Maximum operating temperature and characteristic temperature of a quantum dot laser in the presence of internal loss

Li Jiang* and Levon V. Asryan**

Virginia Polytechnic Institute and State University, Blacksburg, VA 24061

ABSTRACT

Carrier-density-dependent internal optical loss sets an upper limit for operating temperatures and considerably reduces the characteristic temperature of a quantum dot laser. Such internal loss also constrains the shallowest potential well depth and the smallest tolerable size of a quantum dot at which the lasing can be attained. At the maximum operating temperature or when any parameter of the structure is equal to its critical tolerable value, the characteristic temperature drops to zero.

Keywords: Internal optical loss, quantum dot lasers, semiconductor lasers

1. INTRODUCTION

High temperature stability of operation has been predicted for semiconductor quantum dot (QD) lasers [1] and there has already been significant progress in the fabrication of such devices (see [2] and references therein). Ideally, the threshold current density j_{th} of a QD laser should remain unchanged with the temperature and the characteristic temperature, which is defined as $T_0 = \left(\partial \ln j_{\mathrm{th}} / \partial T\right)^{-1}$, should be infinitely high. This would be the case if (i) the overall injection current went into QDs, and (ii) the recombination current in QDs would be temperature-independent. In actual lasers, carriers are first injected into the optical confinement layer (OCL) (which also includes the wetting layer), and then appear in QDs. Hence the recombination processes both in QDs and in the OCL control j_{th} and its T-dependence [3]:

$$\frac{1}{T_0} = \frac{j_{\mathrm{QD}}}{j_{\mathrm{QD}} + j_{\mathrm{OCL}}} \frac{1}{T_0^{\mathrm{QD}}} + \frac{j_{\mathrm{OCL}}}{j_{\mathrm{QD}} + j_{\mathrm{OCL}}} \frac{1}{T_0^{\mathrm{OCL}}}, \tag{1}$$

where T_0^{QD} and T_0^{OCL} are defined similarly to T_0 but for the components of j_{th} associated with the recombination in QDs and in the OCL, respectively. The latter are given as

$$j_{\mathrm{QD}} = \frac{eN_S}{\tau_{\mathrm{QD}}} f_n f_p, \qquad j_{\mathrm{OCL}} = ebBnp, \tag{2}$$

where N_S is the surface density of QDs, τ_{QD} is the spontaneous radiative recombination time in QDs, f_n and f_p are the confined-electron and -hole level occupancies in QDs at the lasing threshold, b is the OCL thickness, B is the radiative constant for the OCL, and n and p are the free-electron and -hole densities in the OCL at the lasing threshold.

* E-mail: lijiang@vt.edu

** E-mail: asryan@mse.vt.edu; Web: http://www.mse.vt.edu/people/faculty/asryan.html; Telephone: 1 (540) 231-7033

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The T-dependence of n and p acts as the major source of such dependence of j_{th} [3, 4]. Thus, when the carrier distribution (below and at the lasing threshold) is described by the equilibrium statistics (relatively high T), n and p depend exponentionally on T,

$$n = n_1 \frac{f_n}{1 - f_n}, \tag{3}$$

where $n_1 = N_c^{\mathrm{OCL}} \exp\left(-E_n/T\right)$, $N_c^{\mathrm{OCL}} = 2\left(m_c^{\mathrm{OCL}} T/2\pi\hbar^2\right)^{3/2}$, m_c^{OCL} is the electron effective mass in the OCL, T is the temperature measured in units of energy, and E_n is the carrier excitation energy from a QD to the OCL (see the inset in Fig. 3); the equation for p is similar to (3).

Different factors can also contribute to the T-dependence of $f_{n,p}$ and hence of j_{QD}, thus making T_0^{QD} finite. In [3], violation of charge neutrality in QDs ($f_n \neq f_p$) was shown to be such a factor.

2. INTERNAL LOSS AS A SOURCE OF TEMPERATURE DEPENDENCE

Here we study the effect of carrier-density-dependent internal optical loss in the OCL on the T-dependence of j_{th}. As in other injection lasers [5]–[8], such a loss can strongly affect the temperature stability of QD lasers [9]. This work is based on [10], where j_{th} has been calculated in the presence of the n-dependent internal loss. To neatly clarify the effect of internal loss, the charge neutrality [separately in QDs ($f_n = f_p$) and in the OCL ($n = p$)] is assumed here. In general, the internal loss coefficient α_{int} increases with the carrier density n. Presenting α_{int} as $\alpha_0 + \sigma_{\mathrm{int}} n$, where α_0 is the constant component, and σ_{int} is the effective cross section for the internal absorption loss processes [10], the lasing threshold condition is written as

$$g^{\max}\left(2 f_n - 1\right) = \beta + \alpha_0 + \sigma_{\mathrm{int}} n, \tag{4}$$

where $g^{\max}$ is the maximum (saturation) gain (see eq. (20) in [10]), $\beta = \left(1/L\right)\ln\left(1/R\right)$ is the mirror loss, L is the cavity length, and R is the facet reflectivity.

In the absence of the n-dependent internal loss ($\sigma_{\mathrm{int}} = 0$), $f_n = \mathrm{const}\ (T)$ [see (4)] and hence $j_{\mathrm{QD}} = \mathrm{const}\ (T)$, and $T_0^{\mathrm{QD}} = \infty$. As seen from (4), the n-dependent internal loss couples n and f_n and, in view of the T-dependence of n, makes f_n and j_{QD} also T-dependent. Thus, T_0^{QD} becomes finite. The following expression is obtained for T_0^{QD}:

$$\frac{1}{T_0^{\mathrm{QD}}} = \frac{1}{\dfrac{3}{4} + \dfrac{\beta + \alpha_0 - \sigma_{\mathrm{int}} n_1}{4 g^{\max}} - f_n} \frac{\sigma_{\mathrm{int}} n_1}{2 g^{\max}} \left(\frac{3}{2}\frac{1}{T} + \frac{E_n}{T^2} \right), \tag{5}$$

where f_n is calculated from eqs. (3) and (4) and given by eq. (9) in [10].

The n-dependent α_{int} also alters the T-dependence of j_{OCL} since the free-carrier density is strongly affected. The expression for T_0^{OCL} is

$$\frac{1}{T_0^{\mathrm{OCL}}} = \frac{3}{2}\frac{1}{T} + \frac{2E_n}{T^2} + \frac{1}{1 - f_n}\frac{1}{T_0^{\mathrm{QD}}}. \tag{6}$$

As seen from (6), T_0^{OCL} is decreased due to the carrier-density-dependent internal loss (the reciprocal of T_0^{OCL} in the absence of such a loss is given by the sum of the first two terms in the right-hand side).

3. RESULTS AND DISCUSSION

Below, a GaInAsP/InP heterostructure lasing near 1.55 μm is used for calculations. The parameters are as follows (unless otherwise specified): the root mean square (RMS) of relative QD size fluctuations $\delta = 0.05$ (Gaussian distribution is assumed), $b = 0.28$ μm, $N_S = 6.11\times10^{10}$ cm^{-2}, $\alpha_0 = 3$ cm^{-1}, $\sigma_{\rm int} = 2.67\times10^{-17}$ cm^2, $L = 1.628$ mm, and $\beta = 7$ cm^{-1}.

As seen from Fig. 1, T_0 is considerably reduced due to the n-dependent internal loss. At room temperature, T_0 is about twice as low as that neglecting such a loss.

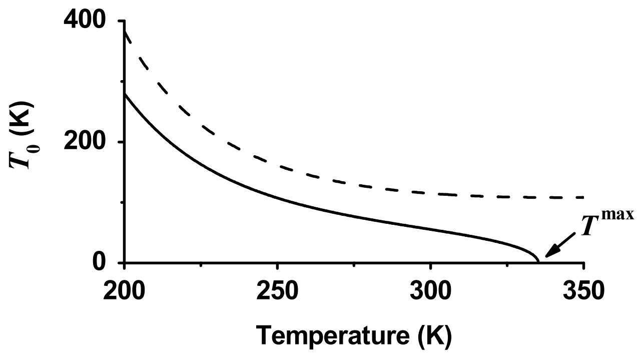

Fig. 1: Characteristic temperature against T calculated including (solid curve) and neglecting (dashed curve) the carrier-density-dependent internal loss in the OCL.

T_0 falls off profoundly with increasing T (Fig. 1). At a certain temperature $T^{\rm max}$, presenting the maximum operating temperature of the device ($T^{\rm max} = 335$ K for the specific case considered), T_0 goes to zero. Hence even in the absence of heating effects, the n-dependent internal loss itself sets an upper limit for operating temperatures of a QD laser. The point is that the carrier density n and hence the internal loss $\alpha_{\rm int} = \alpha_0 + \sigma_{\rm int}\, n$ increase continuously with T. At the same time, the maximum gain of a laser can not exceed $g^{\rm max}$ [see (4)]. For $T > T^{\rm max}$, the lasing condition (4) can not be satisfied. The following transcendental equation is derived for $T^{\rm max}$:

$$\frac{1}{\left(T^{\rm max}\right)^{3/4}} \exp\left(\frac{E_n}{2T^{\rm max}}\right) = \frac{\sqrt{2\left(m_c^{\rm OCL}/2\pi\hbar^2\right)^{3/2}\sigma_{\rm int}}}{\sqrt{2g^{\rm max}} - \sqrt{g^{\rm max} + \beta + \alpha_0}}\,. \tag{7}$$

The carrier density n in the OCL [eq. (3)] is also strongly controlled by the excitation energy E_n from a QD. The smaller E_n, the easier for carriers to escape to the OCL and hence the higher are n and $\alpha_{\rm int}$. Just as $T^{\rm max}$ exists, there is a lowest excitation energy, $E_n^{\rm min}$, below which no lasing is attainable in a structure. From (7), an explicit expression is apparent for $E_n^{\rm min}$,

$$E_n^{\rm min} = T \ln\left[\frac{N_c^{\rm OCL}\sigma_{\rm int}}{\left(\sqrt{2g^{\rm max}} - \sqrt{g^{\rm max} + \beta + \alpha_0}\right)^2}\right]. \tag{8}$$

Since E_n decreases with reducing QD size (E_n is the separation between the quantized energy level and the top of the well — see the inset in Fig. 3), there also exists the smallest tolerable QD size $a^{\rm min}$. It has been known (see, e.g. [11]) that, in contrast to one-dimensional symmetrical potential well (which supports the quantized energy level no matter how thin it is), there is a smallest size of a three-dimensional (even symmetrical) well (QD), beyond which no bound state can exist. As seen from the present analysis, a more strict condition should be satisfied to attain lasing in the presence of the n-dependent internal loss. Just having a confined energy level in a QD is not sufficient — the level should be so deeply localized that the carrier density in the OCL and the internal loss are low enough for holding the lasing condition (4).

$E_n^{\min}$ decreases with reducing σ_{int} [eq. (8) and Fig. 3]. At a certain value of σ_{int} given by

$$\sigma_{\text{int}}^{*} = \frac{\left(\sqrt{2g^{\max}} - \sqrt{g^{\max} + \beta + \alpha_0}\right)^2}{N_c^{\text{OCL}}}\,, \tag{9}$$

the minimum tolerable excitation energy turns to zero, $E_n^{\min} = 0$. For a specific structure considered here, $\sigma_{\text{int}}^{*} = 0.57\times10^{-17}\ \text{cm}^2$. On further decreasing σ_{int}, eq. (8) would formally give negative $E_n^{\min}$. Hence, for $\sigma_{\text{int}} \le \sigma_{\text{int}}^{*}$, the restriction placed by the n-dependent internal loss on the shallowest potential well depth or the smallest QD size is removed — the minimum size is solely determined by the condition of existence of a bound state.

As shown previously [4, 10, 12], there exist the critical tolerable values of the QD-structure parameters beyond which no lasing is attainable. These critical quantities are the maximum RMS of QD-size fluctuations $\delta^{\max}$, the minimum surface density of QDs $N_S^{\min}$, the minimum cavity length $L^{\min}$, and the maximum cross-section of internal loss $\sigma_{\text{int}}^{\max}$. As shown here, there are three more critical parameters ($T^{\max}$, $E_n^{\min}$, $a^{\min}$) in the presence of the n-dependent α_{int}.

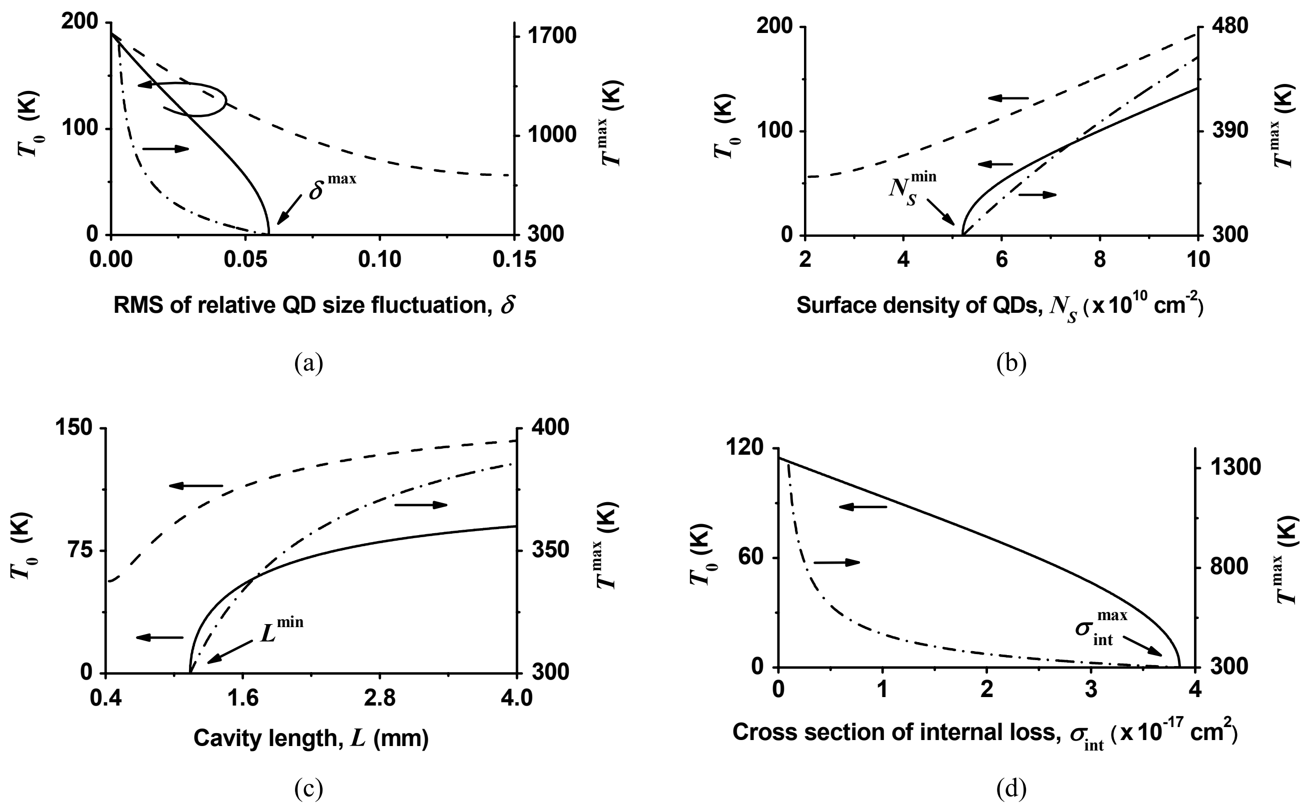

Fig. 2: Characteristic temperature calculated including (solid curve, left axis) and neglecting (dashed curve, left axis) the carrier-density-dependent internal loss in the OCL, and maximum operating temperature (dash-dotted curve, right axis) against RMS of QD size fluctuations (a), surface density of QDs (b), cavity length (c), and cross section of internal absorption loss (d).

Fig. 2 shows $T^{\max}$ and T_0 versus the structure parameters. The maximum gain $g^{\max}$ is a function of the RMS of QD size fluctuations δ and the surface density of QDs N_S ($g^{\max} \propto N_S/\delta$, see eq. (20) in [10]). As seen from (4), varying $g^{\max}$ affects f_n and n and hence the temperature characteristics of a laser. The greater δ or the smaller N_S (i.e. the smaller is $g^{\max}$), the lower are T_0 and $T^{\max}$ [Fig. 2(a) and (b)]. In the presence of the n-dependent internal loss, T_0 decreases with increasing δ or decreasing N_S faster than that neglecting such a loss [Fig. 2(a) and (b)]. While T_0 in the absence of the n-dependent internal loss remains nonvanishing (though low) with increasing δ (or decreasing N_S), T_0 in the presence of such a loss turns to zero at the critical value $\delta = \delta^{\max}$ (or $N_S = N_S^{\min}$). As $\delta \to 0$ or $N_S \to \infty$, $g^{\max}$ becomes infinitely high and $T^{\max} \to \infty$ [see eq. (7) and Fig. 2(a) and (b)].

T_0 and $T^{\max}$ reduce with decreasing cavity length L [Fig. 2(c)]. T_0 in the absence of the n-dependent internal loss remains nonvanishing with decreasing L while that in the presence of such a loss turns to zero at $L = L^{\min}$. As $L \to \infty$, i.e. $\beta \to 0$, both T_0 and $T^{\max}$ remain finite [for $T^{\max}$, see also eq. (7)].

Although σ_{int} is not an easily controllable parameter in a given structure, in order to illustrate its effect on T_0 and $T^{\max}$, we also present here the dependences on σ_{int} [Fig. 2(d)]. T_0 and $T^{\max}$ decrease with increasing σ_{int}; at the critical value $\sigma_{\text{int}} = \sigma_{\text{int}}^{\max}$, T_0 becomes zero. Like with $g^{\max} \to \infty$, $T^{\max}$ becomes infinitely high when $\sigma_{\text{int}} \to 0$ [Fig. 2(d) and eq. (7)]. This tendency is readily seen also from eq. (4) — if $\sigma_{\text{int}} \to 0$ (α_{int} becomes temperature-independent: $\alpha_{\text{int}} \to \alpha_0$) or $g^{\max} \to \infty$, the solution for f_n exists at any T.

In the presence of the n-dependent internal loss, the critical tolerable values of the parameters depend on T. In Fig. 2, the room-temperature critical tolerable values are used. That is why when any of the parameters (δ, N_S, L, or σ_{int}) approaches its critical value ($\delta^{\max}$, $L^{\min}$, $N_S^{\min}$, or $\sigma_{\text{int}}^{\max}$, respectively), $T^{\max}$ reduces to 300 K. Beyond the critical tolerable value of any parameter, $T^{\max}$ goes below 300 K, i.e. no room-temperature lasing is possible.

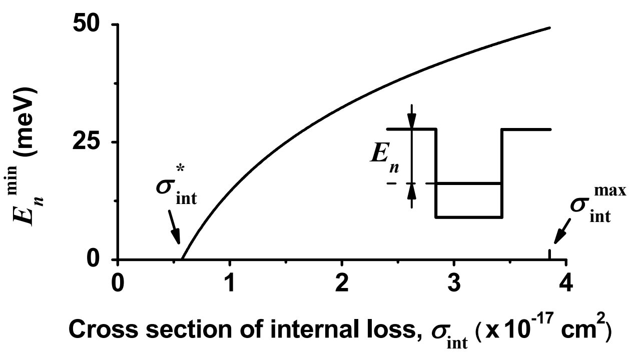

Fig. 3: Minimum tolerable excitation energy from a QD against cross section of internal absorption loss.

4. CONCLUSIONS

The carrier-density-dependent internal loss in the OCL considerably reduces the characteristic temperature T_0 and sets an upper limit $T^{\max}$ for operating temperatures of a QD laser. Such a loss also constrains the shallowest potential well depth and the smallest tolerable size of a QD at which the lasing is attainable. When $T = T^{\max}$ or any parameter of the structure is equal to its critical tolerable value, T_0 drops to zero.

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