Design, fabrication, and investigation of 2 μm GaSb-based diode lasers

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**NANYANG
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**DESIGN, FABRICATION, AND INVESTIGATION OF 2 UM
GASB-BASED DIODE LASERS**

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SCHOOL OF ELECTRICAL & ELECTRONIC ENGINEERING

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DESIGN, FABRICATION, AND INVESTIGATION OF 2 UM GASB-BASED DIODE LASERS

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School of Electrical & Electronic Engineering

A thesis submitted to the Nanyang Technological University
in partial fulfillment of the requirement for the degree of
Doctor of Philosophy

2019

Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research, is free of plagiarised materials, and has not been submitted for a higher degree to any other University or Institution.

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Supervisor Declaration Statement

I have reviewed the content and presentation style of this thesis and declare it is free of plagiarism and of sufficient grammatical clarity to be examined. To the best of my knowledge, the research and writing are those of the candidate except as acknowledged in the Author Attribution Statement. I confirm that the investigations were conducted in accord with the ethics policies and integrity standards of Nanyang Technological University and that the research data are presented honestly and without prejudice.

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Authorship Attribution Statement

This thesis contains material from 5 papers published in the following peer-reviewed journals where I was the first author.

Chapter 4 is published as X. Li, H. Wang, Z. Qiao, Y. Liao, Y. Zhang, Y. Xu, Z. Niu, C. Tong, and C. Liu. Temperature- and current-dependent spontaneous emission study on 2 μm InGaSb/AlGaAsSb quantum well lasers. *Japanese Journal of Applied Physics* **56**, 050310 (2017). DOI: 10.7567/JJAP.56.050310.

The contributions of the co-authors are as follows:

- Prof. H. Wang and Dr. C. Liu provided the initial project direction. Dr. C. Liu and I determined the topic of this paper.
- I fabricated the devices, recorded and analyzed the spontaneous emission spectra.
- I drafted the manuscript, and it was revised by Prof. H. Wang, Dr. C. Liu, and Dr. Z. Qiao.
- Dr. Y. Liao, Dr. Y. Zhang, Dr. Y. Xu, Dr. Z. Niu, and Dr. C. Tong performed the epitaxial growth of the laser wafers.

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The contributions of the co-authors are as follows:

- Prof. H. Wang, Dr. C. Liu, and Prof. G. I. Ng provided the initial project direction. Dr. Liu and I determined the topic of this paper.
- I fabricated the devices, recorded and analyzed the optical spectra, electrical spectra, and pulse train data. I also calculated the modal gain.
- Dr. Z. Qiao and Ms. X. Guo assisted in building the experimental setup and recording the data.

- I drafted the manuscript, and it was revised by Prof. H. Wang, Dr. C. Liu, and Dr. Z. Qiao.
- Dr. Y. Zhang, Dr. Z. Niu, and Dr. C. Tong performed the epitaxial growth of the laser wafers.

The second one is X. Li, H. Wang, Z. Qiao, X. Guo, W. Wang, G. I. Ng, Y. Zhang, Y. Xu, Z. Niu, Cunzhu Tong, and C. Liu. Investigation of regime switching from mode locking to Q-switching in a 2 μm InGaSb/AlGaAsSb quantum well laser. *Optics Express* **26**, 8289-8295 (2018). DOI: 10.1364/OE.26.008289.

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- I fabricated the devices, recorded and analyzed the optical spectra, electrical spectra, and pulse train data.
- Dr. Z. Qiao, Ms. X. Guo, and Dr. W. Wang assisted in building the experimental setup and recording the data.
- I drafted the manuscript, and it was revised by Prof. H. Wang, Dr. C. Liu, and Dr. Z. Qiao.
- Dr. Y. Zhang, Dr. Y. Xu, Dr. Z. Niu, and Dr. C. Tong performed the epitaxial growth of the laser wafers.

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- I fabricated the devices and performed the simulations.
- I drafted the manuscript, and it was revised by Prof. Wang, Dr. Liu, and Dr. Qiao.

- Y. Zhang, Z. Niu, and C. Tong performed the epitaxial growth of the laser wafers.

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Abstract

High-performance light sources operating in the 2 μm range are key components for a number of applications such as medical diagnostics, eye-safe light detection and ranging (LIDAR), wind velocity measurement, free space and advanced optical communications, plastic material processing, optical pumping for solid-state lasers and optical parametric oscillators (OPO), etc. In this wavelength range, laser emission was achieved in many different host crystals and fibers with Tm^{3+} and Ho^{3+} ions as well as InP- and GaSb-based semiconductor materials. Among these lasers, semiconductor diode lasers have their specific advantages: flexible wavelength tuning by engineering the bandgap of the active region, compactness, high efficiency, easy electrical pump, integration opportunities with silicon photonic circuits, which make them very desirable. For the two semiconductor material systems, GaSb-based materials are preferred since relatively high strain is inevitable for InP-based materials to emit light in the 2 μm range, which brings difficulties in material growth.

Two different GaSb-based laser structures were used to fabricate all the devices in this work. The main difference between these two structures is one uses AlGaAsSb barrier with higher aluminum composition to improve the carrier confinement. According to their lasing wavelength, they are referred to as 1960 nm laser structure and 2020 nm laser structure, respectively in this thesis.

First, Fabry-Pérot (FP) ridge waveguide lasers were fabricated with a developed standard fabrication process based on our process capability. The threshold current densities of the fabricated lasers are as low as $\sim 96 \text{ A/cm}^2$, which is among the lowest values for a 2 μm GaSb-based diode laser. The characteristic temperatures T_0 and T_1 are 103 and 606 K, respectively near room temperature, which are also very impressive. In addition to these performance parameters, the carrier recombination behaviors within the fabricated lasers were systematically investigated both electrically and optically. Ideality factor (electrical, via voltage current characteristics) and Z parameter (optical, via spontaneous emission) were used for the investigations as they are good reflections of the three main recombination processes (Shockley-Read-Hall (SRH), radiative, Auger). Besides Z parameter, through the analysis of the activation energy derived from the spontaneous emission, it is found that severe thermal loss of holes at large injection currents cannot be ignored. The

findings in the ideality factor and spontaneous emission studies are in very good agreement with each other.

On the other hand, high-frequency optical pulse trains are desirable for a number of applications in chemistry, telecommunications, medicine, and military. For example, real-time monitoring of chemical reactions, ultra high bit rate optical communications, ultrafast electro-optical sampling and optical coherence tomography (OCT). There are mainly three techniques to obtain ultrafast pulses: gain switching, Q-switching and mode locking. Compared to the other two techniques, mode locking technique allows the generation of pulses with shorter pulse duration and higher repetition frequencies, which makes it more desirable for many applications. First, shorter pulse duration provides higher resolution. It can slow down some fast-moving objects such as molecules or electrons and therefore measure some ultrafast processes, e.g., the relaxation processes of carriers in semiconductors, chemical reaction dynamics, and electro-optical sampling of high-speed electronics. Second, higher repetition frequency means higher transmission capacities in communications. One example is ultrashort pulse train emitted from a mode-locked laser can be used to realize optical time division multiplexing (OTDM). This is one form of time division multiplexing (TDM), which is widely used in optical fiber communications to increase the overall data transmission capacities. In addition, many longitudinal modes (different frequencies) are included in the light emission from a mode-locked laser, which enables the lasers to work as multi-wavelength light sources by combining appropriate optical filters. Since these modes (frequencies) are precisely locked to longitudinal mode spacing, they are very promising for another capacity improvement technique: wavelength division multiplexing (WDM).

Due to the above attractions, monolithic two-section mode-locked lasers (MLLs) were fabricated and fully characterized. Stable mode locking was achieved in these lasers under a variety of bias conditions up to 80 °C. Hysteresis was observed in a fabricated laser at temperatures higher than 60 °C with small negative absorber bias voltages (V_a). Cavity length and gain/absorber length ratio were analyzed. After this, mode gain, different working regimes (instabilities), phase noise/timing jitter, frequency tuning of these MLLs were systematically investigated. All these characterization works were the first time done on a 2 μm mode-locked diode laser.

Furthermore, tunable single frequency operations are favorable in sensing and optical communication applications, e.g., tunable diode laser absorption spectroscopy

(TDLAS), wavelength division multiplexing (WDM) technique. Another very trending field is III-V/silicon integration. To make the reason short, it combines the light emitting capability of III-V with the high design freedom and complementary metal-oxide-semiconductor (CMOS) compatibility of silicon (Si) photonics, which is very promising for large bandwidth intra- and inter-chip connections, compact and low-cost sensing and communication devices, etc.

Two III-V/Si integration methods: wafer bonding and edge coupling have been investigated. For the wafer bonding method, a tapered waveguide GaSb-based laser, bonded onto silicon on insulator (SOI) circuits with an Al_2O_3 bonding layer was designed and simulated via the beam propagation method (BPM) simulations. The thermal property of the GaSb-on-Si laser has been calculated using a constant heat spreading model, and the results show that the devices using Al_2O_3 bonding layer have a much lower ($\sim 70\%$) thermal resistance as compared to the one using SiO_2 bonding layer. For the edge coupling method, a $2\text{ }\mu\text{m}$ external cavity tunable laser with Si photonic chip as the wavelength selective component is designed, fabricated, and characterized. The semiconductor optical amplifiers (SOAs) were fabricated from the 1960 nm laser wafer with 4.5° to 6.5° tilted waveguides. Si vernier wavelength filter was simulated and optimized using Lumerical softwares. At the juncture of writing this thesis, a tuning range of $\sim 60\text{ nm}$ with side mode suppression ratio (SMSR) of higher than 10 dB was achieved in one fabricated laser. 60 nm is among the largest tuning ranges for a tunable diode laser in the $2\text{ }\mu\text{m}$ wavelength range.

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Chapter 1 Introduction

1.1 Background and motivation

1.1.1 2 μm wavelength range

First things first - why 2 μm wavelength? Light sources operating in the 2 μm wavelength range are promising for a number of applications. A large part of these applications is originated from the absorption characteristics of liquid water and atmospheric water vapor in this wavelength range. Figure 1.1 shows the absorption coefficients of liquid water (red), water vapor in the atmosphere (green), and ice (blue) as a function of wavelength [1].

Fig. 1.1. (a) Absorption coefficients of liquid water (red), water vapor in the atmosphere (green), and ice (blue) as a function of wavelength [1]. (b) Enlarged view of the absorption spectra around 2 μm .

For liquid water, its absorption coefficient exhibits a local maximum at the wavelength of $\sim 2 \mu\text{m}$, as a result, the penetration depth of light at this wavelength in liquid water drops rapidly to only a few hundred microns (as shown more clearly in Fig. 1.2 [2]).

Fig. 1.2. Absorption and penetration depth in water and other biological tissue constituents for different wavelengths [2].

This is the reason why the 2 μm wavelength range is considered “eye safe”. Our eyes, whose main component is water, strongly absorb the light at these wavelengths to keep the sensitive retina from it. It is critical for applications where eye safety is very important. Owing to the same reason as the “eye safe”, the lasers emitting in the 2 μm wavelength range allow very precise cutting of the targeting biological tissues without causing too much excessive heating of the surrounding areas. In addition, due to blood coagulation, the bleeding during surgeries is effectively suppressed. These features make 2 μm lasers ideal for many medical applications.

At the same time, as shown of the water vapor absorption spectrum in Fig. 1.1, there is an evident absorption local minimum at wavelength slightly longer than 2 μm , which results in an atmospheric window as shown in Fig. 1.3 to allow long-distance propagation of the light around this wavelength without intermediate absorption. Thus, the 2 μm radiation is quite promising for many free space applications since it can propagate losslessly and is “eye safe” at the same time. The applications include light detection and ranging (LIDAR), wind velocity measurement, free space optical communications including low-cost metro networks, secure short-range communication networks on a battlefield, etc [2].

Fig. 1.3. Atmospheric windows in the infrared.

In addition to the free space optical communications, the 2 μm wavelength range also shows potential in another area of communications. Currently, telecommunications through single-mode fibers are mainly in the near-infrared telecom wavelength region (1.3 to 1.55 μm). But the maximum capacity of this wavelength range is not infinite, instead, there will be a “capacity crunch” (see Fig. 1.4). In order to meet the continued steep growth in transmitted data volumes on all media, a promising solution is to use new spectral bands at longer than 1.55 μm for next-generation optical communication systems with ultra-low loss multi-mode photonic crystal optical fiber communications (<http://www.modegap.eu/>) [3, 4]. It is predicted that the capacity increase will accrue primarily in a new transmission wavelength window centered at around 2 μm . Thus semiconductor laser diodes, with emission wavelength at $\sim 2 \mu\text{m}$, are highly desirable for this system.

Fig. 1.4. Record data transmission capacity of fiber transmission systems [4].

Moreover, there are a number of relevant gases whose characteristic absorption lines lie in this wavelength range as shown in Fig. 1.5 [5]. These gases may be greenhouse gases, potentially lethal trace gases which are by-products of an unforeseen catastrophe, decomposition or residue explosive compounds and chemo-biological agents, etc. Therefore, semiconductor lasers emitting in the 2 μm range are particularly useful for high sensitivity gas detection for environmental control, industrial process monitoring, and security.

Fig. 1.5. Absorption lines of various gas species in the infrared wavelength range. The right vertical axis shows the absorption strength of H_2O and CO_2 in inverse scale. The absorption strength of all other gases is shown on the left vertical axis [5].

The 2 μm wavelength range is also attractive in material processing, especially for the plastic materials that are transparent in the visible and near-infrared wavelength range [2]. These relevant plastic materials usually show sufficient absorption around 2 μm to allow direct processing with lasers operating at this wavelength without the help of additional absorbent.

Other applications for the 2 μm laser systems include pumping solid-state lasers doped with holmium, pumping optical parametric oscillators (OPO) emit at longer wavelengths in the mid-infrared, etc [2].

1.1.2 Mode locking

High-frequency optical pulse trains are desirable for a number of applications in chemistry, telecommunications, medicine, and military. For example, real-time monitoring of chemical reactions, ultra high bit rate optical communications, ultrafast electro-optical sampling and optical coherence tomography (OCT) [6]. There are mainly three techniques to obtain ultrafast pulses: gain switching, Q-switching and mode locking.

Table 1.1 gives a summary of the three optical pulse generation techniques. Gain switching is a method for pulse generation by modulating the laser gain via the pump power. For diode lasers, it can be easily achieved with a pulsed current source, or with a modulated signal. This technique normally generate nanosecond (ns) to picosecond (ps) pulses. The repetition rate can be flexibly tuned within a certain range but the pulse parameters are with large fluctuations. On the other hand, the peak power and pulse energy with this technique are fairly limited since carriers are consumed by stimulated emission faster than they are injected. Q-switching is more suitable to generate pulses with very high pulse energy. Instead of modulating the laser gain in gain switching, this technique modulates the intracavity losses and thus the Q factor of the laser resonator. In this way, the large amount of energy stored in the upper-state energy level will be released to a giant pulse. The pulse repetition rate with Q-switching is relatively low (typically in the kHz to MHz scale), while the pulse duration is normally long (in the ns scale). Compared to the above two techniques, mode locking technique allows the generation of pulses with extremely short pulse duration (down to several femtoseconds (fs)) and high repetition frequency (up to the THz scale). These characteristics of mode locking make it more desirable for many applications.

Table 1.1. Comparison of three optical pulse generation techniques.

Technique	Pulse duration	Pulse energy	Pulse repetition rate
Gain switching	ns to ps	fairly limited	kHz to GHz, easy to adjust within a certain range but with large pulse parameter fluctuations
Q-switching	long, normally ns	very high	kHz to MHz

Mode locking	very short, ps to fs	not necessarily high but normally with high peak power	MHz to THz with stable pulse parameters
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First, shorter pulse duration provides higher resolution. It can slow down some fast-moving objects such as molecules or electrons and therefore measure some ultrafast processes, e.g., the relaxation processes of carriers in semiconductors, chemical reaction dynamics, and electro-optical sampling of high-speed electronics [7]. Second, higher repetition frequency means higher transmission capacities in communications. One example is ultrashort pulse train emitted from a mode-locked laser can be used to realize optical time division multiplexing (OTDM). This is one form of time division multiplexing (TDM), which is widely used in optical fiber communications to increase the overall data transmission capacities.

In addition, many longitudinal modes (different frequencies) are included in the light emission from a mode-locked laser, which enables the lasers to work as multi-wavelength light sources by combining appropriate optical filters. Since these modes (frequencies) are precisely locked to longitudinal mode spacing [8], they are very promising for another capacity improvement technique: wavelength division multiplexing (WDM).

Besides the above advantages in optical fiber communications, pulse trains at some specific repetition frequencies (e.g. 5 GHz) generated by mode-locked lasers can also be used as optical clock signals for the future inter- and intra-connections in electronic circuits, e.g., as optical clocks for computer motherboards [9-11].

It is also obvious from the above that if we want to realize the advanced telecommunications in the 2 μm range, mode-locked lasers at $\sim 2 \mu\text{m}$ are essential.

In the following several paragraphs, the basic idea and mechanism of mode locking will be introduced using a simplified model. As we know, a laser resonator can support a number of longitudinal modes. The number of modes is determined by the width of the gain profile and the optical length of the laser cavity. The electric field of a single longitudinal mode can be written as

$$E(t) = E \cos[\omega t + \varphi(t)] \quad (1.1)$$

where ω is the angular frequency. The total electric field in a multimode laser resonator, assuming it supports N longitudinal modes, is the superposition of all these longitudinal modes, which is

$$E(t) = \sum_{i=1}^N E_i \cos[\omega_i t + \phi_i(t)] \quad (1.2)$$

the angular frequency interval between two adjacent longitudinal modes, $\Delta\omega$ or $\omega_{i+1} - \omega_i$, is

$$\Delta\omega = \frac{\pi c}{nL} \quad (1.3)$$

where c is the speed of light, n is the effective refractive index, and L is the length of the laser resonator.

When the laser is free running and lack of mode locking mechanism, the phases of the modes are random and independent, and there is no fixed relationship between them (Fig. 1.6(a)). As a result, the total laser intensity will just fluctuate with time, e.g., Fig. 1.7 shows the intensity variation of a free running laser working in the continuous wave (cw) mode. The average intensity of this laser remains constant, but its instant intensity varies with time.

Fig. 1.6. Electric fields of five longitudinal modes when they are (a) out of phase, and (b) locked in phase.

Fig. 1.7. Intensity variation of a free running laser.

In contrast, if a mode locking technique is applied to bring a fixed phase relationship between the modes involved, the results of the total electric field will be totally different. Here for the convenience of the mathematical analysis, a simplified situation is considered. We assume that the phase of all the modes involved when $t = 0$ are the same

$$\varphi_i(t) = \varphi_0 = 0 \quad (1.4)$$

and all the modes have the same amplitude

$$E_i = E_0 \quad (1.5)$$

with these two assumptions, the total electric field in the laser resonator is

$$E(t) = E_0 \frac{\sin(N \frac{\Delta\omega t}{2})}{\sin(\frac{\Delta\omega t}{2})} \cos \omega_0 t \quad (1.6)$$

this electric field can be considered as a carrier wave of frequency ω_0 (the frequency of the central mode) whose amplitude is modulated by the function

$$A_N(x) = \frac{\sin(Nx)}{\sin(x)} \quad (1.7)$$

the intensity of the laser output is proportional to the square of the total electric field amplitude

$$I(t) \propto E_0^2 \frac{\sin^2(N \frac{\Delta\omega t}{2})}{\sin^2(\frac{\Delta\omega t}{2})} \quad (1.8)$$

Figure 1.8(a) draws an example graph of this function when $N = 8$. As it shows, the output consists of a train of pulses. The time interval between two adjacent pulses is denoted by τ_{RT} , and the pulse width is denoted by Δt_p .

Fig. 1.8. Resulting intensity of a laser when (a) 8 and (b) 16 longitudinal modes are locked in phase.

Now we are trying to determine τ_{RT} and Δt_p . τ_{RT} is just the difference in t when the intensity function $I(t)$ reaches two adjacent maxima. To obtain the maximum of this function, there should be

$$\sin^2\left(\frac{\Delta\omega t}{2}\right) = 0 \quad (1.9)$$

which yields a series of t

$$\frac{\Delta\omega t_m}{2} = m\pi \quad (1.10)$$

where m is an integer. Thus

$$\tau_{RT} = t_{m+1} - t_m = \frac{2\pi}{\Delta\omega} = \frac{2nL}{c} \quad (1.11)$$

so the time interval between two adjacent pulses is just the round trip time of the laser cavity. At the same time, we know that $\sin(x) \approx x$ when x is small. Under this condition, the intensity of a pulse is $N^2 E_0^2$, which is N^2 times of a single longitudinal mode. It indicates that the more the modes are locked in phase, the higher the intensity (peak power) of the mode-locked pulses.

Regarding the pulse width, we consider the full width at minimum of an individual pulse. To obtain the minimum of the intensity function $I(t)$, there should be

$$\sin^2\left(N \frac{\Delta\omega t}{2}\right) = 0 \quad (1.12)$$

similar to Eq. (1.9), to meet Eq. (1.12)

$$N \frac{\Delta\omega t_m}{2} = m\pi \quad (1.13)$$

so, the pulse width can be expressed as

$$\Delta t_p = \frac{2\pi}{\Delta\omega N} \quad (1.14)$$

compare this expression to that of τ_{RT} , it is found that

$$\Delta t_p = \frac{\tau_{RT}}{N} \quad (1.15)$$

which means the pulse becomes narrower when more modes are included. This conclusion is shown evidently in Fig. 1.8(b), in which the modes involved doubles compared to Fig. 1.8(a). On the other hand, if we assume that all the longitudinal modes are locked in phase within the gain profile which has a bandwidth of $\Delta\nu_g$, the pulse width also can be expressed as (since $N = \Delta\omega_g/\Delta\omega$)

$$\Delta t_p = \frac{1}{\Delta\nu_g} \quad (1.16)$$

this expression indicates that the mode-locked pulse width is inversely proportional to the gain bandwidth, so the broader the gain profile, the shorter are the mode-locked pulses.

1.1.2.1 Instabilities and noise of mode-locked lasers

The uniform pulse train in Fig. 1.8 corresponds to the perfect mode locking with no instabilities. Practically, various kinds of instabilities may coexist with the mode locking. For example, with Q-switching instability, a mode-locked laser may generate several bunches of pulses instead of a uniform pulse train. Especially when passive mode locking technique is used with a saturable absorber, which is the case for the mode-locked diode lasers in this work, the laser may show different working regimes. This issue will be systematically investigated in Chapter 5. In addition, the mode-locked pulses may be accompanied with large cw component under some operation conditions.

Even without these particular instabilities, a variety of noise still exist in the output of a mode-locked laser: intensity noise (intensity fluctuation between pulses), phase noise (phase fluctuation of locked longitudinal modes), timing jitter (deviation of the temporal pulse positions from those in a perfectly periodic pulse train), etc. In a not so strict way, phase noise (frequency domain) and timing jitter (time domain) can be regarded as the same thing. They are often of special interest since they are closely related to the data transmitting capacity and time resolution of a mode-locked pulse

train.

Phase noise refers to the fluctuations of the optical phase of the output. It can be understood as follows. In the above mode locking mechanism derivation process, a single longitudinal mode is considered as a line at the frequency ω_i in the frequency domain, and this line is a “perfect line” without any widths. But in a real laser system, quantum noise, in particular spontaneous emission of the gain medium would couple into the resonator modes, and it is inevitable. This will lead to phase fluctuation of a longitudinal mode (fluctuation of $\phi_i(t)$ in Eq. (1.2)). If we check the frequency domain (the optical spectrum), a longitudinal mode is not a “perfect line” at the frequency ω_i anymore. Instead, it will be with a finite width. Note that if only the quantum noise is considered, the resulting phase noise (linewidth) will be the so-called quantum-limited phase noise. A simple formula was presented by Schawlow and Townes to calculate this linewidth. According to the formula, the linewidth decreases with longer cavity/round-trip time, lower cavity loss, and higher output power (Fig. 1.9). However, this quantum-limited noise is the theoretically achievable minimum, and it is very difficult to actually reach. There always are some other contributors to increase the actual phase noise, e.g. a coupling of intensity noise to phase noise via nonlinearities, phase noise resulting from some technical noise influences (e.g. temperature fluctuations).

Fig. 1.9. Three factors that determine phase noise (linewidth) of a mode-locked laser.

On the other hand, when every longitudinal mode is not a “perfect line” anymore, the resulting total electric field (Eq. (1.6)) will no longer be with an exact repetition frequency anymore either. This means the mode-locked pulses will not be emitted with an exact time interval as expected, or in another word, timing jitter exists in this pulse train.

Regarding the phase noise measurement of mode-locked lasers, it will be introduced in Chapter 5 together with a systematical and detailed investigation of the

phase noise properties of our fabricated 2 μm GaSb-based mode-locked lasers.

1.1.2.2 Mode locking techniques

To achieve mode locking, two techniques are commonly used: active mode locking and passive mode-locking. For active mode locking, the gain or loss of a laser system is actively modulated in a periodic way. If the modulation is synchronized with the resonator round trips, a train of ultrashort pulses can be generated. With the help of the high stability modulation signal at radio frequency (RF), and lower carrier density (less loss is introduced) which decreases the spontaneous emission level, active mode locking is able to generate pulses with very low phase noise. On the other hand, limited by the relatively slow modulation rate, the pulses generated by this technique are only available with picoseconds durations. Furthermore, external RF sources with required frequencies and currents are very costly at high frequencies, and for diode lasers, the modulation of carriers becomes inefficient at high frequencies due to parasitic effects [12].

Regarding passive mode locking, it is usually realized with a saturable absorber. With the interaction between the intracavity light and the saturable absorption introduced by the absorber, the mode locking operation establishes automatically. Prior to the establishment of the mode locking operation, like the case shown in Fig. 1.7, as the loss of the absorber is intensity-dependent, a tiny peak with higher intensity will always encounter less loss and become stronger. Since the loss of the absorber is modulated by the short pulses themselves, the modulation speed becomes much faster (if the recovery time of it is sufficiently short) than an electrical modulator in the active mode locking cases. Due to this reason, passive mode locking enables the generation of much shorter (femtosecond) pulses since the pulse width is inverse proportional to the fourth root of the curvature in the loss modulation [13]. On the other hand, due to lack of a high stability driving source and high carrier level (more loss is introduced) which increases the spontaneous emission rate, the phase noise of the generated pulse train is usually high.

Conventional passive mode-locking mechanisms are well explained by two fundamental models (Fig. 1.10): slow saturable absorber mode locking with dynamic gain saturation and fast saturable absorber mode locking without gain saturation [14].

Fig. 1.10. Slow saturable absorber mode locking (left) and fast saturable absorber mode locking (right) [14].

In both cases, the duration of the generated pulse is defined by the net gain window, and this window will become narrower when the absorber recovery time becomes shorter. For the slow absorber, corresponding to most of the mode-locked diode lasers (including the lasers in this work), the pulse is shortened in the absorber section to determine its leading edge, while it is broadened in the gain section to determine its trailing edge, as shown in Fig. 1.10 (left). Actually, when the pulse energy is very low, the pulse can only saturate the absorber but not the gain. If this is the case, the generated pulse is even shorter. However, this is not desired when high pulse energy is also needed. For the fast absorber, corresponding to most of the mode-locked solid-state lasers, the pulse is solely determined by the recovery time of the absorber while the gain saturation is negligible due to the much longer upper state lifetime and the smaller gain cross section of solid-state lasers, as shown in Fig. 1.10 (right).

In some cases (particularly mode-locked diode lasers), active and passive mode locking are simultaneously applied, which is the so-called hybrid mode locking. To achieve hybrid mode locking, an external RF signal with a frequency close to the intrinsic passive mode-locking frequency is fed to the absorber section. Such hybrid mode-locked lasers combine the advantages of both active and passive mode locking. To be specific, it has negligible impact on the pulse width and shape as well as the optical spectrum, and the phase noise is dramatically improved at the same time. In

addition, the repetition frequency can be tuned by the external RF signal, and the tuning range can be tens of megahertz [6]. However, this technique still requires an external RF source, which is costly at high frequencies.

1.1.3 Single-frequency and tunable operations

Laser light from a free-running diode laser normally contains many longitudinal modes (with different frequencies). However, single-frequency and tunable single-frequency laser sources with narrow optical bandwidth are of interests and desired in many important applications.

The first one is optical gas sensing and monitoring. Optical method, as compared to other methods (e.g., sensing with metal oxide materials or photo-ionization detector), is usually more straightforward and can achieve a higher frequency resolution. Instantaneous response time allows one to perform in-situ monitoring. Optical sensing is also safer (especially with the “eye-safe” wavelength at $\sim 2\ \mu\text{m}$) since it does not suffer from problems such as catalyst poisoning. Amongst all the optical sensing schemes, tunable diode laser absorption spectroscopy (TDLAS) seems to be the most leading edge [15]. As indicated by the term itself, tunable laser is an essential component for this application, sweeping wavelength to achieve the absorption signature of each gas. For similar reason, various laser cooling methods require a specific laser wavelength very precisely at or near some atomic resonance.

Another significant field requiring single-frequency and tunable single-frequency operations is optical fiber communications. In order to strongly increase the transmission capacities, the wavelength division multiplexing (WDM) technique is one of the most commonly used techniques. For the WDM technique, single-frequency light sources with narrow linewidth are essential. Further, single-frequency operation is still not enough. The single-frequency light sources should be able to cover a wide wavelength range, say 40 nm. This can be realized with a distributed feedback (DFB) laser array with tens of laser emitters, or to reduce the manufacturing and operational costs, with more promising tunable lasers. As mentioned, the $2\ \mu\text{m}$ semiconductor lasers also have potential to be used in advanced telecommunications. To realize it, single-frequency and tunable single-frequency operations are essential.

In addition, A tunable laser can be used for photonic device characterization, e.g.

Si photonic devices.

1.1.4 III-V/silicon integration

In the integrated circuit industry, interconnect bandwidth becomes a major source of uncertainty for high-performance chips. This is caused by the scaling rate of electrical interconnect components cannot catch up with the scaling rate of the transistors. A promising way to solve this problem is to switch to optical interconnects instead. In addition to the bandwidth advantage, optical interconnects also provide some other strengths, e.g., voltage isolation, reduced power dissipation, architectural advantages, etc. Amongst all the optical materials for interconnects, silicon (Si) stands out with its complementary metal-oxide-semiconductor (CMOS) compatible process, which will considerably reduce the cost. Besides, Si photonics does exhibit a large degree of design freedom, and many key functional components for optical communications have been demonstrated [16, 17]. Of course, the primary wavelength for the moment is 1.55 μm , but as mentioned above, 2 μm remains its attraction due to the improved bandwidth. Besides bringing the optical communication capacity for intra- and inter-chip connections, Si photonics also offers potential to develop extremely compact fully integrated transceivers in both 1.55 and 2 μm wavelength range.

In addition to its potential in the above optical communication applications, Si photonics is also desired in making compact and low-cost gas and biosensors. Most present optical sensing systems consist of discrete optical components and bulk gas cells, which limits their viability for applications in portable and economical gas analysis. In contrast, Si photonics allows all functional components of a gas or bio sensor to be integrated on a single tiny chip [18-20], which makes it very attractive in compact sensing systems. As mentioned earlier, the absorption lines of many important industrial gases (e.g., NH_3 , CO , and CH_4) and biological substance (e.g., blood glucose) fall into the 2 μm wavelength range. Again, Si photonics exhibits its potential to develop another 2 μm compact device.

For all the above applications, 2 μm compact lasers are essential. However, they are normally based on GaSb-based compound semiconductors. Making high-performance lasers out of silicon especially electrically pumped ones is still very unrealistic due to the intrinsic material property. Thus an effective integration method

of these two material systems is highly desired. To date, there are several pathways to do III-V and Si integration: edge or grating coupling, flip-chip bonding, direct/adhesive wafer bonding, hetero-epitaxial growth, etc. Edge or grating coupling is the most straightforward method. It avoids the heterogeneous integration process, reducing the fabrication complexity. But the tradeoff is the fabricated device is actually not a monolithic one. It also provides thermal isolation, and allows for the individual optimization of the III-V and Silicon photonic chips. But very tight mechanical alignment is needed, and the coupling loss is relatively high. Flip-chip bonding refers to that an individual laser chip/die is flip chipped on the Si photonic chip. This method leads to a monolithic device, but the fabrication complexity increases and it also needs very tight alignment. This method is less attractive when the process uniformity is highly desired, e.g., in WDM technique when a large number of laser chips are needed. Direct/adhesive wafer bonding overcomes the drawbacks in flip-chip bonding, enabling the simultaneous fabrication of laser arrays. However, wafer bonding needs strict surface treatments, and temperature/pressure control, which complicates the process. With regard to the hetero-epitaxial growth, very thick buffer layers and complicated structures to filter dislocations are needed. These layers may potentially reduce the coupling efficiency. Up till the present moment, there is no conclusion which integration method is the best, and all of them are still being explored and optimized.

1.2 Aims of this work

As a sum up of this chapter, the motivation behind this work lies in the fact that the ever demanding need for different kinds of convenient and compact laser sources in the 2 μm range. Thus, our aims of this work are to develop and investigate a set of such laser sources for a number of applications. The lasers include (i) 2 μm conventional Fabry-Pérot (FP) ridge waveguide lasers, (ii) 2 μm mode-locked lasers (MLLs), and (iii) 2 μm tunable single-frequency lasers. In addition, the III-V/Si integration methods will be studied to combine the advantages of the two worlds.

This work brings together several research strengths of our group, i.e. expertise in semiconductor diode lasers and silicon photonics, as well as world-class fabrication and characterization facilities and equipment.

1.3 Structure of the thesis

Chapter 2 is the literature review. This chapter will follow the order of contents in Chapter 1.

Chapter 3 will introduce the epitaxial structures used for fabricating all the devices in this research work as well as a developed standard fabrication process of single-section ridge waveguide lasers.

Chapter 4 will give a detailed overview of the fabricated single-section lasers. In addition, the carrier recombination behaviors within these lasers will be systematically investigated in-depth in both electrical (via ideality factor) and optical way (via sidewall spontaneous emission).

In Chapter 5, monolithic two-section MLLs will be fabricated and fully characterized. Their mode gain, working regimes, phase noise/timing jitter, frequency tuning will be carefully investigated.

Chapter 6 will focus on two III-V/Si integration methods: wafer bonding and edge coupling. A designed tapered waveguide GaSb-based laser structure, bonded onto Si waveguides, will be simulated. An external cavity III-V/Si tunable vernier laser will be fabricated and characterized.

Chapter 7 will be the conclusions and future works.

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Chapter 2 Literature review

2.1 Diode lasers emitting in the 2 μm wavelength range

Laser emission in this wavelength range was achieved with many different host crystals and fibers doped with Tm^{3+} and Ho^{3+} ions [1] as well as InP- and GaSb-based semiconductor materials [2-5]. Among these lasers, semiconductor diode lasers have their specific advantages: flexible wavelength tuning by engineering the bandgap of the active region, compactness, high efficiency, easy electrical pump, integration opportunities with silicon photonic circuits. Here we will focus on the progress of the 2 μm semiconductor lasers.

High performance 2 μm laser diodes have been demonstrated from InP-based quantum well (QW) laser structures. For example, Luo et al. presented an InP-based semiconductor laser with two InAs/InGaAs QWs, emitting at ~ 2150 nm [3]. However, as shown in Fig. 2.1, for InP material system to emit light in the 2 μm range, relatively high strain is inevitable. This brings difficulties in material growth.

Fig. 2.1. Band gap and lattice constant of different III-V compound semiconductor materials [6].

In contrast, GaSb-based QW lasers are less critical in material growth compared to the highly strained InGaAs QW on InP. Thus, it is more advantageous for

wavelengths in the 2 μm range. According to Rattunde et al., GaSb-based laser structure can be used to emit light from 1.85 to 2.35 μm [7]. In fact, the upper limit is even higher. Researchers at Stony Brook and TU München have realized room temperature lasing from GaSb-based QW structures at longer than 3 μm [8-10]. The first GaSb-based diode laser (2.2 μm) working at room temperature was demonstrated by Caneau et al. in 1985 [11]. Although it is just a double-heterostructure laser with a threshold as high as 6.9 kA/cm^2 , its InGa(As)Sb/AlGaAsSb material system continues to be used by most of the GaSb-based lasers in the 2 μm range afterward. In addition to the high threshold, the output powers of the lasers with double-heterostructures are very low. This state remains until 1992. Choi et al. at MIT [12] reported the first GaSb-based diode laser (2.1 μm) with quantum well structure. The output power reached 190 mW per facet at room temperature while the threshold was lowered dramatically to 260 A/cm^2 . Soon, they further scaled the output power to watt-level (1.9 μm , cw output power of 1.3 W at 12 $^{\circ}\text{C}$ [13]), and set the threshold record for GaSb-based diode laser (2.05 μm , room temperature threshold as low as 50 A/cm^2 [4]).

For most of these GaSb-based QW lasers in the 2 μm range, broadened waveguide design seems very popular. It usually comprises high Al-concentration AlGaAsSb cladding layers and thick waveguide layers (typically 400 nm). This structure increases the optical confinement in the QW region while the confinement in the doped cladding layers is reduced. As a result, high modal gain and low internal loss are provided, leading to low threshold and high output power. However, the beam divergence in the fast axis ($\theta_{\perp}$) of this design is usually large (typically in the range of 63°-67°). This weakness limits the coupling efficiency to optical fibers or other collection optics in which a divergence of less than 45° is normally required.

In 2006, researchers at Fraunhofer-Institut [14] designed a new epitaxial structure with a thin waveguide layer (140 nm) and a low Al-concentration cladding layer to spread the optical mode while maintaining the high confinement of the QW. They also reduced the doping concentration of the cladding layer to maintain the low internal loss. The refractive index profile of the new structure is shown in Fig. 2.2. As a result, the beam divergence is dramatically reduced from 67° to 44° while the threshold is kept unchanged.

Fig. 2.2. Refractive index profile of the conventional broadened waveguide structure (A) and the improved waveguide design (B) [14].

In 2010, researchers at Stony Brook [15] further improved this thin waveguide structure by incorporating it with asymmetric waveguide and cladding layers. In this way, the optical mode was spread more into the n-cladding. Figure 2.3 shows the calculated band alignment and near field distribution. The fast axis divergence was further reduced to 42° . In addition, the fabricated laser also exhibited low threshold (110 A/cm^2) and high output power (cw output power of 1.5 W at 20°C).

Fig. 2.3. Calculated band diagram of the asymmetric waveguide overlapped with near field distribution [15].

On the other hand, there is a weakness in the conventional InGa(As)Sb/AlGaAsSb material system, the inadequate valence band offset, which results in poor confinement of holes. It usually causes a poor high temperature performance and becomes more severe when the In-concentration of the QW is increased to emit light longer than 2 μm . Several solutions were proposed to overcome this weakness, e.g., to introduce more strain in the QW, to increase the Al-concentration of the AlGaAsSb barrier/waveguide layer [8], to use the quaternary AlGaInAsSb instead of the quaternary AlGaAsSb [9, 10], etc. In some more sophisticated designs, a hole stopper layer is applied (Fig. 2.3).

Table 2.1 gives a summary of the above work developing GaSb-based diode lasers as well as performance improvements on different parameters.

Table 2.1. Summary of work developing GaSb-based diode lasers.

Year	Structure (barrier/Al)	λ (μm)	T (K)	J_{th} (A/cm^2)	Power	$\theta_{\perp}$	Ref
1985	double-hete rostructure (quaternary/ 0.27)	2.2	290	6.9 k	very low ($75 \times 250 \mu\text{m}^2$)		[11]
1992	QW (quaternary/ 0.2)	2.1	293	260	190 mW ($100 \times 1000 \mu\text{m}^2$)		[12]

1994	QW (quaternary/ 0.25)	1.9	285	143	1.3 W (300×1000 μm^2)		[13]
1998	QW (quaternary/ 0.25)	2.05	283	50	1.01 W (100×2200 μm^2)		[4]
2005	QW (quinternary /0.21)	3.26	293	4 to 7 k	>10 mW (14×500 μm^2)		[9]
2006	QW (quaternary/ 0.3)	2.3	280		70 mW (6×1000 μm^2)	44°	[14]
2006	QW (quaternary/ 0.3)	2.0	290		1.96 W (150×1000 μm^2)	44°	[14]
2008	QW (quaternary/ 0.35)	3.1	285	<800	80 mW (100×2000 μm^2)		[8]
2008	QW (quinternary /0.20)	3.36	285	~750	15 mW (100×2000 μm^2)		[10]
2010	QW (quaternary/ 0.3)	1.95	293	110	1.5 W (100×3000 μm^2)	42°	[15]

2.2 Mode locking

Mode locking has been achieved in a variety of lasers. Starting from dye lasers in the 1970s, very short pulses were generated taking advantage of the normally broad gain profile of the laser dyes. But these lasers were replaced gradually as the solid-state lasers become more and more mature [16]. The solid-state lasers allow for very short pulses, very high pulse energies/average output powers, and high pulse quality. However, they normally need large and expensive setups with a lot of discrete optical components, which limit their uses in some applications. Fiber lasers can also generate very short pulses with relatively cheap setups [17]. But fiber amplifiers are needed to deliver high output powers. Another weakness of solid-state and fiber lasers is that they can hardly generate pulses with very high repetition rate. Compared with the above types of lasers, mode-locked semiconductor lasers are extremely compact and low cost with ability to generate up to terahertz repetition rate pulses [18]. In addition, they can be electrically pumped in a very convenient way. The weakness for this type of lasers, especially the conventional edge-emitting ones, is that their output

power is limited. More recently, a new category of mode-locked semiconductor lasers rise up, which is the optically pumped vertical external-cavity surface-emitting lasers (VECSELs) [19]. They were demonstrated to compete with solid-state lasers, particularly if a combination of high output power, multi-gigahertz pulse repetition rate, and short pulse duration is required.

Here, same as last part, we will focus on the progress of the conventional mode-locked semiconductor lasers.

2.2.1 Pulse duration

Shorter pulse duration means higher observation or measurement resolution. As we have mentioned in Chapter 1, passive mode locking is able to generate much shorter pulses than active mode locking. Note that despite hybrid mode locking can actually generate even slightly shorter pulses due to the combined action of saturable absorption, saturable gain, and active gain modulation [20], the requirement of the external electrical modulator makes it more complex and thus less attractive. On the other hand, an external cavity normally has no contribution to the improvement of the pulse width [20]. So here we will focus on the monolithic passively mode-locked semiconductor lasers.

The first aspect to affect the pulse duration is the laser structure. To generate a shorter pulse, semiconductor quantum dot (QD) structures are considered to be more ideal compared with QW structures which are benefit from the inhomogeneous broadening of the QD structures, leading to a broader gain profile [21]. For a monolithic mode-locked QW laser, the shortest pulse ever reported is 490 fs, demonstrated by researchers at University of Glasgow on a two-section AlGaInAs/InP QW laser emitting at 1.55 μm [22]. Regarding the monolithic mode-locked QD lasers, in 2005, Rafailov et al. reported pulse duration as short as 390 fs at a 21 GHz repetition rate from a GaAs-based two-section mode-locked QD laser [23]. In 2008, researchers from Canada reported generation of transform-limited Gaussian-pulses at 92 GHz repetition rate with a pulse width of 312 fs on an InAs/InP mode-locked QD laser, which is the shortest pulse from electrically pumped mode-locked semiconductor laser at room temperature [24]. Recently, at a very low temperature (20 K), Finch et al. achieved a shorter pulse duration of 290 fs at a repetition rate of 20 GHz [25]. To the best of my knowledge, this is the shortest pulse ever generated by a

monolithic mode-locked semiconductor laser.

Another aspect is the laser's contact configuration and bias condition. If the laser process has been completed on a certain wafer, waiting for cleaving, a small gain/absorber length ratio is favorable to get shorter pulses. This can be easily understood in the way (if a two-section configuration is assumed) that a circulating pulse in the laser cavity is actually shortened in the absorber section while broadened in the gain section. A small ratio means the pulse will experience more pulse shortening and therefore become shorter. The optimization of the gain/absorber section length ratio will be discussed in more details in Chapter 5. On the other hand, when the contact configuration (length ratio) is fixed after cleaving, a more negative absorber reverse bias will cause the generated pulses to be shorter, while a larger gain section current normally leads to wider pulses. The reason is these bias conditions enhance the effects of shortening and broadening of the two sections, respectively.

M. G. Thomspon et al. at University of Cambridge and L. Zhang et al. from University of New Mexico did systematical investigations on this aspect [26, 27]. As shown in Fig. 2.4 [26], the pulse width decreases with more negative absorber reverse bias while the minimum pulse width keeps dropping when the gain/absorber length ratio becomes smaller. With the optimum absorber length and bias condition, a pulse width of 800 fs is obtained on a 1.3 μm mode-locked QD laser. Fig. 2.5 [27] on the other hand, shows the variation of the pulse width with the gain current. Their findings are in good agreement with the above theoretical analysis.

Fig. 2.4. (a) Pulse duration versus reverse bias for different gain/absorber length ratios. (b) Minimum pulse duration and corresponding peak power for the different gain/absorber length ratios [26].

Fig. 2.5. Pulse width as a function of the gain current at different absorber biases [27].

Table 2.2 gives a summary of the above work obtaining ultrashort pulses from mode-locked diode lasers as well as the special methods/techniques used to achieve them. All the works in the table are based on passive mode locking.

Table 2.2. Summary of work obtaining ultrashort pulses.

Year	Laser type	Wavelength (μm)	Pulse duration	Special methods/techniques	Ref.
2012	monolithic QW	1.52	490 fs		[22]
2005	monolithic QD	1.26	390 fs		[23]
2008	monolithic QD	1.541	312 fs		[24]
2013	monolithic QD	~ 1.22 (20 K)	290 fs	low temperature	[25]

2.2.2 Pulse repetition frequency

The pulse repetition frequency (or repetition rate) of a mode-locked laser is intrinsically determined by the pulse round trip time as well as the number of the pulses circulating in the laser cavity. For a monolithic mode-locked semiconductor laser, two-section or multi-section waveguide is popularly used with all the functional

sections integrated on a single laser chip. Figure 2.6 shows an example of such devices [28]. It comprises a gain section and an absorber section. When working in the mode locking regime, the gain section is forward biased (I_g) while the absorber section normally needs to be reverse biased (V_a). For such devices, the most effective and straightforward method to change the repetition rate is to change their cavity length. In this way, The lowest Frequencies ever reached is around 5 GHz with a cavity length of 8 mm [29], while the highest frequency achieved is 80 GHz with a 0.5 mm-long cavity [30]. This method cannot guarantee an infinite small cavity length since there is a maximum possible modal gain for any material system. Besides, when the cavity becomes very short, the output power will be extremely low. On the other hand, a very long cavity is also not preferred since the thermal issues may become more and more severe.

Fig. 2.6. Schematic diagram of a two-section passively mode-locked laser [28].

In addition to the two-section or multi-section, mode locking has also been achieved in single section devices. Owing to the removal of the absorber section which lowers the total loss, the allowed cavity length is further reduced. Researchers at CNRS, France reported subpicosecond pulse generation with a repetition rate of 346 GHz from an InAs/InP quantum dash (elongated quantum dot) single section laser emitting at 1.55 μm [31]. However, for such single section devices, the mode locking mechanism, as well as the stability and dependence of the pulsation regime on the operating parameters remains unclear.

A more advanced method to break through the 80 GHz limit is harmonic mode locking. Shin Arahira et al. did a lot of work on this. They have demonstrated the extremely high repetition rate of 1.54 THz through the 40th harmonic generation on a monolithic four section mode-locked laser (a gain section, an absorber section, a phase-control section, and a distributed Bragg reflector (DBR) section) emitting at 1.55 μm [32].

Another technique to achieve very high repetition rate is the colliding pulse mode locking (CPM). Instead of placing the saturable absorber at one end of the cavity, the saturable absorber region is placed in a particular position of the laser cavity. If the saturable absorber is precisely at the center of the gain section (symmetric), there will be two counter-propagating pulses meeting in the saturable absorber to bleach it more easily than only one pulse. Consequently, mode locking will be realized at the second harmonic of the fundamental frequency, and the pulse repetition rate is doubled. For example, Chen et al. fabricated lasers with cavity length of 2.1, 1.0, 0.534 and 0.25 mm to generate optical pulses with repetition rates of 39.2, 80.4, 156, and 350 GHz, respectively [33]. If the SA is not at the midpoint of the cavity, instead, it is placed at an integer fractional position of the cavity length (asymmetric, L/n , L is the cavity length and n is an integer), there will be more than one pulse existing in the longer gain section. In this situation, the n^{th} harmonic of the fundamental frequency is expected. For example, sub-THz (860 GHz) was realized by Shimizu et al. through the twelfth harmonic generation [34]. In a more complicated case, we can also place more than one SA along the cavity (MCPM). This situation can be simply seen as several CPM units grouped together. The order of the harmonic generated is determined by the particular geometry of the laser (e.g., the situation of Fig. 2.7 corresponds to the sixth harmonic [35]).

Fig. 2.7. An example of MCPM which corresponds to the sixth harmonic [35].

To achieve a repetition rate much lower than 5 GHz, monolithic devices are no longer effective. Instead, external cavity configurations are needed. In this way, researchers at University of Cambridge reported a record low repetition rate of 310 MHz [36]. The configuration is shown in Fig. 2.8, and it is based on a two-section quantum dot laser.

Fig. 2.8. External cavity mode-locked laser configuration [36].

Furthermore, frequency tuning is also of interests to better meet the application-required repetition frequencies. In an external cavity mode-locked laser, the repetition frequency can be chosen in a wide range by simply moving the end mirror. For a monolithic mode-locked laser, frequency tuning can be achieved via the bias condition. For example, a tuning range of 300 MHz around the fundamental frequency of 33.48 GHz was reported in a 1.55 m mode-locked QD laser [37]. As we mentioned before, frequency tuning is also possible in hybrid mode locking by varying the external RF signal. In this way, a tuning range of 30 MHz has been realized [38].

Table 2.3 gives a summary of the above work obtaining very high/low repetition frequencies from mode-locked diode lasers as well as the special methods/techniques used to achieve them. All the works in the table are also based on passive mode locking.

Table 2.3. Summary of work obtaining very high/low repetition frequencies.

Year	Laser type	Wavelength (μm)	Repetition frequency	Methods/techniques	Ref.
2008	external cavity QD	1.3	310 MHz	external cavity	[36]
2005	monolithic QD	1.26	5 GHz	long cavity	[29]
2006	monolithic QD	1.3	80 GHz	short cavity	[30]
2009	monolithic QDash	1.55	346 GHz	single-section device with shorter cavity	[31]
1994	monolithic QW	1.55	1.54 THz	harmonic mode locking	[32]
1997	monolithic QW	1.56	860 GHz	colliding pulse mode locking (CPM)	[34]

2.2.3 Peak power

As mentioned in Chapter 1, mode-locked semiconductor lasers can be used to generate optical clock signals for the future inter- and intra-connections in electronic circuits. Sufficiently high peak power is very significant for this application to make sure the signal generated from a single mode-locked laser can be detected by hundreds of photodetectors.

For pulse durations below a few tens of picoseconds, the peak power is unable to be measured directly with a photodetector. The peak power is then often calculated from the pulse duration τ_p (measured e.g. with an optical autocorrelator) and the pulse energy E_p (calculated), which can be expressed as

$$P_{peak} = k \frac{E_p}{\tau_p} \quad (2.1)$$

where k is a constant determined by the pulse shape. For sech^2 and Gaussian shapes, its values are 0.88 and 0.94, respectively. The pulse energy E_p can be calculated from the laser output power P_{out} and the repetition rate f :

$$E_p = \frac{P_{out}}{f} \quad (2.2)$$

Ideally, the highest peak power is obtained when the highest laser output power and the shortest pulse duration are achieved simultaneously. However, this normally does not happen in a mode-locked semiconductor laser. As we have pointed out in the last section, to generate a shorter pulse, longer absorber, smaller gain current, and

more negative absorber reverse bias are preferred. But all these conditions lead to a lower laser output power. Thus, it is usually unrealistic to achieve high output powers in these devices while simultaneously maintaining a Fourier-limited short pulse duration.

As far as we know, the highest peak power from a conventional stripe waveguide two-section mode-locked laser is 1.7 W achieved by Gubenko et al., with a pulse width of 3.2 ps at 5 GHz [39]. Tapers can be used to further increase the peak power. By doing this, this value reached as high as 2.25 W with a pulse duration as short as 400 fs by White et al. [40]. Besides, Researchers at MIT demonstrated a new waveguide geometry in 2006 [41]. They used a very thick n-type waveguide layer combined with a very deep etch (below the active region) to successfully fabricate the so-called slab-coupled optical waveguide lasers (Fig. 2.9). With this particular geometry, higher-order modes will be coupled into the slab, where they are below threshold so that only the fundamental mode lases. As a result, the output beam is nearly diffraction-limited even when the ridge is somewhat wider than the conventional ridge waveguide lasers. They also set new power record with a peak power of 5.8 W at 4.29 GHz. In addition, the beam quality, M^2 , was better than 1.2 in both directions [41].

Fig. 2.9. Schematic diagram of a slab-coupled optical waveguide laser [41].

Table 2.4 gives a summary of the above work obtaining high peak powers from mode-locked diode lasers as well as the special methods/techniques used to achieve them. All the works in the table are also based on passive mode locking.

Table 2.4. Summary of work obtaining high peak powers.

Year	Laser type	Wavelength (μm)	Peak power	Special methods/techniques	Ref.
2005	monolithic QD	1.26	1.7 W		[39]
2010	monolithic QD	1.3	2.25 W	tapered waveguide	[40]
2006	monolithic QW	1.5	5.8 W	slab-coupled optical waveguide	[41]

2.2.4 Phase noise/timing jitter

Timing jitter is an important noise parameter that is directly related to the time resolution or transmission capacity when the MLLs are used for the practical applications. As mentioned in Chapter 1, active mode locking exhibits the best jitter performance, followed by hybrid mode locking. The jitter performances of free run passively mode-locked lasers, especially semiconductor-based ones are usually poor due to lack of stable modulation signal as well as a high quantum noise level caused by high spontaneous emission rate. In this section, we will focus on the methods to improve the jitter performance of passively mode-locked semiconductor lasers.

In addition to how the absorber length affects the pulse duration, the research group in University of Cambridge also investigated the influences of the absorber length on the integrated timing jitter [42]. We have known that for optimization of the pulse duration, a longer absorber is preferred to obtain shorter pulses. However, the reverse is found to be true when optimizing the timing jitter. This is clearly shown in Fig. 2.10. The lowest phase noise occurs when the absorber is 260 μm , while this absorber length corresponds to the longest pulse duration. The reason is a longer absorber means higher cavity loss and lower output power, and these in turn result in high quantum noise level. So there is a tradeoff when we decide the absorber length, and this issue will be discussed in greater detail in Chapter 5.

Fig. 2.10. RF spectra for the optimum timing jitter performance for different absorber lengths (left) and pulse duration for the corresponding absorber lengths [42].

Regarding how the bias condition affects the jitter is actually more complicated.

It needs the coordination between the gain current and the absorber bias voltage to reach the optimum jitter. This issue will be investigated in more details in Chapter 5.

For free-running passively mode-locked lasers, the best jitter performance is reported by researchers at University College Cork, Ireland. They demonstrated a pulse-to-pulse jitter as low as 25 fs/cycle (500 fs, 1 MHz to 100 MHz) on a 1.3 μm two-section quantum dot laser [43].

There are several methods to improve the jitter of passively mode-locked semiconductor lasers. The most conventional one is the hybrid mode locking. It was first demonstrated by M. G. Thompson et al. in 2003 on a monolithic InGaAs QD laser [44]. The RF linewidth was reduced from 720 to 97 kHz and the phase noise at a 5 MHz offset was reduced by 11.7 dB. In 2007, significant progress was reported by M. Kuntz et al. [38]. An integrated jitter as low as 190 fs (1 kHz to 1 GHz) was achieved on a mode-locked QD laser.

Another noise reduction method is optical injection locking with the master/slave laser configuration, including cw single/dual tone injection using a master laser with narrow optical linewidth [45, 46], and injection locking by another mode-locked laser with narrow RF linewidth [47]. The results after cw injection locking include phase noise reduction, optical linewidth reduction, optical spectrum narrowing, and pulse broadening of the slave laser (Fig. 2.11). Regarding the injection locking by a MLL, it is more like all the parameters of the slave laser are pulled towards those of the master laser, as shown in Fig. 2.12 [47]. In addition, cw injection locking also increases the repetition frequency tuning range of the slave laser. For example, a tuning range as large as 342 MHz was demonstrated by T. Habruseva et al. using dual tone injection [46]. At the same time, the integrated jitter of the slave laser was reduced to 120 fs (10 kHz to 1 GHz). In this work, they also tried the combination of hybrid mode-locking together with optical injection locking. It turns out the performance is worse than dual tone injection (240 fs integrated jitter and a tuning range of 167 MHz).

Fig. 2.11. Optical spectra (b) and corresponding RF spectra (d) of a two-section MLL before (dashed-line/blue) and after (solid-line/red) cw single tone injection locking [45].

Fig. 2.12. (a) Optical spectra of the master laser (blue). (b) Optical spectra of the slave laser before (black) and after (red) injection locking. Inset shows the RF spectra of the master laser (blue), the

slave laser before (black) and after (red) injection locking, respectively [47].

For the master/slave laser configuration, an external high-performance laser source (master laser) is necessary. Alternatively, the injection locking has another form, which is the so-called self-injection locking. It is realized by injecting a small part of the laser light back into the laser cavity. Figure 2.13 shows a typical setup for self-injection locking. By using this setup, the RF linewidth of a 40 GHz mode-locked QD laser is reduced from its original value by 99% to 1.9 kHz by researchers at TU Berlin [48]. The corresponding pulse-to-pulse jitter is also reduced to a record low value of 23 fs.

Fig. 2.13. Setup for self-injection locking [48].

Mode-locked lasers with external cavities also exhibit better phase noise characteristics than the monolithic ones. The reason is these lasers have much smaller active waveguide proportion (compared to the 100% proportion of monolithic lasers), longer cavity, and normally smaller cavity loss. All of these factors contribute to a lower quantum noise level and a smaller emission linewidth. D. J. Derickson et al. have reported jitter comparison between monolithic and external cavity mode-locked diode lasers back in 1991 [20].

Table 2.5 gives a summary of the above work obtaining low jitters from mode-locked diode lasers as well as the special methods/techniques used to achieve them.

Table 2.5. Summary of work obtaining low jitters.

Year	Laser type	Wavelength (μm)	Jitter	Special methods/techniques	Ref.
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2006	monolithic QD	1.3	25 fs/cycle (500 fs, 1 MHz to 100 MHz)		[43]
2007	monolithic QD	1.29	190 fs, 1 kHz to 1 GHz	hybrid mode locking	[38]
2014	monolithic QD	1.29	120 fs, 10 kHz to 1 GHz	cw injection locking	[46]
2016	monolithic QW	1.55		injection locking by another MLL	[47]
2013	monolithic QD	1.31	23 fs/cycle (219 fs, 10 kHz to 1 GHz)	self-injection locking	[48]

2.3 Single-frequency and tunable operations

The first demonstrated monolithic single frequency diode laser was a distributed Bragg reflector (DBR) laser, where a Bragg mirror was fabricated at one end of the laser gain section to provide positive feedback to the laser modes within the reflector bandwidth [49].

Fig. 2.14. Schematic diagram of a 1.62 μm GalnAsP/InP DBR laser [49].

Wavelength variation can be achieved in such lasers by varying the temperature of the gain region via the drive current, or by varying the operation temperature of the whole device. In both cases, since the reflection band of the Bragg mirror is shifted less than the gain maximum, continuous wavelength tuning can only be achieved in a very limited range. After that, a mode hopping (blue shift) will occur. Mode hopping free tuning over a larger wavelength region is possible by coordinated tuning of the Bragg mirror and the gain structure. For this purpose, two- and three-section DBR lasers were developed, as shown in Fig. 2.15 [50]. However, the tuning range is still very limited ($\sim 5\text{-}10\text{ nm}$).

Fig. 2.15. Schematic diagrams of two- and three-section DBR lasers [50].

Another type of monolithic single frequency diode laser is the distributed-feedback (DFB) laser. It may be the most popular single frequency diode laser even at today. Semiconductor DFB lasers are realized by providing positive feedback to particular wavelengths using an integrated grating structure. The grating structure can be formed on top of the active region. However, this method requires time-consuming regrowth techniques. An easier way is to fabricate laterally coupled (LC) structures, where the gratings are on both sides of the active region [51, 52]. One example is shown in Fig. 2.16 [52], where an AlGaInAs/InP LC-DFB laser was demonstrated by Wang et al. to emit in the $1.55\text{ }\mu\text{m}$ range. For DFB lasers, wavelength tuning is often possible over several nanometers by tuning the temperatures and due to the concurrent shift of the gain structure and the Bragg

grating, the continuous tuning range of the DFB lasers will be higher than that of the DBR lasers. However, this tuning range is still far away from the required tuning range of many applications.

Fig. 2.16. AlGaInAs-InP laterally coupled distributed feedback (LC-DFB) laser [52].

According to L. A. Coldren, The DBR and DFB lasers are actually “never intended or appropriate for wide tunability” [50], which means they are single frequency lasers instead of tunable single frequency lasers. In the early 1980s, the group of L. A. Coldren made the first efforts to develop a real tunable diode laser. They etched a deep groove through the active region of the laser to separate it into two cavities which are butt coupled to each other (Fig. 2.17) [50]. Actually, the configuration of this laser is very similar to the two-section mode-locked lasers.

Fig. 2.17. Schematic diagram of a two-cavity butt coupled laser [50].

After that, a number of more sophisticated widely tunable single frequency laser structures were proposed. The most straightforward one was to use DFB laser array [53, 54]. The DFB elements in the array are fabricated with a slightly different grating pitch. In this way, each DFB element delivers about 3 to 4 nm tuning range with offset to each other, and the array is able to cover a specific wavelength range, say the C-band from 1530 to 1565 nm with around 8 to 10 DFB elements. Figure 2.18 shows an example of this structure from NEC [53].

Fig. 2.18. Schematic diagram of a DFB laser array [53].

Another approach is improved DBR lasers which are known as the sampled-grating DBR lasers [55, 56]. This kind of lasers includes two differently spaced and independently tuned DBRs at each end of the gain section (Fig. 2.19) [57]. By exploiting the vernier effect, they are able to offer a tuning range as wide as 40 nm [56], which covers the entire C-band.

Fig. 2.19. Schematic diagram of a SG-DBR laser [57].

Regarding the vernier effect, it is widely used in the tunable laser designs. Basically, two wavelength selective elements with slightly different free spectral range (FSR) are needed to make use of it. As shown in Fig 2.20, the wavelength where alignment happens is selected. Together with the mechanism to shift the peak wavelength of one or both wavelength selective elements, wavelength tuning is achieved. If the difference in the FSRs is denoted as δ_{FSR} , it is much less than the mode space of either DBR (FSR_1 or FSR_2). Thus, a tuning enhancement of $\text{FSR}_1/\delta_{\text{FSR}}$ (or $\text{FSR}_2/\delta_{\text{FSR}}$) is achieved. This is the reason why a much larger tuning range is available by this kind of lasers.

Fig. 2.20. Schematic diagram of the vernier effect.

Taking advantage of the vernier effect, some other tuning structures have also been demonstrated. Figure 2.21 [58] and 2.22 [59] show two examples where the vernier effect is realized by two rings with different SFRs fabricated in SOI platforms. The difference between these two structures is their III-V/Si integration method. Tuning ranges of 55 nm in the C-band [58] and 54 nm in the O-band [59] were achieved.

Fig. 2.21. Schematic diagram of a tunable laser using the vernier effect. The integration method is edge coupling [58].

Fig. 2.22. Schematic diagram of another tunable laser using the vernier effect. The integration method is direct wafer bonding [59].

We note that in Fig. 2.21, a semiconductor optical amplifier (SOA) is used for light amplification. A SOA is essentially like a diode laser which the facet reflection is suppressed to achieve travelling-wave (TW) operation. Otherwise gain ripple would degrade its performance. To achieve TW operation, normally two methods are used:

anti-reflection (AR) coating and angled facet. For the latter one, tilted or curved waveguides are popularly used. Of course, a combination of AR coating and angled facet is also adopted to increase the design freedom. For the device in Fig. 2.22, there is also a SOA. This SOA is an integrated one with tapered structure, and it also works in the TW mode.

In addition to using Si photonic chips as the external wavelength selective elements, other discrete optical components, i.e., gratings, prisms, birefringent filters etc., are also possible to achieve the same functionality. Figure 2.23 shows two widely used external cavity configurations [60, 61].

Fig. 2.23. Two widely used external cavity configurations with discrete optical components acting as wavelength selective elements.

2.4 III-V/silicon integration

2.4.1 Edge or grating coupling

This is the most straightforward method to integrate III-V light emitting module with Si photonic circuits. In addition to the conventional fiber-based coupling, a typical example using this integration technology is external cavity tunable lasers (Fig. 2.21). As mentioned in Chapter 1, the main drawback of this method is the requirement of very tight mechanical alignments, which usually causes a relatively high coupling loss. To overcome this drawback, some schemes were proposed to facilitate the couplings. For example, researchers at NTT designed a spot size converter using low refractive index polymer cladding to enlarge the mode size and reduce the reflection at the coupling facet at the same time (Fig. 2.24) [62]. Lens groups are also used to facilitate the edge coupling efficiency [63]. However, the

discrete lenses run counter to our integration intentions, and the entire size of the device becomes larger.

Fig. 2.24. A spot size converter designed by researchers at NTT [62].

2.4.2 Flip-chip bonding

Researchers at Fujitsu and Toshiba demonstrated two similar III-V/Si lasers, as shown in Fig. 2.25 [64] and 2.26 [65]. The post-fabricated single III-V chips were flip chip bonded on Si photonic chips. In both cases, SSCs were used to facilitate the coupling and allow more alignment tolerance. These schemes also use edge-coupling, but the III-V chips are bonded instead of moving freely. Evanescent coupling is also possible by bonding a single III-V chip on top of a Si passive waveguide. However, both of the two coupling methods need tight alignment and the uniformity between chips are not guaranteed.

Fig. 2.25. Schematic diagram of an III-V SOA flip-chip bonded on a Si photonic chip [64].

Fig. 2.26. Schematic diagram of another III-V SOA flip-chip bonded on a Si photonic chip [65].

2.4.3 Direct/adhesive wafer bonding

This integration method is the most promising technique for high-volume and low-cost productions when the wafer bonding technique is ready and mature. Research groups at UCSB and Ghent University did plenty of impressive works using direct bonding and DVS-BCB adhesive bonding, respectively. The basic process flow of III-V/Si lasers using these bonding techniques is summarized in Fig. 2.27 [66].

Fig. 2.27. Basic process flow of III-V/Si integration using this bonding technique [66].

For a fabricated laser using this technique, there are several light confinement schemes. For example, the laser mode can be guided in the III-V region only and then coupled into the SOI waveguide circuit using an adiabatic taper structure (Fig. 2.28) [67].

Fig. 2.28. Schematic diagram of an III-V/Si laser. The laser mode is defined by the III-V part, and then coupled to the Si waveguide [67].

Differently, in the case of the directly bonded lasers developed by UCSB, a III-V/Si hybrid mode concept is used, in which the mode is confined by the Si waveguide, while the overlap with the III-V region provides the gain (Fig. 2.29) [68].

Fig. 2.29. Schematic diagram of an III-V/Si laser. The laser mode is defined by the Si waveguide, and the III-V part is acting to amplify the light [68].

Instead of defining the optical mode solely by III-V or Si waveguides, Sun et al. at Caltech used both III-V waveguide and Si waveguide to form the two facets of the laser cavity (Fig. 2.30) [69].

Fig. 2.30. Schematic diagram of an III-V/Si laser. The laser mode is defined by the III-V part and Si part together [69].

In addition to the above hybrid FP lasers, hybrid DFB and DBR lasers as well as the widely tunable lasers are also demonstrated. Figure 2.31 shows the side view of the schematic of hybrid DFB lasers [70]. The lateral grating can be fabricated in either the III-V region or the Si region. An example of hybrid DBR lasers is shown in Fig. 2.32 [70], while Fig. 2.33 gives the schematic of a tunable vernier laser with two ring resonators [66].

Fig. 2.31. Side view of III-V/Si DFB lasers [70].

Fig. 2.32. Schematic of a III-V/Si DBR laser [70].

Fig. 2.33. Schematic of a III-V/Si tunable vernier laser with two ring resonators [66].

Besides, the integration of two-section mode-locked lasers with Si has also been demonstrated by researchers at UCSB (Fig. 2.34) [71].

Fig. 2.34. Schematic of a III-V/Si two-section mode-locked laser [71].

For majority of the above III-V/Si lasers, cleaved facets are included to act as the laser cavity mirrors or coupling edges. Some other coupling structures can be used to make the lasers more integrated, e.g., grating coupler (Fig. 2.35 [66] and Fig. 2.33 [66]), partial reflector (Fig. 2.36 [72]), etc.

Fig. 2.35. Schematic of a III-V/Si laser using grating as output coupler [66].

Fig. 2.36. Schematic of a III-V/Si laser using partial reflector as output coupler [72].

2.4.4 Hetero-epitaxial growth

Several attempts have been made to epitaxially grow both lattice matched and mismatched III-V materials on Si substrates. For the growth of lattice matched III-Vs, dilute nitride material Ga(NAsP) based on GaP has been developed by researchers in Marburg, Germany [73]. Single quantum well laser structure achieved lasing at 943 nm under electrical injection up to room temperature. The growth of highly mismatched antimonides on Si has also been demonstrated. For example, with the very thin 4 nm-wide $\text{In}_{0.2}\text{Ga}_{0.8}\text{Sb}$ QWs grown on Si, room temperature lasing at 1.55 μm under pulsed regime with threshold current density of 5 kA/cm^2 was achieved by Université Montpellier [74]. Alternatively, 2 μm microcylinder QW lasers on Si under optical pump has been reported by USC and UNM [75].

For this growth method, QD structures are more attractive than conventional bulk materials and QW structures due to their improved tolerance to dislocations. The performance of III-V QD laser structures directly grown on Si substrates are also

rapidly approaching the performance of those grown on GaAs substrates. With the recent demonstration of electrically pumped continuous wave QD lasers on Si with very low threshold current density (62.5 A/cm^2) by researchers at University College London [76], it seems that large lattice mismatch between III–V materials and Si is no longer a fundamental hurdle for direct epitaxial growth of III–V layers on Si substrates. Of course, very thick dislocation filter layers and GaAs buffer layer are still critical in this work, and some sophisticated coupling structures are needed to couple light efficiently to the Si-based photonic circuits.

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Chapter 3 Laser structures and fabrication process

This chapter begins by introducing two different 2 μm GaSb-based epitaxial structures used for fabricating all the devices in this research work. After that, detailed fabrication process of single-section ridge waveguide lasers, as well as semiconductor optical amplifiers (SOAs), is given step by step, including some points need attention. All the fabrications mentioned in this work were developed and done in the cleanrooms of Nanyang NanoFabrication Centre (N2FC) at Nanyang Technological University, Singapore. For the fabrication of the two-section mode-locked lasers, it includes several additional steps, and will be introduced in Chapter 5.

3.1 2 μm GaSb-based laser structures

As mentioned before, GaSb-based materials are less critical in material growth compared to the highly strained InP-based materials for wavelength around 2 μm , and actually, GaSb material system can achieve lasing at longer than 3 μm at room temperature under cw operation without any unacceptable strain. So we chose GaSb-based laser structures in this work.

The epi-wafers used for device fabrication are from The Institute of Semiconductors of the Chinese Academy of Sciences (CAS). They were grown on (100) n-GaSb substrates by molecular beam epitaxy (MBE). The detailed growth process is similar to that described in [1]. There are two different epitaxial structures which are summarized in Table 3.1. The two structures are very similar, both comprising a 10 nm-thick $\text{In}_{0.2}\text{Ga}_{0.8}\text{Sb}$ single quantum well (SQW). Single QW structures were chosen. The main consideration is the simplicity and success rate of epitaxial growth. At the same time, the threshold is lower compared to multi QW structures. Although multi QW structures have larger gain/output power and better temperature characteristics, we use the single QW structure at the present stage.

The lattice constants of InSb and GaSb are 0.6479 and 0.6096, respectively. So, the lattice constant of the QW material $\text{In}_{0.2}\text{Ga}_{0.8}\text{Sb}$ can be calculated using Vegard's law as $0.2 \times 0.6479 + 0.8 \times 0.6096$, which is 0.6173. This lattice constant corresponds to a compressive strain of $\sim 1.26\%$ to GaSb (the lattice constant is 0.6096 nm). Basically, the main difference is the Al composition of the barrier layers. One structure uses

$\text{Al}_{0.25}\text{GaAsSb}$ (structure I) while the other uses $\text{Al}_{0.2}\text{GaAsSb}$ (structure II). As mentioned before, the direct result of a higher Al composition is the better confinement of the carriers. At the same time, the AlGaAsSb barriers are intended to be lattice matched with the GaSb substrate no matter what the Al composition is. In addition, the QW material and width of the two structures are intended to be exactly the same. As a result, the two structures should operate at almost the same wavelength. Of course, the larger Al composition of structure I increases the depth of the QW and consequently enhance the QW confinement. As a result, the electron and heavy hole energy levels will move away from the bottom of the conduction band and the top of the valence band, respectively [2]. This increases the QW transition energy, and thus results in a shorter wavelength. This effect is slight and thus causes a small wavelength blueshift for structure I. However, according to Fig. 3.1 which shows the lasing spectra of the two structures near threshold at 40 °C (narrow ridge waveguide devices with a ridge width of 5 μm , and the detailed fabrication process will be given in the next section), the lasing wavelength for structure I is ~ 1960 nm, which is distinctly shorter than that for structure II (~ 2020 nm). The reason may be due to some uncontrollable factors during the growth which increase the compressive strain of the QW region. For convenience, structure I will be referred to as 1960 nm laser/laser structure/laser wafer, while structure II will be referred to as 2020 nm laser/laser structure/laser wafer.

Table 3.1. Complete epitaxial structures of the two different laser wafers

	Layer	Material	Thickness (nm)			Layer	Material	Thickness (nm)
Structure I	7	GaSb	130	Structure II		7	GaSb	250
	6	$\text{Al}_{0.5}\text{GaAsSb}$	2000			6	$\text{Al}_{0.5}\text{GaAsSb}$	1500
	5	$\text{Al}_{0.25}\text{GaAsSb}$	270			5	$\text{Al}_{0.2}\text{GaAsSb}$	270
	4	$\text{In}_{0.2}\text{Ga}_{0.8}\text{Sb}$	10			4	$\text{In}_{0.2}\text{Ga}_{0.8}\text{Sb}$	10
	3	$\text{Al}_{0.25}\text{GaAsSb}$	270			3	$\text{Al}_{0.2}\text{GaAsSb}$	270
	2	$\text{Al}_{0.5}\text{GaAsSb}$	2000			2	$\text{Al}_{0.5}\text{GaAsSb}$	1500
	1	GaSb	500			1	GaSb	500
	0	GaSb	700 μm			0	GaSb	700 μm

Fig. 3.1. Lasing spectra of structure I (upper) and structure II (lower) near threshold at 40 °C.

The 2020 nm laser structure has been calculated by 8-band k dot p method [3]. The results are illustrated in Fig. 3.2, including the first two electron subbands and the first three heavy-hole bands. It is clear that the fundamental transition is $\sim 2.0 \mu\text{m}$, which validate this design.

Fig. 3.2. $\text{In}_{0.2}\text{Ga}_{0.8}\text{Sb}/\text{Al}_{0.2}\text{GaAsSb}$ QW band structure calculation.

3.2 Single-section ridge waveguide laser fabrication

The standard fabrication process of GaSb ridge waveguide lasers has been developed based on our process capability. This process has been used for the device fabrications in our published works before [4, 5], which turns out to be very reliable. The key fabrication process steps are summarized in the following figures, with the cross-sectional schematics of the device and photos of the real samples at different major fabrication steps. In these schematics, purple represents SiO₂, green represents the heavily doped GaSb contact layer, blue represents the cladding and waveguide layers, red represents the active region, brown represents the GaSb substrate, and yellow represents the metal.

1. Step 01: 200nm SiO₂ by plasma enhanced chemical vapor deposition (PECVD)

The 200 nm-thick SiO₂ layer deposition by PECVD at 200 °C (this is a relatively low temperature for PECVD process since GaSb-based materials are basically not so stable at high temperatures) after a cleaning process (acetone, IPA, DI water) is performed on the GaSb wafer. This layer will act as the hard mask during the etching process in step 03.

2. Step 02: dry etching SiO₂ (200 nm) to form hard mask

After the PECVD deposition, the SiO₂ layer is photolithographically patterned and etched by dry etching with photoresist as the etching mask. It is illustrated in Step 02. The detailed processes are as follows:

a. HMDS: 90 °C for 90 seconds;

- b. Spin coating of Positive Tone Resist (4000 rpm for 30 s to coat AZ5214E with $\sim 1.4 \mu\text{m}$ resist thickness), exposure and development (a photo of the real sample after development is shown in Fig. 3.3)
- c. Dry etching of $\text{SiO}_2 = 200 \text{ nm}$;
- d. Photoresist removal (flood exposure (90 s) and development (5 min));

Fig. 3.3. A photo of the real sample after photolithography.

3. Step 03: ridge waveguide formation with ridge height of $\sim 1.6 \mu\text{m}$ (above the active region, SiO_2 is used as hard mask)

In order to form the ridge waveguide structure, part of the GaSb wafer needs to be etched off. The ridge structure is needed to confine light in the lateral horizontal direction and help to prevent the excessive current spreading. Step 03 schematically shows the formation of ridge waveguide structure with etching process. There are two major types of etching: wet etching and dry etching. Wet etching uses aqueous solutions

as etchant, whereas dry etching uses gaseous plasma in Inductively Coupled Plasma (ICP).

In short, wet etching results in smooth surface and sloped sidewalls (beneficial for covering when doing the dielectric and metal depositions later), while dry etching usually leads to vertical sidewalls, uniform ridge width, and increased roughness of the sidewalls. The wet etching method is used in this fabrication. In developing an etching process, two things must be considered: etch rate in order to get the right ridge height (how much material is removed per unit time) and etch selectivity (the ratio of the material etch rate to the mask etch rate). For GaSb-based materials, the etchant we use is H_3PO_4 : $\text{C}_6\text{H}_8\text{O}_7$: H_2O_2 (40%): DI H_2O = 20 ml: 20 g: 40 ml: 200 ml. Here one significant thing to note is that after the preparation of the etchant, one must let it sit for at least 20 min or use dummy wafer to do etching process for at least 20 min, instead of carrying out the etching process on the laser samples immediately. Based on our experience, the surface of the laser samples, as well as the sidewall of the ridge waveguide, will be very uneven.

4. Step 04: SiO_2 removal, and new 200-nm-thick SiO_2 deposition
 - a. 200 nm SiO_2 dry etching;
 - b. 200nm SiO_2 deposition by PECVD at 200 °C (a photo of the real sample after SiO_2 deposition is shown in Fig. 3.4).

Fig. 3.4. A photo of the real sample after SiO₂ deposition.

5. Step 05: contact window definition on the ridges

The purpose of this step is to expose the GaSb contact layer for current injection. The detailed processes are shown below:

- a. AZ5214E litho (1.4 μm resist thickness with HMDS, image reversal);
- b. 200 nm SiO₂ buffered oxide etch (BOE) (Fig. 3.5 shows a photo of the real sample after BOE, we can see clearly from the figure that GaSb contact layer in the contact window region is exposed while other regions of the device are coated with SiO₂);
- c. Strip photoresist in heated acetone (170 $^{\circ}\text{C}$, 5 min, three times);

Fig. 3.5. A photo of the real sample after contact window definition.

6. Step 06: P-metal (Ti/Au: 50/300 nm) deposition

The p-side metal is deposited on the GaSb wafer to form ohmic contact for current injection. The detailed processes are as below:

- a. $\text{HCl} : \text{H}_2\text{O} = 1 : 10$ for 30 s to remove the native oxide;
- b. $\text{Ti/Au} = 50/300$ nm deposition by e-beam evaporation (Fig. 3.6 shows an SEM image of a real sample after p-side metal deposition. Actually the thicker the metal, the better the contact. In addition, the metal should be thick enough to make sure the good covering as well as that it can be a reliable mask for isolation etching of a mode-locked laser. However, a too thick metal deposition will increase the difficulty of cleaving as well as lift-off process of a mode-locked laser);

Fig. 3.6. SEM image of the cross-section of a real sample.

7. Step 07: Substrate lapping to $\sim 120\ \mu\text{m}$ -thick for better cleaving and backside metallization by Ni/Ge/Au/Ni/Au

This step is polishing the bottom side of GaSb substrate for n-side contact. The thickness of the wafer can be controlled by polishing. In general, the target thickness is ~ 100 to $130\ \mu\text{m}$, as thinner wafers are typically easier to cleave and has exhibited reduced series resistance. After the polishing step, n-side ohmic contact is formed with Ni/Ge/Au/Ni/Au deposition on the bottom of the GaSb substrate. The electrical properties of alloyed AuGe offer relatively lower contact resistance to n-type GaSb. The detailed processes are shown below:

- a. Fix the sample p-side down on a glass plate with CrystalbondTM;
- b. Thin down the substrate with Al_2O_3 powder ($10\ \mu\text{m}$ for coarse grinding and $3\ \mu\text{m}$ for fine grinding, respectively)
- c. Strip the CrystalbondTM in heated acetone to peel off the sample
- d. Ni/Ge/Au/Ni/Au = 5/25/100/20/300 nm deposition by e-beam evaporation

8. Step 08: Cleave and bond the laser bars or the single devices to a heat-sink

In this step, laser bars or single laser chips are cleaved by hand. Then the last step is the bonding process of the laser chips to heat-sinks with AuSn solder, as illustrated in Fig. 3.7. AuSn solder is widely used to bond semiconductor lasers due to its high reliability.

Fig. 3.7. A photo of the bonding process between chip and heat-sink with AuSn solder.

3.3 Summary

To sum up, we used laser wafers with two different laser structures to fabricate all the devices in this work, including single-section ridge waveguide lasers, SOAs, two-section MLLs, etc. The main difference of the two structures is one uses AlGaAsSb barrier with higher Al composition to improve the carrier confinement. The lasing wavelengths of the two structures are slightly different. According to this, they will be referred to as 1960 nm laser/laser structure/laser wafer and 2020 nm laser/laser structure/laser wafer, respectively.

For the fabrication process of single-section ridge waveguide lasers, first, standard photolithography and wet chemical etching were carried out to form the ridge. A SiO₂ layer was deposited on top of the wafer, and contact window was opened by lithography and the following buffered oxide etch (BOE) process. After Ti/Au was evaporated on top of the laser sample to form the p-side contact, the laser

sample was thinned to a thickness of $\sim 120\text{ }\mu\text{m}$, and Ni/Ge/Au/Ni/Au was evaporated to form the n-side contact. In the end, the laser sample was cleaved into laser bars or single laser chips. Some of the lasers would be mounted on heat-sinks, waiting for characterization.

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Chapter 4 Single-section ridge waveguide lasers

Single-section lasers here refer to single-section Fabry-Perot (FP) ridge waveguide lasers. The term “single-section” is in contrast to the “two-section” mode-locked laser devices in the next chapter. This chapter begins by giving a detailed overview of the characterization of the fabricated single-section lasers. Next, the carrier recombination behaviors within these GaSb-based lasers as well as how temperature affects these behaviors are systematically investigated in-depth in both electrical (via ideality factor) and optical way (via sidewall spontaneous emission). We compared and analyzed the findings in the two ways, trying to tell what is really happening in the lasers. These investigations are beneficial for having a better understanding of the GaSb-based diode lasers, thus provide a guideline for further improvement.

4.1 Device overview

In order to confirm the material quality and the fabrication process, the two kinds of grown wafers were processed into basic FP ridge waveguide lasers using the developed fabrication process described in the last chapter. The fabricated lasers are with different ridge widths (from 5 to 90 μm) and cavity lengths (from 0.5 to 4 mm). Both facets of the lasers are kept as-cleaved without coatings. The ones with wider ridge were mounted on CuW heat sinks with AuSn solder. The electrical and optical characteristics of these lasers were systematically measured on a laser diode mounting fixture equipped with temperature electronic controller (TEC), and the results were compared. According to the results, the 1960 nm laser structure performs better in many aspects as expected, such as lower threshold current density, higher slope efficiency as well as output power, higher characteristic temperatures as well as operation temperature, and so on. As such, in the following device overview section, the results presented are mainly from the 1960 nm lasers.

Figure 4.1 shows the temperature-dependent light output power and voltage vs. injection current (L-I-V) curves of one fabricated 1960 nm laser. The ridge width and cavity length of the laser are 5 μm and 2190 μm , respectively. The operation temperature is only raised to 80 °C which is limited by the TEC, and it is obvious that

the laser can work at even higher temperatures. The output power corresponds to one facet of the laser.

Fig. 4.1. Temperature-dependent L-I-V curves of one fabricated 1960 nm laser.

As can be seen from Fig. 4.1, at 20 °C, the laser works well in continuous wave (cw) mode with a threshold current of ~59 mA, corresponding to a current density of 539 A/cm². Much lower threshold current density of 96 A/cm² was achieved in a 2019 nm laser with much wider ridge (115 × 1180 μm²). This is among the lowest values for such GaSb-based lasers emitting at 2 μm and above. Note that this is not contradictory to what we claimed above that the threshold current density of the 2019 nm laser is higher. The reason is only 2019 nm wafer was processed into lasers with such wide ridges, and a wider width generally means worse thermal dissipation, but also lower threshold current density. Focus on the 1960 nm laser in Fig. 4.1 again. The laser shows a maximum output power of more than 25 mW per facet with an injection current of 300 mA at 20 °C. When the operation temperature is raised, the threshold current increases consistently, attributed mainly to the carrier overflow at elevated temperatures. At the same time, the slope efficiency drops gradually with temperature. To quantify the threshold current and slope efficiency changes, two characteristic temperatures T_0 and T_1 are widely used. The variation of the threshold current density (I_{th}) and slope efficiency (η_s) with temperature (T) for a semiconductor laser can be empirically expressed as [1]

$$I_{th}(T) = I_0 \exp\left(\frac{T}{T_0}\right) \quad (4.1)$$

$$\eta_s(T) = \eta_0 \exp\left(-\frac{T}{T_1}\right) \quad (4.2)$$

where I_0 and η_0 are two constants, T_0 and T_1 are the characteristic temperatures whose values are the measures of the temperature sensitivity of the threshold current density and slope efficiency, respectively. To extract T_0 and T_1 , temperature dependences of I_{th} and η_s (on logarithmic scales) are determined and shown in Fig. 4.2.

Fig. 4.2. Temperature-dependences of I_{th} and η_s (on logarithmic scales).

T_0 is determined to be ~103 K near room temperature, and decreases consistently when temperature rises. This T_0 is significantly higher compared to that of other reported GaSb-based quantum well lasers, whose typical T_0 is 60 to 80 K [2, 3]. At the same time, T_1 is as high as 606 K near room temperature, which is very impressive, even comparable to some quantum dot lasers [4]. These outstanding high temperature performances suggest good material quality.

With regards to the I-V curves in Fig. 4.1, the series resistance and turn-on voltage of the laser diode can be extracted from them. As we know, the turn-on voltage is roughly proportional to the bandgap energy of the material, and it was determined to be ~0.45 V (corresponding to a current density of 10 A/cm²) for the tested laser at 20 °C. When the temperature increases, its value drops consistently to

~0.35 V at 80 °C. This distinct decrease is related to the bandgap shrinkage at increasing temperature on one hand. On the other hand, the energy of the carriers becomes higher when temperature rises, which makes it easier for them to overcome the p-i-n junction potential barrier. At the same time, the series resistance also keeps decreasing, all the way down from 3.66 Ω at 20 °C to 1.96 Ω at 80 °C, which is due to the same reason as the turn-on voltage.

It is known that there are two parameters that cause the lasing wavelength to shift, which are junction temperature and drive current. The main way for the temperature to affect the lasing wavelength is to change the bandgap of the p-i-n junction and therefore the peak of the gain profile. The temperature dependence of the lasing wavelength is recorded and fitted, as shown in Fig. 4.3. As we can see, the lasing wavelength increases linearly as temperature rises with a rate of 0.93 nm/K. The Lasing spectra just above threshold at four different temperatures has also shown in the inset of Fig. 4.3.

Fig. 4.3. Temperature dependence of the lasing wavelength. Lasing spectra just above threshold at four different temperatures has also shown in the inset.

Regarding the drive current, normally it acts to fine tune the allowed longitudinal mode shift by varying the effective cavity length of the laser. This effect occurs because carrier density in the p-i-n junction and the instantaneous junction temperature change the refractive index of the junction material and therefore the effective cavity length. Because the largest current we applied was only 300 mA, it did not cause obvious wavelength redshift.

The net modal gain ($G_{\text{net}} = \Gamma \cdot g - \alpha_i$) spectra of a fabricated 2020 nm laser at 20 °C are shown in Fig. 4.4 [5]. G_{net} is computed from amplified spontaneous emission (ASE) spectra obtained at different injection currents using Eq. (4.3) [6, 7].

$$G_{\text{net}}(\lambda) = \Gamma g_{\text{material}}(\lambda) - \alpha_i = \frac{1}{L} \ln \frac{\sqrt{S(\lambda)} - 1}{\sqrt{S(\lambda)} + 1} + \frac{1}{2L} \ln \left(\frac{1}{R_1 R_2} \right) \quad (4.3)$$

where α_i is the internal loss, S is the ratio of intensity maximum $P(\lambda)$, and minimum $V(\lambda)$ in the consecutive FP resonances in the whole wavelength range, as expressed in the inset of Fig. 4.4, L_c is the cavity length, and R_1 and R_2 are facet reflectivities.

The inset of Fig. 4.4 gives the FP modes in greater detail. The sharp peak and valley indicate excellent mode spacing as expected. In calculating the G_{net} , we used the known laser cavity length L_c . The laser facet reflectivity R is determined by $[(n-1)/(n+1)]^2$, where n is the group refractive index, obtained from the ASE spectrum. It can be seen from Fig. 4 that, when the current is 36 mA, just below the threshold (37 mA), the maximum gain is reached. Assuming a modal gain of zero at long wavelengths, we extracted the internal loss (α_i) to be $\sim -5 \text{ cm}^{-1}$, which indicates the high quality of the laser material again.

Fig. 4.4. Net modal gain spectra at different injection currents of one fabricated 2020 nm laser at 20 °C [5]. The inset gives the FP spectra in greater detail.

4.2 Ideality factor

As we mentioned in Chapter 2, numerous progress has been made in both GaSb-based materials and devices. Despite these achievements, fundamental investigations are still highly desirable to understand the ultimate limits of the devices. For instance, the carrier recombination behaviors within the lasers directly affect the laser performance such as threshold current density (J_{th}), power efficiency, temperature characteristics, etc. However, a systematic study of the carrier recombination in GaSb-based lasers remains lacking.

As one of the commonly used parameters, ideality factor is a reflection of carrier transport and recombination within the devices in an electrical way. Its value suggests the dominant carrier recombination type or the proportions of different recombination types. For example, in a single p-n junction, the ideality factor changes when different recombination dominates the forward current: recombination in the neutral regions (1.0); Shockley-Read-Hall (SRH) recombination in the space charge region (2.0); radiative recombination in the space charge region (1.0); Auger non-radiative recombination in the space charge region (2/3).

In this section, a systematic study of the ideality factor on a working 2 μm GaSb-based laser (1960 nm laser structure, the same one in the above overview section) is carried out. Temperature-dependent differential resistance and the well-known product curve of the laser are drawn and analyzed.

Electrically, a laser diode is considered to include a forward-biased pn junction with a QW, and a series resistance R_s . The QW may further “manage” the carriers overcome the pn junction potential barrier, facilitating carrier recombinations especially the radiative recombination since it increases the carrier density. Specific analysis of the mechanism and the effects of the QW on the ideality factor will be given in the following part. The series resistance R_s comes mainly from the neutral n and p regions. In general, the current-voltage (I-V) relationship of a p-n junction can be written as [8]

$$I = I_s \left[\exp\left(\frac{eV_j}{nkT}\right) - 1 \right] \quad (4.4)$$

where I_s is the reverse-saturation current, e is the electron charge, V_j is the voltage across the junction, n is the ideality factor, k is the Boltzmann constant, and T is the temperature. For $V_j > 3kT/e$, the -1 term can be ignored and so the above expression

reduces to

$$I = I_s \exp\left(\frac{eV_j}{nkT}\right) \quad (4.5)$$

then V_j can be expressed as

$$V_j = \frac{nkT}{q} (\ln I - \ln I_s) \quad (4.6)$$

The total voltage applied to the laser diode (V) equals the sum of the voltage across the junction (V_j), and the voltage across the series resistance R_s . We can write the expression

$$V = V_j + IR_s \quad (4.7)$$

Figure 4.5 shows this I-V relationship of the tested 2 μm GaSb-based laser at 30 and 60 $^{\circ}\text{C}$. Just as we mentioned in the above device overview section, the turn-on voltage (the voltage required to induce a forward-bias current density of 10 A/cm^2) of the laser diode at 60 $^{\circ}\text{C}$ ($\sim 0.38 \text{ V}$) is lower than that at 30 $^{\circ}\text{C}$ ($\sim 0.43 \text{ V}$).

Fig. 4.5. I-V relationship of the tested 2 μm GaSb-based laser at 30 and 60 $^{\circ}\text{C}$.

Now if we take the derivative of V to I , the differential resistance of the laser diode can be obtained (using Eq. (4.6) and (4.7)), which is

$$\frac{dV}{dI} = \frac{nkT}{q} \frac{1}{I} + R_s \quad (4.8)$$

it is a combination of two parts. The first term on the right-hand side is the differential

resistance of the p-n junction, and the second term is the series resistance. If dV/dI is plotted as a function of $1/I$, the ideality factor n can be obtained from the slope of the plot which is nkT/q . At the same time, the intercept at $I=0$ equals R_s . Figure 4.6 shows such plots at 30 and 60 °C.

Fig. 4.6. dV/dI vs. $1/I$ plots for the tested 2 μm GaSb-based laser according to Eq. (4.8) at 30 and 60 °C. The rapid change in dV/dI near lasing threshold is shown in the inset.

The plots can be divided into three parts:

First, when the applied voltage is very small to be less than the turn-on voltage of the p-n junction, almost all the voltage will be applied on the junction. The equivalent resistance of the junction will be very large, and the effect of the series resistance is negligible. Note that the voltage applied on the p-n junction equals the separation between the electron quasi-Fermi level and hole quasi-Fermi level.

Second, when the applied voltage is larger than the turn-on voltage but the laser has not lased yet, the differential resistance of the p-n junction will keep reducing with increasing voltage (or current). If the ideality factor of the junction n is a constant, this reduction should be linear. Carriers continue to flow into the QW, accumulating and recombining in it, and the separation between the quasi-Fermi levels becomes larger. In this part, the increasing voltage starts to apply on the series resistance. As shown in Fig. 4.6, the differential resistance of the laser diode at 60 °C

keeps being lower than that at 30 °C, which is due to the same reason as the lower turn-on voltage. At currents between 10 and 20 mA, n is determined to be 2.15 and 2.55 at 30 and 60 °C, respectively. The reason why n is larger at higher temperature will be analyzed in the following paragraphs.

It is known that the carriers flowing into the QW are supposed to have three main recombination processes [9]:

- 1) Shockley-Read-Hall (SRH) recombination which is a defect- or impurity-related nonradiative recombination. Its rate is proportional to the carrier density (N) in the active region, resulting in an ideality factor of 2, and can be written as $R_{SRH} = V(N/\tau)$, where V is the volume of the active region and τ is the lifetime of the carrier lifetime;
- 2) radiative recombination whose rate is proportional to N^2 , resulting in an ideality factor of 1, and can be written as $R_{\text{spn}} = VBN^2$, where B is the radiative recombination coefficient;
- 3) Auger NR whose rate is proportional to N^3 , resulting in an ideality factor of 2/3, and can be expressed as $R_A = VCN^3$, where C is the Auger recombination coefficient.

Generally speaking, when the carrier density is very low, SRH recombination will dominate the carrier consumption. As the increase of the carrier density, radiative recombination starts to take over due to the quadratic growth of its rate with the carrier density. Auger recombination only dominates when the carrier density is very high since normally C is much smaller than B .

Since the existence of the QW increases the carrier density, it actually facilitates the radiative recombination at small current, thus leading to a smaller ideality factor. Now we can explain why the ideality factor at 60 °C is larger. When temperature is raised from 30 to 60 °C, more severe carrier overflow occurs to lower the carrier density within the QW region. The carriers overflowing into the AlGaAsSb waveguide layers will be dominated by the SRH recombination since the carrier density there is very low, giving a large ideality factor. So under the effect of this process, the radiative recombination at 60 °C is suppressed compared to the 30 °C case, and the ideality factor increases. It also confirms our above analysis on the carrier recombination behaviors of the laser at different carrier density levels. Regarding the reason why the absolute value of the ideality factor is relatively large (larger than 2), it may be due to some other carrier loss channels introduced either by the growth or by the process. In addition, note that the doping concentration of the n-GaSb substrate is low ($\sim 10^{17}/\text{cm}^3$), and the annealing process is not carried out on

the tested laser since high temperature annealing may worsen its performance. So the n-GaSb substrate/metal contact should exhibit some rectifying characteristics, which is also a possible reason for a relatively large ideality factor.

Third, when lasing action starts, ideally, the two quasi-Fermi levels will be pinned at the threshold, and hence the voltage across the p-n junction also becomes pinned at its threshold owing to the intense stimulated emission [10]. The differential resistance of the p-n junction disappears suddenly, and all the increasing voltage applies to the series resistance. This is one of the most distinguishing features of lasers, separating light-emitting diode (LED) operation from laser operation. Therefore, a sudden decrease of the total differential resistance, to the value of the series resistance, can be observed at the lasing threshold as shown in the inset of Fig. 4.6. The series resistance of the laser diode is determined to be 3.75 and 2.65 Ω at 30 and 60 $^{\circ}\text{C}$, respectively.

In addition to the dV/dI plot, there is an alternate plot which is also convenient to directly determine the value of the ideality factor. As we mentioned above, at the lasing threshold, the junction voltage will be pinned at its threshold value, while the differential resistance of the junction disappears. The derivative dV/dI above threshold is therefore a constant equal to the series resistance R_s . At the same time, the product $I dV/dI$ which can be expressed as (using Eq. (4.8))

$$I \frac{dV}{dI} = \frac{nkT}{q} + IR_s \quad (4.9)$$

should decrease abruptly from $nkT/q + IR_s$ to IR_s and then continue to increase with current at a rate equal to R_s . So if this product is plotted as a function of the current, we can easily determine the ideality factor and series resistance of the laser diode by the intercept at $I = 0$ and slope after lasing threshold, respectively. Figure 4.7 shows such plots at 30 and 60 $^{\circ}\text{C}$. The plots give ideality factors of 2.15 (30 $^{\circ}\text{C}$) and 2.57 (60 $^{\circ}\text{C}$), which is in very good agreement with the values determined from the dV/dI plots.

Fig. 4.7. $I(dV/dI)$ vs. I plots for the tested 2 μm GaSb-based laser according to Eq. (4.9) at 30 and 60 $^{\circ}\text{C}$, and L - I curves at the same temperatures.

In addition, because of the linear current scale, this product is more convenient for direct measurement of the lasing threshold than the derivative dV/dI alone, and the threshold determined by it is quite accurate as shown in Fig. 4.7. This may prove extremely convenient in production applications where a bare laser die must be characterized before mounting and packaging. This method of characterization permits threshold calculation without the time consuming (and expensive) inconvenience of having to position the die in front of a detector.

4.3 Sidewall spontaneous emission

In addition to using the ideality factor to investigate carrier recombination in an electrical way, carrier recombination can also be analyzed in an optical way. For example, spontaneous emission (SE) reflects directly the intensity of the carrier radiative recombination. The measurement of SE has been used as a powerful tool to investigate the intrinsic recombination mechanisms in several electrical injection lasers such as GaAs-based QW, QD, and InP-based QW lasers [11-15]. However, a systematic SE study on 2 μm GaSb-based lasers remains lacking.

Furthermore, as we mentioned in Chapter 2, there is an intrinsic drawback in GaSb-based QW structures, which is the inadequate confinement of the holes in the active region, and the impacts of this drawback on the carrier recombination behaviors

have not been revealed experimentally.

In this section, temperature-dependent SEs at different biasing currents have been measured from the sidewall of a working 2 μm GaSb laser. Since we want to see the effects of the inadequate confinement on the carrier recombination, this laser is fabricated from the 2020 nm laser wafer. By extracting and analyzing the local Z power parameter, better insights into the effects of I_{bias} and T on the carrier recombination mechanisms are obtained. In addition, the carrier loss mechanisms have also been investigated in detail.

For easier measurement of the SE from the sidewall, the laser we use here has a relatively wide ridge ($115 \times 1180 \mu\text{m}^2$). The measurement method is schematically shown in the inset of Fig. 4.8. It was collected by a multimode optical fiber and fed into an optical spectrum analyzer (OSA, AQ6375). Since there is almost no feedback in the direction perpendicular to the laser ridge, the measured SE does not undergo significant amplification or absorption. SE spectra were recorded at different I_{bias} values from 25 mA with a step of 25 mA. For clarity, SE spectra at four different I_{bias} values measured at 20 $^{\circ}\text{C}$ are shown in Fig. 4.8. The SE spectral intensity increases with I_{bias} and the spectral peaks locate at slightly shorter than 2020 nm. This peak is attributed to the transition from the first electron band (E1) to the first heavy-hole band (HH1) on the basis of band structure calculations, as shown in Fig. 3.3.

Fig. 4.8. SE spectra of the tested laser at four different I_{bias} at 20 $^{\circ}\text{C}$. The inset shows the schematic diagram of the SE measurement configuration.

The integrated SE intensities (P_{SE}) at different I_{bias} values at 20 °C were calculated from the SE spectra as shown in Fig. 4.9 (squares). It is well known that P_{SE} can reflect the carrier density (N) within QWs, and theoretically, when the lasing action starts, N will be pinned at its threshold owing to the intense stimulated recombination. Therefore, P_{SE} should also be pinned at the lasing threshold. This postulation is confirmed by the experimental data at 20 °C in Fig. 4.9: P_{SE} remains almost unchanged after lasing (shown by hollow squares). The same phenomenon has also been observed in our GaAs-based QD laser [11] and some InP-based QW lasers [10].

Fig. 4.9. Integrated SE intensities (P_{SE}) at different I_{bias} values calculated from the SE spectra at four different temperatures (20, 40, 60, and 80 °C). The hollow squares represent the results obtained after lasing at 20 °C.

To analyze the carrier recombination behaviors with the variation in I_{bias} , the following model [9], which gives the relationship between I_{bias} and P_{SE} , was used:

$$I_{bias} = \left(\frac{e^2 V}{R} \right)^{1/2} \left(\frac{1}{\tau_{nr}^2 B} \right) \left(\sqrt{P_{SE}} \right)^1 + \frac{e}{R} \left(\sqrt{P_{SE}} \right)^2 + \left(\frac{e^2}{R^3 V} \right)^{1/2} \left(\frac{C}{B^{3/2}} \right) \left(\sqrt{P_{SE}} \right)^3 \quad (4.10)$$

where e is the electron charge, V is the volume of the active region, R is the ratio of the detected intensity P_{SE} to the actual intensity P (i.e., $P_{SE} = R \times P$), τ_{nr} is the nonradiative lifetime, and B and C are the radiative recombination and Auger recombination coefficients, respectively.

In this model, prior to lasing, the injected carriers are supposed to have the three recombination processes which are the same as in the ideality factor section, corresponding to the three terms on the right-hand side of Eq. (4.10). Since all the three terms on the right-hand side of Eq. (4.7) have the factor $(\sqrt{P_{SE}})$, Eq. (4.10) can be expressed as

$$I_{bias} \propto (\sqrt{P_{SE}})^Z \quad (4.11)$$

where Z is the local Z power parameter, which ranges from 1 to 3 if the current is dominated by defect- or impurity-related NR ($Z \approx 1$), radiative recombination ($Z \approx 2$), or Auger NR ($Z \approx 3$). The actual Z value reflects the proportions of these three recombination processes. Note that this model does not consider the carrier leakage that may cause Z to be more than 3.

To extract the Z values of the tested laser at 20 °C, $\ln(I_{bias})$ is plotted against $\ln(P_{SE}^{1/2})$ in Fig. 4.10(a) (squares indicate the experimental data). The Z values are the slopes of this plot and can be obtained by second-order polynomial fitting to the experimental data shown by dashed lines in the figure. The Z values at 20 °C are shown in Fig. 4.10(b) (squares). Z increases with I_{bias} , which is due to the following reasons: when I_{bias} increases, n within the active region also increases. Since the rate of Auger NR follows N^3 , while it is on the order of N^2 for radiative recombination, the contribution of Auger NR will increase. This in turn increases the Z value from 2 to 3. Note that the Z value exceeds 3 when $I_{bias} = 150$ mA, suggesting that carrier leakage (thermionic carrier emission to the outside of the QW) cannot be ignored at high I_{bias} values.

Fig. 4.10. (a) Double logarithmic plots of $\ln(I_{\text{bias}})$ as a function of $\ln(P_{\text{SE}}^{1/2})$ at four different temperatures (20, 40, 60, and 80 °C). The points are the experimental data, while the dashed lines show the second-order polynomial fitting curves of the experimental data. (b) Z values as a function of I_{bias} at above four temperatures.

Subsequently, in order to investigate how working temperature affects the carrier recombination behaviors, the SE spectra at 40, 60, and 80 °C were measured. Figure 4.9 shows the calculated P_{SE} values at such temperatures, and the double logarithmic plots at these three temperatures are shown in Fig. 4.10(a). As can be seen from the figure, the four fitting curves are almost parallel to each other, indicating that there is no distinct difference between the Z values at different temperatures. This can be seen more clearly in Fig. 4.10(b), in which Z is I_{bias} -dependent rather than T-dependent.

The Z value is around 2 at a low I_{bias} (50 mA), suggesting that the majority of the injected carriers recombine radiatively, and the laser exhibits a very high efficiency

under low injection currents. In fact, Z is smaller than 2 at a lower I_{bias} (< 50 mA, not shown in Fig. 4.10(b)), this is when the SRH recombination dominates. Increasing Z to around 3.1 when I_{bias} is 150 mA indicates that Auger NR becomes dominant at high current injection. These conclusions of carrier recombination types at different carrier density levels are the same as that in the ideality factor section. With further increase in I_{bias} , the lasing action initiates in the 20 °C case and Z becomes almost infinite. In the higher temperature cases, a Z value as high as 3.6 at 300 mA is observed. Such a high Z value could be attributed to the increased carrier leakage at high I_{bias} values.

The Z value is insensitive to temperature, which is a consequence of the power law dependences of the recombination processes on the carrier density N included in the applied model. First, it is commonly observed that, under the same I_{bias} , N decreases with working temperature owing to a more severe carrier loss, which causes a larger Z value. Moreover, the radiative recombination rate R_{spon} is proportional to N^2 , while the Auger NR rate R_A is proportional to N^3 . R_A decreases more significantly when temperature increases, which results in a smaller Z value. Under the effects of these two mechanisms, Z maintains a fixed value. This finding also implies that, at higher temperatures, thermionic carrier emission may replace Auger NR to become the dominant NR process which obstructs a lasing action. A similar phenomenon has also been found in 1.55 μm InP QW lasers [16].

To further investigate the carrier loss mechanisms with respect to I_{bias} and T , P_{SE} is plotted as a function of $1000/T$ at three different I_{bias} values (50, 100, and 200 mA) as shown in Fig. 4.11. The temperature-dependent SE follows the Arrhenius dependence and can be interpreted using the model below, and the activation energy (E_a) can be extracted by it.

$$P_{\text{SE}}(T) = \frac{I_0}{1 + C_{\text{NR}} \exp(-E_a / k_B T)} \quad (4.12)$$

where I_0 and C_{NR} are constants, E_a is the activation energy, and k_B is the Boltzmann constant. The best fit to the experimental data gives E_a values of 230, 210, and 190 meV at 50, 100, and 200 mA, respectively.

Fig. 4.11. Arrhenius plot of P_{SE} at three different I_{bias} values (50, 100, and 200 mA). The points are the experimental data, while the dashed lines show the fitting curves of the experimental data obtained using a model that involves the activation energy. The inset shows the band structure of the QW and barrier.

It is believed that E_a is related to the total confinement energy (E_{Total}) of carriers in the QW region [17]. E_{Total} of an electron-hole pair in a QW can be expressed as $E_g(\text{Barrier}) - E_g(\text{SE})$, as shown in the inset of Fig. 4.11. In our 2020 nm laser structure, the barrier material is $\text{Al}_{0.2}\text{GaAsSb}$ whose band gap is determined to be ~ 964 meV using the equation given by Vurgaftman et al. [18]. The SE peaks locate at ~ 2020 nm [$E_g(\text{SE}) = \sim 614$ meV]. These results correspond to an E_{Total} of ~ 350 meV. In addition, since $\text{In}_{0.2}\text{Ga}_{0.8}\text{Sb}/\text{Al}_{0.2}\text{GaAsSb}$ has a compressive strain of $\sim 1.26\%$, the valence band of the QW will be shifted upward ~ 13 meV on the basis of the model-solid theory [10]. All these factors result in a final ΔE_V of ~ 109.5 meV. Then, the energy from the top of the valence band to the first heavy-hole band is determined to be ~ 7.5 meV by solving the 1-D finite potential well Schrödinger equation. Thus, the potential barrier heights of holes and electrons are ~ 102 and ~ 248 meV, respectively, in the $\text{In}_{0.2}\text{Ga}_{0.8}\text{Sb}/\text{Al}_{0.2}\text{GaAsSb}$ QW structure.

By comparing the two barrier heights with E_a at the three different I_{bias} values, it can be found that, under a low I_{bias} (e.g., 50 mA), E_a fits the potential barrier height of electrons well. This indicates that, although the electron loss and the hole loss coexist throughout the entire current range for determining the overall E_a , the thermal loss of

electrons is the dominant carrier loss mechanism under a low I_{bias} . When I_{bias} increases, the hole loss becomes more crucial, which is evident by the marked reduction in E_a towards the potential barrier height of holes. This confirms the poor hole confinement of the 2020 nm laser structure, and reveal its impacts on the carrier recombination behaviors. The total carrier loss increases owing to the decrease in E_a .

4.4 Summary

In this Chapter, in order to confirm the material quality and the developed fabrication process, the two kinds of laser wafers were processed into basic FP ridge waveguide lasers. The Chapter begins by giving a systematic device overview of the fabricated lasers on many aspects, including temperature-dependent L-I-V (threshold current density as low as 96 A/cm^2), characteristic temperature T_0 and T_1 (103 and 606 K near room temperature), wavelength shift with temperature (0.93 nm/K), modal gain ($13.55(\text{net}) + 5(\alpha_i) \text{ cm}^{-1}$), etc.

Next, in order to gain more information on the carrier recombination behaviors within the fabricated lasers, the ideality factor (electrical) and spontaneous emission (optical) were systematically investigated. For the ideality factor, it was carried out on a 1960 nm laser. Temperature-dependent differential resistance curve (dV/dI vs. $1/I$ plot) and the well-known product curve ($I(dV/dI)$ vs. I plot) of the laser were drawn and analyzed. The ideality factor and series resistance of the laser were extracted from these two kinds of plots. It is found that the ideality factor at 60°C is larger than that at 30°C . This finding can be well explained by the power law dependences of the three recombination processes (SRH, radiative, Auger) on the carrier density N , which in turn confirms our analysis on the carrier recombination types of the laser at different carrier density levels. For the spontaneous emission, it was carried out on a 2020 nm laser to better find out the effects of the inadequate hole confinement on the carrier recombination. The Z parameter was defined by a model including the above mentioned three recombination processes. The value of Z indicates the same findings of the carrier recombination types as that in the ideality factor study. There is no obvious temperature dependence of Z from 20 to 80°C , which is also well explained by the power law dependences of the recombination processes. Furthermore, through the analysis of the activation energy, it is found that severe thermal loss of holes at high I_{bias}

cannot be ignored.

The findings in the ideality factor and spontaneous emission studies are in very good agreement with each other, and they converge to three main conclusions:

First, the existence of the QW increases the carrier density. As a result, it facilitates the radiative recombination at small current.

Second, when the QW carrier density is very low, SRH recombination dominates the carrier consumption. As the increase of the QW carrier density (increasing injection current), radiative recombination starts to take over due to the quadratic growth of its rate with the carrier density. With further increase of the QW carrier density, Auger recombination becomes more and more significant if the lasing action does not start. So the newly injected carriers contribute less to the radiative recombination. Or in another word, the initiation of lasing action becomes more difficult at larger injection current, not to mention the emerging thermal issues.

Third, when temperature rises, more severe carrier overflow impedes the QW carrier density increase. More injected carriers are wasted by recombining outside the QW. Consequently, a larger injection current is needed to reach the necessary amount of radiative recombination. However, many thermal issues may appear. So at higher temperatures, carrier overflow may replace Auger NR to become the dominant NR process which obstructs a lasing action.

The three conclusions are very beneficial for having a better understanding of the GaSb-based diode lasers, i.e. the physics behind their performance.

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Chapter 5 Two-section mode-locked lasers

This chapter presents a thorough investigation of monolithic two-section (gain section and absorber section) passively mode-locked lasers (MLLs). It begins with a detailed overview of such devices, including fabrication process, some basic performance parameters, cavity length, and gain/absorber length ratio determination, etc.

The rest of this chapter focuses on several characterization works on these lasers. First, modal gain characteristics of the fabricated lasers under different bias conditions were calculated using Hakki-Paoli method. It is followed by bias-dependent working regimes, from cw mode locking to Q-switched mode locking to pure Q-switching. After that, phase noise/timing jitter of the fabricated MLLs was studied to see how it changes with bias condition as well as at high temperatures. At last, repetition frequency tuning results of the MLLs were shown and analyzed. All these characterization works are done for the first time on 2 μm mode-locked diode lasers.

5.1 Device overview

5.1.1 Fabrication process

Figure 5.1 shows the schematic diagram of a two-section mode-locked laser [1]. Its fabrication process is basically identical to that of the single-section laser until contact window definition on the ridges (step 05 in the single section laser fabrication process). After that, instead of directly depositing the p-metal, another step of photolithography was carried out to define the gain and absorber sections, as well as the electrical isolation region between them. Next, Ti/Au (50/300 nm) were evaporated on top of the GaSb laser to form the p-side contact. Subsequent lift-off and wet etching processes realized the 10 μm -wide electrical isolation. In our fabrication, the high-conductivity contact layer and part of the p-cladding layer were etched off. A

resistance of $\sim 1.1 \text{ k}\Omega$ was achieved between the two sections with a etch depth of $\sim 1.5 \text{ }\mu\text{m}$. Finally, the lapping and cleaving process become the same again as that of the single-section laser. Figure 5.2(a) displays a photo of one cleaved laser bar with several devices on it, and an enlarged view of the region within the white frame is shown in Fig. 5.2(b).

Fig. 5.1. Schematic diagram of a two-section passively mode-locked laser [1]. When working in the mode locking regime, the gain section is forward biased (I_g) while the absorber section needs to be reverse biased (V_a).

Fig. 5.2. (a) Optical microscope photograph of one cleaved laser bar which contains several two-section lasers. (b) Enlarged view of the contents within the white frame in (a).

For all the tested lasers in this chapter, the ridge width is $\sim 5 \mu\text{m}$, which provides single lateral mode operation. As for the cavity length and gain section/absorber section length ratio, they will be discussed later in this section.

5.1.2 Experimental setup

The experimental setup for characterizing the mode-locked lasers is also shown in Fig. 5.3. The output light from the gain section facet was coupled into a single mode fiber. Then the light was split into two equal parts by a 50:50 fiber optic coupler: one was fed into a high-speed $2 \mu\text{m}$ InGaAs p-i-n detector (ET-5000F with a bandwidth of $>12.5 \text{ GHz}$, and a rise time of $<28 \text{ ps}$) followed by a real-time oscilloscope (DSO93004L); the other part was further split by a 10:90 fiber optic coupler. The 10% part was guided into an optical spectrum analyzer (OSA, AQ6375), and the 90% part was fed into another high-speed detector followed by an electrical spectrum analyzer (ESA, N9030A). the tested lasers were placed on a laser diode mounting fixture equipped with temperature electronic controller (TEC).

Fig. 5.3. Schematic diagram of the experimental setup for characterizing the two-section mode-locked lasers.

5.1.3 Experimental results

In this part, some typical performance parameters of such two-section lasers are presented. The results are from a $5 \times 2940 \mu\text{m}^2$ device (1960 nm laser structure) with a gain section/absorber section length ratio of 2630/300. Both facets of the device are left as-cleaved.

5.1.3.1 L-I-V and hysteresis

The tested laser lased in cw mode up to 80 °C. Figure 5.4 shows the L-I curves of the laser in the cw mode when V_a was varied from 0 (unconnected) to -2.4 V at 20 °C. I_g was increased from 0 to 200 mA at each V_a . The threshold current increases consistently with increasing negative V_a owing to the stronger absorption. Note that when the absorber is unconnected, the L-I curve exhibits a turn-on jump at lasing threshold, which is common for devices with a saturable absorber [2, 3]. This jump is attributed to a rapid increase of the carrier density in the absorber QW region caused by photon density increase as the lasing action starts, and the electric field is not strong enough to sweep the carriers out of the QW region immediately. This process decreases the absorption of the absorber, which subsequently results in the output power jump. The light output power reached ~12 mW at 200 mA when $V_a = 0$ V, and no thermal rollover is observed. The current-voltage characteristic (I-V) of the gain section under this condition is also shown in the figure.

Fig. 5.4. L-I curves of the tested laser in the cw mode when V_a was varied from 0 (unconnected) to -2.4 V at 20 °C. It also shows the I-V curve at $V_a=0$ V.

The L-I curves of the laser at various temperatures when $V_a=0$ V are shown in Fig. 5.5. The consistently increasing threshold current can be mainly attributed to the carrier overflow. The turn-on jump becomes more and more distinct with increasing temperature, and hysteresis loop starts to emerge from 60 °C. This bistability phenomenon has also been observed by some groups [4-6], while other groups did not [7, 8]. In the following paragraphs, this turn-on jump and hysteresis will be discussed.

Fig. 5.5. L-I curves of the tested laser at various temperatures when $V_a=0$ V.

The intensity-dependent loss of a saturable absorber (SA) can be described by a two-state model (high absorption state and low absorption state):

$$\alpha(I) = \frac{\alpha_{sat}}{1 + \frac{I}{I_{sat}}} + \alpha_0 \quad (5.1)$$

where α_{sat} is the saturable loss which sets the upper limit of the SA loss, α_0 is the loss when the intensity is extremely high (the lower limit of the SA loss), and I_{sat} is the saturation intensity (required intensity to reduce the loss to the middle point of the losses at the two absorption states).

To cause hysteresis, a significant turn-on jump is necessary. For obtaining this jump, the high absorption state of the SA has to be narrow (low saturation energy) to let the SA go across its rapid absorption reduction segment during the onset of lasing, like the cases shown in Fig. 5.6(a). In contrary, if the saturation energy is too high, leading to a very wide high absorption state like the case shown in Fig 5.6(b), the initiation of lasing is unable to cause an obvious absorption reduction of the SA. In addition, the difference between the two absorption states should be as large as possible. In this way, more carriers can be accumulated to contribute to the light

output after lasing threshold, or in another word, to make the turn-on jump more dramatic. As a result, the intensity after lasing will be far away from the corner intensity, like the 80 °C curve in Fig. 5.6(a). If the gain section current is reduced to decrease the intensity at this moment, there will not be significant absorption increase. So the L-I curve will not return the same way, instead, the intensity will decrease linearly for a while until reaching the corner value.

Fig. 5.6. Absorption of a SA at different conditions. (a) when the SA is unconnected at 20 and 80 °C. (b) when the SA is biased at -2 V at 80 °C.

According to the above analysis, a small negative V_a at high temperatures is preferred. As an example, the $V_a=0$ V at 80 °C case in Fig. 5.6(a) shows higher absorption before lasing threshold while its saturation energy is still kept at a low level. This higher absorption can be attributed to two reasons. One is the imaginary part of the refractive index of the active region materials increase. Another is the enhanced thermal sweep-out of the carriers at elevated temperatures.

5.1.3.2 RF spectra, pulse train, and optical spectra

In the tested laser, stable mode locking was achieved over a wide range of bias conditions up to 80 °C. The RF spectra were measured with a broadband electrical amplifier (PE15A3256). A typical RF spectrum observed at 20 °C under the bias

condition of $I_g=180$ mA, $V_a=-2$ V is shown in Fig. 5.7. The fundamental repetition rate with more than 55 dB signal to noise ratio is at ~ 13.34 GHz, corresponding to the photon round-trip time in the 2.94 mm-long laser cavity. The second harmonic at 26.68 GHz is also marked in the figure. The RF peak at the fundamental repetition rate is shown in greater detail in the upper inset of Fig. 5.7. It has a linewidth as small as 60 kHz, which indicates an efficient mode locking mechanism and low noise operation. The lower inset of Fig. 5.7 shows the pulse train observed on the oscilloscope. The time interval between two pulses is ~ 75 ps, corresponding well to the fundamental repetition rate at ~ 13.34 GHz.

Fig. 5.7. RF spectrum observed at 20 °C under the bias condition of $I_g=180$ mA, $V_a=-2$ V. The upper inset shows the RF peak at the fundamental repetition rate in greater detail, while the lower inset shows the pulse train observed on the oscilloscope.

Optical spectrum under the same bias condition as that in Fig. 5.7 is shown in Fig. 5.8. The spectrum can be perfectly fitted to a Gaussian curve, which indicates that the ultrashort pulses emitted from the laser are Gaussian pulses. The spectrum centering at ~ 1958 nm gives a full width at half maximum (FWHM) of ~ 7.4 nm, and more than 80 longitudinal modes spaced by ~ 0.172 nm are included. If unchirped Gaussian pulses are assumed which have a time-bandwidth product of ~ 0.441 , a minimum pulse width of ~ 760 fs is expected. Using the pulse width estimation method in Ref.

[9] gives a similar result.

Fig. 5.8. Optical spectrum and its Gauss fit under the same bias condition as that in Fig. 5.7 ($I_g=180$ mA, $V_a=-2$ V).

5.1.4 Cavity length and gain/absorber length ratio

Now we go back to address this very important issue during cleaving. This is the first thing to be determined when we cleave the laser wafer into a single mode-locked laser or a laser bar. For the cavity length, as we know, the intrinsic shortest cavity length is limited by the maximum possible modal gain. However, the limited bandwidth of the high-speed photodetectors in the $2\text{ }\mu\text{m}$ range resets this value to around 2 mm. On the other hand, a very long cavity is also not preferred since some thermal issues may come up.

Regarding the gain/absorber length ratio, the first thing to consider is also the capability of lasing. According to a work by researchers at TU Berlin [10], it can be assumed that the maximum possible gain of the gain section has the same absolute value as the maximum possible loss of the absorber section. With this assumption, the loss introduced by the absorber section can be compensated by a gain section with the same length. Then to achieve the lasing condition, another part of gain section is

needed to compensate for the internal loss and the mirror loss. In this way, the limit of the gain/absorber length ratio can be determined, and of course, it is cavity length-dependent. Figure. 5.9 illustrates the calculation results for a two-section QD laser. As shown, if a moderate modal gain and cavity length, say 15 cm^{-1} and 2 mm, are assumed, the proportion of the gain section needs to be at least around 70%. Although the mode gain of QW lasers is higher than QD lasers with ground state lasing, e.g., $>18.55 \text{ cm}^{-1}$ for our GaSb-based $2 \text{ }\mu\text{m}$ laser as calculated in Chapter 4, this proportion does not decrease significantly. Of course, a very short absorber is not favorable as well. In that case, mode locking may not be achieved anymore, or it can only be achieved with a very high reverse bias, which results in reduced lifetime and higher risk to be burned.

Fig. 5.9. Limits for the cavity length and gain/absorber length ratio of two-section QD lasers [10].

After meeting the above two most basic requirements, we are focusing on the performance of the two-section lasers. As we have mentioned in Chapter 2, there are several tradeoffs when determining the gain/absorber length ratio. Generally, a shorter absorber means higher average output power, better noise characteristics, and longer pulses, while a longer absorber often leads to lower average output power, higher

phase noise, and shorter pulses. Thus, it is not possible to achieve a theoretically high peak power (highest average power and shortest pulse at the same time). It is also not possible to generate a pulse train with both very short pulse duration and very low jitter. In addition, bias condition also affects the performance of a two-section mode-locked laser, which makes the situation even more complicated. Thus after the fabrication of such lasers, especially with a new material system, optimization works are critical to find some optimum configurations and bias conditions.

5.2 Modal gain characteristics

In this section, we are aiming to gain better insight into the influence of the bias condition on the gain characteristics of such mode-locked lasers, and how it thereby affects their light emission (e.g. wavelength, spectral content when working in the mode locking regime, etc). These issues are critical for the use of such mode-locked lasers as light sources for the practical applications mentioned in Chapter 1. To do this, the modal gain of a fabricated two-section laser (1960 nm structure, $5 \times 2130 \mu\text{m}^2$ with a gain section/absorber section length ratio of 1890/230) was calculated by performing the Hakki-Paoli method [11] with Eq. (4.3). To refresh your memory, it is written here again

$$G_{net}(\lambda) = \Gamma g_{material}(\lambda) - \alpha_i = \frac{1}{L} \ln \frac{\sqrt{S(\lambda)} - 1}{\sqrt{S(\lambda)} + 1} + \frac{1}{2L} \ln \left(\frac{1}{R_1 R_2} \right) \quad (5.2)$$

where Γ is the confinement factor, $g_{material}$ is the material gain, α_i is the internal loss due to crystal defects and dopant atoms in the waveguide. S is the peak-to-valley ratio of the FP resonances (the inset of Fig. 4.4) which can be directly obtained from the ASE spectra [12], L is the cavity length (2.13 mm), and R_1 and R_2 are facet reflectivities ($R = 0.34$ is used for both facets).

Figure 5.10 shows the calculated net modal gain spectra for a range of I_g when V_a was fixed at -1 V, while its inset shows the FP modes in greater detail. It can be seen from Fig. 5.10 that, with increasing current, the net modal gain becomes larger to

compensate the mirror loss ($(1/2L)\ln(1/R_1R_2) \sim 5.0 \text{ cm}^{-1}$), which is the threshold value for lasing. The measured gain never reaches this value even at the lasing threshold (91 mA). This is owing to the difficulty in accurately measuring S in the limit $S \rightarrow \infty$ (the first term on the right-hand side of Eq. (1) $\rightarrow 0$) [13]. Figure 5.10 also shows the lasing spectrum at $I_g=93 \text{ mA}$. The laser lases exactly at the location of the net modal gain peak, and same case was observed at all other V_a .

Fig. 5.10. Net modal gain spectra of the laser for a range of I_g when V_a was fixed at -1 V. This figure also shows the lasing spectrum at $I_g=93 \text{ mA}$. The inset shows some of the FP modes in detail.

Figure 5.11(a) shows the V_a -dependent net modal gain spectra from -1 to -5 V, all of them were measured just below threshold. The net modal gain peak redshifts consistently by around 20 nm with increasing negative V_a , which can be mainly attributed to the absorption spectrum shift due to the quantum confined Stark effect (QCSE). This has been confirmed by the perfect quadratic dependence of the gain peak position with V_a shown in Fig. 5.11(b). Same phenomenon was reported in a GaAs-based multi-section laser [14], which implies the well known electric field-induced redshift of the absorption peak in these two material systems. At the same time, since the lasing actions start exactly at the locations of the net modal gain peaks for the laser under testing, it also implies a potential application for tunable

operation. This tunable mechanism is just the one L. A. Coldren used to develop the first widely tunable laser as mentioned in Chapter 2 (Fig. 2.17). As expected, at all absorber biases, the peak net modal gain has similar value which is mainly determined by the mirror loss.

Fig. 5.11. (a) V_a -dependent net modal gain spectra of the laser from -1 to -5 V. (b) Modal gain peak positions at different V_a extracted from (a).

Figure 5.12 shows the V_a - and I_g -dependent gain bandwidth of the tested laser. For each V_a , the gain bandwidths with I_g increased to threshold are shown. Basically, increasing I_g results in a broadening of the gain curve with all applied V_a . Regarding the gain bandwidth at threshold, it is large when $V_a = -1$ V, and just slightly changes from -2 to -4 V. At $V_a = -5$ V, the gain bandwidth increases markedly again, which indicates that the laser is able to support more longitudinal modes to lase. The inset of Fig. 5.12 shows the lasing spectra when the laser works well in the mode locking regime at $V_a = -4$ V and -5 V. The spectrum at $V_a = -5$ V is obviously wider than it at $V_a = -4$ V, which confirms the analysis on the gain bandwidth. The wider spectrum also indicates the potential to obtain shorter pulses, and that more channels can be expected when the laser is used as a multiwavelength light source [15].

Fig. 5.12. V_a - and I_g -dependent gain bandwidth of the laser. The inset shows the lasing spectra at $V_a = -4$ and -5 V when the laser is working well in the mode locking regime.

5.3 Working regimes

As mentioned in Chapter 1, various kinds of instabilities may exist in a mode-locked laser (e.g. Q-switching instability), and especially when passive mode locking technique is used with a saturable absorber, which is the case in this work, the laser may show different working regimes. In this section, we are trying to figure out how bias condition of such mode-locked lasers affects their instabilities and working regimes so as to guide them to work in our favorable regimes.

The work was carried out on a fabricated two-section laser that comes from the same laser bar as the one in the modal gain study (1960 nm structure, $5 \times 2130 \mu\text{m}^2$ with a gain section/absorber section length ratio of 1890/230). Figure 5.13 shows the RF spectra at different V_a when I_g was fixed at 130 mA (well above lasing threshold). Three pulsed working regimes are clearly shown. At $V_a = -1.5$ V as shown in Fig. 5.13(a), stable cw mode locking is achieved. This is characterized by a strong RF peak with more than 40 dB signal to noise ratio at ~ 18.40 GHz, corresponding to the photon round-trip time in the 2.13 mm-long laser cavity. When V_a is varied to -1.9 V, Q-switched signal emerges to coexist with the mode-locked signal (QML regime).

The fundamental Q-switched frequency is at 900 MHz, with clear higher harmonics. At a more negative V_a of -2.1 V, both Q-switched signal and mode locked signal still remain with only relative intensities changed. The weight of Q-switched signal increases and its fundamental frequency increases slightly to 950 MHz. When the negative V_a is further increased to -2.6 V, pure Q-switching operation emerges with a fundamental frequency of 850 MHz. The reasons for the bias-dependent operations will be discussed later.

Fig. 5.13. RF spectra of the laser at different V_a when I_g is fixed at 130 mA to work in different regimes: (a) cw mode locking ($V_a=-1.5$ V), and the inset shows the RF peak in greater detail. (b) QML-1 ($V_a=-1.9$ V). (c) QML-2 ($V_a=-2.1$ V). (d) pure Q-switching ($V_a=-2.6$ V).

The pulse trains and optical spectra under the above four bias conditions are shown in Fig. 5.14. When the laser works in the cw mode locking regime as shown in

the lowest panel of Fig. 5.14(a), a uniform mode-locked pulse train is exhibited. The time interval between two pulses is ~ 54.41 ps as shown in the partially enlarged view besides, corresponding well to the RF peak at ~ 18.40 GHz in Fig. 5.13(a). Its corresponding optical spectrum shown in the lowest panel of Fig. 5.14(b) is wide and symmetric with a full width at half maximum (FWHM) of ~ 3.6 nm, and more than 40 longitudinal modes spaced by ~ 0.238 nm are included.

For the two QML regimes, the mode-locked pulse energy becomes no longer constant, but modulated according to a Q-switched envelope, i.e. several bunches of pulses instead of a uniform pulse train is shown. The time interval between two pulses within each bunch keeps unchanged (~ 54.41 ps). The time interval between two bunches is ~ 0.77 ns ($1/1.30$ GHz), corresponding to a value between the fundamental frequency and second harmonic in Fig. 5.13(b) and 5.13(c). The Q-switched lasing and mode-locked lasing happen at different wavelengths and it is perfectly exhibited in the figure. Their spectra coexist with changes in the relative intensities, which have the same trend as it shows in the RF signals. Compared to that of the mode locking, the spectra of Q-switching are narrow. According to the modal gain study in the last section, a more negative V_a causes a redshift of the lasing spectra in such two-section lasers. When V_a is varied to a more negative value (e.g., from -1.5 to -1.9 V), Q-switching tendency will be induced, but the mode locking operation is already very well established around 1960 nm, this forces the Q-switching operation to happen at longer wavelengths (~ 1970 nm in this case).

A more negative V_a takes the laser to the pure Q-switching regime as shown in the highest panel of Fig. 5.14(a). The Q-switched pulse width is ~ 0.17 ns, and the pulse interval is ~ 1.18 ns as shown in the thumbnail view besides, which corresponds well to the fundamental frequency of the Q-switched signal.

Fig. 5.14. (a) Pulse trains and (b) optical spectra under the four bias conditions in Fig. 3. From the lowest panels to the highest ones for both (a) and (b): cw mode locking ($I_g=130$ mA, $V_a=-1.5$ V); QML-1 ($I_g=130$ mA, $V_a=-1.9$ V); QML-2 ($I_g=130$ mA, $V_a=-2.1$ V); pure Q-switching ($I_g=130$ mA, $V_a=-2.6$ V).

It is well known that the working regime of a saturable absorber incorporated laser depends on the interplay between the gain saturation and the saturable absorption [16]. The tested laser has gone through all the three pulsed working regimes which are commonly observed in a saturable absorber incorporated laser, and the only thing changed is the voltage applied to the absorber V_a . It seems the analysis of the working regimes has been brought to a simple situation.

According to Ref. [16], to theoretically analyze the stability of the mode-locked pulse, which decides the switching between cw mode locking and Q-switched mode locking, we can set up coupled differential equations for the evolution of the mode-locked pulse energy E_P and the laser gain g . Here the pulse energy is defined as the average intracavity laser power times the cavity round-trip time T_R . In this way, quite similar equations as usually used for the analysis of simple Q-switching are obtained:

$$T_R \frac{dE_P}{dt} = [g - l - q_P(E_P)]E_P \quad (5.3)$$

$$\frac{dg}{dt} = -\frac{g - g_0}{\tau_L} - \frac{E_P}{E_{sat,L} T_R} g \quad (5.4)$$

where l is the linear internal loss due to crystal defects and dopant atoms in the laser waveguide, q_P is the round-trip loss in pulse energy introduced by the saturable absorber, g_0 is the laser gain when pulse energy equals 0, τ_L is upper-state lifetime of the laser medium. $E_{sat,L}$ is the saturation energy of the gain. Then, two reasonable assumptions are made. First, the duration of the mode-locked pulses is not obviously longer than the absorber recovery time. Second, the absorber recovery time must be much shorter than the cavity round-trip time. With these assumptions, the pulse energy-dependent loss introduced by the absorber can be expressed as

$$q_P(E_P) = q_0 \frac{E_{sat,A}}{E_P} [1 - \exp(-\frac{E_P}{E_{sat,A}})] \quad (5.5)$$

where q_0 is the saturable absorption of the absorber when pulse energy equals 0, $E_{sat,A}$ is the absorber saturation energy.

By solving these equations, a criterion can be obtained:

$$E_P \left| \frac{dq_P}{dE_P} \right| < \frac{T_R}{\tau_L} + \frac{E_P}{E_{sat,L}} \quad (5.6)$$

if the laser operates well above threshold, which is the case in this work, the first term on the right-hand side of relation (5.6) can be neglected. This eliminates the effects of the upper-state lifetime, and the saturation energy becomes the only relevant parameter of the gain medium. The physical background of this criterion, combining with the real case in this work, can be understood as follows.

For the cw mode locking and QML regimes, the mode-locked pulses are able to be formed. At $V_a = -1.5$ V (cw mode locking), the pulse energy is large, and if it rises slightly owing to relaxation oscillations, the pulse energy first grows exponentially owing to the stronger bleaching of the absorber. However, since the pulse energy is large enough, the increased pulse energy starts to saturate the gain. As a result, the pulse energy is pulled back to the previous value [16]. In contrast, at $V_a = -1.9$ or -2.1 V, the pulse energy decreases compared to that at $V_a = -1.5$ V due to the stronger absorption of the absorber. The gain saturation will be insufficient to stop an

exponential pulse energy rise caused by relaxation oscillations. Subsequently, the pulse energy cannot be sustained at a constant, and QML operation is formed. For pure Q-switching regime ($V_a = -2.6$ V in this case) on the other hand, the intracavity intensity decreases further, causing the mode-locked pulses unable to be formed. The total cw intensity inside the cavity increases as the absorber is bleached. If the gain cannot respond fast enough, pure Q-switching operation will be formed [17].

5.4 Phase noise/timing jitter

Again, as mentioned in Chapter 1, even without the instabilities, the output of a mode-locked laser still contains noises (e.g. intensity noise, phase noise, etc). Among different kinds of noises, phase noise (frequency domain)/timing jitter (time domain) are often of special interest since they are closely related to the data transmitting capacity and time resolution of a mode-locked pulse train.

We have also known that compared to active mode locking, the phase noise/timing jitter performance of passive mode locking is usually poor due to the lack of an external reference source. Therefore, a thorough study of our fabricated 2 μm GaSb-based passively MLLs is necessary to find out the optimum working condition of the lasers as well as some guidelines for improving their noise characteristics.

5.4.1 Basics of phase noise/timing jitter measurement and calculation

According to Chapter 1, phase noise contains noise components at different frequencies. If it is of interest to which extent different noise frequencies contribute to the overall noise, a power spectral density (PSD) $S_\phi(f)$ is very useful. It is obtained by calculating the ratio of power in a 1 Hz bandwidth at different offset frequency to the power in the carrier (Fig. 5.15). In general, it contains much more noise information than optical linewidth which is only determined by low offset frequency noise.

Fig. 5.15. Schematic of PSD.

For a mode-locked laser, the PSD of its phase noise can be conveniently obtained from its RF spectra. We just need to use its repetition frequency as the carrier, and measure the RF power at different offset with respect to the RF power at the carrier.

Once we have the single sideband (SSB) PSD of the phase noise $S_\phi(f)$, the timing jitter can be quantified by two quantities [18]. The first one is the integrated root-mean-square (rms) timing jitter using the popular von der Linde method [19]

$$\sigma^i = \frac{1}{2\pi f_c} \sqrt{2 \int_{f_1}^{f_2} S_\phi(f) df} \quad (5.7)$$

where f_c is the repetition frequency (carrier frequency), and f_1 and f_2 determine the offset frequency range over which the power spectral density is integrated. In this work, we use 100 kHz and 1 GHz as integration borders. For the integrated jitter of a mode-locked diode laser, phase noise at low offset frequency (lower than 1 MHz as for the case shown in Fig. 5.16(b)) usually contribute much more than high offset frequency, which is clearly shown in Fig. 5.16.

Fig. 5.16. A sample SSB-PN spectra of the phase noise for one fabricated MLL (a) and contributions of different offset frequencies to the integrated jitter (b).

As the timing jitter of passively MLLs is cumulative. It is more appropriate to define a jitter per pulse cycle, the pulse-to-pulse rms timing jitter

$$\sigma^{p-p} = \frac{1}{\pi f_c} \sqrt{2 \int_0^{+\infty} \sin^2\left(\frac{\pi f}{f_c}\right) S_\phi(f) df} \quad (5.8)$$

If the PSD at low frequency offset is assumed to be Lorentzian-shaped, which has been proved to be reasonable in passively mode-locked lasers [20, 21], the PSD can be completely determined by the RF linewidth $\Delta\nu_{RF}$

$$S_\phi(f) = \frac{\Delta\nu_{RF}}{\pi f^2} \quad (5.9)$$

this way, the pulse-to-pulse rms timing jitter can be simply expressed as

$$\sigma^{p-p} = \sqrt{\frac{\Delta\nu_{RF}}{2\pi f_c^3}} \quad (5.10)$$

From the above, it is clear that for a mode-locked diode laser, both the integrated jitter and pulse-to-pulse jitter are actually determined by the phase noise at low offset frequency. According to the measurement results of our fabricated lasers, the relative magnitude of the integrated jitter always keeps in good agreement with the phase

noise at 1 MHz offset. So we can actually approximately describe the variation trend of the integrated jitter without calculating the entire PSD, and only using the phase noise at 1 MHz offset, which is more convenient.

5.4.2 Experimental results

All the results shown here are from a fabricated MLL which is the same one as in the device overview section (1960 nm structure, $5 \times 2940 \mu\text{m}^2$ with a gain section/absorber section length ratio of 2630/300). At 20 °C, the range of V_a for stable mode locking operation starts from -0.8 V. When V_a becomes less negative than this value, the mode locking operation will be with large cw component, while when V_a exceeds a certain value which depends on I_g , Q-switching instability will emerge.

First, the effects of V_a on the phase noise is investigated. Figure 5.17(a) shows the RF spectra at the first three measured V_a (-0.8, -1, and -1.2 V) when I_g is fixed at 170 mA. It is clearly shown that when V_a is varied to be more negative, the base of the RF peak become consistently narrower, which implies that the RF peak may also get narrower to result in a lower integrated jitter. However, the detailed view of the main peaks as shown in Fig. 5.17(b) indicates that several distinct sidebands exist at V_a =-0.8 V. The existence of the sidebands squeezes the main peak to make it narrower. Actually, the phase noise at 1 MHz offset at V_a =-0.8 V is even slightly lower than that at V_a =-1.2 V. This result is shown more directly in the noise spectra in Fig. 5.17(c). The phase noise at V_a =-0.8 V keeps being a bit lower until reaching the intersection at ~4 MHz. The thermal noise floor is reached at ~200 MHz. The sidebands are also clearly shown in Fig. 5.17(c). Although the existence of these sidebands does increase the phase noise at their corresponding offset frequencies, it has only very slight effect on the integrated jitter since all the sidebands are at relatively high offset frequencies which contribute little to the total integrated jitter. On the other hand, as shown in Fig. 5.17(b), the main peak of the RF spectrum shifts to a higher repetition frequency when V_a is varied to -1.2 V. It is owing to the increasing absorption, causing a carrier density increase in the active region to compensate the loss, which leads to a lower

effective refractive index (free-carrier plasma effect).

Fig. 5.17. (a) RF spectra at the first three measured V_a (-0.8, -1, and -1.2 V) when I_g is fixed at 170 mA. (b) Detailed view of the main peaks at $V_a = -0.8$ and -1.2 V. (c) SSB-PN spectra at $V_a = -0.8$ and -1.2 V.

Figure 5.18(a) shows the variation of the calculated integrated jitter with V_a when I_g is fixed at 170 mA. The variation trend of the integrated jitter here is very typical. To be specific, for a given I_g , there exists an optimum V_a to achieve the lowest timing jitter. It is the same situation at a given V_a . Figure 5.18(b) gives such variation of the calculated integrated jitter with I_g when V_a is fixed at -1.8 V. The integrated jitter reaches its minimum at $I_g = 170$ mA. Same findings were reported in [22] on a QD laser. Before this optimum bias condition, the integrated jitter is supposed to drop

consistently, just like the base width of the RF peak. However, under some specific bias conditions, the timing jitter does not follow this trend. It is owing to the existence of sidebands, or the effectiveness of the squeezing by the sidebands if they exist under both bias conditions. Figure 5.18(a) also shows the phase noise at 1 MHz offset under the same bias conditions, which confirms that the integrated jitter keeps in accord with phase noise at 1 MHz offset.

Fig. 5.18. (a) Variations of the calculated integrated jitter and phase noise at 1 MHz offset with V_a when I_g is fixed at 170 mA. (b) Variation of the calculated integrated jitter with I_g when V_a is fixed at -1.8 V.

In addition to the integrated jitter, we also calculated the pulse-to-pulse jitter using Eq. (5.10). Figure 5.19 shows the high-resolution scan (RBW=10 kHz) of a RF spectrum under the bias condition of $I_g=180$ mA, $V_a=-2$ V. This bias condition falls into the region corresponding to the lowest integrated jitters at 20°C . As shown, the RF linewidth is ~ 60 kHz, resulting in a pulse-to-pulse timing jitter of ~ 63 fs/cycle.

Fig. 5.19. High-resolution scan (RBW=10 kHz) of an RF spectrum under the bias condition of $I_g=180$ mA, $V_a=-2$ V.

When temperature rises, stable mode locking can be maintained at less negative V_a (-0.6, -0.2, and 0 V at 40, 60, and 80 °C, respectively). This is mainly attributed to the enhanced thermal sweep-out of the carriers at elevated temperatures. At the same time, the RF linewidth and timing jitter improve obviously. Figure 5.20 shows some typical examples of the measured RF spectra at 40, 60, and 80 °C. The base of the RF peak narrows consistently with temperature, while its power drops gradually. At each temperature, same variation trend as that at 20 °C is clearly exhibited with the help of the insets in Fig. 5.20(a) (detailed view of the RF peaks at $V_a=-0.6$ and -1 V) and 5.20(b) (detailed view of the bases of the RF peaks).

Fig. 5.20. Some typical examples of the measured RF spectra at 40 (a), 60 (b), and 80 °C (c). The inset in (a) gives a detailed view of

the main peaks at -0.6 and -1 V, while the inset in (b) shows a detailed view of the bases.

Figure 5.21 displays three phase noise spectra corresponding to local minimums of the integrated jitter at 20, 40, and 60 °C, respectively. The integrated jitter reduces from 3.15 ps at 20 °C to 1.39 ps at 60 °C. The offset frequency to hit the thermal noise floor decreases dramatically from 400 MHz at 20 °C to 4 MHz at 60 °C, and the phase noise keeps being lower before the thermal noise floor at 60 °C. The lower corner frequency and phase noise also match up with the narrower RF peak. These improvements at higher temperatures may be due to the spontaneous coefficient decrease [23].

Fig. 5.21. Three SSB-PN spectra corresponding to local minimums of the integrated jitter at 20, 40, and 60 °C, respectively.

Further measurements were carried out to confirm the effects of the absorber length on the phase noise. To do this, two devices are prepared. They are with the same gain section length (~2630 μm considering the cleaving uncertainty) and an absorber length ratio of 3:1 (300 μm , referred to as long device:100 μm , referred to as short device). Of course, to achieve stable mode locking, more negative V_a is needed

for the short device. Figure 5.22 shows the calculated I_g -dependent integrated jitter for the two devices. The absorbers were biased at two fixed V_a , -1.8 V for the long device and -2.8 V for the short device. The overall variation trends of the integrated jitter for both devices are very similar, while the short device exhibits obviously lower jitter. These results follow the well-known tradeoff as mentioned in the above cavity length and gain/absorber length ratio section, which is shorter absorber will result in lower phase noise and longer pulse simultaneously.

Fig. 5.22. Calculated I_g -dependent integrated jitter for two devices with different absorber length.

5.5 Frequency tuning

It has also been mentioned in the literature review Chapter that repetition frequency tuning of a mode-locked laser is of interest to better meet the application-required frequencies with consideration of a typical 1% cleaving uncertainty. In addition, an investigation of repetition frequency tuning at high temperatures is even more desirable since some applications do include high temperature situations.

The laser used for this investigation is still the one in the device overview section (1960 nm structure, $5 \times 2940 \mu\text{m}^2$ with a gain section/absorber section length ratio of 2630/300). In order to investigate how the repetition frequency changes under different bias conditions, and at high temperatures, the RF spectra of the laser were systematically recorded at 20, 40, 60 and 80 °C.

First, V_a was fixed at -1 V, which is a moderate absorber bias voltage for this laser to achieve stable mode locking. Figure 5.23(a) presents the repetition frequency as a function of I_g at 20, 40, and 60 °C. The repetition frequency at 80 °C is not shown since threshold current becomes significantly higher than that at the presented three temperatures. There is no overlap of I_g in the stable mode locking region, which is not suitable for comparison. At each temperature, the frequency decreases consistently and linearly with I_g at the rates of -0.60, -0.29 and -0.15 MHz/mA for 20, 40 and 60 °C respectively.

Fig. 5.23. (a) Repetition frequency as a function of I_g at 20, 40, and 60 °C (V_a was fixed at -1 V). (b) Corresponding optical spectra.

This decrease is commonly observed in two-section mode-locked lasers [9, 24], and is due to several reasons, all of which are originated from current induced temperature increase: increased laser cavity length due to thermal expansion; increased refractive index (n_{eff}) due to band gap shrinkage. These processes caused by I_g increase have been summarized in Fig. 5.24.

Fig. 5.24. Frequency tuning mechanism caused by I_g increase.

On the other hand, the repetition frequency increases as a whole when the temperature rises. We interpret it by the decrease in n_{eff} of the laser waveguide caused by wavelength redshift at higher temperatures as shown in Fig. 5.23(b). As can be seen from the figure, at a fixed temperature, the lasing wavelength keeps almost unchanged with I_g . This indicates that although the active region temperature rises as I_g increases, this rise is actually not so significant. In contrast, when the operation temperature is increased from 20 to 40 °C, or from 40 to 60 °C, it shows a 20 to 30 nm jump in the lasing wavelength. This jump is the combined effect of the band structure changes of both the gain section and absorber section (subsequently changes its absorption peak). It directly results in the n_{eff} decrease, and thus leads to a higher repetition frequency. Of course, the above-mentioned temperature related factors which cause the repetition frequency to drop also exist. So when temperature rises, two opposite mechanisms (summarized in Fig. 5.25) exists simultaneously to affect the repetition frequency. In the I_g range shown in Fig. 5.23(a), the latter one prevails except $I_g=150$ mA, where the two mechanisms cancel with each other.

Fig. 5.25. Frequency tuning mechanism caused by operation temperature rise.

Next, I_g was fixed at 190 mA, which is well above the threshold current for all the three temperatures shown in Fig. 5.26(a) (20, 40, and 60 °C). Again, the repetition frequency at 80 °C is not shown for the same reason. At each temperature, the overall trend of the repetition frequency with increasing V_a keeps the same, increasing at the initial stage, becoming stable, and then dropping slowly. The increase has been reported by some groups [24], while some other groups reported the opposite trend [4, 10]. In our opinion, the interplay between two mechanisms (summarized in Fig. 5.27) determines whether the repetition frequency increases or decreases. First, when V_a becomes more negative, the absorber introduces more loss to the laser, which causes an increase in the carrier density level within the active region to compensate for this extra loss. As a consequence, n_{eff} decreases due to the free-carrier plasma effect. At the same time, more negative V_a leads to more significant bandgap shrinkage, which increases n_{eff} of the absorber section.

Fig. 5.26. (a) Repetition frequency as a function of V_a at 20, 40, and 60 °C (I_g was fixed at 190 mA). (b) Corresponding optical spectra.

Fig. 5.27. Frequency tuning mechanism caused by V_a changing to a more negative value.

Same as the results in Fig. 5.23(a), the repetition frequency becomes higher as the operation temperature rises, which is also attributed to the wavelength redshift as shown in Fig. 5.26(b). Note that at each temperature, more negative V_a does not result in straight wavelength redshift. It seems a bit inconsistent with the previous finding.

However, the mode locking regime is a multi-wavelength behavior. Tens of, or even hundreds of longitudinal modes are being considered. So when the bias condition is varied to change the mode locking state, the spectrum is more likely to expand or contract instead of to straightly redshift. Which longitudinal modes will be included when V_a becomes more negative depends on the relative positions between the gain and absorption spectra as well as their profiles, determining which longitudinal modes would more tend to lase. Again, the two opposite temperature induced mechanisms cancel with each other at $V_a = -1.6$ V, resulting in a very close repetition frequency at 20 and 40 °C.

Moreover, the spectra at 40 °C are generally and markedly wider than those at 20 °C. Taking two symmetric spectra at these two temperatures for example, as shown in Fig. 5.23(b), FWHM of the spectra almost triples from 2.7 nm at 20 °C to 7.4 nm at 40 °C. It further expands to be as wide as 12.4 nm at more negative V_a as shown in Fig. 5.26(b), which is comparable to or even wider than that of mode-locked QD lasers. The expansion indicates that more longitudinal modes will be locked in phase at 40 °C. A possible reason for this increase is the gain bandwidth increase at high temperatures, similar to what we observed at large negative V_a in our previous modal gain study [1]. This also shows the potential to obtain shorter pulses, and more channels/comb lines can be expected when the laser is used as a multi-wavelength light source.

5.6 Summary

In this Chapter, monolithic two-section MLLs emitting at 2 μm were fabricated using the 1960 nm laser wafer and characterized. Stable mode locking was achieved in these lasers under a variety of bias conditions up to 80 °C. Hysteresis was observed in a fabricated laser ($5 \times 2940 \mu\text{m}^2$ with a gain section/absorber section length ratio of 2630/300) at temperatures higher than 60 °C with a small negative V_a . The mechanism behind this phenomenon was discussed. Cavity length and gain/absorber length ratio were analyzed in terms of capability of lasing and performance.

Next, modal gain of a fabricated two-section laser was calculated by performing the Hakki-Paoli method. It was found that the lasing action moves to longer wavelengths markedly with increasing negative V_a due to the redshift of the gain profile. The light output contains more longitudinal modes in the mode locking regime if the gain bandwidth is larger at a certain V_a . These findings provide information on how modal gain affects a MLL's output characteristics.

Subsequent chapter sections focused on instabilities and phase noise/timing jitter. By fixing the gain current at 130 mA and varying the absorber bias voltage from -1.5 to -2.6 V, the tested laser went through three distinct pulsed regimes: cw mode locking, Q-switched mode locking, and pure Q-switching. The regime switching mechanism was given based on the interplay between the gain saturation and the saturable absorption. For the phase noise/timing jitter, it was investigated by measuring the single sideband phase noise spectra. At a fixed temperature, for a given gain section current (I_g) or absorber bias voltage (V_a), there exists an optimum bias condition to achieve the lowest timing jitter. The existence of sidebands may result in a narrower RF linewidth. When temperature is increased, the phase noise/timing jitter improves obviously. This may be due to the spontaneous efficiency decrease at elevated temperatures.

At last of this chapter, the repetition frequency tuning with three parameters (I_g , V_a , and T) was measured and the tuning mechanisms were analyzed. To sum up, when the other two parameters are fixed, the repetition frequency keeps reducing with I_g due to current induced temperature increase. When V_a becomes more negative, there are two opposite mechanisms coexisting to determine whether the repetition frequency is higher or lower. If the operation temperature is raised, again, the wavelength redshift and temperature related processes compete with each other to give the results.

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Chapter 6 Hybrid III-V/silicon lasers

This Chapter focus on two III-V and Si integration methods: wafer bonding and edge coupling. For the wafer bonding method, we designed a tapered waveguide GaSb-based laser structure, bonded onto SOI circuits with an Al_2O_3 bonding layer, using the RSOF BeamProp software. The thermal resistance has been calculated and compared to that with a SiO_2 bonding layer. Regarding the edge coupling method, we fabricated and characterized an external cavity tunable laser with a GaSb-based SOA (1960 nm laser structure) and a Si photonic chip as the wavelength selective component.

6.1 Simulations of III-V/silicon integration using wafer bonding

So far, there are few reports on the design of III-V lasers, integrated onto Si waveguide circuits, with emission wavelength around 2 μm and above. Even in these limited reports, the device performance still needs to be further improved in terms of operation temperature and output power [1]. For example, Hattasan et al. have reported the first GaSb-based laser integrated onto a SOI waveguide using BCB adhesive wafer bonding, working under cw operation with output power of a few tens of μW only. Therefore, further efforts on GaSb-based lasers integrated onto SOI platforms are greatly desired.

6.1.1 Device design

GaSb-based materials have higher refractive index (3.896 for GaSb) [2] than Si (3.451) [3]. Therefore, intrinsically, the light is not easy to couple down from the higher-index GaSb QW region to the underlying Si waveguide region. So the meticulous design of the GaSb laser waveguide as well as the Si waveguide is necessary.

Tapered structures have been demonstrated to efficiently facilitate coupling the light from the InP QW region to the underlying SOI waveguide [4-7]. However, they have not been evaluated for the GaSb QW laser integrated onto SOI platforms yet. For the bonding material selection, conventionally, SiO₂ has been used as bonding material for wafer bonding of III-V materials onto SOI waveguides [8]. But due to its large thermal resistivity ($\sim 71.43 \text{ K}\cdot\text{cm}/\text{W}$) [9], heat dissipation becomes a big problem, especially for lasers whose performances are affected significantly by thermal properties. BCB is also widely used for adhesive wafer bonding, but its thermal resistivity is even larger ($\sim 344.83 \text{ K}\cdot\text{cm}/\text{W}$) [10]. Recently, we have reported the low temperature heterogeneous InP bonding on a Si wafer with an Al₂O₃ bonding layer [11, 12]. Due to its much lower thermal resistivity ($\sim 2.56 \text{ K}\cdot\text{cm}/\text{W}$) [13], Al₂O₃ becomes a very promising candidate for bonding III-V lasers onto SOI wafers.

The schematic diagram of the proposed device structure, i.e., a tapered-waveguide GaSb QW laser bonded onto a SOI waveguide with an Al₂O₃ bonding layer, and its cross-section are shown in Fig. 6.1. For the entire device, the width of the Si waveguide (W_{Si}) is kept uniform while the width of the III-V structure varies along the Z axis (in the main light amplification region, the width of III-V structure is $4 \mu\text{m}$ as shown in Fig. 6.1). The length of the entire III-V region is $1000 \mu\text{m}$, including two tapered coupling structures ($50 \mu\text{m}$ each) and a $900\text{-}\mu\text{m}$ -long uniform region. Light emitted from the III-V laser can be coupled into the Si waveguide gradually through the tapered coupling structures and can keep oscillating in it. Every time passing through the III-V region, the light is coupled back into the III-V laser and gets amplified.

Fig. 6.1. Schematic diagram of the GaSb QW laser bonded on Si and its cross-section (not to scale).

6.1.2 Refractive indices determination and evanescent coupling simulations

The entire hybrid device using the same epitaxial structure with the tested lasers (for bonding purpose, we changed the thickness of the p-side waveguide layer and removed the p-side cladding layer) has been generated with beam propagation method (BPM) by a RSOF T BeamProp software. The details of the III-V structure integrated onto the SOI platform, from the Si waveguide surface to the III-V side, are 50 nm bonding layer, 50 nm GaSb contact layer, 100 nm p-type $\text{Al}_{0.2}\text{GaAsSb}$ waveguide layer, 10 nm $\text{In}_{0.2}\text{Ga}_{0.8}\text{Sb}$ quantum well layer, 270 nm n-type $\text{Al}_{0.2}\text{GaAsSb}$ waveguide layer and 1500 nm n-type $\text{Al}_{0.5}\text{GaAsSb}$ cladding layer. Figure 6.2 shows the refractive index profile of the entire device (GaSb QW laser onto SOI waveguide) (a) as well as the enlarged refractive index profile of its $\text{In}_{0.2}\text{Ga}_{0.8}\text{Sb}$ QW active region (b).

Fig. 6.2. (a) Refractive index profile of the entire device and (b) detailed profile of the quantum well.

Table 6.1. Refractive indices of relevant materials

Material	Refractive Index
Si	3.451
SiO ₂	1.465
Al ₂ O ₃	1.738
GaSb	3.896
Al _{0.5} GaAsSb	3.457
Al _{0.2} GaAsSb	3.724
In _{0.2} Ga _{0.8} Sb	3.848

The specific values of the refractive indices used in the BPM simulation are given in Table 6.1 [3, 14-17]. For the refractive index determination of the InGaSb material, we use the method described in [14]. The equations are expressed as

$$\varepsilon_1(\omega) = A \left[f(\chi_0) + \frac{1}{2} \left[E_0 / (E_0 + \Delta_0) \right]^{1.5} f(\chi_{os}) \right] + B \quad (6.1)$$

$$n(\omega) = \varepsilon_1(\omega)^{0.5} \quad (6.2)$$

where A and B are the constant terms arising mainly from the energy bandgaps of the material, E₀ is direct bandgap energy, Δ₀ is spin orbit splitting energy, ω is circular frequency and

$$f(\chi_0) = \chi_0^{-2} \left[2 - (1 + \chi_0)^{0.5} - (1 - \chi_0)^{0.5} H(1 - \chi_0) \right] \quad (6.3)$$

$$f(\chi_{os}) = \chi_{os}^{-2} \left[2 - (1 + \chi_{os})^{0.5} - (1 - \chi_{os})^{0.5} H(1 - \chi_{os}) \right] \quad (6.4)$$

$$\chi_0 = \hbar\omega / E_0 \quad (6.5)$$

$$\chi_{os} = \hbar\omega / (E_0 + \Delta_0) \quad (6.6)$$

and

$$H(y) = \begin{cases} 1 & \text{for } y \geq 0 \\ 0 & \text{for } y < 0 \end{cases} \quad (6.7)$$

where h-bar is Planck constant divided by 2π.

For the refractive index determination of AlGaAsSb materials lattice matched with GaSb, an improved single-effective-oscillator model [15] is used and the

equations are expressed as

$$n^2 - 1 = \frac{E_d}{E_0} + E^2 \frac{E_d}{E_0^3} + \frac{\eta}{\pi} E^4 \ln\left(\frac{E_f^2 - E^2}{E_\Gamma^2 - E^2}\right) \quad (6.8)$$

$$E_f^2 = 2E_0^2 - E_\Gamma^2 \quad (6.9)$$

$$\eta = \pi E_d / 2E_0^3 (E_0^2 - E_\Gamma^2) \quad (6.10)$$

where E is the photon energy $h\nu$, E_0 and E_d are two single-effective-oscillator parameters and E_Γ is the direct bandgap energy.

In order to find proper widths of the Si waveguide and III-V structure, a series of optical mode distribution simulations using both Al_2O_3 and SiO_2 as bonding materials have been carried out. The details of the simulation procedure are as follows: the width of the Si waveguide was kept constant at 2 μm and the width of the III-V structure was varied from significantly less than 2 μm (0.3 μm) to 4 μm . The thickness of the bonding layer is 50 nm. As can be seen from the results shown in Fig. 6.3 (two curves with circular symbols), there is almost no difference in light power in the Si waveguide by using either Al_2O_3 or SiO_2 bonding layer. And when the III-V structure is very narrow, like less than 0.4 μm , almost all the light is coupled into the Si waveguide. Then there is a dramatic change when the width of the III-V structure exceeds 0.4 μm , which is the portion of light in the Si waveguide decreases rapidly due to the better confinement of the III-V structure. Then when the width of the III-V structure increases further to more than 0.8 μm , light distribution changes only marginally.

Fig. 6.3. Normalized power in the Si waveguide when either the III-V structure or Si waveguide width changes.

This is the basic idea of taper coupling and it is widely used for evanescent coupling in III-V on SOI hybrid devices [4-7]. Due to the width change of the III-V structure along the taper, light also redistributes. Fig. 6.4 shows the top view of the device together with optical mode distributions at different positions of the Z axis. At the main amplification region (a) where both width and refractive index of the III-V structure are larger than the Si waveguide, almost all the optical mode distributes in the III-V structure. In the taper coupling region (b, c), optical mode starts to emerge in the Si waveguide and the narrower the III-V structure is, the more portions of optical mode stay in the Si waveguide. When there is no III-V structure above the Si waveguide (d), the optical mode stays in the Si waveguide only. These results confirm the relationship between optical mode distributions and structure widths shown in Fig. 6.3.

Fig. 6.4. Optical mode distributions at different positions of the Z axis.

In addition, we can also tune the width of the Si waveguide while keeping the width of the III-V structure at a modest value, like $0.5\ \mu\text{m}$. The simulation results have been shown in Fig. 6.3 (the discrete points) together with the corresponding Si waveguide widths. So far, the optical mode distributions can be tuned freely by adjusting the structure widths.

Besides the variation of widths, three bonding layer thicknesses (25 nm, 50 nm, and 100 nm) are also used to study their influences on the coupling efficiency. As can be seen from Fig. 6.3, for the three thicknesses, the difference in light power in the Si waveguide by using either Al_2O_3 or SiO_2 bonding layer is trivial, which indicates no compromise in optical coupling efficiency when Al_2O_3 is used to replace the conventional SiO_2 as bonding material. The bonding layer thickness does have some influence on the coupling efficiency. Overall, less light remains in the Si waveguide for thicker bonding layers, which could be beneficial for light amplification.

6.1.3 Thermal resistance

In this part, for the purpose of quantitatively estimate the heat dissipation

improvement brought by the use of Al_2O_3 bonding material, the total thermal resistance of the proposed device with both Al_2O_3 bonding layer and SiO_2 bonding layer have been calculated. Since the SOI wafer is wide enough compared to the III-V lasers, the total thermal resistance for downward transfer of heat flux can be seen as the sum of resistance of each layer from the active region of the GaSb laser where heat is generated to the Si waveguide, and it can be calculated by a constant heat spreading model [18]. The mode has been widely used in hybrid devices and other electronic and photonic devices such as HBTs and lasers [19, 20].

The III-V structure was calculated as a rectangle in the X-Z plane with length L and width W , as shown in Fig. 6.5. The length L was kept constant at $1000 \mu\text{m}$ while the width W was varied from $0.3 \mu\text{m}$ to $4 \mu\text{m}$ during the calculations. For bonding layer thickness, we also chose the three values used in coupling efficiency simulations to test whether it is a critical factor for total thermal resistance. The expression of thermal resistance is

$$R_\theta = \int_0^{D_i} \frac{\theta}{(L+2y)(W+2y)} dy \quad (6.11)$$

where D_i is the thickness of the calculated layers, θ is the thermal conductivity.

Fig. 6.5. Parameters for thermal resistance calculation.

As can be seen from the results in Fig. 6.6, there are significant reductions in thermal resistance by using Al_2O_3 as the bonding material no matter how thick the bonding layer is. And bonding thickness barely affects the total thermal resistance when Al_2O_3 is used due to its low thermal resistivity. In the main light amplification

region where the width of the III-V structure W equals $4\text{ }\mu\text{m}$, the thermal resistance is reduced by around 70% when the thickness of the bonding layer is 50 nm.

Fig. 6.6. Thermal resistance for downward transfer of heat flux.

6.2 III-V/silicon external cavity tunable lasers

In addition to the above integration simulations using wafer bonding method, we also tried the edge coupling method. Taking advantage of the design freedom of Si photonics and its compactness, combined with the demand for tunable single frequency operation, we developed a $2\text{ }\mu\text{m}$ external cavity tunable vernier laser with Si photonic chip as the wavelength selective component. This section will discuss the design and experimental results of the fabricated laser.

6.2.1 Device design

Illustrated in Fig. 6.7(a) is the 3D schematic of the external cavity tunable laser consisting of the III-V SOA and the Si photonic tunable wavelength filter. Figure 6.7(b) gives the mask design of the Si photonic tunable wavelength filter with its dimension. For the SOA, its dimension is $\sim 2400(\text{length}) \times 500(\text{width})\text{ }\mu\text{m}^2$. The two

ring resonators have slightly different circumferences and are with integrated heaters to tune their FSRs. Via the vernier effect, positive feedback can be realized when the two resonant peaks of the two rings coincide, and one will be able to perform discrete or continuous wavelength tuning by applying a voltage across one or both heaters respectively. In our design, the lasing emission will be produced at the end of the SOA waveguide.

Fig. 6.7. (a) 3D schematic of edge-coupled 2 μm external cavity tunable vernier laser (not to scale). (b) Mask design of the Si photonic tunable wavelength filter with its dimension.

The SOAs used here were fabricated from the 1960 nm laser wafers with a ridge width of $\sim 5 \mu\text{m}$ to provide single lateral mode operation, and their ridge waveguides are tilted with angles from 4.5° to 6.5° to suppress lasing. Figure 6.8 shows the optical spectra of a fabricated SOA (4.5°) with injection current from 20 to 200 mA. It can be seen that the output starts to saturate at 180 mA, which proves that the lasing action is effectively suppressed. The spectrum at 180 mA has a FWHM of $\sim 90 \text{ nm}$, which makes a very wide wavelength tuning range possible. Actually for the SOA part, it is

very similar to the FP laser, just with tilted waveguide. Thus here we will focus on the Si photonic chip design.

Fig. 6.8. Optical spectra of a fabricated SOA (4.5°) with injection current from 20 to 200 mA.

The Si photonic tunable wavelength filters were fabricated from SOI wafers with 220 nm-thick top Si layer. First, single mode condition of the Si waveguide was performed using the Lumerical MODE Solutions software. The cutoff waveguide width for the higher order mode (TE₀₁) was found to be 800 nm as indicated in Fig. 6.9. In our design, the waveguide width was selected to be 600 nm. With this width, a 2-3 dB/cm propagation loss was measured experimentally in the 2 μm wavelength range.

Fig. 6.9. Single-mode condition of the 220 nm SOI waveguides at 2 μm .

Next, bend loss of the 600 nm-wide waveguide was computed by 2.5D FDTD in the Lumerical MODE Solutions software. As indicated in Fig. 6.10, bend loss becomes negligible when the radius exceeds 10 μm .

Fig. 6.10. Bend loss condition of $600 \times 220 \text{ nm}^2$ Si waveguide.

The 1×2 MMI-based reflector was computed with the Eigenmode Expansion Method at 1.95 μm . The optimized parameters and loss characteristics of the reflector are shown in Table 6.2.

Table 6.2. Parameters and characteristics of MMI/MMI-based reflector

Parameter/Characteristic	Value
Coupler length	24.2 μm
Coupler width	6 μm
Output waveguide separation	3.14 μm
Output waveguide radius	18 μm
Input/output waveguide taper length	30 μm
Input/output waveguide taper width	1.35 μm
Coupler insertion loss (simulation)	0.7 dB
Coupler insertion loss (experimental)	~0.7 dB
Reflector round trip loss (experimental)	~1.4 dB

In order to increase the edge coupling efficiency, a spot size converter (SSC) with a taper structure was designed to match the mode at the facet of the SOA (mode area= $4.6 \times 1 \mu\text{m}^2$) to the mode of the Si waveguide. To do so, the cross section of the Si waveguide was transformed from $0.6 \times 0.22 \mu\text{m}^2$ to a slab waveguide ($6 \times 0.06 \mu\text{m}^2$) with the SSC. With this design, the coupling loss can be as low as 0.85 dB theoretically as shown in Fig. 6.11.

Fig. 6.11. Mode overlap between slab waveguide ($6 \times 0.06 \mu\text{m}^2$, left) and SOA (right) mode fields.

The tip width of the spot-size converter was selected to be 150 nm. The taper length optimization was performed using the Lumerical MODE Solutions software. From Fig. 6.12, one could see that as the taper length exceeds 100 μm , the value of conversion loss stays approximately at 0.5 dB. The variation of conversion loss beyond 100 μm is due to insufficient mesh accuracy during computation. However, the trend is easily visible.

Fig. 6.12. Variation of SSC loss against taper length.

Figure 6.13 shows the schematic of a single ring resonator filter with two bus waveguides. We can compute the FSR of this ring resonator as Eq. (6.12) where n_g and c refer to the group index of the waveguide and speed of light respectively.

$$FSR = \frac{c}{L_{ring} n_g} \quad (6.12)$$

Fig. 6.13. Schematic of a single ring resonator filter.

For a double ring vernier filter, its tuning range is determined by the FSRs of the two ring resonators composing it [21]:

$$\Delta\lambda = \frac{\lambda^2}{c} \left| \frac{FSR_{ring1} \cdot FSR_{ring2}}{FSR_{ring1} - FSR_{ring2}} \right| \quad (6.13)$$

based on this equation, the two ring resonators were designed to have relatively small radius in this work (16.8 and 18.2 μm for ring 1 and 2, respectively). This will allow for large FSRs, and as indicated by Eq. (6.13), the tuning range can be increased. Figure 6.14(a) narrates the simulated transmission spectra of the double ring filter (with a 220 nm gap between the ring resonator and the bus waveguides). The individual transmission spectra of the two ring resonators are depicted in Fig. 6.14(b).

Fig. 6.14. (a) Simulated transmission spectra of the vernier filter with gap = 220 nm. (b) Simulated transmission spectra of the 2 different ring resonators with gap = 220nm. (c) Simulated transmission spectra of the vernier filter with gap = 140 nm. (d) Simulated transmission spectra of the vernier filter with gap = 400 nm.

There is another critical parameter to influence the tuning range and the side mode suppression ratio (SMSR) of the lasing spectra, which is the coupling gap between the ring resonator and the bus waveguides. Figure 6.14(c) and (d) show the transmission spectra of the vernier filter when the coupling gap is 140 and 400 nm, respectively. It is distinct that as the coupling gap increases, the SMSR of the transmission spectra which is directly related to the SMSR of the lasing spectra improves as well. This is owing to the narrower mode linewidth at the weak coupling condition (large coupling gap) resulting from improved Q factor of the ring resonator. But there exists a tradeoff, which is the mode selection will also be weakened at weak coupling condition. This may result in threshold current increase and tuning range reduction.

6.2.2 Experimental results

Figure 6.15 illustrates the tuning operation of the laser when $I_{\text{SOA}} = 450$ mA. The discrete peaks are achieved by changing the voltage across one heater. Peaks with SMSR of higher than 10 dB are observed across a 60 nm tuning range. These lasing spectra are collected from the output via a lensed fiber connected to the Optical Spectrum Analyzer (OSA, AQ6375). The SOA and the silicon photonic chip are kept at 22 °C during the measurements.

Fig. 6.15. Tuning operation of the laser when $I_{\text{SOA}} = 450$ mA. The discrete peaks are achieved by changing the voltage across one heater.

60 nm is among the largest tuning ranges for a tunable diode laser in the 2 μm wavelength range. Tunable diode lasers in the 2 μm wavelength range are rarely reported or commercially available. In 2016, researchers at COBRA, Netherland demonstrated a monolithic InP-based tunable diode laser with the entire photonic integrated circuits (PIC) fabricated on an InP-based multiproject wafer (MPW) [22]. A tuning range of 31 nm centered at 2027 nm was achieved. Wang et al. at Ghent

University reported a tunable diode laser using the similar scheme with the one in this work [23]. They achieved a tuning range of 58 nm. In addition, we also bought a commercial benchtop 2 μm tunable diode laser for Si photonics measurement. The laser uses a Littrow configuration to realize a 66 nm effective wavelength tuning range, but the discrete grating and the motor make it very bulky.

The output power of the laser at $I_{\text{SOA}} = 450 \text{ mA}$ is estimated to be 1.9 mW at least. This takes into consideration the 11.25 dB coupling loss between the SOA waveguide and the lensed fiber.

6.3 Summary

In this Chapter, two III-V and Si integration method: wafer bonding and edge coupling have been investigated. For the wafer bonding method, a tapered waveguide GaSb QW laser, bonded onto SOI circuits with an Al_2O_3 bonding layer was designed and analyzed. The BPM simulations show that, with our design, the light in the GaSb QW active region can be successfully coupled into the underlying SOI waveguide. The thermal property of the GaSb-on-Si laser has been calculated using a constant heat spreading model, and results show that the devices using Al_2O_3 bonding layer have a much lower (~70%) thermal resistance as compared to the one using SiO_2 bonding layer. Our results suggest that Al_2O_3 bonding layer could be a promising candidate for GaSb lasers integrated on SOI circuits, where thermal dissipation could be critical.

For the edge coupling method, a 2 μm external cavity tunable vernier laser with Si photonic chip as the wavelength selective component was designed, fabricated, and characterized. The SOAs were fabricated from the 1960 nm laser wafer with 4.5° to 6.5° tilted waveguides. Si vernier wavelength filter was simulated and optimized using Lumerical software. At the juncture of writing this thesis, a tuning range of ~60 nm with SMSR of higher than 10 dB was achieved in one fabricated laser.

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Chapter 7 Conclusions and future work

7.1 Conclusions

In this research work, a set of 2 μm GaSb-based diode lasers were successfully designed, fabricated and investigated, including conventional FP ridge waveguide lasers, two-section mode-locked lasers, and external cavity tunable lasers. The InGaSb/AlGaAsSb single quantum well structure was used as it allows for the wavelengths in the 2 μm range without any unacceptable strains. The following part of this section will summarize the main contents, major findings and results obtained throughout the course of this research work.

Chapter 1 is the introductory chapter, giving some background knowledge related to this work. It begins with the main practical applications of 2 μm laser sources, followed by the basic ideal of mode locking, instabilities and noises of a mode-locked laser, mode locking techniques together with the pros and cons of each technique, etc. Next, why tunable single frequency operation is desired in sensing and optical communication was introduced. In the following part, the significance of III-V/Si integration was analyzed. To make the conclusion short, it combines the light emitting capability of III-V with the high design freedom and CMOS compatibility of Si photonics. At last, the Chapter gave the aims of this work and structure of this thesis.

Chapter 2 is the literature review. This chapter followed the order of contents in Chapter 1. It begins with the history of GaSb-based diode lasers, followed by a systematical review of mode-locked diode lasers from four aspects: pulse duration, repetition frequency, peak power, and phase noise. Next, it narrated how tunable operation developed from DFB/DBR lasers to real and widely tunable lasers. At last, the four III-V/Si integration methods were carefully reviewed.

In Chapter 3, two different laser structures used to fabricate all the devices in this work were introduced. The main difference of the two structures is one uses AlGaAsSb barrier with higher Al composition to improve the carrier confinement.

According to their lasing wavelength, they are referred to as 1960 nm laser structure and 2020 nm laser structure, respectively in this thesis. This Chapter also summarized the fabrication process for single-section ridge waveguide lasers.

In Chapter 4, the two kinds of laser wafers were processed into basic FP ridge waveguide lasers. This chapter begins by giving a systematic device overview of the fabricated lasers, including temperature-dependent L-I-V (threshold current density as low as 96 A/cm^2), characteristic temperature T_0 and T_1 (103 and 606 K near room temperature), wavelength shift with temperature (0.93 nm/K), modal gain ($13.55(\text{net}) + 5(\alpha_i) \text{ cm}^{-1}$), etc. Next, the ideality factor (electrical) and spontaneous emission (optical) of the fabricated lasers were systematically investigated to gain more information on the carrier recombination behaviors within them. It was found that the ideality factor at 60°C is larger than that at 30°C , which can be well explained by the power law dependences of the three recombination processes (SRH, radiative, Auger) on the carrier density N . For the spontaneous emission, the Z parameter was defined by a model including the above mentioned three recombination processes. There is no obvious temperature dependence of Z from 20 to 80°C , which is also well explained by the power law dependences of the recombination processes. In addition, through the analysis of the activation energy, it is found that severe thermal loss of holes at high I_{bias} cannot be ignored. The findings in the ideality factor and spontaneous emission studies are in very good agreement with each other.

In Chapter 5, monolithic two-section MLLs were fabricated and fully characterized. Stable mode locking was achieved in these lasers under a variety of bias conditions up to 80°C . Hysteresis was observed in a fabricated laser at temperatures higher than 60°C with small negative V_a . Cavity length and gain/absorber length ratio were analyzed. The subsequent chapter sections systematically investigated the mode gain, different working regimes (instabilities), phase noise, frequency tuning of these MLLs. The mode gain was calculated by performing the Hakki-Paoli method. It was found that the lasing action moves to longer wavelengths markedly with increasing negative V_a due to the redshift of the gain profile. The light output contains more longitudinal modes in the mode locking

regime if the gain bandwidth is larger at a certain V_a . Next are the instabilities and phase noise/timing jitter. By fixing the gain current at 130 mA and varying the absorber bias voltage from -1.5 to -2.6 V, the tested laser goes through three distinct pulsed regimes: cw mode locking, Q-switched mode locking, and pure Q-switching. The regime switching mechanism is given based on the interplay between the gain saturation and the saturable absorption. The phase noise/timing jitter was investigated by measuring the single sideband phase noise spectra. At each fixed temperature, there exists an optimum bias condition to achieve the lowest timing jitter. The existence of sidebands may result in a narrower RF linewidth. When temperature is increased, the phase noise/timing jitter improves obviously. At last of this Chapter, the repetition frequency tuning with three parameters (I_g , V_a , and T) was measured and the tuning mechanisms were analyzed. The finding is when the other two parameters are fixed, the repetition frequency keeps reducing with I_g . When V_a becomes more negative, there are two opposite mechanisms coexisting to determine whether the repetition frequency is higher or lower. If the operation temperature is raised, again, the wavelength redshift and temperature related processes compete with each other to give the results.

In Chapter 6, two III-V/Si integration method: wafer bonding and edge coupling have been investigated. For the wafer bonding method, a tapered waveguide GaSb QW laser, bonded onto SOI circuits with an Al_2O_3 bonding layer is designed and analyzed. The BPM simulations show that, with our design, the light in the GaSb QW active region can be successfully coupled into the underlying SOI waveguide. The thermal property of the GaSb-on-Si laser has been calculated using a constant heat spreading model, and results show that the devices using Al_2O_3 bonding layer have a much lower (~70%) thermal resistance as compared to the one using SiO_2 bonding layer. For the edge coupling method, a 2 μm external cavity tunable laser with Si photonic chip as the wavelength selective component is designed, fabricated, and characterized. The SOAs are fabricated from the 1960 nm laser wafer with 4.5° to 6.5° tilted waveguides. Si vernier wavelength filter was simulated and optimized using Lumerical software. At the juncture of writing this thesis, a tuning range of ~60 nm

with SMSR of higher than 10 dB was achieved in one fabricated laser.

7.2 Future work

Suggestions for future work as a follow up to this project are as follows:

1. Since the tunable laser developed in Chapter 6 uses the edge coupling method, it is actually not a real monolithic integrated device. However, this work made a really great start by proving the feasibility of our present setup. A lot of works can be done in the future taking advantage of the high design freedom and compactness of Si photonics, including
 - Diode laser stabilization using Si disks or rings
 - Self-injection locking of two-section MLLs using Si photonic chips
 - Dual-comb system using two-section MLLs and Si photonic chips
 - Basically all the other present diode laser performance improving techniques using fibers or discrete optical components can be tried with Si photonic chips. In this way, the device will become extremely compact.

At the same time, the tunable laser performance can be further improved by optimizing the polishing process of the Si photonic chip facet since the SOA-Si photonic chip coupling loss represents the most significant source of loss in the laser cavity.

On the other hand, a flip-chip bonding process can be developed to make the III-V/Si external cavity tunable laser a real monolithic integrated device.

2. Some new waveguide structures can be investigated, especially the ring lasers. Semiconductor ring lasers (SRLs) may refer to lasers with many different cavity shapes, e.g. circular, racetrack, and square. For every cavity shape, a variety of guiding mechanisms are available, e.g. microdisks for whisper gallery modes, rib waveguides, and ridge waveguides. SRLs are very promising as light sources in photonic integrated circuits. They can be positioned anywhere on a substrate since neither cleaving nor polishing is needed to form the cavity facets.

3. Last but even more important, some efforts can be put in exploring real applications of all the above devices in communications, sensing, chemical or medical measurements, etc. This is the ultimate goal of developing these devices.

Publications

Journal papers

1. **X. Li**, H. Wang, Z. Qiao, Y. Zhang, Z. Niu, C. Tong, and C. Liu, “Design and analysis of 2- μm InGaSb/GaSb quantum well lasers integrated onto silicon-on-insulator (SOI) waveguide circuits through an Al_2O_3 bonding layer,” *IEEE J. Sel. Topics Quantum Electron.*, vol. 22, no. 6, p. 1500507, 2016.
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