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Comparison of InP- and GaSb-based VCSELs emitting at 2.3 μm suitable for carbon monoxide detection

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ABSTRACT

Carbon monoxide (CO) is a prominent and toxic gas mainly generated by imperfect burning in fires or ovens. For trace gas monitoring and fire detection a compact, long term stable and calibration-free CO sensor is desirable. One very interesting measuring method is Tuneable Diode Laser Absorption Spectroscopy (TDLAS), which utilizes the unique properties of Vertical-Cavity Surface-Emitting Lasers (VCSELs). Two approaches to reach the required wavelength range for the absorption lines of CO at around 2350 nm are discussed in this paper. The first approach is an expansion of the emission wavelength range of the now well-established lasers based on InP and a second and new one is fabricating VCSELs based on GaSb. From the epitaxial point of view the gain of the active material and the realization of a tunnel junction as well as optical, thermal and electrical characteristics of the mirror materials are important issues. For a proper choice of the device design the structuring of the used materials also plays a fundamental role— in particular the substrate removal. With simultaneous considerations of all these crucial issues, devices on InP and GaSb substrates have been fabricated. Both types work in continuous-wave mode, generating light in single-mode emission at the desired wavelength of the CO absorption line, which enables CO measurements down to a concentration limit of 2 ppm.

1. Introduction

Because of the 300 times higher chemical affinity of carbon monoxide to hemoglobin compared with oxygen, CO is classified as a highly toxic gas [1]. It can be generated by that of partial oxidation of carbon containing compounds like that in smoldering fires or in combustion. Tuneable Diode Laser Absorption Spectroscopy (TDLAS) [2] is a well-known measuring method, which provides advantages of quick and sensitive measurements as well as auto-calibration and long-term stability and is therefore suitable for gas-sensing applications where high reliability is requested [3]. The requirements on an appropriate light source are continuous-wave and single-mode operation at room temperature. VCSELs, compared with distributed feedback lasers, are the better choice for all relevant performance data, except output power. Especially low power consumption and a larger wavelength tuning range as well as lower manufacturing costs are the most prominent advantages.

The wavelength range around 2.35 μm, is very interesting for CO gas detection because absorbance and selectivity of CO absorption lines are highest at wavelengths in the near infrared [4]. In general two light generating materials are possible for reaching 2.35 μm; GaInAs, highly strained on InP, and GaInAsSb on GaSb. The first approach to achieve this wavelength has been the modification of the well-known devices on InP, creating a reference for the recently fabricated devices based on GaSb. A comparison of the epitaxy and fabrication related challenges of both types, as well as the device results and corresponding CO measurements, is presented in this work.

2. Epitaxy

The epitaxial structures are realised in a cluster of two Veeco Gen II systems. In addition to the standard configuration of the arsenic-based material system (Gallium, Indium, Aluminium, Silicon) one machine is equipped with a Riber KPC 250 phosphorous cracker and a CBr_4-system and the other one is equipped with a Veeco antimony cracker and a Tellurium source.

Since many years VCSELs with emission wavelengths ranging from 1.3 to 2.0 μm, based on InP substrates, have been fabricated

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using a mature technology by VERTILAS. To expand this wavelength range to the desired new wavelength at 2.3 μm, most of the integral parts of the device like the mirrors and the tunnel junction, have to be adjusted. But as for the active region, highly strained GaInAs, a new development is necessary, because with the standard rectangular quantum wells of 8 nm widths the strain exceeds the critical limit already beyond an emission wavelength of 2.05 μm. By implementing triangular shaped wells and significant strain compensation in the barriers this problem could be overcome [5]. These 13 nm thick wells are realized with a linear gradient in Indium content between lattice matched GaInAs and pure InAs using a digital alloy. In the shown device the active region is grown at around 430 °C and exhibits a reasonable photoluminescence at 2.3 μm (FWHM at 4.2 K: 10 meV).

On the other hand the active region on GaSb can be realized without any strain-related restrictions at an emission wavelength of 2.3 μm with the quaternary compound GaInAsSb (FWHM at 4.2 K: 5 meV), providing a much better optical quality compared to that of the InP-based material and offering the potential for further expansion of the wavelength range (Fig. 1). More challenging in this newer material system is the handling of mixed group-V materials. In particular, the uncertainty of the available material data, only weak selectivities in wet chemical etching processes and strong dependencies of material parameters on growth conditions are generate a lot of difficulties. The thermal instability, especially of the quantum well material GaInAsSb leads to blue-shift of the emission wavelength during post-growth thermal treatment like that seen in the overgrowth of the structured tunnel junction with GaSb, which reduces the accuracy of meeting the right emission wavelength of the device. To reduce this influence of the miscibility gap the active region consists of five 11 nm thick compressively strained $Ga_{0.63}In_{0.37}As_{0.11}Sb_{0.89}$ QWs grown at around 480 °C, separated by $Al_{0.33}Ga_{0.67}As_{0.03}Sb_{0.97}$ barriers.

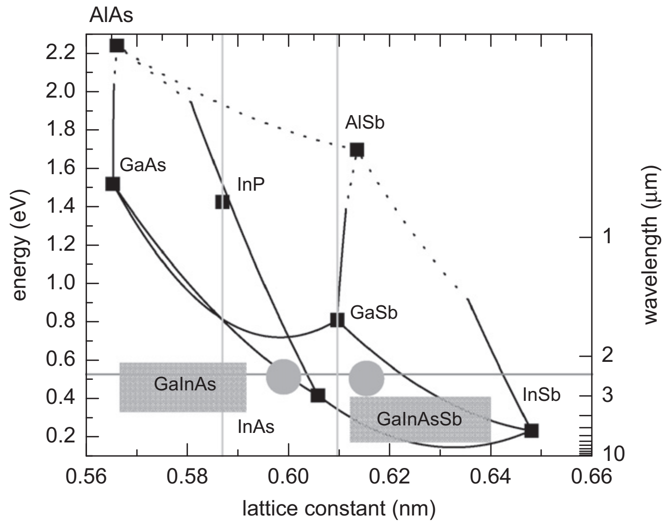

Fig. 1. Landscape of semiconductor: Energy versus band gap. The possible material choice to reach the desired wavelengths of 2.35 μm is GaInAs on InP and GaInAsSb on GaSb.

Another important component of the epitaxial structure is the Distributed Bragg Reflector (DBR). For the subsequent device processing the optical, thermal and electrical behaviour of the DBR is of great significance. The 12 μm thick, lattice-matched AlInAs/GaInAs DBR on InP has a relatively small index contrast ($\Delta n = 0.32$), which results in a thick layer stack that maintains reflectively and additionally in a very small heat conductance [6]. The significant higher index contrast on GaSb ($\Delta n = 0.65$), using a 7 μm thick, lattice-matched AlAsSb/GaSb DBR has a four times higher heat conductance and allows therefore more design freedom for the devices compared with InP ones [7]. Otherwise, the electrical behaviour of the DBR is better on InP, the lower conduction band offset and the lower effective masses compared with the materials on GaSb mainly reduces the electrical resistance.

Beside the active region and DBR, the third key-element of the VCSEL is the tunnel-junction. It can be realized in both material systems with the same excellent value of the specific resistance of $2 \times 10^{-6}\,\Omega\,cm^{-2}$. On InP the standard low band gap material GaInAs with extremely high carbon and silicon doping (each $1.5 \times 10^{20}\,cm^{-3}$) is used. For the GaSb-based material system the broken gap aligned materials, GaSb and InAsSb, both doped with silicon (each $1 \times 10^{19}\,cm^{-3}$) realize the tunnel junction. Thereby, the amphoteric character of silicon provides *p*-doping in GaSb and *n*-doping in InAsSb.

3. Fabrication

After the base structure (mirror, active zone and tunnel junction) is grown, the tunnel junction is structured and overgrown in a second epitaxial step with InP and GaSb, respectively (Fig. 2). This buried tunnel junction (BTJ) works as a current restriction and a *p*- to *n*-type carrier conversion to reduce ohmic and optical losses. The cavity is completed by a dielectric mirror (CaF_2/ZnS on InP, amorphous silicon/SiO_2 on GaSb). On GaSb this dielectric mirror is used as top mirror from which light is coupled out. This means an upside-up design is used and therefore the very difficult removal of the GaSb substrate is not necessary. This results in a considerably easier fabrication procedure than on InP, where the high thermal resistance of the epitaxial mirror allows only an upside-down design.

4. Results of the devices

Exhibiting different material properties and fabrication procedures, both devices operate at room temperature in continuous-wave mode with single-mode emission up to 90 °C (GaSb) and 50 °C (InP). In case of devices with a BTJ-diameter of 6 μm,

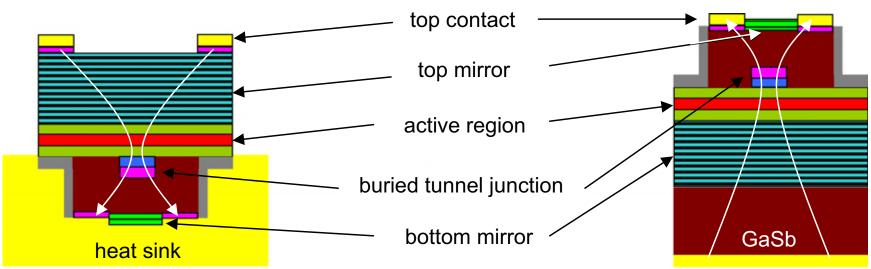

Fig. 2. left: Upside-down InP-based VCSEL and right: Upside-up GaSb-based VCSEL. The white arrows indicate the current flow. Light is emitted via the top mirror.

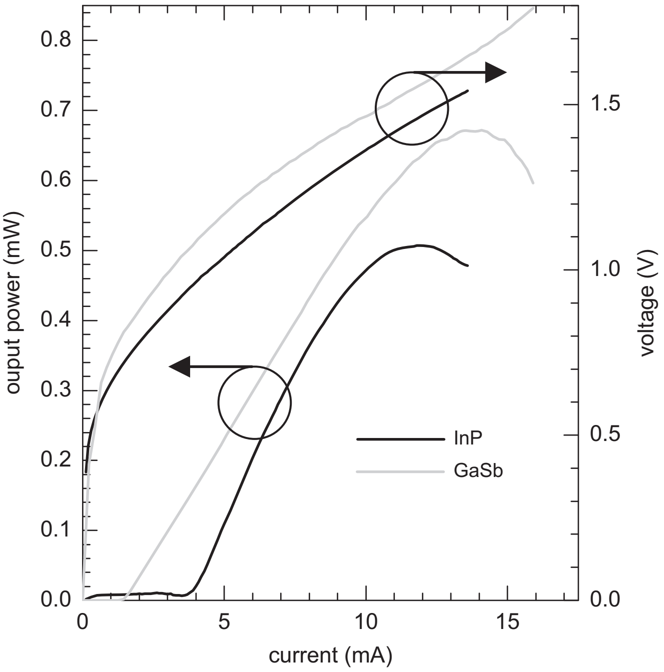

Fig. 3. *P–I* and *U–I* characteristics of InP-based (black) and GaSb-based (grey) VCSELs with 6 μm BTJ-diameter working at 20 °C in cw-operation.

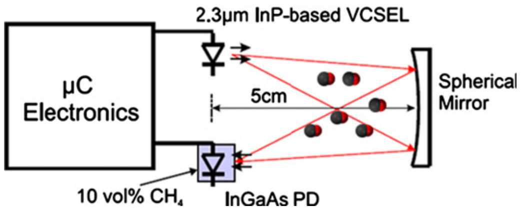

Fig. 4. Measuring set-up: Tuneable Light source, GaInAs photodetector and free optical path (10 cm). The photo detector is filled with 10%, methane enables an auto-calibration of the set-up.

maximum output powers of 0.67 mW (GaSb at 1.66 V and 13.5 mA) and 0.51 mW (InP at 1.45 V and 11.8 mA) have been measured at 20 °C (Fig. 3). The higher optical gain of GaSb based devices results in a significantly lower threshold current (GaSb: 1.5 mA; InP: 3.8 mA), higher output power and higher operating temperature (GaSb: 90 °C; InP: 50 °C). However, the lower electrical conductivity of the epitaxial mirror leads to higher voltages compared with devices on InP. The electro-thermal tuning of the emission wavelength of both device types is around 1 nm/mA, resulting in a tuning range of about 8 nm.

The thermal dependency of the emission wavelength on the heat sink temperature is important to have a possibility to adjust the wavelength range for the gas detecting experiment. For GaSb-based devices the wavelength can be changed by 0.24 nm/K. The value for InP-based devices is measured to be 0.17 nm/K, which gives an indication that heat management on InP is better than heat removal via DBR and substrate on GaSb.

5. Absorption measurements

For the CO measurements, a VCSEL and a GaInAs photodiode are used in a set-up with a free optical path length of 10 cm (Fig. 4). A wavelength range from 2364 to 2367 nm is chosen because in this range methane (CH_4) absorption lines are present. With 10% methane concentration inside the detector housing,

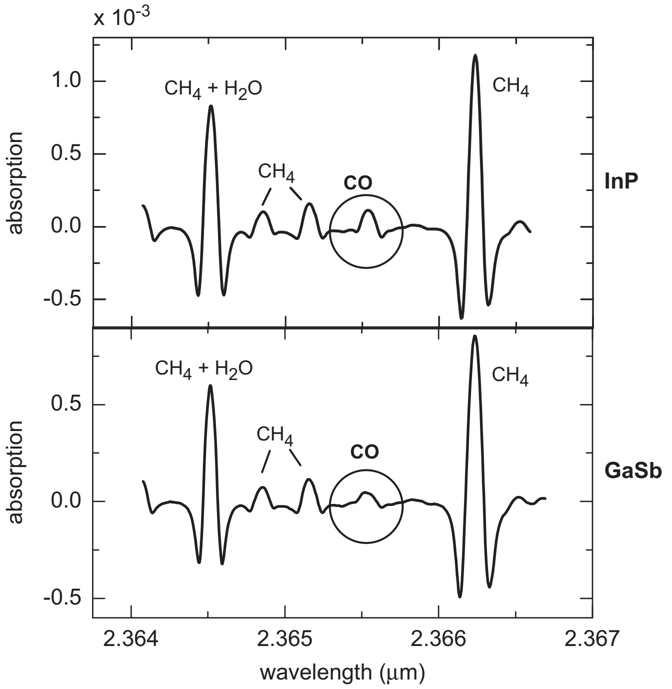

Fig. 5. Second-harmonic spectra of a wavelength scan of an InP-based VCSEL (upper graph, heat sink temperature: 33 °C, current: 8.5–11 mA) and a GaSb-based VCSEL (lower graph, 82 °C, 4.8–8 mA).

auto-calibration of the wavelength can be realized. As mentioned above the heat sink temperatures of both lasers were adjusted to reach the desired wavelength range. As for the GaSb-based VCSEL a heat sink temperature of 82 °C was necessary, which is an extreme circumstance (maximum output power ~100 μW; threshold current: 3.6 mA) for this device and on that emphasizes its excellent properties. This situation illustrates the difficulties in the production of VCSEL structures for a specific wavelength, as this requires both detailed knowledge of material information, such as refractive indices and layer thicknesses, as well as high reproducibility of the MBE system. The former is not the case for antimony containing compounds. Wavelength variations of the device, of more than 12 nm (corresponding to deviations of 0.5%), cannot be compensated for via the temperature of the heat sink.

The emission wavelength of the InP-based device fits already very well to the desired wavelength range; therefore the heat sink temperature for measurement was close to room temperature (33 °C). The wavelength scan is then performed by changing the laser current, for InP-based devices from 8.5 to 11 mA and for GaSb-based ones from 4.8 to 8 mA. For better analysis of the photo diode signal, current is modulated at 10 kHz to calculate after a Fourier transformation the second-harmonic spectrum [8,9] (Fig. 5). A carbon monoxide gas detection experiment at 2.3655 μm down to a concentration limit of 2 ppm at a measuring frequency of 1 Hz is demonstrated with InP-based as well as with GaSb-based VCSELs [10].

6. Conclusions

With both technologies, the proven InP-based BTJ-VCSELs as well as the new devices based on GaSb, excellent devices can be fabricated, are suitable for the particularly important gas sensing applications measuring CO at 2.3 μm. This emission wavelength was achieved with triangular shaped GaInAs quantum wells on InP, as well as with GaInAsSb QWs on GaSb. Gas sensing experiment with both devices at 2.3655 μm revealed a concentration limit for carbon oxide of 2 ppm, emphasizing the capability for commercial applications. The reliably performing devices on InP are serving as a reference for the devices on GaSb, with which the achievable wavelength range is expected to be extendable up to 3 μm in the future.

Acknowledgement

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