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Quantum cascade lasers transfer-printed on silicon-on-sapphire

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We demonstrate coupling of the laser mode into a passive waveguide by transfer-printing fully processed mid-infrared quantum cascade lasers onto a silicon-on-sapphire platform. The laser waveguide mode is coupled into a silicon waveguide via an adiabatic taper. The experimentally achieved coupling efficiency of the taper is estimated to be \(\sim 10\%\), and theoretical calculations show that coupling efficiency over 75% is achievable by reducing the adhesive layer thickness to below 100 nm. Light coupling to silicon waveguides is confirmed by images taken at the output facet of a 3-mm-long passive Si waveguide with a mid-infrared camera. Our technique enables the development of heterogeneous photonic systems integrated with a wide range of fully processed semiconductor laser devices, including buried-heterostructure lasers, which was not previously possible. Published by AIP Publishing. https://doi.org/10.1063/1.5002157

Mid-infrared (mid-IR, \(\lambda = 3–15\) \(\mu\)m) photonic integration is of great interest for a variety of applications, including sensing, power combining, wavelength tuning, beam steering, and frequency conversion.1,2 Monolithic integration of mid-IR optoelectronic devices with a low-loss photonic platform offers a means to realize compact and cost-effective mid-IR photonic integrated circuits (PICs). While traditional mid-IR applications are based on the assembly of discrete optical components, mid-IR PICs ultimately combine all active and passive devices in a single chip, where highly sensitive, alignment-free, multi-functional mid-IR systems can be designed.

Quantum cascade lasers (QCLs)3 are the only electrically pumped semiconductor light sources that can operate at room temperature over the entire mid-IR spectral range. The tuning range of a modern mid-IR QCL can be in excess of 30% of its center frequency,4 and continuous-wave QCLs operating at room temperature are now available for the wavelength range from 3 \(\mu\)m (Ref. 5) to 15 \(\mu\)m.6 The high performance continuous-wave QCLs are produced using buried-heterostructure devices in which the laser ridge is “buried” in the overgrown semi-insulating InP layer that provides ridge-wall insulation with low optical loss and high thermal conductance. Efforts to minimize the power consumption of mid-IR QCLs have led to devices with only 0.5 W of power dissipation at room temperature.7 A combination of laser- and detector-operation capability of mid-IR QCLs has been used for creating QCL-based monolithic sensors using plasmonic waveguides.8

Dielectric waveguides can offer significantly lower losses for mid-IR light propagation, compared to plasmonic waveguides. In particular, mid-IR optical loss coefficients as low as 0.74 dB/cm were estimated at the 4.5 \(\mu\)m wavelength for the ring-resonators fabricated in a commercially available silicon-on-sapphire (SOS) platform.9 Integration of mid-IR light sources with the SOS platform is thus highly appealing for the development of mid-IR PICs. Several approaches to monolithic integration of mid-IR QCLs with low-loss dielectric waveguides have been demonstrated in the literature. Montoya et al. have used selective, low-dose proton implantation to compensate n-type doping in the QCL active region and cladding layers and create passive waveguides in the QCL wafer itself.10 Gilles et al. proposed to use an InGaAs layer below the InGaAs/AlInAs QCL active region as an underlying passive waveguide that can be directly grown on InP.11 Those homogeneous-integration approaches do not require a wafer-bonding process that would add complexity in fabrication. However, the major disadvantage of these approaches is the inefficient use of the relatively expensive QCL-heterostructure material.

The first heterogeneous integration of mid-IR QCLs on a silicon (Si)-based platform has been reported by Spott et al.12 Using direct wafer bonding, the authors demonstrated coupling of a hybrid laser mode into a Si waveguide fabricated in a Si-on-nitride-on-insulator platform. However, the laser ridge waveguides for the direct wafer bonding approach have to be fabricated after the wafer-bonding step. Thus, it is challenging to realize mid-IR PICs using high-performance buried-heterostructure QCLs due to InP-regrowth requirements.

Here, we demonstrate an alternative approach to integration of mid-IR QCLs on a Si-based photonic platform by using a transfer-printing technique that allows transferring and optical coupling of fully processed QCL devices, including buried-heterostructure lasers, onto virtually any passive photonic platform. We transfer-print ridge-waveguide mid-IR QCLs operating at \(\lambda \approx 4.7\) \(\mu\)m onto a SOS wafer using SU-8 epoxy as an adhesive layer. Coupling of the QCL optical mode to the Si waveguide was achieved via an adiabatic taper. A reference device without the taper and Si waveguide sections produced a peak output power of 22 mW, while QCL devices taper-coupled to a 3-mm-long, 5-\(\mu\)m-wide Si
waveguide section produced a peak output power of 2 mW from the Si waveguide facet, all at room temperature. The emission profile from the Si waveguide facet confirms that the QCL light is coupled, predominantly, to the fundamental Si waveguide mode.

The integrated QCL-on-SOS device consists of a QCL gain section, an adiabatic taper section, and a Si waveguide section as shown in Fig. 1(a). The gain section provides optical gain by confining the laser mode in the QCL active region. The effective refractive index of the TM_{00} fundamental mode of mid-IR QCLs is approximately 3.25 in the 4–12 μm spectral range. Bonding of a QCL with a thin lower-cladding layer onto a Si platform will cause significant modal leakage from the active region to the underlying Si layer whose index (n_{Si} ≈ 3.4) is higher than the effective index of the laser mode in a QCL waveguide, resulting in an increased laser threshold-current density. On the other hand, using a thick lower cladding layer to prevent modal leakage will decrease the taper coupling efficiency. A solution used in the QCL hybrid lasers\(^\text{12}\) is to position the laser material on the top of a narrow-width Si waveguide. In this method, the optical mode distribution between the laser active region and the Si waveguide core is controlled by the widths of the Si waveguide and the QCL ridge. However, such an approach requires QCL fabrication after the epi-transfer process is completed, which we want to avoid.

Our design allows us to achieve both high optical-mode confinement to the QCL active region in the gain section and good laser-mode coupling efficiency to the Si waveguide by optimizing the thicknesses of the Si layer in the SOS wafer, the lower InP cladding layer in the laser structure, and the SU-8 bonding layer. Figure 1(b) shows the schematic of the laser-mode transition to the Si waveguide in the taper section, and Fig. 1(c) shows the simulation results for the device structure used in the experiment. The results are obtained with 3-dimensional beam-propagation simulation software (RSoft BeamProp) for the experimental device parameters given below. The width \(w\) of the QCL waveguide in the taper section varies with the position \(z\) as follows:

\[
w(z) = w_0 + (w_1 - w_0) \left(\frac{z}{L_t}\right)^\alpha,
\]

where \(w_1\) and \(w_0\) are the waveguide widths at the beginning and at the end of the taper, respectively, \(L_t\) is the taper length, and \(z\) is the nonlinear factor. After several iterations of simulation, the optimal taper parameters were determined to be \(w_1 = 6 \text{ μm}, w_0 = 0 \text{ μm}, L_t = 0.8 \text{ mm},\) and \(z = 0.5\). The computed fundamental-optical mode intensity profiles in the gain, taper, and silicon-waveguide sections are shown in Figs. 1(d)–1(f).

Coupling of a QCL mode into the underlying Si waveguide occurs via the adiabatic taper section as shown in Fig. 1(a). As the QCL mode propagates in the taper section, the effective index of the laser mode becomes smaller and, near the taper tip, comparable to that of the effective index of the Si-waveguide mode at which point the laser mode transitions from the QCL active region to the Si waveguide core. Figure 2(a) shows the simulated effective indices of the fundamental mode of the QCL and Si waveguides at the wavelength of 5 μm for different waveguide dimensions. The layer sequence of the QCL used in the simulation is given below. The simulation shows two important criteria in designing our hybrid device: the maximum Si thickness and the taper width at which the mode transition occurs. The effective index matching between the fundamental QCL mode and the fundamental Si mode is only possible when the thickness of the Si layer is below ~1.9 μm. The Si thickness above this value will lead to the mode leakage in the gain section of the device. The SOS wafer used in this work had a 1.2-μm-thick Si layer in order to maintain good laser mode confinement in the gain section and to allow for a taper tip width that can be fabricated by optical lithography. At this Si thickness, the mode transitions from the QCL active region to the Si waveguide for the taper width of around 1.5 μm, which can be readily fabricated by optical lithography.

The calculated taper coupling efficiency is shown in Fig. 2(b). The coupling efficiency is estimated as the ratio of the optical power in the Si waveguide to that in the gain section [cf. Fig. 1(a)]. In the simulation, the taper length was 1 mm, and the waveguide loss was neglected. The coupling efficiency is strongly dependent on the SU-8 layer thickness. The coupling efficiency increases to 75% as the SU-8 thickness decreases to 100 nm.

For the proof-of-concept demonstration, a QCL structure was grown on a semi-insulating InP substrate by metalorganic chemical vapor deposition. The growth started with a 2-μm-thick InP buffer layer (Si: 2 × 10^{16} \text{ cm}^{-3}) followed by a 330-nm-thick In_{0.53}Ga_{0.47}As (Si: 7 × 10^{17} \text{ cm}^{-3})
current-injection layer. Then, a 100-nm-thick InP (Si: $5 \times 10^{16} \text{ cm}^{-3}$) lower cladding layer was grown followed by a 1.5-µm-thick strain-balanced In$_{0.669}$Ga$_{0.331}$As/In$_{0.362}$Al$_{0.638}$As active region, sandwiched between two In$_{0.53}$Ga$_{0.47}$As (Si: $2 \times 10^{16} \text{ cm}^{-3}$) layers—a 200-nm-thick layer below the active region and a 300-nm-thick layer above the active region. The 30-stage active region was based on the structure reported in Ref. 13 designed to produce a peak gain at $\lambda \approx 4.7 \, \mu\text{m}$. The laser sequence of one QCL stage is 3.8/1.2/1.3/4.3/1.3/3.8/1.4/3.6/2.2/2.8/1.7/2.5/1.8/2.2/1.9/2.1/2.1/2.0/2.1/1.8/2.7/1.8, where the layer thicknesses are given in nanometers and the sequence starts with the injection barrier. Barrier thicknesses are denoted in bold, and the underlined layers were nominally Si-doped to $1.0 \times 10^{17} \text{ cm}^{-3}$. The laser structure was completed with a 2.7-µm-thick InP (Si: $2 \times 10^{16} \text{ cm}^{-3}$) first upper cladding layer followed by a 150-nm-thick InP (Si: $2 \times 10^{17} \text{ cm}^{-3}$) second upper cladding layer, a 200-nm-thick InP (Si: $5 \times 10^{16} \text{ cm}^{-3}$) plasmon-confinement layer, and a 150-nm-thick InP (Si: $2 \times 10^{19} \text{ cm}^{-3}$) capping layer.

The QCL wafer was processed into 6-µm-wide ridge waveguide QCL devices with the taper section formed by conventional photolithography and a dry etching process. Figure 3(a) displays the QCL device structure after transfer-printing to a SOS wafer. Details of our transfer-printing method were described in Ref. 14. In short, a piece of the InP wafer with completely processed QCLs (including the taper sections) was attached to a glass slide holder using a crystal glue (Crystalbond 509). The InP substrate and buffer layer were removed by selective etching, using the In$_{0.53}$Ga$_{0.47}$As current injection layer as an etch-stop layer. The epi-layer with processed QCL devices was bonded onto a SU-8 coated SOS wafer. Finally, the crystal glue and the glass slide holder were removed using acetone.

The processed SOS wafer was diced into chips with an approximately 5-µm-long QCL gain section, a 0.8-µm-long taper section, and a 3-µm-long Si-waveguide section. The chips were then further diced so that the 5-µm-long QCL gain section was separated into a 2.4-µm-long Fabry-Perot QCL device on top of SOS with the gain section only (referred to as the reference device) and a 2.6-µm-long QCL gain section connected to the 3-µm-long Si waveguide via the taper section (referred to as the Si-waveguide device). The 2.4-µm-long Fabry-Perot QCL section on SOS was used as a reference device to experimentally estimate the taper coupling efficiency.

Figure 4 shows a set of confocal laser-scanning microscopy images of the taper section of the completely processed Si-waveguide device. Also shown there are scanning electron microscopy (SEM) images of the back facet of the same device. The images indicate that the SU-8-layer thickness is $\approx 250 \, \text{nm}$. Figure 4 also confirms that the Si waveguide is well-aligned with the QCL taper section.

All devices were mounted epide-on-top on copper heatsinks using indium solder and wire-bonded for measurements. The measurements were performed at room temperature with a...
current pulse of 50 ns at a repetition rate of 2.5 kHz. Mid-IR power from the Si waveguide facet was collected using a 2-in. focal length, 2-in. diameter ZnSe lens and directed to a calibrated liquid-nitrogen-cooled InSb photodetector. A Fourier transform IR spectrometer with a resolution of 0.2 cm\(^{-1}\) was then used to record emission spectra. Emission images were taken by using liquid-nitrogen cooled InSb focal plane arrays (FLIR Systems, Inc., InSb A6753sc).

Figure 5 shows the mid-IR spectra of the reference and Si-waveguide devices. The emission spectrum of the Si-waveguide device is collected from the facet of the Si waveguide section. The reference device shows a constant mode spacing (\(\sim 0.67\) cm\(^{-1}\)) consistent with the TM\(_{00}\) mode lasing in the 2.4-mm-long Fabry-Perot cavity. The Si-waveguide device shows different spectral behaviors, with three separate groups of modes. The mode spacing of the spectra from the Si-waveguide device is non-uniform, which suggests that non-zero reflections in the taper section and at the end of the Si-waveguide section may create a multi-mirror active-passive cavity device.\(^{15,16}\) To investigate the effect of the coupled cavities on the spectral behavior of the hybrid device, taper sections with different lengths can be implemented, which will be performed in the future.

Light-current-voltage characteristics of the reference and the Si-waveguide devices are plotted in Fig. 5(b). For the optical-power measurements of the Si-waveguide device, a stripe of an absorbing liquid crystal film was mounted by using crystal glue on top of the Si waveguide to block mid-IR light scattered from the end of the QCL taper, as shown in Fig. 5(a). For the current-density calculations, the effective area of each device is determined by the area of the top metal contact that covered only the QCL gain section in the Si-waveguide device [cf. Fig. 1(a)]. From this analysis, the threshold-current densities of the reference and the Si-waveguide devices are found to be 5.3 kA/cm\(^2\) and 5.6 kA/cm\(^2\), respectively, thus showing a 6% increase in threshold for the Si-waveguide device. Peak powers of 22 mW and 2 mW were measured from the facet of the reference device and the Si-waveguide facet of the Si-waveguide device, respectively. Neglecting the unknown loss in the Si waveguide section, the data indicate that our taper coupling efficiency was at least \(\sim 10\%\). Our simulations, shown in Fig. 2(b), predict 35% taper coupling efficiency for the 250-nm-thick SU-8 adhesive layer used in our devices. Further investigations of the SOS-waveguide loss and the coupling efficiency are planned for the future.

Finally, Fig. 6 presents measurements of the near- and far-field emission patterns from the Si-waveguide facet of the Si-waveguide device. Figures 6(b) and 6(c) show the mid-IR near-field images taken at the facet of the Si
waveguide, while the Si-waveguide device is biased with a current of 950 mA. The images confirm that the measured power in Fig. 5(b) is indeed the output from the Si-waveguide facet. The measured and simulated far-field beam pattern profiles of the emission from the Si-waveguide facet are displayed in Figs. 6(d) and 6(e) for the lateral (horizontal) direction (d) and the transverse (vertical) direction (e).

We experimentally confirmed coupling of the fundamental optical mode of the QCL into the Si waveguide with at least ~10% coupling efficiency by using a 0.8-mm-long QCL taper section. Our theoretical simulations show that coupling efficiency above 75% is achievable for the SU-8 layer thickness below 100 nm. The heterogeneous integration of mid-IR QCLs with a Si-based passive waveguiding platform is expected to be useful for the development of multi-functional mid-IR PICs for a wide range of applications.

In conclusion, we have demonstrated the heterogeneous integration of fully processed mid-IR QCLs to a SOS platform, based on the transfer-printing technique. Our method allows transferring virtually any type of QCL devices, including buried-heterostructure lasers, onto virtually any substrate.

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