Room-temperature continuous wave (RT-CW) electrically pumped 1550 nm indium phosphide (InP)-based laser diodes are realized on complementary metal-oxide-semiconductor (CMOS) compatible silicon (Si) substrates by direct heteroepitaxy. Dynamic properties are investigated by gain switching and small signal modulation measurements. A maximum 3 dB bandwidth of 5.3 GHz is demonstrated, along with a narrow optical pulse with a width of 1.5 ns. The dark current density of 490 mA cm⁻² at −1 V bias is an order of magnitude higher than identical devices grown and fabricated on native InP substrates. Also, reliability measurements and failure analysis are carried out for the lasers on Si. The lasers operate stably over 200 hours (h) at 10 °C under CW operation without apparent change in threshold or output power. In sharp contrast, a rapid failure occurs at 60 °C under pulsed operation following 5.6 h of aging. To further improve device characteristics for lasers on Si, the dislocation density of the InP template is reduced by introducing a 2 μm-thick compositionally graded In₀.₄Ga₀.₆As buffer. The resulting surface defect density is as low as 4.5 × 10⁷ cm⁻², which is expected to improve the performance and reliability of long wavelength lasers grown directly on Si.

1. Introduction

Silicon photonic integrated circuits (PICs) are able to reduce the cost, size, and power consumption of optical transceivers. The most critical component is the on-chip laser source, which is ordinarily implemented with III–V compound semiconductors due to their direct bandgap and subsequent high device efficiencies. The attempts to achieve short-wavelength infrared (SWIR) light sources on Si substrates date back to the early 1990s, when the first C-band InP-based laser was epitaxially grown on miscut (001) Si substrates. Impressive lifetime of over 7000 h and low InP defect density on the order of 10⁶ cm⁻² were demonstrated using an aggressively thick (15 μm) III–V buffer. However, such thick films can generate cracking and degradation, limiting the yield. These films are also not amenable to integration.

Instead, a III–V buffer thickness less than 7 μm is desirable for integration into a silicon photonics (SiPh) process, without any crack formation on the surface. Notable progress has been made with bonding methodologies, where light is evanescently coupled into the Si waveguide beneath the III–V active region. Limitations for such heterogeneous integration approaches include the requirement of precise waveguide alignment and narrow taper formation. Also, the wafer size mismatch and III–V substrate costs are inhibitive. A high thermal impedance, caused by the buried oxide (BOX) layer, limits high-temperature performance of the lasers. Ultimately, it is more appealing to monolithically integrate III–V light sources or gain elements on Si to enable high performance with the lowest cost. To resolve issues related to material defects arising from the lattice, thermal and polarity mismatches between III–V materials and Si, it is therefore critical to study defect generation and methods to effectively engineer defects.

Herein, we report an extended study on the impact of dislocations on the dynamic lasing characteristics and device reliability for the quantum well (QW) lasers grown on Si, in addition to our previously reported static lasing performance including light–current–voltage (LIV) characteristics, thermal impedance, and threshold temperature dependence. A maximum modulation bandwidth of 5.3 GHz was measured for the lasers on Si, nearly half of the value on InP substrate. Low-temperature CW aging and high-temperature-pulsed aging conditions were both applied to the Si-based lasers, suggesting that the high junction temperature limits the device lifetime. More than 200 h of stable operation under 10 °C, CW aging was demonstrated for the lasers on Si, which suffer from a rapid failure after 5.6 h aging at 60 °C under pulsed operation. The high junction temperature and device internal heating are expected to be alleviated by reducing the lasing threshold and improving the material quality of the InP buffer. This could be enabled by optimizing and inserting a compositionally graded In₀.₄Ga₀.₆As buffer between GaAs and InP, to allow for a gradual lattice transition. Significantly reduced dislocations originating from the InP/In₀.₄Ga₀.₆As heterointerfaces were observed, yielding a lower surface defect density of 4.5 × 10⁷ cm⁻² for the InP template on Si.
2. Lasing Characteristics

The material growth was carried out using a Thomas-Swan low-pressure (LP) metalorganic chemical vapor deposition (MOCVD) system. Detailed material growth, characterization, and device fabrication have been presented in the study by Shi et al.\[6\]

Figure 1 shows the global cross-sectional scanning transmission electron microscopy (STEM) image of the 3.95 μm-thick InP buffer grown on V-groove-patterned (001) Si substrate, inserted with GaAs intermediate buffer and multiple stacks of In$_{0.7}$Ga$_{0.3}$As/InP strained-layer superlattices (SLSs).

The devices were then mounted onto ceramic carriers for probing and laser characterization. Basic lasing characteristics have been demonstrated, including a threshold current density of 2.05 kA cm$^{-2}$, a peak output power of 18 mW per facet without facet coatings, and a maximum operation temperature of 65 °C for 20 x 1000 μm$^2$ devices.\[6\] The thermal impedance is measured to be 7.6 °C W$^{-1}$, slightly larger than the value on InP substrate (5.7 °C W$^{-1}$).\[13\]

Table 1 shows the chronological progress in the heteroepitaxy of electrical laser diodes on Si substrates operating at 1550 nm regime. Earlier results in the 1990s have already demonstrated low defect density for InP on miscut (001) Si substrates with an aggressively thick InP buffer.\[13,4\] Reliable FP lasers were realized, demonstrating CW operation at high temperatures.\[13\] However, to realistically integrate lasers with passive SiPh components, and to do so on a CMOS-compatible wafer platform, the development of thinner III-V buffers on on-axis (001) Si is motivated. Some other notable progress includes wavelength shifting of GaSb-based strained QWs to the telecom band.\[14–16\] and modulating Ge bulk crystals toward “quasi-direct bandgap” emission.\[17,18\] Yet, integrating InP on Si is still advantageous,\[19\] so as to exploit the mature InP technologies for integration into SiPh. As shown in Table 1, only by minimizing defect density in the InP buffer can subsequent lasers operate efficiently. Recently, the emergence of InAs/InAlGaAs quantum dash (QDash) as active gain elements boosts the performance of C-band lasers on Si.\[20–23\] The benchmarking here necessitates the further development of high-quality InP buffers by introducing the compositionally graded InGaAs buffer, which will be discussed shortly. More detailed review on short wave infrared (SWIR) lasers on Si were available in the study by Shi and Lau.\[24\]

![Figure 1. Large-area cross-sectional STEM image of the InP-on-Si template.](Image)

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<td>2° to [110]</td>
<td>2 μm GaAs + 13 μm InP</td>
<td>&lt;10$^5$</td>
<td>InGaAs QW</td>
<td>6 x 300</td>
<td>CW</td>
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<td>0.1</td>
<td>&gt;4</td>
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<td>2 μm GaAs + 10 μm InP</td>
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<td>Pulse</td>
<td>2</td>
<td>77 K</td>
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<td>20</td>
<td>MBE[3]</td>
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<td>InGaSb QW</td>
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<td>InAs/InAlGaAs QD</td>
<td>10 x 5000</td>
<td>Pulse</td>
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<td>0.14</td>
<td>57</td>
<td>MOCVD</td>
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<td>1.5 x 10$^8$</td>
<td>InAs/InAlGaAs QD</td>
<td>945 (ring)</td>
<td>Pulse</td>
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<td>0.008</td>
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<td>3 x 10$^8$</td>
<td>InGaAs QW</td>
<td>25 x 2000</td>
<td>Pulse</td>
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<td>50 °C</td>
<td>0.03</td>
<td>&gt;10</td>
<td>MOCVD</td>
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<td>1.1 x 10$^8$</td>
<td>InGaAsP QW</td>
<td>20 x 1000</td>
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<td>2</td>
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<td>0.1</td>
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<td>3.6 x 10$^8$</td>
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<td>6 x 1500</td>
<td>CW</td>
<td>1.3</td>
<td>59 °C</td>
<td>NA</td>
<td>22</td>
<td>MOCVD</td>
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\[5\]Vapor Phase Epitaxy; \[6\]Hydride Vapor Phase Epitaxy; \[3\]Molecular Beam Epitaxy.
Figure 2 shows dark current measurements for $4 \times 550 \mu m^2$ QW lasers grown on InP and Si. The statistical device measurements in Figure 2a shows average dark current densities of 45 and 490 mA cm$^{-2}$ for QW lasers on InP and Si, respectively. The bias applied for these measurements was $-1$ V. Both dark current levels are significantly higher than that typically reported for photodiodes.$^{[25-27]}$ Fabrication was not optimized, and not specifically crafted for photodiode applications. However, dark current measurements do reveal device performance aspects such as leakage current and activation energy.$^{[28]}$ Therefore, we believe significant improvements can be made by improving fabrication. For example, by introducing HCl-based anisotropic wet etching and advanced dielectric deposition techniques, we expect to improve device sidewall passivation. The increased thermal population and deep-level trapping of carriers due to emergence of crystalline defects, are also responsible for the significantly higher dark current on Si.$^{[29]}$ To better understand the thermal performance of the dark current on Si, temperature-dependent current-voltage (IV) curves are shown in Figure 2b. Compared with the QW laser on InP, the IV curves on Si are more convergent under reverse bias, indicating a much lower activation energy ($E_a$). Based on the Arrhenius plot (not shown here), the $E_a$ is 0.21 eV for the QW laser on InP, an order larger than the value on Si. This result suggests that in addition to the severe surface leakage due to imperfect dry etching and sidewall passivation, the dislocations inside the InP-on-Si template are dramatically lowering the activation energy, resulting in multiple carrier leakage paths. Thus, to better facilitate high-performance Si-based photodetectors with low dark currents, the defect densities in the InP buffer and InP/GaAs heterointerfaces should be further reduced.

Gain switching techniques have been adopted to generate short incoherent pulses on the order of hundreds of picoseconds, without the requirement of external cavities.$^{[30]}$ To apply this methodology to the lasers developed here, electrical pulses were superimposed onto a direct current (DC) bias of 100 mA to drive the $10 \times 500 \mu m^2$ laser on Si.$^{[31]}$ The output optical pulses were amplified and measured by an oscilloscope in the time domain. Figure 3a shows the compression of the input pulses at various bias levels. The optical pulse is found to be more compressed with narrower electrical pulses, as shown in the inset image. Driven by an electrical pulse with a current amplitude of 135 mA and a duration of 12.5 ns, the gain-switched optical pulse width is as narrow as 1.5 ns. However, a too narrow electrical pulse would inversely broaden the optical pulse due to insufficient carriers to switch on the laser, whereas a wide driving pulse also results in the broadening of gain-switched pulses.$^{[31]}$ Figure 3b shows that increasing the current amplitude first

**Figure 2.** a) Statistical dark current measurements, and b) temperature-dependent dark current evolution for QW lasers on InP and on Si.

**Figure 3.** a) Optical pulse width versus electrical pulse width at increased current amplitudes. The inset shows a zoomed-in diagram for the short electrical pulse regime. b) Optical pulse width as a function of electrical pulse amplitude with a pulse width of 12.5 ns. Inset demonstrates a gain-switched optical pulse from the Si-based laser diode with a driving current of 175 mA. Black dashed line represents a Gaussian fit to extract the rise and fall time.
causes the optical pulse width to decrease until a second relaxation appears, and then increase due to excessive carrier injection. Here, the minimum optical pulse width is limited by the low modal gain and high gain compression for the QW laser on Si. An example of an optical pulse observed by the oscilloscope is shown in the inset of Figure 3b, demonstrating a pulse width of 1.8 ns. A symmetric rise time ($\tau_r$) of 1.3 ns and fall time ($\tau_f$) of 1.4 ns were extracted from a Gaussian fitting. To further functionalize the gain switching approach for the Si-based lasers, it is more appealing to apply this technique to single-mode lasers to achieve ultrashort single-frequency pulses. This will be investigated in the future work.

Small signal modulation responses were measured with a vector network analyzer (VNA) to evaluate the 3 dB bandwidth ($f_{3dB}$) and damping for both the QW laser on InP and on Si. The devices were probed using a radio frequency (RF) signal-ground (SG) probe. Figure 4 shows the frequency response, $S_{21}$, at progressively increased bias current levels. In addition to the observation of intrinsic carrier-photon resonance (CPR), a peak centered at $\approx$8.25 GHz was noticed, due to the appearance of photon–photon resonance (PPR). The occurrence of PPR can substantially increase the 3 dB modulation bandwidth. So far, it has been applied in distributed feedback (DFB) lasers, distributed Bragg reflector (DBR) lasers, and coupled-cavity-injection-grating lasers. The observed PPR here is probably due to a self-feedback from external fiber lens or other components. As a result, the measured maximum $f_{3dB}$ for lasers on InP substrate is 9.1 GHz. However, the Si-based laser is damped at a maximum bandwidth of 5.3 GHz. The reduced bandwidth can be attributed to several factors including larger gain compression, faster gain saturation, longer carrier transportation as well as a more severe carrier thermalization. The influence of these factors can be understood through the definition of the K-factor, which evaluates the damping of the frequency response and limits the intrinsic maximum $f_{3dB}$. The K-factor is given as

$$K = 4\pi^2 \left( \tau_p + \frac{\varepsilon}{(\varepsilon \tau_0 / \chi)} \right)$$

$$\chi = 1 + \tau_r / \tau_c$$

where $\tau_p$ is the photon lifetime in the laser cavity, $\tau_c$ is the carrier transport time in the active region, $\tau_0$ is the thermionic emission time from the QWs, $\varepsilon$ is the gain compression factor, $\tau_0$ refers to mode velocity, and $\chi$ is the laser gain. Due to the relatively high density of dislocations, along with much lower activation energy for the Si-based laser, the $\varepsilon$ and $\tau_0$ values are significantly larger than for the QW lasers on native InP substrates. Meanwhile, as the carriers in Si-based QW lasers are more likely to be nonradiatively dissipated via lattice vibration, heating, and deep-level trapping, $\tau_0$ and $\chi$ are considerably lower. The carrier transport time $\tau_c$ is longer as well. These factors result in a higher $\chi$ and $K$-factor on Si, together with a reduction in differential efficiency by a ratio of $1 - 1/\chi$. Therefore, it is important to further lower the dislocation density for the InP-on-Si virtual substrates.

3. Reliability and Failure Analysis

It is necessary to analyze the robustness and reliability of the Si-based lasers, so as to evaluate their potential for practical applications. Several mechanisms could lead to sudden failure or wear-out degradation for general semiconductor lasers, including internal joule heating, thermal run away, recombination-enhanced dislocation growth, dark line defects (DLDs) or dark spot defects (DSDs), and catastrophic optical mirror damage (COMD). There are a number of reports on reliability and lifetime of InP-based lasers on Si,[3,5,17] and GaAs-based lasers on Si.[38,40] Impressive lifetimes of tens to hundreds of years have been demonstrated. Device failure mechanisms, however, vary across different material systems and device structures. Therefore, it is of interest to carry out failure analysis and thermal robustness for the InP-based multi-quantum well (MQW) laser on Si demonstrated here, and to evaluate the factors that contribute to device aging.

We first carried out thermal anneal of the device under current biasing to evaluate the ability to handle chip temperatures of 60 °C or higher. Some devices were subject to a series of temperature cycles, as shown in Figure 5. The lasers were initially measured at room temperature under CW operation (20 °C in Figure 5a and 15 °C in Figure 5b). The stage temperatures were then elevated to higher temperatures (60 and 120 °C) for annealing while the devices were biased at their initial threshold currents (320 and 375 mA, respectively). Afterward, the devices were cooled to room temperature and measured again under CW operation. Figure 5 shows a rapid degradation of the devices after

Figure 4. Small signal $S_{21}$ measurements for a) $20 \times 500 \mu m^2$ QW lasers on InP and b) on Si, at various bias current levels.

high-temperature anneal. In Figure 5a, the threshold was increased by 16% after 1 h annealing at 60 °C, with an evident decrease in the output power, and the laser then fails after 2 h of CW operation. The situation is even more severe in Figure 5b, where a significant output power reduction was observed, together with a threshold increase by 43% (inset of Figure 5b).

It is well known that the typical mean time to failure (MTTF) of a semiconductor laser is dependent on the injection current density \(J\), the junction temperature \(T_J\), and the activation energy \(E_a\) according to the following expression\(^{19}\)

\[
\text{MTTF} \propto J^{-1}e^{\frac{E_a}{kT}}
\]

The temperature-dependent dark current measurement in Figure 2 has uncovered a much lower \(E_a\) for lasers on Si, which would degrade their MTTF. To determine the dominating factors resulting in the rapid failure of the devices, two reliability experiments were conceived and carried out: CW aging at low temperature (10 °C) to evaluate the role of recombination-enhanced processes due to large current injection, and pulsed aging at high temperature (60 °C) to understand the impact of stage temperature (or junction temperature as the internal joule heating would be reduced under pulsed operation). Figure 6a shows the aging test result of a 20 × 750 µm² laser at 10 °C under a constant CW bias current of 1.3 × initial threshold (520 mA). The laser diode operates stably over 200 h without any apparent increase in threshold or any reduction in output power, and the device is still working after aging test. The vibration in the data points is primarily attributed to the fluctuation of the stage temperature, controlled by a thermoelectric cooler (TEC). Modal changes in the multimode FP laser also aggravate the vibration during device aging. Although it is inaccurate to extrapolate the MTTF with such fluctuant data, the results shown in Figure 6a indicate that the device lifetime can be greatly prolonged with a reduced junction temperature. Typical lasing characteristics during the aging test are shown in Figure 6b. The inset image indicates no decrease in the total slope efficiency during the first 200 h.

Another 20 × 500 µm² laser bar was subject to accelerated aging at an elevated temperature of 60 °C under pulsed operation, to reduce the internal device heating by a high injection current of 1.35 × initial threshold (520 mA). In contrast to the stable operation at low temperatures, the device degrades suddenly after 5.6 h, showing a rapid power drop (Figure 6d). The threshold and output power degrade gradually before the device completely fails. No apparent change in the total slope efficiency is shown in the inset of Figure 6d. This phenomenon suggests that compared with the recombination enhanced defect reactions by high current injection, the thermal effect is more detrimental to device operation.

Electron channeling contrast imaging (ECCI) was later applied to examine the dislocation distribution and cross-sectional facet condition for the aged device (following device wear-out at 60 °C), as shown in Figure 7a. The advantage of adopting the ECCI method compared with cross-sectional TEM image is that no sample preparation is required, and moreover, one can continuously monitor the device aging process without damaging the device structure. A high density of V-shaped defects originating from the MQW region was detected (Figure 7a). These V-defects arise from either the stacking faults or threading dislocations generated by the InP-on-Si template, as shown in the zoomed-in image of Figure 7b. Although the V-defects deteriorate the MQW and separate confined heterostructure (SCH) interfaces (Figure 7b), as they were formed before device aging, they should not be regarded as the reason for the rapid failure of the lasers. Extended DLDs were observed in the QW region, InP buffer, and the SLSs (shown by yellow arrows in Figure 7b-d). These DLDs were found to introduce new misfit dislocations and to promote the climbing of threading dislocations, leading to device degradation. In addition to the appearance of DLDs in the active region, a “pit” appears at the edge of the facet, which could be suspected to be caused by the thermal run away process when heat builds up at the sharply peaked area,\(^{41}\) or due to rough-edged DLDs, similar to the observation by Foran et al.\(^{42}\) The facet damage would inevitably reduce their reflectivity or increase the nonradiative carrier recombination at the facets.\(^ {43}\) Here, the white flakes were dust and contamination formed during sample handling and did not contribute to device aging.

Based on the two different aging conditions and results, it is evident that a high junction temperature prominently limits the

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**Figure 5.** LI curves of 20 × 500 µm² laser diodes before and after a) 60 °C and b) 120 °C annealing under biasing currents of 320 and 375 mA, respectively. The inset shows zoomed-in LI curves near the threshold region.
device reliability, even though the current injection induced recombination-enhanced process would also introduce dislocation climbing and nonradiative recombination. Therefore, to further improve device characteristics, it is desirable to lower the lasing threshold and the temperature dependence by reducing the dislocation density inside the InP buffer and by engineering the laser structures. The junction temperature rise above the heat sink temperature is given by

\[ \Delta T = (I^2 R_s + IV_j)Z_T(1 - \eta_p)D \]

(4)

where \( R_s \) is the diode electrical resistance, \( V_j \approx E_g/e \) is the junction voltage, \( Z_T \) is the thermal resistance, \( D \) is the pulse duty cycle, and \( \eta_p \) is the power conversion efficiency.

4. Perspective: Improving InP Material Quality with Compositionally Graded InGaAs Buffers

To improve the material quality of the InP buffer, it is sensible to avoid the abrupt InP/GaAs interface (defect density on the order
of $10^{10} \text{ cm}^{-2}$), although other dislocation filtering techniques such as thermal cycle annealing (TCA), aspect ratio trapping (ART), and dislocation filters can be applied.\cite{46,12,44} Hence, a compositionally graded buffer would be ideal to gradually accommodate the lattice transition from GaAs to InP. Earlier research has attempted to study the role of InGaAs or InGaP for InP grown on GaAs substrates.\cite{45} However, it should be mentioned that the growth of InP on a GaAs substrate is quite different from InP grown on GaAs-on-Si. As has been comprehensively discussed,\cite{46} threading dislocations inside the GaAs/Si template would shorten the migration length of the misfit segments in the subsequent InP buffer growth. Meanwhile, the appearance of branch defects in InP grown on a GaAs-on-V-grooved Si (GoVS) template would impede the dislocation motion, thus increasing the TD density.

Following preliminary optimization, by increasing the growth temperature of a graded In$_{0.4}$Ga$_{0.6}$As buffer from 600 to 650 °C, and growing InGaAs buffers on a higher-quality GoVS template, a “three-step” InP buffer was regrown on top of the InGaAs layers. Four periods of In$_{0.73}$Ga$_{0.27}$As/InP SLSs were introduced to further filter the residual dislocations. The complete grown structure was characterized with cross-sectional STEM (Figure 8a). Compared with the InP-on-Si buffer without graded InGaAs, significantly reduced defect densities are observed. The elimination of SFs in InP, which mainly arise from the lattice mismatches between InP and (In)GaAs, was achieved. This observation is further quantified by statistical ECCI measurement shown in Figure 8b. The surface defect density is $\approx 4.5 \times 10^7 \text{ cm}^{-2}$, more than two times lower than the previous InP-on-Si template. Nevertheless, the final surface of the InP is rougher (root-mean-square value of 9.42 nm) after the insertion of graded InGaAs buffer, due to a larger strain inside the InGaAs layer and a rougher interface between InP and In$_{0.4}$Ga$_{0.6}$As.\cite{46}

Another concern lies in the lower thermal conductivity of the InGaAs buffer than InP or GaAs binaries. This might inhibit a good thermal dissipation of the heat in the active region through the InGaAs buffer. Even so, improved material quality may result in the elimination or reduction of thermal barriers that were believed to limit the performance of the lasers realized without graded InGaAs.

The lower defect density for InP on top of the InGaAs buffer is primarily attributed to the less defective interface between InP and In$_{0.4}$Ga$_{0.6}$As, as the lattice mismatch (0.9%) is considerably lower than that for InP/GaAs (3.7%). The STEM images of InP/GaAs and InP/InGaAs interfaces are shown in Figure 9. More than an order of magnitude reduction in threading dislocations is achieved for the InP/In$_{0.4}$Ga$_{0.6}$As interface, compared with InP/GaAs. By optimizing the InGaAs buffer, fewer branch defects are observed, and the InP material quality is improved as a result (Figure 9b,c). Most of the misfit dislocations in Figure 9c are migrated laterally due to the slow strain relaxation of the graded InGaAs layers.

The optical quality of the two InP-on-Si templates was evaluated based on RT photoluminescence (PL) in Figure 9d. The higher InP peak intensity as well as a stronger integrated PL intensity is acquired when the InP surface defect density reduces from $1.15 \times 10^8 \text{ cm}^{-2}$ to $4.5 \times 10^7 \text{ cm}^{-2}$. Future work will be focused on lasers grown on templates with different defect densities to study the impact of defects on InP-based device performance.

Figure 8. a) Cross-sectional STEM image of the InP-on-Si template with the insertion of compositionally graded InGaAs buffer. b) Representative ECCI images and c) $10 \times 10 \mu m^2$ AFM images of the InP surface with graded InGaAs buffer.

Figure 9. Close-up STEM view of the a) InP/GaAs, b) nonoptimized InP/In$_{0.4}$Ga$_{0.6}$As/GaAs, and c) optimized InP/In$_{0.4}$Ga$_{0.6}$As/GaAs heterointerfaces. d) RT-PL spectra of InP-on-Si templates with two different surface defect densities.
5. Conclusion

We first demonstrated an InP buffer on CMOS-compatible V-groove patterned (001) Si substrates with a low defect density of $1.15 \times 10^7$ cm$^{-2}$. Electrically pumped laser diodes were grown and fabricated on top of the InP-on-Si template and demonstrated RT-CW operation with favorable lasing characteristics. The dynamic properties of these Si-based lasers were assessed with gain-switching and small-signal modulation response measurements. The maximum 3-dB bandwidth was 5.3 GHz, and a narrow optical pulse width of 1.5 ns was generated using the gain-switching technique. Moreover, device aging tests were carried out, under both 10 °C CW operation and 60 °C pulsed operation. High current injection was applied to evaluate recombination-enhanced degradation. Results demonstrate that the lasers work stably at low temperatures but degrade rapidly at elevated temperatures. To further reduce dislocations inside InP buffers, a compositionally graded InGaAs buffer was attempted to relax the large strain by a gradual lattice transition. An even lower defect density of $4.5 \times 10^7$ cm$^{-2}$ for the InP grown with incorporation of graded InGaAs layers was produced. The improved optical quality was verified by the RT-PL comparison.

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Conflict of Interest

The authors declare no conflict of interest

Keywords

dislocation filtering, III-V heteroepitaxy on Si, laser dynamics, reliability, semiconductor lasers

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