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# Laterally-coupled distributed feedback lasers with optimized gratings by holographic lithography etching

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**Abstract**: GaSb-based laterally coupled distributed feedback (LC-DFB) quantum well lasers with a wavelength of 2 μm were successfully prepared. Second order Bragg gratings are fabricated by holographic lithography and inductively coupled plasma etching (ICP). The etching conditions for grating preparation are optimized and a single longitudinal mode lasing at room temperature is obtained. The room temperature peak power output per facet exceeds 5 mW with a maximum side-mode suppression ratio of more than 24 dB.

**Key words**: GaSb-based, laterally coupled distributed feedback, laterally coupled distributed feedback (LC-DFB), holographic lithography, second order Bragg grating

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# 全息光刻制备 LC-DFB 及光栅刻蚀优化

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**摘要**：成功制备出室温激射波长为 2 μm 的 GaSb 基侧向耦合分布反馈量子阱激光器. 采用全息曝光及电感耦合等离子体刻蚀技术制备二阶布拉格光栅. 优化了光栅制备的刻蚀条件，并获得室温 2 μm 单纵模激射. 激光器输出光功率超过 5 mW，最大边模抑制比达到 24 dB.

**关　键　词**：镓锑基；侧向耦合分布反馈；LC-DFB；全息光刻；二阶布拉格光栅

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## Introduction

Lasers operating in the infrared region are of particular interest for molecular spectroscopy[1] as characteristic absorption bands of important industrial gases. GaSb-based lasers operating within the 2 ~ 3 μm wavelength range have a broad applications in gas spectroscopy by using tunable diode laser absorption spectroscopy[2-4]. For accurate sensing, the laser should emit on a narrow line width with single longitudinal mode and exhibit a moderate tuning range[5-6]. These can be achieved by introducing a distributed feedback (DFB) grating in the cavity of a GaSb-based diode laser[7]. However, the traditional method of preparing a distributed feedback (DFB) grating is to introduce a buried grating for mode selecting.

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This method requires the re-growth techniques[8-9]. Typically GaSb-based lasers have a high content of aluminum in the waveguide layers, which easily forms natural oxide in contact with air, making the buried grating technically challenging to fabricate[10-11]. Laterally-coupled distributed feedback (LC-DFB) lasers mitigate this problem by using a patterned lithographically grating out of the waveguide ridge[12]. This approach enables fabrication of the semiconductor structures in single epitaxial growth step, thus reducing the cost and avoiding the issues related to oxidation of AlGaAsSb layers[13]. So far, LC-DFB layers have been demonstrated with GaAlAs-GaAs, InGaAsP-InP, AlGaAsSb-GaSb Materials systems[14-16].

Owing to the mode selecting mechanism of LC-DFB lasers, the defining of subsize grating is more important and difficult. Among previous reports, Bragg grating has been fabricated by using electron beam lithography (EBL)[17], nanoimprint lithography[18], and holographic lithography[19]. Although electron beam lithography is a direct-write technique, it is often costly and slow for mass-manufacturing. Nanoimprint lithography is suitable to scale up the production of these lasers enabling low cost fabrication of the laser chips. However, it is difficult to control the thickness of the embossed plastic and uniformity. The most important question is how to alignment with the second edition. As the result, holographic lithography suitable for low-cost and high-throughput processing.

In this letter, we report the growth and fabrication process of GaSb-based type-I quantum well semiconductor lasers in detail. Second-order surface-defined lateral Bragg grating devices were fabricated by holographic lithography. In order to improve the coupling coefficient of the grating and light waves, the etch depth of the ridge waveguide and grating needs to be increased. The grating etching condition was optimized to obtain a vertical, deep, smooth, and fine etching gratings. These devices can produce single-mode emission near 2 μm and generate more than 5 mW of CW emission at room temperature, with excellent side-mode suppression ratio (SMRS) of more than 23 dB.

## 1　Design and fabrication

### 1.1　Material growth

The laser diodes were grown by solid source Gen-Ⅱ molecular beam epitaxy (MBE) on an n-GaSb (100) substrate[20-21]. Active region of the laser structure was comprised of one In$_{0.2}$GaSb quantum well (10 nm) with Al$_{0.35}$GaAsSb barrier layers (20 nm) embedded in Al$_{0.35}$GaAsSb waveguide layer (270 nm). The undoped region was surrounded by lattice matched Al$_{0.55}$GaAsSb cladding layers (1 500 μm). The structure was capped by a 250 nm highly p-doped GaSb contact layer for achieving a good Ohm contact with the p-side electrode mental. Typical epitaxial structure of the devices is shown in Fig. 1.

### 1.2　Device fabrication

The traditional fabrication of distributed feedback (DFB) grating requires epitaxial regrowth method, which increases manufacturing costs and results in rapid oxidation of Al-containing layers. A new method was used to fabricate the Laterally-coupled distributed feedback gratings. Unlike the traditional methods, we divide the fabrication of ridge waveguide and grating into two steps. Firstly, ridge waveguide was formed by inductively coupled plasma (ICP) with a gas mixture of SiCl$_4$ and Ar$_2$. Secondly, the sample was spin coated with photoresist, and then the second-order grating was defined alongside the ridge waveguide by holographic lithography. The shallow etching of the grating sharply reduces the high aspect ratio in ICP etching demanded by the traditional deep etching approach and also reduces the difficulty of preparing gratings. After the etching of the grating, a 200 nm thick SiO$_2$ protecting mask was deposited on the surface of the ridge by plasma enhanced chemical vapor deposition (PECVD) for insulation and planarization. Conventional UV lithography with ICP dry etching was used to open a contact window on SiO$_2$. The p-side top Ohm contacts were formed by 50/50/1 000 nm of Ti/Pt/Au using magnetron sputtering. The bottom Ohm contacts were achieved by AuGeNi/Au of 50/300 nm using high vacuum thermal evaporation equipment. Then the n surface electrode of the device is annealed rapidly for 2 minutes at 335 degrees. Finally, the sample was mounted p-side up on copper heat sink for characterization. Figure 2 shows the morphology of the waveguide and grating under scanning electron microscope.

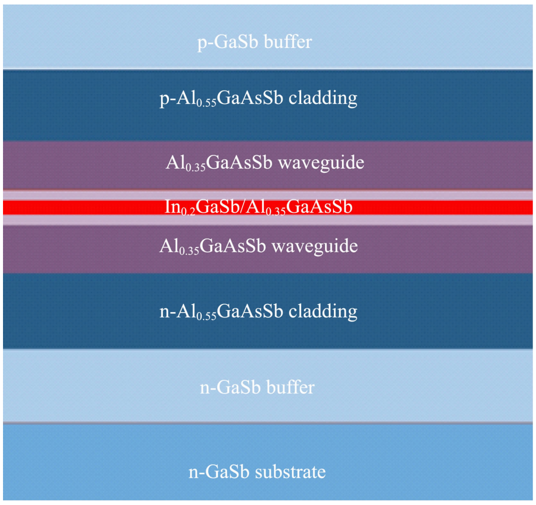

Fig. 1　Epitaxial structure used to fabricate the LC-DFB laser

图 1　侧向耦合分布反馈激光器的外延结构

### 1.3　Optimization of the grating

Inductively Coupled Plasma (ICP) offers an extremely effective means of pattern transfer into III-V semiconductor devices. Previous investigations shows that the particles will follow the material into the tunnel during the process of etching. That will introducing nonradiative recombination center, which could introduce damages to the material. The DFB lasers Bragg grating layer is very close to the active region. If the ICP parameters are not introduced in the etching process, a large number of nonradiative recombination centers will greatly increase the carrier scattering rate and decrease the carrier lifetime, thus affecting the device of optical and electrical properties[22-24]. Therefore, optimizing the key process parame-

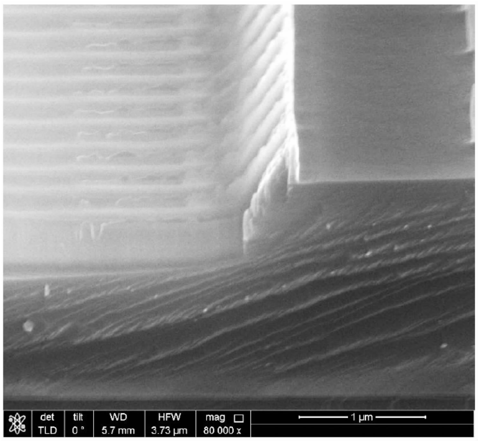

Fig. 2 SEM diagram of a laterally coupled distributed feedback laser
图2 侧向耦合分布反馈激光器的SEM图

ters of ICP etching and reducing etching damage is the key to fabricating good-performance gratings.

In the process of etching, the etching rate can be effectively reduced by increasing the etching rate and decreasing the particle energy. This paper used the mixture of $Cl_2/Ar_2/BCl_3$ as the etching gas. $BCl_3$ can improve the etching surface characteristics which mainly based on chemical etching, but this etching gas have a low etching rate. Argon ion bombarding the material surface which is mainly based on physical etching. Figure 3 shows the different etching conditions and etching morphologies. Figure 3(A) shows the component etching gas of $BCl_3$ and $Ar_2$ ratio is 1:8 at the RF power of 80 W. It's clear that argon ratio is much higher than three boron chloride, which makes the physical etching mainly and chemical etching supplemented. A triangular grating can be formed. When we raised the ratio of $Ar_2/BCl_3/Cl_2$ to 3:5:4 at the RF power of 60 W, the rate of chemical etching increased greatly. With the decrease of argon ratio, the effect of physical etching was weakened. As Fig. 3(B) shows. It is obvious that the grating was inverted triangular. The bottom of the grating had a serious erosion, and the chemical etching rate was too fast, which necessitate to reduction the ratio of $BCl_3/Cl_2$. As shown in Fig. 3(C), we changed the corresponding gas ratio to 5:2:2, which resulted in a low etch rate. The etching power of ICP affects the density of the plasma and determines the ionization rate of the etched gas. With the increase of power, the ionization rate of gas increases, so the etching rate increases. However, excessive etch rates will result in rough etched surfaces. Considering the interaction between the physical and chemical etching, we changed the gas ratio of $Ar_2/BCl_3/Cl_2$ to 5:3:1 at RF power of 50 W. We can obtained ideal rectangular grating topography as shown in Fig. 3(D).

The design of our LC-DFB lasers is based on the modified coupled wave theory[25]. The device modal effective refractive index $n_{eff}$ is calculated to be 3.45 while the electric-field overlap factor $\Gamma_{grating}$ is calculated to be 0.46% which describes the extent to the electric field overlaps with the grating[26]. The period of the second order grating, $\Lambda$ , is calculated to be 580 nm for a wave range of 2 μm according to the deformation of the Bragg equation.

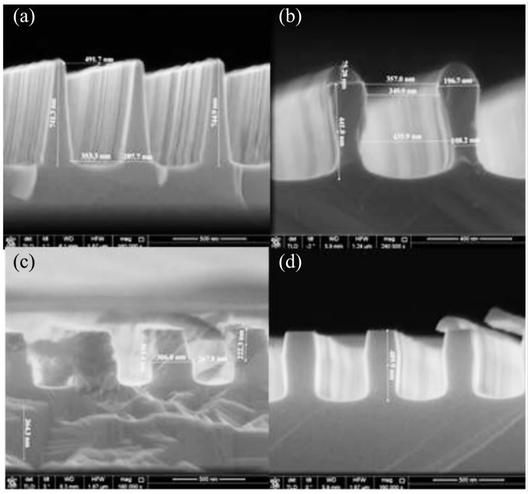

Fig. 3 The SEM of different etching conditions of grating topography
图3 不同刻蚀条件下光栅的SEM

## 2 Measurement

The preliminary results exhibit a stable single-mode oscillation around 2 μm with a high side mode suppression ratios (SMSR) under continuous wave (CW) operation. All the laser performance was measured without facet coating. The measurements of lasers output power were done by a pyroelectric detector and the emission spectra were scanned using a Fourier transform infrared spectroscopy (FTIR) system. All measurements were done for a component with as-cleaved facets.

Figure 4 presents the emission spectrum of the LC-DFB laser at 300 mA in temperature of 20°C. The laser shows single mode emission at a wavelength of 1 971 nm and a side mode suppression ratio of more than 20 dB. The corresponding laser spectrum of FP reference sample is shown as an inset. It's clear that the DFB gratings have effective filter to the wavelength. We can select the ideal wavelength by adjusting the period and order of the grating.

Figure 5 shows the light-current-voltage (LIV) characteristics of the laser at 20°C in continuous wave (CW) regime. We can achieve the largest light power is more than 5 mW with the injection current of 265 mA at room temperature. Under low operating currents, multimode emission is observed from these lasers because the gain spectrum is on the short wavelength side of the DFB grating. As the current increases, the gain spectrum is red-shift toward the grating wavelength and a single-mode operation is observed[27]. The high turn-on voltage of 2 V is more likely caused by the poor Ohm contact from the annealed AuGeNi/Au contact on the bottom of the n-GaSb substrate.

The maximum achieved side mode suppression ratio (SMSR) is 24 dB at an operating temperature of 20°C

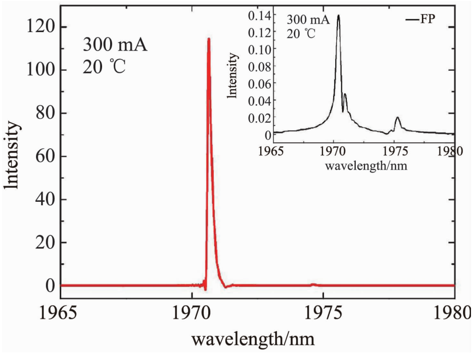

Fig. 4 Emission spectrum for as-cleaved 1 500 μm long device under an injected current of 300 mA at a wavelength of 1.971 μm in temperature of 20°C. The inset shows the laser spectrum of FP at the same conditions

图 4 器件解离成 1 500 μm 腔长，当注入电流为 300 mA 时获得 1.971 μm 的室温连续激射波长. 小图所示为同等条件下的 FP 腔激射波长

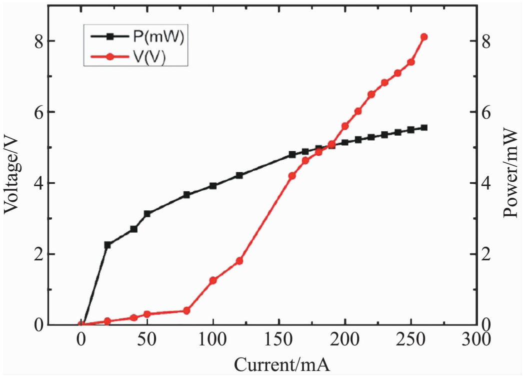

Fig. 5 Light-current-voltage and characteristic curve of second-order LC-DFB CW laser at room temperature

图 5 二阶侧向耦合分布反馈激光器在室温下的 IVP 特征曲线

with the drive current of 350 mA, which is shown in Fig. 6. Despite the higher turn-on voltage, the threshold current and the side mode suppression (SMSR) of our devices grown on GaSb-based substrates are compare favorably to high order DFB lasers. Several changes can be made in the future to reduce the turn-on voltage through optimizing the Ohm contact between the metal and epitaxy. It's also can be removed by redesigning the laser such that the n-side contact is fabricated on the top-side of the device[28] or by using δ doping to reduce the negative impact of a contact anneal[29]. Further development of the process is also needed for improving the grating profile and increase the etching depth of the Bragg grating, which can enhancing the coupling of the lateral grating with the optical mode in the cavity and increasing the SMSR.

## 3 Conclusion

In summary, we have fabricated GaSb-based 2 μm laterally-coupled distributed feedback lasers with second order gratings through holographic lithography. The epitaxy was completed in a single growth step, so the regrowth of oxidated Al content in epitaxy layer was avoided. We optimized the etching condition of the grating and obtained the rectangular grating while the ratio of etching gas of Ar/$BCl_3$/$Cl_2$ is 5∶3∶1. The CW laser emission wavelength is around 2 μm in a single longitudinal mode at room temperature. The device exhibits an output power over 5 mW at room temperature and has an side mode suppression ratio of 24 dB which is enough for gas sensing application in infrared wavelength.

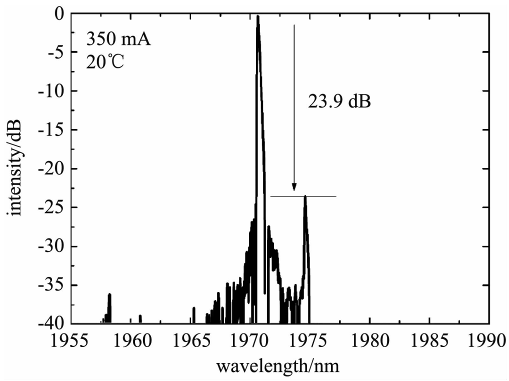

Fig. 6 The output spectrum of an LC-DFB laser shows an SMSR of 24 dB with an injecting current of 350 mA

图 6 当注入电流为 350 mA 时，LC-DFB 输出光谱的边模抑制比为 24 dB

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