Lasing characteristics of InAs quantum-dot microdisk from 3 K to room temperature

Toshihide Ide and Toshihiko Baba^{a)}

Yokohama National University, Department of Electrical and Computer Engineering, 79-5 Tokiwadai, Hodogaya-ku, Yokohama 240-8501, Japan

Jun Tatebayashi, Satoshi Iwamoto, Toshihiro Nakaoka, and Yasuhiko Arakawa

University of Tokyo, Research Center for Advanced Science and Technology, 4-6-1 Komaba, Meguro-ku, Tokyo 153-8904, Japan

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We fabricated a microdisk laser with five-stacked InAs quantum-dot (QD) active region, and demonstrated the lasing operation from 3 K to room temperature by femtosecond pulsed photopumping. At room temperature, the threshold power was estimated to be 0.75 mW, when the influence of the surface recombination at the disk edge was neglected. The lasing wavelength was 1.2–1.3 μm , which corresponded to excited states of the QDs. The temperature dependence of the threshold, slope efficiency, lasing wavelength, and linewidth are explained by the rapid increase in nonradiative recombination and internal absorption at critical temperatures of 200–230 K. © 2004 American Institute of Physics. [DOI: 10.1063/1.1787157]

The quantum-dot (QD) active region in semiconductor lasers is promising for the low threshold, high-speed, and temperature-insensitive operation.^{1,2} The microdisk laser (MDL) is a kind of microlaser, which realizes a 10 μW (or μA) order ultralow threshold.^{3,4} The QD MDL will extend the above advantages, and add other unique features, i.e., the turnstile operation and the Purcell effect,⁵ which are suitable for high-speed single-photon emission. However, the lasing temperature in QD MDLs was no higher than 140 K until recently.^{6–9} An improvement toward the room-temperature (RT) operation is the increase in Q factor. However, the RT operation was not achieved, even when the Q factor was enhanced from 3000 to 12 000 at low temperature.⁶ This suggests that increased internal losses near RT disturb the lasing. Another improvement considered is the gain enhancement by stacking QD layers. In previous studies of QD MDLs, the number of layers was no larger than two. Very recently, Yang *et al.*¹⁰ reported the RT lasing in a MDL with five QD layers. In this study, we observed lasing characteristics in a QD MDL from 3 K to RT, and investigated the issues.

In the experiment, 880-nm-thick $\text{Al}_{0.6}\text{Ga}_{0.4}\text{As}$ bottom layer, the active region composed of five 7-nm-QD layers, and 10-nm-GaAs/25-nm- $\text{Al}_{0.1}\text{Ga}_{0.9}\text{As}$ /25-nm-GaAs cover layers were grown on GaAs substrate by metalorganic vapor phase epitaxy. The QD layers included self-assembled InAs QDs, which were grown by Stranski–Krastanow mode at 500 °C and buried by 5-nm-InGaAs strain-compensate layer and 15-nm-GaAs barrier layers.¹¹ The in-plane QD density was $2 \times 10^{10} \text{ cm}^{-2}$. When the upper four QD layers were removed by a wet etching, wavelengths λ of the ground state were observed to be 1.34 μm , those of excited states 1.27 and 1.18 μm , respectively, and the full width at half maximum (FWHM) ΔE of the RT photoluminescence (PL) spectrum was $\sim 30 \text{ meV}$. When without the etching, the five QD layers exhibited an inhomogeneous broadening of $\Delta E = 85 \text{ meV}$ due to the nonuniformity between layers. At λ

$= 0.99 \mu\text{m}$, another weak peak from InGaAs layers was observed. In the fabrication process, a circular mesa was formed by electron-beam lithography and Cl_2/Xe inductively coupled plasma etching. The disk shape and the pedestal were formed by HF etching. Figure 1 shows a 5- μm -diameter device. The surface and sidewall roughness was less than 20 nm. In the measurement, the MDL was photopumped by a Ti-sapphire laser at $\lambda = 0.78 \mu\text{m}$ with a pulse width (FWHM) Δt of 200 fs, a repetition frequency of 76 MHz, and a focused spot of $\sim 2 \mu\text{m}$. Light output was analyzed by a monochromator with InGaAs charge-coupled device array. The device temperature was controlled from 3 K to RT.

Figure 2 shows the intensity and spectral linewidth (FWHM) of mode peaks at $\lambda = 1.16, 1.19, 1.23, 1.26$, and $1.29 \mu\text{m}$, which were measured at RT with a monochromator resolution of 0.5 nm. The lower horizontal axis is the time-averaged irradiated power P_i . Four peaks at shorter wavelengths exhibit the evidence of the lasing, i.e., a clear kink and the spectral narrowing. The lasing wavelengths correspond to the excited states of the QDs. Thresholds in P_i were 0.8, 0.6, 0.4, and 0.3 mW, respectively. The lower threshold at the longer wavelength clearly indicates the carrier filling

FIG. 1. Scanning electron micrograph of 5- μm -diameter MDL.

^{a)}Electronic mail: baba@ynu.ac.jp

FIG. 2. Intensity and spectral linewidth characteristics for five emission peaks.

from lower QD states. The absorption efficiency of the pump pulse is estimated to be 20% from the disk thickness $d = 0.185 \mu\text{m}$, reflectivity at the disk surface $R \sim 30\%$, average absorption coefficient inside the disk $\alpha \sim 13\,000 \text{ cm}^{-1}$ and the multiple absorption in the disk expressed as $(1-R)(1 - e^{-\alpha d})/(1 - Re^{-\alpha d})$.¹² With this efficiency, P_t is converted to the absorbed power P_{ab} , as shown on the upper horizontal axis of Fig. 2. To further convert P_{ab} into a pulse peak power, the duty ratio of the pulse and the difference between the pulse width Δt and the carrier lifetime τ_c have to be taken into account. For lasing, carriers must be accumulated during the carrier lifetime τ_c .¹³ Against the short pulse pumping, P_{ab} should be converted to the effective peak power P_{eff} of a pulse having the same pulse energy and a pulse width equal to τ_c . By using a streak camera, τ_c of the as-grown wafer was measured to be $\sim 1 \text{ ns}$ at RT. Assuming this as τ_c of the MDL, P_{eff} is estimated to be 0.75 mW for the mode peak at $\lambda = 1.26 \mu\text{m}$. However, this is an underestimated value, since τ_c of the MDL is shortened from the wafer lifetime by the surface recombination at the disk edge. In the estimation of the surface recombination, the number of carriers in InGaAs layers is important. If carriers generated by the pumping were completely captured by the QDs, the threshold carrier density N_{th} estimated from P_{ab} and the total QD volume would be $\sim 4 \times 10^{19} \text{ cm}^{-3}$. This value is not possible actually, since it is much higher than an upper limit density in the QDs of $\sim 5 \times 10^{18} \text{ cm}^{-3}$. Therefore, $>90\%$ carriers initially stay in InGaAs. Some of the carriers are captured by the QDs within τ_c of the QDs (=wafer lifetime of 1 ns), but others are dissipated in InGaAs mainly by the surface recombination. Considering a typical surface recombination velocity of $4 \times 10^5 \text{ cm/s}$ for this material¹⁴ and the sidewall area to volume ratio of InGaAs, the surface recombination lifetime is calculated to be 0.3 ns . Thus, τ_c in the MDL is thought to be

FIG. 3. Lasing spectra at twice the threshold. Dotted line shows PL characteristic of as-grown wafer at RT. Arrows indicate two excited states of the lowest QD layer.

around 0.25 ns , which increases the threshold to ~ 4 times higher.

Even if the surface recombination is excluded from the estimation, the effective threshold $P_{\text{eff}} = 0.75 \text{ mW}$ is still four to five times higher than those of GaInAsP compressively strained quantum-well (CSQW) MDLs with the same diameter.⁵ The higher threshold is explained by the lower optical confinement factor Γ into QDs, the large inhomogeneous broadening, and the shorter τ_c of the wafer. Considering the in-plane QD density and the number of layers, Γ is calculated to be 1.2% . It is six times lower than in GaInAsP MDLs, and so can compensate for a high material gain expected for QDs. The normalized spectral width $\Delta E/E$ of the inhomogeneous broadening is nearly twice the typical FWHM of the gain spectrum in the GaInAsP CSQW. This broadening simply increases the threshold. The lifetime $\tau_c = 1 \text{ ns}$ is three to four times shorter than that of the GaInAsP CSQW. It is thought to be due to the nonradiative recombination inside the QDs.

Figure 3 shows lasing spectra at twice the threshold of the strongest peak. Both spectra at different temperatures exhibit a series of neighboring two peaks (main peak and subpeak). Similarly to those in another whispering gallery mode

FIG. 4. Temperature dependence of threshold (solid line) and relative slope efficiency (dotted line).

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FIG. 5. Temperature dependence of lasing wavelength (solid line) and spectral linewidth (dotted line).

(WGM) cavity with QDs,¹⁵ they arise from two different polarizations. Considering the flat shape of Stranski-Krastanow QDs and the different optical confinement factors, the main and subpeaks are thought to be the in-plane and out-of-plane polarizations, respectively. The interval between two main (sub) peaks was 35 (37) nm. It is explained as the interval between different order WGMs for an orbital diameter of $4.46 \mu\text{m}$ and a modal group index of 2.9 (2.7).

Figure 4 shows the temperature dependence of threshold in P_{eff} excluding the surface recombination effect and relative slope efficiency of the strongest peak. Figure 5 shows the temperature dependence of lasing wavelength and spectral linewidth of the peak at twice the threshold. All results are consistently explained as follows. At low temperature, the nonradiative recombination inside the QDs are negligible, so the threshold determined by the cavity Q is low. The peculiar increase at 77 K is caused by the carrier overflow from higher excited states,¹⁶ which is not easily recovered due to a very high carrier mobility around this temperature. The increase in N_{th} leads to the remarkable blueshift of the wavelength at this temperature by the carrier plasma effect. Above 200 K, the threshold rapidly increases by the chain increase in nonradiative recombination, N_{th} , and carrier overflow. The characteristic temperatures T_0 were 274 K and 85–33 K below and above 200 K, respectively. The decrease of the slope efficiency is due to the increase in internal absorption loss, i.e., free carrier absorption and intervalence band absorption; the absorption reaches a critical value comparable to other cavity losses at 230 K with the increase in N_{th} . The wavelength redshifts by 0.5 nm/K at 77–230 K due to the temperature dependence of the material band-gap en-

ergy. Above 230 K, the redshift is saturated due to the carrier filling effect. The linewidth broadens up to 0.7 nm due to the wavelength chirping caused by the carrier plasma effect against the short pulse pumping. When considering the number of initially excited carriers, the maximum carrier plasma shift of 1 nm is estimated, which is close to the measured value.

In conclusion, we fabricated an InAs QD MDL and observed lasing characteristics from 3 K to RT. At RT, the threshold effective pump power excluding the surface recombination effect was 0.75 mW . The lasing wavelength was $1.26 \mu\text{m}$, which corresponded to excited states of the QDs. From temperature dependences, the increase in nonradiative recombination at $>200 \text{ K}$ and internal absorption at $>230 \text{ K}$ were estimated. The QD wafer in this study showed the wide inhomogeneous broadening. The reduction of this broadening will lower the threshold carrier density and lead the ground-state lasing.

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