RZ 3967 (# ZUR1908-023) 24/08/2019
Materials Science 2 pages

Research Report

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This is the accepted version of the article published by IEEE: S. Mauthe, N. Vico Triviño, Y. Baumgartner, P. Staudinger, P. Tiwari, M. Sousa, Da. Caimi, T. Stöferle, H. Schmid, and K. E. Moselund "Novel Integration Approach for III-V Microdisk Cavities on Si," *in Proc. IEEE 16th International Conference on Group IV Photonics (GFP), 2019.*
10.1109/GROUP4.2019.8853880

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***Abstract*—We present and evaluate a novel integration approach for III-V microdisk cavities on Si. We demonstrate InP room-temperature microdisk lasers and compare the performance to similar InP microdisks fabricated via direct wafer bonding. InP allows for future integration of QWs for the NIR spectral range.**

Keywords— **Heterogeneous integration, III-V materials on silicon, Microdisk lasers, Optical pumping, Semiconductor lasers.**

I. Introduction

Integrating efficient III-V light sources on Si has been a long-standing goal for photonic integrated circuit chips to enable new electro-optical functionalities for both on-chip and off-chip applications. Due to the indirect bandgap of Si however, new materials suitable for efficient light generation are required. III-Vs exhibit promising properties like a direct, tunable bandgap and high electron mobility. The main obstacle when integrating III-Vs on Si is the significant lattice and thermal mismatch. We recently developed a novel growth approach to monolithically integrate high-quality III-V material on Si, called template-assisted selective epitaxy (TASE [1]). TASE allows for new device concepts such as lateral doping and quantum wells (QWs) orthogonal to the substrate, dense co-integration of different III-Vs, and in-plane integration with Si electronics and passive components [2,3]. Using this approach, we recently demonstrated single crystalline, room-temperature (RT) GaAs microdisk cavities lasing at ~850 nm [4]. For the future integration with Si passives however, emission wavelengths beyond the Si bandgap are desired. Here, we extend our approach to InP and demonstrate RT lasing at ~900 nm from hexagonal microdisks [5]. InP is a key material for the future integration of QWs, and hence, the future goal of emission beyond the Si bandgap. To validate our TASE approach, we compare TASE microdisks with similarly shaped InP microdisks integrated via a mature direct wafer bonding technique. We also present the preliminary results on InP microdisks embedding two InGaAs/InP QWs orthogonal to the substrate by TASE.

II. Integration of III-V Microdisks

Microdisks are integrated on Si (111) using a direct cavity growth based on TASE as depicted in Fig. 1(a) and (b). A 200 nm silicon oxide layer is deposited and a small opening (~200 nm) etched down to the Si substrate (Fig. 1(a) step 2). The oxide thickness provides sufficient isolation of the optical mode from the underlying Si while allowing for a high-yield nucleation of the III-V material on Si. Next, a sacrificial amorphous Si (α-Si, 300 nm) layer is deposited, patterned, and covered with oxide forming a template for the subsequent growth (Fig. 1(a) step 3 and 4). Small openings are patterned in the SiO_2 shell to provide access and allow etching of the sacrificial α-Si layer (Fig. 1(a) steps 4 and 5). Finally, III-V material is selectively grown from the exposed Si seed into the hollow oxide template using metal-organic chemical vapor deposition (MOCVD). Fig. 1(b) depicts the growth of the III-V material as a function of time. Due to the oxide template, the growth is limited in vertical direction and is forced to expand laterally. This leads to the growth facets expanding orthogonal to the substrate in a radial fashion and allows for the controlled integration of lateral QWs by switching the precursor materials during growth.

III. Results and Discussion

Fig. 1(c) shows a scanning electron microscopy (SEM) image of a hexagonal InP microdisk integrated via TASE. The hexagonal shape indicates a single crystalline structure epitaxially aligned with the underlying Si (111) substrate. Scanning transmission electron microscopy (STEM) performed on the InP microdisks confirm the single crystallinity and hence, suggest a high quality InP base layer for the subsequent QW growth (Fig. 1(d)-(g)). Photoluminescence (PL) spectroscopy performed on the InP hexagonal microdisk using a picosecond-pulsed excitation at 750 nm reveal a spontaneous emission peak at ~880 nm at 300 K for low excitation powers (see Fig. 2(a)). With increasing excitation powers, a strong emission peak emerges at 840 nm increasing strongly non-linearly (see Fig. 2(b)). The double log light in-light out (LL) curve depicted in Fig. 2(c) indicates lasing behavior of the TASE structure. Using a double linear LL plot, the lasing threshold is determined to ~200 $\mu J/cm^2$. A second InP sample was fabricated for comparison using the mature direct wafer bonding approach. Hexagonal shapes similar to the grown TASE ones were etched and measured optically (see inset Fig. 2(a)). Under strong optical excitation, the bonded hexagon shows two distinct emission peaks at ~870 nm and ~920 nm (Fig. 2(a) and (b)) with a lasing threshold of ~170 $\mu J/cm^2$. The lasing threshold and the LL curves of the TASE and bonded devices compare favorably confirming the attractiveness of our approach (Fig. 2(c)). To demonstrate new capabilities offered by TASE, we integrated InGaAs/InP QWs. Fig. 3(a) shows an SEM image revealing two QWs at the periphery of a microdisk. Compared to QWs integrated via planar growth and bonding, the QWs in TASE are oriented orthogonal to the substrate (see Fig. 3(b)-(d)) allowing for new device concepts. Their optical characterization is currently under investigation.

IV. Conclusion

In conclusion, we demonstrated RT lasing from InP TASE microdisks and assessed the viability of the TASE approach by comparing to similar devices integrated via direct wafer bonding. TASE allows for high crystalline quality material and offers the ability to integrate QWs orthogonal to the substrate. With this work, we demonstrate the high potential of TASE and pave the way for new device concepts.

We received financial support from H2020 ERC project PLASMIC grant #678567, H2020 project DIMENSION grant #688003, and the Swiss National Science Foundation project number 200021_156746.

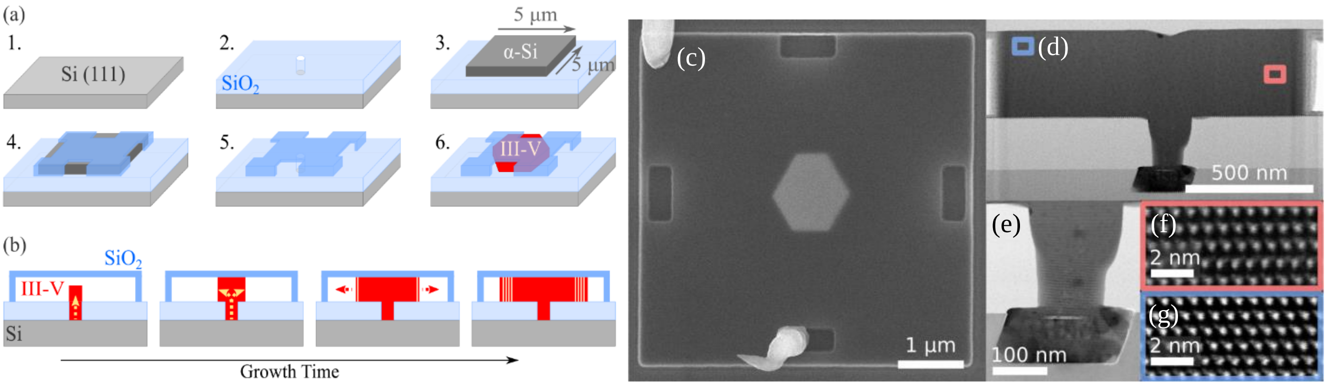

Fig. 1 (a) Fabrication steps in the TASE-based approach. (1.) Si (111) substrate. (2.) Deposition and patterning of an SiO_2 layer. (3.) Deposition and patterning of sacrificial α-Si layer. (4.) Deposition and partially opening of an SiO_2 shell around the α-Si layer. (5.) XeF_2 dry etching of the α-Si layer. (6.) Growth of the III-V material. (b) Schematic growth of the III-V crystal in the cavity. Dashed arrows indicate the growth direction. (c) SEM image of a hexagonal InP crystal. (d) TEM image of the microdisk in (c) revealing a single crystalline structure [5]. (e) Detailed image of the InP nucleation seed and stem. (f)-(g) High resolution images of marked regions on the right (f) and left (g) side of the microdisk.

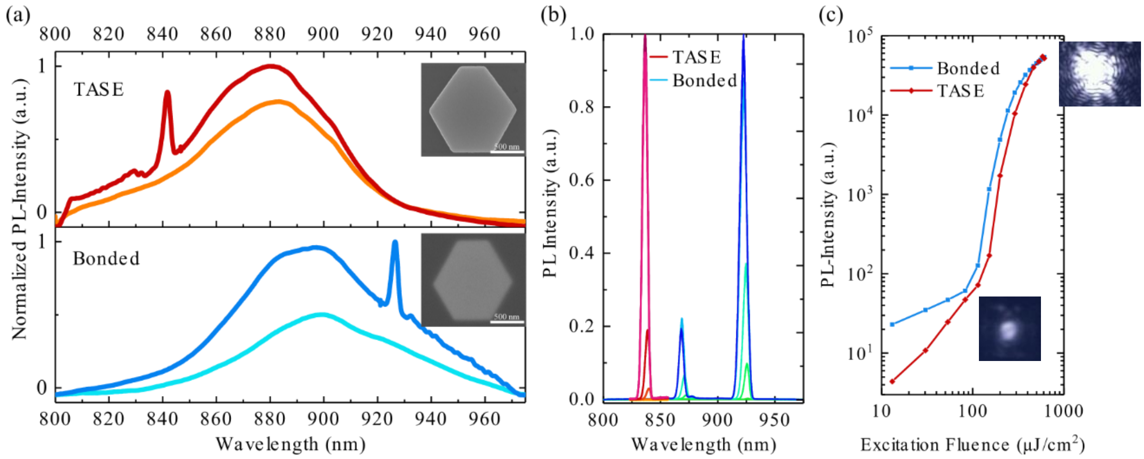

Fig. 2 (a) PL-measurements of the TASE and bonded InP microdisks below and at threshold excitation fluence. The insets show an SEM image of the measured devices. (b) Increasing lasing peaks for increasing pump intensities of structures in (a) at 300 K. (c) Log-log LL curves for TASE and bonded microdisks. The images on the right-hand side show the far-field images of the emitted light of the TASE structure below and above threshold.

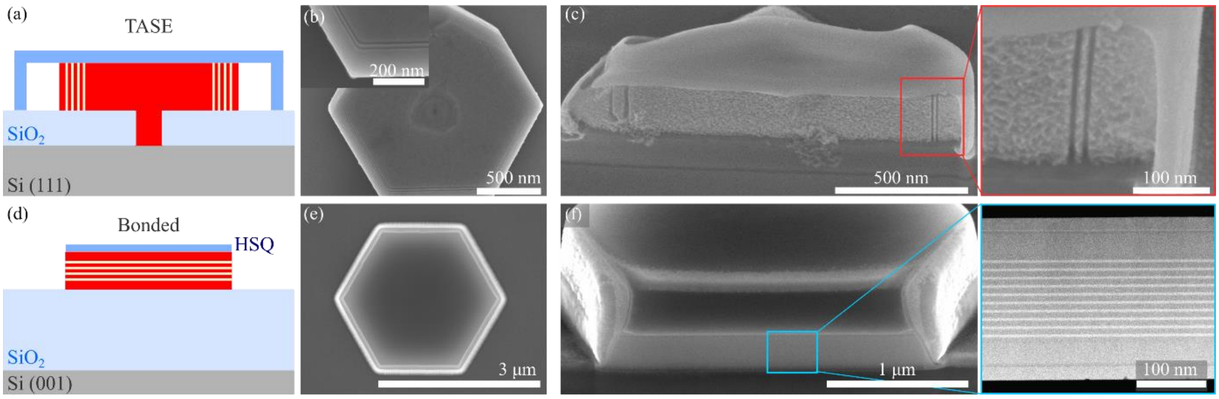

Fig. 3 Comparison between TASE vertically integrated InP/InGaAs QWs (top) and common horizontally integrated QWs via direct wafer bonding (bottom). (a) Schematics of TASE QWs. (b) SEM image of a TASE microdisk with QWs at the periphery. The inset shows a close-up. Optical characterization under investigation. (c) Cross-section of device in (b). (d) Schematics of bonded QWs. (e) SEM of bonded and etched strain compensated InAlGaAs QW microdisk. (f) Cross-section and STEM image of QW sample in (d).

Acknowledgment

We acknowledge the BRNC team for technical support and J. Leuthold for technical discussions.

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