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Demonstration of Distributed Feedback Silicon Evanescent Quantum Dot Laser

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Abstract

We report a distributed feedback silicon evanescent laser using InAs/GaAs quantum dot as gain medium. A single mode operation under continuous wave condition is obtained at 1266 nm with side mode suppression ratio higher than 40 dB.

1. Introduction

III-V semiconductor lasers wafer-bonded onto silicon waveguides are promising components for the realization of silicon photonic integrated circuits (PICs) for next-generation ultra-low-power-computation and telecommunications [1]. Quantum dots (QDs) are considered suitable as an optical gain media for lasers in PIC applications, due to their superior lasing characteristics [2]. In the previous work, we demonstrated the first hybrid silicon evanescent quantum dot laser successfully [3]. This result was achieved by III-V/Si hybrid structure through a direct wafer bonding, adiabatic taper couplers, and distributed Bragg reflectors (DBR) to define a laser cavity. Distributed feedback (DFB) lasers are also suitable for the PIC applications due to their single mode operation and short cavity lengths allowing small footprint. So far, hybrid silicon DFB lasers have been demonstrated using multiple quantum well as gain medium [4,5]. However, the hybrid silicon DFB laser utilizing QDs as active layer was not demonstrated. In this work, we report distributed feedback silicon evanescent QD laser for the first time.

2. Device Design and Fabrication

Design

Figure 1 shows illustrations of the distributed feedback silicon evanescent QD laser. The cross-sectional view of the device (Fig. 1 (b)) is similar to the hybrid silicon evanescent quantum dot laser reported in [3]. A difference of this device is a wafer bonding method. In this work, we introduced a wafer bonding method using spin-on-glass(SOG) as an adhesive material. SOG is a representative spin-on dielectric material used for semiconductor industry. SOG can be used as a bonding material with controlled thickness [6], which gives us enhancement of bonding yield. The DFB region consists of InAs/GaAs quantum dot layer and side wall grating with quarter wave shift under the III-V layer. The silicon waveguide under this region has the grating etched on the sides of silicon waveguide and is narrow enough to confine the optical mode into the quantum dot layer. Reversed taper couplers act

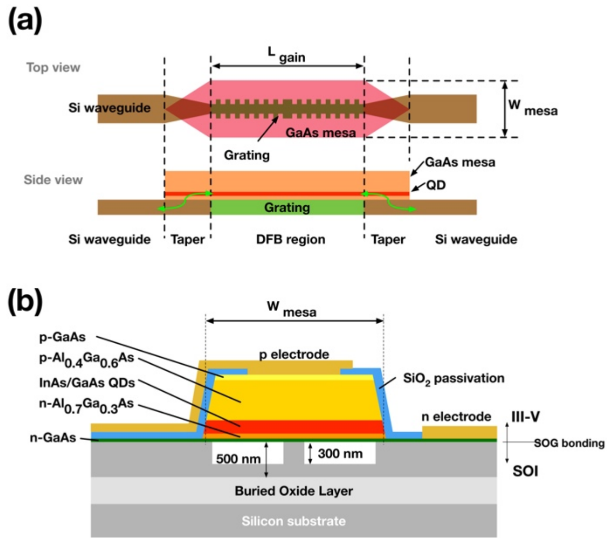

Fig. 1 (a) Top view and side view of the distributed feedback silicon evanescent quantum dot laser. (b) Cross-sectional schematic structure of the laser device in the DFB region.

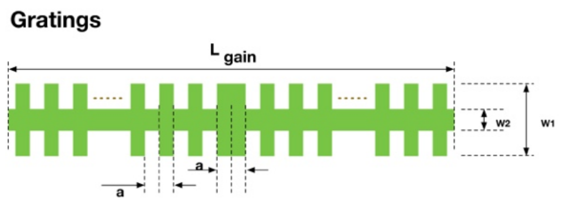

Fig. 2 Schematic of top view of the grating structure with quarter wave shift in the center of grating.

to provide a mode transition between the GaAs/AlGaAs mesa and silicon waveguide by varying the width of both the silicon rib waveguide (W_{si} from 0.5 μm to 2.5 μm) and GaAs/AlGaAs mesa (W_{mesa} from 5 μm to 1 μm). Figure 2 shows schematic of the grating that is defined by four parameters: length of the grating L_{gain}, period a, wide width W_1, and narrow width W_2. An important parameter for device design is the grating coupling coefficient. The grating coupling coefficient, κ, can be calculated as:

$$\kappa = \frac{2(n_{eff1} - n_{eff2})}{\lambda} \quad (1)$$

where n_{eff1} and n_{eff2} are the effective refractive indices of the III-V/Si hybrid structure related to W_1 and W_2 of the width of grating, respectively. λ is the optical wavelength and this equation is assuming a 50 % filling factor and 1st order grating. The effective indices are calculated using finite elements method solver. For single-mode operation, proper coupling strength $\kappa \cdot L$ is required. To obtain single mode lasing, we designed $\kappa \cdot L$ to be a range of from 0.5 to 2.0. The grating period is set 191 nm for the center wavelength to be 1266 nm. Other parameters are as follows: L_{gain} = 1 mm, L_{taper} = 0.6 mm, W_{mesa} = 5 μm.

Fabrication

First, SOI wafer is processed to form the silicon waveguide with the grating and taper structure by electron-beam lithography and dry etching methods. Then for the SOG bonding, InAs/GaAs quantum dot and SOI silicon waveguide wafers are diced and cleaned. SOG solution is only applied on the GaAs wafer with 5,000 rpm 60 sec spin coating, followed by soft bake on a hotplate 100 °C for 1 minute in order to prevent void formation. The GaAs and SOI dices brought into contact and annealed at 300 °C for 3 h under a uniaxial pressure of 0.1 MPa. The thickness of SOG after wafer bonding is measured 40 nm. A subsequent GaAs substrate removal is conducted to complete the layer transfer process with selective wet chemical etching. After the quantum dot laser structure layer transfer, ridge lasers are formed. The details of ridge laser fabrication are described in [3]. A modified process is to form GaAs mesa taper structures with photomask pattern. Note that these taper structures are formed by wet chemical etching with photoresist mask, their end tip width become about 1 μm unlike the ideal sharp taper structure. Finally, one side of the silicon waveguides are cleaved to form silicon waveguide facet for optical measurement.

3. Results and Discussion

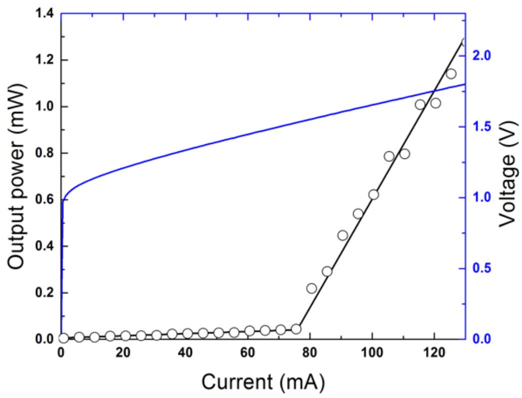

Fig. 3 Output power-current-voltage (LIV) curve

Grating parameters fabricated in this work are as follows: a = 191 nm, W_1 = 410 nm, W_2 = 200 nm. The calculated coupling coefficient is 50 cm^{-1}. The output power from the silicon waveguide facet was measured. The injection current dependence of the optical output power is shown in fig. 3 under continuous wave operation at room temperature. The laser threshold current is 76 mA. Figure 4 shows the lasing spectrum at a 100-mA continuous wave current injection around a wavelength of 1266 nm which is the center wavelength calculated. A clear single mode lasing with over 40 dB side-mode suppression ratio (SMSR) is seen. Since the waveguide facets are not antireflection coated, the Fabry-Pérot laser modes are also shown in fig. 4, which can be removed with antireflection coating on silicon waveguide facet.

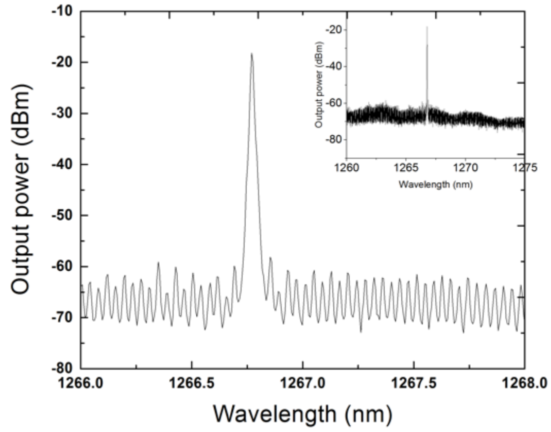

Fig. 4 The lasing spectrum at 100 mA current injection with a 40-dB side mode suppression ratio. (inset) The lasing spectrum over 15 nm span.

4. Conclusions

We demonstrated a distributed feedback silicon evanescent quantum dot laser for the first time. The laser fabricated by conventional semiconductor laser fabrication process following SOG wafer bonding method to transfer the quantum dot laser epitaxial layer onto the silicon waveguide. The laser showed a 76-mA threshold current under continuous wave operation at room temperature and single mode output with larger than 40 dB side mode suppression ratio at 1266 nm.

Acknowledgements

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