

# High Spectral Purity High-Power GaSb-based DFB Laser Fabricated by Nanoimprint Lithography

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**Abstract**— The Development of single-mode distributed feedback lasers emitting high output powers in a broad wavelength range from 1980 nm to 2035 nm is reported. A unique feature of the development is the fabrication of lateral feedback gratings by nanoimprint lithography. We have varied a wide range of design parameters and studied their effect on the performance of the laser. The best uncoated devices exhibited a side-mode suppression ratio as high as >50 dB at output powers in excess of 14 mW. Moreover, a tuning range of over 12 nm was measured. After coating the facets with dielectric mirrors, the laser diodes could deliver an output power of more than 30 mW. In this paper we prove the suitability of Nanoimprint lithography to the fabrication of GaSb-DFB laser diodes by demonstrating state-of-the-art devices made using imprint lithography.

**Index Terms**— diode lasers, distributed feedback laser, gallium antimonide, molecular beam epitaxy

## I. INTRODUCTION

GaSb-based lasers diode (LD) operating in single mode at mid-infrared wavelength range (2–4  $\mu\text{m}$ ) are attractive light sources for a large variety of applications, such as trace gas measurement and greenhouse gas monitoring owing to in this wavelength range [1]. Emission in single longitudinal mode and wavelength tunability, are essential features for spectroscopic applications. These can be achieved by introducing a distributed feedback (DFB) grating in the cavity of a diode laser. DFB lasers operating at 2.05  $\mu\text{m}$  emission wavelength are suitable candidates for detection of CO<sub>2</sub> and linewidth as low as 100kHz [1b] has been reported for high power 2  $\mu\text{m}$  DFB LD although typical linewidth is in the range of some MHz. In conventional DFB-lasers the buried grating is patterned directly onto waveguide prior to epitaxial regrowth of claddings. However, typically GaSb-based lasers have a high content of aluminum in the waveguides, which easily forms a natural oxide in contact with air, making the buried grating technically challenging to fabricate, although recent demonstrations also present regrowth based LDs with high performance [1c]. Moreover, even for more established DFB laser technology using InP materials, the regrowth procedure adds significantly to the complexity of the process.

An alternative method for realizing a DFB-laser is to use surface gratings [2]. One possible implementation makes use of laterally-coupled (LC) metallic surface gratings, which

have been successfully used for several groups to realize GaSb DFB (LC-DFB) [3-8, 8b]. In this approach, the metallic grating is typically patterned with electron-beam lithography (EBL), which has its limitations in cost-effective large-scale production due to its low wafer throughput and high cost of the instrument. In addition, the metallic grating generates absorption loss reducing the output power [9].

Alternatively, the mode selection can be obtained by etching the grating on a side of the ridge waveguide [10, 11] forming the laser cavity. However, in this case the coupling efficiency to an optical waveguide mode is limited if resolution of the patterning method is limited since high order gratings need to be employed [12]. In turn, this limits the operation range for single-mode and indeed the side-mode suppression ratio.

We have developed a LC-DFB process based on patterning the waveguides and gratings using cost-effective nanoimprint lithography (NIL). Our approach does not require epitaxial regrowth. Patterns are replicated from EBL-based templates using soft and flexible stamp replicated from template [13]. Stamp can conform to the shape of the GaSb substrate allowing large area imprint. With our stamp technology we have demonstrated, with good pattern fidelity imprinting over 3" wafers [14], typical or larger size used in GaSb LD manufacturing. In this process the need for using expensive EBL systems is reduced to minimum; a stamp can be utilized for hundreds of times and the stamping can be made on a full scale-wafer. The used method allows similar design freedom and resolution what is obtainable with EBL but allows high productivity and low cost that has been traditionally only obtainable with resolution limited optical lithography.

We have previously utilized this technology to demonstrate GaSb-based DFBs operating at 1.95  $\mu\text{m}$  [15]. In this paper, we report significant advances concerning low current density threshold for lasing, high output power, broad tunability and excellent side-mode suppression ratio. These achievements prove that UV-NIL lithography is a viable method to produce high precision gratings leading to state-of-the-art GaSb DFB-LDs.

## II. DEVICE PROCESSING

The process steps and design variations of the laser chips are the following.

### *Epitaxy*

The gain structure was grown using molecular beam epitaxy. We developed a lattice-matched heterostructure comprising the following layers: n-type GaSb substrate, GaSb buffer (300 nm), n-doped Al<sub>0.5</sub>GaAsSb<sub>0.93</sub> cladding (1500 nm),

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$\text{Al}_{0.2}\text{GaAsSb}_{0.97}$  waveguide layer (130 nm), two compressively-strained InGaSb quantum wells (10 nm),  $\text{Al}_{0.2}\text{GaAsSb}_{0.97}$  waveguide layer (130 nm), p-doped cladding layer (1500 nm), and a highly p-doped GaSb contact layer (200 nm). A  $\text{SiO}_2$  layer with a thickness of 200 nm was deposited on the GaSb top contact using plasma-enhanced chemical vapor deposition (PECVD).

### Processing

We used a soft NIL technology and cured the resist in an EVG620 mask aligner (EV-Group, Austria). The NIL-stamp consisted of a thin layer of patterned hard-PDMS on thin glass to provide rigidity. This combination was mounted on a thick PDMS cushion [13]. Our nanoimprint process uses a lift-off structure with two resist layers. The first layer is polydimethylglutarimide (PMGI) that is used as the sacrificial layer. The second layer is UV-curable resist deposited on top of the PMGI and soft-baked. A PDMS stamp prepared from a silicon master template was pressed on the NIL-resist and cured by UV. Following the exposure, the residual resist layer in the bottom of the pattern was etched with oxygen plasma using reactive ion etching (RIE). Subsequently, the PMGI resist was developed to obtain an undercut for the lift-off. A 10 nm thick Ni layer was deposited by electron-beam evaporation on top of the patterned wafer as an etch mask. Finally, the lift-off was completed by dissolving the remaining resist. The grating pattern to the semiconductor layers was done by dry etching. First, the  $\text{SiO}_2$  layer was etched in RIE utilizing the Ni etch mask. The semiconductor layers were patterned with inductively coupled plasma (ICP) using an Oxford Plasmalab 100+ ICP180 system. Temperature of the sample carrier used in ICP was controlled to 20 °C and flow rate of etching gasses was 19.8 sccm and 4.0 sccm for  $\text{Cl}_2$  and  $\text{N}_2$ , respectively. The ICP source power was 400W and RF field power source was set to 80 W. Etching was done under a pressure of 3 mTorr.

After the removal of the remaining  $\text{SiO}_2$  mask layer, we used typical process steps involved in processing of edge-emitting ridge-waveguide lasers. Thus a silicon nitride insulation layer with a thickness of 450 nm was deposited by PECVD. The insulating layer was opened from the top of the ridge waveguide using conventional UV lithography and RIE. A Ti/Pt/Au p-metal layer was deposited by electron-beam evaporation.

The etch depth in the ICP step plays a significant role in the operation of the devices. Sufficiently deep etching is required to reach suitable coupling between the DFB grating and the optical mode. At the same time, over etching should be avoided, since it increases cavity losses. The un-etched cladding thickness, determined with an electron microscope inspection, was 200 nm.

The 500  $\mu\text{m}$  thick GaSb wafer was thinned to 140  $\mu\text{m}$  and polished prior to Ni/Au/Ge/Au n-contact deposition. Finally the n-contact was annealed at 300 °C and the sample was cleaved. For measurement purposes, the chips were mounted p-side up on submounts.

### Design variations

Multiple imprint patterns were prepared to study the design variations on the laser characteristics. The structure of the

laser and the parameters varied during the study are shown in Fig. 1. The grating extension length,  $l$ , period of the third order grating,  $L$ , ridge width,  $W$ , and lengths of the laser chips,  $L_c$ , were varied. Different periods were tested and results included in this paper were from LDs with period of 855nm. We prepared lasers with both uncoated facets and dielectric mirrors on the facets to increase the output power.

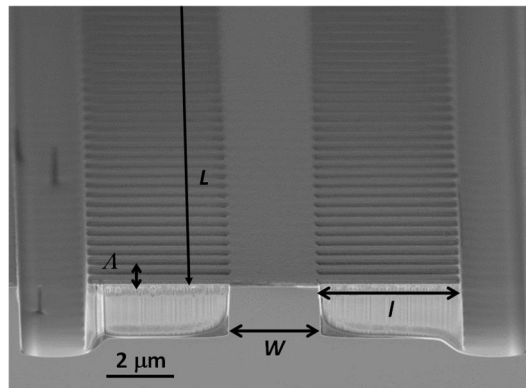


Fig. 1. SEM picture of the feedback grating and the design variables.

### III. CHARACTERIZATION

The optical output power was measured with a calibrated integrating sphere. Temperature of the chips was maintained and controlled with a thermo-electric cooling element. Optical spectrum was measured with a Yokogawa AQ6375 optical spectrum analyzer using a multimode graded index fiber.

#### Effect of the chip length and lateral grating extension

Devices with  $L_c=600 \mu\text{m}$  and  $L_c=1000 \mu\text{m}$  cavities without coated facets were compared. For 600  $\mu\text{m}$  cavity length the maximum output was 9 mW per facet, while the 1000  $\mu\text{m}$  long component reached 12.5 mW. Emission for both remained single-mode for all currents at room temperature.

The 1000  $\mu\text{m}$  device was further measured to determine its tunability with temperature and injection current. The laser was tunable over a 12 nm wavelength range from 2024 nm (100 mA) to 2036 nm (600 mA), not shown here. At 10 mW output power the SMSR was 50 dB.

The effect of the extension length,  $l$ , of the lateral grating was studied for  $l=1.5 \mu\text{m}$  and  $l=5.0 \mu\text{m}$ . Large  $l$  facilitates current leakage but at the same time it helps to achieve sharp etching profile near the area where the fundamental transverse mode is confined that supports high coupling between grating and fundamental transverse mode. Altogether the experiment shows that effect of this parameter was small. In terms of the threshold current,  $l=1.5 \mu\text{m}$  had  $I_{th}=68 \text{ mA}$  and  $l=5 \mu\text{m}$  had  $I_{th}=56 \text{ mA}$ .

#### Effect of the ridge width

The effect of central ridge width was studied by comparing devices with  $W=1.5, 2.5$  and  $3.5 \mu\text{m}$ . A typical IL-curve for this variations corresponding to  $L_c=600 \mu\text{m}$  is presented in Fig. 2. The worst laser performance was found for 1.5  $\mu\text{m}$  ridge width. The threshold current was the highest and the maximum output power only 4 mW. The highest threshold along with the worst slope efficiency can be only explained by

the high optical losses associated to interaction of the highly laterally confined mode with semiconductor – insulator surface. Increasing the ridge width to 2.5  $\mu\text{m}$  more than doubled the output power to 10 mW. Further increase of the ridge width to 3.5  $\mu\text{m}$  resulted in output power of 13 mW. However, the broadest ridge width resulted in multimode behavior observed from the spectrum (not shown) as well as clear kinks in the IL-curve.

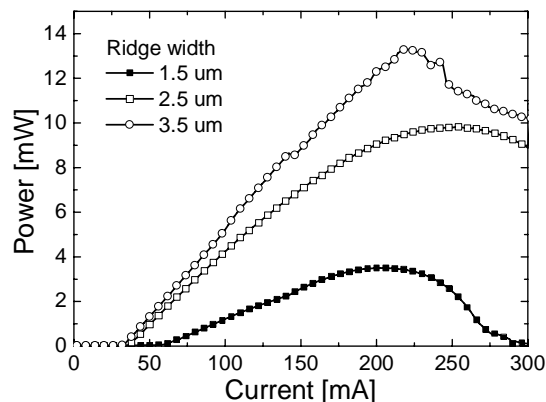


Fig. 2. Effect of ridge width,  $W$ , on the laser output.

#### Effect of dielectric coatings

To further improve the output power, we studied the effect of the dielectric coatings on the facets of the lasers. We used two pairs of Si/SiO<sub>2</sub> layers with quarter-wave thicknesses as the backside HR-mirror for the laser with  $W=3.5 \mu\text{m}$ . The reflectivity was 84 % at the operating wavelength. A single-layer of SiO<sub>2</sub> was used as an AR-coating to reduce the front facet reflectivity to 1.4 %. Maximum output power at 20 °C increased up to 25 mW, as shown in Fig. 3.

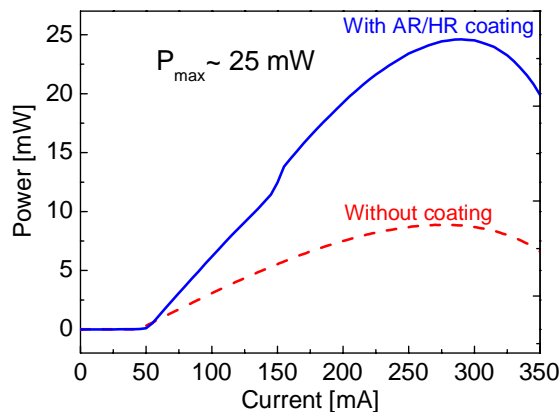


Fig. 3. ILV-curve of AR/HR-coated devices.

The operation of the laser is affected by a combination of feedback from the DFB-grating and the Fresnel reflection from the mirrors or the facets. The multimode behavior observed in uncoated devices having 3.5  $\mu\text{m}$  ridge width was not as evident for the coated chips. Combined reflectivity, defined as  $\sqrt{R1R2}$ , of the coated laser cavity was 10.8 %. The

as-cleaved mirror of GaSb material had a reflectivity of approximately 31 %, three times than for the coated mirrors we have used. This reduction in the reflectivity will suppress the Fabry-Perot modes and improves single-mode operation. Spectra of the AR/HR-coated laser at several operation currents are shown in Fig. 4. Tuning range for AR/HR coated LDs was 8 nm.

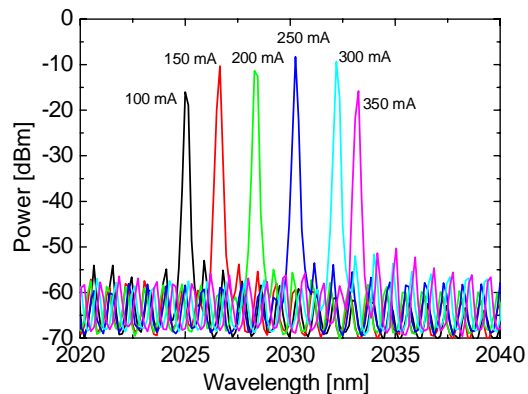


Fig. 4. Spectra of the AR/HR-coated laser.

#### IV. CONCLUSION

A manufacturing process for GaSb-based DFB lasers based on utilizing a single epitaxial growth step and cost-effective high-yield NIL process was presented. By adjusting the design parameters of the LC waveguide lasers, we were able to increase the room temperature output power from 2 mW per facet to approximately 14 mW. By depositing reflection coatings on the laser facets, the single-mode output was further increased to 25 mW. In addition, optimization of the ICP-etched grating profile allowed for significantly higher SMSR than reported before, with a maximum SMSR value of 50 dB (previously reported SMSR was 30 dB).

Single-mode DFB emission were tunable over 12 nm wavelength range with current and temperature variation. By preparing devices with different grating periods, wavelength coverage from 1980 nm to 2040 nm was obtained from a single epitaxial structure design.

The presented technology is suitable for relatively low-cost manufacturing of DFB laser diodes using in spectroscopic applications, where precise wavelength tunability and single-mode operation are crucial.

Our following research will focus on devising an optimized design for specific application wavelength based on the experimental observations presented in this paper. In addition, we intend to measure the optical linewidth from fibre-packaged components to further characterize their single-mode performance.

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