III-V Micro/Nano-lasers and photodetectors in the Telecom Band Grown on SOI

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Abstract: We present our recent progress on the III-V micro/nano-lasers and photodetectors (PD) grown on (001) silicon-on-insulators (SOI) for integrated silicon photonics (Si-photonics) using vertical and lateral selective epitaxy. © 2022 The Author(s)

OCIS codes: (140.3410) Laser resonators; (230.5590) Quantum-well, -wire and -dot devices; (040.5160) Photodetectors; (130.3120) Integrated optics devices

1. Introduction

With the progressively improvement of III-V lasers and PDs on Si reported [1], efficient light coupling between active devices and well-established passive components has become the next critical step towards fully integrated Si-photonics. Lasers and PDs with impressive performance fabricated on blanket hetero-epitaxy of III-V on Si have been reported. However, the thick buffer layers for defect reduction makes efficient light coupling between active components and Si-waveguides difficult. Alternatively, selective hetero-epitaxy of III-V on SOI leading to bufferless devices through unique defect management techniques can promotes efficient light coupling into Si-waveguides. Techniques of selective epitaxy such as vertical aspect ratio trapping (ART) and nano-ridge engineering (NRE) produce III-V devices with a vertical configuration, while methods such as template-assisted selective epitaxy (TASE) and lateral ART construct devices with an in-plane lateral configuration [2]. In this paper, we briefly summarize our demonstrations of lasers and PDs with these two configurations. Challenges and opportunities of each approach are also discussed.

2. III-V lasers and photodetectors on SOI with vertical configuration

2.1. III-V nano-ridge lasers on SOI

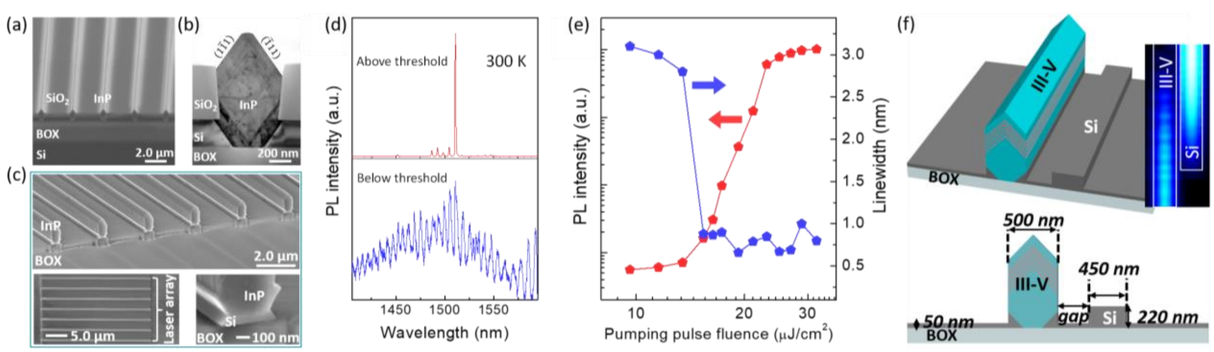

Fig. 1. (a) Tilted-view scanning electron microscope (SEM) photo and (b) Transmission electron microscope (TEM) image of the as-grown InP on SOI. (c) SEM images of the finalized laser array. (d) Room temperature PL spectra of the optically pumped InP/InGaAs lasers below and above threshold. (e) Peak intensity and line-width plotted in a logarithmic and liner scale, respectively. (f) Coupling scheme and field exchange image between the III-V laser and Si rib waveguide.

By combining our previously developed lateral ART [2] and the vertical ART methods, we devised a unique metal organic chemical vapor deposition (MOCVD) growth scheme for the direct epitaxy of high-quality III-V materials inside trapezoidal troughs patterned on SOI. Bufferless III-V lasers on the Si-photonics standard 220 nm (001) SOI platforms were demonstrated using this method. Uniform nano-ridge structures were grown on the trench-patterned 220 nm SOI (Fig. 1(a) and (b)) and fabricated into Fabry-Perot laser array as depicted in Fig. 1(c). The designed growth technique promotes the formation of planar defects instead of threading dislocations, and thus produces III-V materials with greatly improved crystalline qualities compared with those grown using vertical ART technique as evidenced by the decreased cavity length (<40μm) and lasing threshold (Fig. 1(d) and (e)) [3].

Efficient light coupling between the optically pumped nano-ridge lasers and Si-waveguides can potentially be realized through the evanescent coupling scheme as illustrated in Fig. 1(f). However, for electrically driven lasers, the thick cladding for minimizing the metal-induced loss will generate a large height difference between III-V active region and Si-waveguides thereby complicating the light coupling between them.

2.2. III-V nano-ridge photodetectors on SOI

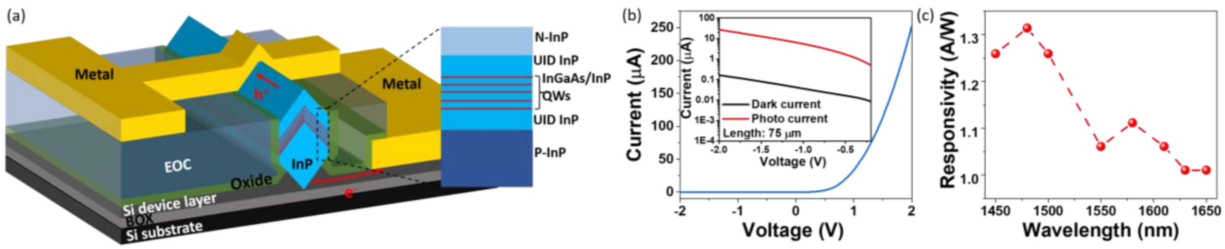

Fig. 2. (a) Device architecture of the bufferless InP/InGaAs PD grown on SOI. (b) I-V curve of the PD with 500 nm width and 75 μm length, inset: zoomed-in dark current and photocurrent in log scale. (c) responsivity plotted as a function of probing wavelength.

Building from our previously reported InP/InGaAs nano-ridge lasers grown on (001) SOI, we demonstrated bufferless InP/InGaAs nano-ridge PDs on SOI for on-chip light detection in the telecom band [4]. The p-i-n III-V nano-ridges were grown on a highly doped p+-Si device layer (Fig. 2(a)) with the sequence illustrated in the cross-sectional schematic in Fig. 2(a). The fabrication was completed using self-aligned planarization and etch-back process without any E-beam lithography process involved for the 500 nm wide nano-ridges. The dark current without light illumination and photocurrent under 21 μW input light at 1.5 μm are shown in Fig. 2(b). The operation spectral range and the corresponding photosensitivity of the nano-ridge PDs were measured from 1450 nm to 1650 nm and summarized in Fig. 2(c).

The p-i-n InP/InGaAs PDs display a high responsivity over a 200 nm operating wavelength range from E band to L band. However, the high-speed performance was limited by the defective III-V/Si interface that the current must go through.

3. III-V lasers and photodetectors on SOI with lateral configuration

3.1. Monolithic InP/SOI platform

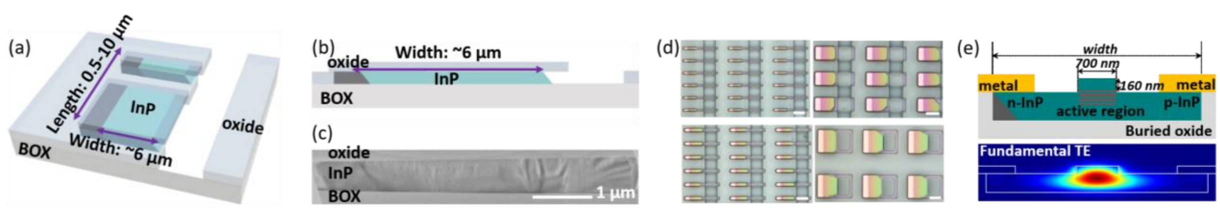

Fig. 3. (a) and (b) 3D and cross-sectional view of the InP/SOI template with 6.0 μm wide InP bars and membranes. (c) Global TEM image of InP membrane by 10 μm pattern length along epitaxial direction. (d) Optical microscope images of as-grown InP array with different pattern length: 500 nm, 1 μm, 5 μm and 10 μm, respectively (scale bar: 5 μm). (e) Schematic showing the design and simulated mode of electrically driven lasers grown on SOI with an III-V width of 3.5 μm. The quantum wells are regrown on the InP /SOI templates.

Towards efficient light coupling between high-performance III-V devices and Si-waveguides, as well as having sufficient material volume for realizing electrically driven lasers, we developed a monolithic InP/SOI platform for integrated photonics by leveraging our previously devised "lateral ART" and incorporating the concept of "TASE". On this platform, dislocation-free InP segments with a thickness of 480 nm, a width adjustable from a few hundred nanometers to 7 micrometers by growth time, and patterned lengths from a few hundred nanometers to tens and possibly hundreds of micrometers are selectively grown on (001) SOI wafers and intimately placed with the Si device layer (Fig. 3(a) and (b)). Antiphase boundaries (APB) and threading dislocations (TD) are essentially eliminated as shown in a representative global-view TEM image in Fig. 3(c). Fig. 3(d) displays the microscopic photos of the InP sub-micron bars and membranes grown on SOI. We also exemplified the potential and versatility of this platform for integrated photonics through the demonstration of room temperature lasing of InP from subwavelength bars, square cavities and micro-disks at around 900 nm by optical pumping [5].

The InP membranes could potentially serve as templates for subsequent regrowth of numerous InP-based optoelectronic structures. Furthermore, benefit from the large material volume of the InP membrane on this platform which is not available in traditional selective hetero-epitaxy, electrically driven lasers can be potentially realized with the structure design and simulated mode profile illustrated in Fig. 3(e).

3.2. High-performance photodetectors on SOI

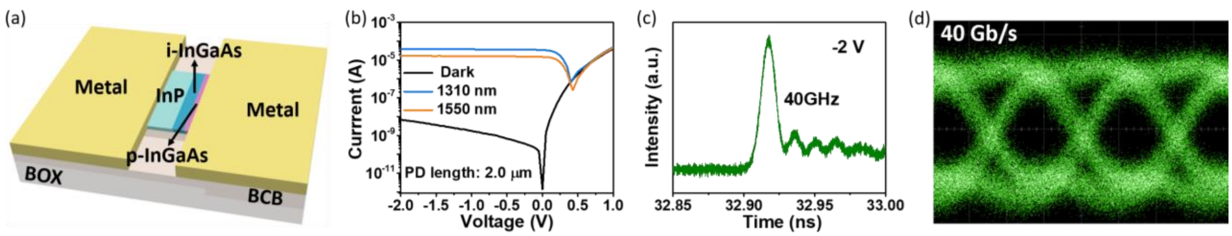

Fig. 4. (a) Device architecture of the III-V PD on SOI with lateral configuration. (b) Dark current and photocurrent at 1310 nm and 1550 nm of a PD with a length of 2 μm. (c) Output electrical pulse measured from the device with 2.0 μm length. (d) Measured eye diagrams at 40 Gb/s for the PD with 2.0 μm length.

Based on the developed monolithic InP/SOI platform, n-InP, i-InP, i-InGaAs, and p-InGaAs were grown laterally in sequence for the fabrication of p-i-n photodiodes. The as-grown sample was fabricated into top illuminated PDs of different lengths (0.5 μm to 5 μm) using well-controlled planarization process and subsequent contact metal formation (Fig. 4(a)). The PDs demonstrate very good photo-response in both O band and C band with an operation wavelength span of over 400 nm as plotted in Fig. 4(b). The lowest measured dark current was 0.55 nA, and responsivities at 1550 nm and 1310 nm were calculated to be 0.3 A/W and 0.8 A/W, respectively [6]. The extracted 3-dB bandwidth of around 40 GHz through impulse-response measurements and clearly open eye diagram at 40 Gb/s demonstrate the high-speed feature of our PDs and prove their capability of practical applications in optical communications (Fig. 4(c) and (d)).

The co-planar configuration of the epitaxial III-V and Si device layer allows for the adoption of butt-coupling schemes to efficiently couple the Si-waveguides with the III-V PDs. Preliminary experimental results show a coupling efficiency of around 70% while maintaining similar responsivity and high-speed performance simultaneously. The butt-coupling strategy can also be applied to the integration of electrically pumped lasers and Si-waveguides on this platform.

4. Conclusion

In conclusion, we demonstrated III-V micro/nano-lasers and PDs directly grown on SOI using two different approaches of selective epitaxy. The bufferless nano-lasers and PDs built on nano-ridges on SOI feature a vertical configuration. The III-V lasers and PDs built on the monolithic InP/SOI platform feature an in-plane lateral configuration. Our results here mark a critical step towards fully integrated Si-based photonic integrated circuits.

Acknowledgments

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