博士論文（要約）

Study on Hybrid Silicon Evanescent Quantum Dot Lasers

（シリコン上エバネッセント型ハイブリッド量子ドットレーザに関する研究）

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In the current information explosion and digital revolution era, higher data transmission and processing rate are needed to deal with a large amount of information, and silicon photonics is taken as a promising technology for realizing the high-performance communication and computation systems with low power consumption. In the last decade, passive optical communication components on silicon have been deeply developed such as optical modulators, photodetectors, waveguides, (de)multiplexers, and so on. These components are even demonstrated and reported with industrial levels. However, since silicon is an indirect band gap material that exits poor light-generating capability, the light sources on silicon still poses a challenge nowadays. III-V compound semiconductor lasers have shown great performances and been utilized as light sources for optical communication applications. Among all semiconductor lasers, quantum dot laser has been particularly considered as a suitable light source in silicon photonics as well as photonic integrated circuits application via its superior properties such as low threshold conditions, high temperature operation, and reflection tolerance. The way to integrate sophisticated III-V compound semiconductor lasers on silicon is now known quite suitable for the light sources of silicon photonics. However, due to the dissimilarities between silicon and III-V materials such as mismatches of lattice constant as well as coefficient of thermal expansion, the integration of III-V on silicon has been widely studied, including heterogeneous material growth, flip-chip bonding, and wafer bonding technology. Though the direct growth of III-V material on silicon have been reported recently, we believe that the best solution of material integration for the case of light sources

on silicon is a wafer bonding, which enables an efficient optical coupling of the optical mode to other optical components. Especially, the direct bonding approach, which is to transfer the III-V semiconductor laser structure onto the silicon, and followed by the process of forming the laser devices, does not require complicated alignment technology nor additional coupling structure for achieving efficient optical mode coupling, and is thus quite potential for low-cost and mass manufacture in the future. Moreover, unlike the heterogeneous growth that is always limited by materials' nature, it is free from material's dissimilarity, providing larger flexibility to the device or system design. The first hybrid silicon laser was presented by Bowers' group in UCSB in 2006. They successfully demonstrated lasers on silicon fabricated by plasma-activated wafer bonding technique, and the laser emission coupled to the silicon waveguide by evanescent coupling. After then several groups have demonstrated hybrid laser on silicon waveguide with various bonding methods and device structures. However, these demonstrations of hybrid evanescent lasers are all based on quantum well lasers so far, and no reports on quantum dot lasers. Furthermore, although there are several reports on direct-bonded quantum dot lasers on silicon substrate with low threshold current density and stable high-temperature operation, the device with efficient optical coupling to silicon waveguide is not realized yet. This thesis focuses on the demonstration of hybrid silicon evanescent laser with quantum dot as a gain medium. By designing laser structures on silicon waveguide and finding moderate fabrication method, the hybrid silicon evanescent quantum dot lasers are successfully realized.

In chapter 2, fundamentals of quantum dot lasers are described, and then followed by the fabrication method of quantum dots used in semiconductor laser. Finally, the reason why quantum dot laser has superior performances than others are described, including its superiority as the light source for photonic integrated circuit with high-density integration and low-power consumption.

In chapter 3, designs of the hybrid silicon evanescent quantum dot lasers are presented. The laser device consists of three parts: gain region, optical coupling region, and reflection components. For the design of hybrid structure in the gain region, we studied optical mode distribution with various parameters to maximize the optical gain. In the coupling region, we designed tapered silicon waveguide as the coupling efficiency to be the highest with parameters of waveguide thickness, taper length, and width. All the reflection components are side wall grating in the silicon waveguide. There are mainly two types of gratings designed here: distributed Bragg reflector and distributed feedback grating. To define the laser cavity, distributed Bragg reflectors are formed outside of the III-V region. The reflectors have reflectivity of 90 % and a stop band set at around gain spectrum peak. For DFB laser, to achieve single wavelength emission, the grating width is moderately designed with studying effective indices and coupling coefficient as changing waveguide width and distance between the active layer and the silicon waveguide.

In chapter 4, the fabrication method of the hybrid silicon evanescent quantum dot lasers is described in detail. The fabrication mainly consists of three parts: silicon waveguide fabrication, laser structure layer transfer, and post-bond fabrication process. On the silicon-on-insulator (SOI) wafer, the designed waveguides and gratings are formed by electron beam lithography and dry etching. The III-V layer transfer onto silicon waveguide is done by direct wafer bonding and subsequent GaAs substrate removal. The post-bond device fabrication process is conventional laser diode fabrication processes with photolithography, wet chemical etching, sputtering, and electron beam deposition. It should be noted that we took some modifications on conventional fabrication process to get successful device fabrication with dedicate structures, which is presented in detail in this chapter.

The demonstration and characterization of hybrid silicon evanescent quantum dot laser is shown in Chapter 5. For pulsed current injection, the laser can operate at high temperatures up to 115°C with a characteristic temperature T0 of 303 K near room temperature. The spectrum and near field pattern of silicon waveguide facet are the evidences that the laser cavity is defined by distributed Bragg reflectors and the light coupled to silicon waveguide as designed. A continuous wave (CW) operation is also achieved by reducing the mesa width down to 8 microns. For CW operation, the laser can still operate up to 90°C thanks to the quantum dot as the gain medium.

In chapter 6, a further demonstration of single mode operation in hybrid silicon evanescent quantum dot laser with distributed feedback grating is presented. A single mode operation under CW condition is obtained at 1266 nm with a side mode suppression ratio higher than 40 dB, which is practical for optical communication use.

Finally, this thesis ends with chapter 7, conclusions of this research and the future perspective are discussed in this chapter.