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Investigation of Temperature-dependent Lasing and Optical Gain Characteristics of 1.3- μm InAs Quantum Dot Laser

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Abstract: temperature-dependent lasing and optical gain characteristics were investigated on the InAs quantum dot lasers up to 120 °C. The laser showed high performance and the gain bandwidth is found to be insensitive to the temperature.

OCIS codes: (140.5960) Semiconductor lasers; (230.5590) Quantum-well, -wire and -dot devices;

1. Introduction

Since the first laser demonstration [1], quantum dot (QD) structures have attracted great research interests due to their unique physical properties [2-9]. QD structures have promised and demonstrated many intrinsically unique properties and advantages compared to other semiconductor gain material schemes, such as bulk structure and quantum well (QW) structure, for photonic devices' applications [3, 6].

Notwithstanding those numerous achievements [6], further intense investigations are highly desirable to fully reveal and realize the unique advantages of QDs for device application. For instance, QD laser is expected to have temperature insensitive threshold current (I_{th}) and be able to work at high temperature. P-doping in the QD structures is often used to achieve temperature insensitive QD lasers [8]. However, the high temperature lasing characteristics of a p-doped QD laser, especially, the modal gain characteristics at high temperature, have seldom been investigated and reported.

In this work, we fabricated the GaAs-based 1.3- μm p-doped InAs QD lasers with high performance. The lasers successfully worked up to 120 °C. The modal gain characteristics of the fabricated QD laser have been investigated with Hakki Paoli method from room temperature (20 °C) to 120 °C. It was found that the gain bandwidth of the investigated QD laser, unlike that from a typical QW laser, is not sensitive to the temperature.

2. Experimental details

In this work, self-assembled InAs/InGaAs/GaAs QD structures were grown on Si doped GaAs (100) substrates by solid source molecular beam epitaxy (SSMBE). The structures consist of the 10-layer QD active region: InAs (2.32 ML)/ $\text{In}_{0.15}\text{Ga}_{0.85}\text{As}$ (5 nm). The p-doping of carbon atoms with the concentration of $5 \times 10^{17} \text{ cm}^{-3}$ was incorporated into a 10-nm-thick GaAs layer, which was situated in the middle of each 33-nm-thick spacer between the two adjacent QD layers. The whole active region was then sandwiched between two C- and Si-doped $\text{Al}_{0.35}\text{Ga}_{0.65}\text{As}$ cladding layers. A 200-nm-thick p+-GaAs cap was used as p-contact layer for current injection.

The QD wafer was processed into ridge waveguide (RWG) lasers with the ridge width (w) of 4 μm by standard photolithography, wet chemical etching ($\text{H}_3\text{PO}_4:\text{H}_2\text{O}_2:\text{D.I.H}_2\text{O}=1:1:5$) as well as isolated with pulsed anodic oxides as described previously [7]. The etching was stopped above the QD active region, where most of the p-doped $\text{Al}_{0.35}\text{Ga}_{0.65}\text{As}$ upper cladding layer was removed in order to suppress the lateral current spreading. Ti/Au (50/300 nm) was used as the p-contact and Ni/Ge/Au/Ni/Au (5/20/100/25/300 nm) was used as the n-contact on the backside of the lapped substrate ($\sim 100 \mu\text{m}$). After metal alloying at 400 °C for three minutes, the as-cleaved lasers, with different laser cavity length (L), were tested under continuous wave (CW) condition with p-side down mounted on a heatsink from room temperature (RT) to high temperature (120 °C).

3. Results and discussion

Fig.1 shows the typical temperature (T)-dependent (20-120°C) CW power-current-voltage (P-I-V) characteristics from a QD RWG laser with a cavity length of 1500 μm ($4 \times 1500 \mu\text{m}^2$). Testing was carried out up to 120 °C, which was limited by our equipment. The laser showed a low I_{th} around 36 mA (threshold current density, J_{th} : $\sim 600 \text{ A/cm}^2$) at 20 °C and I_{th} of 50 mA (J_{th} : 833 A/cm^2) at 120 °C, from which a high characteristic temperature (T_0) of $\sim 300 \text{ K}$ in the whole testing temperature range can be derived.

Fig. 1. Temperature-dependent (20-120 °C) CW P-I-V characteristics of an InAs QD RWG laser ($4 \times 1500\mu\text{m}^2$).

Fig. 2 shows the lasing characteristics of the QD laser at 20, 60, 100 and 120 °C, respectively. The laser centered at 1297 nm at room temperature (20 °C), and 1334 nm at 120 °C. From our previous work [5, 7], it is noted that the lasing peak corresponds to the ground state emission in the InAs/InGaAs QD structures.

Fig. 2. The lasing spectra from the QD laser ($4 \times 1500\mu\text{m}^2$) at 20, 60, 100, and 120 °C, respectively.

Fig. 3(a) shows the optical gain spectra of the QD laser at room temperature (20 °C). The modal gain data is derived from the multiple amplified spontaneous emission (ASE) spectra experimentally obtained at different injection currents by Hakki Paoli method [4]. The ASE spectra were recorded with an optical spectral analyzer (OSA, AQ6317C) with the spectral resolution of 0.02 nm. The inset shows the FP modes in greater detail. The sharp peak and valley indicate excellent mode spacing as expected, which also assures the accuracy of the derived modal gain data.

Fig. 3(b) shows the comparison of the maximal optical modal gain of the QD laser at both 20 °C and 120 °C. The bias conditions were chosen to be just before the threshold current at respective temperature. At both temperatures, the maximal modal gain has similar values, which is limited by the mirror loss, $1/L(\ln(1/R))$, $\sim 6 \text{ cm}^{-1}$. Furthermore, it is interesting to note that the gain bandwidth (the difference of the wavelength of those points, where the peak gain decreases half of the peak [10]) is similar for the studied QD laser at both 20 °C and 120 °C, which is around 23 nm. This is in distinct contrast to the typical QW laser, whose gain bandwidth is significantly broadened at high temperature [10]. Further in-depth investigations on the relationship of temperature-dependent modal gain characteristics and temperature sensitivity in p-doped QD lasers are on the way.

Fig. 3. (a) Net modal gain spectra vs. injection current at 20 °C from a QD laser ($4 \times 1500 \mu\text{m}^2$). The inset shows the FP spectra in greater detail and (b) Maximal net modal gain at different temperatures (20 and 120 °C).

4. Conclusions

In summary, we have fabricated the GaAs-based 1.3- μm InAs/InGaAs QD lasers with high performance. The InAs QD lasers successfully worked up to 120 °C with a high T_o of $\sim 300 \text{ K}$. The modal gain characteristics of the fabricated QD laser have been investigated with Hakki Paoli method at both room temperature (20 °C) and 120 °C. It was found that the gain bandwidth of the investigated QD laser, unlike that from a typical QW laser, is not sensitive to the temperature.

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