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Novel, simple model for high temperature stability of InAs/GaAs self-assembled quantum dot lasers with optimum *p*-type modulation doping

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1. Introduction

1.3 µm InAs/GaAs self-assembled quantum dot (QD) lasers with *p*-type modulation doping structures have received much attention for achieving high temperature stability around room temperature (RT).[1] An infinite or even negative characteristic temperature (T_0) was demonstrated above RT recently.[2-4] However, it is difficult to compare the doping densities among many research groups, since different structures and calibration methods were employed. Therefore, how to optimize *p*-doping densities to achieve the best temperature stability is still unclear.

In this work, we show that a theoretical model of the temperature-dependent threshold current densities (J_{th}) of QD lasers can be simplified by using an assumption of equal state-filling among QDs for operation conditions near the threshold. Based on this simple method, the effects of varied *p*-type modulation doping levels on the temperature-dependent threshold behavior of QD lasers have been analyzed. The calculated temperature-dependent J_{th} makes a good agreement with our experimental results of varied doping levels. Further investigation shows there is an optimized *p*-doping level which can provide the highest T_0 value above RT.

2. Theory

For the lasing QDs, which are involved in generating and lasting the lasing light, there are mainly three carrier transfer processes near the threshold, as shown in the upper-right inset of Fig. 1: (a) stimulated emission process, which dominates the carrier recombination near the threshold in the lasing QDs; (b) carrier injection process, which is getting faster when increasing the injection current; (c) redistribution of carriers due to thermal excitation from other QDs. This thermal redistribution process is an important mechanism for the sub-threshold behaviour of the QD structures. However, near and above the threshold, it is much slower than the stimulated emission process, and the contribution of those redistributed carriers can be ignored.[3] Therefore, the photon coupling process between the ground (GS) and first excited QD states (ES) becomes relatively important for the temperature-dependent J_{th} of QD lasers, and also the heavily filled QD states at threshold

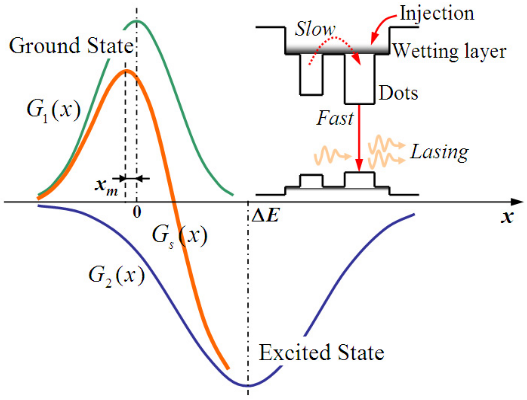

Fig. 1. A schematic picture of the coupling between two Gaussian functions for the GS and ES. The inset shows the carrier processes in QD lasers near the threshold condition.

makes the carrier distribution among QDs tend to be uniform.[3] By ignoring the carrier redistribution process, a equal state-filling among QDs is therefore assumed for the operation condition near the threshold in our theoretical model discussed in this work.

Figure 1 shows the photon coupling process between the gain spectra of the GS and first ES. Both of them are normally expressed by Gaussian functions as follows:

$$G_s(x) = g_0(f_1^c + f_1^v - 1)[G_1(x) + \alpha_c G_2(x)] \quad , \tag{1}$$

where $\alpha_c = 2\cdot(f_2^c + f_2^v - 1)/(f_1^c + f_1^v - 1)$ reflects the carrier distribution ratio between the GS and ES, G_1 and G_2 are normalized Gaussian functions, and g_0 is the gain coefficient. If the coupling between GS and ES is considered, the peak gain of the whole QD ensemble G_s^m can be expressed as (assuming the peak gain position $x_m \rightarrow 0$ and $|x_m| << \Delta E$):

$$G_s^m = g_m(f_1^c + f_1^v - 1)\left\{1 + \alpha_c \frac{\sigma_1}{\sigma_2} \exp\left[-\frac{(\Delta E)^2}{2\sigma_2^2}\right]\right\} \quad , \tag{2}$$

where σ_1 and σ_2 are the line-width of Gaussian functions of G_1 and G_2, ΔE is the energy separation between the GS and ES, and g_m is the maximum GS gain with full state-filling.

Without the photon coupling process, the threshold condition holds when the peak gain of GS approaches the threshold gain: g_{th}. Therefore,

$$g_{gs}^{m} = g_{th} = \varepsilon g_{m} \quad , \tag{3}$$

where $\varepsilon = f_1^c + f_1^v - 1$. Now, the peak gain of the whole QD ensemble is derived to be:

$$G_s^m = g_{th}\left\{1 + \alpha_c \frac{\sigma_1}{\sigma_2}\exp\left[-\frac{(\Delta E)^2}{2\sigma_2^2}\right]\right\} \quad , \tag{4}$$

which is slightly departed from the real threshold condition. By comparing equation (4) with g_{th}, the peak gain of the GS at threshold needs to be modified from g_{th} to be ($x_m \rightarrow 0$):

$$g_{gs}^{m} = g_{th}\left\{1 - \alpha_c \frac{\sigma_1}{\sigma_2}\exp\left[-\frac{(\Delta E)^2}{2\sigma_2^2}\right]\right\} \quad . \tag{5}$$

The second term in the big bracket presents the photon coupling mechanism from the first ES. Therefore, the peak gain of GS at threshold will change with the temperature due to the photon coupling mechanism.

The fluctuation of the GS peak gain results in the J_{th} change with varied temperatures. To simply relate the GS peak gain with the J_{th} of QD lasers, it is assumed that the peak gain of GS follows a logarithmic gain-current relation with the current injected into QDs. The temperature-dependent J_{th} can be obtained by the summation of both the current injected into QDs and wetting layers:

$$J_{th} = J_0 \exp\left(\frac{g_{gs}^{m}}{g_0^{*}} - 1\right) + J_w \quad , \tag{6}$$

where g_0^* and J_0 are the saturation gain parameters. J_w is the current for the wetting layer. We have assumed the Auger process dominated the carrier recombination in the wetting layer.

3. Results

In the theoretical calculation, the following parameters are used: the band offset coefficient c = 0.75, the peak-emission energy of the GS E_{gs} = 0.95 eV, the energy separation between the GS and ES ΔE = 60 meV, the band-gap energy of the wetting layer E_w = 1.18 eV, the line-width of the Gaussian functions for the GS and ES σ_1 = 18 meV and σ_2 = 28 meV, and the threshold-gain constant ε = 0.3.

Figure 2 shows the temperature-dependent J_{th} obtained from different *p*-doping levels. An infinite T_0 around RT presents with a doping level of 20 acceptors/dot, whereas a negative T_0 can be obtained with less doping of 15 acceptors/dot. Further increasing the doping levels results in lower fluctuation of J_{th} which tends to be monotonically depended on the temperature, but the RT T_0 will get lower in the same time. The blue(closed circles), red(squares) and green(triangles) curves in this figure correspond to the doping levels of 0, 15, and 50 acceptors/dot, which reproduce behaviours of the temperature-dependent J_{th} very similar to our experimental results as are represented in the inset. Thus, this theoretical model can fully explain the *p*-doping effects on the threshold current of QD lasers with varied doping levels. Furthermore, an optimized doping level is observed in this calculation within the doping range of 15-20 acceptors/dot, with a maximum T_0 value of 440 K for the temperature range from 0 to 50 ºC.

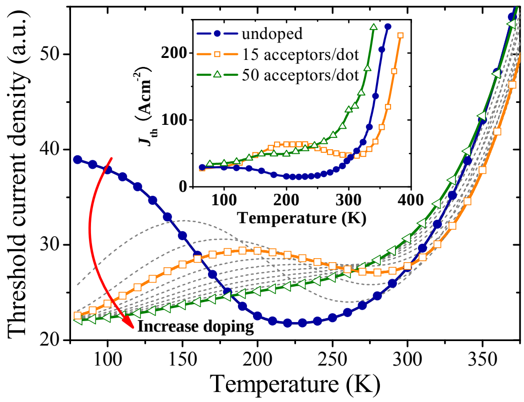

Fig. 2. Calculated temperature-dependent J_{th} for QD lasers with increasing doping levels (0, 5, 10, …, 50 acceptors/dot). The inset shows experimental results obtained from QD lasers with doping levels of 0, 15, 50 acceptors/dot.[4]

4. Conclusions

In summary, the theoretical model with a photon coupling mechanism for QD lasers has been simplified for operation conditions near the threshold by using an assumption of equal state-filling among QDs. This simple model can account for the effects of different *p*-doping levels on the temperature-dependent performance of QD lasers, and a good agreement with experimental results has been demonstrated. Further investigation based on this model has shown that there is an optimized doping level, which can provide the highest T_0 value above RT.

References

[1] O. B. Shchekin and D. G. Deppe, Appl. Phys. Lett. **80**, 3277 (2002).
[2] S. Fathpour, Z. Mi, P. Bhattacharya, A. R. Kovsh, S. S. Mikhrin, I. L. Krestnikov, A. V. Kozhukhov, and N. N. Ledentsov, Appl. Phys. Lett. **85**, 5164 (2004).
[3] C. Y. Jin, H. Y. Liu, K. M. Groom, Q. Jiang, M. Hopkinson, T. J. Badcock, R. J. Royce, and D. J. Mowbray, Phys. Rev. B **76**, 085315, (2007).
[4] T. J. Badcock, R. J. Royce, D. J. Mowbray, M. S. Skolnick, H. Y. Liu, M. Hopkinson, K. M. Groom, and Q. Jiang, Appl. Phys. Lett. **90**, 111102 (2007).