# Influence of a tilted cavity on quantum-dot optoelectronic active devices*

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**Abstract:** Quantum-dot laser diodes (QD-LDs) with a Fabry–Perot cavity and quantum-dot semiconductor optical amplifiers (QD-SOAs) with 7° tilted cavity were fabricated. The influence of a tilted cavity on optoelectronic active devices was also investigated. For the QD-LD, high performance was observed at room temperature. The threshold current was below 30 mA and the slope efficiency was 0.36 W/A. In contrast, the threshold current of the QD-SOA approached 1000 mA, which indicated that low facet reflectivity was obtained due to the tilted cavity design. A much more inverted carrier population was found in the QD-SOA active region at high operating current, thus offering a large optical gain and preserving the advantages of quantum dots in optical amplification and processing applications. Due to the inhomogeneity and excited state transition of quantum dots, the full width at half maximum of the electroluminescence spectrum of the QD-SOA was 81.6 nm at the injection current of 120 mA, which was ideal for broad bandwidth application in a wavelength division multiplexing system. In addition, there was more than one lasing peak in the lasing spectra of both devices and the separation of these peak positions was 6–8 nm, which is approximately equal to the homogeneous broadening of quantum dots.

**Key words:** quantum dot; semiconductor optical amplifier; laser diode; inhomogeneous broadening
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## 1. Introduction

Semiconductor quantum dots (QDs) have attracted the considerable attention of physicists and engineers for many years due to their unique characteristics such as three-dimensional carrier confinement, the potential to deliver stability of atomic sources within a compact and efficient semiconductor device[1], and the potential to make ultrafast devices with the two key features of high differential gain and fast carrier relaxation into the active states[2]. The size of a QD is comparable with the de Broglie wavelength, which leads to completely discrete energy levels and a delta function-distributed density of states[3]. With the development of material growth technology and nano-processing systems, there are many types of QDs, among which the III–V semiconductor QDs grown by the Stranski–Krastanow (S–K) mode are more developed because of their direct band gap for optoelectronic device application. After the first realization of the QD laser diode (QD-LD) in 1994[4], much progress has been made on low threshold current density, high characteristic temperature, high differential gain and high modulation bandwidth lasers. In addition, quantum-dot superluminescent diodes (QD-SLDs)[5] and quantum-dot semiconductor optical amplifiers (QD-SOAs)[6, 7] have been developed subsequently. In particular, QD-SOAs have attracted more and more attention due to their distinctive features such as high saturation output power, broadband gain, and high-speed response for application in next-generation optical networks[8–10]. However, unlike the QD-LD, the QD-SOA is usually operated at a high current to get a maximum material gain coefficient, which is essential for ultrafast and pattern-effect-free optical amplification and processing[11]. The fabrication of such a device needs to reduce the reflection from the cavity facets to suppress lasing and usually uses a tilted cavity structure.

In this paper, we fabricate QD-LDs with a Fabry–Perot (F–P) cavity and QD-SOAs with a 7° tilted cavity using regular photo-lithography and a mask of $SiO_2$. High performance of QD-LDs is demonstrated, and the effects of the tilted cavity on QD-LDs/SOAs are investigated.

## 2. Experiment

The QD-LD/SOA materials were grown by a Riber-32p solid-source molecular beam epitaxy (MBE) system on n-doped GaAs substrates using the S–K self-organization mode. The epitaxial structures contained a buffer layer comprising of 5 layers of n-doped GaAs/AlGaAs quantum well structure and a 255 nm GaAs layer, n- and p-doped $Al_xGa_{1-x}As$ (the value of $x$ was varied from 0.1 to 0.65 and held before being reduced to 0.1) gradient refraction index separate confined hetero-structures which sandwiched the active region, and a 250 nm heavily p-doped GaAs cap layer. The active region had 10 layers of QDs and each layer contained 6-period InAs/GaAs (0.367 ML/0.5 ML) and a 15 nm GaAs spacer

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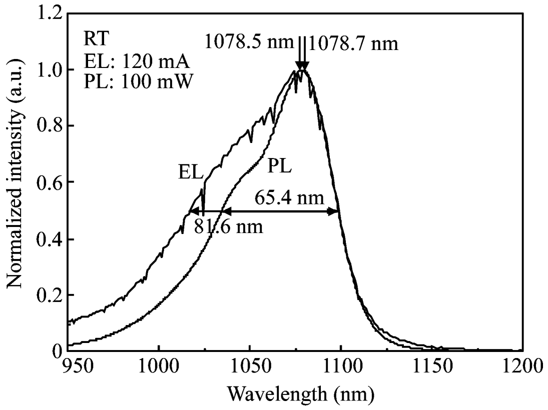

Fig. 1. PL spectra of quantum dot structures and EL spectra of the QD-SOA below the threshold current, both measured at room temperature.

layer. The substrate temperature was 600 °C for the GaAs and AlGaAs layers and 500 °C for the InAs QDs. The deposition rates were ⩽ 1 $\mu$m/h, ⩽ 0.7 $\mu$m/h and ⩽ 0.1 ML/s for GaAs, AlGaAs and InAs, respectively. The $As_2$ beam equivalent pressure was $5 \times 10^{-6}$ torr.

Device fabrication began with the formation of a 6 $\mu$m ridge stripe which would shrink because of the undercutting when using the wet-etching technique. The QD-SOA was fabricated using a 7° tilted ridge waveguide geometry, while the QD-LD was fabricated using a straight ridge. A thin $SiO_2$ layer followed by chemical-vapor deposition. The part of the $SiO_2$ layer above the ridge was etched to enable the deposition of Ti-Au for the p-side electrical contact. Finally, a Au-Ge-Ni contact on n-side was deposited after the substrate had been thinned down. The metal contacts were alloyed to form ohmic contacts. The stripe widths of the QD-LDs and QD-SOAs were 4.7 and 4.3 $\mu$m, respectively. Both device lengths were 3 mm and the cavity facets were uncoated. Photoluminescence (PL) spectra were measured under the excitation of the 514.5 nm line of an $Ar^+$ laser and detected with a Bruke-IFS 120HR Fourier transform infrared spectrometer.

## 3. Results and discussion

Figure 1 shows the room temperature PL spectrum of the InAs/GaAs QD structure and electroluminescence (EL) spectrum of the QD-SOA below the threshold current. The PL and EL spectra are found to have nearly the same peak wavelength and profile. The QD-SOA exhibits a broad EL full-width at half-maximum (FWHM) of 81.6 nm at the bias current of 120 mA. Figures 2 and 3 with their inserts show the threshold characteristics as well as lasing spectra of the QD-SOA and QD-LD.

For the QD-LD, a low threshold current of less than 30 mA, confined by the resolution limit of the testing system, was achieved and a high single facet output power of 133 mW (pulsed, 10 kHz, 0.1%) was obtained at the injection current of 400 mA. In addition, a relatively high slope efficiency of 0.36 W/A, accounting for a good average external differential quantum efficiency in the QD-LD, can be calculated. Due

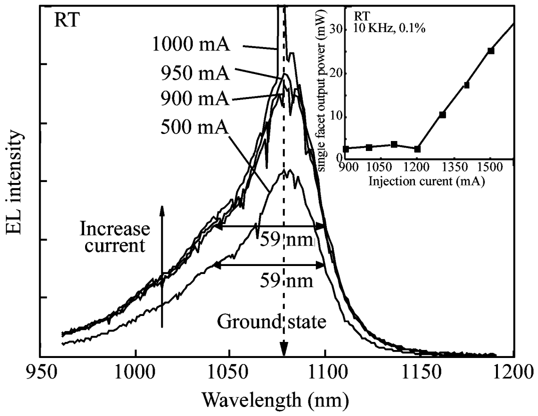

Fig. 2. EL spectra of the QD-SOA at the vicinity of the threshold current. The peak at 1000 mA bias current is outside this figure. The insert is the *P*–*I* curve of the QD-SOA.

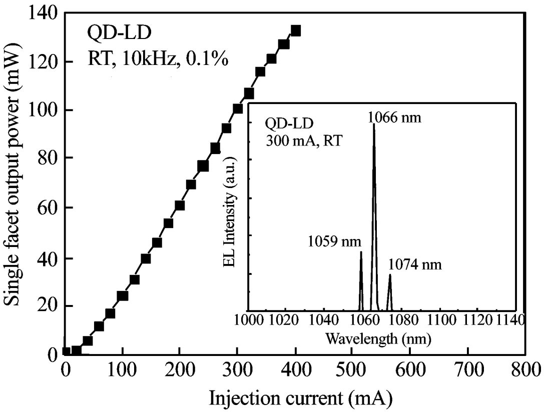

Fig. 3. Light output power-injection current curve of the the QD-LD measured at room temperature under a pulsed injection. The insert is the EL spectrum of the QD laser at 300 mA injection current.

to the tilted cavity, the reflection from the QD-SOA facets is much smaller than that from the QD-LD facets. As a result, the light oscillation in the SOA cavity is much smaller than that in the LD cavity, which leads to a high threshold current of about 1000 mA. Generally, as optical amplification or processing devices, SOAs are operated at an injection level without lasing. Moreover, the QD structure with separate dot energy levels and continuous wetting layer energy state can reach high population inversion at a high injection level, where the wetting layer acts as a carrier reservoir for the dot levels and the material gain coefficient of the ground level attains a maximum (i.e. constant gain value). With the tilted cavity design, our QD-SOA can operate at an injection current of 950 mA (i.e. current density of 7.4 kA/$cm^2$) which is possible for pattern-effect-free processing according to theoretical predictions[11].

From Fig. 2, it can be seen that the position of the ground level of 1077.7 nm and the FWHMs of EL spectra before lasing do not change appreciably with varying injection levels. As we know, a high injection current may lead to a large thermal effect. There is possibly a balance in the QD-SOA between the thermal red shift of the band gap and carrier band-filling effects with the increasing of bias current. Since the spectrum broadening is temperature independent, it demonstrates that the spectrum shape is due to dot inhomogeneity. The different

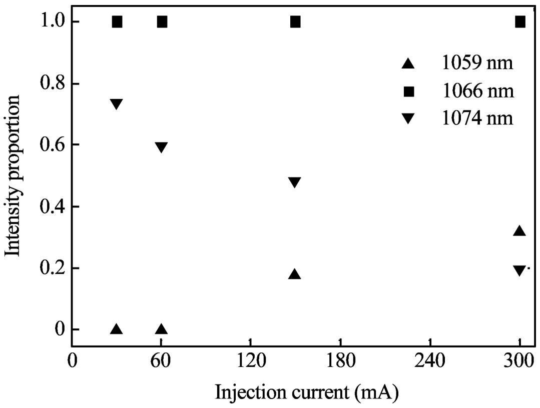

Fig. 4. Variation of the mode proportion with injection current.

peak positions and FWHMs between SOAs shown in Figs. 1 and 2 are probably caused by material differences across the wafer. Large inhomogeneous broadening of the QD structure is promising for the QD-SOA to achieve broad gain bandwidth, which is beneficial to the wavelength division multiplexing (WDM) system.

The insert in Fig. 3 is the lasing spectra of a QD-LD measured at 300 mA pump current. It shows three lasing peaks. The peak positions are 1066, 1074 and 1059 nm. With the increase of injection level, the proportion of the three modes varies. The variation can be seen in Fig. 4. The $y$-axis is the ratio of each mode to the main mode of 1066 nm which is normalized to 1. The composition of the 1074 nm mode decreases with increasing injection current while the composition of the 1059 nm mode increases from 0 to 0.32. In Fig. 5, the new lasing lines on both sides of the central mode at a high bias current can also be seen in the QD-SOA. Many reasons, such as cavity mode oscillation, lateral-cavity spectral hole burning[12], leakage of modes into the transparent substrate[13], and effect of homogeneous broadening[14], can account for the multimodes in QD devices. The mode separation shown in Fig. 5 is 7–8 nm, which does not match up to this cavity mode separation of 0.054 nm, but is very similar to the results in Ref. [14]. At room temperature, homogeneous broadening connects spatially isolated and energetically different quantum dots and collects carriers to central lasing modes, leading to collective lasing of the dot ensemble. Due to thermal redistribution, carriers congregate to lower energy levels in larger dots and then radiate at a low injection level. The long wavelength mode of 1074 nm precedes the short one of 1059 nm. By increasing the injection current, gain saturation occurs and other quantum dot ensembles with different energy levels become occupied. Larger population inversion takes place beyond the homogeneous broadening scope and the intensity of the 1059 nm mode increases. With a further increase of injection level over 300 mA, all the modes exhibit a few red-shifts. This can be explained by the thermal effect at such a high injection level. The wavelength separation of 6–7 nm between two nearest modes in Fig. 5 approximately equals to the homogeneous broadening of our QD-SOA. It has the potential to obtain a large wavelength detuning conversion with the novel wavelength converter based on the QD-SOA due to the large homogeneous broadening of QDs at room temperature.

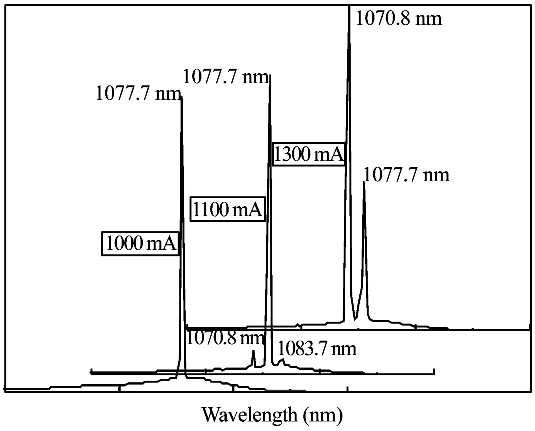

Fig. 5. Lasing spectra of the QD-SOA at different injection levels. The coordinates are added for comparison.

## 4. Conclusion

QD-LDs and QD-SOAs have been fabricated. With a tilted cavity design, the QD-SOA has a smaller reflection than the QD-LD with a F–P cavity, inducing a high threshold current. The QD-SOA can operate at a high injection current of 950 mA (i.e. current density of 7.4 kA/cm$^2$) without lasing. In contrast, for the QD-LD, the threshold current is below 30 mA and the slope efficiency is 0.36 W/A at room temperature. There are two additional advantages of QD-SOAs: inhomogeneous and homogeneous broadening. Attributed to QD dispersion, the inhomogeneous broadening of EL spectra can reach 81.6 nm. The homogeneous broadening of optical gain in QDs is 6–7 nm. They are promising for multi-wavelength application in the WDM system and large detuning conversion with a novel wavelength converter based on the QD-SOA.

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