Analysis of the Current Dependency of the Small Signal Gain Spectrum in InAs/InP(100) Quantum-Dot Amplifiers

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Abstract—**InAs/InP(100) quantum-dot amplifiers have been fabricated with a 1700nm peak wavelength. The measured small-signal gain spectra have been analyzed with a quantum-dot rate-equation model. The average energies of the ground state E_{GS}=0.716eV and the excited state E_{ES}=0.760 transitions have been determined. The origin of the spectral behavior has been analyzed.**

Keywords-Semiconductor optical amplifier; quantum dot; gain measurements; rate equation; integrated optoelectronics

I. INTRODUCTION

The use of quantum-dot (QD) optical amplifiers in optical devices can have a number of benefits over the use of bulk or quantum well amplifiers. These advantages are due to the three dimensional carrier confinement in the QDs. One of the advantages is the control of the average dot size during the growth process [1] which is a direct control of the central wavelength in the operating range of the amplifier. This enables the design of active integrated optical devices for non-telecom purposes on InP substrate outside the 1550nm wavelength region. In order to be able to apply this gain material optimally in devices, 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 to determine the average energy levels of the ground state (GS) and the excited state (ES) and to understand the spectral behavior.

II. DEVICES AND MEASUREMENTS

The gain measurements are performed on 7mm two-section InAs/InP(100) QD devices as described in [2]. The QD wavelength is however in these devices tuned into the 1700nm region during the grow process. The photoluminescence spectrum (PL) is given in Fig. 1a. The long section of the device is used as an amplifier with a defined injection current densities and the short section is used as an absorber with a -3V reverse bias applied. The gain is determined with a measurement technique based on the analysis of the ASE spectra from different lengths of amplifiers [3]. The single pass ASE is measured from 22 parallel amplifiers on a single chip with lengths between 4.94mm and 6.48mm. The absorber is used to absorb light generated and amplified in the other direction and so prevent optical feedback. The maximum amount of feedback signal was determined to be -18dB in the most unfavorable amplifier current density and absorber length combination. The small signal gain is determined at 5 different injection current densities (continuous wave) between 1550nm and 1800nm wavelength. The resulting gain spectra are given in Fig. 1b (solid). Note that this measurement technique is not suitable for measurements below transparency due to the low signal level of the attenuated ASE far from output of the amplifier. Gain spectra at higher injection current densities could not be measured due to a to high feedback signal through the absorbers.

There are two aspects in these gain spectra which should be noted. First, we cannot make a clear distinction between gain from the GS and gain from the ES. Gain spectra as well as PL spectra from InAs QD on GaAs substrate show two clear peaks which can be assigned to the GS and ES transitions[4]. In our PL spectra (Fig. 1a) and gain spectra from InAs QD on InP substrate (Fig 1b) a single broad peak is observed, which complicates the determination of the average GS and ES energy. The second notable aspect is the continuous increase in the gain spectrum towards the shorter wavelength region with increasing injection current densities. In practice 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 needs to be, the longer the operating wavelength will be.

III. MODEL

To analyze the QD gain measurements we have set up a simulation of the QD amplifier gain with a QD rate equation model. The model we have used is based on the model 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) populations are each modelled using 31 equations to describe the inhomogeneous broadening due to the dot size distribution. The rate equations are solved in

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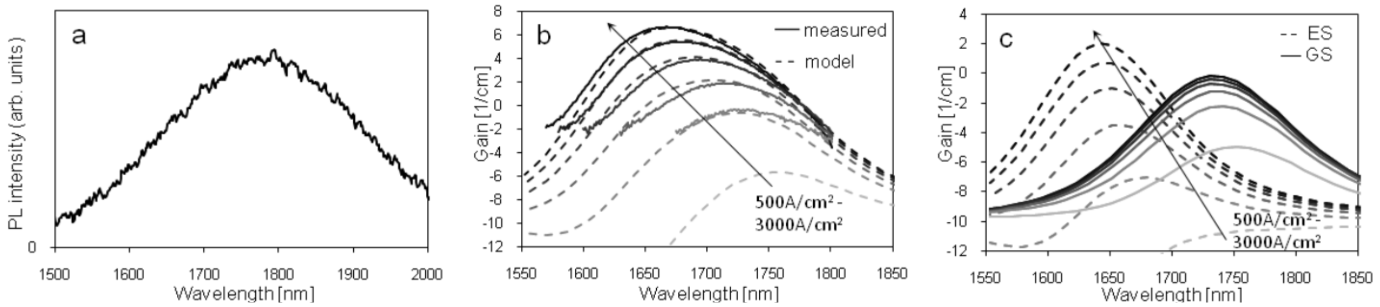

Figure 1. (a) Photoluminescence spectrum of QD amplifier structure. (b) Small signal gain spectra for a QD amplifier with current densities between 500A/cm2 (light gray) and 3000A/cm2 (black). Measured gain spectra (solid), and simulated (dashed). (c) Simulated gain spectra from GS (solid) and ES (dashed) seperately for current densities between 500A/cm2 (light gray) and 3000A/cm2 (black).

the time domain until a steady state is reached. 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 one third.

IV. ANALYSIS AND RESULTS

We did analyze the gain measurements by comparing the measured gain spectra with the calculated gain spectra. There are two effects which together cause the large broadening in the gain spectrum towards the shorter wavelength region with increasing injection current density. The first effect is the upcoming ES with increasing injection current densities. At low injection current densities all carriers relax to the GS and contribute to gain at the GS wavelength. At higher injection current densities part of the carriers will relax more to the ES due to the high occupation of carriers in the GS. The carriers in the ES contribute to gain at the ES wavelength. This upcoming ES gain can clearly be recognized in gain spectra from InAs QD on GaAs substrate [4] where a second peak can be detected around the ES wavelength. In our InAs QD on InP substrate we also did measure this upcoming ES gain, however, in this material system the GS and ES peak do overlap which makes there is no clear distinction between the two peaks. The large broadening in the measured gain spectrum can be assigned to this upcoming gain from the ES. It is however not the only effect which changes the gain spectrum with increasing injection current density. If it was the only effect we would have measured a jump in peak wavelength from the GS to the ES wavelength instead off a continuous shift in peak wavelength.

The second effect is the dot size dependent escape rate from the QD to the WL. After the relaxation from a carrier into a dot, it still can escape from the dot due to thermal energy in the material. The escape rate is directly dependent on the difference between the energy level in the dot and the energy level of the WL [4]. This means that due to the inhomogeneous dot size distribution the escape rate from the smaller dots is higher than the escape rate from the larger dots. The capture rate of the dots is however not dot size dependent and therefore the filling probability in the larger dots is higher than that of the smaller dots. If we look at the gain from e.g. only the ES we see that at low injection current densities the gain is higher in the relative longer wavelength region due to the relative higher filling probability in the larger dots Fig. 1c. When the injection current increases also smaller dots get occupied which extends the gain spectrum towards the shorter wavelength region. This dot size dependent escape rate causes the continuous shift in peak wavelength in the gain spectrum from GS wavelength to ES wavelength.

With the QD amplifier rate equation model we did determine the average energy level of the ES, E_{GS}=0.716eV (1730nm), and the ES, E_{ES}=0.760eV (1630nm) in our QD amplifier as well as the energy level of the WL, E_{WL}=0.843eV (1470nm) by fitting the simulated gain spectra to the measured gain spectra Fig. 1c (dashed). From the simulations we discovered that the energy difference between the GS and ES determines the amount of shift towards the shorter wavelength region with increasing injection current density. The energy difference between the ES and the WL determines the influence of the dot size dependent escape rate. Variations of the value of the basic time constants in the model do not have an influence on the shape change of the gain spectrum, only on the transparency current densities of the GS and ES gain.

V. CONCLUSION

The average energy level of the ES and GS as well as the energy level of the WL in our QD amplifiers could be determined by comparing the measured gain spectra with the simulated gain spectra. The simulations show that two effects together give rise to the increase in gain towards the shorter wavelength region with increasing injection current density; the upcoming ES gain with increasing injection current density and the dot size dependent escape rate from the dots to the WL.

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