textsuperscript{84}.

![Figure 3.7](image1.png)

Figure 3.7. Material gain spectra for bulk GaAs at 3.6 K. a, gain spectra for different carrier density (from $1 \times 10^{16}$ cm$^{-3}$ (blue) to $1 \times 10^{15}$ cm$^{-3}$ (grey)). b, peak gain variation with carrier density and logarithmic fitting curve.
Power dependence PL measurements at 3.6 K shows the common blueshift (shift of the spectral emission towards shorter wavelength) in the longitudinal modes with an increase of excitation power for GaAs/AlGaAs core-shell NWs\textsuperscript{17,42,47,58,59,61,77–79,85}, figure 3.8a. This phenomenon is attributed to the reduction of the material refractive index with an increase of carrier density\textsuperscript{85}. The separation between longitudinal modes (Δλ), according to Fabry-Perot resonances relations, is equal to the square of central wavelength (λ\textsubscript{0}) divided by two times the group refractive index (n\textsubscript{g}) and cavity length (L) (12 μm), \[ Δλ = \frac{λ^2_0}{2n_gL}. \] The wavelength difference between M2-M1 and M3-M2 are 1.5 nm, 2.4 nm (figure 3.8c) and the group refractive indexes calculated are 19 and 11.7 respectively. TRPL measurements are required to obtain a better calculation of the modes separation since the modes split in TRPL spectra.

The L-L curve is obtained by plotting the spectral output power as a function of the optical excitation power, and the spectral output power by integrating the PL emission across a narrow spectral range centred at the lasing mode peak. The typical features of L-L curve for a laser such as S-like behaviour in the log-log scale, and the “knee” at the threshold are exhibited in figure 3.8b for a GaAs core-shell NW at 3.6 K. Below and above the lasing threshold (~300 W/cm\textsuperscript{2}), the intensity of the light emitted increase linearly with the pump power in the log-log scale, and the carriers recombine with spontaneous and stimulated process, respectively. During the threshold (grey area) the spectral intensity rises linearly with higher slope than previous regimes. This tendency is a clear signature of amplified spontaneous emission which creates a “knee” shape very usual in laser L-L curves.

Previous authors\textsuperscript{17,42,47,58,59,61,77–79,85} focused the laser beam with a microscope lens, keeping the circular shape of the optical excitation source. In this work, a cylindrical lens is used to change the typical circular shape of a laser to elliptical, figure 3.8d. In this way, the entire NW is excited and the power used to obtain lasing can be reduced. The laser shape also influences the pump power fraction absorbed by the NW core (η\textsubscript{p}),
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\[
\eta_p = \frac{\sigma_{\text{abs}} \cdot f_{\text{core}}}{A_{\text{Spot}}}
\]

Equation 3.2

where \(\sigma_{\text{abs}}\), \(f_{\text{core}}\) and \(A_{\text{Spot}}\) are the absorption coefficient factor, the fraction absorbed in core relative to the total power absorbed in the NW, and the excitation source size. The laser spot was approximated to a rectangle with an area of 54 \(\mu\text{m}^2\) (figure 3.4d). The values of \(\sigma_{\text{abs}}\) (3.6 \(\times\) 10\(^{-8}\) \(\text{cm}^2\)) and \(f_{\text{core}}\) (60\%) were obtained from the work of Saxena et al.\(^{17}\).

Figure 3.8. a, PL spectra at different excitation power with the output light intensity normalised to the highest excitation power; inset, PL spectra with the spectral intensity normalised for each set of power. b, spectral output power (circle). Solids line, rate equation modelling for different \(\beta\)-factor with a threshold gain of 1870 cm\(^{-1}\). Grey area, amplified spontaneous emission regime, it divides the L-L curve into the spontaneous (left-side) and stimulated (right-side) emission regime. Lower left and upper right inset, NW pictures during spontaneous and stimulated emissions, respectively. Lower right inset, L-L curve in a linear scale. c, PL spectra at 17 W/cm\(^2\) fitted with three Gaussian curves. d, optical excitation source shape.
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The experimental data were fitted using the carrier and photon density rate equations for NWs/nanolasers\(^\text{17}\) which describes the temporal evolution of carrier density \(N\) in the active region by an optical source and photon density \(S\) in the cavity mode, figure 3.8b:

\[
\frac{dN}{dt} = \frac{\eta_p P}{h\omega V} - \frac{N}{\tau_{nr}} - \frac{N}{\tau_{sp}} - CN^3 - v_g g S \quad \text{Equation 3.3}
\]

\[
\frac{dS}{dt} = \Gamma v_g (g - g_{th}) S + \Gamma \beta \frac{N}{\tau_{sp}} \quad \text{Equation 3.4}
\]

\(P\) is the optical excitation power and equal to \(P_p \cdot \text{sech}^2(1.76t/\Delta t)\); where \(P_p\) is the peak power and \(\Delta t\) is the pulse width, 300 fs. The peak power is the pump power average measured in the experiment \((P_{\text{ave}})\) divided by the pulse frequency \((f_{\text{pump}}, 80\text{MHz})\) and the pulse width, \(P_p = P_{\text{ave}}/(f_{\text{pump}} \cdot \Delta t)\). \(h\omega\) and \(V\) are the excitation energy, and the volume of the NW excited respectively. The group velocity of 3.6 \((v_g = c/n_g)\) and the confinement factor of 0.71 \((\Gamma)\) were obtained from the work of Saxena et al.\(^\text{17}\).

The non-radiative lifetime is estimated using the spontaneous emission decay time measured at power density below and above the lasing threshold. 1200 ps \((\tau_r)\) is the spontaneous emission lifetime with an excitation power of 17 W/cm\(^2\), section 3.2.1. Above the lasing threshold, the spontaneous lifetime component reduces to 400ps \((\tau_{sp})\), section 3.2.1. The spontaneous emission decay time during coherent light emission can be decomposed following:

\[
\frac{1}{\tau_{ms}} = \frac{1}{\tau_r} + \frac{1}{\tau_{nr}} \quad \text{Equation 3.5}
\]

The estimated valued of the non-radiative lifetime is 600 ps. 1200 ps and 600 ps are the values for the spontaneous \((\tau_{sp})\) and non-radiative \((\tau_{nr})\) lifetime introduced in equation 3.3 and equation 3.4.

The spontaneous emission or \(\beta\)-factor \((\beta)\), the threshold gain \((g_{th})\), and the non-radiative recombination coefficient or Auger coefficient \((C)\) are the parameters estimated by fitting the rate equation with the experimental data, figure 3.8b. The \(\beta\)-factor of 0.34 is
higher than that obtained at room temperature by Saxena et al.\textsuperscript{17} work and similar to that measured at a low temperature in Mayer et al.\textsuperscript{47} work. The higher is the β-factor, the more significant is the spontaneous emission that couples into longitudinal modes. For instance, a poor coupling of the spontaneous emission creates noise in the lasing emission affecting the linewidth, the modulation responses, and the number of longitudinal modes in a laser\textsuperscript{86}. The non-radiative spontaneous coefficient estimated is \(4.4 \times 10^{-21}\) cm\(^6\) s\(^{-1}\), nine orders of magnitude higher than the calculated by Saxena et al.\textsuperscript{17}. The low Auger coefficient value is resulting from the reduction of non-radiative processes at low temperature. Finally, the threshold gain estimated of 1820 cm\(^{-1}\) is akin to the obtained by Saxena et al.\textsuperscript{17} at room temperature. The confinement factor, NW length, and mirror and waveguide losses\textsuperscript{28} can only modify the threshold gain.

The insets in figure 3.8b represent the pictures of an NW emitting above and below the lasing threshold. During stimulated emission, the output light at the end of the facet shows an interference pattern. Saxena et al.\textsuperscript{17} proved that the interference pattern behaves as two coherent dipole emitters. Below lasing threshold, the NW photoluminescence can be seen along the nanostructure and at the facet end, determining the excellent quality of the NW growth.

### 3.2.2 Pump power dependence in μ-TRPL measurements at 3.6 K

Figure 3.3 represented the temporal evolution in the emission spectra of a 10 μm length NW with 8 longitudinal modes. In the following TRPL spectra, the number of longitudinal modes will be reduced as a result of the geometry of the nanostructure measured. The separation of the modes will also decrease because of the longer NW length, 12 μm. The carrier lifetime and the longitudinal mode spectral position as a function of the pump power will be extracted from the TRPL spectra and plotted for a better comprehension of the GaAs core-shell NW emission dynamic. The spontaneous recombination process will dominate at low excitation power, with carrier lifetime on the order of ns. On the other hand, the stimulated process will be activated with the increase of the optical pump power, and the carrier lifetime will decrease more than two orders of magnitude. Finally, the spectral position in the longitudinal modes will show a redshift along the emission dynamics and with optical pump power rise. This spectral
position shift is caused by the change of the material refractive index with the carrier concentration variation.

The next figures illustrate the μ-TRPL measurements at different excitation power. For instance, figure 3.9 describes the temporal evolution below the lasing threshold. At low excitation power, two longitudinal modes appear in TRPL spectra, M1 at 820.3 nm and M2 at 821.6 nm, figure 3.9a. The emission decay time measured in M2 is 1200 ps, similar to the GaAs carrier lifetime. Figure 3.9b describes the emission dynamic with an excitation power ten-times higher. At this excitation power, the carrier lifetime decreases down to 420ps, and a third longitudinal mode gets visible. The reduction in the emission decay time lies on the activation of the stimulated recombination process with the input power. In both measurements, the spectral position of the resonance modes in PL measurements differs with the spectral position of the highest intensity point measured by μ-TRPL. Indeed, the resonance modes are shifting towards longer wavelength with time, see black curve in figure 3.9b. The shift in TRPL spectra is the results of the change in the material refractive index with the variation of carrier concentration during the recombination process. This phenomenon also causes a discrepancy in the spectral position of the highest intensity point between PL and TRPL measurements. For instance, the maximum intensity points in TRPL are 821.6 nm and 819.4 nm at 17W/cm² and 170W/cm² respectively for M2 mode, while the maximum intensity points in PL are 821.8 nm and 819.9 nm. PL spectra show the integration over the time of the time evolution of the emission spectra, while TRPL spectra represent the time evolution of the emission spectra. The spectral position of the maximum intensity in PL measurements shifts towards longer wavelength in comparison with TRPL measurements because of the redshift of the longitudinal modes during the recombination process.
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Figure 3.9. TRPL measurements of a single GaAs core-shell NW with 12 μm length and 340 nm width at 3.6 K. a, excitation power of 17 W/cm². Centre, TRPL spectra, and M2 spectral position as a function of time (black line). Above, PL spectra extracted from TRPL spectra. Right, M2 longitudinal mode decay time. b, excitation power of 170 W/cm². Centre, TRPL spectra, and M2 spectral position as a function of time (black line). Above, PL spectra extracted from TRPL spectra. Right, M2 longitudinal mode decay time.

Figure 3.10. TRPL measurements of a single GaAs core-shell NW with 12 μm length and 340 nm width at 3.6 K. a, excitation power just below lasing threshold (280 W/cm²). Centre, TRPL spectra, and M2 spectral position as a function of time (black line). Above, PL spectra extracted from TRPL spectra. Right, M2 longitudinal mode decay time. b, excitation power just above lasing threshold (440 W/cm²). Centre, TRPL spectra, and M2 spectral position as a function of time (black line). Above, PL spectra extracted from TRPL spectra. Right, M2 longitudinal mode decay time.

Figure 3.10 represents the TRPL measurements with an excitation power near the lasing threshold (300W/cm²) (a) and above (b). During amplified spontaneous emission, spontaneous recombination mechanism competes directly with stimulated processes.\(^{87}\)
As a consequence, the emission decay time is larger than the light emitted during stimulated emission regime. TRPL measurements near and above the lasing threshold also reveal a decrease in carrier lifetime of two orders of magnitude in comparison with the emission decay time at 17 W/cm².

Figure 3.11. TRPL measurements of a single GaAs core-shell NW with 12 μm length and 340 nm width at 3.6 K. a, excitation power of 1100 W/cm². Centre, TRPL spectra, and M2 spectral position as a function of time (black line). Above, PL spectra extracted from TRPL spectra. Right, M2 longitudinal mode decay time. b, excitation power of 2600 W/cm². Centre, TRPL spectra, and M2 spectral position as a function of time (black line). Above, PL spectra extracted from TRPL spectra. Right, M2 longitudinal mode decay time.

Finally, figure 3.11 shows the temporal evolution far above the lasing threshold (300W/cm²). The lowest carrier lifetime measured (23 ps) was obtained with a power density of 1100 W/cm² (figure 3.11a). This value differs with the published by Mayer et al. (~3 ps) for the same nanostructure during coherent light emission. We also observed an increase of lifetime with pump power above 1100 W/cm². The “slower” carrier dynamic observed is caused by the resonance modes redshift during the recombination process. The high carrier concentration generates a blueshift in the semiconductor material gain peak, leading a reduction in the material refractive index and blueshift in the lasing mode emission. Once the recombination process starts, the carrier concentration decreases and the refractive index increases, producing a redshift along the lasing modes with time. This effect is also visible if we compared the highest intensity emission in TRPL spectra for different excitation power. For instance, the mode M2 has the maximum intensity at 820.6 nm (figure 3.9a) for a power density
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of 1100 W/cm², and 812.9 nm is the spectral position for the maximum intensity at 2600 W/cm², figure 3.11a.

The following figures illustrate the resonance mode M2 decay time curves extracted from TRPL measurements for a set of optical pump power, figure 3.12. The curve’s slope increases (i.e. decay time decreases) with an increase of excitation power as a consequence of the transition between spontaneous to stimulated emission. The experimental curves below the lasing threshold were fitted with a single exponential function. And, the time constant estimated correspond with the spontaneous emission decay time, figure 3.12b. On the other hand, the experimental curves during amplified spontaneous and stimulated emission regime were approximated with a double exponential function, figure 3.12b. The highest value of the time constant determines the spontaneous emission lifetime while the lowest refers to the stimulated emission decay time.

Figure 3.12. a, normalised carrier lifetime curves for different excitation power extracted from TRPL measurements. b, emission decay time and fitted curve (black curve) for excitation powers, below lasing threshold (17 W/cm²), close to lasing threshold (350 W/cm²), and above lasing threshold (1100 W/cm²).

Figure 3.13a shows the carrier lifetime value as a function of the optical pump power and summarises the study done in this section. The typical feature in the L-L curve can also be distinguished in this study. At low excitation power, the carriers recombine by the spontaneous mechanism. The increase of carrier concentration activates stimulated processes and the emission lifetime decrease, obtaining the usual “knee” characteristic
in L-L curves. The minimum emission decay time measured is gained with an excitation power of 1100 W/cm$^2$, where stimulated process dominates over spontaneous mechanism. Finally, the strong redshift in the lasing modes originates an emission decay time increase for power density above 1100 W/cm$^2$.

![Figure 3.13](image)

**Figure 3.13.** M2 decay time as a function of the excitation power, the value was obtained by fitting the experimental data with an exponential function.

### 3.2.3 Study of the longitudinal modes redshift at 3.6 K

In previous section, TRPL spectra for GaAs/AlGaAs NWs have been studied at different excitation powers. The spectra showed a redshift of the longitudinal modes emission during the recombination process. High optical pump power generates large carrier density, as a consequence the refractive index of the material decrease$^{87-90}$. During the emission of stimulated or spontaneous light, the carrier concentration decrease and the refractive index increase. The reduction is caused by the band-filling, band-gap shrinkage and plasma effects$^{87,89-92}$. The change in the material refractive index affects the resonance mode spectral position, resulting in a shift toward longer wavelength during the recombination process. In this section, the spectral position of the resonance modes with time will be analysed, estimate the refractive index variation.
and, calculate the enhancement linewidth factor or $\alpha$ factor for GaAs core-shell NWs nanolasers.

![Figure 3.14. a, longitudinal mode M2 time evolution for a set of optical pump power. b, temporal evolution of M2 spectral position for an excitation power below, during, and above the lasing threshold fitted with an exponential function.](image)

The temporal evolution in the longitudinal mode spectral position shows similar behaviour as the decay curves reported in the section above, figure 3.14. The spectral mode position was obtained by searching the maximum intensity in M2 at each time slot. Below the lasing threshold, the spectral position of M2 decreases exponentially with a time constant of 1.2 ns. The increase of the excitation power reduces the emission decay time as the carrier lifetime do. Likewise, the spectral mode position shifts exponentially with two time constants during population inversion. Stimulated recombination process governs the time constant with the lowest value and spontaneous mechanism, the highest, figure 3.11b. The time constants values are in the same order of magnitude as the estimated for the carrier lifetime, stressing the relationship between carrier density and redshift phenomena.

### 3.2.3.1 Estimation of the refractive index change

Equation 3.6 determines the spectral mode position ($\lambda_m$) as a function of the refractive index ($n_g$, group refractive index), the length of the cavity (L, NW length) and the mode number (m)$^{28}$. On the other hand, equation 3.7 relates the spectral separation between the mode m and m+1 ($\Delta \lambda$) with the wavelength value for those modes ($\lambda_m$ and $\lambda_{m+1}$).
the refractive index and the length of the cavity. The group refractive index is estimated at each time slot by fitting the equation 3.6 with the spectral position of the modes appeared in TRPL spectra, figure 3.15. During the fitting process, the mode order and the group refractive index are the parameters to modify in order to fit the theoretical spectral mode position with the experimental measured in TRPL spectra. The NW length is 12 μm.

\[
\lambda_m = n_g \frac{2L}{m} \quad \text{Equation 3.6}
\]

\[
\Delta\lambda = \frac{\lambda_m \cdot \lambda_{m+1}}{2L n_{eff}} \quad \text{Equation 3.7}
\]

According to Mayer et al., longitudinal modes of two transverse modes can appear in the emission of GaAs core-shell NWs. In this work, the fitting results also predict the resonance of two transverse modes with their own longitudinal modes. The transverse mode \(a\) dominates the longitudinal mode at 822.1 nm during spontaneous emission, and the refractive index estimated is 9.661, black diamond points in figure 3.15a. On the other hand, the transverse mode \(b\) has a strong influence in the longitudinal mode at 821.2 nm and the refractive index measured is inferior to \(a\), 9.649, white hexagonal points in figure 3.15a. Those values of refractive index agrees with the FDTD simulations published in the work of Saxena et al. where they calculated a group refractive index of 9.5 for the transverse mode TM01 near the cut-off. Their work also determined that the transverse modes with lower threshold gain and consequently with higher probability to appear were the modes TE01 and TM01.

The material refractive index decreases with an increase of the carrier concentrations, affecting the separation between modes. As a consequence, the longitudinal mode \(m\) of the transverse mode \(a\) approaches the longitudinal mode \(m+1\) of the transverse mode \(b\), figure 3.15. For instance, a protuberance or “belly” is observed in the longitudinal mode \(m\) of the transverse mode \(a\) at 819 nm with powers density of 170 W/cm² and 240 W/cm², caused by the longitudinal mode \(m+1\) of the transverse mode \(b\). The extreme situation occurs along stimulated emission where the transverse modes merge, figure 3.15d. Above the lasing threshold, it is not clear if there is a transverse mode that dominates over the other one, or both transverse modes are lasing.
The stimulated carrier lifetime is in the order of tens of ps. As a consequence, the carrier concentration sharply decreases, and hence the group refractive index strongly increases in the same time slot. For instance, the NW excited with an excitation power of 1400 W/cm² shows an initial group refractive index of 6.851 and 6.817 for transverse mode a and b respectively, figure 3.15c. The recombination process starts, and 600 ps later the group refractive index is 9.322 and 9.296 for transverse mode a and b, respectively. The substantial reduction in the group refractive index results in modes hopping at this time interval. Mode hopping is measured at excitation powers in the regimes of amplified
spontaneous and stimulated emission due to the significant variation in the group refractive index during population inversion, figure 3.15b & c and figure 3.16a.

![Figure 3.16](image)

Figure 3.16. a, net reduction of the group refractive index change as a function of the excitation power. $\Delta n$ was obtained by fitting the Fabry-Perot resonance equations into the modes observed in TRPL spectra. Grey area, amplified spontaneous emission region, it divides the curve into the spontaneous (left-side) and stimulated (right-side) emission regime. b, refractive index change estimated for the transversal modes at 822.1 nm and 821.2 nm.

Additionally, the net group refractive index change as a function of the excitation power curve reveals the typical features of an L-L curve for a laser, figure 3.16a. The S-like shape and the three emission regime are distinguishable in figure 3.16a. The lasing threshold estimated also agrees with the results obtained in the spectral emission intensity as a function of the excitation power study.

According to the work of Manning et al\textsuperscript{93}, the refractive index change in a longitudinal mode follow:

$$\delta n = \frac{n_{\text{eff}}}{\Gamma \lambda} \delta \lambda$$  \hspace{1cm} Equation 3.8

where $n_{\text{eff}}$ is the effective refractive index (2.5\textsuperscript{17}), $\Gamma$ is the confinement factor (0.71), $\lambda$ the final wavelength of the mode (822.1 nm for the transverse mode $a$ and 821.2 nm for the $b$) and $\delta \lambda$ is the difference between the final and initial wavelength of the longitudinal mode. The values obtained are plotted in figure 3.16b.

Mainly, three effects cause a shift in the refractive index of a semiconductor material with the injection of carriers: band-filling, band-gap shrinkage and plasma effects \textsuperscript{87,89–89}. 

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The band-filling effect takes into consideration the blue-shift of the gain media due to the injection of carriers. The material absorption decreases for photons slightly above the energy bandgap, caused by the occupation of carriers in low energy levels. The material absorption variation results in a blue-shift of the material gain and a reduction of the refractive index material. The bandgap shrinkage effect stems from the energy reduction between the conduction and valence band with the Coulomb force appearing between carriers. This effect creates an increase in the refractive index for wavelengths above the bandgap and a reduction for wavelengths below the bandgap. And, the plasma effect generates a decrease of the refractive index, due to the absorption of a photon by a free carrier, and the promotion of the free-carrier to high energy level within a band.

3.2.3.2 Estimation of the linewidth enhancement factor

Schawlow and Townes were the first to calculate the linewidth of a laser, even before the emission of coherent light was demonstrated. The finite value of the laser linewidth lies on the noise of the spontaneous emission in the resonance cavity. Once the semiconductor laser was invented, the linewidth values obtained using the work published by Schawlow and Townes were inferior to the experimentally measured. Henry enhanced the linewidth calculation with the inclusion of the phase coupling to intensity fluctuations, which broadens the laser spectral lines by a factor of \((1 + \alpha^2)\).

The linewidth enhancement factor \(\alpha\) (also called Henry factor or alpha factor) is the ratio between the variation of the real and complex part of the refractive index with carrier density. And, it can be determined as the ratio between the total variation of the refractive index \(\delta n\) and the change in the laser gain media \(\delta g\) with the injection of carrier 95:

\[
\alpha = \frac{dn_r/dN}{dn_i/dN} = -\frac{4\pi}{\lambda} \frac{\delta n}{\delta g} \quad \text{with } \delta n_i = \text{equal to } -\frac{\lambda}{4\pi} \delta g \quad \text{Equation 3.9}
\]

The change in the laser gain media was estimated using the temporal evolution of carrier density given by the laser rate equation simulation, figure 3.17a. The value
obtained for the enhancement factor are, 2 for the transverse mode \( a \) and longitudinal mode at 822.1 nm, and 1.3 for transverse mode \( b \) and longitudinal mode at 821.2 nm, figure 3.17b. The typical values are between 4 to 7 for bulk lasers\(^{96}\). Therefore, NWs nanolasers offer lower phase fluctuation and line broadening with the injection of carriers than bulk lasers.

**Figure 3.17.** a, calculation of the imaginary refractive index change given by the variation of the gain during the recombination process. b, estimation of the \( \alpha \) factor for the transverse mode \( a \) and \( b \).

### 3.2.4 Temperature dependence above and below the lasing threshold

The thermal activation of non-radiative recombination processes affects the carrier recombination mechanism, and hence the longitudinal mode redshift in TRPL spectra. In the following section, \( \mu \)-TRPL measurements above the lasing threshold for a set of temperature will help us to understand the influence of non-radiative recombination mechanism in the temporal evolution of the resonance modes.
As it was mentioned above, the thermal activation of non-radiative recombination reduces the temporal evolution of the NW emission. For instance, the spontaneous emission decay time decreases two orders of magnitude from 3.6 K to room temperature, figure 3.5a. As a consequence above certain temperature, the redshift is not visible in the streak camera images, figure 3.18. In particular, TRPL measurements show a distinguishable lasing modes redshift at 85 K and 140 K. However, the recombination process gets “faster” for temperature above 200 K. The “fast” carrier dynamic generates a refractive index change in an inferior temporal span. Therefore, the lifetime of the lasing mode redshift also decreases with temperature. Above 200K, the non-radiative recombination plays an important role, reducing the carrier lifetime more than an order of magnitude in comparison with 3.6K, figure 3.5a. As a consequence, the redshift is
undetectable by the streak camera system. The reduction in the temporal evolution of the refractive index change creates a spectral linewidth increase due to the redshift lifetime is beyond the streak camera resolution.

3.3 GaAs-AlGaAs core-multishell NWs optical properties

Having described the optical properties of GaAs/AlGaAs core-shell nanolasers, this section will analyse the emission of GaAs/AlGaAs core-multishell NW, figure 3.2e. The seven concentric QWs generate an increase in the material gain and bandwidth, better control of the lasing threshold, and wavelength tunability. The spectral intensity study as a function of the excitation power will show a reduction in the lasing threshold for Multi-QW (MQW) NWs in comparison with bulk GaAs NWs. The temporal evolution in the NW emission will also reveal a redshift in the longitudinal modes along the recombination process, caused by the material refractive index reduction with carrier concentration. The refractive index change will be quantified using the Fabry-Perot relations, equation 3.6. The refractive index difference will increase with the excitation power, likewise the spectral intensity will rise. The lasing threshold estimated will agree for both studies.

On the other hand, the carrier lifetime will decrease with the optical pump power due to the activation of stimulated recombination process. For instance, the emission decay time will differ in two orders of magnitude for excitation power below and above the lasing threshold. The emission decay time studies as a function of excitation power will also report a lasing threshold identical to the estimated by the spectral intensity and refractive index change analysis. Finally, the increase in temperature will activate non-radiative recombination processes, affecting the nanolaser carrier dynamic. As a consequence, the redshift will occur in a slot time inferior the experiment resolution, and hence it will not be visible in TRPL spectra. The inclusion of quantum confinement structures in the NWs generates a blueshift in the spectral emission in comparison with bulk GaAs NW emission, figure 3.19. PL and TRPL measurements also show two recombination channels. The emission at 814 nm behaves as carriers recombining in bulk GaAs. Because of the emission decay time (1.2ns) and spectral wavelength (820nm) are akin to the measured in bulk GaAs NWs. This recombination channel is
located at the core of the NW. On the other hand, the photoluminescence light measured in the range between 780 nm to 805 nm is generated in the concentric GaAs QWs. The QWs emission decay time is three times shorter than the bulk material due to the carrier confinement in the QW structures\textsuperscript{98,99}, figure 3.19c.

Figure 3.19. Experimental data for a single of GaAs/AlGaAs core-multishell NW with 12\textmu m length and 360nm diameter at low excitation power and 3.6 K. Centre, PL spectra. The maximum at 795 nm corresponds with the MQW emission, while at 814 nm with the GaAs emission (NW core). Up, TRPL spectrum. Left, decay time curves obtained from TRPL spectrum. Blue line, MQW emission lifetime. Red line, GaAs decay time curve.
Figure 3.20. μ-TRPL measurements with an excitation power below the lasing threshold for a single of GaAs/AlGaAs core-multishell NW with 9μm length and 360nm diamete. a, at 8.6 K. b, at 100 K. c, 293 K.

In order to understand the thermal activation of non-radiative recombination, μ-TRPL and μ-PL measurements for a set of temperature is illustrated in figure 3.20 and figure 3.21. The emission temporal evolution spectra of MQW GaAs NWs shows a blueshift and additional recombination channels from 3.6K to 25K, figure 3.19, figure 3.20 and figure 3.21. In QWs structures, localised excitons dominate the recombination process at low temperatures. Above 3.6 K, the exciton ionisation and the thermal population of higher exciton states compete with localised excitons during the recombination mechanism forming additional recombination channels, a blueshift in the peak emission from 3.6 K to 25 K, and an increase of PL decay time. Above 25 K, the typical bandgap shrink in semiconductor materials shifts towards longer wavelength the core-multishell NW emission spectra. On the other hand, PL spectra illustrate a linewidth...
increment with temperature. The broader emission might be caused by; the occupancy of free carriers at higher energy level due to the Fermi-Dirac distribution\textsuperscript{103}; and the real-space energy-band modulation produced by the fluctuation in the QW thickness\textsuperscript{103}.

The thermal population of higher exciton subbands and exciton ionisation activation increases the radiative emission decay time of QWs materials\textsuperscript{100–102}. The emission decay time rise is shown in figure 3.21a. The carrier lifetime rises from 400 ps to 1 ns in the range of temperatures from 3.6K to 100 K. However, the PL decay time rise stops at temperatures above 100 K where non-radiative recombination such as carrier thermal escape\textsuperscript{104} are activated, figure 3.21a. In particular, the carrier lifetime decreases one order of magnitude from 100 K to 293 K.

3.3.1 Pump power dependence in µ-PL measurements at 3.6K

Bulk GaAs NWs reported a blueshift of the spectral emission with an increase of excitation power. Likewise, spectral peak position studies for core-multishell NWs as a function of the optical pump power shows a blueshift in the longitudinal modes peak position, figure 3.22a. The increase of carrier concentration with the excitation power causes a reduction of the material refractive index, and hence a blueshift in the spectral emission of the NW, see section 3.2.1.
Figure 3.22. PL spectra of GaAs/AlGaAs core-multishell NW with 9 μm length and 360 nm diameter at different excitation power with output light spectral intensity normalised to the highest excitation power. Inset, PL spectra with normalized intensity for a set of optical pump power. b, light-input light-output experimental results. The data were fitted with a linear function to stress the different regimes, spontaneous emission (red line), amplified spontaneous emission (green line) and stimulated emission (blue line). Grey area, amplified spontaneous emission regime; it divides the curve between the spontaneous emission (left-side) and the stimulated emission (right-side) regime. Lower right inset, L-L experimental data on a linear scale. c and d, NW picture during spontaneous and stimulated emission respectively.

The spectral output power studies as a function of the excitation power estimate a lasing threshold of 150 W/cm². The inclusion of quantum confinement structure derives in a reduction by half of the lasing threshold in comparison with bulk GaAs NWs. Three regimes are observed in the L-L curve for MQW GaAs NWs, figure 3.22b. The red line indicates the tendency of the carriers recombining spontaneously. At this particular regime, the output intensity increases linearly in the log-log scale. The slope curve changes when the input power exceeds the lasing threshold, and the amplified spontaneous emission regime starts, green line. The rising tendency of the output light saturates with the domination of the stimulated recombination process over the spontaneous (stimulated emission regime), blue line. The slope variation of the spectral intensity generates the typical features of an L-L laser curve such as the S-like in log-log scale and the “knee” shape.
Figure 3.22c and d shows the NW pictures emitting above and below lasing threshold, respectively. The typical interferences patterns for NWs-nanolaser appear in the picture when the input power exceeds the lasing threshold. Below the lasing threshold, the photoluminescence reveals a homogeneous emission of the entire NW, and hence the excellent quality of the NW growth.

3.3.2 Pump power dependence in μ-TRPL measurements at 3.6K

The temporal evolution in bulk GaAs NW optical emission suggested a redshift in TRPL spectra as a consequence of the change in the material refractive index during the recombination process, see section 3.2.2. Longitudinal modes in GaAs/AlGaAs NW core-multishell will also be affected by this phenomenon. Figure 3.23a and b represent the TRPL spectra with an excitation power below and near the lasing threshold respectively, 3.5W/cm² (a) and 140 W/cm² (b). Two longitudinal modes are resonating in the NW cavity. The emission decay time for M1 is 370ps at 3.5W/cm² and 520ps at 140W/cm². The rise in carrier lifetime is resulting from the major carrier concentration in the quantum confinement structures, generated by the excitation process.⁹⁸,¹⁰⁵

Figure 3.23. TRPL measurements of a single GaAs/AlGaAs core-multishell NW with 9 μm length and 360 nm width at 3.6 K. a, excitation power of 3.5 W/cm². Centre, TRPL spectra and M1 spectral position as a function of time (black line). Right, temporal evolution of the longitudinal mode M1. Above, PL spectra. b, excitation power of 140 W/cm². Centre, TRPL spectra and M1 spectral position as a function of time (black line). Right, temporal evolution of the longitudinal mode M1. Above, PL spectra.
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Above and near above the lasing threshold, the carrier lifetimes decrease ten and five times respectively in comparison with below, figure 3.24. The activation of stimulated emission results in the reduction of emission decay time. In this regime, the longitudinal modes lifetime curves are fitted with a double exponential function, where the smallest decay time corresponds with the stimulated emission and the highest to the spontaneous, figure 3.24. In amplified spontaneous emission regime, the stimulated recombination processes are competing with the spontaneous.

![Figure 3.24](image_url)

Figure 3.24. TRPL measurements of a single GaAs/AlGaAs core-multishell NW with 9 μm length and 360 nm width at 3.6 K. a, excitation power of 280 W/cm². Centre, TRPL spectra and M1 spectral position as a function of time (black line). Right, temporal evolution of the longitudinal mode M1. Above, PL spectra. b, excitation power of 420 W/cm². Centre, TRPL spectra and M1 spectral position as a function of time (black line). Right, temporal evolution of the longitudinal mode M1. Above, PL spectra.

Above 490W/cm², the high concentration of carrier generates a significant reduction in the material refractive index. The redshift in the longitudinal modes gets higher than 3 nm, figure 3.25. Moreover, the time evolution in the longitudinal mode M1 emission illustrates two maxima, figure 3.25. The addition of quantum confinement structures in the NWs reduces the emission decay time in comparison with bulk materials, see section above. As a consequence, the stimulated recombination time decreases down to the temporal resolution of the experimental set-up (20ps), figure 3.25.
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Figure 3.25. TRPL measurements of a single GaAs/AlGaAs core-multishell NW with 9 μm length and 360 nm width at 3.6 K. a, excitation power of 630 W/cm². Centre, TRPL spectra and M1 spectral position as a function of time (black line). Right, temporal evolution of the longitudinal mode M1. Above, PL spectra. b, excitation power of 2600 W/cm². Centre, TRPL spectra and M1 spectral position as a function of time (black line). Right, temporal evolution of the longitudinal mode M1. Above, PL spectra.

The material refractive index also changes below the temporal resolution. And, the redshift in the longitudinal modes is created in a span inferior 20 ps. For instance, the maximum intensity in the longitudinal mode M1 is at 785.5 nm at 0 ps and 785.7 nm at 20 ps for an excitation power of 2600 W/cm², figure 3.26. At 40 ps, there appears two maxima at 785.7 nm and at 789.2 nm. And, the longitudinal mode shifts to 789.4 nm at 60 ps. Before the recombination process starts, the high carrier density creates an elevate reduction of the refractive index. The stimulated emission begins and a significant number of carriers are recombined in 20 ps. The reduction of carrier concentration in the material originates an increase of the material refractive index. The fast difference in the material refractive index creates two maximum in PL spectra and in the emission decay curves for M1. The first maximum (M1-1) is dominated by stimulated recombination process with a carrier lifetime below the temporal resolution of the experimental set-up. The second (M1-2), spontaneous and stimulated mechanisms are competing with decay times of 70ps and 250ps for 630W/cm² and 2600W/cm², respectively. On the other hand, a third lasing mode gets visible in TRPL spectra at 2600W/cm² resulting from the high carrier density generated at this power, figure 3.25.
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Figure 3.26. Spectral emission of a single GaAs/AlGaAs core-multishell NW with 9 μm length and 360 nm width at 3.6 K, 2600 W/cm², and different emission time. The PL spectrum was integrated from the TRPL spectrum. The rectangle in the right spectrum correspond with the range of wavelength illustrated in the left spectrum.

The emission decay time curves for M1 describe a carrier lifetime rise from 3.5 W/cm² to 140 W/cm², resulting from the increment of carriers with pump power in the quantum confinement structures \(^98,105\), figure 3.27 & figure 3.28. Above the lasing threshold (150 W/cm²), the emission dynamics get faster. And, the decay curves behave as a double exponential function, where the spontaneous emission possess the longest decay time and vice versa for stimulated emission, figure 3.27b. The amplified spontaneous emission regime starts at 150 W/cm², and the rate of the carriers that recombine by stimulated process increases with power. Far above the lasing threshold (above 500 W/cm²), the stimulated emission dominates over spontaneous, and the carrier lifetime measured decrease below the temporal resolution of the experimental set-up. Finally, the emission decay time as a function of the power density illustrates a “break” in the transition between amplified spontaneous and stimulated emission regime. The “fast” carrier dynamic during coherent emission creates a refractive index change below the temporal resolution of the experimental set-up. Consequently, two spectral intensity maxima appear in the emission decay curves, see figure 3.25 and figure 3.27a. The first
maximum with an emission decay time below the temporal resolution of the experimental set-up is the stimulated emission lifetime and is the one shown in figure 3.28.

Figure 3.27. a, M1 emission decay time curves at different excitation power. b, experimental data fitted with exponential curves (black curve) for pump powers, below lasing threshold (3.5 W/cm²), close to lasing threshold (280 W/cm²), and above lasing threshold (490 W/cm²).
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3.3.3 Study of the longitudinal modes redshift at 3.6 K

The increment of carrier density with excitation power drives a reduction of the material refractive index, which produces a blueshift in the nanolaser emission. In the experiment carried out, the laser pulse excites the nanolasers generating electron-hole pairs. The carrier concentration decreases with time due to recombination mechanism. The carrier reduction creates a refractive index rise, consequently the longitudinal modes resonating in the NW redshift along the recombination process.

The spectral mode position decays exponentially with time likewise the carrier lifetime, figure 3.29a. As a consequence, the longitudinal modes shift with a single decay time constant in the order of hundreds or few thousands of ps for excitation power below the lasing threshold. And, two decay time constants appear with optical pump powers above the lasing threshold. The spectral mode position lifetime in the order of tens of ps is related with the stimulated carrier recombination process, while the one in the order of hundreds or few thousands of ps with the spontaneous. Thus, the spectral mode

Figure 3.28. M1 carrier lifetime as a function of the excitation power in logarithmic scale. The value was obtained by fitting the experimental data with exponential functions. Regime 1, 2, and 3 correspond with the spontaneous emission, amplified spontaneous emission, and stimulated emission decay time. Inset, linear scale.
position studies obtain values of time constants in the same order of magnitude as the carrier recombination studies.

Figure 3.29. a, M1 spectral position as a function of time for a set of optical pump powers. b, spectral mode position dynamic for excitation power below and above lasing threshold fitted with single and double exponential functions, respectively.

GaAs core-shell NWs showed two transverse modes travelling inside the NW. Each transverse mode generates longitudinal modes that behaved according to the Fabry-Perot interference equation, equation 3.6. On the other hand, TRPL spectra analysis reports a single transverse mode resonating inside the core-multishell NW cavity, figure 3.30. 0.03 is the maximum change in the group refractive index for excitation powers below the lasing threshold. And, it corresponds to a change in the group refractive index from 9.119 to 9.145, figure 3.30b. Above and near the lasing threshold, the longitudinal modes order begin to hop due to the refractive index change. In particular, the group refractive index changes from 6.416 to 7.302 at 140 W/cm$^2$, and from 4.705 to 9.145 at 2600 W/cm$^2$, figure 3.30c and d respectively.
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Figure 3.30. a, a, b, c and d, TRPL spectra at 3.6 K for a single GaAs core-multishell NW with 9 μm length, 360 nm width and excitation power of 17 W/cm², 100 W/cm², 140 W/cm² and 2600 W/cm², repectively. The points inset in the TRPL spectra reveal the longitudinal modes for the transversal mode propagating in the NW cavity. The white rectangle in figure c and d represent the region where the modes are hopping.

Figure 3.31 illustrates the net difference in the group refractive index. It behaves as the output power spectra as a function of the excitation power curve. Three regimes are distinguishable. At low excitation power, the net difference in the refractive index increases linearly in the log-log scale, spontaneous emission regime. The grey area indicates the amplified spontaneous regime, and the curve slope sharply rises. Then, the net difference in the refractive index saturates, and the stimulated regime starts.
Figure 3.31. Net reduction of the group refractive index change as a function of the excitation power. $\Delta n$ was obtained by fitting the Fabry-Pero resonance equations into the modes observed in TRPL spectra. Grey area, amplified spontaneous emission region, it divides the curve into the spontaneous (left-side) and stimulated (right-side) emission regime. The experimental data was joined with a line to emphasize the tendency of the group refractive index difference.

The comparison between core-shell and core-multishell GaAs/AlGaAs NWs in the refractive index difference is challenging due to the different wavelength emission and NW dimension. The net difference in refractive index for core-multishell GaAs/AlGaAs NWs is two times higher than core-shell NWs for excitation power above lasing threshold. Core-multishell NWs also present a sharper transition between spontaneous emission and stimulated emission. The carrier confinement may lead to a high concentration of carriers, and hence in a significant refractive index change and better spontaneous light coupling.

### 3.3.4 Temperature dependence above and below the lasing threshold

The longitudinal modes redshift in TRPL spectra has shown a strong dependency on the carrier concentration, and hence on the recombination process. For instance, the temporal evolution of longitudinal mode M1 spectral position curves experiences a
similar tendency as the emission decay curves. On the other hand, non-radiative recombination process can be activated by an increase of the excitation power\textsuperscript{106} or temperature\textsuperscript{107}, affecting the emission dynamic during the recombination process. Therefore, the thermal activation of non-radiative recombination may alter the spectral position dynamic of the longitudinal modes.

Figure 3.32. μ-TRPL measurements of a single core-multishell NW with 9 μm length and 360 nm width, with an excitation power above the lasing threshold. a, at 50K. b, at 200K. c, at 225K. d, at 293K.

The spontaneous emission decay time reduces with temperature as a consequence of the thermal activation of non-radiative processes, section above. For instance, the carrier lifetime decrease by half from 150 K to 200 K. The activation of non-radiative mechanism also affects the longitudinal mode redshift as figure 3.32 suggests. At 50K, the TRPL spectrum reports clear longitudinal lasing mode shifting towards longer wavelength, while the “tail” of the modes gives rise to a residual emission at 200K. The
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redshift completely disappears from the TRPL spectra for temperatures above 225 K. The fast recombination process leads in a time reduction of the refractive index change, and hence a decrease of the modes redshift lifetime. Consequently, the change in the refractive index is carried out below the temporal resolution for temperature above 225 K.

3.4 Summary

Summing up the results, it can be concluded that the carrier dynamics and optical properties emission for GaAs/AlGaAs NWs core-shell and core-multishell have been studied with PL and TRPL measurements. The spectral intensity as a function of the power density in the log-log scale shows the typical S-like behaviour in coherent light emitters for both NWs structures. Three regimes are clearly distinguishable in the L-L curves. At low excitation power, spontaneous process dominates the carrier recombination mechanism and the spectral intensity increase linearly in the log-log scale (spontaneous emission regime). The slope sharply increases in the L-L curves with input power near the lasing threshold. At this regime, the stimulated recombination process competes with spontaneous (amplified spontaneous regime). Finally, the light emitted in NWs saturates with power above the lasing threshold and stimulated light lead the emission (stimulated regime). This S-like behaviour is shown in both nanostructures. However, the core-multishell NW presents lower lasing power threshold than the core-shell because of the inclusion of quantum confinement structure.

The rate equations are modelled using the experimental L-L curve for GaAs/AlGaAs core-shell NWs. As a result, the approximate value of the spontaneous emission factor and the lasing gain threshold has been obtained. The β-factor quantifies the noise coming from the spontaneous emission in a laser. This work estimates a beta factor for GaAs/AlGaAs core-shell NWs at 3.6 K of 0.34. The higher is the β-factor, the more significant is the spontaneous emission that couples into longitudinal modes. On the other hand, the gain threshold obtained is similar to that measured in previous publications for the same nanostructures17,59,79.
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TRPL spectra at 3.6 K revealed faster recombination process during spontaneous emission for core-multishell NW in comparison with core-shell due to the higher confinement of carriers. In addition, both nanostructures showed a shift in the longitudinal modes towards longer wavelength during the recombination process, below, during, and above the lasing threshold for core-shell and core-multishell GaAs/AlGaAs NWs. This phenomenon is the results of the material refractive index change caused by the variation of carrier density during the recombination process. In particular, the refractive index decreases with an increase in the carrier concentration. Along the recombination process, the carrier concentration reduces, and hence the refractive index rise. As a result, the spectral position of the longitudinal modes redshifts along the emission decay time.

The refractive index change has been estimated by fitting the Fabry-Perot relations with the longitudinal mode spectral position on TRPL measurements. Fabry-Perot relations determine the spectral position of the longitudinal modes, the spectral separation between them and the refractive index of the material. The analysis showed two transverse modes resonating in core-shell NWs and a single one for the core-multishell NWs. It is complicated to compare the net group refractive index difference for both nanostructures because of the spectral wavelength and NWs dimensions are different. Core-multishell GaAs/AlGaAs NWs presented a higher difference in the group refractive index and sharper transition between spontaneous to stimulated emission. The carrier confinement can result in an increment of the refractive index change. However, there is not enough evidence to confirm this.

The lasing threshold has also been analysed with carrier lifetime and refractive index change as a function of the power density for core-shell and core-multishell NWs. Both studies suggested clear evidence of the different regimes in the recombination mechanism (spontaneous, amplified spontaneous and stimulated) in both NWs. However, the tendency is different. The carrier lifetime decreases with the excitation of power, while the refractive index change increases.

Finally, TRPL temperature dependence measurements described a significant reduction of carrier lifetime for temperature above 100 K and 150 K for core-shell and core-
multishell NWs, respectively. The decrease in the emission dynamics is a result of the thermal activation of non-radiative mechanism. The thermal activation of non-radiative recombination also affects the longitudinal mode redshift. The NWs refractive index changes in a range of time in the order of ps for temperature above 200 K. And hence, the longitudinal mode shifts towards longer wavelength in the same span time. As a consequence, the shift in the resonance modes is not visible in TRPL measurements for temperature above 200 K and 225 K for core-shell and core-multishell NWs, respectively. TRPL temperature dependence also illustrated a redshift in the spontaneous emission due to the shrinking of bandgap with temperatures. And, the emission linewidth increase predicted by the Fermi-Dirac distribution.
Chapter 4.

Emission properties of InGaAs NPs in SOI

Nowadays, over half of the world is online. On average, each user spends six hours a day on internet. Most of the time, mobile phones are the chosen device to keep consumers online. The worldwide data average used by smartphones is 2.9 GB per month\textsuperscript{108}. Cisco predicts an increase of 25% of the global traffic crossing the Internet and IP WAN networks from 2016 to 2021. Then, the global traffic per year will be 20.6 Zettabytes ($10^{21}$ bytes)\textsuperscript{109}. Active users will not generate most of the data traffic, rather what is called the internet of things. Cisco summary also predicts that over 90% of data traffic remains local to the data centre, generating a significant electric power demand. For instance, U.S data centres use more than 90 tera-watt per hour of electricity a year\textsuperscript{110}. In order to reduce power consumption in the data centre, a new era of interconnects will be necessary to develop.

Optical networks have extensively been used since the first transatlantic optical fibre telephone cable went into operation in 1988. This technology has provided high bandwidth, low latency and low power consumption. It has been adopted to send and receive information in the kilometres and metres range. Therefore, the interconnection development must come from optical technologies for communications in the millimetres or micrometres range (chip to chip or on-chip interconnects)\textsuperscript{15,17,79,111,112}.

Distributed feedback (DFB) lasers are the coherent light source developed for long-range communications. On the other hand, mid-range datacomms uses vertical-cavity surface-emitting lasers (VCSELs). VCSELs operates with smaller active gain media than DFB lasers. However, the active gain media size for a coherent light source in short-range of communication must be in the order of the micrometres or nanometers. Light emitters at this range may also be compatible with the actual silicon integrated circuit technology.

Photonic crystal\textsuperscript{113–116}, microdisks\textsuperscript{117–122}, metal-clad cavities\textsuperscript{116,123,124}, plasmonic\textsuperscript{18,125,126}, nanowires\textsuperscript{17,29–35} and nanopillars\textsuperscript{15} lasers offer coherent light sources with a small active
gain volume and compatible with silicon platforms. In particular, nanopillars (NPs)/nanowires (NWs) on Si are gaining significant attention as a monolithic coherent light source. The principal difference between NPs and NWs lies in the growth process. NPs are site-controlled using a patterned mask, while NWs use a self-catalysed. NPs/NWs also allow the growth of III-V semiconductor materials on Si because of their small footprint reduces the mismatch between both materials.

III-V semiconductor materials bring direct band gap, high refractive index material and bandgap tunability by varying the alloy composition. Then, the high-quality integration of III-V semiconductor materials on Si is essential for the development of a coherent light source in optoelectronic devices. The one-dimensional structure of NPs/NWs combined with the high refractive index of III-V semiconductor materials makes these nanostructures an ideal Fabry-Perot resonator cavity defined by the facets where the active gain media enclose the nanolaser structure.

Kim et al.\textsuperscript{18} work observed stimulated light emitted from an InGaAs/InGaP core-shell NWs array at room temperature. The coherent light was resulting from the resonance in a one-dimensional photonic crystal. In this publication, the light emitted was also coupled into silicon on insulator waveguide. On the other hand, Chen et al.\textsuperscript{15} group published the emission of coherent light from a single InGaAs/GaAs core-shell NP optically pumped at 4K. Strong confined helically propagating modes generated the stimulated output light. Chen et al.\textsuperscript{15} also modelled the relation between the NP dimension, wavelength emission and field profile for a set of helically propagating modes with FDTD techniques.

In this chapter, the emission dynamics of InGaAs NPs will be studied for excitation power below and above the lasing threshold. The time evolution for InGaAs NP emission will show a decrease of carrier lifetime with the transition from spontaneous to stimulated carrier recombination process. The optical properties of passivated and unpassivated InGaAs NPs will be also compared. Passivated NPs will show an increase of the carrier lifetime due to the reduction of non-radiative process on the NP surface. Finally, the polarisation study will reveal a circular polarisation light for a helical mode propagating inside the InGaAs/InGaP NP.
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4.1 Growth process and structure description

In this section, a brief summary of the growth process for InGaAs NPs published by Kim et al.\textsuperscript{18,127} will be presented. The NPs were fabricated by Hyunseok Kim at Department of Electrical Engineering, University of California Los Angeles inside the group led by Diana L. Huffaker. InGaAs NPs are grown on Silicon on insulator (SOI) (111) wafer lightly p-doped with Boron by metalorganic chemical vapour deposition (MOCVD), figure 4.1. The NPs features, such as diameter and separation between them (pitch), are patterned in a 20nm thick silicon nitride ($\text{Si}_3\text{N}_4$) mask for selective area epitaxy, figure 4.1b. Before the growth process start, the native oxide is removed by 6:1 buffered oxide etch solution for 60 s and rinsed with DI water.

![Figure 4.1](image)

Figure 4.1. Schematic growth process. a, SOI (111) substrate. b, $\text{Si}_3\text{N}_4$ mask with lithography pattern. c, InGaAs NP growth. d, passivation with InGaP.
Triethylgallium (TEGa), trimethylindium (TMIn), and tertiarybutylarsine (TBAs) are used as precursors and hydrogen as a carrier gas. The sample is first baked for thermal de-oxidation at 860 °C and 13 minutes in the MOCVD reactor. Then, the temperature is decreased to 690 °C, and the InGaAs nanopillar growth is initiated by flowing TEGa, TMIn, and TBAs simultaneously. The molar flow rates used corresponds to a gas phase composition of In/(In+Ga)=0.257 and V/III flow rate ratio of 24.1, figure 4.1c. The InGaAs/InGaP core-shell NPs are passivated in-situ by growing InGaP shells for 45 s at 600 °C with gas phase indium composition (In/(In+Ga)) of 0.75, figure 4.1d. Finally, the sample is cooled down with TBAs to prevent desorption.

The NPs quality and geometry is measured with scanning electron microscopy (SEM), figure 4.2. The height range for the NPs growth is between 700nm to 1000nm, figure 4.2b. On the other hand, the NPs diameter experiences an over-growth in comparison with the nanohole size patterned in the lithography mask. For instance, figure 4.2a shows the SEM picture for a grid with separation between NPs of 500nm and nanohole of 80nm. The diameter measured is approximately double the size of the nanohole patterned.
4.2 Optical properties of InGaAs unpassivated NPs

In this section, up-standing InGaAs unpassivated NPs will be studied with $\mu$-PL and $\mu$-TRPL techniques. Power dependence PL and TRPL will report coherent light emission for this nanostructure at 7K. The lasing threshold will be estimated by extracting the spectral power and the carrier lifetime as a function of the optical pump power. Both studies will agree with the lasing threshold estimation. The spectral emission temporal evolution measurements will reveal a single lasing mode, well localised in the wavelength and time spectra scale for an excitation power above the lasing threshold. TRPL spectra will also contribute to the calculation of the full width at half maximum (FWHM) of the lasing mode.

Figure 4.3a illustrates the PL emission for a set of NPs with 500 nm separation and 120 nm of nanohole diameter. The emission spectrum reveals three intensity maxima. The main peak at 1067 nm corresponds with the InGaAs NP radiative emission. Defects in the NP crystal generates the radiative recombination at longer wavelength (1152 nm and 1332 nm). TRPL spectrum reports two peaks at the same wavelength as PL studies for a spectral span window from 1000 nm to 1200 nm, figure 4.3c. The carrier lifetime curve for the emission wavelength at 1067nm is fitted with a double exponential curve with emission decay times of 15 ps and 74 ps, figure 4.3d. On the other hand, the recombination channel at 1152 nm shows an emission decay time of 71ps.

Finally, the laser spot size measured is $\sim$2 $\mu$m. If the distance between NPs is 500 nm, between 13 to 21 NPs will be excited, figure 4.3d. And, a range of 4 to 8 NPs is optically pumped with a pitch of 1000 nm. These calculations are fundamental to estimate the excitation power in a single NP.
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4.2.1 Pump power dependence in μ-PL measurements at 7K

Carriers are typically recombined spontaneously in PL processes. However, it is possible to obtain stimulated emission in a semiconductor material at certain conditions. Population inversion in the gain media and a resonance cavity are essential to obtain coherent light emission. It is crucial to distinguish a semiconductor material emitting spontaneous or stimulated light. PL at different excitation power measurements provides the spectral output power (light-output) as a function of the excitation power...
(light-input). The light input-light output (L-L) curve breaks the spectral emission into the region of spontaneous emission and the region of stimulated emission.

Power dependence in PL shows two PL emissions at 7 K, ~1060 nm and ~1160 nm, for a set of InGaAs NPs with 500 nm pitch and 80 nm nanohole diameter, figure 4.4a. The maximum intensity emission switches between 1060nm for low excitation power and 1160 nm for high. 1060 nm emission corresponds with radiative carrier recombination of InGaAs NP while 1160 nm with recombination channel created by defects in the NP crystal, see section below. At low excitation power, the recombination channel of the InGaAs NP dominates. The channel created by the defects in the NP crystal begins to lead the emission with excitation power above 1 kW/cm². However, the maximum intensity returns to 1060nm with power density above 160 kW/cm² because of the activation of stimulated mechanism.

Figure 4.4. PL spectra of InGaAs NPs with 500 nm pitch and 80 nm nanohole diameter at different power density. Inset, PL spectra with normalised intensity for a set of power density. b, light-input light-output experimental curve extracted from the previous figure. The data were fitted with two linear functions to emphasise the different regions, spontaneous emission (red line) and stimulated emission (blue line). Lower and upper left insets, NP pictures during spontaneous and stimulated emission respectively.

The L-L curve is obtained by integrating the emission spectra across a narrow spectral centred at the lasing mode peak as a function of the excitation power, figure 4.4b. During spontaneous emission, the output power increases linearly with the pump power. Then, the slope rises sharply, and the region of stimulated emission starts. This behaviour is clear evidence of NP lasing with a threshold of 160 kW/cm². The NP
emission pictures also illustrate the transition between spontaneous to stimulated emission, insets figure 4.4b. During coherent light emission, it appears a bright spot in the regular elliptical shape of the standing NPs emission resulting from a single NP lasing.

The lack of experimental data in the region of stimulated light is due to the high power density necessary to obtain coherent light emission. The energy transfer in the excitation process causes an increase of the NP temperature. The nanometre dimension and low thermal conductivity makes the InGaAs NPs a poor heat dissipater. Heat excess affects the performance of nanolaser. For instance, the nanolaser stops to emit coherent light for power density above 180 kW/cm$^2$ as a result of the optical cavity deterioration on thermal rollover.

4.2.2 Pump power dependence in $\mu$-TRPL measurements at 7K

PL spectra at different power have been shown for a set of NPs with 500 nm separation between them and 80nm nanohole diameters in the section above. According to the measurements in figure 4.3, the peak emission with the shortest wavelength is generated by the radiative recombination channel of InGaAs and the other two by recombination processes created by the defects in the NP crystal. In this section, the temporal evolution for the emission of a set of NPs with 500 nm pitch and 80 nm nanohole diameter will be described at 7 K.

The following TRPL spectra will reveal the temporal evolution of the NPs emission at different excitation power. For instance, figure 4.5 shows the TRPL spectra at 24 kW/cm$^2$ and 64 kW/cm$^2$. Komolibus et al.$^{128}$ measured a carrier lifetime for InGaAs/GaAs core-shell NPs two order of magnitude larger than the NPs studied in this desertion, figure 4.5a. The decreasing in the emission lifetime is caused by the non-radiative recombinations channels on the NP surface, and it can be avoided with a passivation process. Chang et al.$^{81}$ compared the optical properties of unpassivated, passivated and doped GaAs NWs. They found a decrease in the emission lifetime of two orders of magnitude between passivated and unpassivated and one order of magnitude between doped and unpassivated.
Figure 4.5. TRPL measurements of InGaAs NPs with 500 nm pitch and 80 nm nanohole diameter at 7 K. a, excitation power of 24 kW/cm²; b, excitation power of 64 kW/cm².

Figure 4.6. TRPL measurements of InGaAs NPs with 500 nm pitch and 80 nm nanohole diameter at 7 K. a, excitation power of 160 kW/cm²; b, excitation power of 180 kW/cm² with the high-resolution grating.

Below 24 kW/cm², the carrier lifetime is 13ps and close to the experimental temporal resolution of the experiment, figure 4.5a and regime 1 in figure 4.7b. The carrier concentration increase with an increase of power, then the emission decay time rises, figure 4.5b and regime 2 in figure 4.7b. The carrier lifetime time begins to decrease when the powers density crosses 160 kW/cm², figure 4.6 and regime 3 in figure 4.7b. Then, stimulated process dominates over spontaneous during the carrier recombination. Above the lasing threshold, the emission decay curves are decomposed in two exponential functions, figure 4.7a. The time constant with the shortest value ($\tau_{st}$)
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describes the carrier lifetime along the stimulated process, while the largest ($\tau_{sp}$) during the spontaneous.

During coherent light emission, the carrier lifetime measured acquires values below the temporal response of the set-up. And, the lasing mode appears in TRPL spectra as a well-localised spot in the time and wavelength spectral scale, figure 4.6b and figure 4.7. The full width at half maximum of the helical mode (FWHM) has also been measured using the streak camera system, figure 4.6b. TRPL spectra reveal an FWHM of 1 nm. Chen et al.\textsuperscript{15} also showed an FWHM for InGaAs NWs of a few nanometres which is comparable with the data achieved in this work, figure 4.6b.

![Figure 4.7](image_url)

Figure 4.7. a, emission decay curves fitted with exponential functions(black curve) for powers density, below lasing threshold (24 kW/cm\textsuperscript{2} and 64 kW/cm\textsuperscript{2}), close to lasing threshold (160 kW/cm\textsuperscript{2}), and above lasing threshold (180 kW/cm\textsuperscript{2}). b, carrier lifetime as a function of the power density in logarithmic scale. The emission decay time values were obtained by fitting the experimental data with exponential functions. Spontaneous emission dominates regimes 1, and 2, and stimulated emission the regime 3.

4.3 Optical properties of InGaAs passivated NPs

In the following section, the optical properties of up-standing InGaAs NPs passivated with InGaP is analysed with micro-PL and micro-TRPL techniques at low temperature. The study of PL emission at different excitation power will report coherent light emission. In particular, it appears two helical modes centred at a wavelength of 820nm and 910nm. This nanolaser can be considered as a single mode coherent light source as
a result of the approximately 100nm gap between the modes. The helical modes will show different values of lasing thresholds. For instance, the mode at 820 nm will emit coherent light at power density above 64 kW/cm\(^2\). For the mode at 910 nm, the stimulated emission will be at power density above 160 kW/cm\(^2\). The L-L curve will also be analysed with the carrier and photon density rate equation for each helical mode. Hence, the gain threshold and the spontaneous amplified factor will be estimated.

A carrier lifetime study with an increase of the power density will be also shown in this section. The emission decay time decreases with the power density, as a consequence of the transition between spontaneous to stimulated emission. And, the lasing threshold estimated will agree with the calculated by the L-L curve for both lasing modes. The FWHM will be also estimated using TRPL spectra.

Finally, the polarisation profile for the helical mode at 820nm will be analysed. The polarisation angle diagram shows a circular-like shape which corresponds to a helical mode with azimuthal and axial high mode numbers.

It is well known that passivation procedure for this type of nanostructure reduces the non-radiative recombination on the NPs surface. PL spectra for passivated NPs show a single peak emission at 1050nm, figure 4.8. On the other hand, it has been reported three recombination channels for unpassivated NPs in the section above, figure 4.3. The formation of additional peaks at a longer wavelength in unpassivated NPs lies on the creation of non-radiative recombination channels on the surface. Consequently, two radiative recombination channels appear at lower energy.

The passivation process also influences the emission dynamics. The temporal evolution for the emission of unpassivated NPs (figure 4.3) is two orders of magnitude shorter than passivated (figure 4.9). Previous publications also measured a shorter carrier lifetime for unpassivated samples caused by the recombination of carriers by non-radiative mechanism on the surface of the nanostructure. Therefore, surface passivation enhances the nanostructure optical properties and reduces the non-radiative recombination.
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Figure 4.8. PL spectra for passivated NPs with nanohole diameter of 100nm and 500nm pitch. The NPs were excited with 320 W/cm$^2$ at 7K. The blue curve corresponds with the fitting curve of the analytical spontaneous emission spectrum. The intraband scattering lifetime of carriers estimated from the fit is 20fs.

Figure 4.9. a, TRPL spectrum for NPs with nanohole diameter of 100nm and 1000nm pitch. The NPs were excited with 2.4 kW/cm$^2$ at 7 K. b, carrier lifetime curve extracted from a. The PL decay curve is fitted with an exponential function and the spontaneous carrier lifetime calculated is 3.6ns.
4.3.1 Pump power dependence in μ-PL measurements at low temperature.

Nanolaser L-L curve.

The carrier and photon density rate equations (equation 3.3 and equation 3.4) describe the temporal evolution of the spontaneous and stimulated light in a semiconductor gain media. On the other hand, the L-L curve shows the empirical transition between spontaneous and stimulated emission. The fitting of the experimental curve with the theoretical model is essential to understand the carrier recombination mechanism of the nanostructure.

Prior to the rate equation computation, the material gain media must be modelled. In chapter 1, parabolic band structure for the conduction and valence bands were assumed to obtain the gain media equation, equation 1.15. On the other hand, Chen et al.\textsuperscript{15} and Vurgaftman et al.\textsuperscript{84} introduced the parameters used in this section to calculate the material gain media curves, table 4.1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective electron mass</td>
<td>$m_e^*$</td>
</tr>
<tr>
<td>Effective light hole mass</td>
<td>$m_{lh}^*$</td>
</tr>
<tr>
<td>Effective heavy hole mass</td>
<td>$m_{hh}^*$</td>
</tr>
<tr>
<td>Interband matrix element</td>
<td>$E_p = \frac{2m_0}{\hbar^2}</td>
</tr>
<tr>
<td>Energy band gap</td>
<td>$E_g$</td>
</tr>
<tr>
<td>Material refractive index</td>
<td>$n_r$</td>
</tr>
<tr>
<td>Spin-orbit bandgap</td>
<td>$\Delta_{SO}$</td>
</tr>
</tbody>
</table>

Table 4.1 Parameter used to calculate the optical gain of a bulk In$_{0.257}$Ga$_{0.743}$As NP obtained from the work of Chen et al.\textsuperscript{15} and Vurgaftman et al.\textsuperscript{84}.

Before the material gain curves modelling, it is necessary to calculate the quasi-Fermi energy level for a given injected carrier and the lineshape function. For the quasi-Fermi
energy level calculations, the contributions of light and heavy hole must be considered. The lineshape function modelled is a hyperbolic secant function to avoid unphysical absorption below the band gap\(^{17}\), equation 1.16. \(\tau_{in}\) or the intraband scattering lifetime is estimated by fitting the experimental spontaneous PL spectra at low excitation power with the analytical spontaneous emission spectrum, equation 1.17. The fitting is shown in figure 4.8, and the intraband scattering lifetime calculated is in the same order of magnitude as the calculated by Chen et al.\(^{15}\) for a similar nanostructure.

Regarding the material gain spectrum, a set of curves at different carrier density has been modelled using the parameters listed in table 4.1, figure 4.10a. Once the curves are modelled, the peak gain variation with carrier density is extracted, and approximated with the logarithmic function showed in equation 3.1, figure 4.10b. The estimated carrier density at which the material became transparent (\(N_{tr}\)) is \(3.6 \times 10^{17}\) cm\(^{-3}\), see also figure 4.10a.

![Figure 4.10. Material gain spectra for bulk In\(_{0.26}\)Ga\(_{0.74}\)As at 4 K. a, gain spectra for different carrier density. b, peak gain variation with carrier density (circle), logarithmic fitting curve (blue line).](image)

So far, the optical gain has been modelled. The following step is the simulation of the rate equation and the fitting with the L-L curve. The emission spectra with an increase of power density indicate two lasing modes separated by 100 nm, figure 4.12a. The mode at 821 nm reports a lasing threshold of 64 kW/cm\(^2\), mode 1 in figure 4.12a and figure 4.13a. The second mode emits stimulated light at 909 nm with 160 kW/cm\(^2\) of lasing threshold, mode 2 in figure 4.12a and figure 4.13b. Chen et al.\(^{15}\) have
demonstrated helically propagating modes in short InGaAs/GaAs core-shell NPs nanolasers, figure 4.11. This type of resonance modes are forming in an interface with similar refractive index and with circular-like geometry, see section 4.3.3.

Figure 4.11. Diagram of the helical mode resonating inside an InGaAs/InGaP NP.

The modes observed in InGaAs/InGaP core-shell NPs can be the results of two helically propagating modes with different transverse field profile. Or, it can be caused by the formation of longitudinal modes in a resonance cavity, where the separation between modes is inversely proportional to the length of the cavity. In up-standing InGaAs NPs, the optical cavity is defined by the interfaces Si-InGaAs and InGaAs-Air. For the interface InGaAs-Air, the refractive index contrast is enough to create a low loss mirror ($n_{\text{InGaAs}}=3.7$ and $n_{\text{Air}}=1$). However, the refractive index contrast is very low in the interface InGaAs-Si ($n_{\text{Si}}=3.3$). This low reflective index contrast creates high losses in the optical cavity mirror. And therefore, the longitudinal modes formation is challenging. In addition, the work of Chen et al.\textsuperscript{15} with helical modes contribute to conclude that two helical modes are resonating in the NP.

The output power intensity as a function of the power density shows the typical features of coherent light sources, figure 4.13. In the logarithmic scale, the spontaneous emission
intensity rises linearly with the input power. If the excitation power reaches the amplified spontaneous region, the curve slope increases sharply, and the carriers recombine by stimulated and spontaneous recombination processes. The output light intensity saturates when the majority of carriers recombine by stimulated mechanism, initialising the stimulated emission region. The slope variation in the output power intensity results in the standard “knee” behaviour and the S-like shape in the log-log scale for coherent light emitters, figure 4.13. It is important to note that the output power intensity data were obtained by integrating a narrow spectrum centred at the lasing modes.

Figure 4.12. Optical emission for a set of In$_{0.26}$Ga$_{0.74}$As NPs with nanohole diameter of 100nm and 500nm pitch. a, PL spectra for a set of power density. Red line PL spectrum, low optical pump power at 7K. Green line PL spectrum, excitation power during mode 1 lasing threshold at 7K. Magenta line PL spectrum, excitation power above the lasing threshold of mode 1 at 4K. Blue line PL spectrum, excitation power above the lasing threshold of mode 2 at 4K. The measurements were taken with a monochromator and InGaAs detector for the blue and magenta PL spectra, and with a spectrometer for the other two PL spectra. b, emission picture for a set of NPs below the lasing threshold. c, emission picture for a set of NPs above lasing threshold.

The L-L curve is fitted with the carrier and photon density rate equations for nanolasers$^{17}$, equation 3.3, equation 3.4, figure 4.13. The NP modelled has a dimension of 250 nm (length of the sides) by 850 nm (height). The group velocity of 4.2 ($v_g = c/n_g$), the confinement factor of 1 ($\Gamma$), and the fraction absorbed by the NPs ($\eta_p$) were obtained from the work of Chen et al.$^{15}$. 

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3600 ps ($\tau_r$) is the spontaneous emission lifetime with an excitation power of 2.4 kW/cm$^2$, figure 4.9. Above the lasing threshold, the spontaneous lifetime component reduces to 300ps ($\tau_{ms}$), figure 4.14c. The spontaneous emission decay time during coherent light emission can be decomposed following the equation 3.5. The estimated valued of the non-radiative lifetime is 280 ps. 3600 ps and 280 ps are the values for the spontaneous ($\tau_{sp}$) and non-radiative ($\tau_{nr}$) lifetime introduced in the rate equations.

Figure 4.13. Nanolaser output power responses as a function of the excitation power emission for a set of In$_{0.26}$Ga$_{0.74}$As NPs with nanohole diameter of 100nm and 500nm pitch (circle). Solid lines, laser rate equation simulations at different $\beta$-factor. Grey area, amplified spontaneous emission region, it divides the L-L curve into the spontaneous (left-side) and stimulated (right-side) emission region. Lower right inset, L-L curve on a linear scale. a, helical mode at 821 nm (mode 1). b, helical mode at 909 nm (mode 2).

The spontaneous emission factor ($\beta$), the non-radiative recombination coefficient (C) and the threshold gain ($g_{th}$) are the estimated parameters in the computation of the carrier and photon density rate equation. The $\beta$-factors estimated were 0.0023 and 0.014 for mode 1 and 2, respectively. At 821 nm, the emission of InGaAs NPs is null or negligible for low optically pump power, figure 4.13a. As a result, the fitting curve for mode 1 mismatch with the experimental data for low excitation power. Therefore, the $\beta$-factor for mode 1 may deviate with the value computed. However, previous work for similar nanostructures reported spontaneous factor in the same order of magnitude that the calculated for mode 2$^{15,17}$. The low $\beta$-factor for this nanostructure determine the lack of efficiency to couple the spontaneous light into the NP.
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The third order of non-radiative coefficients estimated for the modes 1 and 2 are $1.0 \times 10^{-38}$ cm$^6$·s$^{-1}$ and $1.7 \times 10^{-38}$ cm$^6$·s$^{-1}$, respectively. And, the gain threshold of 610 cm$^{-1}$ and 1700 cm$^{-1}$ are the values calculated in the fitting process for the laser modes 1 and 2, respectively. On the other hand, the Q-factor is calculated using the gain threshold and the following relation:

$$ Q = \frac{2\pi n_g}{\lambda \Gamma g_{th}} $$

Equation 4.1

530 and 170 are the Q-factor estimated for mode 1 and 2 respectively. The Q-factor values are akin to the published in the work of Chen et al. The Q-factor illustrates the losses in the resonance cavity. Therefore, high Q-factor describes an optical cavity with low losses and vice versa for low Q-factor values.

4.3.2 Pump power dependence in μ-TRPL measurements at low temperature

The previous section has described the spectral emission of InGaAs NPs at low temperature. In the following section, the temporal evolution of the NPs emission is analysed with TRPL techniques for a set of power density at low temperature. The carrier lifetime shows a decrease with the pump power as a result of the transition from spontaneous to stimulated emission. And, the lasing threshold estimated in the carrier dynamics study agrees with the obtained in PL.

Figure 4.9 showed the TRPL spectrum at 7K and low excitation power for a set of NPs with 1000 nm of pitch and 100 nm of nanohole diameter. The emission decay time measured was 3.6 ns, and it was obtained by fitting a single exponential function. Figure 4.14a reveal the TRPL spectrum at 7 K and higher optically pump power for the same set of NPs. The increase of excitation power results in a carrier lifetime decrease for the spontaneous emission (from 3.6 ns to 0.76 ns). And also, a second recombination channel appears with carrier lifetime in the order of tens of ps, figure 4.14a and c. The additional recombination channel is generated by the activation of non-radiative processes stemming from the high power density applied to the NP. The elevate excitation power creates a increased of the NP temperature. InGaAs NPs are poor heat
dissipaters due to the nanometre dimension and the low thermal conductivity of the material. Therefore, the nanostructure can be deteriorated on the thermal rollover and non-radiative channels can be generated.

Figure 4.14. a, TRPL measurements for InGaAs NPs with 1000 nm of pitch and 100 nm of nanohole diameter at 7 K and power density of 16 kW/cm². b and d, TRPL measurements for InGaAs NPs with 500 nm of pitch and 100 nm of nanohole diameter at 4 K. b, excitation power below lasing threshold (16 kW/cm²). d, excitation power above lasing threshold (64 kW/cm²). The dashed circle emphasises the helical mode. c, emission decay curve for a and b, centred at 1010 nm and 980 nm respectively.

Two recombination channels are also visible for the set of NPs with 500 nm of pitches and 100 nm nanohole diameters with an excitation power below the lasing threshold and temperature of 4 K, figure 4.14b and c. In this nanostructure, the emission decay time also reveals two recombination channels. The emission decay time of 30 ps describes the carriers recombining by non-radiative recombination process, while 300 ps is the spontaneous emission decay time. The emission wavelength shifts towards shorter
wavelength from the NPs with 1000 nm pitch to 500 nm pitch. The blueshift is resulting from the different geometry and temperature between the set of NPs.

Above 64 kW/cm², the NP with 500 nm pitch and 100 nm nanohole diameter starts to lase at 821 nm, figure 4.14d and figure 4.15a. The lasing modes appear in TRPL spectra as a high spectral intensity spot well localised in the wavelength spectral scale, and with a carrier lifetime below the time resolution of the experimental set-up, figure 4.14d and figure 4.15. Figure 4.14d reveals the TRPL spectrum for the full emission spectra window at 64 kW/cm². The spectrum reports coherent light emission at 821 nm. On the other hand, figure 4.15 illustrates two TRPL spectra with a spectral window expanded. Figure 4.15a shows the TRPL spectrum at 86 kW/cm². This power density corresponds with a power above the lasing threshold for the helical mode 1, but below the lasing threshold for the helical mode 2. The FWHM measured is 1.5 nm. And the emission decay time is below the temporal resolution of the experimental set-up (8 ps). In figure 4.15b, the TRPL spectrum reveals the helical mode 2. The FWHM measured is 1 nm. The emission decay time is also below the temporal resolution of the experimental set-up (11 ps).

![Figure 4.15](image)

Figure 4.15. TRPL measurements of InGaAs NPs with 500 nm of pitches, 100 nm of nanohole diameters at 4 K, and narrower wavelength span in comparison with figure 4.14. a, excitation power of 86 kW/cm² and wavelength span for mode 1. b, excitation power of 160 kW/cm² and wavelength span for mode 2.

Finally, the emission decay time is extracted at a different set of excitation power, figure 4.16. For both modes, the lasing threshold estimated using the spectral output power
agrees with the carrier lifetime analysis as a function of the power density. For the L-L curve, the output power increases with the power density, revealing the usual features of L-L curves. The carrier lifetime with the power density also reports the S-like shape at log-log scale and the standard “knee” in the transition between spontaneous to stimulated emission. However, the carrier lifetime studies describe a decreasing tendency, while the tendency in the output power studies is decreasing.

Figure 4.16. a and b, emission decay time for the lasing mode one and two respectively as a function of the excitation power. The first three experimental data (light green) were obtained for a set of NPs with 1000 nm of pitch and 100 nm of nanohole diameter at 7 K. The rest (dark green) were measured at 4K and for a set of NPs with 500 nm of pitch and 100nm of nanohole diameter.

4.3.3 Polarisations study

The work of Saxena et al.\textsuperscript{58} and Chen et al.\textsuperscript{15} have demonstrated helically propagating modes in NPs nanolasers. These modes are similar to the resonant modes in hexagonal nanocavities observed by Nobis et al.\textsuperscript{131}. In this work, the modes found for this type of nanocavities are referred to as whispering-gallery modes (WGMs). The WGMs have a transverse field profile complementary to the azimuthal helically propagating modes in NPs nanolasers. In contrast with hexagonal nanocavities, axial direction resonance modes also appear in NPs nanolasers.

The practically identical refractive index between the Si substrate (\(n_r \approx 3.6\)) and InGaAs NPs (\(n_r \approx 3.7\)) complicates the reflection between interfaces, necessary to obtain strong
feedback in the material gain. However, helically propagating modes facilitate total internal reflection at the interface due to the near-90 degree angle of the incident light at the surface of Si, and hence high reflectivity between the two materials, figure 4.11. Chen et al.\textsuperscript{15} also analysed the possibilities to control the modes by changing the NP geometries and the interface angle.

![Figure 4.17](image.png)

Figure 4.17. Polarization angle diagram for InGaAs NPs with 500 nm of pitch and 100 nm of nanohole diameter. The lasing mode corresponds with the one with a wavelength of 821 nm.

Turning now to the polarisation features, helically propagating modes are well studied in the work of Saxena et al.\textsuperscript{58} and Chen et al.\textsuperscript{15}. Note that the output light focused in the monochromator was collected from the top of the NP, and therefore the modes acquired are produced at the interface air-NP. Helical modes reveal a “butterfly” shape in the polarisation angle diagram at the low order of azimuthal and axial mode numbers\textsuperscript{15,58}. Higher order the “butterfly” shape turn into an ellipse-like, and then circular-like. In figure 4.17, the polarisation angle of the lasing mode at 821 nm for InGaAs NPs with 500 nm of pitch and 100 nm of nanohole diameters reports circular-like shape. The
polarization angle study suggests high mode numbers of azimuthal and axial in helically propagating modes guided inside the NP.

### 4.4 Lasing properties for passivated NPs with different geometries

Two coherent light modes were measured with different lasing thresholds for NPs with 500 nm pitch and 100 nm of nanohole diameter. The coherent light is the results of two helical modes resonating in the NP. The helical modes emit coherent light at 821 nm and 909 nm. In this section, the output light features will be examined for passivated NPs with 1000 nm pitch and 100 nm of nanohole diameter and 500 nm pitch and 80 nm of nanohole diameter at 4K.

![Figure 4.18](image)

Figure 4.18. Optical properties for a set of NPs with 1000 nm of pitch and 100 nm nanohole diameter at 4K. a, output power intensity as a function of the excitation (L−L curve). Inset, spectrum with an excitation power above lasing threshold. b, TRPL spectrum for an excitation power of 290 kW/cm².

The output power intensity as a function of the power density reveals coherent light emission for a set of passivated NPs with 1000 nm pitch and 100 nm of nanohole diameter. The lasing threshold estimated is 150 kW/cm², and the spectral emission 835 nm. On the other hand, the set of passivated NPs with 500 nm pitch and nanohole diameter of 80 nm generates stimulated light at 904 nm with a lasing threshold of 120 kW/cm², figure 4.19. The work of Chen et al. describes the relationship between NP
geometry and the helically propagating mode. The helical mode modelled showed a dependency between the NP geometry and the emission wavelength. Each helical mode has the resonance in their particular range of wavelength. This dependency is reported in the table 4.2.

Figure 4.19. Optical properties for a set of NPs with 500 nm pitch and nanohole diameter of 80 nm at 4K. a, output power intensity as a function of the excitation (L−L curve). Inset, spectrum with an excitation power above lasing threshold. b, TRPL spectrum for an excitation power of 140 kW/cm².

<table>
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<tr>
<th>Pitch</th>
<th>Nanohole diameter</th>
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<tr>
<td>500 nm</td>
<td>100 nm</td>
<td>821 nm</td>
<td>909 nm</td>
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<td>835 nm</td>
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</tr>
<tr>
<td>500 nm</td>
<td>80 nm</td>
<td>909 nm</td>
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</tr>
</tbody>
</table>

Table 4.2. Modes dependency with the NP geometry

Finally, the time evolution in the NPs emission illustrates the typical behaviour of coherent light emitters for both NPs geometries. In both sets, the helical mode appears as a short pulse with high spectral intensity and well localised in the time and wavelength domain. TRPL spectra also reveal the spontaneous emission as a broader linewidth and higher lifetime in comparison with the stimulated emission.


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4.5 Summary

In summary, the optical properties of passivated and unpassivated InGaAs NPs have been compared micro-PL and micro-TRPL measurements. Three recombination channels appeared in the spectral emission of InGaAs unpassivated NPs, in contrast with the single channel of passivated samples. The additional recombination centres in unpassivated NPs are caused by non-radiative processes on the surface of the NP. The temporal evolution in the emission spectra is also affected by the non-radiative recombination process on the NP surface, generating a reduction of carrier lifetime of two orders of magnitude in comparison with the passivated sample.

The study of carrier lifetime and spectral emission intensity as a function of the excitation power agreed in the lasing threshold estimated for unpassivated and passivated NPs. Therefore, the transition between spontaneous and stimulated emission can be obtained with the analysis of the increase in the output power intensity, or with the reduction of carrier lifetime as a function of the power density.

In the case of unpassivated sample, the coherent light was measured from the set of NPs with 500 nm pitch and 80 nm nanohole diameters at 7K. Other geometries of NPs were not able to emit stimulated light for the unpassivated sample. The lasing wavelength observed and the power threshold estimated was 1055 nm and 160 KW/cm\(^2\) respectively.

On the other hand, four sets of passivated NPs generate stimulated light, table 4.3. A dependency in the helical mode spectral position with the NP geometry has been reported. Each dimension of NPs has an optimum helically propagating mode, and every mode emits in a specific wavelength. In particular, the coherent light is measured from NPs with nanohole diameter above 80 nm independently of the distance between the NPs. Two lasing modes was observed for the set of NPs with 500 nm of pitch and 100 nm of nanohole diameter with emission wavelength of 820 nm and 910 nm and lasing threshold of 64 KW/cm\(^2\) and 160 kW/cm\(^2\), respectively. The lasing modes are attributed to the propagation of two helically modes resonating along the NP.
Chapter 4 Emission properties of InGaAs NPs in SOI

Finally, the polarisation study showed circular polarisation for the 820 nm mode and set of NPs with 500 nm of pitch and 100 nm of nanohole diameter. The circular polarisation suggests guided helically propagating modes with azimuthal and axial high mode numbers.

<table>
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<th>Pitch</th>
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<td>500 nm</td>
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<tr>
<td>500 nm</td>
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Table 4.3. Summary of the passivated NPs set emitting coherent light.
Chapter 5.

Summary, conclusions and future work

5.1 Summary and conclusions

In this dissertation, the optical properties of GaAs/AlGaAs core-shell and core-multishell NWs, and InGaAs passivated and unpassivated NPs have been studied using advanced spectroscopy techniques such as μ-PL and μ-TRPL. The nanostructures were studied under different conditions for an in-depth analysis. For instance, power dependence μ-PL contributes to estimate the lasing threshold and localise the different emission regimes in nanolasers. On the other hand, power dependence μ-TRPL shows the emission dynamic response with optical pump power. In lasers structures, the emission decay time decreases with the excitation power due to the transition from spontaneous to stimulated recombination process. Finally, temperature dependence in μ-PL and μ-TRPL reveals the thermal activation of non-radiative processes. The study carried out for this type of nanostructure represents the first step forward to develop a monolithic coherent light source in Si platform using III-V NWs/NPs.

After an introduction and some description of the experimental setup in chapters 1 and 2, chapter 3 opens with the analysis of GaAs/AlGaAs core-shell and core-multishell NWs. Following the work of Saxena et al.\textsuperscript{17,58}, Mayer et al.\textsuperscript{61} and Stettner et al.\textsuperscript{42}, the laser threshold estimation and the laser rate equation modelling were carried out at 3.6 K for GaAs/AlGaAs core-shell and core-multishell NWs. Then, an extensive study of the NWs emission dynamic was described. A redshift in the modes spectral position along the carrier recombination was observed in TRPL spectra for both nanostructures. The redshift is resulting from the increase of the material refractive index due to the carrier concentration decrease. The excitation process leads in the creation of multiples electron-hole pair. The elevate carrier concentration produces a decrease in the material refractive index. Then, the carrier concentration reduces with the recombination process, and the material refractive index rises. Therefore, the longitudinal modes spectral position shifts towards longer wavelength during the emission time, as it is
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ruled by the Fabry-Perot resonator equations. The fitting of the Fabry-Perot relations with the TRPL spectra for a set of power at 4K reported the resonance of two transverse modes for GaAs/AlGaAs core-shell NW and a single one for the multishell. The linewidth enhancement factor was also calculated for the two transverse modes travelling along the bulk GaAs NWs with values of 2 and 1.3.

The GaAs/AlGaAs NWs study finished with the analysis of the NWs emission with an increase of temperature. The carrier lifetime is rapidly reduced for temperature above 200 K, generating a decrease in the redshift lifetime undetectable for the experimental set-up. Instead, an increase of the laser mode linewidth is observed. The reduction in the emission decay time is caused by the thermal activation of non-radiative processes.

The following chapter described the emission properties of InGaAs NPs unpassivated and passivated with InGaP. Power dependence PL reported lasing thresholds pump power of 160 kW/cm² for unpassivated and 64 kW/cm² for the passivated sample. In unpassivated NPs, a single laser mode was measured. The NP stopped to lase at power slightly above lasing threshold due to the deterioration of the optical cavity with elevates excitation power. On the other hand, the passivated sample showed two lasing modes with different laser threshold for a certain NP geometry. This nanolaser can be considered as a single mode coherent light source because of the high separation between the modes, 100nm.

Spontaneous emission for unpassivated sample presented lower carrier lifetime and two peak emission more than passivated NPs for excitation power below the lasing threshold. The passivation process prevents non-radiative recombination on the surface. Hence, the emission decay time rises, and the recombination process occurs in a single channel. Power dependence μ-TRPL illustrated a reduction of carrier lifetime with the increase of excitation power for both samples. The laser threshold calculated with TRPL studies agreed with PL experiments.

Finally, a polarisation analysis was carried out, obtaining a circular-like shape for the passivated sample and for the helical mode at 821 nm. Previous studies for this type of nanostructures concluded that the modes travelling in InGaAs NPs are helically propagating modes. These types of modes are susceptible to the NPs dimensions. For
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this reason, different NPs geometry obtained different spectral position of the helical modes and the lasing threshold.

The principal difference between NWs and NPs lies in the growth process. The NPs are site-controlled using a patterned mask, while the NWs use a self-catalysed, Ga-droplet mediated, vapour-liquid-solid growth mode. In this work, we described the optical emission of InGaAs NPs and GaAs NWs. The addition of Indium in GaAs materials produces a shrinking of the alloy bandgap, and hence the optical emission redshifts. The main spontaneous emission with passivated InGaAs NPs is at 1050 nm while GaAs bulk NWs is at 820 nm. On the other hand, NWs are laying down in sapphire substrates while NPs are standing in SOI substrate. Then, NWs showed longitudinal modes and transversal modes during spontaneous and stimulated emission. And, NPs reported helically propagating modes due to the similar refractive index in the interface NP-substrate. In addition, stimulated emission in GaAs NW was achieved with lower excitation power than NPs. However, the spectral position for one of the lasing modes in InGaAs NPs possessed longer wavelength than GaAs NWs.

The mode redshift in TRPL spectra for GaAs NWs was not visible in InGaAs NPs. The faster recombination process in InGaAs NPs in comparison with GaAs NWs can lead to a change in the refractive index below the temporal resolution of experimental set-up. And hence, the phenomenon described in GaAs NWs is not detected the NP. Likewise, it is not visible at higher temperatures in the GaAs NWs.

In conclusion, both types of structure offer great potential as a monolithic coherent light source for on-chip and chip to chip communications. Also, it is difficult to choose for one the nanostructure due to the early stage of the research. Therefore, it is necessary to keep analysing and improving the NWs and NPs nanolasers performance for a better quality of the emission properties. Next section, the future work required to advance in the development of coherent light emitters using NWs/NPs nanostructures will be reported.
5.2 Future work

Coherent light emission has been proved and analysed for InGaAs NPs and GaAs NWs optically pumped. However, further developments are fundamental to adopt these nanostructures into optoelectronic technologies:

- **NWs/NPs electrically driven.** The following step for this type of nanostructures is to achieve coherent light emission with electrical excitation power. So far, the work of Duan et al.\(^{44}\) is the first and the only group that published coherent light emission from a single NW electrically pumped. Chu\(^{132}\) et al. also published lasing in NWs electrically pumped, nevertheless the coherent light was emitted for a group of NW. In NWs/NPs, it is challenging to obtain NWs/NPs with uniform P-type and N-type dopants along the nanostructure and create a metal contact in the nanometric facet during the growth process. Moreover, the metal contact in the facets would increase the losses in the nanolaser due to the light absorbed by the metal. In order to reduce the absorption losses and create a homogeneous doped structure, the growth process design must be further investigated.

- **Mode selection, directionality and collimation.** The lasing mode selection, directionality control and light collimation are the next requirements to develop a monolithic light source using NWs/NPs. The lasing mode selection and directionality can be manipulated using Bragg gratings on the substrate, or on NPs/NWs. The gratings must be engineered to reflect the entire light in one of the facets. And, the opposite facet might filter and partially reflect the wavelength of interest.

The dimension reduction in the semiconductor lasers makes the output light much divergent. Microscale lasers collimate the output light using micro-lenses. For instance, some VCSELs lasers integrate a cylindrical polymer droplet as micro-lens to reduce the light beam divergence. Similarly, NPs/NWs lasers may incorporate a nano-lens to collimate the output light beam. Another solution could be the shaping of one of the facets. The end of the nanostructure might be
designed to decrease the divergence, avoiding the integration of a nano-lens. This method would reduce the losses, avoiding reflections on the nano-lens.

- **Telecom wavelengths.** The principal objective is the integration of NWs/NPs nanostructures on group IV in particular silicon. For this, the emission wavelength must belong to the telecom wavelength range, and hence the output light must shift to a longer wavelength. For instance, the emission redshift can be achieved by introducing a high concentration of Indium, Nitride or Antimony in the gain medium.

- **Heat dissipation.** The heat can affect the performance of a nanolaser. In Chapter 4, the lasing emission at very low temperature has been shown. Coherent light emission at room temperature was not successful due to the degradation of the nanostructure. The low heat dissipation in III-V NPs/NWs is caused by the small dimension and low thermal conductivity of the surrounding medium. To increase the heat sinking, the nanostructure must be in contact with a heat dissipator material. The metal contact for the electrical injection can also be used to sink the heat. Another possibility is to coat the NWs/NPs with a low-index conductive dielectric, such as Indium Tin oxide (ITO) film.
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