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Author(s)	Cao, Yu-Lian; Ji, Hai-Ming; Yang, Tao; Zhang, Yan-Hua; Ma, Wen-Quan; Wang, Qi-Jie
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**Three-region characteristic temperature in p-doped quantum dot lasers**

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## Three-region characteristic temperature in p-doped quantum dot lasers

Yu-Lian Cao,<sup>1,2,a)</sup> Hai-Ming Ji,<sup>3</sup> Tao Yang,<sup>3,a)</sup> Yan-Hua Zhang,<sup>1</sup> Wen-Quan Ma,<sup>1</sup>  
 and Qi-Jie Wang<sup>2</sup>

<sup>1</sup>Nano-Optoelectronics Laboratory, Institute of Semiconductors, Chinese Academy of Sciences,  
 Beijing 100083, People's Republic of China

<sup>2</sup>NOVITAS, Nanoelectronics Centre of Excellence, School of Electrical and Electric Engineering, Nanyang  
 Technological University, Singapore, 639798, Singapore

<sup>3</sup>Key Laboratory of Semiconductor Materials Science, Institute of Semiconductors, Chinese Academy  
 of Sciences, Beijing 100083, People's Republic of China

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We have investigated the temperature dependence of threshold in p-doped 1.3  $\mu\text{m}$  InAs/GaAs quantum dot (QD) lasers with ten layers of QDs in the active region. It is found that the dependence of threshold current density on the temperature within the temperature range from 10 to 90 °C can be divided into three regions by its characteristic temperature ( $T_0$ ): negative, infinite, and positive  $T_0$  regions. Furthermore, the  $T_0$  region width is dependent on the cavity length: the longer cavity length of the QD lasers correspondingly the wider  $T_0$  region. Additionally, for the broad area laser, the threshold modal gains of the lasers with different cavity lengths can be fitted by an empirical expression as a function of the threshold current density, when at the temperatures of 30, 50, and 70 °C. We find that the transparency current density ( $J_{\text{tr}}$ ) remains almost unchanged under different temperatures according to the extracted parameters from these fitted results, which indicates that  $J_{\text{tr}}$  plays an important role in balancing the  $T_0$  between negative region and positive one. © 2014 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4862027>]

Self-organized quantum dots (QD) have attracted considerable attention because of their potential applications in optoelectronic devices. For QD lasers, low threshold current density ( $J_{\text{th}}$ ) and high temperature stability were predicted in the early 1980s.<sup>1,2</sup> Recently, significant efforts have been made to improve the characteristic temperature ( $T_0$ ) of 1.3  $\mu\text{m}$  quantum dot lasers for applications in the photonic networks<sup>3–5</sup> such as using p-type modulation doping in the active region. High  $T_0$  has not only been theoretically predicated but also been measured in p-doped quantum dot lasers.<sup>6–10</sup> For example, at cryogenic temperature, the threshold current of QD laser remains constant (as characterized by infinite  $T_0$ ) or decreases with temperature (as characterized by negative  $T_0$ ).<sup>10</sup> A few explanations have been proposed for these phenomena,<sup>8–11</sup> but no consensus has been reached till now. Recently, some researchers proposed that transparency current plays a critical role in the negative  $T_0$  region for both undoped and p-doped QD lasers.<sup>12</sup>

In this letter, the temperature dependence of threshold current is investigated in detail for the p-doped 1.3  $\mu\text{m}$  InAs/GaAs quantum dot lasers with different cavity lengths within application temperature range from 10 to 90 °C. The dependence of threshold current density on the temperature can be divided into three regions by its  $T_0$ : negative  $T_0$  region, infinite  $T_0$  region, and positive  $T_0$  region. By fitting the dependence of threshold modal gain on the threshold current density under different temperature, we found that  $J_{\text{tr}}$  was independent on the temperature, which indicates that  $J_{\text{tr}}$  plays an important role in balancing the  $T_0$ , as reported in the literature.<sup>12</sup>

The laser structure was grown by solid-source molecular beam epitaxy. The self-assembled InAs/GaAs quantum dot active region was sandwiched between two 1.5- $\mu\text{m}$ -thick  $\text{Al}_{0.35}\text{Ga}_{0.65}\text{As}$  cladding layers. The QD active region consisted of 10 layers InAs/ $\text{In}_{0.15}\text{Ga}_{0.85}\text{As}$  QDs separated by a 33-nm-thick spacer between the QD layers. A 0.2  $\mu\text{m}$  P+-GaAs contact layer was used for electrical contact. The density of quantum dots is  $5 \times 10^{10} \text{ cm}^{-2}$ . 10 nm-thick P-GaAs layers were included in the spacer layers, which were doped with acceptor density of  $5 \times 10^{17} \text{ cm}^{-3}$ . The P-GaAs contact layer and a part of p- $\text{Al}_{0.35}\text{Ga}_{0.65}\text{As}$  cladding layer were etched off to fabricate 100  $\mu\text{m}$ -wide broad area and 6  $\mu\text{m}$ -wide ridge waveguide lasers by standard lithography. After the etching, Ti-Au was sputtered on the samples for p-side electrode, then the wafer was thinned to about 100  $\mu\text{m}$ , and AuGeNi/Au was evaporated for n side electrode. The broad-area lasers of various lengths in the range of 400–4000  $\mu\text{m}$  were obtained by cleaving, with uncoated facets. For ridge waveguide lasers, one facet was coated with high-reflection film with reflectivity of 95%, while the other facet was left uncoated. Light-current characteristics of broad area lasers were measured in pulse mode (1  $\mu\text{s}$ , 10 KHz) of biasing with the devices mounted on a copper heat-sink to avoid significant current heating.

Fig. 1 shows the light-current characteristics of the lasers with the cavity length of 1000  $\mu\text{m}$  under different temperature, from 10 °C to 90 °C. In addition, as a sample, the inset in Fig. 1 shows a lasing spectrum measured at the current of 45 mA, where the lasing wavelength is about 1.29  $\mu\text{m}$  at room temperature. Fig. 2 shows the dependence of logarithmic threshold current density on the temperature for the ridge waveguide lasers with the cavity lengths ( $L$ ) of 1000, 800, and 400  $\mu\text{m}$ . As shown in Fig. 2, the dependence of threshold

<sup>a)</sup>Authors to whom correspondence should be addressed. Electronic addresses: caoyl@semi.ac.cn and tyang@semi.ac.cn

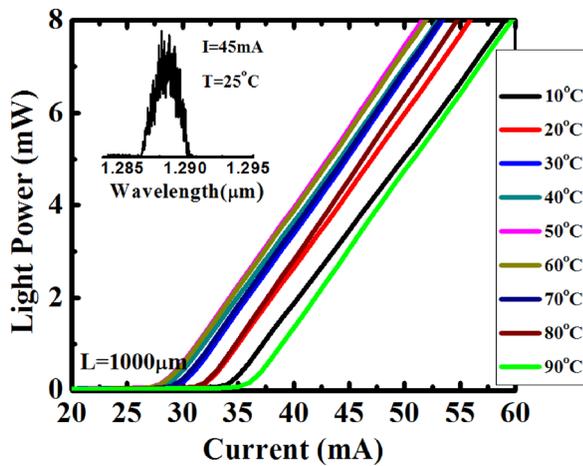


FIG. 1. Light-current characteristics over 10–90 °C temperature range for 1000  $\mu\text{m}$  cavity ridge waveguide lasers; the inset shows the lasing spectrum of the doped QD device with the cavity length of 1000  $\mu\text{m}$  at the current of 45 mA.

current density on the temperature can be divided into three regions for the three kinds of lasers with different cavity lengths by its  $T_0$ : negative  $T_0$  region, infinite- $T_0$  region, and positive  $T_0$  region. At first, when the temperature increases from 10 °C to 30 °C, the threshold current decreases, resulting in a negative  $T_0$ . Then with the temperature increasing, the

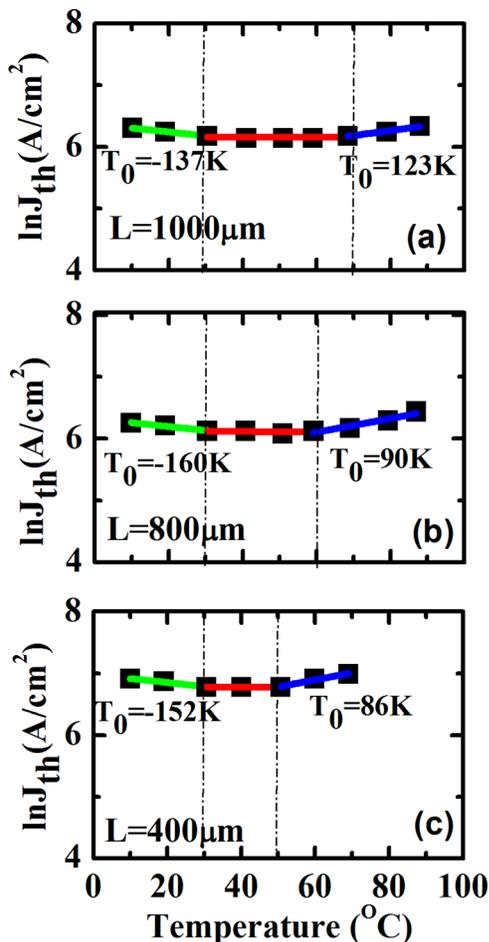


FIG. 2. The temperature dependence of logarithmic threshold current density for the lasers with different cavity lengths. The dashed dotted lines separate the temperature range of different  $T_0$  region. The areas between two dashes represent infinite- $T_0$  ranges.

threshold current density  $J_{\text{th}}$  remains almost constant over limited temperature range, resulting in  $T_0$  of infinity, as shown in Figs. 2(a)–2(c). Finally, the threshold current density begin to increase above 50, 60, and 70 °C for the three cavity length lasers, behaved like quantum well lasers, this is because that the carrier escape rate increases at high temperature, resulting in positive  $T_0$ . The excited-state lasing occurs when the temperature is above 70 °C for the laser diode with short cavity length of 400  $\mu\text{m}$ , so we only fit the data from 10 °C to 70 °C. However, the excited state lasing does not appear in the whole temperature range for the lasers with long cavity lengths of 1000 and 800  $\mu\text{m}$ , as shown in the Figs. 2(a) and 2(b).

For the three-region characteristic temperature, infinite  $T_0$  is a transition process from negative  $T_0$  to positive  $T_0$ , which is a completing tradeoff from the two different temperature mechanisms. However, the infinite  $T_0$  temperature occurs above 0 °C, not below, it is different with other results reported.<sup>13</sup> Compared with the results from the lasers with different cavity lengths, we can see that the infinite- $T_0$  region is wider for the lasers with longer cavity length. For example, as cavity length increases from 400  $\mu\text{m}$  to 800  $\mu\text{m}$  and 1000  $\mu\text{m}$ , the corresponding infinite- $T_0$  region become wider from 30–50 °C to 30–60 °C and 30–70 °C temperature range, respectively. This is because the loss decreases as cavity length increases, which pushes the modal gain far away from the saturation gain region, leading to a differential gain increase.<sup>11,14</sup> It is of significance for the practical application because the infinite- $T_0$  region overlapped with the device operating temperature range.

In fact, negative  $T_0$  was reported not only in the InAs/GaAs QD lasers but also in InAs/AlGaInAs QD lasers based on the InP substrate.<sup>15</sup> A few explanations for the negative  $T_0$  phenomenon have been proposed, which include delayed thermal redistribution of carrier within QD ensemble,<sup>11</sup> the photon coupling between different size QDs,<sup>9</sup> and a decrease of the Auger recombination with temperature,<sup>8</sup> but no consensus has been reached yet. However, many experimental results have exhibited that the negative  $T_0$  depends strongly on p-doping level, and the highest temperature that the negative  $T_0$  exists is approaching to room temperature when the doping density is high enough.<sup>13</sup> Our results are consistent with those reported, where the temperature ranges of the negative  $T_0$  regions are exactly the same for the three lasers that fabricated from the same wafer but with different cavity lengths, as shown in Fig. 2.

Recently, the researchers proposed that transparency current plays a critical role for negative  $T_0$  in both undoped and p-doped QD lasers.<sup>12</sup> To clarify this question, we calculated the modal gain of broad-area lasers by measuring the threshold current density for different cavity lengths under 30, 50, and 70 °C, respectively, as shown in Fig. 3. As at threshold the modal gain compensates the total losses, we have built the dependence of modal gain on the threshold current density as depicted in Fig. 3. The threshold modal gain  $g_{\text{mod}}$  is obtained experimentally by the relationship  $g_{\text{mod}} = \alpha_i + \ln(I/R)/L$ , where  $\ln(I/R)/L$  represents the mirror loss, internal loss  $\alpha_i$  is of 2.1  $\text{cm}^{-1}$  obtained by linear fitting. The data have been fitted by the empirical expression,<sup>16</sup>  $g_{\text{mod}} = g_{\text{sat}} \{1 - \exp[-\gamma(J_{\text{th}} - J_{\text{tr}})/J_{\text{tr}}]\}$  in which  $g_{\text{sat}}$  is

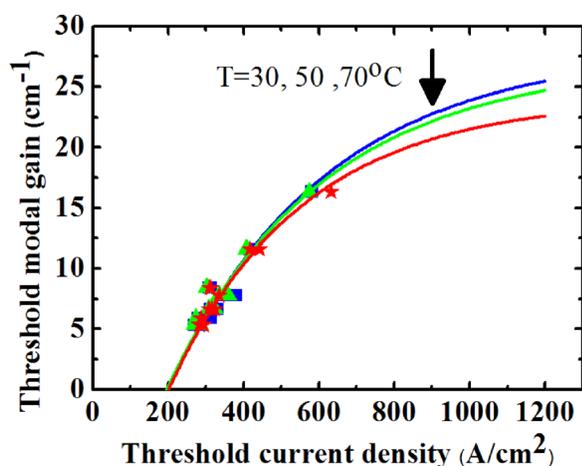


FIG. 3. The modal gain as a function of threshold current density for broad area lasers in the pulsed condition under different temperature. Squares, triangles, and stars indicate experimental data derived from the laser under different temperature 30, 50, and 70 °C, respectively. The blue, green, and red solid curves are fitted according to the experimental data.

TABLE I. The parameters used for fitting modal gain.

	$J_{tr}$ (A/cm <sup>2</sup> )	$g_{sat}$ (cm <sup>-1</sup> )	$\gamma$
T = 30 °C	200	28	0.48
T = 50 °C	196	27	0.48
T = 70 °C	201	24	0.57

saturation modal gain,  $\gamma$  is a nonideality factor,  $J_{th}$  is the threshold current density, and  $J_{tr}$  is the transparency current density. The obtained nonideality factor  $\gamma$  is in the range of 0.45–0.6, and the  $g_{sat}$  are 28, 27, and 24 cm<sup>-1</sup>, whereas  $J_{tr}$  are 200, 196, and 201 A/cm<sup>2</sup> at 30, 50, and 70 °C, respectively. The parameters used for fitting the modal gain are listed in Table I. It is found that the  $g_{sat}$  decreases with temperature increasing, while the  $J_{tr}$  is almost unchanged. From the Fig. 3, it is found that  $g_{sat}$  decreases with temperature increasing, this is because homogeneous broadening increases as temperature increases.<sup>17,18</sup> However, the fitting  $J_{tr}$  value error fluctuation is  $\pm 4$  or 5, and approximately stable when temperature increases from 30 to 70 °C. In Ref. 12, Gokhan Ozgur *et al.* think  $J_{tr}$  plays a critical role in stabilizing the  $T_0$  when temperature changing. With p-doping QD stacks (in our case, 10 stacks) increasing,  $J_{tr}$  makes up a significant fraction of threshold and decreases the threshold current dependence on temperature. In this paper, almost unchanged  $J_{tr}$  compensates the positive  $T_0$  by the negative  $T_0$  within limited temperature range. At higher temperature, the carrier escape rate increases, so that the  $J_{tr}$  compensation is not enough to stabilize the threshold with temperature changes, resulting in positive  $T_0$ , as shown in Fig. 2.

In conclusion, we fabricated the broad area and ridge waveguide p-doped 1.3  $\mu$ m InAs/GaAs QD lasers with 10 stacks QD layers. A temperature-independent result has been

shown under certain temperature range. Above this temperature range, the threshold current density shows similar increasing trend as that of quantum-well lasers, while it decreases with the temperature below this temperature range. The existence of the negative  $T_0$  is found to be relevant to the p-doping density, which makes its temperature range unchanged for the lasers with different cavity lengths due to the same p-doping densities of these lasers. However, in the infinite  $T_0$  region, as a transition region from the negative  $T_0$  to the positive  $T_0$ , its temperature range increase with the laser cavity length. In addition, the almost constant  $J_{tr}$  achieved from the fitting of threshold modal gain can trade-off the threshold current increasing from negative  $T_0$  to positive  $T_0$  at some extent.

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