Low-threshold InP quantum dot and InGaP quantum well visible lasers on silicon (001)

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Monolithically combining silicon nitride (SiN) photonics technology with III-V active devices could open a broad range of on-chip applications spanning a wide wavelength range of ~400–4000 nm. With the development of nitride, arsenide, and antimonide lasers based on quantum well (QW) and quantum dot (QD) active regions, the wavelength palette of integrated III-V lasers on Si currently spans from 400 nm to 11 μm with a crucial gap in the red-wavelength regime of 630–750 nm. Here, we demonstrate the first red InAsGa0.5P QW and far-red InP QD lasers monolithically grown on CMOS compatible Si (001) substrates with continuous-wave operation at room temperature. A low-threshold current density of 550 A/cm² and 690 A/cm² with emission at 680-730 nm was achieved for QW and QD lasers on Si, respectively. This work takes the first vital step towards integration of visible red lasers on Si allowing the utilization of integrated photonics for applications including biophotonic sensing, quantum computing, and near-eye displays.

The primary application for Si photonics technology to date is integratrd photonic transceivers for telecommunications where off-chip or hybrid-integrated InP-based lasers emitting in the C- or O- bands (~1.3-1.6 μm) serve as the light source [1]. Leveraging the CMOS foundry, Si photonics now enables an increasing number of applications including mapping and navigation [2], spectroscopy [3], and quantum communication [4]. Applications that rely on visible lasers, such as biosensing [5], atomic clocks [6] and spatial mapping [2] could greatly benefit from the ability to generate, guide and sense light on a chip [7]. As another example, integrated photonics could help overcome the limitations of free-space optics for trapped-ion quantum computing relying on 674 nm lasers to drive transitions in ⁸⁷Sr⁺ ion qubits [8]. Low-loss SiN waveguide technology [9] is a key enabler for visible photonics based devices to integrate visible sources on Si are currently lagging behind.

Despite elevated threading dislocation density (TDD) values of ~10⁶-10⁸ cm⁻² [10], recent efforts have yielded a wide range of monolithic lasers on Si utilizing GaAs, InP, and GaSb-based active regions. For example, InAs QD lasers on GaAs/Si (001) emitting at 1.3 μm, have been demonstrated with threshold current density (Jth) values as low as 62.5 A/cm² for room temperature (RT), continuous-wave (CW) operation [11]; Jth = 100-300 A/cm² is more typical for InAs QD lasers on Si [12, 13]. In addition, Shang et al demonstrated an extrapolated operation lifetime of 22 years with a constant current stress at 80°C by preventing the formation of misfit dislocations in the InAs QD active region [12-14]. As another example, InGaAsP multiple quantum well (MQW) lasers on InP/Si (001) emitting at 1.55 μm with CW, RT operation and Jth = 1-3 kA/cm² have also been reported [15, 16]. Finally, GaSb-based QW lasers emitting at 2.3 μm were recently demonstrated using on-axis Si substrates with Jth = 200-300 A/cm² and CW operation up to 80°C [17, 18]; further references on epitaxial III-V lasers on Si can be found in recent review articles [10, 19, 20]. Despite the impressive development of near- and shortwave-infrared lasers on Si based on both QD and QW active regions, there are no reports for electrically injected red lasers on Si. Development of monolithic visible red lasers on Si would fill a crucial gap in the wavelength palette of integrated lasers on Si, which already spans from 400 nm [21] to 11 μm [22].

InGaAsP QWs and InP QDs are a versatile platform for high-efficiency diode lasers emitting in the 630-800 nm wavelength regime. InP QD lasers on GaAs emitting in the 680-750 nm [23, 24]
phenomenon and have demonstrated watt-class power output [26] with $J_{th}$ of 295 A/cm$^2$ [27]. Kwon et al. demonstrated the first In$_{0.4}$Ga$_{0.6}$As QW lasers on 6° offcut Si (001) using a 10 µm-thick SiGe buffer with TDD = 2×10$^6$ cm$^{-2}$ [28]. Despite the well-controlled TDD, the lasers only operated pulsed with a high $J_{th}$ of 1.65 kA/cm$^2$, and moreover, the use of offcut Si substrates renders such devices incompatible with Si photonics foundries [28]. More recently, Luo et al. demonstrated optically pumped InP QD microdisk lasers on Si (001) [29]. Despite the excellent performance of phosphide-based visible lasers on GaAs, further work is required to monolithically integrate visible lasers and optical amplifiers on Si (001).

To date, no electrically injected red laser has been demonstrated on exact Si (001), preventing visible integrated photonics from fully leveraging advances in high-performance SiN, passive optical components and Si photodetectors. In this article, we demonstrate the first visible In$_{0.4}$Ga$_{0.6}$As QW and InP QD lasers monolithically grown on foundry-compatible Si (001) substrates with CW, RT operation. Despite a moderate increase in $J_{th}$ caused by threading dislocations, our visible lasers on Si (001) compare favorably with earlier-reported devices based on similar active regions grown on GaAs (001). Low-threshold, monolithically integrated visible lasers on Si can serve as an important low-cost enabler for visible optoelectronics applications ranging from quantum information [4] to near-eye displays [30].

All lasers were grown in a Veeco Mod Gen II solid-source molecular beam epitaxy (MBE) system on GaAs (001) and GaAs/Si (001) without any intentional offcut. We grew relaxed GaAs on GaP/Si (001) templates commercially available from NaP doubles GmbH using a combination of thermal cycle annealing and dislocation filtering [31] (Supplement 1): the total thickness of the buffer layer was ~2.15 µm. The laser structure [Fig. 1(a)] includes an optical cavity consisting of 1000 nm n- and p-Al$_{0.5}$Ga$_{0.5}$As (AllnP, hereafter) cladding layers and a 150 nm Al$_{0.4}$Ga$_{0.6}$As QWs ($x = 0.34$) continuous graded index waveguide (GRIN-WG). We grew In$_{0.4}$Ga$_{0.6}$As$_{0.2}$P barrier reduction layers (BRL) between the GaAs contact and AllnP cladding layers to mitigate voltage drops resulting from band offsets [32]. The cladding waveguide and BRLs were lattice matched to GaAs, as confirmed by high-resolution x-ray diffraction. The active region of the single QW (SQW) laser consists of a compressively strained 7 nm In$_{0.4}$Ga$_{0.6}$As QW surrounded by 50 nm, 2.1 eV Al$_{0.6}$Ga$_{0.4}$As$_{0.2}$P (AlGaNp, hereafter) spacer layers, lattice matched to GaAs. The active region of the InP multiple quantum dot (MQD) lasers utilizes a QD in a well design (QDWell) with 3.5 monolayers (ML) InP QDs capped by a 7 nm In$_{0.6}$Ga$_{0.4}$As$_{0.2}$P QW and surrounded by 16 nm AlGaNp spacer layers; the QDWell structure was repeated 3x in the InP MQD laser. All laser structures underwent post-growth rapid thermal annealing (RTA) at 950°C for 1 s to improve the optical quality of the active region [33] prior to fabrication of uncoated, broad-area lasers (Supplement 1). Details of the beneficial effect of RTA on both photoluminescence and laser threshold characteristics will be discussed in a future publication. Laser testing was performed under CW injection with devices sitting on a temperature-controlled stage [See Supplement 1 for further details]. Reliability studies are planned for the future, but we see no evidence of degradation over the time spent characterizing these devices.

The bright-field transmission electron microscope (BF-TEM) image in Fig. 1(b) shows an entire InP MQD laser structure grown on GaAs/Si. The striated contrast throughout the device is common for ternary and quaternary AlGaInP alloys grown by MBE and results from weak phase separation during growth [34]. The active region shows 5 layers of coherently strained InP QDs exhibiting a mottled, dark strain contrast, while the apparent absence of threading dislocations indicates that the TDD in the active region is close to or below the detection limit of ~1×10$^{11}$ cm$^{-2}$. Importantly, no misfit dislocations are observed in the active region, despite the compressive strain present in both the InP QDs and In$_{0.4}$Ga$_{0.6}$As$_{0.2}$P QWs. A high-angle annular dark-field scanning TEM (HAADF-STEM) image of a single QDWell layer in Fig. 1(c) shows the composition contrast of individual InP QDs. The density of buried InP QDs, calculated using BF-TEM is >1×10$^{11}$ cm$^{-2}$,
lasers on GaAs establishes that our material quality is at or area lasers. The ultra-high output power of > 10 mW, while the InP MQD laser exhibits a slightly higher of 230 A/cm² (77 A/cm² per QD-WELL layer) due to its thicker active region. Although a pulsed value of 190 A/cm² has been reported previously for InP MQD lasers, these are the lowest CW values on GaAs (001) that we are aware of. Fig. 2(b) shows that the InGaP SQW laser emits at 691.5 nm and the InP MQD laser emits in the far-red regime at 726.8 nm; both exhibit multiple transverse and longitudinal modes, as expected for broad-area lasers. The ultra-low CW of our InGaP SQW and InP MQD lasers on GaAs establishes that our material quality is at or near state-of-the-art values and enables us to observe the performance of our lasers on Si without the deleterious point defects that have been reported in MBE-grown phosphides [36].

A critical precursor towards demonstrating low-J₀ red lasers on Si was to develop high-performance benchmark devices on native GaAs substrates, and Fig. 2(a) shows the light intensity vs current density (L-I) characteristics of broad-area InGaP SQW and InP MQD lasers on GaAs tested under CW operation at 20°C. The InGaP SQW laser shows a low J₀ of 170 A/cm² with an output power of > 10 mW, while the InP MQD laser exhibits a slightly higher of 230 A/cm² per QD-WELL layer) due to its thicker active region. Although a pulsed value of 190 A/cm² has been reported previously for InP MQD lasers, these are the lowest CW values on GaAs (001) that we are aware of. Fig. 2(b) shows that the InGaP SQW laser emits at 691.5 nm and the InP MQD laser emits in the far-red regime at 726.8 nm; both exhibit multiple transverse and longitudinal modes, as expected for broad-area lasers. The ultra-low CW of our InGaP SQW and InP MQD lasers on GaAs establishes that our material quality is at or near state-of-the-art values and enables us to observe the performance of our lasers on Si without the deleterious point defects that have been reported in MBE-grown phosphides [36].

InGaP SQW lasers on Si (001) exhibit a CW J₀ of 550 A/cm² [Fig. 3(a)], 3× lower than previously reported pulsed devices on offcut Si [28]. The inset of Fig. 3(a) shows a photograph of the laser (cavity length = 1.25 mm, ridge width = 40 µm) located at the bottom/foreground operating at ~ 5 mW output power with the far-field pattern projected onto a wall, ~50 cm away from figure under-test. The semi-logarithmic lasing spectra of InGaP SQW laser on Si operating above threshold, collected at RT CW showing multiple mode emission centered at 693.9 nm.

**Fig. 2.** Benchmark laser characteristics for devices grown on GaAs: (a) L-I curves for In₀.₆Ga₀.₄P SQW (red, 1.8 mm cavity length with 100 µm ridge) and InP MQD (green, 1.7 mm cavity length with 60 µm ridge) lasers tested CW at 20°C, with In₀.₆Ga₀.₄P SQW (InP MQD) laser exhibiting J₀ = 170 A/cm² (230 A/cm²). (b) Semi-logarithmic laser spectra showing In₀.₆Ga₀.₄P SQW laser emitting at 691.5 nm and InP MQD laser emitting at 726.8 nm with multiple modes. The spectra were collected at RT under CW operation.

**Fig. 3.** (a) L-I curve for In₀.₆Ga₀.₄P SQW laser on GaAs/Si (001) with a cavity length of 1.25 mm and ridge width of 40 µm operating CW at T = 20°C with J₀ = 550 A/cm². (inset) Photograph of In₀.₆Ga₀.₄P SQW laser on Si lasing with output power > 5 mW projected on a wall ~50 cm away from device-under-test. (b) Semi-logarithmic lasing spectra of In₀.₆Ga₀.₄P SQW laser on Si operating above threshold, collected at RT CW showing multiple mode emission centered at 693.9 nm.
recombination at point defects is the most likely reason for the high
on Si is noteworthy considering that earlier worked GaAs/Si with a
much lower TDD of 2×10^6 cm^2 [28]. We believe that non-radiative
recombination at point defects is the most likely reason for the high
J_0 values observed by Kwon et al. on both GaAs and Si, which in turn
dominates the effects of threading dislocations. For comparison,
InAs:GaAs:As QW lasers on GaAs/Si with emission at ~1 µm and
TDD = 1×10^6 cm^2 exhibited pulsed J_0 of 5.6 kA/cm^2, ~60× higher
than their counterparts grown on GaAs (001) [37]. Our InAs:GaP
SQW lasers on Si appear to show a comparatively higher degree of
tolerance to threading dislocations, which may result from the low
carrier diffusivity in phosphides compared to arsenides [38]. In
contrast, GaInAsP:As, Sb, Al, QW lasers grown on GaSb on Si emitting
at 2.3 µm with a TDD = 1.4×10^6 cm^2 show only ~2× increase in J_0
compared to lasers grown on GaSb [39]. Further study is needed to
better understand the complex interplay of bandgap energy and
composition on the dislocation-tolerance of BH-V lasers.

Fig. 4(a) shows the RT, CW J-L characteristics of the first
electrically injected InP MQD laser on GaAs/Si. J_0 of this laser is 690
A/cm^2 (230 A/cm^2 per QD/Well layer), and the inset of Fig. 4(a)
shows a photograph of the InP MQD laser (cavity length = 0.9 mm,
ridge width = 40 µm) operating at ~ 5 mW output. The InP MQD
laser on Si emits with multiple modes centered at 726.2 nm [Fig.
4(b)], nearly identical to our MQD lasers on GaSb. Unlike the slightly
different wavelengths of the SQW lasers described above, here we
attribute the lack of redshift to minor differences in QD growth on
GaAs vs GaAs/Si. Fig.4(c) shows that J_0 of the InP MQD laser on Si
increases from 690 A/cm^2 at 20°C to 1063 A/cm^2 at 50°C. We
extracted a characteristic temperature T_c of 65 K for InP MQD lasers
on Si, which is lower than the value of 88 K for lasers on GaAs
[Supplemental 1]. The lower T_c on Si indicates the need for
improved heat dissipation in the active region and further reduction
of TDD [40].

The InP MQD laser on GaAs/Si shows a J_0 increase of 3×
compared to its counterpart grown on GaAs, which is comparable
to the 2× increase typically seen in InAs MQD lasers on Si [10]. Like
QW lasers on Si, a part of the increase in J_0 could be attributed to the
shorter cavity length and narrower ridges. But based on previous
PL studies where InP QDs showed similar intensity on both GaAs
and GaAs/Si [29, 35], we would have expected that the carrier
confinement offered by the QDs would confer some J_0 advantage
for laser operation over the QWs. The high-level carrier injection
inherent to laser operation may partly explain the qualitative
discrepancy between the PL (taken at very low-level injection) and
laser results. Future studies with optimized device design and
processing could help further unveil the effects of threading
dislocations on visible QW and QD lasers grown on Si.

Fig. 5(a) shows that we achieved low-J_0 operation for red and
far-red lasers on both GaAs and GaAs/Si substrates. Despite a J_0
increase of ~3× caused by threading dislocations, both InAs:GaAs
SQW and InP MQD lasers on Si show comparable J_0 to previously
published red and far-red lasers grown on GaAs (Supplement 1).
We believe that the use of a GRIN design for optical and electrical
confinement, reduction of non-radiative recombination centers
using RTA, and the inherent low diffusivity of carriers in phosphides
are among the key factors for our low-J_0 lasers on Si substrates. Fig.
5(b) shows the spectra of InAs:GaAs SQW and InP MQD lasers on
GaAs and Si spanning from 680-730 nm. The emission wavelength
range can be tailored to a wide range of applications by utilizing
tensile-strained InGaAsP QWs [41] for shorter wavelength and
alloying InP QDs with arsenic for longer wavelength emission [42].
This study indicates that the effect of dislocations on phosphide on Si (001) with respective J0 electrically injected red In lasers testing the extrapolated operation lifetime of In well as longer cavity lengths [18], as well as longer cavity lengths [33]. Future work will also aim towards testing the extrapolated operation lifetime of InGaAsP SQW and InP MQD lasers on Si and understanding their degradation mechanisms.

In conclusion, we demonstrated the first RT, CW, electrically injected red InGaAsP SQW and far-red InP MQD lasers on Si (001) with respective J0 values of 550 A/cm2 and 690 A/cm2. This study indicates that the effect of dislocations on phosphide-based lasers on Si differ significantly, with arsenides showing stronger benefits in J0, by switching from a SQW to a QD active region. III-V lasers based on diverse active region designs, compositions, and bandgap energies can all behave differently when grown on Si, and future studies will undoubtedly lead to deeper insights on these differences. Phosphide-based SQW and QD lasers offer high performance over a wide range of wavelengths from 630-800 nm, and this work establishes that such lasers can be grown on Si (001). Combined with SiN, waveguides, such short-wavelength lasers open the intriguing possibility of direct integration with highly sensitive Si photodetectors [46], circumventing the escalated dark current of epitaxial Ge/Si detectors [47]. Epitaxial QD and QW lasers emitting at 1.3-2.3 μm are becoming increasingly established, and this work takes a vital first step towards integration of red visible lasers that will allow integrated photonics to expand its impact into areas such as on-chip biosensing [48] and quantum computing [9].

FUNDING
We gratefully acknowledge funding from MIT Lincoln Laboratory under the program, ‘Heteroepitaxial III-V/SiN, Integrated Photonics (HIP)’. R.D.H and B.D.L were supported by NASA Space Technology Research Fellowships under grant numbers 80NSSC18K1171 and 80NSSC19K1174, respectively.

ACKNOWLEDGEMENTS
We thank Chris Heidelberger, Reuel Swint, and Paul Juodawlkis for helpful discussions and assistance. We also thank Katherine Lakomy and Prof Kent Choquette for help with initial pulsed testing of the lasers.

DISCLOSURE
The authors declare no conflicts of interest.

DATA AVAILABILITY
Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

SUPPLEMENTAL DOCUMENT
See Supplement 1 for supporting content.

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