III-V-on-silicon membrane photonics for near-infrared and mid-infrared applications

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***Abstract*—We give an overview of our work in the field of heterogeneously integrated III-V-on-silicon photonic integrated circuits for communication and sensing applications.**

Keywords: heterogeneous integration; III-V on silicon

I. Introduction

Silicon-based photonic integrated circuits are gaining considerable importance for a variety of applications, from telecommunications to sensors. The interest in this technology stems mostly from the expectation that the maturity and low cost of CMOS-technology can be applied for advanced photonics products. Other driving forces for silicon photonics include the design richness associated with the high refractive index contrast as well as the potential for integration of photonics with electronics. The lack of silicon light sources and photodetectors for various wavelength ranges requires the integration of III-V semiconductor devices on the silicon platform to complete the toolkit. For these devices thin layers of III-V semiconductors are bonded to silicon. The III-V/silicon laser gets its gain from the III-V layers but couples its output light into a silicon waveguide. For the detectors light is guided in the silicon waveguide layer and is coupled to the absorbing III-V layer stack on top. Besides lasers and detectors, many other types of devices can be realized on this III-V/Silicon platform.

We focus on adhesive die-to-wafer and wafer-to-wafer bonding processes, based on DVS-BCB as a bonding agent, for the integration of III-V semiconductors on silicon. Adhesive bonding is chosen due to the relaxed requirements on the III-V wafer surface quality (contamination, particles, roughness). The technology is described in detail in [1]. Based on this technology, various types of heterogeneously integrated laser sources, photodetectors and other optical functionality were fabricated, which will be outlined in this paper, both for telecom and datacom applications as well as for spectroscopic sensor systems in the short-wave and mid-wave infrared.

II. Datacom/Telecom Applications

A. mW-level output power III-V/silicon lasers

Two device geometries for milliwatt level output power are considered. In a first approach a hybrid mode laser, analogous to the device structure proposed by UCSB/Intel [2], was developed. In this approach the optical mode is predominantly confined to the silicon waveguide layer. The difference between our design and the UCSB/Intel one is the presence of the low-index DVS-BCB bonding layer (sub 100nm) between the silicon waveguide and the III-V epitaxy. Careful design of the epitaxial layer stack is required to accommodate variations in bonding layer thickness. As a proof-of-principle, hybrid 1310nm Fabry-Perot laser diodes were realized. 4mW laser output power from a single laser facet at room temperature was obtained [3]. By incorporating a grating in the top surface of the silicon waveguide layer, single mode lasers with 40dB side mode suppression ratio can be obtained. Since in these devices the optical mode is predominantly confined in the silicon waveguide layer, the confinement factor in the III-V quantum wells is relatively low. This impacts the threshold current of the device. Therefore, an alternative laser architecture was developed, in which the optical mode is fully confined to the III-V waveguide layer in the gain section, while the mode is pushed into the silicon waveguide layer for the (potentially wavelength selective) feedback [4]. 2mW laser output from a cleaved Fabry-Perot device and operation at 70C was obtained.

B. Micro-lasers

Other communication applications (such as intra-chip optical communication) require rather a compact light emitter with moderate output power (10-100 microwatt) and low power consumption. This can be realized using micro-laser sources such as micro-disk lasers and photonic crystal lasers. Micro-disk lasers with threshold currents below 350uA were demonstrated with about 100uW of power evanescently coupled to a silicon waveguide underneath [5]. These micro-disk devices turn out to be very versatile devices since they have been used as optical flip-flop, all-optical gate, switch and modulator [6]. The ultimate down-scaling in size was obtained using photonic crystal lasers evanescently coupled to a silicon waveguide, which were optically pumped through the silicon waveguide layer [7]. A novel device geometry, combining high gain by strong confinement in the III-V layer and wavelength selective feedback by patterning in the silicon layer is also under investigation [8].

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C. Photodetectors

While Ge-photodetectors allow for monolithic integration on a silicon waveguide circuit, III-V semiconductor photodetectors typically outperform Ge detectors in terms of dark current and flexibility in epitaxial layer structure. Therefore, several types of III-V photodetectors were realized on a silicon waveguide platform. InGaAs photodetectors using evanescent coupling between the silicon waveguide layer and the III-V layer show close to theoretical responsivity [9]. For optical access network applications, an alternative device configuration was realized, which is transparent for 1490nm/1550nm upstream signals, while strongly absorbing for the 1300nm downstream wavelength range [10].

D. Membrane optical gates / switches

Besides lasers and photodetectors, also III-V membrane optical gates were realized. These devices are based on a thin (sub 100nm thick) III-V membrane coupled to a silicon waveguide circuit. The gate is based on the strong change in transmission (>40dB) when pumping the quantum wells in the thin film. This allows fabricating an all-optical broadcast and select switch [11]. Besides switching, the same device was used as an optical amplifier and regenerator.

III. SWIR/MWIR SPECTROSCOPY APPLICATIONS

The short-wave (1.4-3µm) and mid-wave infrared wavelength range (3-8µm) is also attractive for several applications. In particular, the field of spectroscopic sensing exploits the strong gas/liquid/solid absorption features in this wavelength range. Given its transparency window (1-4µm), silicon photonics allows realizing integrated spectroscopic systems by combining active III-V devices on Silicon-On-Insulator (SOI) passive circuits in this wavelength range. The availability of an integration platform for this wavelength range could enable ultra-compact, low-cost sensor solutions that outperform existing solutions by their selectivity and sensitivity. This requires the integration of short-wave/mid-wave infrared light sources and photodetectors on top of the silicon waveguide circuit.

As a first step towards fully integrated spectroscopy systems, the heterogeneous integration of short-wave infrared InGaAsSb photodetectors was demonstrated, operating up to 2.5µm. Two device geometries were considered, one based on evanescent outcoupling, and another based on grating-assisted coupling. While the first approach provides the highest responsivity [12], the latter approach has larger tolerances in fabrication since thicker adhesive bonding layers can be used. Responsivities above 1A/W have been obtained in recent experiments at 2.3µm using the evanescent coupling approach.

IV. CONCLUSIONS

The combination of high precision patterning methods in silicon fabs and high gain and efficient detection provided by III-V semiconductors provides a winning combination for advanced integrated opto-electronic devices. The design space is large and there is ample opportunity for optimization towards specific performance objectives. The critical technological step in hybrid III-V / silicon devices is obviously the die-to-wafer bonding step. While early approaches suffered from low yield the technology has now become more mature.

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