Fabrication of Laterally Coupled Distributed Feedback Laser Structures by Two Step RIE in InGaAsSb-AlGaAsSb Material System Grown by MBE

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ABSTRACT

Data is presented on the fabrication of first order gratings in GaSb and AlGaAsSb layers by chlorine-based reactive ion etching (RIE). Also reported is the two-step dry etching process that is most suitable for laterally-coupled ridge waveguide distributed feedback (DFB) lasers with InGaAsSb-AlGaAsSb material system grown by molecular beam epitaxy (MBE). To the best of our knowledge, this is the first demonstration of grating fabrication in GaSb-based material system in which high quality and highly uniform gratings are obtained.

Key words: GaSb, DFB lasers, Gratings, RIE, MBE

1. INTRODUCTION

Semiconductor lasers with emission wavelengths longer than 2.0 μm are of a great interest because they can be used as excellent chemical sensors. A large number of molecules have strong absorption bands in the wavelength region between 2.0 and 3.0 μm including H_2O, CO_2, CO, and N_2O. Tunable diode laser (TDL) spectroscopy employing tunable single frequency semiconductor lasers provides a means in which trace gases can be accurately monitored using systems that are relatively small in size and also low in power consumption. In recent years, GaSb-based lasers have attracted a great deal of attention as alternatives to InP-based lasers, and high performance GaSb lasers have been reported including ultra-low threshold current density[1] and high power operations.[2] Even though stable single longitudinal mode lasers such as distributed feedback (DFB) or distributed Bragg reflector (DBR) lasers are highly desirable for chemical sensing applications or TDL spectroscopy,[3] there have been very limited reports on single frequency GaSb-based lasers. Bleuel et al. have recently reported GaSb-based DFB lasers with Cr surface gratings.[4]

DFB lasers can achieve wavelength selectivity through feedback from a periodic change in index or gain along the laser cavity. This usually requires an interrupted growth, i.e. regrowth over a grating structure, in the fabrication which greatly complicates the epitaxial growth process due to the potential of the introduction of defects at grating/regrowth interface. Determining the proper surface preparation and growth parameters to achieve high quality epitaxial regrowth while preserving the grating structure is technically demanding, particularly with antimonybased laser structures in which oxidation is problematic due to the use of AlGaAsSb in cladding layers.

One way to eliminate the regrowth problem is to introduce the gratings after the lasing cavity is formed and to rely on the coupling of the evanescent optical fields. This has been demonstrated by several groups including etching the gratings directly above the waveguide and injecting the current from the side[5] or by etching the gratings through the cap and upper cladding layer to provide the index guiding for the ridge and selective feedback.[6] An alternative approach is to etch the ridge first and then define the gratings on both sides of the ridge to fabricate a laterally-coupled ridge waveguide DFB laser, and its schematic diagram is illustrated in Figure 1. This approach has been recently reported by our group using InGaAs-GaAs-AlGaAs material system, and excellent d.c. and spectral characteristics have been obtained.[7, 8]

In this paper, we report on the fabrication of first order gratings in GaSb and AlGaAsSb layers by chlorine-based reactive ion etching, and also on laterally-coupled ridge waveguide DFB laser structures with InGaAsSb-AlGaAsSb material system grown by molecular beam epitaxy. To the best of our knowledge, this is the first demonstration of grating fabrication in GaSb-based material system in which high quality and highly uniform gratings are obtained.

2. EXPERIMENTAL METHODS

2.1 MBE Growth of InGaAsSb-AlGaAsSb Laser Structures and AlGaAsSb Layers

In the present work, molecular beam epitaxy (MBE) was employed for the growth of all the epitaxial layers and laser structures reported. Te-doped GaSb (100) substrates were employed.

The substrates were briefly etched in concentrated HCl and rinsed in isopropanol, blown dry and then mounted and loaded into the Riber MBE32P MBE system. Calibration and small test structures were indium mounted, while larger samples and laser structures were grown using indiumless mounting sample holders. The MBE system was equipped with In, Ga, Al, and two Sb standard effusion cells. An arsenic valved cracker was employed to provide a precisely controlled flux of As_4. N- and p-type dopants were GaTe and Be, respectively. These provided p-type carrier concentrations up to 2×10^{18} cm^{-3} in GaSb and up to 1×10^{18} cm^{-3} in the aluminum containing compounds. N-type concentrations up to 1×10^{17} cm^{-3} were routinely obtained in AlGaAsSb and 1×10^{18} cm^{-3} in GaSb epitaxial layers. Substrates were heated under an Sb_4 flux to desorb the surface oxides. Upon oxide desorption, the samples showed a strong (3×1) surface reconstruction, indicative of an atomically smooth clean surface. This desorption temperature along with the (3×1) to (5×1) surface reconstruction transition temperature was used to accurately determine the substrate temperatures employed. Aluminum containing layers were grown in the range of 490-510°C, while the other layers were grown in the range of 430-480°C. Growth temperatures and V/III ratios were optimized to grow laser structures with high optical and structural qualities.

The laser structure studied had a 0.2 μm thick undoped bulk $In_{0.16}Ga_{0.84}As_{0.14}Sb_{0.86}$ active layer between a ~1 μm thick n-type $Al_{0.3}Ga_{0.7}As_{0.02}Sb_{0.98}$ lower cladding layer and a ~1.2 μm thick p-type $Al_{0.3}Ga_{0.7}As_{0.02}Sb_{0.98}$ upper cladding layer. Finally, a p-doped 100nm thick graded layers having Al compositions varied from 0.3 to 0, and a 80nm thick p-doped GaSb contact layer were grown to complete the laser wafer.

2.2 Chlorine-based Reactive Ion Etching (RIE)

All the etching experiments including grating and ridge waveguide etching were performed in a parallel-plate etching system operating at 13.56 MHz. The samples were placed on the quartz plate with a diameter of 30cm that covered the capacitively coupled rf-driven electrode, and etch gases were introduced from holes made on the upper electrode. The electrodes were water cooled, and the system was pumped by a turbo-molecular pump and a base pressure of $\sim 3\times10^{-7}$ Torr was routinely attained.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 First Order Grating Fabrication in GaSb/AlGaAsSb by RIE

First order gratings were fabricated on both GaSb substrates as well as in AlGaAsSb epitaxial layers. A 0.2 μm thick polymethyl methacrylate (PMMA) layer was deposited on the samples by spin-coating, and a 50 keV JEOL electron-beam exposure system was used to write ~20 μm long lines for first order gratings (the grating period was ~300nm). Electron-beam doses were optimized to obtain a grating duty cycle of ~50%. The duty cycle is defined as the unetched grating width divided by the grating period, and a duty cycle of 50% is necessary to maximize the coupling coefficient (κ) of a first order grating. After being developed, samples were loaded into the chlorine-based RIE chamber.

Gratings were first formed on Te-doped (100) GaSb substrates, and grating lines were oriented perpendicular to (011) direction. Process conditions such as gas flow rates, process pressures, and rf powers were optimized to result in square-wave gratings with smooth surfaces and sidewalls. The flow rate of BCl_3 was 7 sccm, the total process pressure was 10 mTorr, the rf power density was 0.2 W/cm^2, and the d.c. bias was around 520 V. The optimized process condition is summarized in Table 1. In Figure 2 (a) and (b) is shown an SEM angled-view and cross-section of gratings formed on GaSb after the PMMA was removed. As shown in Figure 2, rectangular-shaped gratings were obtained with smooth surface and sidewalls along with a high uniformity. The etching rate was 120 nm/min (see Figure 3), and a duty cycle of ~50% was obtained. Gratings were also formed in AlGaAsSb layers (both $Al_{0.3}Ga_{0.7}As_{0.02}Sb_{0.98}$ and $Al_{0.7}Ga_{0.3}As_{0.06}Sb_{0.94}$ layers) lattice matched to GaSb substrates using the same process conditions as for GaSb. As shown in Figure 4, uniform rectangular-shaped grating shapes were also obtained with a duty cycle of ~50%. The etching rate was 100 nm/min for both AlGaAsSb layers. The etching rate for the AlGaAsSb layers was about 80% of that for GaSb (see Figure 3). To the best of our knowledge, this is the first demonstration of high quality gratings fabricated in GaSb-based material system.

3.2 Laterally-coupled DFB Laser Structures

The following processing steps were taken to fabricate a laterally-coupled DFB laser structure using the $In_{0.16}Ga_{0.84}As_{0.14}Sb_{0.86}$-$Al_{0.3}Ga_{0.7}As_{0.02}Sb_{0.98}$ laser wafer. First, ridge waveguides were formed along (011) direction as follows. A 120 nm thick silicon dioxide film was deposited by plasma enhanced chemical vapor deposition (PECVD) at 250°C, and patterned by standard photolithography to form ~4 μm wide stripes. Fluorine-based RIE using a mixture of CF_4 and O_2 gases was employed to etch the oxide film, and then the photoresist was removed. Next, the wafer was loaded into the chlorine-based RIE chamber. A mixture of BCl_3 and Ar was used to form 1.1 μm high ridges by etching the GaSb cap layer and a portion of the $Al_{0.3}Ga_{0.7}As_{0.02}Sb_{0.98}$ upper cladding layer, leaving a residual cladding layer thickness of ~0.25 μm. The total process pressure was 10 mTorr, the rf power density was 0.15 W/cm^2, and the d.c. bias was around 410 V. The process condition employed is also summarized in Table 1. Vertical ridge waveguides were obtained with smooth side walls as observed by SEM, and the etching rate was 100 nm/min.

Then, PMMA was spin-coated on the sample, and the e-beam exposure system was used to position 20 μm long first order grating lines on both sides of the ridge waveguide. Grating lines were oriented perpendicular to the (011) direction. A series of experiments were performed to optimize the PMMA thicknesses as well as the electron beam doses to realize gratings most suitable for LC-DFB lasers. Gratings were etched for 1.5 min in the $Al_{0.3}Ga_{0.7}As_{0.02}Sb_{0.98}$ upper cladding layer by the chlorine-based RIE using the same process condition described in Section 3.1. Figure 5 shows an SEM angled-view of a GaSb-based LC-DFB laser. This SEM photograph demonstrates that the process developed is suitable for laterally-coupled ridge waveguide DFB lasers in which gratings are placed in the immediate vicinity of the ridge to obtain an efficient coupling of evanescent optical modes with lateral gratings etched along the ridge. An SEM cross-section of the same LC-DFB laser wafer that was cleaved parallel to the ridge after staining for 1min is shown in Figure 6. An NH_4OH-based etchant was used as the stain etchant. From the SEM photograph, the grating height was 150 nm, and the residual cladding layer thickness measured from the valley of the grating to the InGaAsSb active layer was 80 nm. In addition, a duty cycle of ~50% was obtained. The excellent controllability over both the grating height and the residual cladding layer thickness was clearly demonstrated. A residual cladding layer thickness of ~100 nm and relatively deep gratings are necessary to maximize the overlap between lateral optical modes and gratings to obtain a high coupling coefficient (κ) from LC-DFB lasers.[7] Work is currently under way to demonstrate LC-DFB lasers with the emission wavelength near 2.3 μm to be employed as CO sensors, and the lasing characteristics of these lasers will be reported elsewhere along with the study on the effect of dry etching process on the optical qualities of GaSb-based laser materials.

4. SUMMARY

In summary, we have demonstrated the fabrication of first order gratings both in GaSb and in AlGaAsSb layers by chlorine-based reactive ion etching as well as the two-step dry etching process that is most suitable for laterally-coupled ridge waveguide distributed feedback lasers with the InGaAsSb-AlGaAsSb material system grown by molecular beam epitaxy. To the best of our knowledge, this is the first demonstration of grating fabrication in GaSb-based material system in which high quality and highly uniform gratings have been obtained.

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FIGURES

Figure 1 Schematic diagram of a laterally-coupled ridge waveguide DFB laser

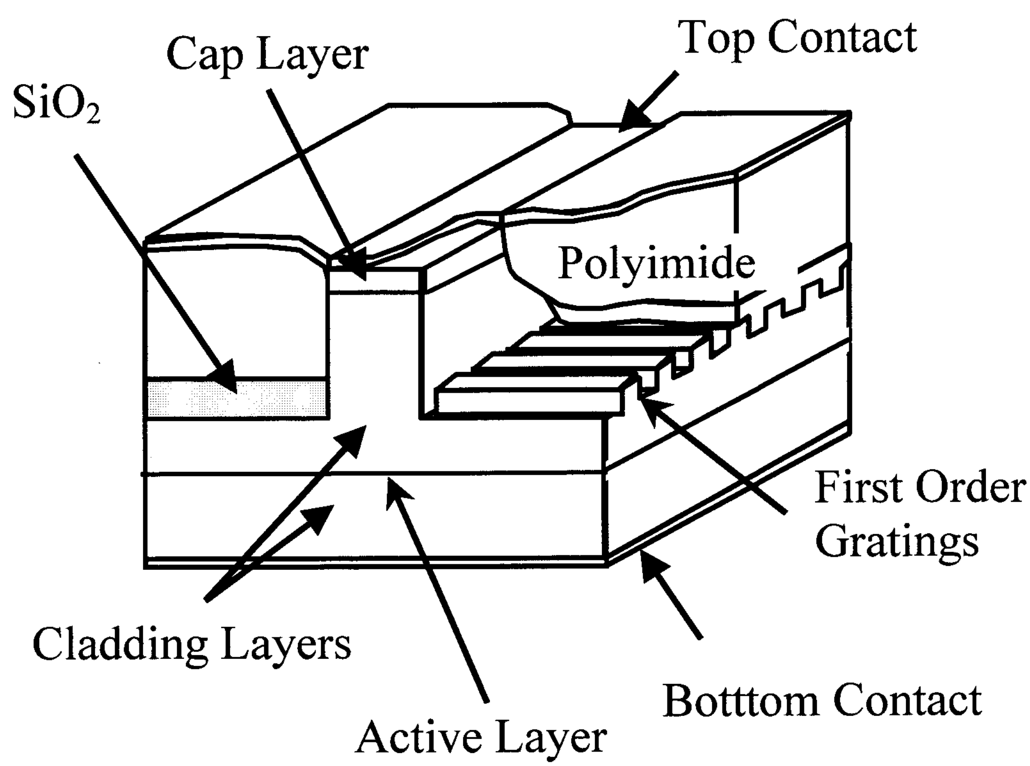
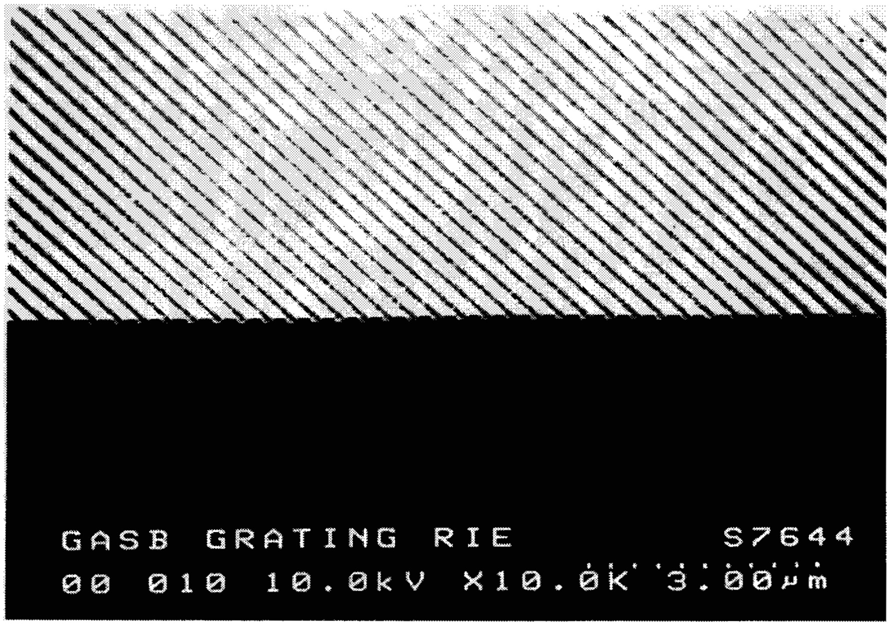


Figure 2 (a) SEM angled-view of gratings formed on GaSb substrate (lower magnification)



(b) SEM cross-section of gratings formed on GaSb substrate (higher magnification)

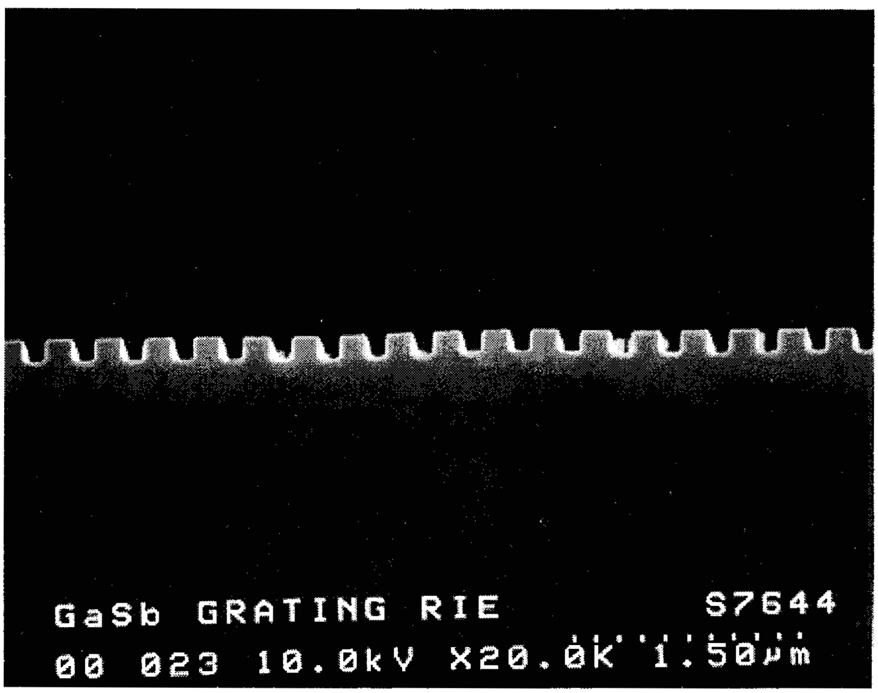


Figure 3 Grating heights vs. etching times for gratings fabricated in GaSb and AlGaAsSb

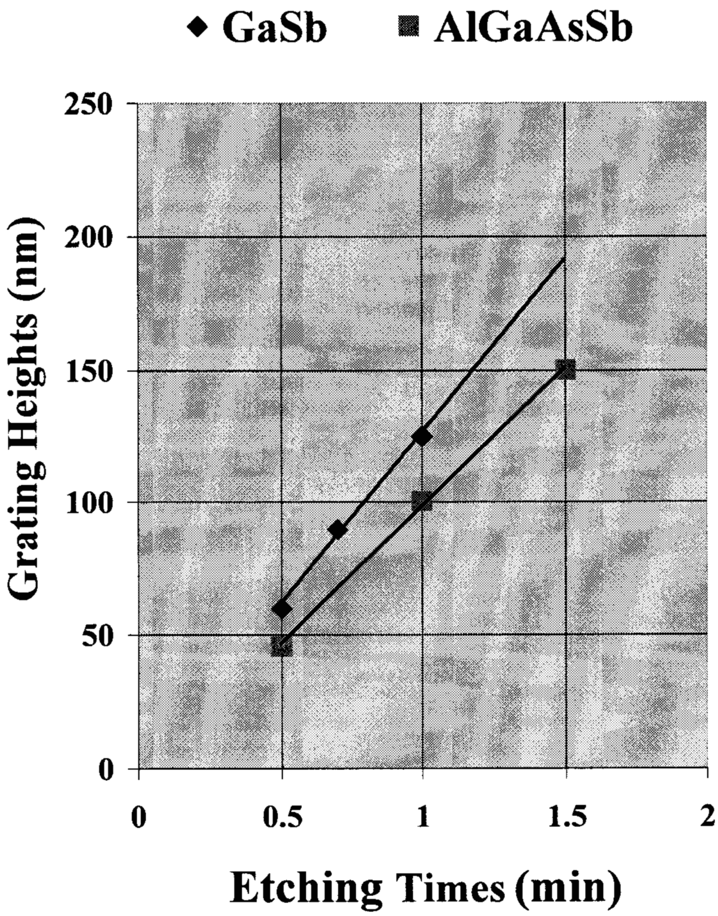


Figure 4 SEM cross-section of gratings formed in AlGaAsSb layer

Figure 5 SEM angled-view of an InGaAsSb-AlGaAsSb LC ridge waveguide DFB laser wafer

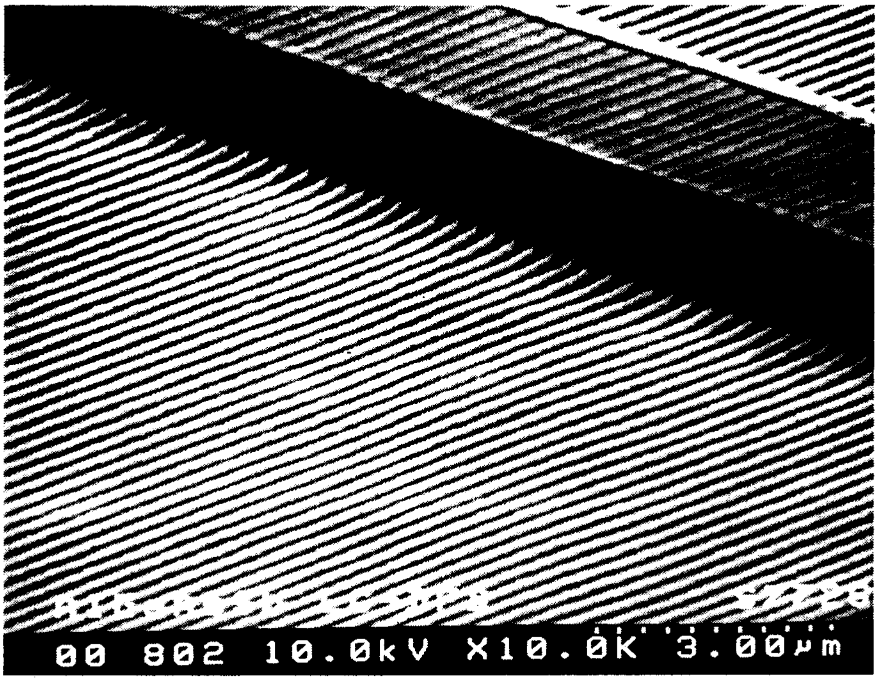


Figure 6 SEM cross-section of the same LC-DFB laser wafer after staining for 1 min

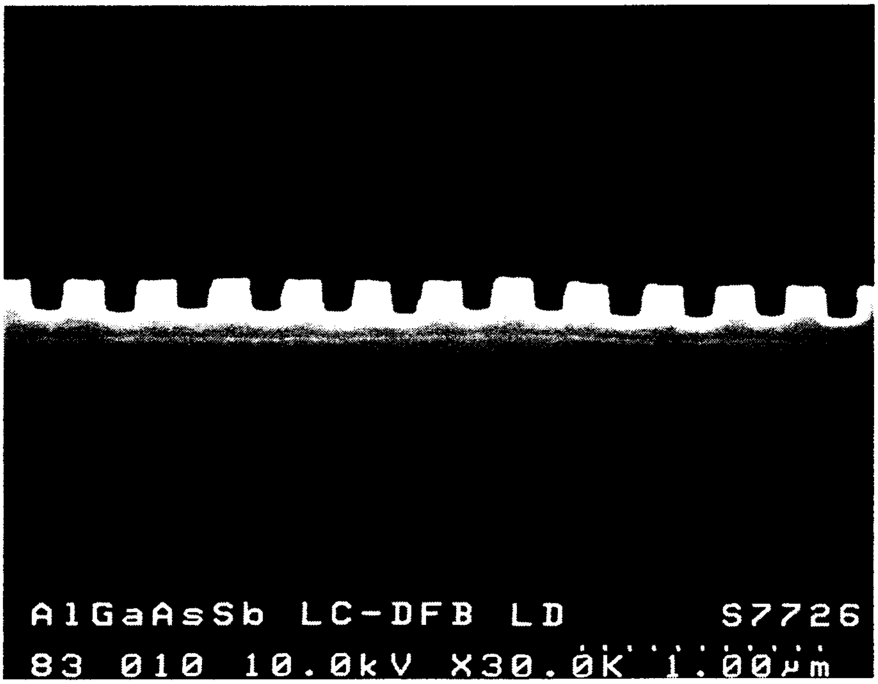


TABLE 1

Process conditions of RIE used to fabricate gratings in GaSb substrate and AlGaAsSb epitaxial layers as well as ridge waveguides for an InGaAsSb-AlGaAsSb LC DFB laser structure

RIE Process	Flow Rate (sccm)		Process Pressure (mTorr)	RF Power Density (W/cm^2)	D. C. Bias (V)
	BCl_3	Ar			
Ridge Fabrication	14	1	10	0.15	410
Grating Fabrication	7	-	10	0.2	520