論文の内容の要旨

論文題目　Fabrication and Characterization of Wafer-Bonded Quantum Dot Lasers on Silicon

(ウェハ融着法によるシリコン基板上量子ドットレーザの作製とその評価に関する研究)

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In the current information explosion era, the conventional electrical interconnection cannot meet the demand of high data transmission rate, and the optical interconnection is introduced for both longer- and shorter-distance transmission. However, the relatively high cost makes it inapplicable to the data center application. Silicon photonics, an ideal candidate for the electrical-to-optical interconnection transition, is thus a promising technology for the industrial-scale photonic-integrated circuits (PICs). Although the passive photonic devices on Si have been systematically studied, the realization of the active Si photonic devices, the efficient light sources, is still a challenge due to the indirect-bandgap nature of Si. III-V semiconductor lasers, which have been deeply studied for long time, are extremely suitable as the light sources for Si. In particular, semiconductor quantum dot (QD) lasers, with advantages of low threshold condition and temperature stability, are thus preferable to the PIC applications. For the integration of III-V light sources on Si, the wafer bonding technology provides a simple and effective way, which is not subject to the lattice-mismatching limitations that usually accompany the direct growth. Moreover, the performances of bonded devices are comparable to the as-grown devices. Due to these merits, we utilize the wafer bonding technology for jointing QD lasers on Si and realize the active Si photonic devices in this study.

This dissertation mainly focuses on the fabrication and characterization of high-performance InAs/GaAs QD lasers wafer-bonded onto Si. The thesis organization and the main conclusions of this study are briefly described as follows.

Chapter 1 gives an introduction on the research background of silicon photonics, and the research motivation as well as the objective in this study.

Chapter 2 to Chapter 4 gives the basic introductions on the topics related to this study. Chapter 2 gives a brief introduction on the Si-based and III-V material-based light sources on Si. The fundamentals of QD lasers, including the basics of quantum dots, gain and threshold of the QD laser, and the principle of modulation properties, is then presented in Chapter 3. Chapter 4 describes the basics of the wafer bonding technology, and gives a brief introduction on the basics and the different bonding methods.

Chapter 5 includes a series of bonding tests to determine the bonding conditions for GaAs on Si, which is prepared for bonding GaAs-based QD lasers onto Si in the following works. We mainly utilized two bonding schemes: the direct bonding method with a simple fabrication process, and the metal-mediated bonding method, which usually offers better electrical and thermal properties. According to the results of the electrical properties of GaAs/Si pairs, the bonding temperature at 300 ^{o}C for direct bonding and metal-metal bonding could provide smallest resistances of the GaAs/Si bonding interface, and this condition is thus applicable to the integration of lasers on Si. We also made an improvement on the bonding strength for the direct bonding by ultraviolet (UV) surface activation. The bonding strength of UV-activated bonding is ten times stronger than that of our original direct bonding method.

In Chapter 6, the determined bonding conditions were then applied to the integration of InAs/GaAs QD lasers on Si. We firstly established the fabrication process and demonstrated the QD lasers on Si with comparable lasing performances as for that of the as-grown lasers. The metal-bonded and direct-bonded QD lasers on Si operate with threshold currents of 140 mA and 100 mA under pulse pumping, respectively, and both of them exhibit room-temperature lasing wavelengths at 1.3 μm.

Chapter 7 consists the demonstration of the modulation properties in the bonded lasers, which is one of the important issues for the communication system. The fabrication and preparation of the laser chips for modulation experiment is described in details. We presented the bonded InAs/GaAs QD lasers on Si under continuous-wave operation. The 600-μm-long bonded laser was performed with a threshold current of 130 mA, with an output power of 15 mW (single facet) at the injected current of 200 mA. We then demonstrated the first direct modulation experiment in QD lasers on Si. Under a bias current of 180 mA, the bonded laser could be modulated with a bit rate up to 6 Gbps, and the extinction ratio according to the eye pattern is 5 dB, as shown in Fig. 1. We also

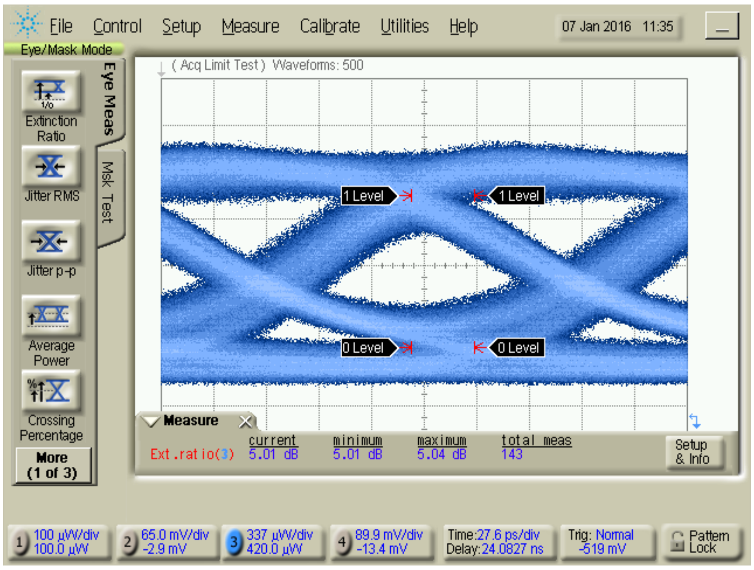

Figure 1. The eye diagram of InAs/GaAs QD lasers on silicon under 6 Gbps modulation speed.

estimated the modulation bandwidth f_{3dB} of 8 GHz according to the eye diagram at different modulation speeds. Noted that we did not introduce any grating structure into the lasers, and there is no coating on the as-cleaved facets, which would improve the modulation properties of the bonded lasers.

On the other hand, we also aim for a realization of the hybrid evanescent lasers, that is, the optical mode exiting in both III-V region and Si waveguide. In Chapter 8, we first established the fabrication technique, and then made a design on the laser structure for achieving the evanescent coupling. The metal-stripe bonding scheme was adapted here for the QD lasers on Si-ribbed silicon-on-insulator (SOI) substrates with the light emission from the III-V region, as shown in Fig. 2. Here the Si rib structure was introduced for imitating the Si waveguide, and the metal stripe was installed as the bonding metal as well as the electrodes, providing ohmic contact to the lasers. In this study, we have successfully demonstrated the broad-area type laser with a threshold current of 520 $A{\cdot}cm^{-2}$, and the ridge-type bonded laser with a threshold current of 110 mA, as shown in Fig. 3. To our best knowledge, this is the first demonstration of InAs/GaAs QD lasers on SOI substrate by directly bonding metal and semiconductor materials. Note that our bonded lasers were all performed without any coating on the as-cleaved facets. After the fabrication part, we further designed the hybrid QD/Si evanescent lasers by adjusting the dimensions of QD laser structures as well as the Si waveguides. According to the simulation, the hybrid laser could be designed with a 150-nm-thick AlGaAs lower clad layer and 0.8-µm-wide Si waveguide to achieve lasing in III-V region, and the optical mode lying in Si for transmission. Moreover, under a fixed 150-nm-thick AlGaAs lower clad layer, the Si

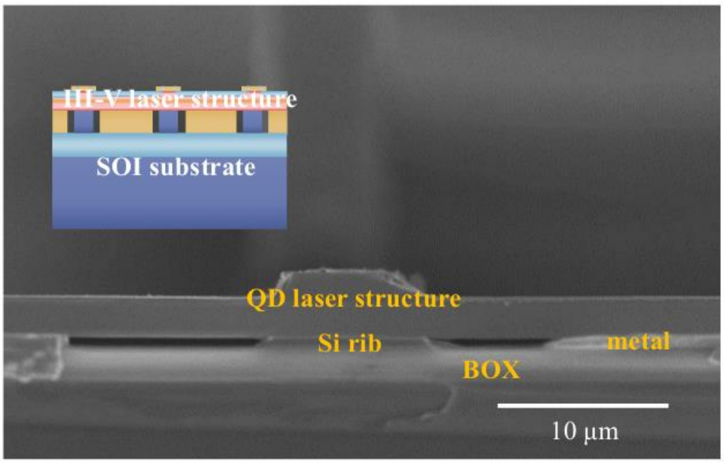

Figure 2. Cross-sectional SEM images of ridge-type QD laser on Si-ribbed SOI substrate by metal-stripe bonding.

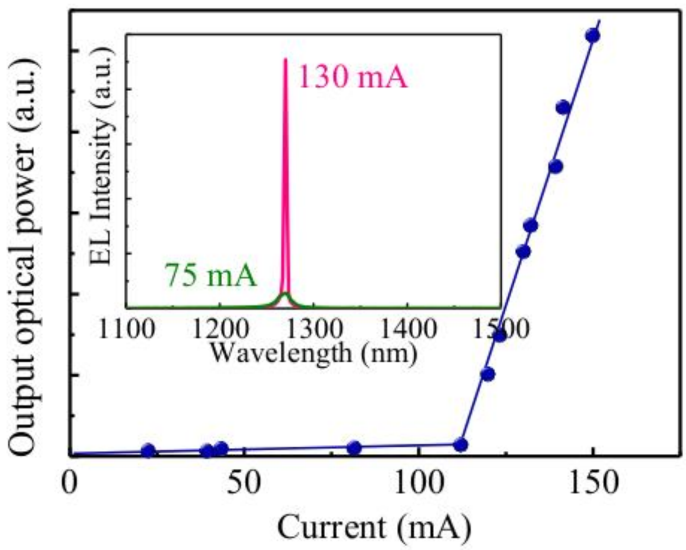

Figure 2. Room-temperature light–current characteristics and (inset) electroluminescence spectra of the broad-area InAs/GaAs QD laser on SOI substrate fabricated by metal-stripe wafer bonding.

waveguide with widths of 0.8 μm and 1.5 μm could be adapted to the design with the adiabatic taper for a compact waveguide design.

The dissertation ends with Chapter 9. The conclusion of this research and the outlook of the future perspective are described in this chapter.