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High performance InAs quantum dot lasers on silicon substrates by low temperature Pd-GaAs wafer bonding

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InAs quantum dot (QD) laser heterostructures have been grown by molecular beam epitaxy system on GaAs substrates, and then transferred to silicon substrates by a low temperature (250 °C) Pd-mediated wafer bonding process. A low interfacial resistivity of only 0.2 Ω cm2 formed during the bonding process is characterized by the current-voltage measurements. The InAs QD lasers on Si exhibit comparable characteristics to state-of-the-art QD lasers on silicon substrates, where the threshold current density Jth and differential quantum efficiency ηd of 240 A/cm2 and 23.9%, respectively, at room temperature are obtained with laser bars of cavity length and waveguide ridge of 1.5 mm and 5 μm, respectively. The InAs QD lasers also show operation up to 100 °C with a threshold current density Jth and differential quantum efficiency ηd of 950 A/cm2 and 9.3%, respectively. The temperature coefficient T0 of 69 K from 60 to 100 °C is characterized from the temperature dependent Jth measurements. © 2015 AIP Publishing LLC.

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Silicon photonics is one of the most promising alternatives to electronic interconnects and nearly all of the components of silicon photonic interconnects have been individually demonstrated.1–5 However, there still remain significant challenges to the realization of complete optical interconnects that are low-cost and have high performance. One of the biggest challenges is the monolithic integration of robust and low-powered lasers with silicon photonic devices. Specifically, current approaches are not robust against temperature variations (requires T < 40–60 °C for operation).6,7 In this context, InAs quantum dot (QD) lasers are attractive candidates due to their suitability for high temperature operation.8–10 Recently, InAs QD lasers were monolithically grown on silicon substrates.11–13 However, this required the use of Silicon (110) substrates offcut 4°–6° toward [110] or [111] planes and various buffer layers were employed to reduce the lattice mismatch effects between III-V and silicon, both of which limit CMOS compatibility. Besides these direct growth techniques, wafer bonding technologies have also been used to integrate high-performance InAs quantum dots lasers on silicon substrates.14–16 The performance of such bonded InAs QD lasers is often degraded by the high temperature of the bonding process (>300 °C for at least a few hours),14–22 which intermixes the InAs QDs and their GaAs capping and spacer layers. On the other hand, it has been demonstrated that Palladium can form a solid alloy with III-V materials, such as PdGaAs or PdInP, by a solid-phase topotaxial reaction at room temperature. This Pd/III-V reaction has previously been used to bond III-V wafers on foreign substrates by Yablomovitch et al. and Bowers et al. for electronic transistor applications,23,24 and demonstrated that the resulting metallurgical Pd/GaAs bond is an Ohmic contact, a thermal contact and a robust, permanent, adherent contact. However, the application of Pd/III-V low temperature bonding beyond the original electronic applications has not been investigated. In this report, we present the growth, fabrication, and characterization of high-performance InAs QD lasers on the silicon substrates achieved by a low-temperature Pd/III-V bonding process. The advantages of using the Pd-mediated bonding process are also demonstrated and discussed.

Figure 1 illustrates the InAs quantum dot laser heterostructures grown on (001) GaAs substrates in a molecular beam epitaxy (MBE) system. The active region contains seven stacks of InAs QD layers. Each QD layer consists of 2.6 monolayer (ML) InAs grown at 500 °C under the growth rate of 0.1 ML/s and capped with 5 nm In0.15Ga0.85As. In our dot growth, compared to others,25 we employed larger dots and small In0.15Ga0.85As capping layer to achieve optimized QD density as well as uniformity and high photoluminescence intensity. In order to increase the temperature performance of the QD lasers, the InAs QDs were modulation doped by beryllium at the concentration of 2 × 10¹⁸ cm⁻³. In the laser heterostructures, the p-type and n-type doped Al0.5Ga0.5As cladding layers are designed to confine the QD emission in the III-V waveguide. Finally, an Al0.85Ga0.15As etch stop layer with a thickness of 30 nm was inserted between the GaAs substrate and InAs QD laser heterostructure. After epitaxial growth, the QD laser heterostructure is bonded to a silicon substrate in a Karl Suss SB8e substrate bonder by the Pd-mediated bonding process. In this process, Ti/Pd with a thickness of 50/250 nm is deposited on a Si substrate by e-beam evaporation. The Ti serves as an adhesion promoter.

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and the Pd is used to form the permanent bond to the GaAs. The III–V wafer is then put in contact with the Pd coated Silicon wafer and several bonding condition combinations were tested (200–350 °C, 1000–1500 mbar, 1–4 h). It was found that permanent bonding can be achieved at a low temperature and time of 250 °C and 1.5 h, respectively, at 1000 mbar pressure which is at least 50 °C and 50% less than previously described metal-mediated bonding techniques. After bonding, the GaAs substrate is removed by a combination of mechanical polishing and wet chemical etching, where the 30 nm Al0.85GaAs in the heterostructure acts as an etch stop layer. After removing the Al0.85GaAs, the ridge waveguide lasers are fabricated by standard process where the waveguide width of 5 μm was fixed and the cavity lengths were varied from 1000 to 2000 μm, respectively. All the laser devices reported in this article are measured with the waveguide facets un-coated (as-cleaved).

The structural properties of the InAs QDs are characterized by atomic force microscope (AFM) and transmission electron microscope (TEM) measurements. In order to perform the AFM measurements, InAs quantum dots without the GaAs capping layers were grown in a separate experiment under the same growth conditions as the ones in the QD laser active regions. Figure 2(a) illustrates the AFM image of the InAs QDs in the area of 1 × 1 μm², and it shows that the InAs QDs have density of ~7 × 10¹⁰ cm⁻² and average base diameter and height of 45 nm and 8 nm, respectively. The cross-sectional TEM image (Figure 2(b)), taken under [110] zone axis illumination, shows that the quantum dots have a dome shape. The dot dimensions appeared to be smaller compared to the ones obtained from AFM measurements due to small strain contrast at the edge of the dots.

The electrical characteristics of the InAs QD lasers on Silicon are measured with a customized probe station, where the samples are loaded with n-side up on a thermolectric cooler (TEC) stage, and, consequently, the device temperature was controlled by the TEC during the measurements. In order to characterize the series resistance at the Pd/III–V bonding interface, a highly doped p-type GaAs substrate was bonded to a low resistance p-type doped silicon substrates with the bonding recipe described above, and a mesa in the GaAs with a size of 0.4 cm² was etched to the Pd bonding interface. The top Ohmic metals to the p-type GaAs and bottom Ohmic metals to the Si consisted of Ti/Pt/Ti/Au with the thickness of 20/20/20/300 nm and 200 nm of aluminum, respectively. As shown in Figure 2(c), the I-V characteristics between the top GaAs and bottom Si contacts exhibit a linear behavior and shows that the Ti/Pd contact is ohmic to both the Si and GaAs substrates. Specifically, the low temperature Pd-mediated bonding shows a very low interfacial resistivity of only 0.2 Ω cm², which is comparable to direct fusion bonding and other metal bonding results with the resistivity varying from 0.1 to 1.3 Ω cm². Moreover, the solid line in Figure 2(c) shows the I-V characteristics between the top GaAs and Pd contact, where it exhibits nearly the same electrical characteristics with slightly lower interfacial resistivity compared to the one obtained from the top/bottom contacts which is 0.24 Ω cm² (dashed line).
The optical characteristics of the InAs QD lasers are seen in Figure 3(a). The solid curve shows the continuous-wave (cw) light-current (L-I) characteristics of the bonded InAs QD lasers with a cavity length and waveguide width of 1.5 mm and 5 \( \mu \text{m} \), respectively, where a threshold current density \( J_{\text{th}} \) and differential quantum efficiency \( \eta_d \) of 240 A/cm\(^2\) and 23.9\%, respectively, is obtained at room temperature operation. In addition, an output power of \( \sim 5 \text{ mW} \) is obtained (from both facets) at an injection current of 45 mA. The lasing spectrum of the hybrid InAs QD lasers is shown in the inset of Figure 3(a) and measured at room temperature with the injection current of 27 mA (1.5\( I_{\text{th}} \)). The lasing emission is around 1.24 \( \mu \text{m} \), close to the O-band communication wavelength. The relatively large blueshift between the peak wavelength of the spontaneous emission and lasing wavelength is due to the minimized heating effect and band filling effect in QDs. Overall, the laser properties shown here are comparable to state-of-the-art self-assembled InAs quantum dot lasers on the silicon substrates, where threshold current densities from 163 A/cm\(^2\) to 900 A/cm\(^2\) have been reported with varied cavity length (0.6–3.5 mm) and ridge width (4–30 \( \mu \text{m} \)).

In order to study the influence of the wafer bonding process, identical ridge waveguide laser devices were made on a native GaAs substrate. The results are seen in the dotted line in Figure 3(a) and an overall comparison is shown in Figure 3(b). It is clear that the bonded laser has better performance as it exhibits a lower threshold current density and improved slope efficiency (240 A/cm\(^2\) and 23.9\% for the bonded compared to 280 A/cm\(^2\) and 10.4\% for the unbonded). In addition, as seen in Figure 3(b), this improved performance is consistently observed for multiple lasers of different cavity lengths. We do note that there is some variation in the unbonded lasers that we believe is due to un-optimized cleaving of the facets across the entire chip but even with this the improvement from bonding is clear. It is believed that the improved performance of the bonded laser can be attributed to the low temperature wafer bonding process and better heat dissipation through the Si substrates compared with the original GaAs substrates, where the thermal conductivity of silicon is three times larger than the one of GaAs (156 W/(m K)) compared to 46 W/(m K)). Finally, Figure 3(c) shows the emission spectra of the bonded and unbonded lasers below threshold (0.9\( I_{\text{th}} \)), where it is seen that both the spectrum shape and peak position were preserved after the bonding process. Thus, this observation also implies that the low temperature bonding process has negligible effect on the QD properties. This is also seen in Figure 4(a) which illustrates the L-I characteristics of the bonded InAs QD lasers at high temperatures from 60 to 100 °C, where a threshold current density, \( J_{\text{th}} \), and efficiency, \( \eta_d \), of 950 A/cm\(^2\) and 9.3\% are achieved at 100 °C operation. We believe the power fluctuations are due to the high current density through the electrical probes used to contact the lasers. The measured temperature dependence of threshold current is shown in Figure 4(b) for a laser with a cavity length of 1.5 mm. The corresponding temperature coefficient \( T_0 \) of 69 K is obtained which is comparable to other state-of-the-art hybrid lasers (~50 K). The \( T_0 \) is measured to be ~50 K for the unbonded lasers as well. It is worth noting that since the laser \( T_0 \) is mainly determined by the materials and laser heterostructure designs, including p-type modulation doping, the measured \( T_0 \) is not expected to exhibit large difference between the bonded and unbonded lasers.
density and slope efficiency of 240 A/cm² and 23.9%, respectively, at room temperature. The InAs QD lasers on Si can be made to operate at 1.3 μm with no significant performance degradation. After further optimization of the device efficiency and epitaxial process, the present hybrid InAs QD lasers can be made to operate at 1.3 μm, which will play a significant role for future silicon photonic integration.

In conclusion, a low interfacial resistivity, low-temperature Pd-mediated wafer bonding technique has been used to realize high quality InAs QD lasers on the silicon substrates. The bonded lasers exhibited better performance than their unbonded counterparts, with a threshold current density and slope efficiency of 240 A/cm² and 23.9%, respectively, at room temperature. The InAs QD lasers on Si also yielded operation at up to 100 °C with no significant performance degradation. After further optimization of the device efficiency and epitaxial process, the present hybrid InAs QD lasers can be made to operate at 1.3 μm, which will play a significant role for future silicon photonic integration.

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