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Measured gain spectra from InAs/InP (100) quantum-dot amplifiers have been analyzed with a quantum-dot rate-equation model. The amplifiers are fabricated to have a peak gain wavelength around 1700nm. Our comparison between measured and simulated gain spectra shows that two effects in the quantum-dot material introduce the 65nm blue shift and change in shape that have been observed in the measured gain spectrum with an increase in injection current density from 1000A/cm2 to 3000A/cm2. The first effect is the shift from GS to ES, and the second effect the dot size dependent filling due to the dot size dependent escape rates.

Introduction

The use of quantum-dots (QDs) in monolithic optical devices, such as semiconductor optical amplifiers (SOAs) and semiconductor lasers, can have a number of benefits over the use of bulk or quantum well gain material. These advantages are due to the three dimensional carrier confinement in QDs. One of the advantages of QDs over bulk or quantum well material is the wavelength tunability. The size and therefore the wavelength of the InAs QDs on the InP(100) substrate can be controlled in the growth process. The average wavelength can thus be tuned to a preferred wavelength region [1]. This technique enables us to design integrated optical devices also for non-telecom purposes outside the 1550nm wavelength window such as optical coherence tomography (OCT) or gas sensing.
In order to be able to apply this gain material optimally in devices for applications in the longer wavelength ranges, we need to understand the behavior of the gain of these QD integrated optical amplifiers. In this paper we compare the measured small signal gain spectra with simulated small signal gain spectra for different injection current densities.

Measurement results

The gain measurements, previously presented in [2], are performed on InAs/InP(100) QD amplifiers which are optimized to emit and amplify light in the 1600nm to 1800nm wavelength region. In Fig 1 the small signal modal gain spectra which are determined from the ASE spectra according to the multisection method [3] are given for different injection current densities.
In these spectra a clear continuous broadening and shift towards the shorter wavelength region can be observed with

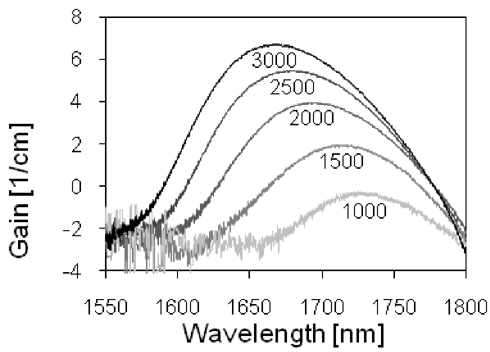

Fig. 1: Measured small signal gain spectra for current densities between 1000A/cm2 (light gray) and 3000A/cm2 (black).

increasing injection current density. This change in the gain spectrum with increasing injection current density can have a large influence on the performance of a device. For example, it means that when this material is used in a laser without wavelength selective devices, e.g. a simple Fabry-Perot laser, the lasing wavelength is strongly dependent on the length of the device. The longer the laser, the lower the gain per unit length or the lower the injection current density needs to be, and thus the laser will operate at a significantly longer wavelength then one that is say twice as short.

QD amplifier model

To understand the origin of the shape and in particular the blue-shift of the gain spectrum with increasing injection current density in our amplifiers, we have set up a simulation of the QD amplifier gain with a QD rate equation model. With this model we want to be able to predict the gain behavior for these QD amplifiers when used in an integrated circuit. Furthermore, the model can be used to determine the average energy levels in the QD system.

The model we have used is based on the QD model previous presented in [4] which has been simplified for our purpose to reduce the calculation time. The model consist of 64 carrier rate equations, one for the separate confinement heterostructure (SCH) and one for the wetting layer (WL). The excited state (ES) and ground state (GS) are both split up in 31 equations, each equation for a different dot size group to cover the inhomogeneous broadening. The 64 coupled rate equations are solved in the time domain until a steady state is reached where all the carrier concentrations do not change anymore. The small signal gain is calculated from the filling probabilities in the ES and GS. The carrier losses in the dots due to stimulated emission were neglected because we only look at the low power ASE spectra far below the lasing threshold. Therefore we did not include a series of equations for the photons, which reduces the number of equations to be solved by nearly one third.

Simulation

There are two major effects in the QD material which can cause the broadening and shift in the gain spectrum with increasing injection current density. The location of the discrete energy levels in the dots as well as the energy level of the WL determines to a large extend the occurrence of these effects. Because of the fact that these energy levels are not exact know, the occurrence of these effects are also not known. With the model we have tried to simulate both effects and investigated the influence of the effect on the gain spectrum. With this knowledge we have estimated the different energy levels. Within this section we will explain both effects, look at the influence of the effect on the gain spectrum by simulating the gain spectra and finally estimate the energy levels by comparing the simulated spectra with the measured spectra.

The first and most obvious effect which could have caused the change in the gain spectrum is contribution from higher energy states in the QDs to the gain spectrum with increasing injection current density. At low injection current densities all the carriers will relax to the GS and will contribute to gain at the GS wavelength. While increasing the injection current density also the GS gets more occupied. At a certain moment part of the carriers cannot relax anymore from the ES to the GS and start to contribute to gain at the ES wavelength. A further increase of the injection current density will only increase the gain from the ES state or even higher energy states.

The second effect which can cause the change in the gain spectrum is the dot-size dependent escape rates from the QD to the WL. The carrier capture time from the wetting layer to the dots is for all the dots the same since it only depends on the occupation probabilities in the different states. The escape time, however, does depend on the dot size. The escape time depends on the energy difference between the energy state in the dot and the wetting layer. In small dots this energy difference is smaller than it is for large dots due to the relative higher energy levels in the small dots. Due to this difference in escape time, the large dots will be more populated than the small dots at low injection current densities and first start to contribute to gain at the longer wavelength region. While increasing the injection current density, also smaller dots get populated and start to contribute to gain at shorter wavelengths.

With the rate equation model both effects could be simulated and analyzed. The effects where simulated by changing the energy levels in the system. All other parameters are kept constant except for the carrier capture time from the SCH to the WL and the carrier recombination time in the WL. These time constants are used to scale the gain spectra, but they have no influence on the shape of the gain spectra.

In the first simulation, where we want to emphasize the upcoming ES, we choose the average energy level of the GS at 0.716eV (1730nm), the average energy level of the ES at 0.760eV (1630nm) and the energy level of the WL at 1.096eV (1130nm). These values are theoretical values and only chosen to emphasize the effect. The energy level of the WL is, for example, chosen to be far away from the energy levels in the dots to minimize the effect of the dot size dependent escape time. In Fig. 2a the simulated spectra are given for injection current densities between 500A/cm2 and 3000A/cm2. In this figure you can clearly see that at low injection current densities gain around the GS wavelength start to appear. With increasing injection current density also gain at the ES starts to appear and becomes stronger than the gain at the ground state wavelength. This upcoming gain from the excited state broadens the gain spectrum towards the shorter wavelength. The way the spectrum broadens towards the shorter wavelength region is however different than in the measured spectra. In the simulation it is a kind of step function from the GS wavelength to the ES wavelength whereas in the measured spectra a continuous broadening and shift towards the short wavelength region is observed.

In the second simulation, where we want to emphasize the dot size dependent escape rates from the QD to the WL, we choose the average energy level of the GS at 0.746eV (1660nm), the average energy level of the ES at 0.755eV (1640nm) and the energy level of the WL at 0.805eV (1540nm). Again these values are theoretical and chosen to emphasize the effect. The GS and ES levels are chosen relative close to each other to

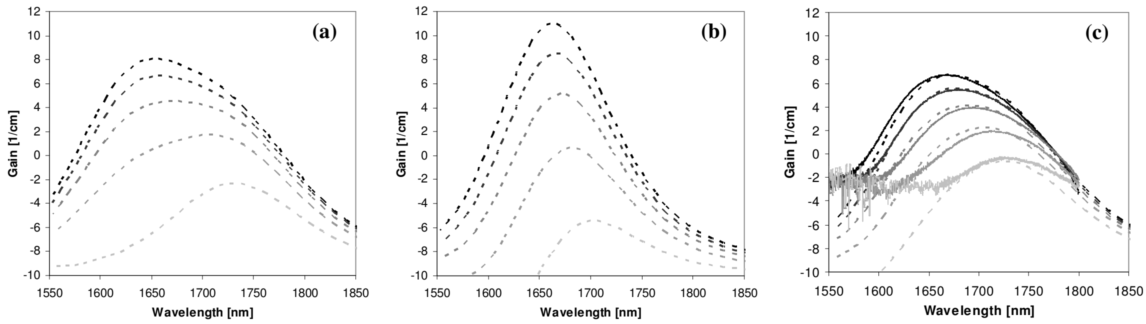

Fig. 2: Small signal gain spectra for a QD amplifier with current densities between 1kA/cm2 (light gray) and 3kA/cm2 (black). (a) Simulated spectra with the first effect (upcoming excited state with increasing current). (b) Simulated spectra with the second effect (dot size dependent filling due to dot size dependent escape rates). (c) Measured gain spectra (solid) and simulated with two effects included (dashed).

minimize the effect of the upcoming ES, and the energy level of the WL is chosen close to the energy levels in the dots to increase the escape rate from the dots to the WL. In Fig. 2b the simulated spectra are given for injection current densities between 500A/cm2 and 3000A/cm2. In this figure also a shift and broadening towards the shorter wavelength region can be observed but the amount of shift is limited by approximately 45nm.

In both simulations the change in gain spectra did not follow the same trend as the change in the measured gain spectrum. We finally did a third simulation in which both effects are included. The resulting gain spectra are given in Fig. 2c together with the measured gain spectra. In this simulation the upcoming ES causes the large change towards the shorter wavelength region whereas the dot size dependent escape rate causes the smooth shift of the gain peak towards the shorter wavelength region. In this simulation we have optimized the energy levels to match the simulated spectra with the measured spectra. The resulting energy levels are 0.716eV (1730nm) for the average GS level, 0.760eV (1630nm) for the average ES level and 0.843eV (1470nm) for the WL energy level. This simulation shows that both effects together give rise to the broadening and gain shift towards the shorter wavelength region.

We expect that the two mechanisms both shift the peak wavelength of the gain spectrum to even shorter wavelengths if there are other higher energy states available in the dots between the ES and the WL. The amount of shift originating from these higher energy states will decrease with respect to the increasing injection current densities due to the increasing number of states per energy range.

Conclusion

In this paper we have compared the measured small signal gain spectra from InAs/InP(100) QD amplifiers with simulated gain spectra. The simulated gain spectra are determined with a QD rate equation model which consists of 64 coupled carrier rate equations. There are two effects in the material which can cause the large broadening and shift in the gain spectrum with increasing injection current density. The upcoming ES with increasing injection current density and the dot size dependent escape rate from the QD to the WL. Comparison between the measurements and the simulations show that both effects together give rise to the broadening and shift in the gain spectrum towards the shorter wavelength region.

Acknowledgement

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