Invited Paper

Heterogeneous GaSb/SOI mid-infrared photonic integrated circuits for spectroscopic applications

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ABSTRACT

Mid-infrared spectroscopy has gained significant importance in recent years as a detection technique for substances that absorb in this spectral region. Traditionally, a spectroscopic system consists of bulky equipment which is difficult to handle and incurs high cost. An integrated spectroscopic system would eliminate these disadvantages. GaSb-based active opto-electronic devices allow realizing mid-infrared light sources and detectors in the 2-3µm wavelength range for such integrated systems. Silicon photonics, based on Silicon-on-Insulator (SOI) waveguide circuits, on the other hand, is a well established technology based on high refractive index contrast waveguides, enabling ultra-compact passive integrated photonic circuits. Moreover, SOI waveguide circuit processing is compatible with CMOS processes. Hence, the integration of GaSb-based active devices onto SOI passive waveguide circuits potentially allows highly compact spectroscopic systems with a large degree of freedom in passive device design to improve the system performance. This approach has a high potential for several applications, e.g. an implantable glucose level monitor and gas sensing devices.

In this paper, we report our work on the integration of GaSb-based epitaxy onto SOI waveguide circuits. The heterogeneous integration is based on an epitaxial layer transfer process using the polymer divinylsiloxane-benzocyclobutene (DVS-BCB) as a bonding agent. The process is performed by transferring the epitaxial layer to an SOI waveguide circuit wafer through a die-to-wafer bonding process. With this approach, a bonding layer of 150 nm thickness is easily achievable. We also report our results on the integration of waveguide-based GaSb p-i-n photodetectors coupled to SOI waveguide circuits using evanescent coupling, which show a responsivity higher than 0.4A/W. The design of active and passive structures and the overall fabrication process will also be discussed.

Keywords: Heterogeneous integration, GaSb p-i-n photodetector, SOI, Silicon-on-insulator, bonding, BCB

1. INTRODUCTION

Spectroscopy is the key technology for diagnostic and monitoring applications involving several substances, e.g. biological molecules and gases. The chemical composition and concentration of the substances can be determined by analyzing the transmission spectrum. The mid-infrared is an attractive wavelength region for analysis, since chemical compounds have strong absorption features in this wavelength region.

GaSb and its compounds are a suitable semiconductor material for active opto-electronic devices e.g. lasers and detector in the short-wave infrared because of its narrow direct energy band gap and its flexibility in band gap engineering. Significant improvements in epitaxial growth and the fabrication process have been demonstrated over the past few years. This resulted in high performance lasers with high output power and room temperature operation, which is suitable for many applications e.g. blood glucose level monitoring and gas sensing.[1-2] Also, several reports are available on GaSb-based photodetectors with low dark current and high responsivity.[3-4] Therefore, with optimum design of these lasers and photodetectors, compact and low power consumption spectroscopic devices can be envisioned.

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Quantum Sensing and Nanophotonic Devices VIII, edited by Manijeh Razeghi, Rengarajan Sudharsanan,
Gail J. Brown, Proc. of SPIE Vol. 7945, 79451K · © 2011 SPIE · CCC code: 0277-786X/11/$18 · doi: 10.1117/12.874659

Silicon-on-Insulator (SOI) wafers consist of a silicon substrate, an SiO_2 bottom cladding with the silicon wire waveguides on top. This layer stack gives rise to high omni-directional refractive index contrast which allows highly compact photonic integrated circuits. Furthermore, the fabrication process is also CMOS compatible, such that a cost effective solution is available in volume manufacturing. SOI is also highly transparent in the near and short-wave infrared region which makes it suitable for telecommunication and some spectroscopic applications.[5] A material loss < 2 $dBcm^{-1}$ in the wavelength range of 1.2-3.6 µm was estimated by ref. 6. Moreover, a different design of the silicon waveguide cross-section such as a suspended silicon rib waveguide allows for low loss in the mid infrared region (up to 8µm).[6]

Traditionally, a spectroscopic system has a large footprint for general substance analysis purposes. This is not suitable for particular applications which require a low-cost, portable and low power consumption system. By combining SOI and GaSb technology utilizing heterogeneous integration technology, the realization of integrated spectroscopic systems-on-chip is enabled. This technique avoids complication in epitaxial re-growth processes to realize active/passive photonic integrated circuits. Consequently, this technology also speeds up the development process of the devices. Several heterogeneous active devices based on InP/InGaAsP compound semiconductors (e.g. lasers, detectors, optical amplifiers) have been demonstrated using this technique, based on different integration technologies.[7-8]

In this paper, we demonstrate a novel device based on the heterogeneous integration of GaSb p-i-n photodiodes onto an SOI waveguide circuit. We describe the device design and the integration and fabrication process. Measurement results are also presented and discussed.

2. HETEROGENEOUS INTEGRATION

Direct bonding and adhesive bonding are the most used technologies for the integration of III-V semiconductors on top of SOI waveguide circuits.[9-10] In our work, we employ an adhesive bonding process using DVS-BCB as adhesive bonding agent. This technique does not require an ultra-clean surface unlike direct bonding, where the bond is formed based on van der Waals attraction between the two wafer surfaces. Moreover, DVS-BCB can accommodate some topography on both the III-V epitaxy and the SOI wafer and still maintain good adhesion. DVS-BCB also has a relatively low absorption in near and shortwave-infrared. Figure 1 illustrates the absorption spectrum of DVS-BCB in the 1 to 3 µm wavelength range. There are strong absorption peaks around 1.7 µm and 2.3 µm due to its C-H bonds. Nevertheless, this absorption is manageable with careful device design.

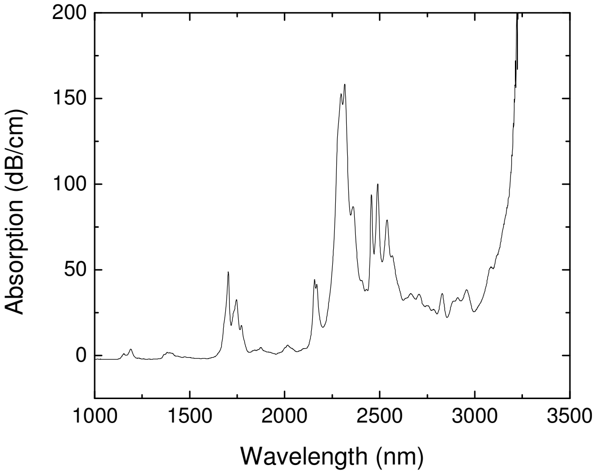
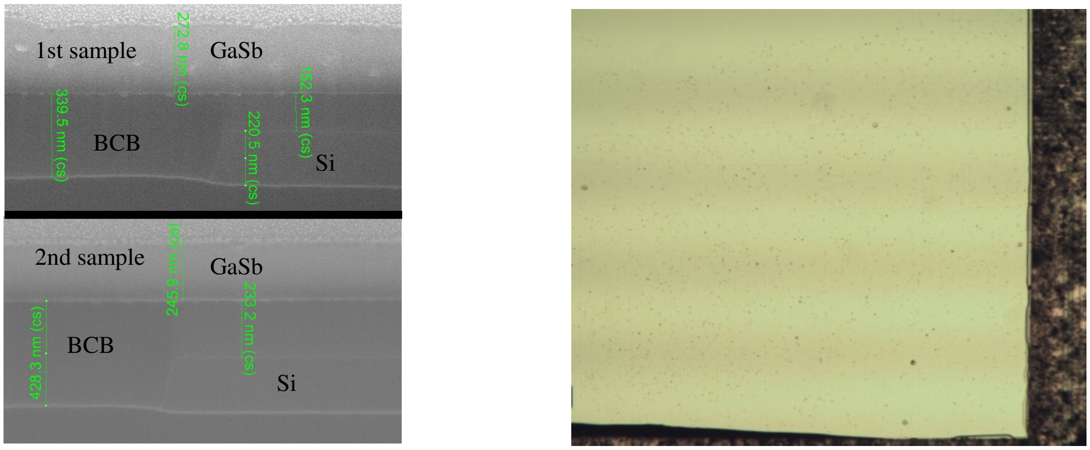


Figure 1 Absorption spectrum of DVS-BCB, measured using a photospectrometer setup

Before the integration process, the SOI and GaSb epitaxy are first prepared. The SOI waveguide wafer is fabricated in imec, Belgium. Epitaxial growth is done at Université Montpellier 2, France. The bonding process starts by cleaning both the SOI and GaSb epitaxy die. The GaSb epitaxy is cleaned with acetone and IPA. The SOI die is cleaned using a standard clean-1 solution ($NH_4OH:H_2O_2:H_2O$) in 1:1:5 v/v at 70 °C for 15 minutes. The DVS-BCB polymer (Cyclotene

3022-35) is diluted using mesitylene in 2:3 v/v to achieve a thin bonding layer. The DVS-BCB is then spin-coated at 3000rpm for 40 seconds on the SOI waveguide dies to approximately achieve a 200 nm thick bonding layer. The sample is baked on a hot plate at 150 °C for 3 minutes to remove mesitylene from the thin DVS-BCB layer. The GaSb die is then transferred onto the SOI substrate at the same temperature. The curing process is done at 250 °C for 1 hour to achieve more than 95% of polymerization. N_2 is used during the curing process to prevent oxidation of the DVS-BCB when the temperature increases.[11] After the bonding process, the GaSb substrate is removed using a combination of mechanical grinding and wet etching. The GaSb substrate is grinded mechanically, leaving approximate 50 µm. The rest of the substrate is then removed by selective wet etching using a mixture of CrO_3 and HF and water in 1:1:3 v/v at 25 °C. The etching rate is ~7µm/minute. An InAsSb layer is used as an etch stop layer, which can be selectively removed by wet etching using a 2:1 v/v citric acid and hydrogen peroxide solution. The etch rate is ~ 100nm/minute.[12] Figure 1a shows an SEM cross-section image of the GaSb layer bonded on an SOI waveguide. A III-V/SOI bonding layer of 150-200nm is easily achievable, which is sufficient for the optical coupling between the SOI waveguide circuit and GaSb-based opto-electronic components. Figure 2b represents the surface of the transferred GaSb epitaxy after the substrate removal process.



(a) (b)

Figure 2 (a) SEM images of 2 dummy samples (GaSb) for bonding tests (b) the image from an optical microscope of the transferred GaSb epitaxial layer after substrate removal.

3. DEVICE DESIGN

The device is designed to couple light evanescently from the SOI waveguide into the photodetector waveguide when phase matching occurs. This approach allows for a high responsivity using a thin absorbing layer, unlike the typical surface illuminated photodetectors. With such a design, besides a relaxed epitaxial growth process, high speed operation can be achieved. Figure 3 shows a schematic of the integrated device. It consists of an SOI waveguide and GaSb-based photodetector on top of the SOI waveguide circuit using BCB as an adhesive layer.

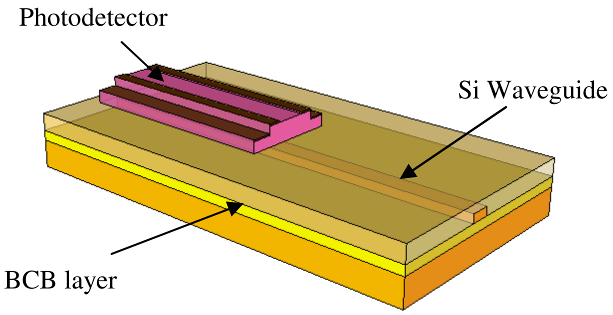


Figure 3 Schematic of the device

The power absorbed in the photodetector depends the intrinsic region thickness of the photodiode as depicted in figure 4. The bonding layer thickness also has a large impact on the light collection efficiency. CAMFR, which is based on a frequency-domain eigenmode expansion technique, is used for this simulation.[13]

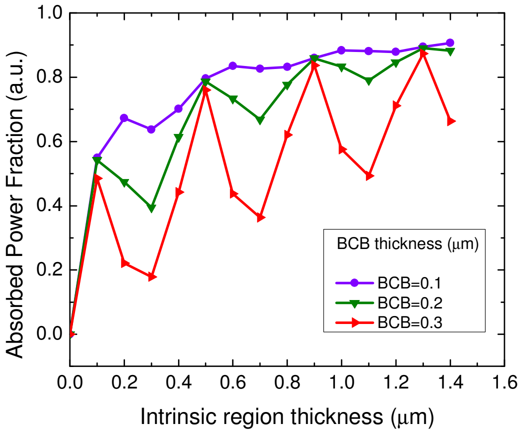
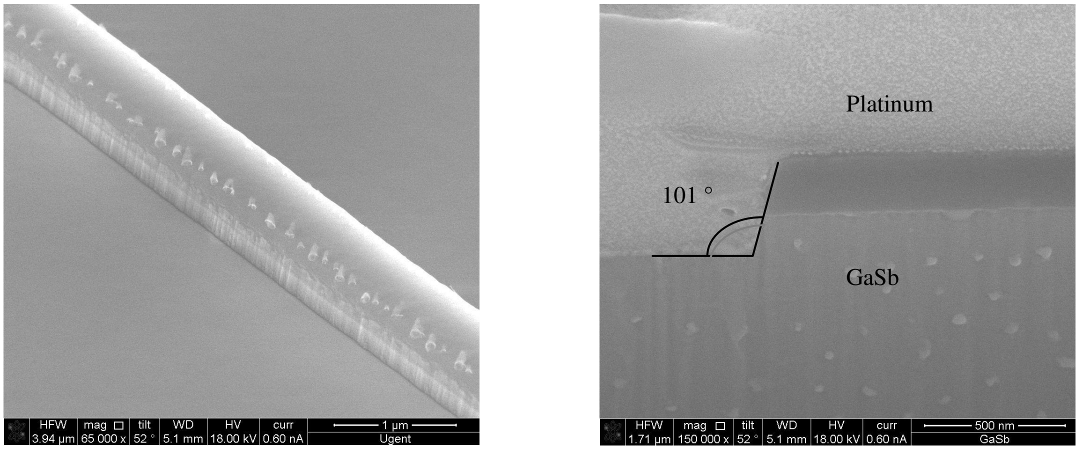


Figure 4 Simulation results of the device, showing that the absorbed power depends on intrinsic region thickness and BCB thickness

4. FABRICATION TECHNIQUE

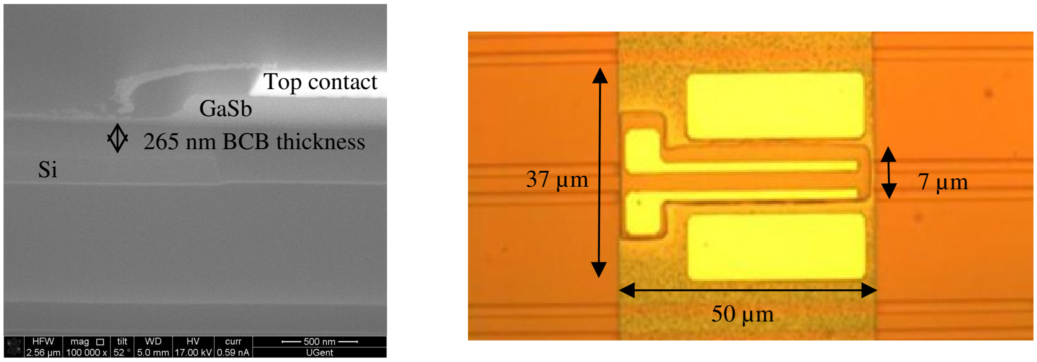
After the bonding process which leaves the epitaxy attached upside down to the silicon waveguide circuit, NiAuGe is deposited on the n–doped GaSb layer to form an n-contact. The photodiode mesa is then formed using inductively coupled plasma reactive ion etching (ICP-RIE) using a CH_4 and H_2 gas mixture. The etch rate is ~3.6 nm/minute. Figure 5 shows etching results of a dummy sample (GaSb substrate) with Ti as a hard mask. The sidewall roughness is relatively high as seen in figure 5a. The etching profile is also shown in figure 5b. The slope is estimated to be 101 degrees. After mesa formation, Ti/Au is deposited onto p-doped GaSb as p-contact (side contacts). The photodiode island is then defined by using wet etching in a solution of $C_4H_4KNaO_6$:H_2O:HCL:H_2O_2 in a ratio of 5g: 70ml: 60ml:5ml. The etch rate is estimated to be 0.5µm/minute.[12] DVS-BCB is used for device passivation. In this prototype device, the absorbing region also consists of GaSb. In future device generations InGaAsSb absorbing regions will be used to extend the wavelength range of the photodetector operation.



(a) (b)

Figure 5 SEM images of a dummy sample (GaSb substrate) for ICP etching tests (a) illustrating side wall roughness (b) showing etching profile

Figure 6a shows a cross section image of the realized device where the p-i-n GaSb photodetector is bonded on top of Si waveguides. The etching profile is found to be similar to that of the dummy sample (Figure 5b). The bonding thickness of the device is estimated to be 265 nm. Top view image of the device from an optical microscope is shown in figure 6b. The total foot print of the device is ~37×50µm^2.



(a) (b)

Figure 6 Images of the realized devices: (a) SEM cross section image (b) top view image from optical microscope

5. MEASUREMENT RESULTS

The photoresponse of the device is measured by coupling light into the SOI waveguide structure using a diffractive grating coupler structure. A reference waveguide is used to normalize the photoresponse to the optical power propagating in the waveguide. The measurement is done at 1.57 µm wavelength (due to availability of source) at room temperature. The V-I characteristic of the device is shown in figure 7, for various optical power levels (power levels indicated on the graph are not taking the large fiber-chip coupling loss into account). The high leakage current is likely caused by ICP etching which gives significant damages on the mesa sidewall. Nevertheless, the device illustrates good photoresponse (~0.4A/W) as a function of applied voltage. Further technology optimization will focus on realizing low dark current devices to improve the sensitivity of the photodetector.

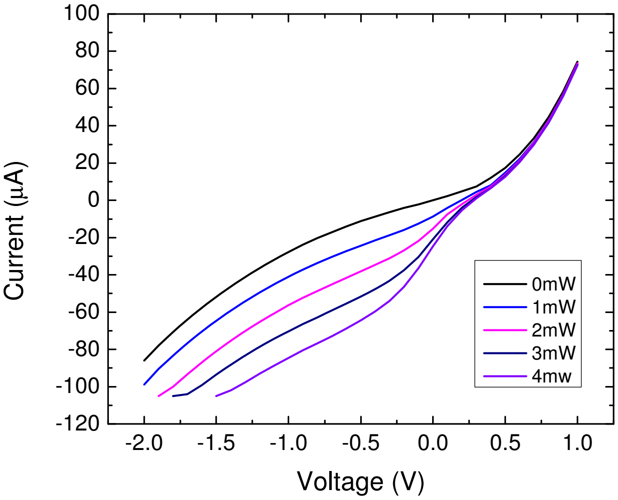


Figure 7 V-I characteristic of the device at different input power levels. The power level indicates output power from tunable laser.

6. CONCLUSION

In conclusion, we demonstrate the first generation of integrated GaSb p-i-n photodetectors on SOI waveguide circuits. Good responsivity of the device (~0.4A/W) is illustrated. The responsivity can be improved by reducing the thickness of bonding layer. A better passivation is required to reduce the dark current of the device. A new design of the epitaxial layer stack would yield significant improvement of this device, which is under way. The successful demonstration of this device is a significant step towards a mid-infrared integrated spectroscopic system.

REFERENCES

[1] Arafin, S., Bachmann, A., Kashani-Shirazi, K., Amann, M. C., "Electrically pumped continuous-wave vertical-cavity surface-emitting laser at ~2.6µm," App. Phys. Lett. 95, 131120 (2009)

[2] Lei, W. and Jagadish, C., "Lasers and photodetectors for mid-infrared 2-3 µm applications," J. Appl. Phys. 104, 091101 (2008)

[3] Shao, H., Torfi, A., Moscicka, D., Wang, W. I., "High detectivity AlGaAsSb/InGaAsSb photodetectors grown by molecular beam epitaxy with cutoff wavelength up to 2.6 µm," J. Crystal Growth 311, 1893-1896 (2009)

[4] Prineas, J. P., Reddy, M., Olesberg, J. T., Cao, C., Veerasamy, S., Fatte, M. E., Koerperick, E., Boggess, T. F., Santilli, M. R., Olafsen, L. J., "Quaternary GaInAsSb 2-2.5 Micron Back-Illuminatined Focal Plane Array for Blood Glucose Monitoring," Proc. SPIE 5276, 113- 121 (2005)

[5] Soref, R., "Mid-infrared photonics in silicon and germanium," Nat. Photonics 4, 495-497 (2010)

[6] Soref, R. A., Emelett, S. J., Buchwald, W. R., "Silicon waveguided components for the long-wave infrared region," J. Opt. A: Pure Appl. Opt. 8, 840-848 (2006)

[7] Fang, A. W., Park, H., Cohen, O., Jones, R., Paniccia, M. J., Bowers, J. E., "Electrically pumped hybrid AlGaInAs-silicon evanescent laser," Opt. Exp. 14(20), 9203 -9210 (2006).

[8] Brouckaert, J., Roelkens, G., Van Thourhout, D., Baets, R., "Compact InAlAs/InGaAs Metal-Semiconductor-Metal Photodetectors Integrated on Silicon-on-Insulator Waveguides," IEEE Photon. Technol. Lett. 19(19), 1484-1486 (2007)

[9] Roelkens, G., Liu, L., Liang, D., Jones, R., Fang, A., Koch, B., Bowers, J. E., "III-V/silicon photonics for optical interconnects," Laser & Photonics Rev. 4(6), 751-779 (2010)

[10] Liang, D., Fang, A. W., Park, H., Reynolds, T. E., Warner, K., Oakley, D. O., Bowers, J. E., "Low-Temperature, Strong SiO_2-SiO_2 Covalent for III-V Compound Semiconductors-to-Silicon Integrated Circuits," J. Electron. Mater. 37(10), 1552-1559 (2008)

[11] http://www.dow.com/

[12] Dier, O., Lin, C., Grau, M., Amann, M-C., "Selective and non-selective wet-chemical etchants for GaSb-based materials," Semicond. Sci. Technol. 19, 1250–1253 (2004)

[13] http://camfr.sourceforge.net