The effect of \( p \)-doping on multi-state lasing in InAs/InGaAs quantum dot lasers for different cavity lengths

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Abstract. The effect of modulation \( p \)-doping on multi-state lasing in InAs/InGaAs quantum dot (QD) lasers is studied for different levels of acceptor concentration. It is shown that in case of the short laser cavities, \( p \)-doping results in higher output power of the ground-state optical transitions of InAs/InGaAs QDs whereas in longer samples \( p \)-doping may result in the decrease of this power component. On the basis of this observation, the optimal design of laser active region and optimal doping level are discussed in details.

1. Introduction

Long-wavelength InAs/InGaAs quantum dot (QD) lasers emitting via QD ground-state (GS) optical transitions of quantum dots near 1.3 \( \mu \)m are important light sources for many practical applications and, in particular, for ultrafast data transmission [1 – 2]. Such lasers are characterized with small injection currents and high temperature stability [3]. However, even if lasing starts at QD GS, further increase in injection may result in an additional short wavelength spectral line centered at 1.2 \( \mu \)m associated with first excited-state (ES) optical transition of QDs [4 – 8]. This, in its turn, results in GS-lasing quenching with the increase in injection current shortly after the onset of multi-state lasing [6, 8]. It is known that \( p \)-doping may be an effective way to increase the power of GS spectral component [9, 10]. However, such an important effect as an influence of \( p \)-doping level on multi-state lasing phenomenon was not studied yet. The key goal of this work is to shed light on this question both experimentally and theoretically.

2. Sample growth and experimental results

To study this question experimentally, we have fabricated two series of samples with short and long cavities. All InAs/InGaAs QD lasers studied in the paper were grown using molecular beam epitaxy (MBE) and had the same stripe width of 50 \( \mu \)m. Cavity length was either 0.5 mm (short samples) or 1.0 mm (long samples). The active region of each sample was comprised of 10 layers of InAs/InGaAs QDs separated by 35 nm-thick GaAs spacers, which were \( p \)-doped with different concentrations of carbon dopant atoms (0, 3, and 5\( \times \)10\(^{17} \) cm\(^{-3} \)). The experimental light-current curves of these samples were measured for these two crucial cavity lengths as it is shown in Fig. 1.

As it can be seen from the Fig. 1a, in case of the long samples, the increase in \( p \)-doping level results in the decrease of \( W_{\text{max GS}} \) – the maximal output power corresponding to the GS of QDs. At the same time, in case of the short samples the situation is opposite – see Fig. 1b. Such a behaviour may be somehow surprising, as previously it was typically assumed that \( p \)-doping always leads to the
enhancement of the output power corresponding to the GS of QDs as well as improves the other characteristics of QD lasers [8 – 10].

![Figure 1(a, b). Experimental dependence of GS and ES components of the output optical power on injection current for p-doped InAs/InGaAs QD lasers having different concentrations of carbon dopant atoms at different cavity lengths of (a) 1.0 mm and (b) 0.5 mm. For both figures, the concentration p-type dopant varies from 0 to 5×10^{17} cm^{-3}.](image)

3. Theoretical description

To describe theoretically an influence of p-doping level on the operation of QD lasers, we used a rate-equation model describing charge carrier dynamics in QDs and photon dynamics in laser cavity in accord with [8]. As it can be seen from the experimental data shown in the Fig. 1, there is a distinct trade-off between the influence of modulation p-doping on multi-state lasing in the case of short and long samples. Qualitatively, such a discrepancy can be interpreted as follows.

On the one hand, the increase in p-doping level leads to the increase in the maximal output power corresponding to the GS of QDs ($W_{\text{max GS}}$) due to the increased hole capture rate because of the reasons discussed in [8, 9]. In particular, this is due to the higher occupancy of the hole energy levels in InAs/InGaAs QDs. This mitigates the competition for the common holes between GS and ES optical transitions of InAs/InGaAs QDs that is one of the key limiting factors for $W_{\text{max GS}}$. On the other hand, the increase in p-doping level typically results in the increase in internal loss ($\alpha_{\text{in}}$), e.g. due to the growth in free carrier absorption and, thus, in the decrease in laser efficiency as it can be seen from the $L$-$I$ curve shown in the Fig. 1a, which becomes less steep as p-doping level increases.

In the case of shorter samples having sufficiently high output loss, GS gain is comparable with its saturated value. Therefore, an effect of p-doping on the suppression of ES-lasing is significant. At the same time, the increase in the internal loss ($\alpha_{\text{in}}$) is insignificant as compared with radiation output loss ($\alpha_{\text{out}}$). For instance, in the case of the sample with $L$=0.5 mm, the increase in p-doping level from 0 to $3\times10^{17}$ cm^{-3} results in the increase in $\alpha_{\text{in}}$ by 0.2 cm^{-1}, while the output loss has a value of ~24 cm^{-1}. Therefore, the external differential efficiency of such a laser remains practically unchanged and $W_{\text{max GS}}$ increases from 0.8 to 2.2W as the level of modulation p-doping increases from 0 to $5\times10^{17}$ cm^{-3} – see Fig. 1b.

In the case of long samples, the output loss ($\alpha_{\text{out}}$) is much smaller as compared to the short samples and GS gain is far from its saturated value. Therefore, the usage of modulation p-doping does not contribute significantly to the ES-lasing suppression. At the same time, in the case of long samples, the increase in $\alpha_{\text{in}}$ plays a more substantial role and contributes to the decrease in the external...
differential efficiency of such lasers – compare the slopes of the red \((3 \times 10^{17} \text{ cm}^{-3})\) and the green \((5 \times 10^{17} \text{ cm}^{-3})\) in the Fig. 1a. As it can be seen from the comparison of the experimental results presented in the Fig. 1a and Fig. 1b, the effect of the decrease in \(W_{\text{max}}^{\text{GS}}\) due to the decreased efficiency in case of the \(p\)-doped samples is much more pronounced in long samples and tends to dominate over the positive effect of the \(p\)-doping. At the same time, in the case of short samples the situation is opposite and the increase in \(p\)-doping level has a positive influence on the GS-power. As a result for a given cavity length there is an optimal concentration of the \(p\)-dopant maximally enhancing the output power corresponding to the GS of QDs.

4. Conclusion
In conclusion, the effect of multi-state lasing was studied both theoretically and experimentally. It was shown that the higher \(p\)-doping level does not necessarily lead to the higher output power corresponding to the GS optical transitions of quantum dots. On the one hand, the increase in the \(p\)-dopant concentration leads to the higher hole capture rate, increases GS gain and mitigates the competition for the common holes between the GS and ES optical transitions. This makes GS-lasing more preferable as compared to ES-lasing. On the other hand, an introduction the \(p\)-dopant atoms increase the internal loss resulting in the reduction in the slope efficiency.

In case of the short samples having high loss, the introduction of modulation \(p\)-doping increases the maximal power of the GS spectral component. In long samples, the effect is opposite because of its influence on internal loss. Thus, the usage of \(p\)-doping occurs to be most beneficial in case of the short samples allowing to increase GS output power.

Acknowledgements
This work is supported by the Russian Scientific Foundation (project #14-42-00006).

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