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Quantum Dot Lasers Monolithically Integrated on Si Substrate

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Abstract

As a promising on-chip light source for Si photonics, quantum dot (QD) lasers on Si has attracted great research interests in recent years. In this paper, we present our latest progress about different types of QD laser monolithically integrated Si substrate which demonstrates a superior performance of QD laser as a Si-based light source compared with its conventional counterparts.

1. Introduction

The Si-based laser is desired as one of the key components for Si photonics [1,2]. Among various approaches, integrating a high-performance III-V QD laser on Si substrate has been considered as a promising way to develop an on-chip optical source which combines both high performance and compatibility to current industrial-standard fabrication process. Compared to conventional lasers, QD lasers show outstanding advantages of low threshold, temperature insensitivity and high defect tolerance. These advantages make it become the ideal active region for laser directly epitaxy on Si substrate. Here, we present our recent results of QD laser monolithically integrated on Si (001) substrate, realising the significant advance of QD lasers as a promising on-chip light source for Si photonics.

2. Results

QD lasers on offcut Si substrate.

In this section, the results of QD lasers on Si substrate with 4° offcut angle by Molecular Beam Epitaxy (MBE) systems were demonstrated. The offcut Si substrate was generally employed to prevent the formation of antiphase boundary caused by polarity difference between III-V materials and Si substrate. By using our unique epitaxial method and improved fabrication process, we have successfully demonstrated the first high performance and long-lifetime 1.3μm QD laser directly on Si [3]. As shown in Fig. 1a, 1μm GaAs buffer was grown in three steps on deoxidized Si substrate to improve the material quality. Four repeats of dislocation filter layers (DFL) consisted of five sets of $In_{0.18}GaAs/GaAs$ strained-layer superlattice and 300nm GaAs spacer were grown subsequently on the buffer. The threading dislocation density after DFLs was successfully reduced to the level of $10^5 cm^{-2}$. Our standard laser structure with five stacks of InAs/GaAs dot-in-well (DWELL) active region were developed upon this platform. An TEM image of active region was

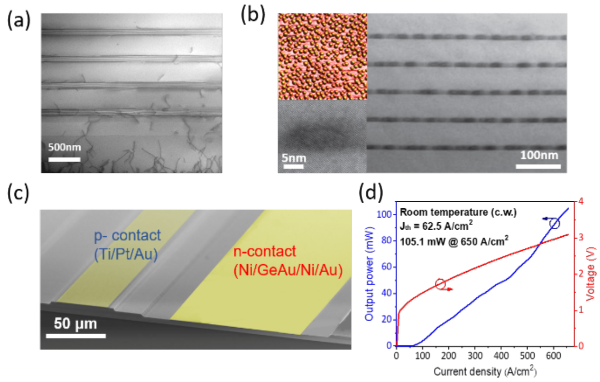

Fig. 1 (a) TEM image of GaAs buffer on Si including DFLs. (b) TEM image of active region, inset: 1×1µm2 AFM image of uncapped QDs and typical geometry of a single QD. (c) SEM image of fabricated broad-area laser. (d) LIV curve of lasing characteristics.

shown in Fig. 1b where QDs were coherently grown. The two inset images presented a 1×1μm^2 AFM image which shows a good uniformity with $3\times10^{10}cm^{-2}$ dot density and the typical shape of a single QD. Broad-area lasers were fabricated as shown schematically in Fig. 1c. The light-current-voltage (LIV) curve of the device was shown in Fig. 1d. An ultra-low threshold current density (J_{th}) of 62.5 A/cm^2 under continuous-wave (CW) at room temperature (RT) was obtained, which was the lowest J_{th} value achieved for any kind of lasers on Si substrate at that time. The single facet output power measured under injection current density of 650 A/cm^2 was

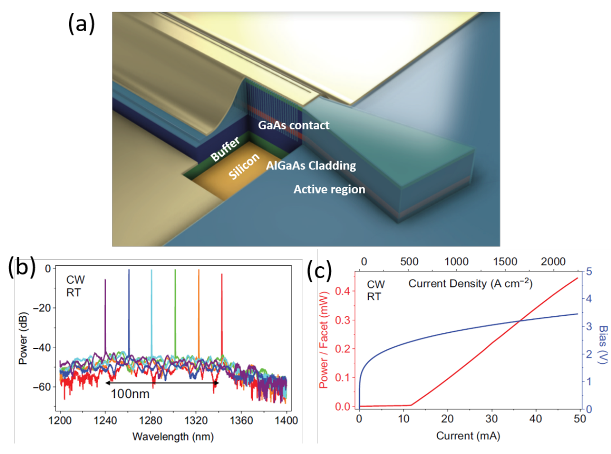

Fig. 2 (a) Schematic structure of fabricated Si-based DFB laser. (b) Optical spectra of a DFB laser array before saturation. (c) LIV curve of a 1 mm long DFB laser.

exceeded 105mW.

Based on the successfully demonstration of broad-area lasers, together with our cooperators, we further developed the first electrically pumped, single mode distributed feedback laser array on Si substrate with CW and RT operation [4]. The device structure was schematically shown in Fig. 2a. The RT characterization results were shown in Fig. 2b and c. A single mode CW lasing was obtained which produces a wavelength range of 100nm around 1300nm at O-band region with 20nm±0.2nm channel space (Fig. 2b). The LIV curve was shown in Fig. 2c, realizing a near-liner curve above threshold at 12.5mA (550A/cm^2). The calculated slope efficiency and wall-plug efficiency were 0.024W·A^{-1} and 0.5%, respectively. As the electrodes were fabricated at epi-layers with less defects compared with III-V/Si interface, the slope resistance of ~20Ω was achieved under operation. The single facet output power of over 0.5mW was achieved under CW condition.

QD lasers on CMOS-compatible Si (001) substrate

Although offcut Si substrate could prevent the formation of antiphase boundary, its fabrication process is not fully compatible to CMOS standard, which needs so-called on-axis Si (001) with offcut angle less then ±0.15°. Therefore, beyond the successful demonstration of QD lasers on offcut Si platform, we further developed broad-area QD lasers and QD photonic crystal (PC) lasers on CMOS-compatible Si (001) substrate in recent years [5-8].

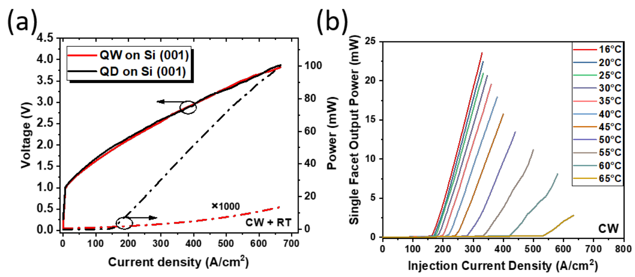

Fig. 3 (a) LIV curve of QD and QW lasers grown on on-axis Si (001) substrate. (b) Temperature dependent LI curve of QD laser under CW condition.

Our approach to achieve QD lasers integrated on CMOS-compatible exact Si (001) was to grown high-quality GaAs buffer on Si platform without intermediate layers [5-7]. The whole device structure was directly deposited on an on-axis Si (001) substrate with the first 40 nm GaAs nucleation and following 360 nm GaAs buffer deposited by metal-organic-chemical-vapor-deposition system. The rest structures were all grown by MBE. For our latest results of 1.3μm broad-area QD laser on on-axis Si (001) substrate, 25 μm×3 mm lasers were fabricated for both QD and QW samples (reference sample) for a comparison [7]. As shown in Fig. 3a, the J_{th} of ~173 A/cm^2 for QD laser has been achieved. Over 100 mW single-facet output power was obtained under injection current density of 670 A/cm^2. In contrast, there was no lasing operation for the QW device at RT even at high injection levels. Fig. 3b presented a temperature dependent LI curve of QD laser on Si (001). The highest CW operation was obtained over 65 °C.

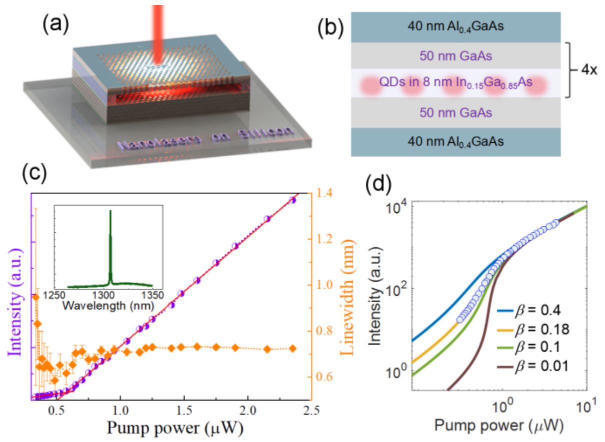

Fig. 4 (a) Schematic diagram of a QD PC laser on on-axis Si (001). (b) A diagram of active region in our PC lasers. (c) Collected L-L curve and linewidth of the lasing peak at 1306 nm. (d) Logarithmic L–L plot of fitted and collected data.

Furthermore, we developed the first monolithic integration of PC laser emitting at 1.3 μm on CMOS-compatible Si (001) substrate [8]. Fig. 4a shows a schematic diagram of PC lasers grown on Si (001). The active region is shown in Fig. 4b, which consists of four repeats of InAs/$In_{0.15}GaAs$ DWELL layers sandwiched by 50 nm GaAs space layers and 40 nm $Al_{0.4}GaAs$ cladding layers. As shown in Fig. 4c, the optically pumped QD PC lasers exhibited single-mode operation with an ultra-low threshold of ~ 0.6 µW and an intrinsic linewidth of ~ 0.68 nm. The logarithmic plot of L-L curve and fitting results of the PC laser shown in Fig. 4d indicated a large spontaneous emission coupling efficiency (β) up to 18% under CW condition at RT.

3. Conclusions

These works discussed in this paper demonstrate that QD laser monolithically integrated on Si (001) substrate can be a promising on-chip optical source for Si photonics. Different approaches also provide new routes to form the basis of future monolithic light sources for the application of optical interconnects in large-scale silicon optoelectronics integrated circuits.

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