GaSb-Based High Power Single-Spatial-Mode and Distributed Feedback Lasers at 2.0 µm

Clifford Frez¹, Kale J. Franz¹, Jianfeng Chen², Leon Shterengas², Gregory L. Belenky², and Siamak Forouhar¹

1 Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., Pasadena, CA 91109
2 Dept. of Electrical Engineering, State University of New York, Stony Brook, NY 11794
Author e-mail address: Clifford.Frez@jpl.nasa.gov

1. Background

Technologies driving the development of optical components operating near 2 µm include lidar for CO₂ remote sensing. In order to produce high energy optical pulses, current lidar systems at this wavelength use fiber amplifiers where the seed laser is a solid state laser. The system complexity and reliability could be substantially simplified if semiconductor lasers existed with performance suitable to replace the current solid state seed lasers. The basic requirements needed for lidar seed lasers are: (1) ~100 mW continuous wave (CW) optical power, (2) single spatial mode emission, (3) single spectral mode emission, and (4) ~100 kHz laser linewidth. State-of-the-art diode lasers operating single mode near 2 µm are limited to output powers near 10 mW.¹² Here, we report our progress in realizing such a semiconductor laser for CO₂ lidar applications, demonstrating devices that meet both the necessary output power and spatial mode profile requirements.

2. Laser Growth and Fabrication

The epitaxial heterostructure was grown using a solid source molecular beam epitaxy system on a Te-doped GaSb substrate.³ The cladding layers were 1.5 µm thick Al₀.₈₅Ga₀.₁₅As₀.₀₇Sb₀.₉₃. The nominally undoped Al₀.₃Ga₀.₇As₀.₀₂Sb₀.₉₈ waveguide layer with a total thickness of about 800 nm contained four 12.5 nm-wide In₀.₂₃Ga₀.₇₇As₀.₁Sb₀.₉ quantum wells centered in the waveguide and spaced 40 nm apart. The compressive strain in the quantum wells was about 1.45%.

We fabricated 3 and 4 µm ridges by inductively coupled plasma reactive ion etching using a thin layer of silicon nitride as a dry etch mask and a BCl₃:Cl₂:Ar etch chemistry. The etching depth was 1.65 µm with smooth sidewalls. We used thick, 0.8 µm SiNₓ to isolate the optical cavity mode from the optically lossy top metal contact. The SiNₓ was also used to electronically isolate the active region. Windows were plasma etched in the dielectric above the ridges for electrical contact. Both n-side (Ti/PtAu) and p-side (Pd/Ge/Au/Pl/Au) metal contacts were electron-beam deposited then alloyed for 1 min at 260 °C. Figure 1 shows a scanning electron micrograph (SEM) of the laser facet. In the foreground, the laser ridge and thick SiNₓ layer are visible; electroplated Au is visible in the background.

Before facet coating, laser bars were cleaved to a 2 mm cavity length. Ar bombardment was used to clean the laser facets. The back facet was high reflectivity (HR) coated with two pairs of Al₂O₃/Si. We estimate a coating reflectivity of 95%. The front facet was anti-reflection (AR) coated using a single layer of Al₂O₃ for a facet reflectivity of 4%. In both cases, Y₂O₃ was used as an adhesion layer. Finally, the lasers were cleaved into chips and mounted junction-side up using a fluxless Au₁₀Sn₉₀ solder process on Au-coated C-mount copper blocks.

Figure 1. Scanning electron micrograph (SEM) of the laser facet without a dielectric coating. The laser ridge width is 3.375 µm.
3. Device Performance and Analysis

Light-current-voltage (LIV) measurements are shown in Fig. 2 for a 4 µm wide ridge laser operating in CW mode. Threshold currents range from 23 mA (10 ºC) to 29 mA (45 ºC) giving threshold current densities of 290 and 360 A/cm², respectively. Even though the laser is mounted p-side up on the submount, thermal rollover up to 500 mA is marginal. At 20 ºC, the peak output power measured at 500 mA drive current was 120 mW.

Amplified spontaneous emission spectra were collected for a laser held at 20 ºC and analyzed using the Hakki-Paoli method. Sub-threshold gain curves are shown in Fig. 3. Given these gain curves along with the LIV measurements of Fig. 2, we calculate the total waveguide loss \( \alpha_{\text{total}} = 11 \text{ cm}^{-1} \), the mirror loss \( \alpha_{\text{mirror}} = 7.6 \text{ cm}^{-1} \), the internal waveguide loss \( \alpha_{\text{int}} = 3.4 \text{ cm}^{-1} \), the slope efficiency at threshold \( \eta_{\text{slope}} = 0.245 \text{ W/A} \), the internal quantum efficiency \( \eta_{\text{int}} = 58.4 \% \), and the differential gain \( \frac{dg}{dI} = 1.59 \text{ cm}^{-1}/\text{mA} \).

![Figure 2. CW light-current-voltage (LIV) results from a 4 µm x 2 mm ridge laser.](image)

![Figure 3. Hakki-Paoli analysis of amplified spontaneous emission showing sub-threshold laser gain and loss at 20 ºC. The laser analyzed had dimensions 4 µm x 2 mm.](image)

![Figure 4. CW lasing wavelengths near room temperature. Each spectrum is taken with a drive current of 200 mA. Measurements were taken for a laser with dimensions 4 µm x 2 mm.](image)

![Figure 5. Intensity map of CW emission for a 3 µm x 2 mm driven at 350 mA. The heat sink temperature was 20 ºC. Emission is primarily single spatial mode.](image)

![Figure 6. Horizontal and vertical cross-sections of the data in Fig. 5 at peak intensity. Gaussian fits are shown in solid black lines. From the Gaussian fit, the full-width at half-maximum (FWHM) for the fast axis of the laser (horizontal direction) is calculated at 10.5ºC and the FWHM for the slow axis (vertical direction) is 64.2º.](image)
Spectra for a laser driven CW at 200 mA are shown in Fig. 4. The emission wavelength ranges from 2.039 to 2.078 µm at 10 and 40 ºC, respectively. At 200 mA, emission is observed primarily on one Fabry-Perot line. Figures 5 shows a map of the angular intensity distribution of laser emission for a 3 µm × 2 mm ridge driven at 350 mA. The laser heat sink was set at 20 ºC for this measurement. The intensity map shows a laser emitting primarily on the zeroth-order single spatial mode. Figure 6 shows cross-sections of the data displayed in Fig. 5, where the cross-sections are taken from the points of peak intensity. Here again, we observe emission primarily on the laser fundamental mode. We use Gaussian fits to calculate the angular divergence, where the σ parameter of the Gaussian function gives the full-width at half-maximum (FWHM) as \(2(2\ln2)\frac{1}{\sigma}\). The FWHM for the fast axis of the laser (horizontal direction) is calculated at 10.5º and the FWHM for the slow axis (vertical direction) is 64.2º.

4. Distributed Feedback Lasers

Initial progress has been made toward narrowing the laser linewidth by fabricating distributed feedback (DFB) lasers. Due to the inability of GaSb-based material systems to support epitaxial regrowth, we have implemented the approach of laterally-coupled DFB structures. In this case, the DFB grating is etched in the cladding to the sides of the laser ridge instead of atop the ridge itself, eliminating the need for a regrowth step.

The DFB fabrication process is similar to the ridge laser process, with a few additional steps. The grating pitch was initially determined by the optical cavity length and the frequency of the Fabry-Perot modes of the laser. A bi-layer mask of ZEP (an E-beam lithography resist) and silicon nitride was used to etch a lateral grating along the laser ridge. The dielectric is used as a barrier between ZEP and the GaSb material. Using E-beam lithography, the grating was written in the ZEP layer and was used to open the dielectric below. The grating was dry etched into the semiconductor using an ICP-RIE system and a mixture of BCl<sub>3</sub>/Cl<sub>2</sub>/Ar gases.

Both first and second order DFB grating were used, along with a variety of grating pitches. A piece of the finished chip is shown in Fig. 7, where a “rainbow” of color diffracted from the grating is apparent. The emission is spectrally single-mode when a 2 mm cavity is driven at 100 mA, as shown in Fig. 8. The temperature tuning rate is 0.2 nm/ºC, consistent with expectation for DFB devices.

5. Conclusion

We have presented our progress toward achieving semiconductor lasers suitable for the application of seed lasers for lidar fiber amplifiers. We have demonstrated CW, room temperature single spatial mode emission near 2.05 µm with output power exceeding 100 mW.

6. Acknowledgements

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7. References