A compact, efficient and monolithically grown III-V laser source provides an attractive alternative to bonding off-chip lasers for Si photonics research. Although recent demonstrations of micro-lasers on (001) Si wafers using thick metamorphic buffers are encouraging, scaling down the laser footprint to nano-scale and operating the nanolasers at telecom wavelengths remain a significant challenge. Here, we report monolithically integrated in-plane InP/InGaAs nano-laser array on (001) silicon-on-insulator (SOI) platforms with emission wavelengths covering the entire C-band (1.55 µm). Multiple InGaAs quantum wells are embedded in high-quality InP nano-ridges by selective-area growth on patterned (001) SOI. Combined with air-surrounded InP/Si optical cavities, room-temperature operation at multiple telecom bands is obtained by defining different cavity lengths with lithography. The demonstration of telecom-wavelength monolithic nano-lasers on (001) SOI platforms presents an important step towards fully integrated Si photonics circuits. © 2018 Optical Society of America

Recent advances in Si based optoelectronic integrated circuits (OEICs) have been underpinned by the development of some key components such as low loss waveguides, high-speed optical modulators and sensitive photo-detectors [1]. However, the final brick, an efficient and scalable on-chip III-V light source, is still missing [2-3]. To bridge the gap between cost-effective electronics and power-efficient photonics, direct hetero-epitaxy of III-V coherent laser sources on Si substrate offers potential lower cost and wider scalability as compared to chip scale bonding approaches [4]. Through buffer engineering, highly efficient electrical injection III-V quantum dot lasers with promising performance has recently been demonstrated [5-7]. Yet scaling device footprint to nano-
the emission wavelength of these nano-lasers are limited to the O band (< 1360 nm) [17]. For compact and efficient inter/intra-chip data communications, expanding the lasing spectra from the 1.3 µm band (< 1360 nm) to the 1.5 µm band is desirable for larger circuit bandwidth and functionality.

In this work, we demonstrate room-temperature in-plane InP/InGaAs nano-laser array epitaxially grown on (001) SOI substrates emitting at the 1.5 µm band. Starting with InP/InGaAs nano-ridges selectively grown inside nanoscale Si trenches on SOI, we achieve strong on-chip mode confinement by designing air-surrounded nano-cavities supported by partially-etched Si pedestals, and thus obtain room temperature stimulated emission under optical excitation. More significantly, the lasing peak can be tuned to cover the E band, the S band and the C band through selective area hetero-epitaxy combined with traditional top-down processing offers an intriguing path towards compact on-chip III-V light sources for Si photonics.

Fig. 1(a) schematically delineates the designed InP/InGaAs nano-laser array directly grown on (001) SOI. We adopted conventional Fabry-Perot (FP) cavity with etched end-facets to examine the feasibility of our design. The in-plane InP/InGaAs nano-lasers are underpinned by Si pedestals with a triangular-shaped cross-section, the size of which is carefully controlled to ensure a strong mode confinement inside the nano-ridge as well as robust mechanical support for the top laser cavity. Note that, the supporting Si pedestal with atomic sharp {111} surfaces also serves as a low-loss waveguide to couple light out from the above laser cavity, providing potential on-chip light manipulation. The fabrication process is briefly outlined in Fig. 1(b). Starting with InP/InGaAs nano-ridges grown on SOI substrates, the oxide spacers were selectively etched away using buffered oxide etch. Then, aiming at minimizing light loss into the Si device layer, the underneath Si was undercut to a triangular-shaped post using potassium hydroxide based selective wet etch. In the next step, an oxide layer with a thickness of 300 nm was deposited onto the sample using plasma enhanced chemical vapor deposition (PECVD). This PECVD oxide provides a uniform coverage of the nano-ridges and the Si pedestals, and serves as a protection mask during the subsequent etching process. Finally, the end-facets of nano-laser cavities with different lengths were defined using focused ion beam milling (FIB), and the oxide mask was selectively removed using buffered oxide etch afterwards. Note that the nano-laser array demonstrated here could also be easily fabricated using traditional photolithography and dry etching process with other dimensions and thus by no means compromises their co-integration with other Si based optical elements.

The InP/InGaAs nano-ridges in this experiment were grown on (001) SOI substrates to ensure a strong on-chip mode confinement inside the as-grown nano-ridges and compatibility with the current Si photonics platform. We started with commercial 4-inch (001) SOI wafers with a 2.0 ± 0.5 µm thick Si device layer, a 1.0 µm thick buried oxide layer and a 500 µm thick Si handle layer. To reduce light leakage into the underlying Si device layer and confine light within the epitaxial III-V alloy, the SOI layer was thinned down to around 600 nm using cyclic thermal oxidation and subsequent buffered oxide etch process [20]. Then [110] oriented SiO$_2$ stripes, with a line pitch of 2.8 µm, a trench opening of 450 nm and a trench length of 15 mm, were defined atop the Si device layer. The large separation of adjacent trenches ensures minimal light coupling between neighboring nano-ridges to allow for probing of the optical properties of individual nano-cavities.

After patterning, we grew InP/InGaAs nano-ridges inside the nano-scale Si trenches using metal organic chemical vapor deposition. A detailed description and development of the hetero-epitaxial process can be found in Ref [21-23]. Fig. 2(a) displays a 70° tilted-view scanning electron microscope (SEM) image of the as-grown sample, showing equally-spaced in-plane InP nano-ridge array inside nano-scale Si trenches. Similar to nano-ridges grown on Si substrates, structures grown on SOI also exhibit a faceted growth front with two convex [111] facets connected by a flat (001) facet [24]. The cross-sectional transmission electron microscope (TEM) photo of one nano-ridge is presented in Fig. 2(b). With a width of 450 nm and a height of 1.0 µm, the nano-ridges could efficiently...
guide optical modes at the telecom bands [25]. The large lattice
mismatch between InP and Si is accommodated through the
formation of a thin layer of high-density planar defects at the III-V/Si
interface, rendering the upper InP main layer with high crystalline
formation of a thin layer of high-density planar defects at the III-V/Si
band (see Fig. 2(c)).

serves as the gain medium for wavelengths in the E, the S and the C
configuration with horizontal light emission. A close-up of the end-
nano-lasers. These nano-lasers feature a highly-ordered in-plane
each nano-laser array consists of 15 equally-distributed individual
nano-ridge array were created by etching two parallel trenches with a length
of 60 µm, a width of 15 µm and a depth of 2.0 µm. Consequently,
the profile exhibits a slight incline towards the nano-ridge tip. These

pedestals and the buried oxide layer is presented in Fig. 3(b). The
atomically-flat {111} facets developed
shown in Fig. 2(d). The atomically-flat (111) facets developed
during the selective area growth process result in sharp interfaces
between the ridge InGaAs and InP continuum, which in turn
minimizes the interfacial non-radiative recombination and
maximizes the light emitting efficiency. At room temperature, the
as-grown InP/InGaAs nano-ridge array emits around 1500 nm and
serves as the gain medium for wavelengths in the E, the S and the C
band (see Fig. 2(c)).

Fig. 3(a) displays a tilted-view SEM image of the finalized
InP/InGaAs nano-laser array on SOI. The end-facets of the laser
cavity were created by etching two parallel trenches with a length
of 40 µm, a width of 15 µm and a depth of 2.0 µm. Consequently,
each nano-laser array consists of 15 equally-distributed individual
nano-lasers. These nano-lasers feature a highly-ordered in-plane
configuration with horizontal light emission. A close-up of the end-
facets of the InP/InGaAs nano-cavities with the supporting Si
pedestals and the buried oxide layer is presented in Fig. 3(b). The
morphology of the end-facets defined by FIB is pretty smooth, while
the profile exhibits a slight incline towards the nano-ridge tip. These
non-vertical profile could in turn result in non-parallel end-facets.
However, the influence on the overall round-trip loss should be
inconsequential since optical feedback of the end-facets comes from
scattering instead of direct reflection because of the sub-

Fig. 4. (a) Room temperature emission spectra around threshold.
Inset shows the emission spectra plotted in a logarithmic scale. (b)
The evolution of the peak intensity and the line-width as the
excitation level increases. Inset presents the progression of peak
cavity. Fig. 4(a) provides the emission spectra of one nano-laser
with a length of 60 µm measured under different pumping fluences.
At low pumping levels, the probed nano-laser feature a broad
spontaneous emission and well-spaced FP resonance peaks. As the
pumping level increases, the peak at 1518 nm amplifies, protrudes
from the background emission, and finally lases. The lasing
behavior is further attested by the clamping of spontaneous
emission around threshold, as shown by the emission spectra plotted
in a logarithmic scale (see the inset of Fig. 4(a)). Single-mode
lasing is achieved, albeit the adoption of simple FP cavity. Fig. 4(b)
displays the evolution of the peak intensity and the line-width at
1518 nm as a function of the excitation levels. A clear S-shape
is detected from the L-L curve, and a lasing threshold around 40
µJ/cm² is extracted. This value is about double of that of the
transferred nano-lasers (smaller than 20 µJ/cm²) [19]. We attribute
the somewhat larger lasing thresholds of nano-lasers on SOI to the
supporting Si pedestals which leads to a reduced modal gain. Far
above threshold, the intensity of the single lasing mode at 1518 nm
is orders of magnitudes higher than the damped background
emission, and a few weak side modes start to appear at the blue
side. The line-width of the lasing peak narrows from 1.2 nm to 0.8
nm around threshold, and then gradually augments to 0.9 nm as the
excitation levels continues to increase. The subsequent broadening
of the line-width above threshold could be ascribed to wavelength
chirp, where the fluctuation of carrier density induces the variation
of refractive index [10, 13, 16]. The inset of Fig. 4(b) summarizes the
progression of the peak position as the pumping level strengthens.
The lasing mode initially blue-shifts below threshold, then saturates
around 1517.5 nm around threshold, and finally red-shifts above
threshold. The variation of the peak position is directly modulated
by the alteration of refractive index. Three different mechanisms,
namely band-filling effects, band-gap shrinkage and free-carrier
absorption, contribute to carrier-induced change of refractive

Fig. 5. (a) PL spectra of one nano-laser with a length of 40 µm measured
below and above threshold. (b) PL spectra of one nano-laser with a length of
50 µm measured below and above threshold. (c) The relationship of the
lasing peak and the length of the nano-cavity.
which consequently causes the initial blue-shift of the lasing peak. As the excitation level escalates and the nano-laser heats up, another effect called “thermal-induced change of refractive index” comes into play and leads to an increased refractive index [28]. The synergized effect of carrier-induced and thermal-induced changes of refractive index brings on the saturation and following red-shift of the lasing peak.

We also observed room-temperature lasing behavior from nano-lasers with different cavity lengths. Fig. 5(a) displays the measured photoluminescence spectra of one nano-laser with a length of 40 µm. Below threshold, we detect a broad spontaneous emission centered around 1.5 µm, modulated by evenly-spaced FP longitudinal modes. The mode spacing around 1.5 µm is extracted as 5.7 nm corresponding to a group refractive index of 4.9. Above threshold, single-mode lasing is obtained at 1420 nm. The measured emission spectra of one nano-laser with a length of 50 µm is presented in Fig 5(b). As expected, the spacing between adjacent longitudinal modes reduces to 4.5 nm. Interestingly, the lasing peak also red-shifts to 1509 nm. Fig 5(c) summarizes the relationship of measured emission spectra of one nano-laser with a length of 50 µm and the threshold, single-mode lasing is obtained at 1420 nm. The correlation between the lasing mode and the cavity length might stem from the wavelength-dependent modal gain and propagation/end-facet loss. A longer mode wavelength features a larger round-trip loss and a smaller modal gain, and thereby necessitates a larger volume of active material to reach threshold. We will fabricate more nano-lasers with a wider length variation to investigate the detailed mechanism.

In conclusion, we have demonstrated room temperature InP/InGaAs nano-laser arrays monolithically integrated on (001) SOI substrate emitting at the telecom bands. Room temperature laser oscillation corroborates the excellent optical quality of III-V nano-ridges directly grown on Si, and affirms the validity of our proposed laser design. Incorporating in-plane nano-laser array with Si-transparent light emission onto CMOS-compatible (001) SOI substrates suggests the feasibility of on-chip consolidation between compact III-V light sources and mature Si photonic components. Future work includes operating the nano-lasers under continuous-wave excitation via advanced cavity designs, and realization of electrically driven telecom InP/InGaAs nano-laser arrays on (001) SOI.

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Full References