GaSb-based integrated Lasers and Photodetectors on a Silicon-On-Insulator Waveguide Circuit for Sensing Applications in the Shortwave Infrared

N. Hattasan[1], A. Gassenq[1], L. Cerutti[2], J. B. Rodriguez[2], E. Tournié[2], G. Roelkens[1]

[1] *Photonics Research Group-UGent/imec, Sint-Pietersnieuwstraat 41, 9000 Gent, Belgium*

[2] *Université Montpellier 2 – CNRS, UMR 5214, Place Bataillon, 34095 Montpellier, France*

Abstract—**We report our results on GaSb photodiodes and lasers integrated on a Silicon–On-Insulator waveguide circuit. The photodiodes operate at room temperature with 0.4A/W responsivity for grating-assisted coupling and >1 A/W for an evanescent design. On the other hand, integrated Fabry-Perot lasers operate in continuous wave at room temperature with a threshold current of 49.7mA.**

Keywords: Silicon-On-Insulator, GaSb, integrated circuits

I. INTRODUCTION

The interest in sensing liquids and gases such as glucose, CH_4 and CO in the shortwave infrared has increased over the past decade due to the low water absorption in this region. Conventional spectroscopic techniques, which may offer high accuracy, require expensive and bulky sources and detectors. However, a compact, low-power system is strongly desirable for many applications such as home used gas sensing and implantable sensors.

GaSb and its compounds are an excellent semiconductor material for the shortwave infrared. Several room temperature operating lasers and detectors have thus far been demonstrated using GaSb, making it suitable for integrated active components [1-3]. Silicon-On-Insulator (SOI), on the other hand, offers mass production of optical circuits with CMOS compatibility. This makes it ideal as a passive integrated optical circuit platform. Combining SOI and GaSb optoelectronic components could thus yield a compact, efficient spectroscopic detection system.

In this paper, we report integrated InGaAsSb photodetectors (grown lattice-matched on a GaSb substrate) on SOI and thin-film Fabry-Perot (FP) lasers on a carrier substrate. For photodetectors, 2 coupling schemes are studied: evanescent and grating-assisted coupling. A high responsivity of >1A/W is achieved in the evanescent coupling design and approximately 0.4A/W for grating-assisted coupling.

For the integrated laser on a carrier, the device operates at ~2.02µm wavelength in continuous wave at room temperature. We obtain lasing with a low threshold current of 31mA in pulse regime and 49.7mA in continuous wave.

This works was supported in part by Glucosens project grant IWT-SBO and ERC-MIRACLE project

II. DESIGN

A. Photodetectors

P-i-n photodiode epitaxy is selected for integration. The energy band diagram of the structure is plotted in Figure 1. The epitaxy is grown by molecular beam epitaxy [4].

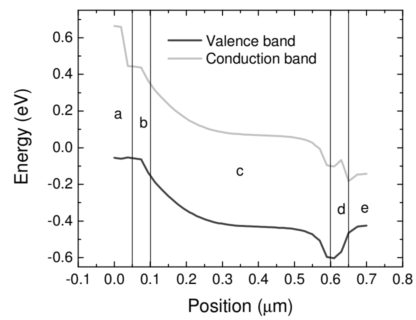

Figure 1: Energy band diagram of the integrated photodetector indicating region (a) as GaSb p-doped, (b)(c)(d) as p-i-n GaInAsSb respectively and (e) as InAsSb n-doped

The epitaxial stack consists of 50nm p-doped ($1.0x10^{18}$ cm^{-3}) GaSb and a 50nm p-doped ($1.0x10^{18}$ cm^{-3}) $Ga_{0.79}In_{0.21}As_{0.19}Sb_{0.81}$ layer as the p-zone of a p-i-n layer stack. A not intentionally doped 500nm thick $Ga_{0.79}In_{0.21}As_{0.19}Sb_{0.81}$ layer is utilized for the intrinsic absorbing region. The n-type region consists of 50nm $Ga_{0.79}In_{0.21}As_{0.19}Sb_{0.81}$ and 50nm $InAs_{0.91}Sb_{0.09}$. Both are doped to $1.0x10^{18}$ cm^{-3}. An $InAs_{0.91}Sb_{0.09}$ layer is chosen as n-contact because of its lower energy bandgap (0.35eV) and low contact resistance.

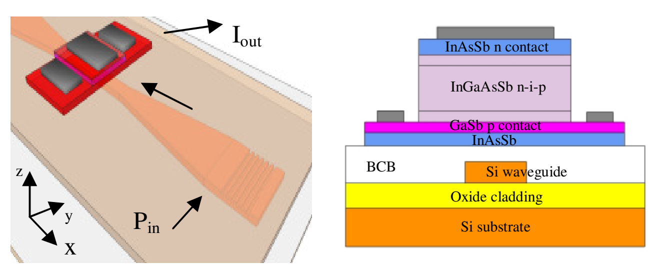

Figure 2: a) schematic of the evanescent coupling scheme b) cross section in y direction of the integrated detector

The use of a wide energy bandgap GaSb layer on the p-side is to prevent diffusion of minority carriers on the p-side. The cut-off wavelength of this epitaxial stack is estimated to be 2.5µm. Two light coupling designs are studied: evanescent and grating-assisted coupling.

1) Evanescent coupling

The structure is shown in figure 2a where the photodiode is bonded on top of an SOI waveguide. Light is coupled into the SOI circuit via a grating coupler and then from the SOI waveguide into the photodiode waveguide evanescently. This design is strongly sensitive to the thickness of the bonding layer. The detail simulation is presented in reference [5]. Figure 2b represents the cross-section schematic of this design.

2) Grating-assisted coupling

The design is presented in figure 3. In this design, the light in the SOI waveguide is diffracted by a grating structure defined on the SOI waveguide, after which it is coupled into the photodiode. In this design, the responsivity is limited by the directionality of the grating and the thickness of the intrinsic layer. The detailed simulation results can be found in reference [6].

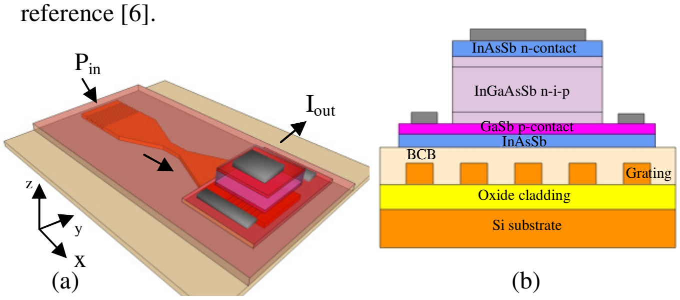

Figure 3: a) Schematic of grating-assisted design b) cross section in x direction

B. Laser

For the laser integration, a standard epitaxial design is selected for the first demonstration in order to evaluate the influence of the bonding process on the laser behavior. The epitaxial stack consists of 300 nm n-doped ($2x10^{18}$ cm^{-3}) GaSb as n-contact, $Al_{0.9}Ga_{0.1}As_{0.07}Sb_{0.93}$ as cladding layer with doping of $2x10^{18}$ cm^{-3} for both p and n type. $Al_{0.25}Ga_{0.75}As_{0.02}Sb_{0.98}$ is used for separate confinement layers and barriers. The stack contains 4 $Ga_{0.76}In_{0.24}As_{0.01}Sb_{0.99}$ quantum wells. 300 nm p-doped ($1x10^{19}$ cm^{3}) GaSb is used as a p-contact. A 100 nm composition grading layer between contact and cladding layer is applied on both p and n type side.

Figure 4 represents the refractive index profile of the quantum well as well as the fundamental laser mode profile. The confinement factor is calculated to be 4%.

III. Integration and Fabrication

The fabrication is divided into 3 parts: SOI circuit fabrication, integration of the epitaxy on SOI and processing of the photodiode and laser. The SOI circuit is processed at *imec* by 193nm deep UV lithography. The details of the SOI fabrication process is given in [7]. The integration of epitaxy on SOI is the same for both lasers and photodetectors, using a die-to-wafer bonding process using a benzocyclobutene (BCB) adhesive bonding layer.

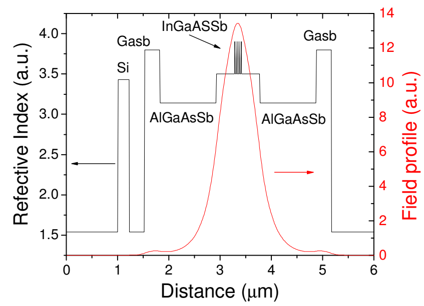

Figure 4: Refractive index profile of the laser epitaxy and laser mode profile

The process starts by cleaning both the epitaxial material and the silicon wafer with acetone and isopropyl alcohol. BCB diluted in mesitylene (2:3 v/v) in order to obtain approximately 250nm bonding thickness is then spin coated on the SOI wafer. The SOI sample is then baked at 150 ºC for 5 minutes to let mesitylene evaporate. The epitaxial die is then attached to the SOI wafer. The sample is then baked at 250 ºC for 1 hour. After bonding, the substrate is removed by mechanical grinding until the thickness of the III-V die is below 50 µm. Then the rest is removed by chemical etching with a mixture of chromic acid (CrO_3) and hydrofluoric acid (HF) (1:3v/v). Around the epitaxial die, side wall protection is applied by using Crystal Bond wax. The etch stop layer is removed using wet etching (citric acid and hydrogen peroxide 100:50 v/v) before n-contact deposition. The n-contact (Ti/Pt/Au 2nm/30nm/50nm) is then deposited on the sample using electron beam evaporation. For the photodiode, a mixture of citric acid:H_2O_2:H_3PO_4:H_2O (55:5:3:220 v/v) is used to etch the mesa. After mesa formation, the p-contact (Ti/Pt/Au 2nm/30nm/50nm) is deposited on the sample. BCB is subsequently applied as passivation material. Ti/Au (20nm/500nm) is then used as the final contact for the probing. The optical and scanning electron microscope image of the evanescent and grating-assisted photodetectors are presented in figure 5a and b respectively.

On the other hand, laser fabrication requires more lithography steps as well as slightly different chemistry. Firstly, Ti/Pt/Au (2nm/30nm/100nm) is deposited as a p-contact. The laser mesa is then formed by a mixture of HCl, H_2O_2 and H_2O (50:1:100 v/v), which etches high aluminum content layers. Sequentially, optical lithography is performed to protect the mesa etched so far. The etching then continues by using a mixture of citric acid:H_2O_2:H_3PO_4:H_2O (55:5:3:220 v/v) to etch SCH and QW layers and then again with the mixture of HCl , H_2O_2 and H_2O (50:1:100) to remove the rest of the epitaxial layer stack until the n-contact layer is reached. GeAuNi is deposited as the n-contact. A Ti/Au (30nm/500nm) layer is used as the final contact.

Fabry-Perot lasers are formed by cleaving. Figure 6 shows a SEM image of the integrated laser.

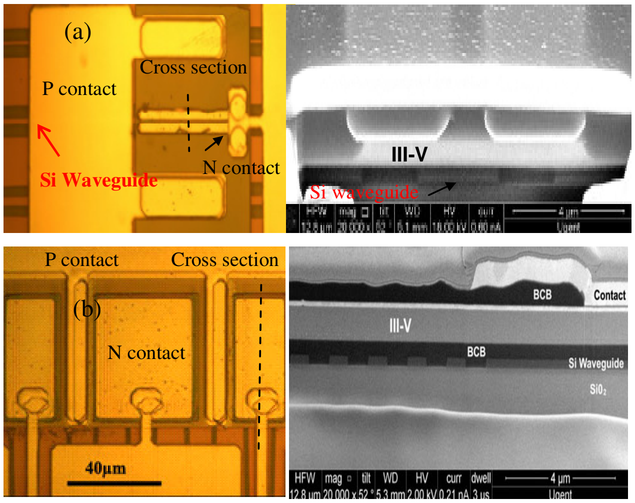

Figure 5: a) optical image (left) and SEM image (right) of evanescent coupling b) optical image (left) and SEM image (right) of grating-assisted coupling

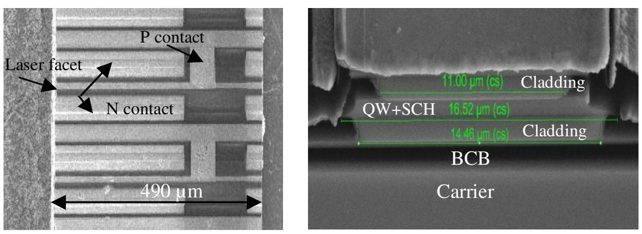

Figure 6: Image of the realized integrated laser a) top view SEM image b) SEM image of the cross section and the laser facet

IV. Measurement Results

A. Photodiode

The device is characterized by injecting light through the grating coupler under an angle of 10 degree, which is then coupled to the photodiode, either through evanescent coupling or grating-assisted coupling.

VI characteristics (at room temperature) for different waveguide-coupled optical input powers for grating-assisted coupling are presented in figure 7. The measurement is performed at room temperature without temperature controller. The dark current is as low as 5.5µA at 1V reverse bias. The responsivity for this device is approximately 0.4A/W at 2.2µm. This lower coupling efficiency is due to the epitaxial design which is not optimum for this case as well as the photodetector grating efficiency which is relatively low. An improved grating coupler design, coined a raised grating, can be used in order to improve the responsivity [8].

A responsivity >1A/W is obtained at 2.2µm for the evanescent coupling approach.

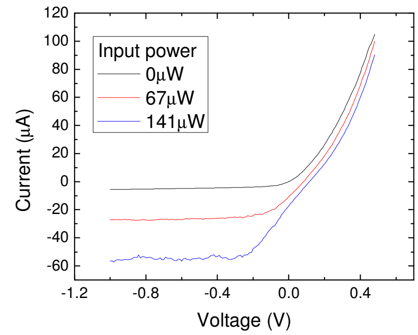

Figure 7: VI characteristic (at room temperature) for different waveguide coupled power level of the device with grating-assisted coupling design

B. Laser

The set up consists of a multimode fiber used to collect light from the fabricated Fabry-Perot lasers horizontally and coupled to a Yokogawa AQ6375 optical spectrum analyzer. The devices are biased using a Keithley 2400 as a continuous current source and a Lightwave LDP3811 as a pulsed current source. The laser is characterized at room temperature without temperature controller. The LIV characteristic of a device with a size of 15µmx490µm is presented in Figure 8. The result represents a low series resistance of 14 Ohm. A low threshold current of 31mA in pulsed regime and 49.7mA in continuous wave are obtained. These correspond to threshold current densities of 422 A/cm^2 in pulsed and 676 A/cm^2 in CW.

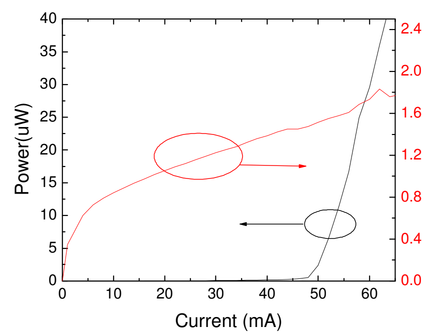

Figure 8: LIV characteristic of the laser with foot print of 15µmx490µm

The optical spectra at different bias current are presented in figure 9. The result shows that the peak wavelength shifts to longer wavelengths at higher bias current due to self-heating. CW operation to 35 ºC is obtained.

V. Conclusion

In conclusion, we have demonstrated the feasibility of integrating GaSb-based photodiodes and lasers on SOI waveguide circuits. These results accelerate significantly the development of fully integrated spectrometers.

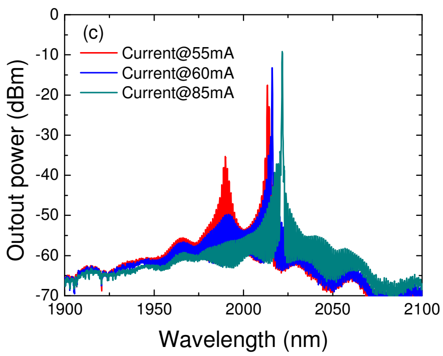

Figure 9: Spectra at different bias current

ACKNOWLEDGMENT

The author would like to thank S. Verstuyft for processing assistance and L. Van Landschoot for SEM images and M. Vanslembrouck for measurement software.

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