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

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We have investigated the temperature dependence of threshold in p-doped 1.3 µm 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 (T0): negative, infinite, and positive T0 regions. Furthermore, the T0 region width is dependent on the cavity length: the longer cavity length of the QD lasers correspondingly the wider T0 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 (Itr) remains almost unchanged under different temperatures according to the extracted parameters from these fitted results, which indicates that Jtr plays an important role in balancing the T0 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 (Jth) and high temperature stability were predicted in the early 1980s.1,2 Recently, significant efforts have been made to improve the characteristic temperature (T0) of 1.3 µm quantum dot lasers for applications in the photonic networks3–5 such as using p-type modulation doping in the active region. High T0 has not only been theoretically predicted but also been measured in p-doped quantum dot lasers.6–10 For example, at cryogenic temperature, the threshold current of QD laser remains constant (as characterized by infinite T0) or decreases with temperature (as characterized by negative T0).10 A few explanations have been proposed for these phenomena,8–11 but no consensus has been reached till now. Recently, some researchers proposed that transparency current plays a critical role in the negative T0 region for both undoped and p-doped QD lasers.12

In this letter, the temperature dependence of threshold current is investigated in detail for the p-doped 1.3 µm 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 T0: negative T0 region, infinite T0 region, and positive T0 region. By fitting the dependence of threshold modal gain on the threshold current density under different temperature, we found that Jth was independent on the temperature, which indicates that Jtr plays an important role in balancing the T0, as reported in the literature.12

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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-µm-thick Al0.35Ga0.65As cladding layers. The QD active region consisted of 10 layers InAs/In0.15Ga0.85As QDs separated by a 33-nm-thick spacer between the QD layers. A 0.2 µm P+-GaAs contact layer was used for electrical contact. The density of quantum dots is 5 × 1010 cm−2.10 nm-thick P-GaAs layers were included in the spacer layers, which were doped with acceptor density of 5 × 1017 cm−3. The P-GaAs contact layer and a part of p-Al0.35Ga0.65As cladding layer were etched off to fabricate 100 µm-wide broad area and 6 µm-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 µm, and AuGeNi/Au was evaporated for n side electrode. The broad-area lasers of various lengths in the range of 400–4000 µm 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 μs, 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 µm 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 µm 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 µm. As shown in Fig. 2, the dependence of threshold
positive T₀ region. At first, when the temperature increases the temperature range of different T₀ region. The areas between two

FIG. 2. The temperature dependence of logarithmic threshold current den-

sity for the lasers with different cavity lengths by its T₀: negative T₀ region, infinite-T₀ region, and positive T₀ region. At first, when the temperature increases from 10°C to 30°C, the threshold current decreases, resulting in a negative T₀. Then with the temperature increasing, the

current density on the temperature can be divided into three regions for the three kinds of lasers with different cavity lengths by its T₀: negative T₀ region, infinite-T₀ region, and positive T₀ region. As cavity length increases, which pushes the modal gain far away from the saturation gain region, leading to a differential gain increase.11,14 It is of significance for the practical application because the infinite-T₀ region overlapped with the device operating temperature range.

In fact, negative T₀ was reported not only in the InAs/GaAs QD lasers but also in InAs/AlGaInAs QD lasers based on the InP substrate. A few explanations for the negative T₀ phenomenon have been proposed, which include delayed thermal redistribution of carrier within QD ensemble, the photon coupling between different size QDs, and a decrease of the Auger recombination with temperature, but no consensus has been reached yet. However, many experimental results have exhibited that the negative T₀ depends strongly on p-doping level, and the highest temperature that the negative T₀ exists is approaching to room temperature when the doping density is high enough. Our results are consistent with those reported, where the temperature ranges of the negative T₀ 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 T₀ in both undoped and p-doped QD lasers. 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 gₘ₀d is obtained experimentally by the relationship gₘ₀d = γ₀ + ln(I/R)/L, where ln(I/R)/L represents the mirror loss, internal loss γ₀ is of 2.1 cm⁻¹ obtained by linear fitting. The data have been fitted by the empirical expression,

gₘ₀d = gₙₐₜ (1−exp[−γ(J−Jₚ)/Jₚ])

in which γ₀ is

FIG. 1. Light-current characteristics over 10–90°C temperature range for 1000 μm cavity ridge waveguide lasers; the inset shows the lasing spectrum of the doped QD device with the cavity length of 1000 μm at the current of 45 mA.
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$^{-1}$, whereas $J_{tr}$ are 200, 196, and 201 A/cm$^2$ 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.$^{17,18}$ However, the fitting $J_{tr}$ value error fluctuation is ±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 density, and $J_{tr}$ is the transparency current density.

In conclusion, we fabricated the broad area and ridge waveguide p-doped 1.3 μm 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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