Heterogeneous integration of O-band GaAs QD-on-SiN Fabry-Pérot laser with observed mode-locking

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ABSTRACT

We demonstrate an O-band Fabry-Pérot laser through the heterogeneous integration of a GaAs-based quantum dot optical amplifier onto a passive silicon nitride cavity using micro-transfer printing. The laser shows an ultra-low threshold current of 20 mA at 18 °C and can deliver nearly 0.4 mW of single-side waveguide-coupled power. The spectral peak can be tuned from 1296 nm to 1334 nm as the temperature increases from 10 °C to 50 °C. Mode-locking is achieved with an injection current of 80 mA and a saturable absorption voltage of -0.6 V, generating a clear RF beat note at 28.6 GHz with a signal-to-noise ratio of 20 dB.

Keywords: Mode-locked lasers, Silicon nitride, InAs/GaAs quantum dot, Heterogeneous integration, Transfer printing

1. INTRODUCTION

Silicon photonics (SiPh) has attracted renewed interest in recent years by setting up SiN platforms, which offer ultra-low loss capabilities enhancing the performance and efficiency of photonic devices.^{1–3} SiN-based components like waveguides, resonators, modulators, photodetectors, (de)multiplexers, and switches have made substantial advancements.^{4–9} Among these components, optical amplifiers are vital building blocks for completing this platform. They enable the possibility of compact, high-performance, and energy-efficient integrated optical sources. Especially, mode-locked comb lasers, with evenly spaced spectral lines, present unique advantages over traditional continuous-wave (CW) laser arrays. By using a single device, namely a comb laser, to handle complex tasks, the overall system complexity and electric power consumption can be significantly reduced.

To introduce efficient light sources in SiPh platforms, different integration approaches have been explored to utilize the superior optical properties of III-V materials. These include flip-chip bonding, pick-and-place-based micro-assembly, (multi-)die-to-wafer bonding, direct epitaxial growth, and micro-transfer printing (μ TP).^{10–12} Amongst these methods, μ TP has emerged as a promising and increasingly mature technology, offering high throughput and the potential for low-cost heterogeneous integration of diverse non-native materials onto SiPh wafers.¹³ However, challenges remain in applying all wavelength ranges, considering the different III-V material systems and light coupling across different layers. InAs/GaAs quantum dots (QDs) are considered an ideal gain material in O-band wavelength range due to their three-dimensional carrier-confinement properties. The intrinsic size diversity of QDs provides broadband gain and also high output power.¹⁴ Therefore, heterogeneous integration of GaAs-based QD materials on SiN (QD-on-SiN) presents a promising approach to outperform the state-of-the-art mode-locked lasers,^{15,16} paving the way for the realization of chip-scale optical atomic clocks.¹⁷

In this work, we demonstrate a heterogeneously integrated GaAs QD-on-SiN mode-locked laser using μ TP, a technology available under license from X-Celeprint, Ltd. The laser features a 2.5 mm-long Fabry-Pérot (FP) cavity, consisting of two identical Sagnac mirrors on both sides and an amplifier in between. GaAs amplifier coupons are fabricated separately and then printed onto IMEC's 200-mm SiN platform. Efficient evanescent coupling is ensured through a proper linear taper design. The laser shows an ultra-low threshold current of 20

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mA and delivers up to 0.4 mW of single-side waveguide-coupled output power. The emission wavelength can be tuned from 1296 nm to 1334 nm as the temperature increases from 10 °C to 50 °C. Mode-locking is achieved under specific reverse bias conditions in the saturable absorber (SA) section, generating a radio frequency (RF) signal at 28.6 GHz. Further optimization will aim to broaden the optical spectrum and enhance the output power.

2. GAAS AMPLIFIER FABRICATION AND MICRO-TRANSFER PRINTING

Following the previous demonstration of micro-transfer-printed GaAs QD-on-Si DFB lasers in [18], an optimized process flow for the integration of GaAs QD mode-locked lasers is developed, as depicted in Figure 1. First of all, top oxides and GaAs/AlGaAs sacrificial layers were removed by wet-etching, followed by deposition of SiN hard mask by plasma enhanced chemical vapor deposition (PECVD). This SiN layer was patterned through an electron beam lithography (EBL) using a thin layer of high-resolution e-beam resist (ARP 6200 series), as shown in Figure 1(a), followed by a CF_4/H_2 based reactive ion etching (RIE) recipe. Afterward, the p-AlGaAs cladding was patterned by ICP etching with a gas mixture of BCl_3/N_2 (Figure 1(b)). Again a thin PECVD SiN layer was deposited on the defined p-cladding mesa structures, and it acted as a hard mask to pattern the QD active region (Figure 1(c)). After the n-contact metal deposition shown in Figure 1(d), the GaAs QD rib waveguide was passivated with another SiN layer which was used as a hard mask again to define the first coupon mesa by etching into the GaAs substrate (Figure 1(e)). The coupon mesa was then encapsulated with a thick SiN/SiOx dual dielectric layer (Figure 1(f)). The topography of the top surface of the sample was planarized using a thick layer of BCB (Figure 1(g)). After etching back the BCB layer, SA electrical isolation trenches were defined by ICP etching down the highly-doped GaAs p-contact layer and then followed by p-type metal deposition (Figure 1(h)). As shown in Figure 1(i), the n contact was then opened by RIE with a thick photoresist mask. The fabrication of GaAs QD SOA was finalized with tether definition (Figure 1(j)), followed by a release step. The release etching was implemented by using a 20 °C 1:1 37% HCl:H₂O solution as depicted in Figure 1(k). After release, the sample is ready for µTP.



Figure 1. Process flow of transfer printable GaAs amplifiers on its native wafer.

The proposed laser was realized on imec's 200-mm low-pressure chemical vapor deposition (LPCVD) Si_3N_4 platform. This platform consists of a 400 nm thick Si_3N_4 as the major device layer, a 100 nm SiO_2 interlayer and a 330 nm thick PECVD a-Si:H layer to facilitate the light coupling.¹⁹ This target wafer was already planarized by chemical mechanical polishing. Therefore, a thin BCB layer can be spin-coated on top of the wafer with good uniformity. A PDMS stamp with a single post of 50 µm x 1800 µm was used to micro-transfer print GaAs coupons. The µTP process was carried out using an X-Celeprint µTP-100 lab-scale tool at room temperature. The post-transfer printing processing includes photoresist encapsulation layer removal, BCB curing, and final metal deposition.



Figure 2. Microscope image of integrated O band lasers with contact pads (a) and zoomed-in view (b).

Figure 2 presents the fabricated O-band laser with metal contact pads, captured under a microscope. The Fabry-Pérot (FP) cavity is defined by two identical Sagnac mirrors, each with a designed reflectivity of approximately 84%. At the center of the cavity, a 1660 µm-long GaAs amplifier provides optical gain. Light is extracted off-chip using SiN-based O-band grating couplers, which have been pre-characterized through reference waveguide exhibiting a coupling loss of 5 dB. Figure 2(b) provides a zoomed-in view of the transfer-printed GaAs coupon. Further magnified microscope image confirms that the misalignment between the GaAs coupon and the underlying Si waveguide is less than 200 nm, ensuring efficient optical coupling. Additionally, the SA section is 100 µm long, occupying 6% of the total amplifier length. The isolation trenches are oriented at a 45-degree angle to minimize intracavity reflections.



3. LASER CHARACTERIZATION

Figure 3. Light-Current-Voltage curve at 18 °C (a) and CW emission spectra at different temperatures (b).

The resulting GaAs QD-on-SiN laser was electrically driven using a PGSGP pico probe with a 200 μ m pitch. Figure 3(a) shows the measured light-current-voltage (L-I-V) curve at 18 °C, from which a differential resistance of 4.5 Ω at 70 mA was calculated. The threshold current was observed to be 20 mA, which is attributed to the unique properties of QDs gain. The waveguide-coupled optical output power could reach 0.4 mW, which can be further improved by integrating longer amplifiers. Figure 3(b) illustrates the CW spectra of the laser at different heat sink temperatures. The spectral peak shifted from 1296 nm to 1334 nm as the chuck temperature increased from 10 °C to 50 °C. It needs to be noted that these spectra were captured with the laser operating at a current slightly above the threshold. At higher injection currents, the laser exhibits a typical multimode FP spectrum.

The mode-locking regime was investigated by directing the light onto a photoreceiver equipped with transimpedance amplifier (Discovery LabBuddy DSC-R409) and analyzing the signal with an electrical spectrum analyzer. At SOA current of 80 mA and a reverse bias of -0.6 V applied to the SA, the maximum beat note signal was recorded with a signal-to-noise ratio of 20 dB, as shown in Figure 4(b). The optical spectrum, obtained from an optical spectrum analyzer and depicted in Figure 4(a), reveals several locked comb teeth with an equal spacing of 28.6 GHz, likely corresponding to the second harmonic of the 14.3 GHz fundamental repetition rate. However, the optical bandwidth remains narrow (~ 1.4 nm), which needs to be further broadened in the future work.



Figure 4. Optical and RF spectrum measured at mode locking point (gain = 80 mA, SA = -0.6 V)

4. CONCLUSIONS

In this work, we demonstrated a heterogeneously integrated GaAs QD-on-SiN Fabry-Pérot laser using µTP technology. The laser features a 2.5 mm cavity with two Sagnac mirrors and a 1660 µm-long GaAs amplifier, delivering nearly 0.4 mW WG-coupled optical power. The lasing wavelength could be thermally tuned from 1296 nm to 1334 nm as the temperature increased from 10 °C to 50 °C. Mode-locking was observed under a SA reverse bias of -0.6 V and an SOA current of 80 mA, with a clear beat note signal at 28.6 GHz. The optical spectrum reveals several comb teeth with equal spacing, confirming the mode-locked operation. While there remains significant potential for broadening the spectrum bandwidth and improving the purity, these results are highly promising as they mark the first demonstration of an O-band mode-locked comb laser on a SiN platform.

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