Modulation $p$-doping as the way to attain multi-state lasing in short-cavity InAs/InGaAs quantum dot lasers

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Abstract. The influence of modulation $p$-doping on the lasing threshold current densities of InAs/InGaAs quantum dot (QD) lasers is studied at different levels of acceptor concentrations. It is found that for both undoped and $p$-doped samples, there exists a critical cavity length at which threshold current densities of the lasing via ground- and excited states of QDs become equal so that multi-state lasing can be observed only in samples having longer cavities. It is shown that the usage of modulation $p$-doping is an efficient way to overcome this limitation and to obtain multi-state lasing even in case of sufficiently short samples.

1. Introduction

For many practical applications including ultrafast data transmission and optical coherence tomography, there is a need for stable optical sources emitting near 1.2-1.3 μm corresponding to the transparency window of Si-based waveguides [1 – 2]. Long-wavelength InAs/InGaAs quantum dot (QD) lasers emitting via the QD ground-state (GS) optical transition allow not only to overlap the required spectral range, but also have small threshold currents and high temperature stability [3]. Even if the lasing starts at QD GS around 1.3 μm, further increase in injection usually results in appearance of an additional short wavelength lasing line near at 1.2 μm associated with the first excited-state (ES) optical transition of QDs, the multi-state lasing, i.e. simultaneous lasing via GS and ES of QDs, takes place [4 – 8].

The multi-state lasing can be useful in view of achieving broader lasing spectra [1] and a larger number of optical channels from a single laser source [9]. However, the GS lasing band is quenched with the increase in injection current shortly after the onset of multi-state lasing [7, 10 – 11]. One of the ways to overcome this effect is the usage of $p$-doping that can be an efficient solution particularly in case of the short samples [10]. At the same time, it is also known that $p$-doping may influence not only the output power corresponding to the GS of QDs but also the lasing threshold current [10 – 12]. This result allows one to expect that the $p$-doping can influence a minimal laser cavity length at which multi-state lasing, i.e. simultaneous lasing via GS and ES of QDs, still can be seen. Studying of this question constitutes the key goal of this work.
2. Experimental details

Three series of InAs/InGaAs QD lasers having different levels of \( p \)-doping of 0, 3 and \( 5 \times 10^{17} \) cm\(^{-3} \) were grown using molecular beam epitaxy (MBE). The active region of each sample was comprised of 10 layers of InAs/InGaAs QDs separated by 35 nm-thick GaAs spacers. The \( p \)-doping was implemented by using of carbon atoms embedded into the central areas of barrier layers. The laser diodes were fabricated to have various lengths and the same stripe width of 50 \( \mu \)m.

The experimental dependences were derived from the light-current curves and emission spectra measured at different injection currents.

3. Experimental results and their interpretation

To study the influence of \( p \)-doping level on the critical length of laser cavity at which multi-state lasing still can be seen, the dependence of threshold current densities of undoped and \( p \)-doped samples on laser cavity length was first measured – see Fig. 1 (a, b, c).

As it can be seen in Fig. 1, the decrease in laser cavity length results in the increase in threshold current density of the onset of the lasing via QD GS (\( j_{th,GS} \)), while threshold current of multi-state lasing (\( j_{th,GS+ES} \)) decreases. The injection current density interval corresponding to the multi-state lasing, i.e. the interval between \( j_{th,GS+ES} \) and \( j_{th,GS} \), tends to shrink as cavity length increases. Therefore, there is a critical cavity length (\( L_{cr} \)) at which threshold current of GS-lasing and of multi-state lasing become equal – see the vertical lines in Fig. 1. The characteristic feature of \( L_{cr} \) is that there is no lasing corresponding to QD GS for the samples shorter than \( L_{cr} \), where pure ES-lasing is only observed. Such a behavior remains true for \( p \)-doped samples as well – compare Fig. 1a, 1b and 1c. This poses a natural limit on the minimum length of laser cavity at which practically useful GS-lasing can be achieved.

However, the usage of modulation \( p \)-doping occurs to be a beneficial method to further increase the range of cavity lengths towards shorter cavities, at which simultaneous lasing via QD GS and ES still can be seen. Indeed, in accord with the experimental results shown in Fig. 1, the increase in the dopant concentration from 0 to \( 3 \times 10^{17} \) cm\(^{-3} \) and to \( 5 \times 10^{17} \) cm\(^{-3} \) results in the decrease of \( L_{cr} \) from 0.49 mm to 0.35 mm and to 0.33 mm respectively. The reason behind is the following: for the same
cavity length, the population inversion of QD GS in the case of p-doped samples is higher than in the case of undoped samples because of the higher occupancy of the hole energy levels due to the extra acceptor atoms [7, 10]. This allows holding the ground-state lasing condition even for cavity lengths shorter than \( L_{cr} \) of the undoped sample. Besides the higher is the concentration of the acceptor atoms, the smaller is \( L_{cr} \). At the same time, one may also note that the values of \( L_{cr} \) of the two p-doped QD lasers are close to each other as compared to \( L_{cr} \) of the undoped laser. In other words, we observe a “saturation” of the p-doping effect when doping becomes higher than 6 acceptors per QD.

It should be noted that the increase in p-doping level also contributes to the increase in the internal loss (\( \alpha_{in} \)) in laser cavity. Indeed, the increase in \( \alpha_{in} \) may be approximated from the experimental dependence of the reciprocal differential quantum efficiency (\( \eta_D^{-1} \)) on laser cavity length \( (L) \) using a well-known relationship \( \eta_D \propto \alpha_{tot}/(\alpha_{in} + \alpha_{tot}) \) as described in [10], where the output loss \( \alpha_{tot} = (1/L) \ln(1/R) \) and \( R \) is a reflectivity of as-cleaved mirrors. For the samples under the study \( R=0.3 \) and \( \alpha_{in} \) values corresponding to the p-doping level increasing from 0 to 3 and to \( 5 \times 10^{17} \text{ cm}^{-3} \) are 0.8, 1.0 and 1.8 cm\(^{-1} \). This trend can be explained by the enhancement of the free carrier absorption in laser cavity with the increase in p-doping concentration.

At the same time, as p-doping level increases, the absolute value of the GS gain also tends to increase mitigating the abovementioned growth in internal loss that can be also seen from the experimental dependence of the GS modal gain on the injection current density – see Fig. 2 at sufficiently high injection current densities. For instance, GS gain of the laser structure with dopant concentration of \( 3 \times 10^{17} \text{ cm}^{-3} \) is higher than in case of the undoped sample as injection current density exceeds 0.3 kA/cm\(^2 \). It is also possible to estimate maximum optical loss at which the GS gain can still balance the ES gain. Using the values of \( L_{cr} \) derived from the Fig. 1a – 1c, these values are 25.4, 35.4 and 38.3 cm\(^{-1} \) for the dopant concentrations of 0, 3 and \( 5 \times 10^{17} \text{ cm}^{-3} \) respectively. This illustrates the abovementioned enhancement of the GS gain that mitigates the increase in internal loss due to the p-doping.

4. Conclusion

In conclusion, the influence of p-doping level on the threshold current densities of ground- and multi-state lasing in InAs/InGaAs quantum dot (QD) lasers was studied in details. It was shown that for each sample, there exists a critical cavity length and multi-state lasing can be observed only for cavities longer than the critical one. This is due to the increased output loss in sufficiently short samples. At the same time, the usage of p-doping occurs to be a beneficial way to overcome this limit: It is shown that the higher is the p-doping level, the smaller is the critical length and, thus, the shorter can be the samples in which multi-state lasing can be observed. This effect can be qualitatively explained as interplay between the contribution of the p-doping into the total loss and GS gain. Although p-doping contributes to the increase in the internal loss, the latter is mitigated by the contribution of p-doping to the GS gain. It should be noted that at sufficiently high levels of p-doping, its effect on cavity critical length becomes limited and saturates at the dopant concentration exceeding 10 acceptors per QD.

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