博士論文（要約）

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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Abridged Thesis

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 materials' limitations. 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 main conclusions of this study are briefly described as follows.

In order to integrate QD lasers on Si, we first made a series of bonding tests to determine the bonding conditions for GaAs on Si. We mainly utilized two bonding schemes: the direct bonding method and the metal-mediated bonding method. According to the properties of the bonded GaAs/Si pairs, the bonding temperature at 300 ^{o}C for direct bonding and metal-metal bonding have best properties 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, where the UV-activated bonding strength is ten times stronger than that of our original bonding.

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.

The modulation properties in the bonded lasers was next presented, which is one of the important issues for the communication system. The 600-μm-long bonded laser was performed under continuous-wave pumping, with a threshold current of 130 mA and a maximum output power of around 15 mW (single facet). The first direct modulation experiment in QD lasers on Si was then demonstrated 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 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.

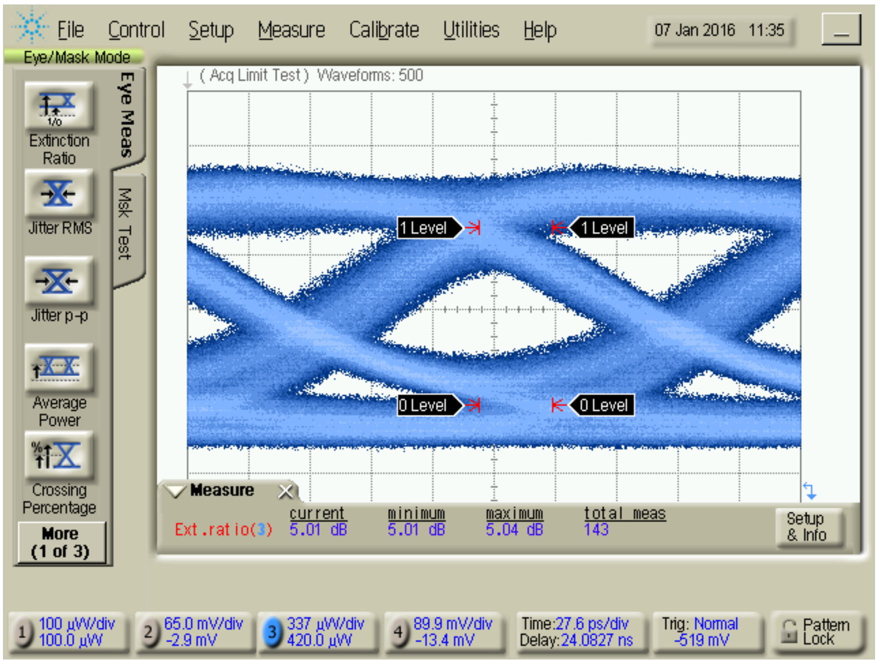

Figure 1. The eye diagram of InAs/GaAs QD lasers on silicon under 6 Gbps modulation speed.

On the other hand, we also aim for a realization of the hybrid evanescent lasers. 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. In this study, we have successfully demonstrated the broad-area type laser with a threshold current density 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. According to the simulation, the hybrid laser could be designed with a fixed 150-nm-thick AlGaAs

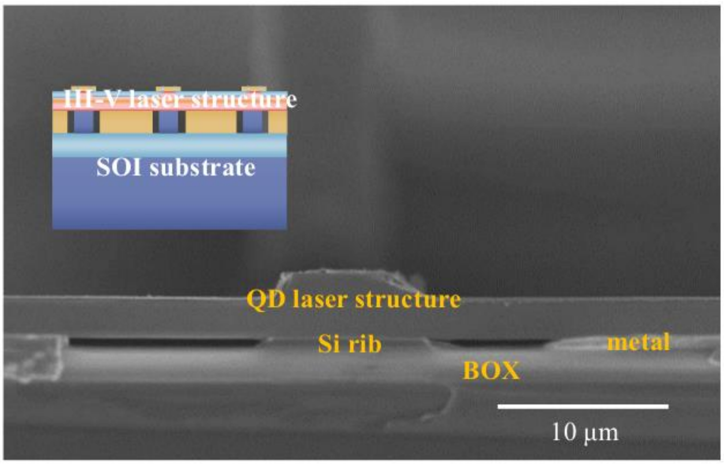

Figure 2. Cross-sectional SEM images of ridge-type QD laser on Si-ribbed SOI substrate by metal-stripe bonding.

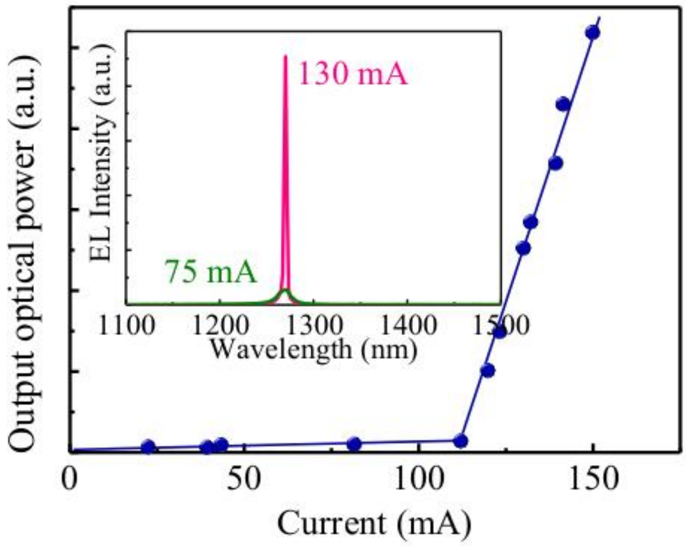

Figure 3. Room-temperature light–current characteristics and (inset) electroluminescence spectra of the broad-area InAs/GaAs QD laser on SOI substrate fabricated by metal-stripe wafer bonding.

lower clad layer, and the Si waveguide with widths of 0.8 μm and 1.5 μm could be adapted to the design with the adiabatic taper for light manipulation with a compact waveguide design.

With simple device structure and fabrication, our result shows an encouraging demonstration for III-V QD lasers on Si, which benefits the silicon photonic integrated circuits for high-speed and low-cost applications.

that our bonded laser was performed with no anti-reflection or high-reflection coating on the manually-cleaved facets, and such treatments on the facets would further increase the laser performance.