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Photonic integration platform for rubidium sensors and beyond

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We have advanced the heterogeneous silicon nitride photonic platform, enabling operation at the 780 nm wavelength range for rubidium sensors and other applications while remaining operable at high temperatures up to 110°C. This platform surpasses other existing technologies with the superior integration of a comprehensive set of active building-block devices to enable fully integrated high-performance systems-on-a-chip.

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Introduction. Photonic integration is necessary to enable next-generation systems, as it offers unrivaled scalability, weight, cost, and power efficiency (SWaP-C). To maximize the SWaP-C benefit, on-chip sources and amplifiers are crucial to realize fully integrated systems-on-a-chip (SoC). Many emerging applications including quantum [1], augmented/virtual reality, sensing, and health-care operate in the visible and near-visible wavelength ranges. Historically, the level of integration at these wavelengths was extremely limited due to challenges in making photonic integrated circuits (PICs) with on-chip gain. Most demonstrations include a single light source, either as a monolithic gallium-arsenide (GaAs) laser or a hybrid (butt-coupled) laser [2]. We address the challenge to scale the technology by extending the heterogeneous GaAs platform [3] to support short wavelength operation with an initial focus on the 780 nm wavelength range and rubidium (Rb)-based sensors and PICs.

Photonic Platform. The improved heterogeneous GaAs platform utilizes high-bandgap materials for active element cladding and contacts, and is designed to support broadband operation from ∼630 nm to ∼900 nm wavelengths. Our initial focus is on Rb-based applications, and here we demonstrate components that were optimized for operation around 780 nm and 795 nm wavelengths utilizing multiple-die to wafer bonding. Some details related to fabrication are shown in Fig. 1(a). Due to the nature of integration, we can realize PICs with 10 s or even 100 s of active components in a wafer-scale process. The flexibility of silicon nitride (SiN) for waveguides enables very low propagation loss, and advanced passive components to support truly SoC functionality for various applications such as timekeeping, precise distance measurements and other applications where high-performance (narrow-linewidth) lasers are locked to an atomic transition.

Toward Large-Scale Integration. Die-to-wafer level integration enables high density of active components, and in Fig. 1(c), we show Fabry–Perot (FP) laser threshold currents and photodetector (PD) dark currents over 140 devices across the full wafer. The high level of uniformity is facilitated by an advanced process that leverages high-quality alignment between actives and passives defined by advanced photolithography. An exemplative FP laser light-current-voltage (LIV) is shown in Fig. 1(b) with >12 mW of optical power in a SiN waveguide at 90 mA drive current with 6% wall plug efficiency at room temperature. Lasing is observed up to 110°C.

Tunable Lasers. The key component for a large number of quantum systems is a narrow-linewidth, low-noise laser. We realize such a laser using ring resonators and utilizing the Vernier effect. The use of ring resonators to make a tunable, frequency-selective mirror enables the use of standard lithography even at 780 nm wavelength and below, compared to using a grating, which typically requires slower, and much more expensive, electron beam lithography. The tunability of our lasers, with just two ring resonators, is around 18 nm or close to 10 THz [Fig. 1(f)], and tuning range can be further extended if additional ring elements are introduced and/or chirped quantum wells (QWs) are utilized. We bond slightly different III-V material with shifted photoluminescence of the QWs to extend the operational range using nominally identical laser designs. The wide tuning range and finessed control mechanism enable one tunable laser to access both the D1 and D2 transition wavelengths of ^{87}Rb in a vapor cell [Fig. 1(g)]. The fundamental (intrinsic) linewidth of such lasers is around 4.35 kHz, which results from the higher propagation loss (∼5 dB/cm) due to the R&D process environment. Given the waveguide propagation loss of <1 dB/cm demonstrated previously [3], we anticipate that optimizing the waveguide loss should enable the fundamental linewidth to achieve a sub-kHz level. Significant improvement in linewidth can be facilitated by injection locking to a high-quality-factor (Q) resonator. By injection locking the heterogeneous GaAs laser with an amplifier to a high-quality SiN resonator with measured intrinsic Q of ∼10 million, the resulting fundamental

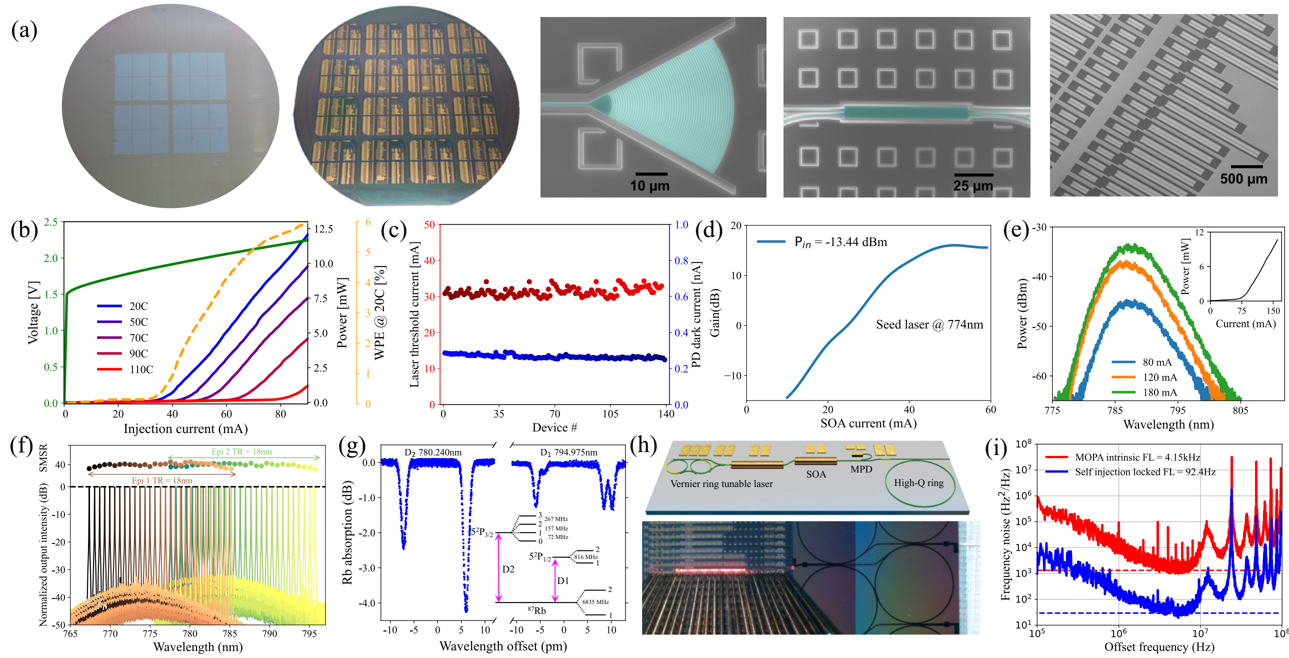

Fig. 1. (a) Heterogeneous wafer after bonding 24 III-V coupons and substrate removal, same wafer at the end of the laser process, and SEM details showing passive components and array of active components. (b) LIV versus temperature for a FP laser. (c) Wafer-level statistics of 140 similar FP lasers and 140 identical PDs. (d) On-chip SOA gain versus injection current. (e) Super-luminescent diode spectra and LI characteristics. (f) Tuning of two identical laser designs utilizing QW bandgap offset of 10 nm between bonded epitaxial stacks. (g) ^{87}Rb D1 and D2 absorption spectra measured by sweeping one tunable laser across the corresponding wavelength range. (h) Photograph and schematic drawing of an injection-locking experiment in which a high-Q resonator is butt-coupled to a narrow-linewidth master oscillator power amplifier (MOPA) laser. (i) Frequency noise measurement for stand-alone MOPA laser, and the same laser under self-injection locking to 10 M Q-factor resonator.

linewidth is only 92.4 Hz [Fig. 1(i)]. In this demonstration, the resonator was butt-coupled [Fig. 1(h)], and a full integration of high-Q resonators can be achieved using two SiN layers as demonstrated for 1550 nm [4]. Operation at shorter wavelengths has a distinct advantage, as lasers are less sensitive to thermal effects and thermal rollover, so thicker dielectric claddings needed for high-Q resonators can be utilized without significant degradation in performance.

Supporting Components. To support more complex PICs, the platform also supports high-performance PDs, high-power broadband sources [Fig. 1(e)], and amplifiers [Fig. 1(d)]. PDs with very low dark currents (100 pA range) were demonstrated and can significantly extend the functionality of the PIC. Amplifiers can be used to gate the output at high speeds, reduce the intensity noise, or amplify the output enabling scaling of complexity. The first generation of amplifiers has >15 dB on-chip gain. Finally, the platform supports all standard passive components with high uniformity, as they are fabricated in a CMOS-like process flow.

Conclusion. Photonic integration is necessary to enable SWaP and scaling for next-generation systems. Heterogeneous integration on SiN, with this demonstration, enables low propagation loss and broadband operation, while multiple die bonding enables active components in a broad wavelength range, down to 780 nm, without a need for re-growth. Use of advanced tools and lithography improves yield and uniformity for large-component-count PICs.

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Data availability. Data are available upon reasonable request.

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