Enhanced Nonlinearity in SOI Microcavities by III-V/SOI Heterogeneous Integration

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Abstract

We demonstrate enhanced nonlinearity in an SOI microcavity by heterogeneously integrating a III-V overlay on top of the SOI waveguide layer. Nonlinear transmission and all-optical modulation is observed.

Introduction

Silicon-on-insulator is emerging as a disruptive technology for the realization of photonic integrated circuits comprising both passive and active functionality. The high refractive index contrast between the silicon waveguide core and the SiO_2 cladding layer is ultimately exploited by using nanophotonic strip waveguides, which are defined by completely etching through a $\lambda/2n$ thick silicon waveguide layer. Optical nonlinearities are expected to occur at modest optical input powers on this waveguide platform, due to the high confinement in the silicon waveguide layer and due to the high quality factor, ultra-compact cavities that can be realized. Nonlinear operation in SOI waveguide circuits typically relies on the carriers created by the relatively weak two photon absorption process or on the weak Kerr effect however [1]. In this paper we present the use of a III-V overlay to further enhance the nonlinearity, as carriers can be created in the III-V layer by an efficient absorption process.

In this paper we demonstrate the heterogeneous integration of a III-V thin film on top of a silicon-on-insulator cavity by means of adhesive DVS-BCB die-to-wafer bonding. This approach requires ultra-thin DVS-BCB bonding layers in order to allow the highly confined optical mode to overlap with the bonded III-V film. We demonstrate the transfer of sub 100nm III-V layers using a 65nm DVS-BCB bonding layer onto SOI racetrack resonator structures. Strong carrier-induced nonlinearities are observed in the transmission characteristics of the III-V/SOI resonator structure at sub 250uW optical input power levels. Also all-optical switching of an optical signal (wavelength conversion) is observed.

III-V/SOI nanophotonic waveguide structures

The considered III-V/SOI nanophotonic waveguide structure is schematically depicted in figure 1. The SOI nanophotonic strip waveguide structure that is used consists of a 220nm thick waveguide layer on top of a 2μm thick SiO_2 buffer layer. While the optical mode is predominantly confined in the SOI waveguide layer, the tail of the optical mode overlaps with the bonded III-V waveguide layer.

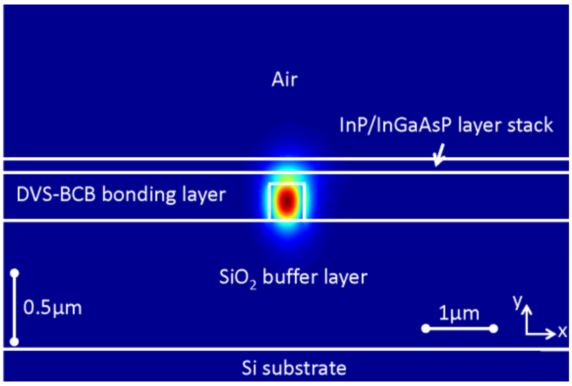

Figure 1: E_x-component of the quasi-TE mode propagating in the III-V/SOI waveguide structure.

The leakage loss of the III-V/SOI mode into the bonded III-V film plays an important role especially in the racetrack resonator cavity design presented in this paper, as it can dramatically lower the quality factor of the racetrack resonator resonances. It is clear that in order to reduce the leakage loss, the bonding layer thickness can be increased. However, this deteriorates the overlap of the guided mode with the III-V layer. Simulations show that the bonded III-V film has to be sub 100nm thick, while the bonding layer thickness has to be in the order of 50nm, in order to keep the radiation losses low for a 5μm radius ring resonator (to maintain a high cavity quality factor) and maintaining a minimum 10% confinement factor in the III-V overlay (to obtain strong nonlinear effects).

DVS-BCB bonding technology

The heterogeneous integration of a III-V film on top of an SOI waveguide substrate was realized using an epitaxial layer transfer technique based on DVS-BCB die-to-wafer bonding [2]. After particle removal and surface conditioning of both the SOI waveguide circuit and III-V die, DVS-BCB is spin coated on top of the SOI waveguide circuit. The III-V die is attached to the SOI waveguide circuit (epitaxial layers oriented downwards) and the III-V/SOI stack is cured at 250C in a nitrogen environment for 1

978-1-4244-2229-6/08/$25.00 ©2008 IEEE

hour. After curing the DVS-BCB film, the InP growth substrate of the III-V die is removed by a combination of mechanical grinding and wet etching until an etch stop layer is reached. This leaves a thin film of III-V material attached to the SOI waveguide circuit as shown in figure 2. A 65nm separation between the III-V layer and SOI waveguide layer is obtained.

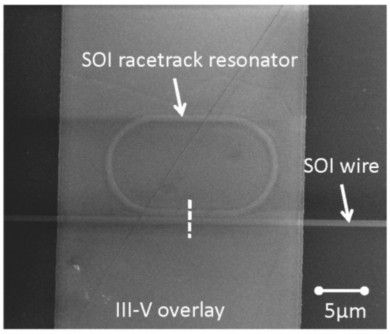

Figure 2: III-V/SOI racetrack resonator notch filter

Nonlinear transmission of a III-V/SOI cavity

The realized III-V/SOI racetrack resonator cavities show strong nonlinear behaviour. This is due to the absorption that takes place in the III-V active layers when using a wavelength shorter than the band gap wavelength of the III-V active layers. This absorption process creates free carriers in the III-V active layer, which reduce the refractive index of the III-V active layer material due to the plasma dispersion effect, band filling and bandgap shrinkage. The reduction of the guided mode effective index results in a blue shift of the resonance spectrum and hence results in a change in transmission as a function of the density of the free carriers, or as a function of the injected optical power. Besides a spectral blue shift due to the reduction of the real part of the guided mode effective index, also the absorption of the III-V active layer is bleached, which results in resonances with a higher quality factor when the input power is increased. This effect is shown in figure 3, showing the transmission characteristics of a III-V/SOI racetrack notch filter (5µm radius, 3µm directional coupler section with a waveguide gap of 300nm). The III-V layer structure used in this experiment consists of three 10nm thick InGaAs quantum wells with a bandgap wavelength of 1.55µm separated by 10nm barrier layers and 7nm InP cladding layers. The quantum well confinement factor was calculated to be 5.2%. A resonance in the Urbach tail of the quantum wells was chosen, in order not to compromise the III-V/SOI resonator quality factor due to excessive absorption in the quantum wells of the III-V overlay. Strong nonlinear transmission is observed, for sub 250uW optical input power. Up to 0.3nm blue shift is obtained in continuous wave operation (which is limited by the thermo-optic effect). A 20dB change in optical transmission can be observed for an optical input power changing from 10 to 100uW. This allows realizing digital-like transmission curves, as will be elaborated on at the conference.

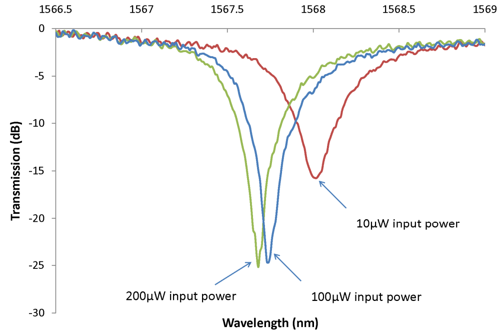

Figure 3: III-V/SOI cavity transmission spectra for varying optical input power

All-optical control of optical data signals in a III-V/SOI cavity – wavelength conversion

Besides the strong input power dependent transmission, III-V/SOI micro-cavities can be used for efficient all-optical modulation (wavelength conversion). This is demonstrated in figure 4, where a resonance of the III-V/SOI racetrack resonator is plotted (for the probe signal) as a function of the optical pump power that is injected in the III-V/SOI cavity at the resonance which is located a free spectral range away (towards the short wavelength side). The carriers that are created by the pump blue shift the probe resonance, thereby obtaining all-optical modulation with an extinction ratio of 8dB, with an input pump power of about 250uW. As this blue shift is due to carrier generation, the speed of this modulation is determined by the free carrier life time, which is about 500ps. Higher operation speed can be obtained however by applying a lateral electric field to sweep the carriers out of the active region, thereby reducing the effective carrier lifetime [1].

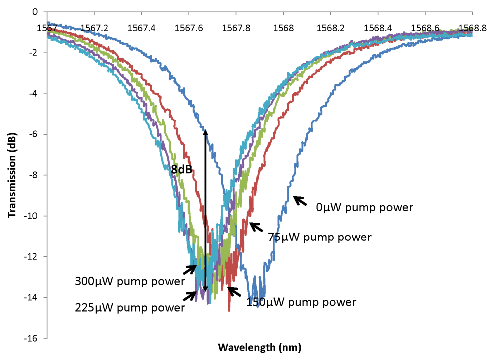

Figure 4: All-optical modulation by blue shifting the probe resonance by an optical pump

References

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