

國立交通大學

光電工程研究所

碩 士 論 文

新型光子晶體雷射製程之研究

**Fabrication of Novel Photonic Crystal
Laser Structures**

研 究 生：張吉東

指 導 老 師：李柏璁 教授

中華民國九十四年七月

新型光子晶體雷射製程之研究

研究生：張吉東

指導老師：李柏璉 教授

國立交通大學光電工程研究所



摘要

在這篇論文中首先我們介紹了光子晶體結構的基本原理以及我們的研究動機，再來對其歷史發展做一概括性的介紹與討論。

在光子晶體的製程中，為了結合雷射共振腔與光子晶體結構，我們使用了電子束微影法、乾式蝕刻和濕式蝕刻的製程去做成一種層狀結構的光子晶體雷射，在另一方面，我們亦引入了非對稱型的光子晶體雷射。

為了得到更好的光譜特性，我們介紹了各種晶圓接合技術去整合含有多層量子井結構的晶圓與其不相容的材料，我們利用直接接合和溶膠接合的方法去接合 1550nm 長波長的多層量子井晶圓與含有 DBR 結構的晶圓或 sapphire，並對於各種接合影響因素與材料的選擇加以討論，最後再對我們的層狀光子晶體雷射和晶圓接合後的樣本做量測。

Fabrication of Novel Photonic Crystal Laser Structures

Student : Chi-Tung Chang

Advisor : Prof. Po-Tsung Lee

Department of Photonics & Institute of Electro-Optical Engineering

Abstract

In this thesis, first we introduce the principles of photonic crystal structures and our research motive. The history and developments of photonic crystal lasers are also described and discussed.

In the fabrication of photonic crystals, in order to combine the laser cavity and photonic crystal structure, we use electron-beam lithography, dry etching, and undercut process to form a membrane photonic crystal laser. We also introduce photonic crystal lasers with asymmetric structure.

In order to obtain better characteristics of photonic crystal lasers, the wafer bonding technology is introduced to integrate MQWs wafer with different incompatible wafers. We utilize the direct bonding method and glue bonding method to integrate the 1550nm long-wavelength MQWs with DBR wafer or sapphire. The effect factors of bonding process and choice of bonding materials are discussed. At last, we measure the photoluminescence spectra of our membrane devices and bonding samples.

Acknowledgements

在各位看到這篇論文的同時,也代表著我人生中的求學生涯已經結束,並即將步入下一個人生階段,在這碩士班的短短兩年過程中,我不只是只滿足在盡我當學生的本分,我也盡力想讓我僅剩無幾的年少生活過的精采,並把握每一天剩下的所有時刻。

在此我最感謝的人莫過於是我的父母,有他們這二十多年來的養育之恩,才会有現在的我,不論在經濟上或是心理上的支持,都讓我感覺生活無虞,真的是非常的感謝他們,其次感謝的是我的指導教授李柏聰老師,感謝她在這兩年來對我的所有包容與耐心,在她的敦敦教誨之下,才讓懵懂未知的我能逐漸步上軌道,到最後能夠順利畢業,真的讓我非常感謝,我還要在此特別感謝朱榮堂學長,感謝他在實驗上不厭其煩的給我建議與指導,讓我在後期能有突破性的進度,也感謝黃世傑學長、蔡豐懋學弟以及各位同學及學弟的幫忙與指導,不論是在研究或玩樂上,唯有你們的陪伴,才能讓我在這兩年的時光中感覺到過的充實與快樂。



2005/07 于新竹交通大學

Contents

Abstract (in Chinese).....	II
Abstract (in English).....	III
Acknowledgements.....	IV
Contents.....	V
Table List.....	VII
Figure List.....	VIII

Chapter 1. Introduction.....1

1-1. Background	1
1-2. Research Motive	2
1-3. Principles of Photonic Crystals	3
1-4. History and Developments	6
1-5. Thesis Overview	10

Chapter 2. Fabrication of Membrane Structures11

2-1. Research Motive	11
2-1. Fabrication of Two-dimensional Photonic Crystal Lasers.....	12
2-3. Conclusions	23

Chapter 3. Wafer Bonding Technology.....24

3-1. Introduction 24

3-2. Research Motive 24

3-3. Various Wafer Bonding Methods 28

3-4. Process for Direct Bonding 34

3-5. Key Issues in Wafer Bonding Process 38

3-6. Substrate removal 42

3-7. Conclusions 42

Chapter 4. Measurement Results.....31

4-1. Patterns Designed 44

4-2. Measurement results 46



Chapter 5. Conclusions.....51

References.....53

Table List

Table. 3-2-1. Thermal conductivities and refractive indices of different materials. (P.27)

Table. 3-4-1. The thermal expansion coefficients of stainless steel and molybdenum material at different temperatures. (P.36)



Figure List

- Fig. 1-1. The photonic crystals can be divided into one-, two-, and three-dimensional structures. (P.1)
- Fig. 1-2. The relations of (a) electronic dispersion and (b) photonic dispersion. (P.2)
- Fig. 1-4-1. The typical TE-like band diagrams of photonic crystal slabs with (a) triangular lattice and (b) square lattice. The band-gap of triangular lattice is much larger than that of square lattice with the same lattice constant and r/a ratio. (P.7)
- Fig. 1-4-2. (a) The illustration of the structure with central post for an electrically-driven single defect photonic crystal micro-cavity laser. (b) The L-I curve of this photonic crystal laser. (P.9-P.10)
- Fig. 2-1-1. The basic structure of a two-dimensional photonic crystal membrane laser. (P.11)
- Fig. 2-2-1. The membrane epitaxial structure. (P.12)
- Fig. 2-2-2. The top view SEM pictures with (a) 1.4 fC, (b) 1.6 fC, (c) 1.8 fC, and (d) 2.1 fC dosages in EBL process. (P.14-P.15)
- Fig. 2-2-3. The top view SEM picture of photonic crystal patterns defined on PMMA layer. (P.16)
- Fig. 2-2-4. The SEM picture of devices after ICP process. (P.17)
- Fig. 2-2-5. These are the etching profiles of InP material along $\langle -1, 0, 0 \rangle$ direction in the $(0, -1, -1)$ plane with etching time (a) 6, (b) 8 minutes, and (c) in the $(0, 1, -1)$ plane with 8 minutes. (P.18-P.19)
- Fig. 2-2-6. The top view of devices after failed undercut process. (P.20)

- Fig. 2-2-7. The V-shape patterns appear in the center of air holes and this means that the undercut process is failed. (P.21)
- Fig. 2-2-8. The top view SEM pictures of two-dimensional photonic crystal micro-cavities after (a) failed and (b) successful undercut processes. (P.21-P.22)
- Fig. 2-2-9. The tilted view SEM picture of two-dimensional photonic crystal membrane structure. (P.22)
- Fig. 2-3-1. Fabrication procedure of two-dimensional photonic crystal membrane lasers. (P.23)
- Fig. 3-2-1. Relation between energy band gap and lattice constant for several III-V compounds. (P.25)
- Fig. 3-2-2. The reflectance of DBR can be up to 99.5% for the wavelength range from 1450 to 1600 nm. (P.26)
- Fig. 3-2-3. A simple illustration of a two-dimensional photonic crystal laser cavity with asymmetric structure where the substrate is replaced by sapphire for better thermal conductivity. (P.28)
- Fig. 3-3-1. The diagram of anodic bonding method. (P.29)
- Fig. 3-3-2. The bond energy of Si on sapphire wafer. (P.31)
- Fig. 3-3-3. The relation between annealing temperature and surface energy under different bonding atmospheres. (P.32)
- Fig. 3-3-4. A picture of the sample after glue bonding to DBR. (P.33)
- Fig. 3-4-1. The epitaxial structure for wafer bonding process. (P.34)
- Fig. 3-4-2. (a) The bonding fixture is composed of molybdenum materials, stainless steels, and graphite plates. (b) The fusion system is composed of chamber, pump, and PID controller. (P.35)
- Fig. 3-4-3. The thermal curves of annealing procedure in (a) DBR-bonding and (b) sapphire-bonding. (P.37)

- Fig. 3-5-1. The rainbow effect is caused by unsmooth wafer surface. (P.38)
- Fig. 3-5-2. The bubbles at the interface will affect the uniformity of wafer bonding. (P.39)
- Fig. 3-5-3. Using the gas of argon as atmosphere makes the bonding process fail. (P.40)
- Fig. 3-5-4. The star-shape texture on the surface of substrate. (P.41)
- Fig. 3-5-5. The texture destroys the QW structure by diffusion. (P.41)
- Fig. 3-7-1. The complete fabrication process of two-dimensional photonic crystal defect cavities bonded to sapphire. (P.43)
- Fig. 4-1-1. The TE-like band diagram of two-dimensional photonic crystal membrane with 0.3 r/a ratio and 500 nm lattice constant. (P.45)
- Fig. 4-1-2. The index profile of the asymmetric photonic crystal slab structure. (P.45)
- Fig. 4-1-3. The typical band diagram of asymmetric photonic crystal slab with 400nm lattice constant and 0.28 r/a ratio. (P.46)
- Fig. 4-2-1. The configuration of our micro-photo-luminescence system. (P.47)
- Fig. 4-2-2. Comparison of glue-bonding samples. (P.48)
- Fig. 4-2-3. The PL spectra of direct bonding samples which are bonded to (a) DBR and (b) sapphire. (P.49)
- Fig. 4-2-4. The spectrum shows that the lasing wavelength is at 1538nm. (P.50)