As-Grown InGaAs Nanolasers for Integrated Silicon Photonics

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Abstract: We report on-chip InGaAs nanopillar lasers directly grown on silicon using a low-temperature, CMOS-compatible MOCVD process. A novel whispering gallery and Fabry-Perot hybrid cavity mode provides optical feedback for laser oscillation in as-grown subwavelength nanopillars.

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1. Introduction

Optical interconnects are of great interest for their potential to overcome the bottleneck currently facing inter- and intra-chip communications as microprocessor speeds continue to scale. However, the lack of monolithic light sources on silicon (Si) has been a major roadblock for chip-scale optical communications. Si-based photonics has subsequently witnessed significant progress in alternative approaches such as heterogeneous integration [1] as well using Si and germanium (Ge) for optical gain [2],[3]. These approaches nonetheless face difficulties of their own. Surface planarity is a challenging requirement for heterogeneous integration, while Si and Ge emitters must overcome the physics of indirect band gaps. Monolithic III-V light sources thus remain a favorable approach for optoelectronic integration if they can be realized. Large lattice mismatch between III-V materials and Si and high III-V epitaxy temperatures have been the primary barriers for realizing monolithic integration. Nanowire growth can accommodate large lattice mismatch, but often at the cost of scalability and growth temperatures. Furthermore, they typically require metal catalysts that are poisonous to Si CMOS devices. To overcome these issues, we recently developed catalyst-free, low-temperature, scalable growth of GaAs nanoneedles on Si substrates [4]. In addition, we fabricated nanoneedle light emitting diodes on silicon using conventional processing techniques [5]. Here, leveraging this new growth platform, we demonstrate III-V nanopillar lasers directly grown on Si, operating up to room temperature (293 K) under pulsed optical pumping (120 fs Ti:sapphire). Optical feedback is achieved via unique cavity modes that possess characteristics of both whispering gallery (WG) and Fabry-Perot (FP) resonances. These modes enable nanopillars of subwavelength dimensions to lase. Wavelength control of these nanolasers has also been achieved and will be discussed. Compatible with CMOS processes, nanopillar lasers hold promise as on-chip light sources for monolithic Si-based photonics.

2. Growth

Nanopillar lasers consist of a bulk InGaAs core cladded by a GaAs shell for surface passivation as depicted in Fig. 1a. They are grown by metal-organic chemical vapor deposition (MOCVD) without metal catalysts at a low temperature of 400 °C on a (111) Si substrate. Vertical nanopillar growth initiates when nanoclusters spontaneously

Fig. 1. (a) A 3-dimensional schematic of the nanopillar laser and its partial cross-section show the InGaAs core and GaAs shell. The inset shows a top-view schematic. (b) The as-grown nanopillar’s well-faceted structure supports natural resonator modes, implementing lasers on silicon without further processing. (c) Nanopillars are grown on silicon substrates with high density under CMOS-compatible conditions.
form sharp needles due to lattice mismatch with the substrate [4,6]. A strongly crystalline-dependent deposition rate results in single crystal growth along the [0001] wurtzite c-axis. The introduction of higher indium content subsequently halts vertical growth, resulting in formation of nanopillars with flat top facets. The dimensions of the pillar can easily scale with growth time by carefully adjusting composition and growth conditions, making this a unique, new growth mode that is not size-limited by lattice mismatch [6]. The nanopillars used in this study typically have a 330 nm base radius and stand ~3 µm tall. However, some are as short as 400 nm with the same base radius. The height range provides an excellent platform for experimental verification of our theoretical modeling. These novel structures possess a hexagonal cross-section because of their single crystalline wurtzite lattice. Because nanopillars are extremely well-faceted (Fig. 1b), they form natural on-chip optical cavities after a single growth step without any further processing. Importantly, nanopillar growth is fully compatible with CMOS processes since it is catalyst-free at 400 ºC, allowing for monolithic integration of these nanolasers with already-fabricated Si electronics. With subwavelength footprints of ~0.34 µm², a high density of nanopillar lasers can be integrated onto silicon for optoelectronic circuitry (Fig. 1c).

3. Results

Relatively broadband spontaneous emission is seen below threshold at ~950 nm. As the pump fluence increases, band filling effects are seen until a cavity peak emerges and full laser oscillation is achieved as shown in Fig. 2a. Strong coherence of nanopillar emission can be seen from a high suppression ratio of 17 dB in the lasing spectra as well as the strong speckles in the near field image (Fig. 2a insets). Extinction ratios as high as 20 dB are achieved in other nanopillar lasers. Total light output as a function of pump fluence (L-L curve) is shown in Fig. 2b, revealing a

![Fig. 2](image)

Fig. 2. (a) Below threshold, broad spontaneous emission (blue) is observed. Above threshold, a strong lasing peak (red) dominates emission. The spectra have been offset for clarity. The insets show camera images of nanopillar luminescence below and above threshold. Clear speckle patterns appear above threshold, a classic signature of laser oscillation. (b) The L-L curve shows clear threshold behavior at ~22 µJ/cm². Additionally, blueshift of the cavity mode is reduced above threshold, which has previously been attributed to clamping of the carrier density and thus carrier-induced refractive index change.

![Fig. 3](image)

Fig. 3. (a) Room temperature operation has been achieved. Spectra show emission below and above threshold. The below threshold curve has been multiplied by x200 for visualization. (b) Nanopillar laser emission wavelength can be controlled by adjusting growth time to tune the cavity resonances. Indium composition is then varied for proper gain-mode overlap.
distinct threshold at 22 µJ/cm². Additionally, blueshift of the lasing wavelength reduces above threshold. This results from clamping of the carrier density and thus carrier-induced refractive index change, which is another signature of laser oscillation in semiconductors. Under similar pumping conditions, nanopillars as short as 400 nm lase with volumes of \(-0.2λd^3\) and all dimensions less than \(λ_0\) (not shown here). Laser oscillation is achieved up to 293 K (Fig. 3a), testifying to the potential of nanopillar lasers for practical applications. In addition to room temperature operation, it is of interest to have wavelength control of these on-chip lasers. Nanopillar dimensions scale with growth time; therefore, resonances can be easily tuned by growth time. Significantly, indium composition can meanwhile be controlled by MOCVD growth to match gain to cavity resonances. As shown Fig. 3b, we use this approach to demonstrate laser emission over a range as wide as 50 nm. This can be improved in the future by going beyond the 12-20% indium composition window that we currently use.

![Figure 4](image-url)

**Fig. 4.** (a) A schematic of the nanopillar laser detailing the orientation of the x-, y- and z-axes. (b) FDTD-simulated field profiles in the xy-plane show that the mode is primarily whispering gallery in nature. However, the WG mode possesses longitudinal FP degeneracies. The fundamental FP degeneracy is shown in (c) while a higher-order degeneracy is plotted in (d). Each degeneracy resonates at a different wavelength. Broken white lines outline the nanopillar and silicon substrate.

Optical feedback is a critical component of the as-grown nanopillar laser given that the back facet, i.e. the pillar and Si interface, sees hardly any index contrast. In principle, this would result in insufficient reflectivity as well as absorptive loss due to the smaller Si band gap. However, we find that optical fields can be strongly confined in nanopillars by WG effects. Fig. 4b shows a finite-difference time-domain (FDTD) simulation of a 6th order transverse magnetic hexagonal WG mode in an untapered pillar on absorptive Si. Intuitively, wavevectors of WG modes are oriented nearly parallel to the substrate such that they strike the nanopillar-Si interface at glancing angles. Thus, high (and possibly even total internal) reflection can be achieved at that interface. Pedestals traditionally used by microdisk resonators are thereby unnecessary in our case.

Due to the finite pillar length, FP standing waves concurrently build in the longitudinal direction, yielding FP degeneracies of the WG modes as shown in Figs. 4c and 4d. Each degeneracy possesses a unique resonant wavelength despite sharing the same transverse field profile. These hybrid effects thus distinguish these cavity resonances from traditional WG modes. The optical confinement offered by WG/FP hybrid modes enable nanoplasers that are subwavelength on all sides with volume \(-0.2λd^3\). For an untapered pillar with a base radius of 330 nm and height of 3µm, a high Q factor of \(-4,300\) is simulated for the mode shown in Fig. 4(c). We estimate significantly lower experimental Q values of \(-200\), which we attribute to the tapering of the nanopillars. Further engineering of the structure is underway for high-Q and high-efficiency III-V nanolasers on Si.

In conclusion, we directly grow III-V nanolasers monolithically on Si for the first time. The subwavelength footprints of the lasers, their compatibility with Si transistor technology, and the facility of integration onto Si substrates promise for practical optoelectronic integration and applications in the future.

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### 4. References