

量子级联激光器简介

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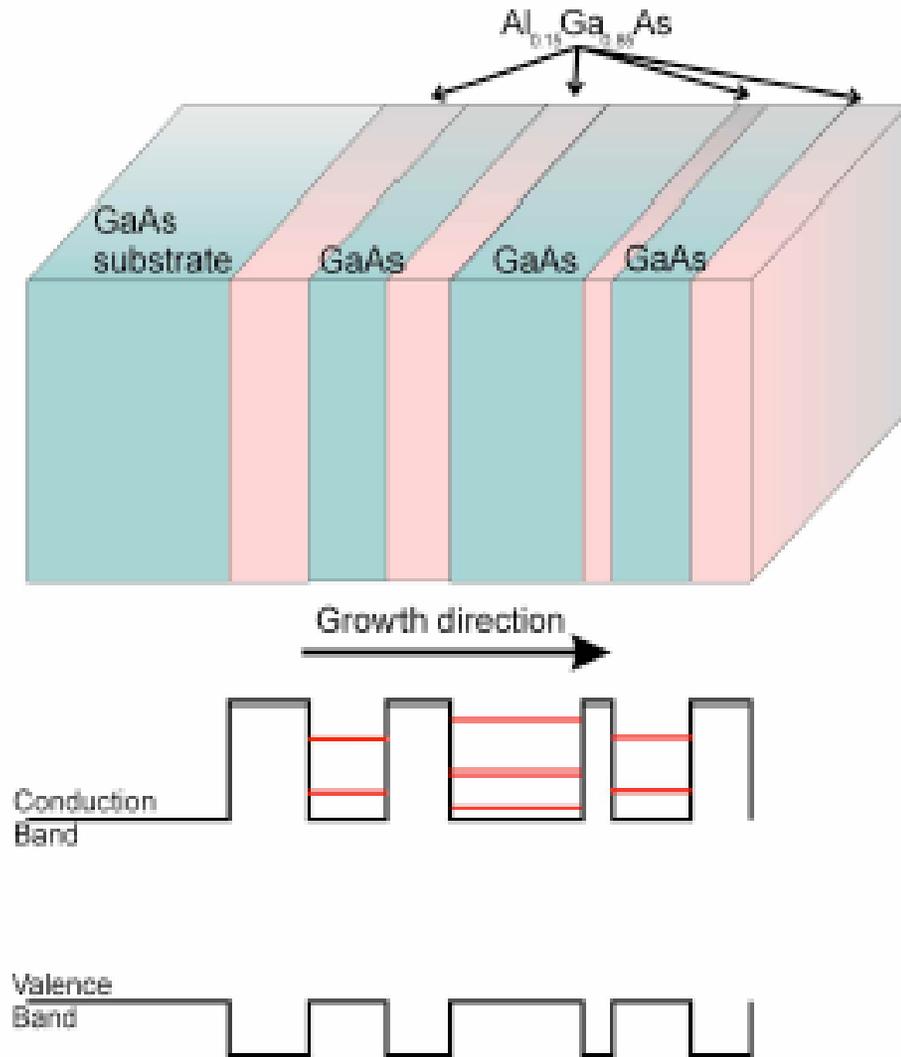
2010年11月04日

报告纲要

- 一. 研究背景
- 二. 工作原理
- 三. 科学技术问题
- 四. 半导体所部分工作

能带工程：新型半导体材料、器件基础

- GaAs and $\text{Al}_x\text{Ga}_{1-x}\text{As}$ (or InGaAs/InAlAs) are lattice-matched, can be grown on top of each other defect-free.
- Different gap energies in GaAs and $\text{Al}_x\text{Ga}_{1-x}\text{As}$ form **quantum wells**.
- **Molecular Beam Epitaxy** (MBE) can grow layer by layer, atomically smooth.
- In essence, with MBE we can design and grow “Artificial Atoms” or “artificial molecules.” We can control the size of wells and relative energy levels.

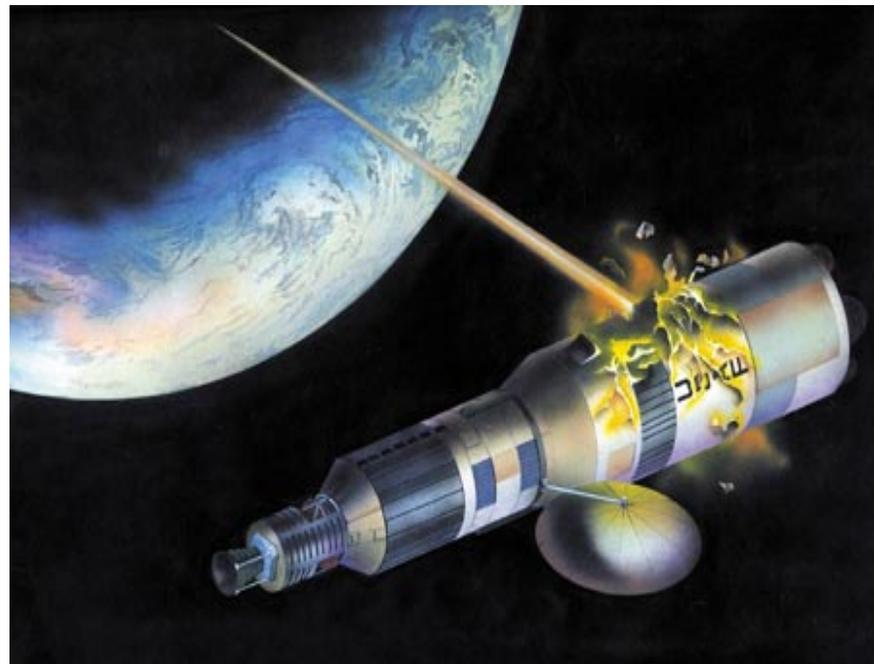


一. 研究背景

一. 量子级联激光器研究背景

$\lambda > 2\mu\text{m}$ 全固态红外激光器:

环境、医学、反恐、通信、红外干扰、深空探测



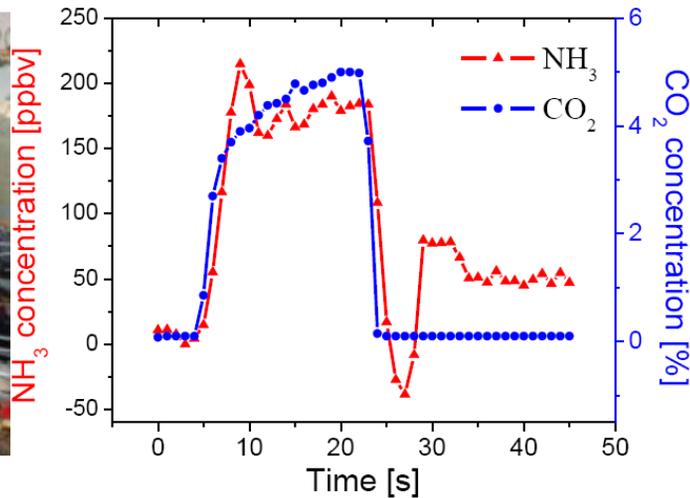
部分应用实例



NASA 的2011年火星探测



Breath analysis facility at St. Luke's Hospital



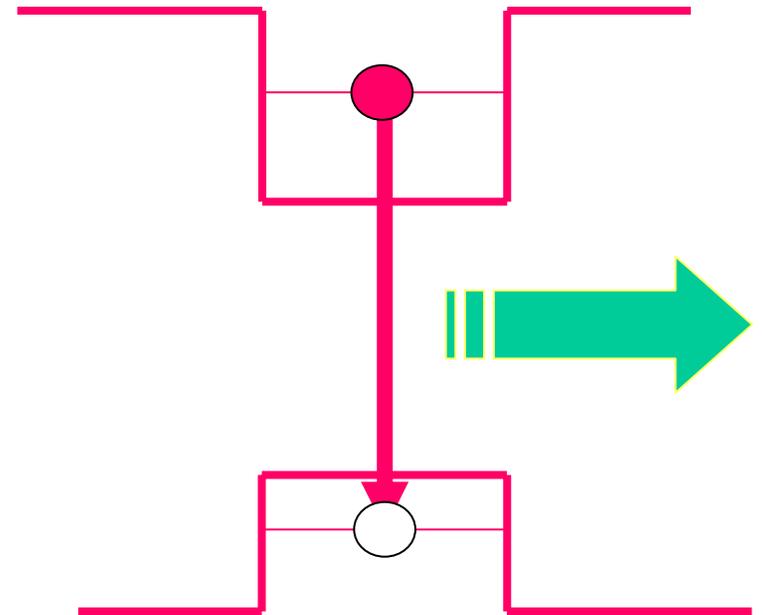
Sensor response @ 45°C

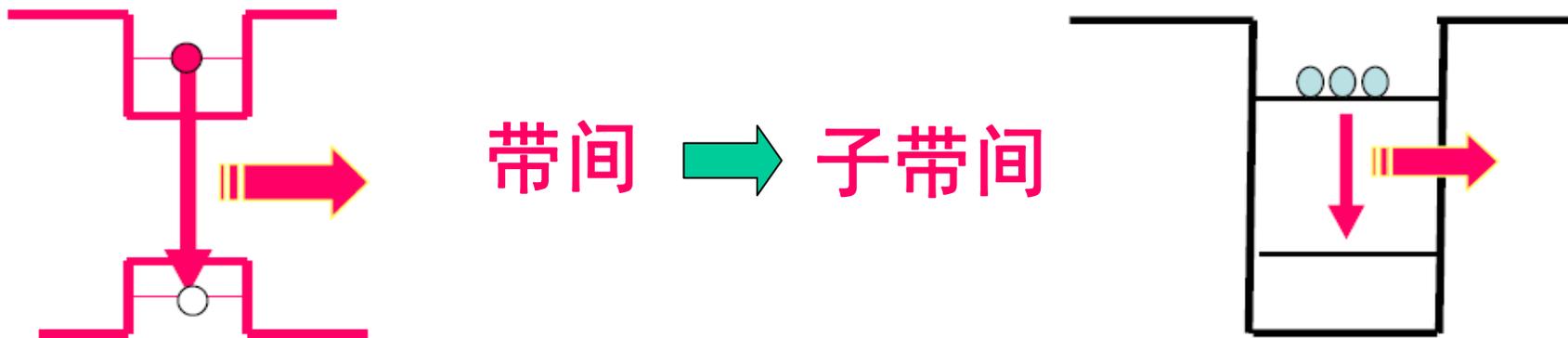
呼吸：400多种分子，
固定的“生化轨迹”

常规半导体激光器

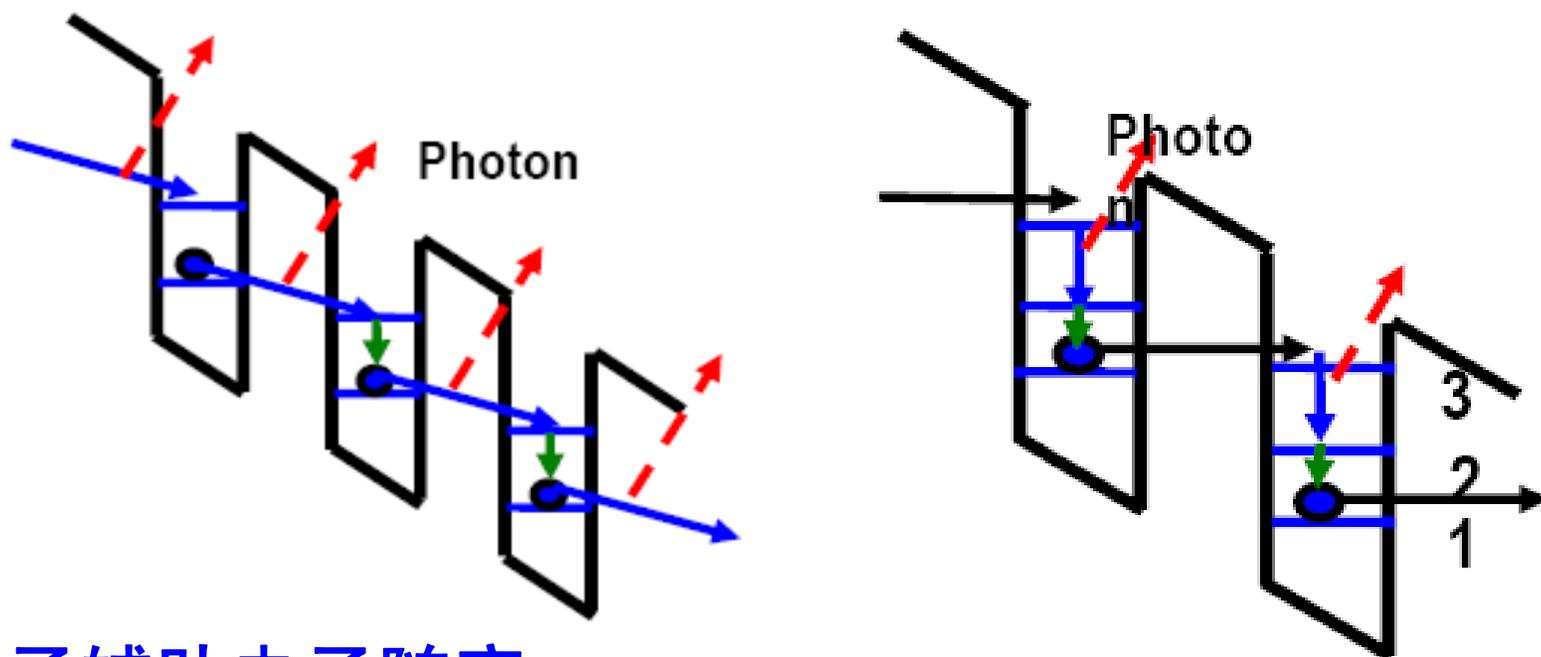
III-V族半导体激光器
难以实现长波长。

采用IV-IV族的铅盐系
及II-VI族的汞硫窄带
隙材料，材料制备技
术不成熟，器件性能
差。





R. F.Kazarinov, R.A.Suris,Sov. Phys.Semicond. 5, 707 (1971)

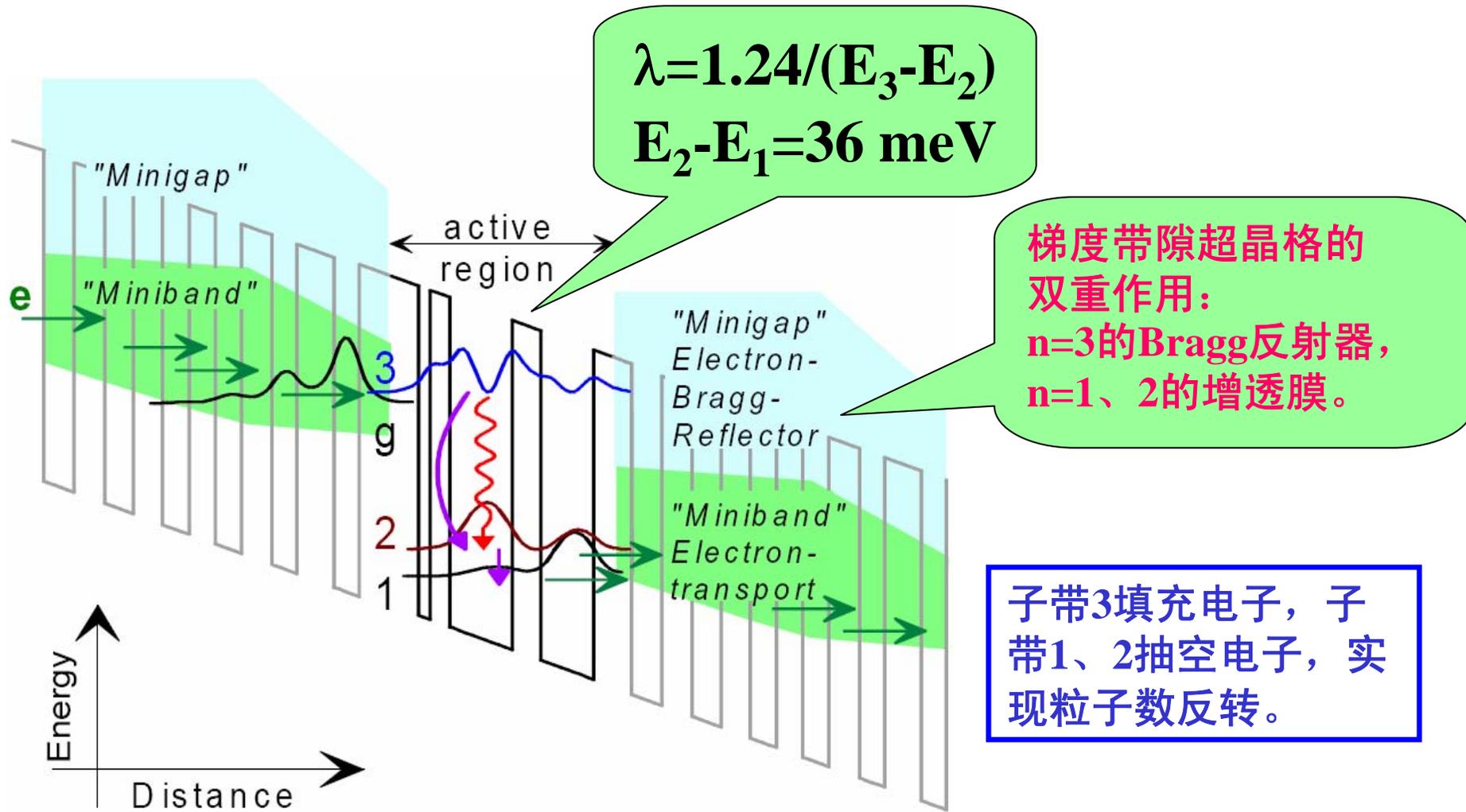


光子辅助电子随穿

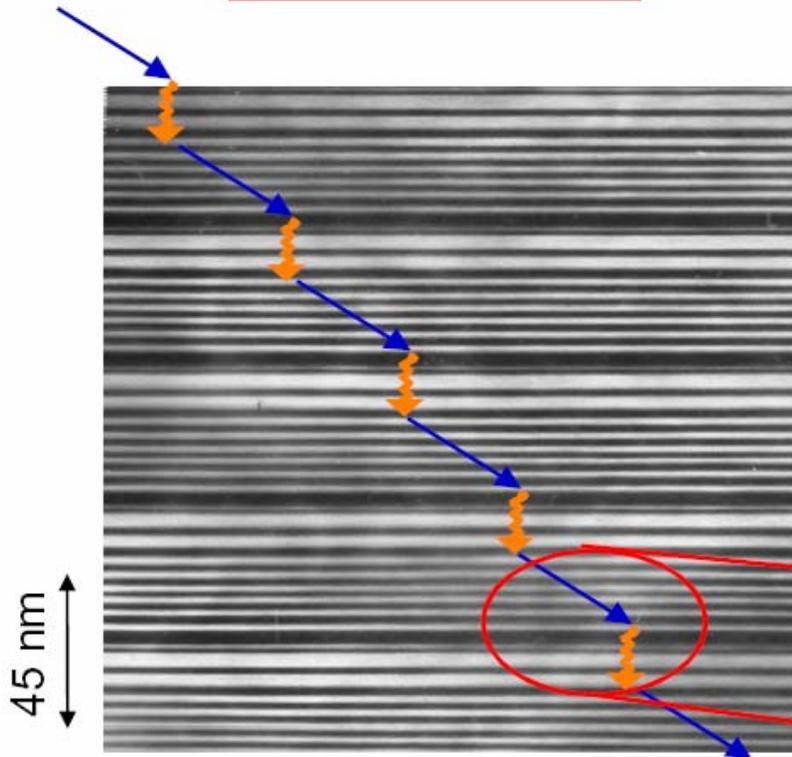
无法实现稳定的粒子数反转

二. 量子级联激光器 工作原理

量子级联激光器(QCL)工作原理

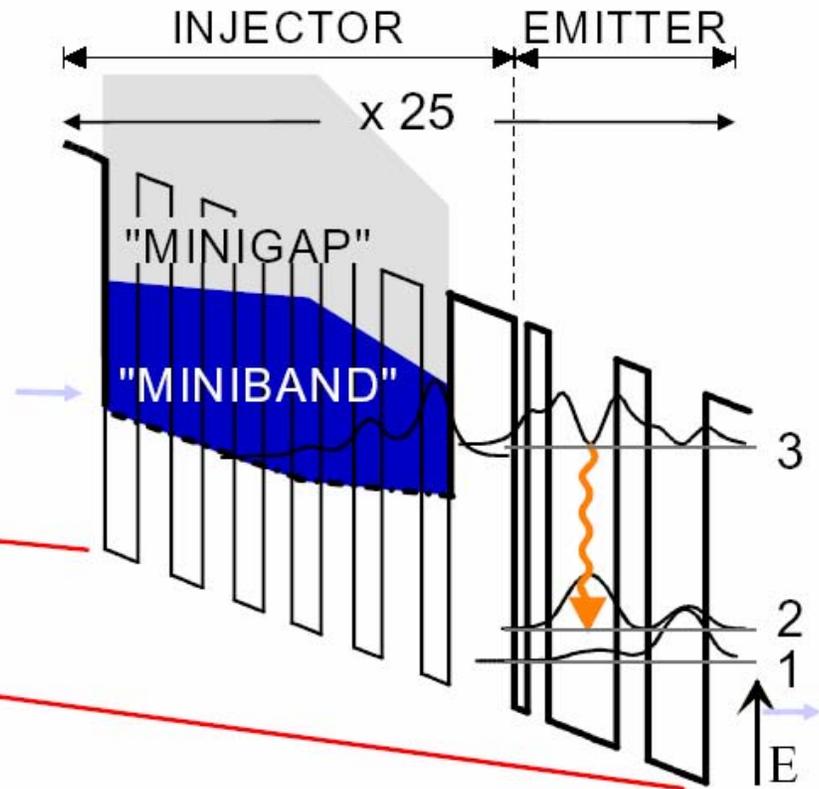


TEM Micrograph

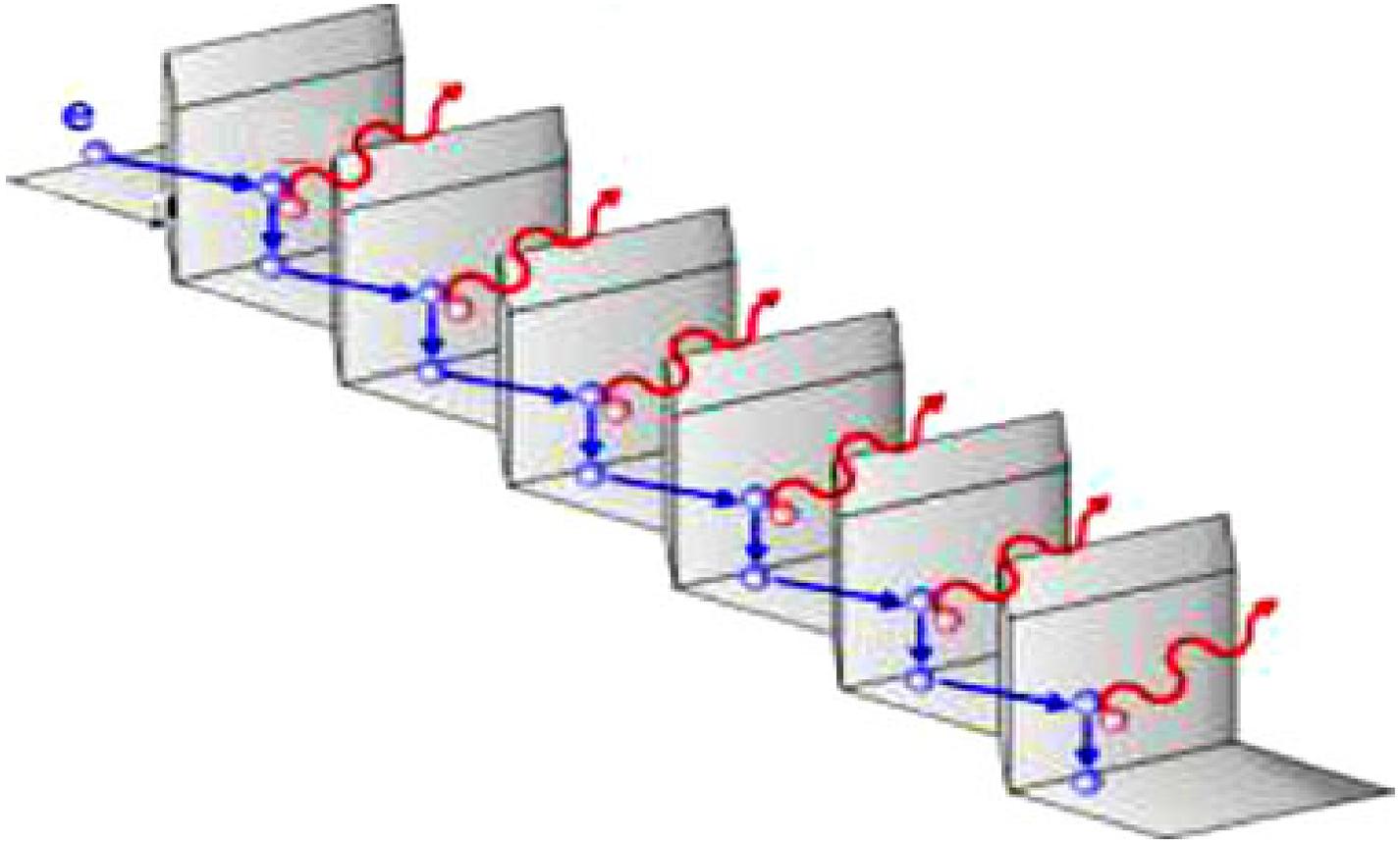


molecular beam epitaxy

Band diagram



级联效果：单电子→多光子
子带跃迁、波长可大范围调节

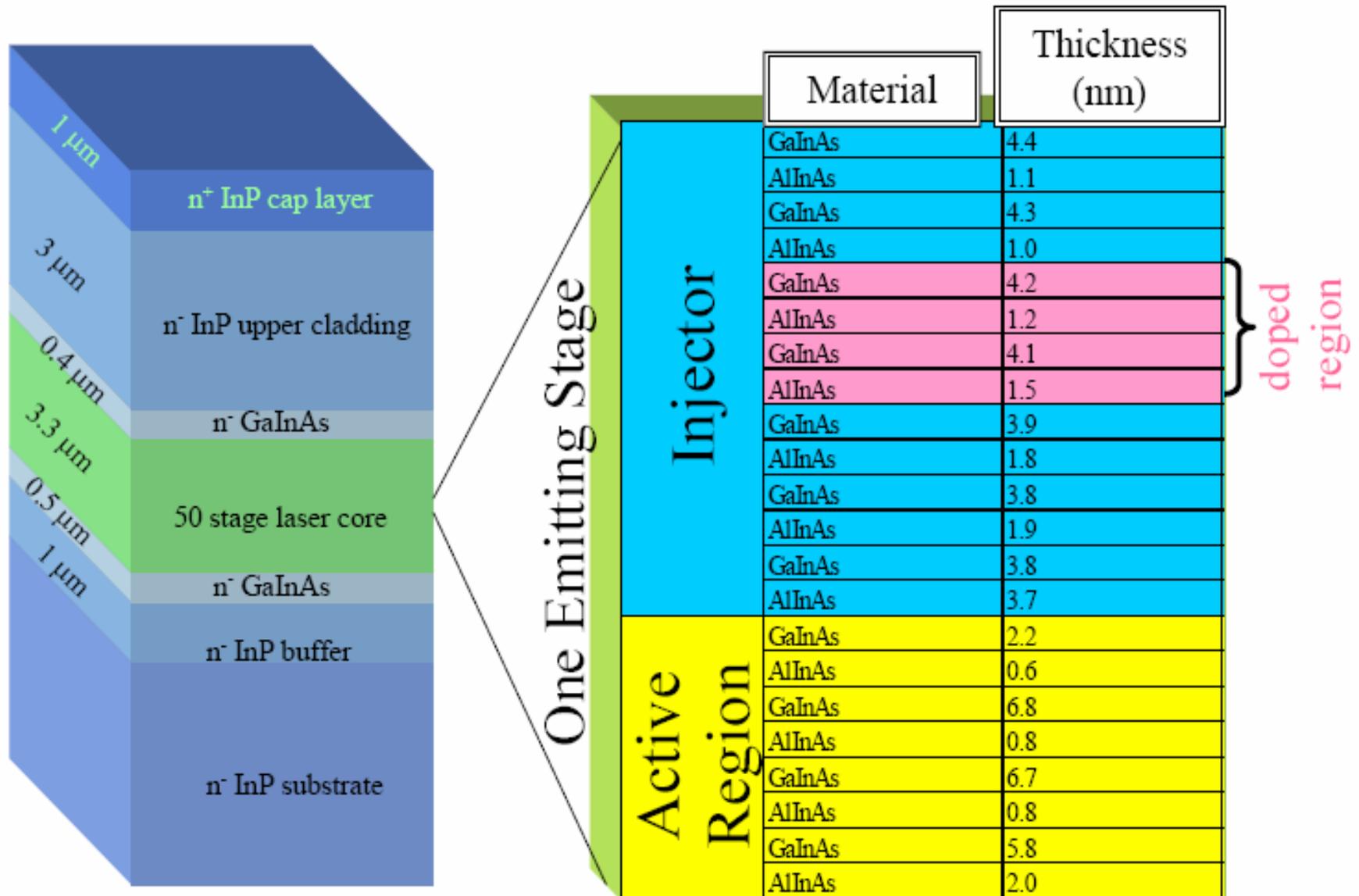


级联效果：单电子→多光子
子带跃迁：波长可调、 $2.65\text{-}300\mu\text{m}$

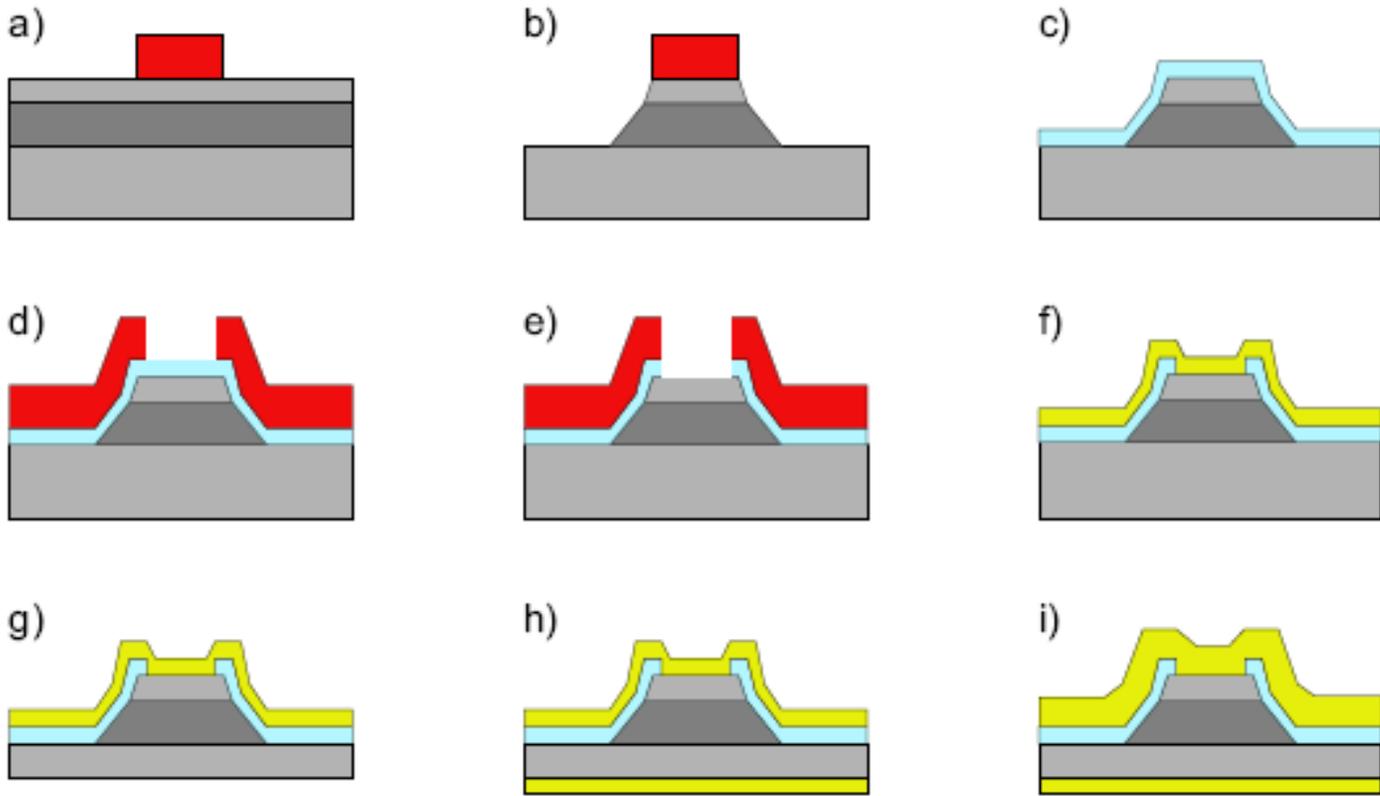
QCL特点

- 1 单极光源
- 2 单电子注入的多光子输出，可获大功率
- 3 工作波长与材料带隙无关
- 4 超高速响应的激光器
- 5 与带隙类别无关，材料选取自由度大
SiGe/Si材料体系。

外延结构

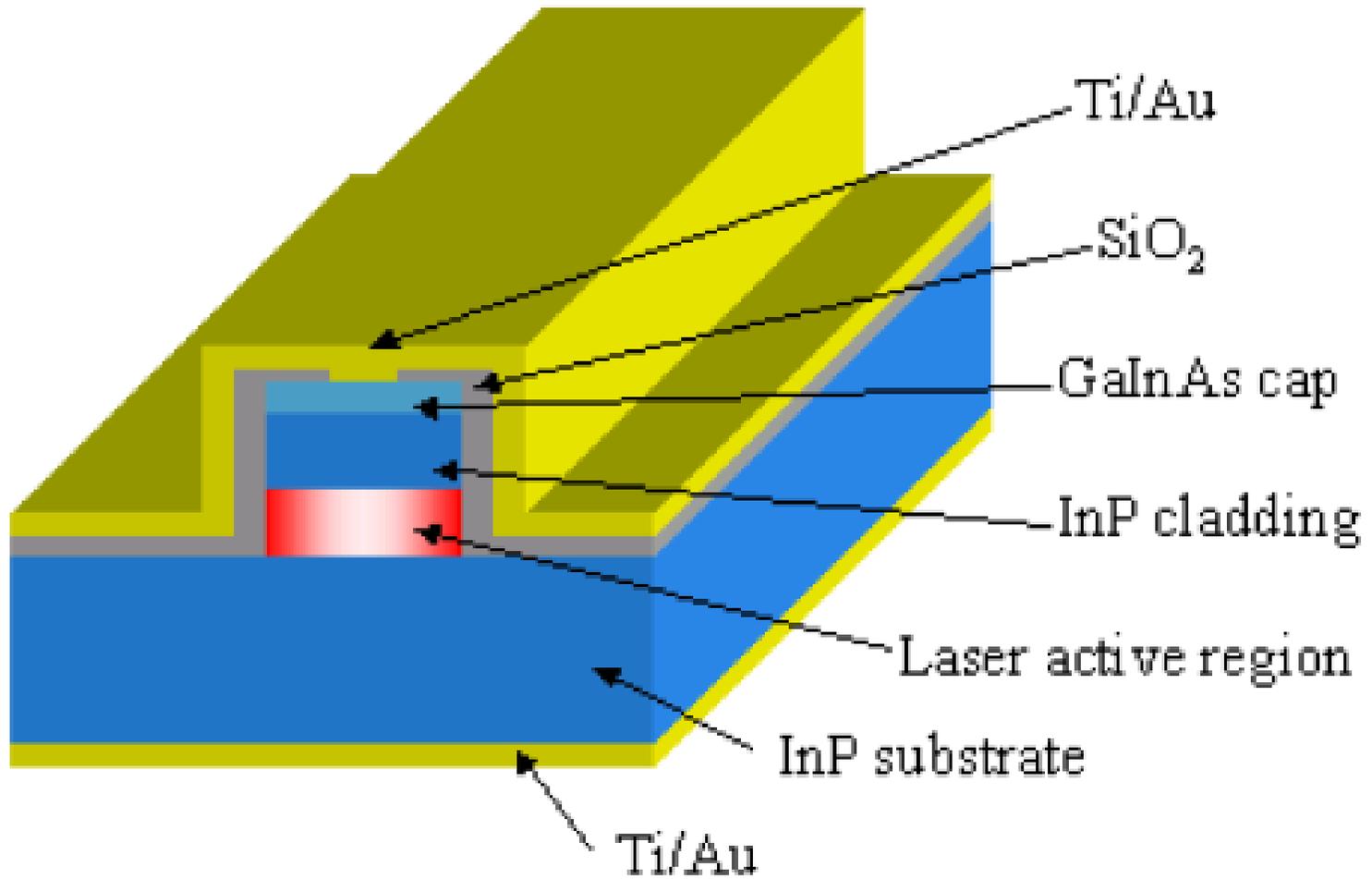






InP top cladding
 Active region and spacers (InGaAs/InAlAs)
 n-doped InP substrate

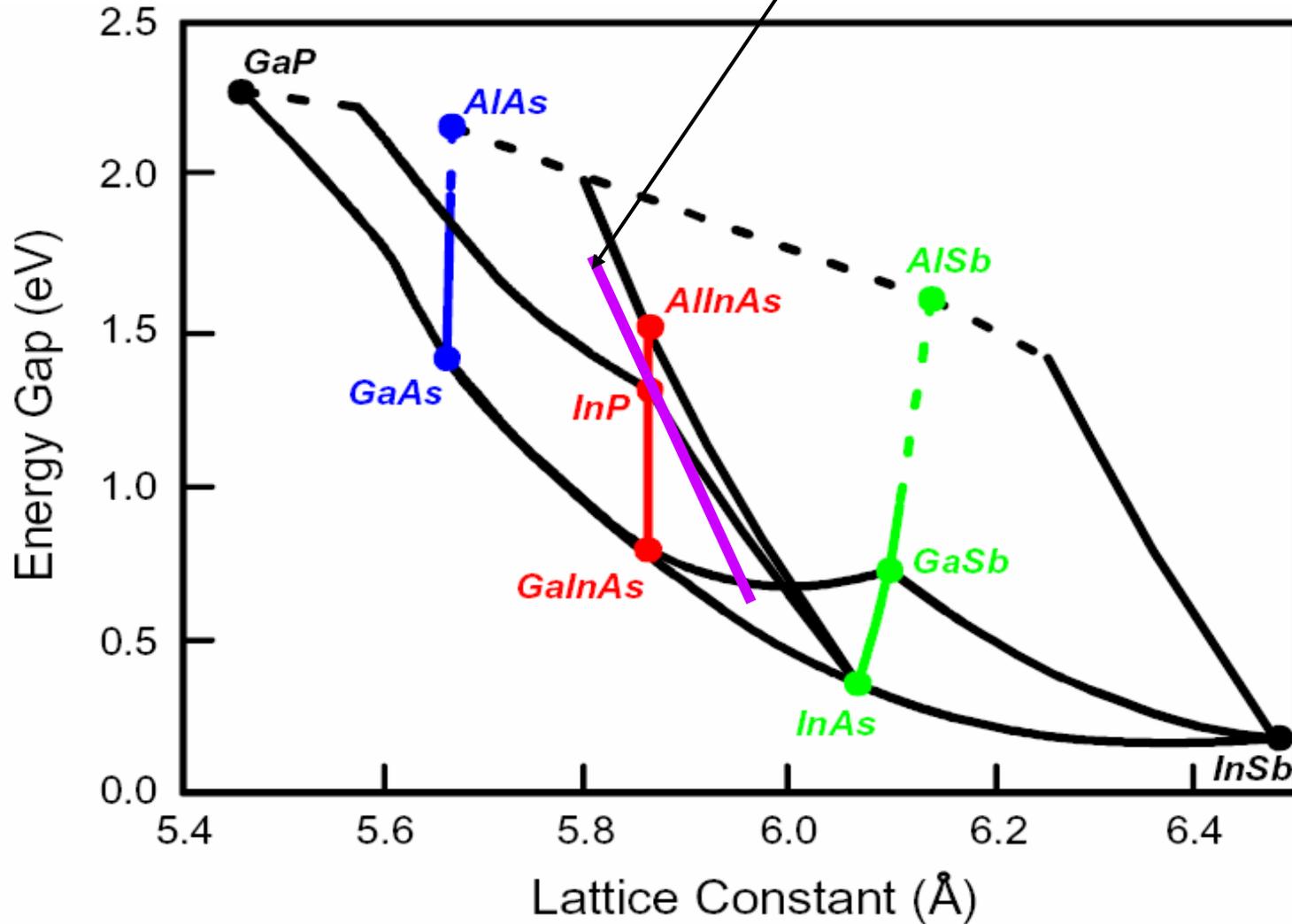
Photoresist
 Silicon nitride
 Metallic contacts



材料体系

应变补偿

$\text{In}_{1-x}\text{Ga}_x\text{As} / \text{In}_{1-y}\text{Al}_y\text{As}$



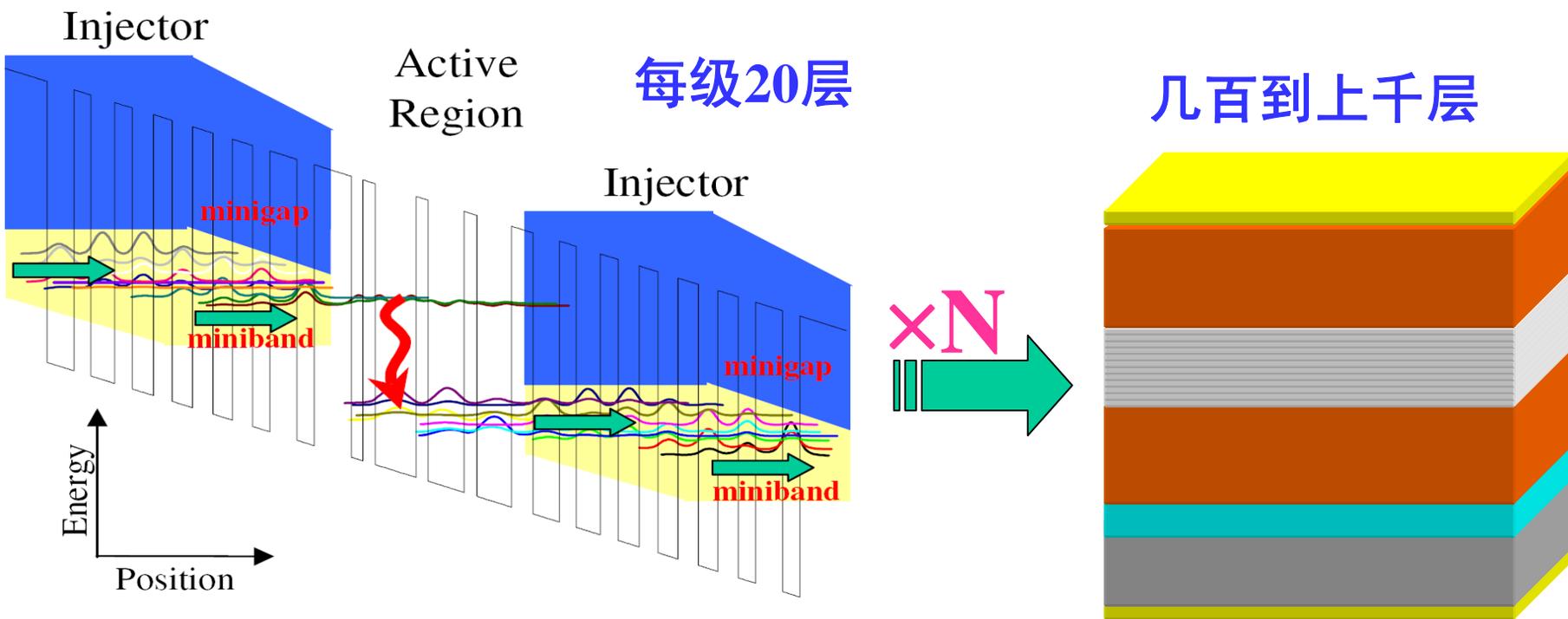
三. 科学技术问题

复杂的子带过程、载流子输运等物理问题

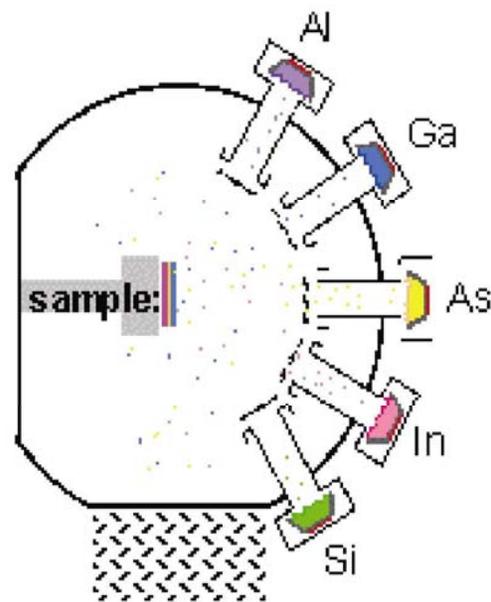
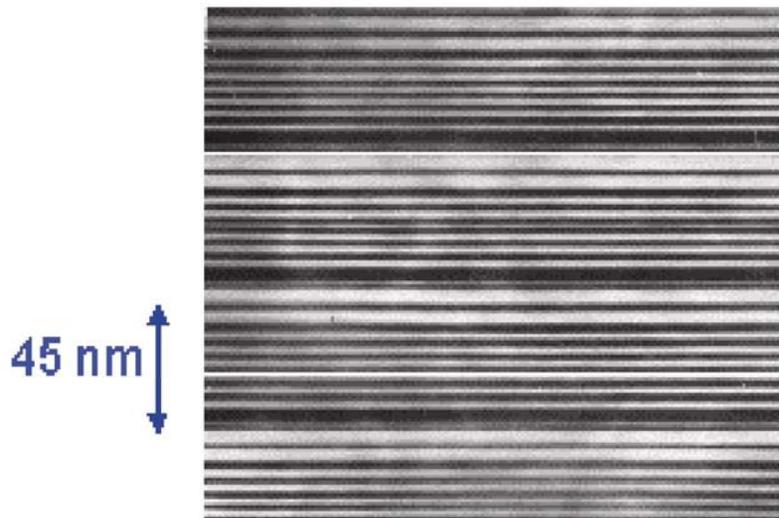
设计：层厚层序、隧穿输运、有源区形式、波导结构。

材料：大于600层，层厚、调制掺杂、界面质量精确控制。

器件：大电流，室温连续工作，热应变、热失配严重，
怎样提高热稳定性、寿命？



QCL突出难点：材料研制

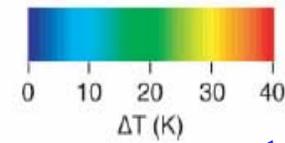
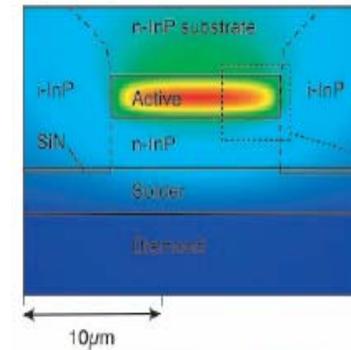


有源区600层以上，每层几个原子单层的三元合金 (InGaAs、InAlAs)，1nm相当于4个原子单层。

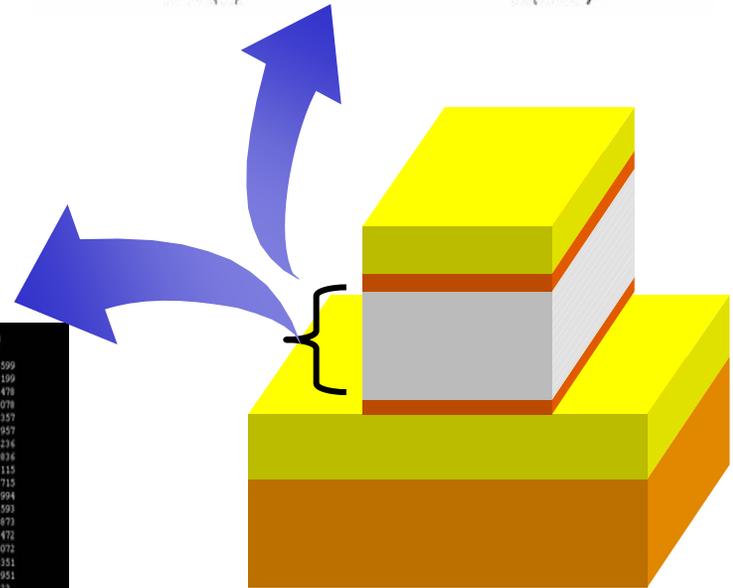
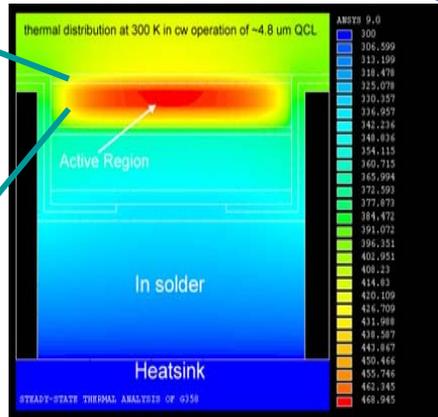
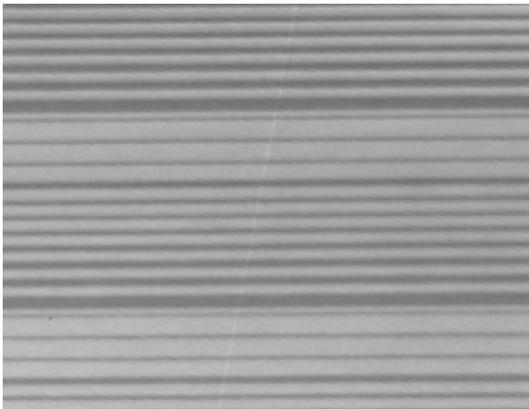
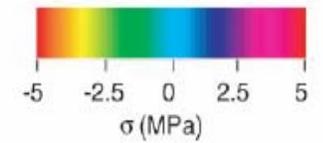
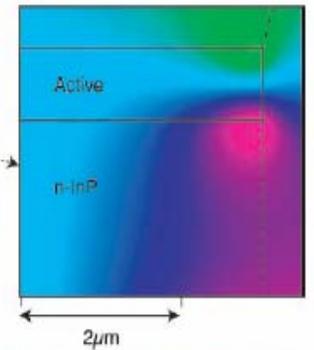
要求原子级界面平整、层厚、组份及均匀性、调制掺杂、晶格失配度等的有效控制。

热失配、热积累； 退化因素、解决策略

B) Temperature

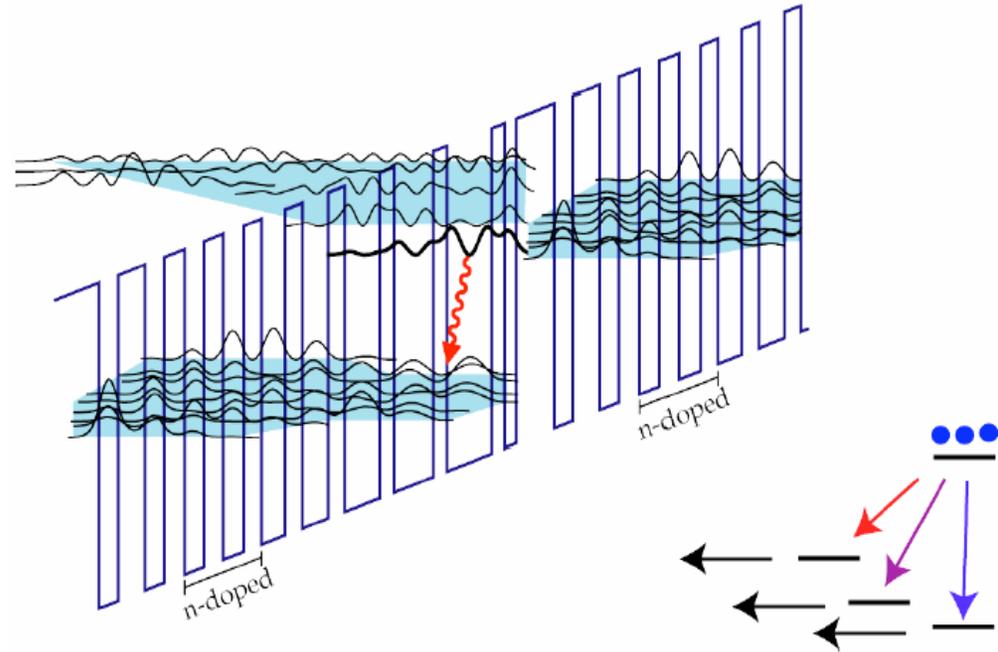
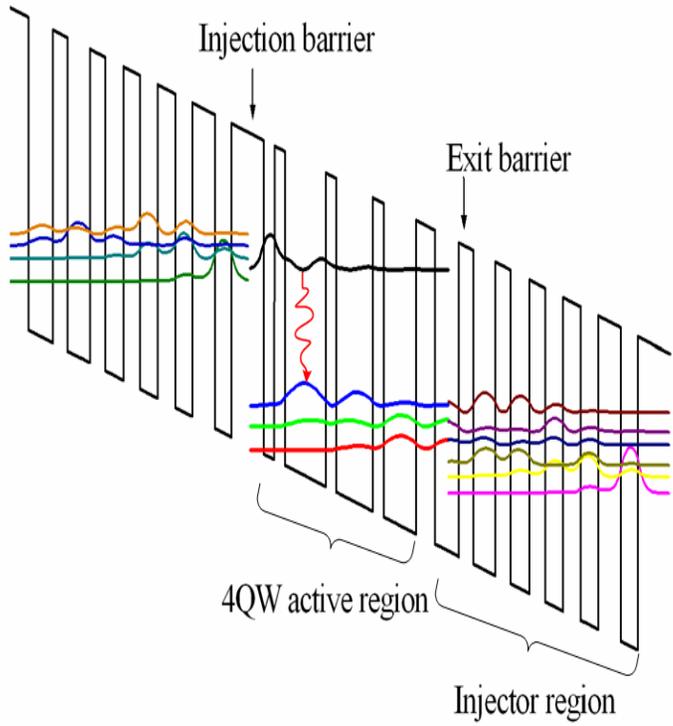
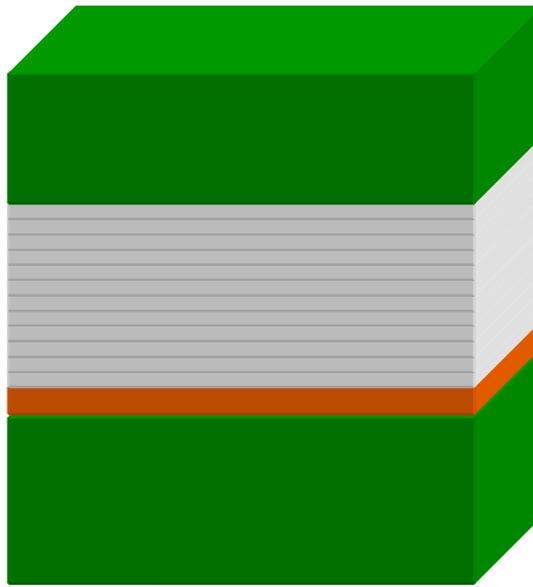


C) Shear stress

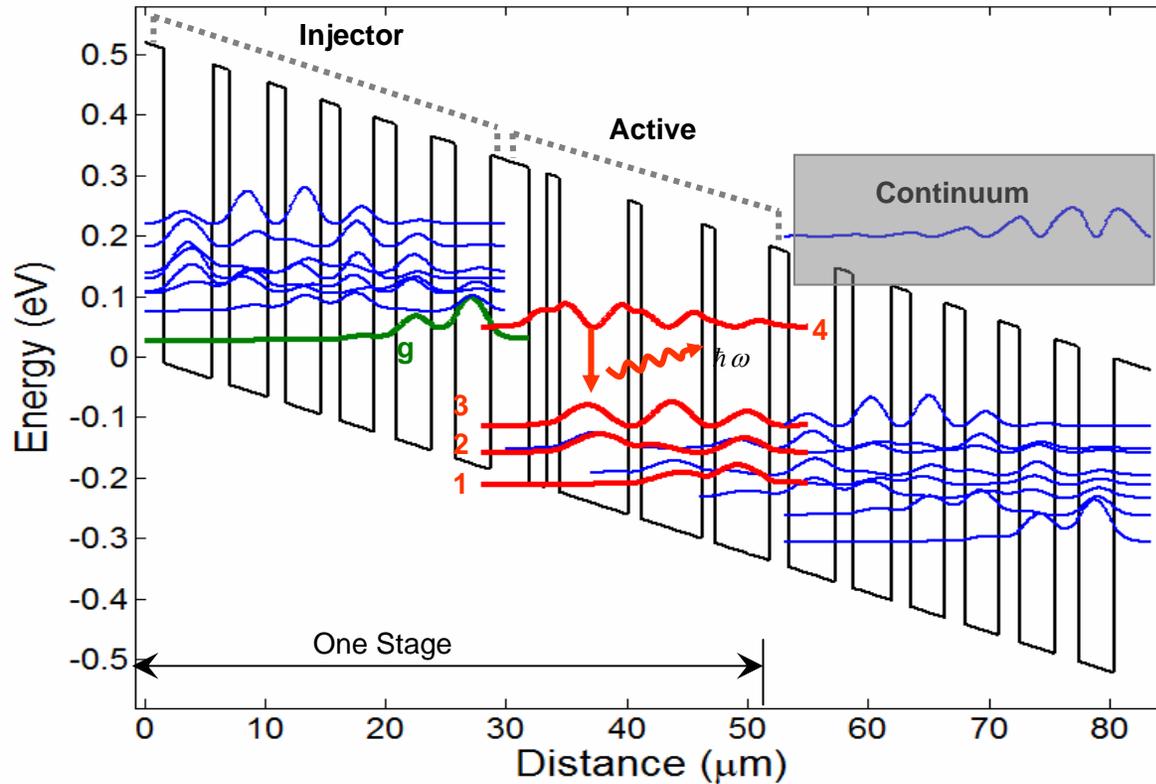


四. 半导体所 部分工作介绍

材料设计:



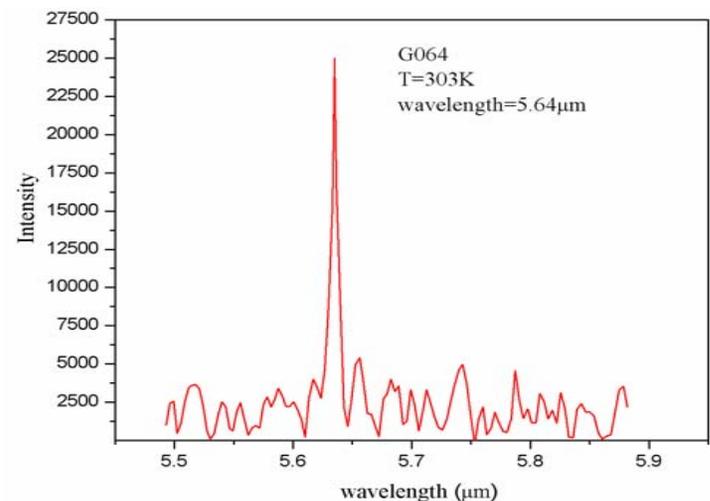
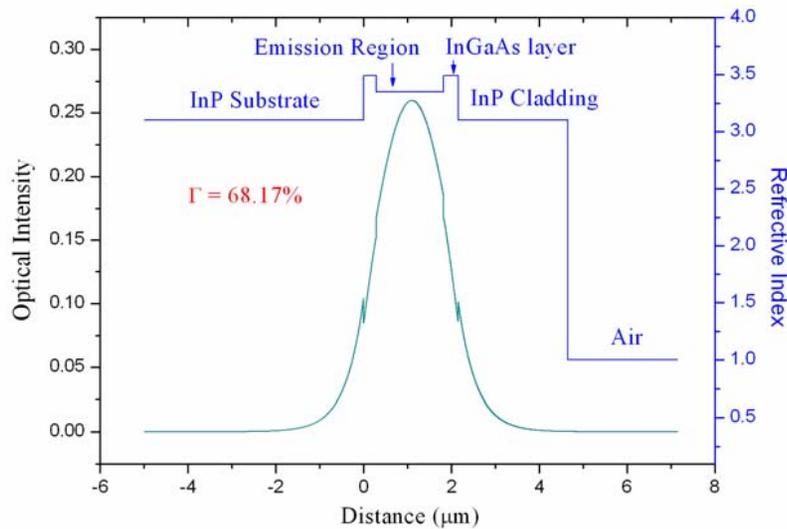
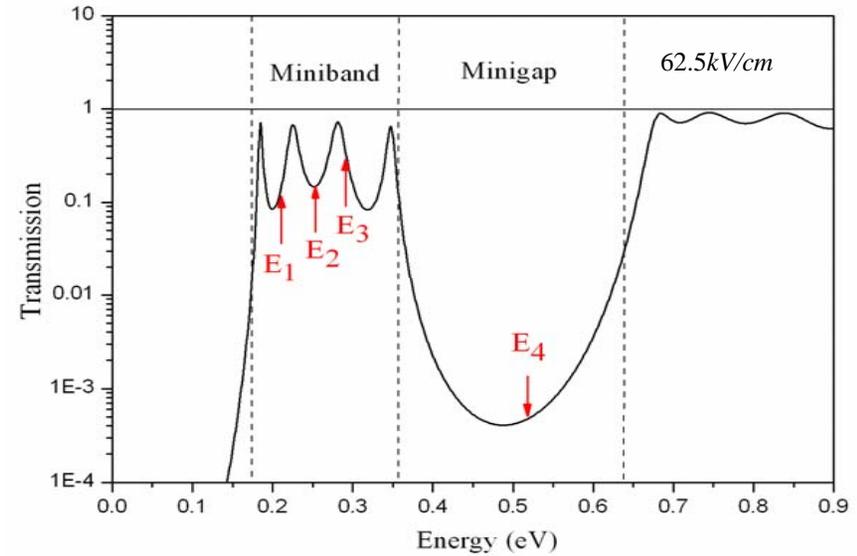
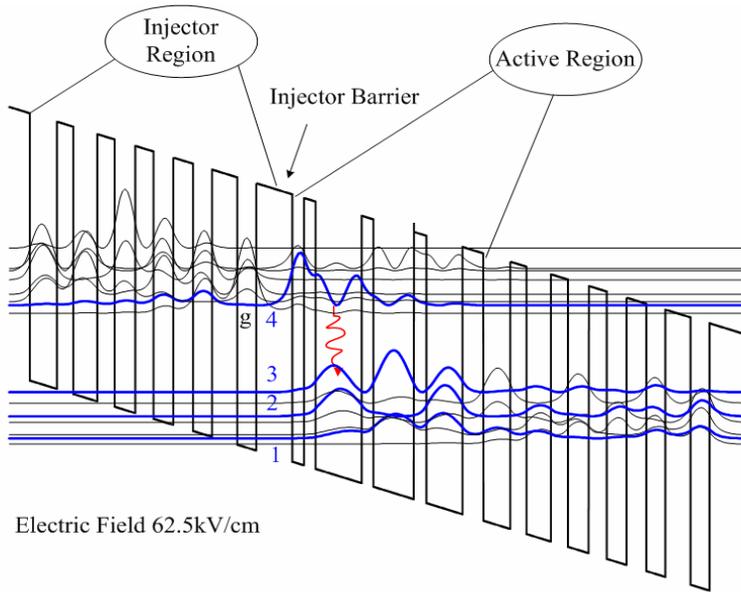
设计实例:



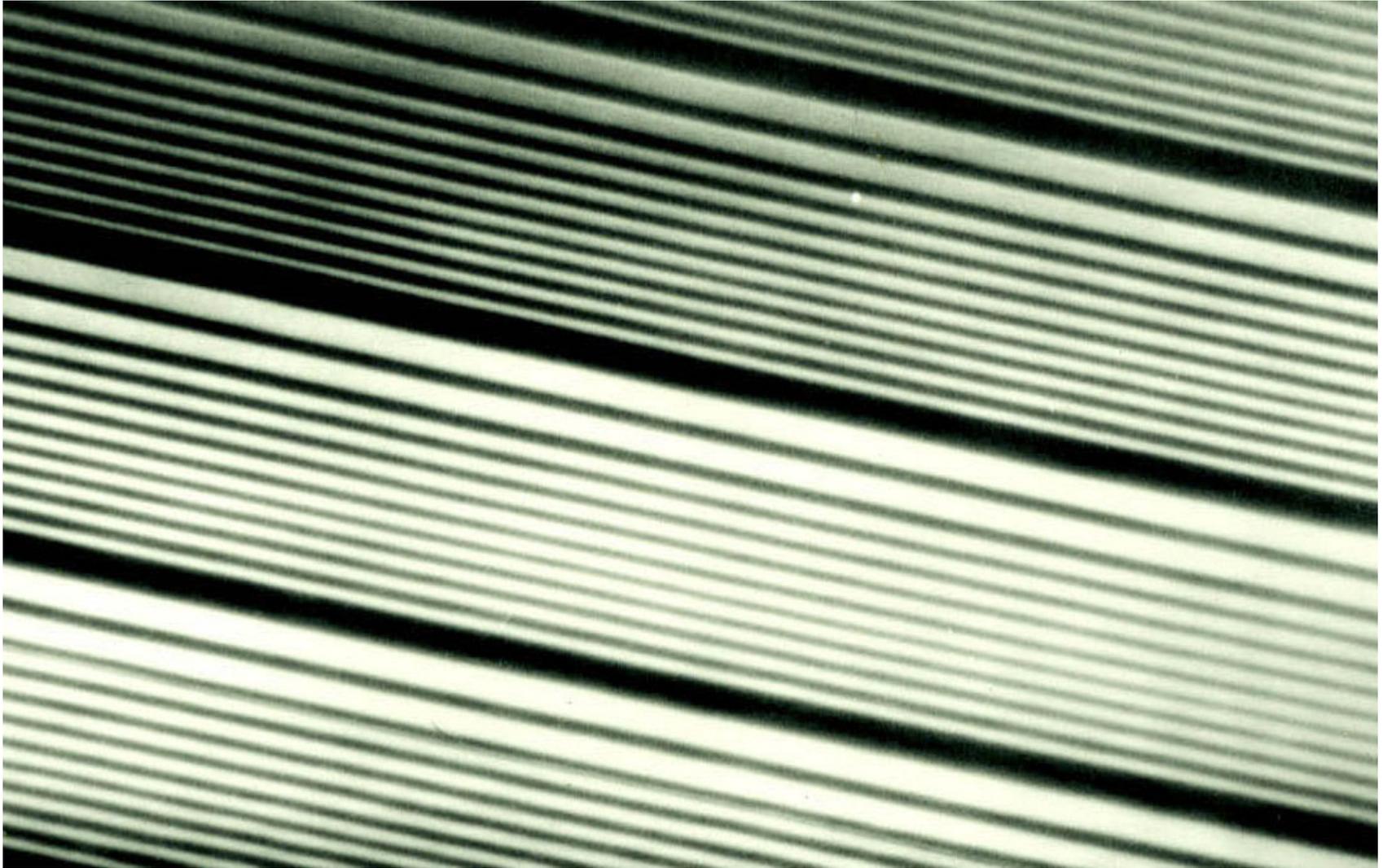
双声子共振有源区结构，材料体系
 $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}/\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ ，激光波长 $7.8\ \mu\text{m}$ 。

设计实例:

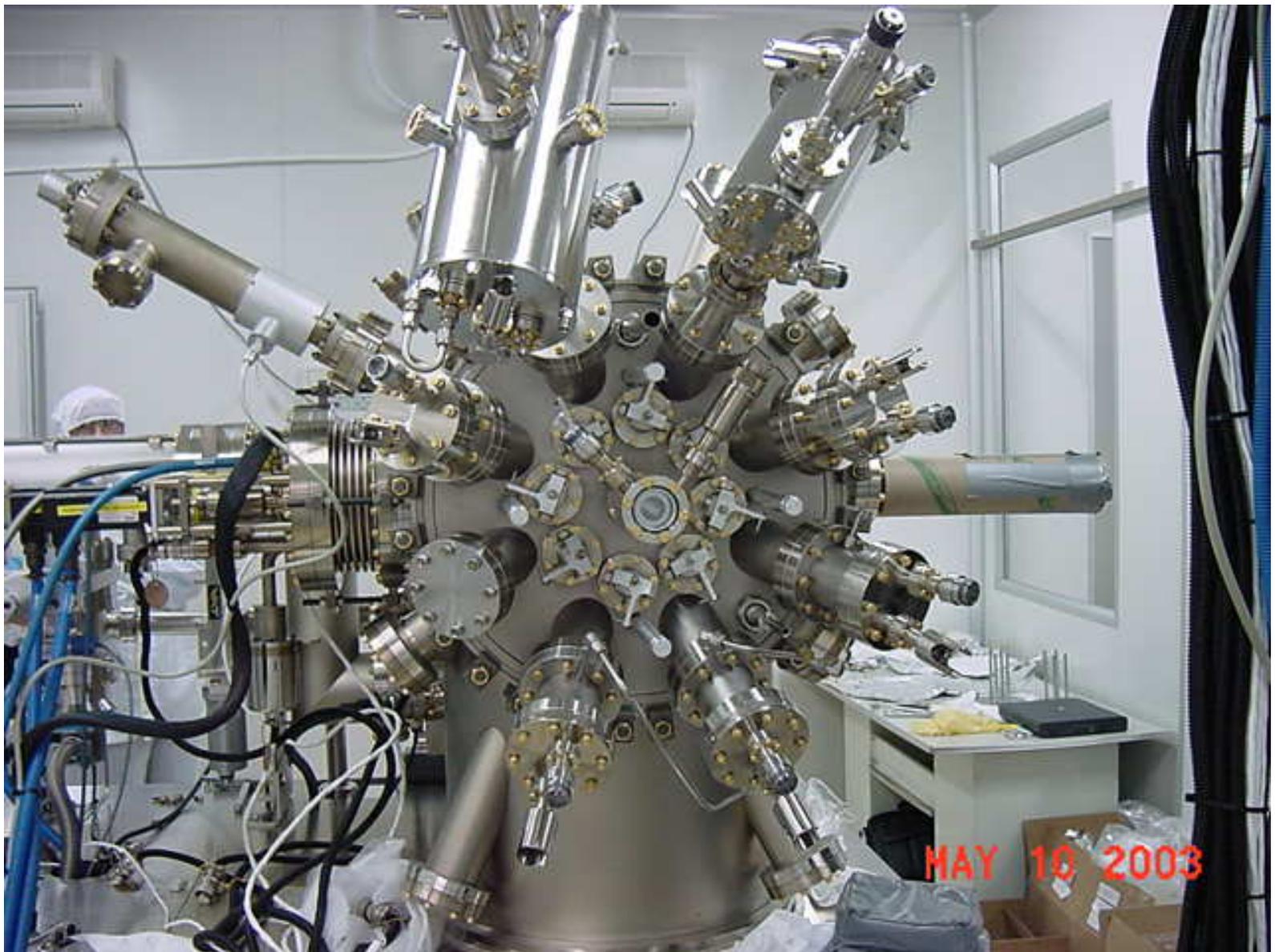
应该补偿双声子共振有源区结构，材料体系
 $\text{In}_{0.6}\text{Ga}_{0.4}\text{As}/\text{In}_{0.44}\text{Al}_{0.56}\text{As}$ ，激光波长 $5.6\ \mu\text{m}$ 。



材料是基础，如何实现高质量外延？



典型QCL有源区横截面SEM



As, P, In, Ga, Al, Si

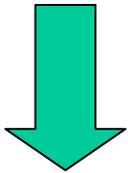
QCL材料的研制次序

1. Compositions (InGaAs, InAlAs)
2. Growth rates
3. Doping
4. InP growth
5. Strain-compensation
6. QCL structures

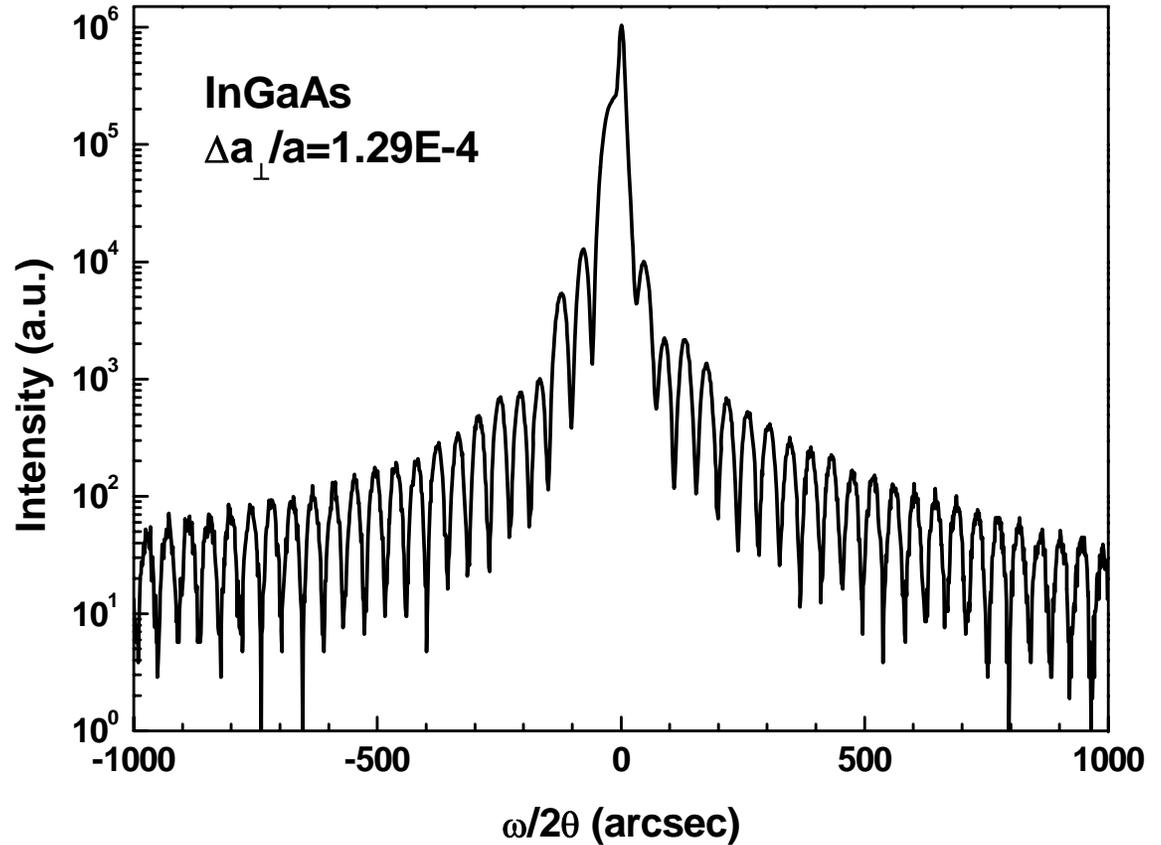
Composition: $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$

V/III ratio 20, Sub = 515°C

**By adjusting
In/Ga ratio,**



**Anticipated
composition**

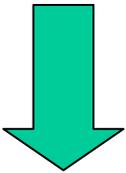


Double crystal X-ray diffraction result

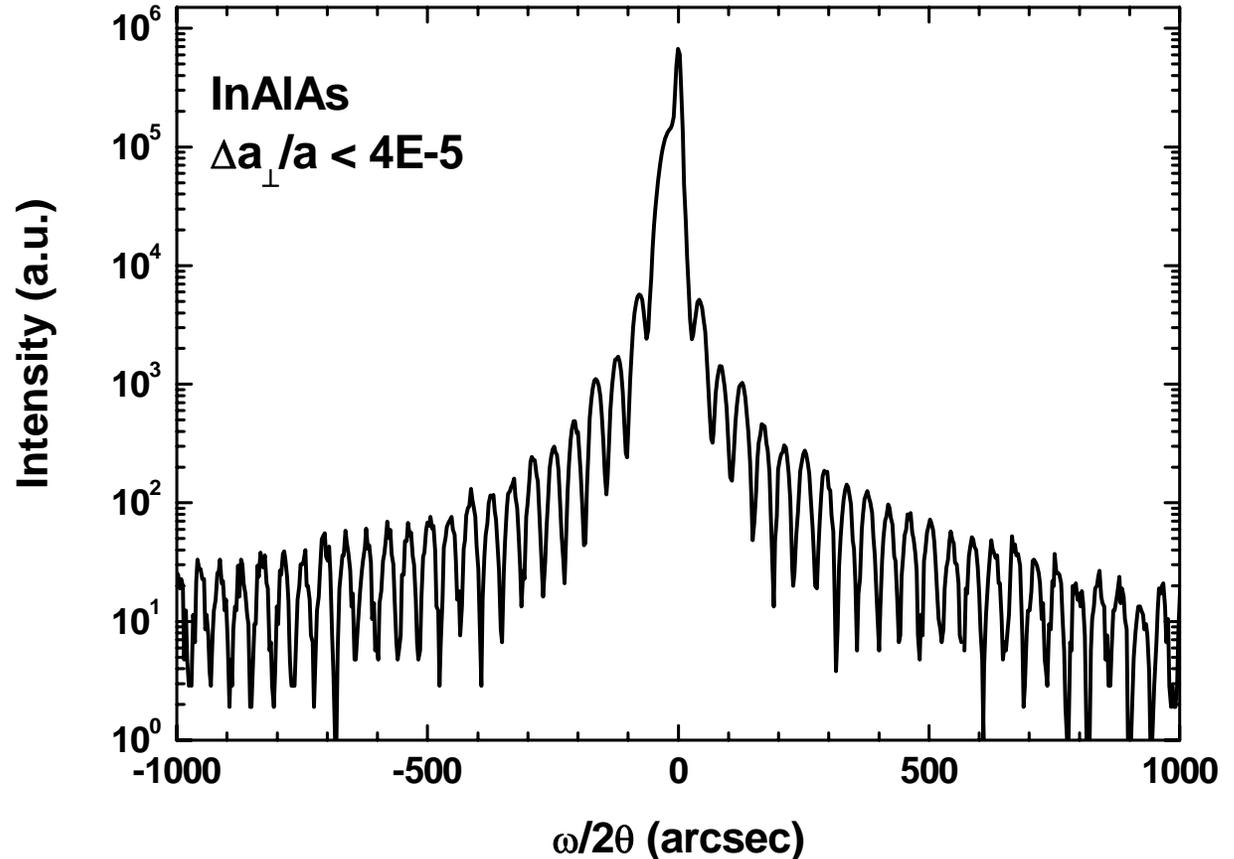
Composition: $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$

V/III ratio 20, Sub = 515°C

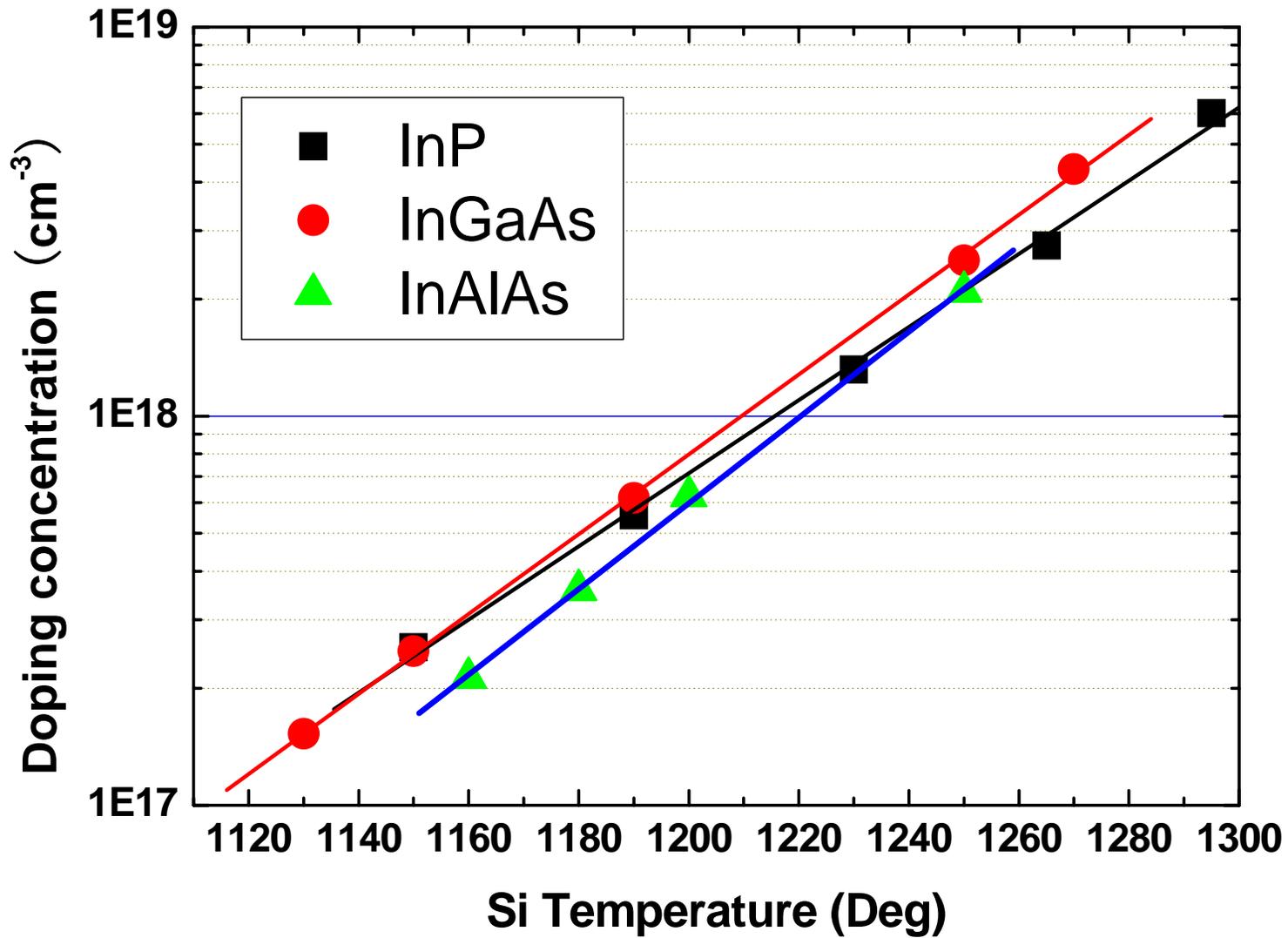
**By adjusting
In/Al ratio,**



**Anticipated
composition**



Double crystal X-ray diffraction result¹



InP growth



valved cracker of P

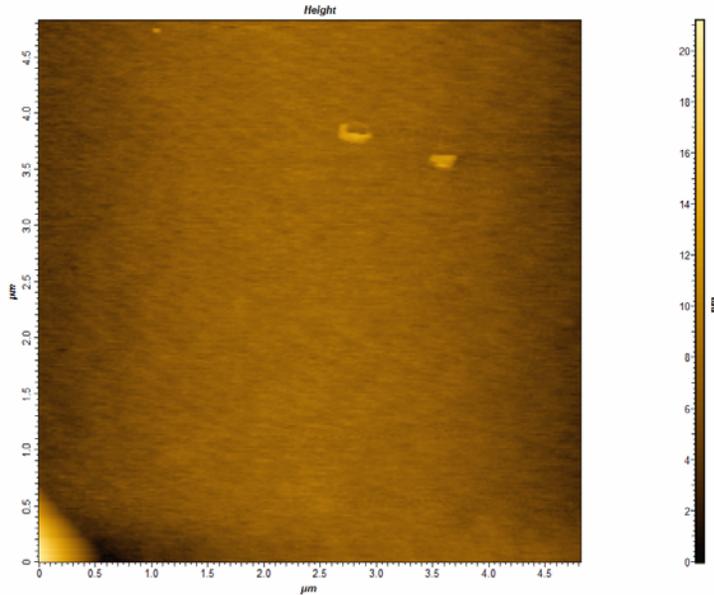
**Cracker: 950°C,
conversion P_4 to P_2 .**

Red p: 350-360°C

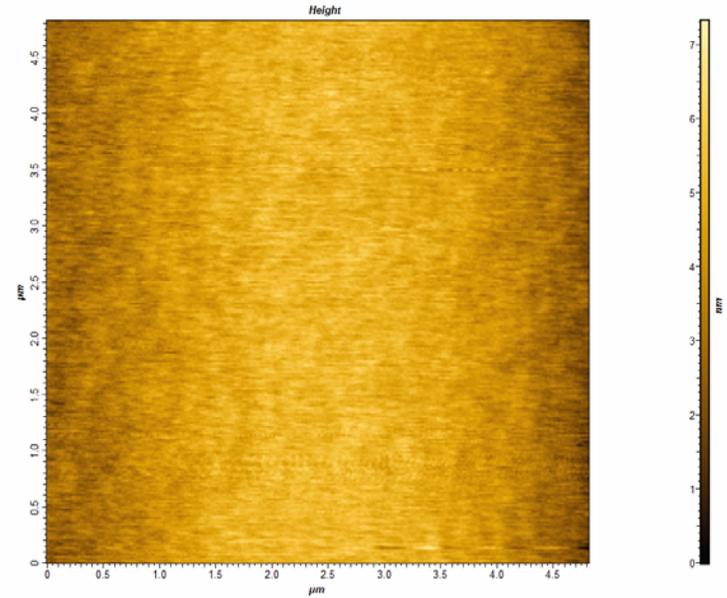
White P: 80-90 °C

**P_2 pressures: $0.2-2 \times 10^{-5}$ Torr
 P_2 /In flux ratios : 5-25**

sub=460°C, V/III ratio=10



sub=490°C, V/III ratio=15-22



Optimal growth parameter:
Sub= 490°C,
P₂ /In = 20:1,
Growth rate: 0.6-0.9mm/h.

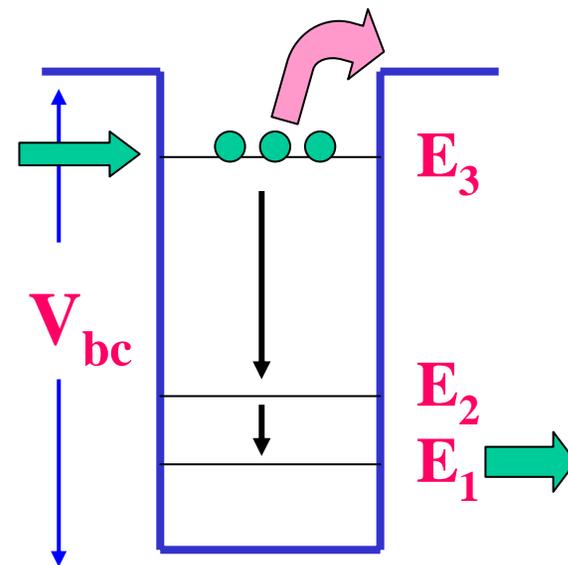
**We can grow QCL materials
on condition that :**

Precise control:
each layer thickness,
compositions,
doping,
interfaces sharpness.

提高性能从源头开始?

$$\lambda = 1.24 / (E_3 - E_2)$$

相邻子带 $\Delta E = (0.56 - 0.62) V_{bc}$,
这是一个不可能达到的极限,
还必须考虑一个纵向光学声子
(36meV) 的弛豫能级。



必须增大导带带阶 V_{bc}

阱层: $\text{In}_x\text{Ga}_{(1-x)}\text{As}$, $x \uparrow$, $E_g \downarrow$

垒层: $\text{In}_y\text{Al}_{(1-y)}\text{As}$, $y \downarrow$, $E_g \uparrow$



$\text{In}_{0.53}\text{Ga}_{0.47}\text{As}/\text{In}_{0.52}\text{Al}_{0.48}\text{As}$
匹配于InP衬底

$\text{In}_x\text{Ga}_{(1-x)}\text{As}/\text{In}_y\text{Al}_{(1-y)}\text{As}$
($x > 53\%$, $y < 52\%$)

导带带阶提高

使器件设计更具灵活性，
拓宽设计的波长范围。

+

能有效地降低阈值电流

+

有效地降低穿透位错

各层In组分偏离匹配条件



各层都存在应变

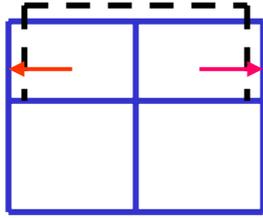


材料生长更难!

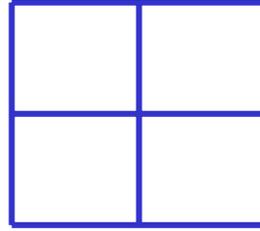
怎样解决困难?

InGaAs/InP为例

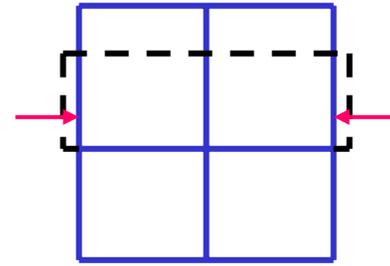
$X < 0.53$ 张应变



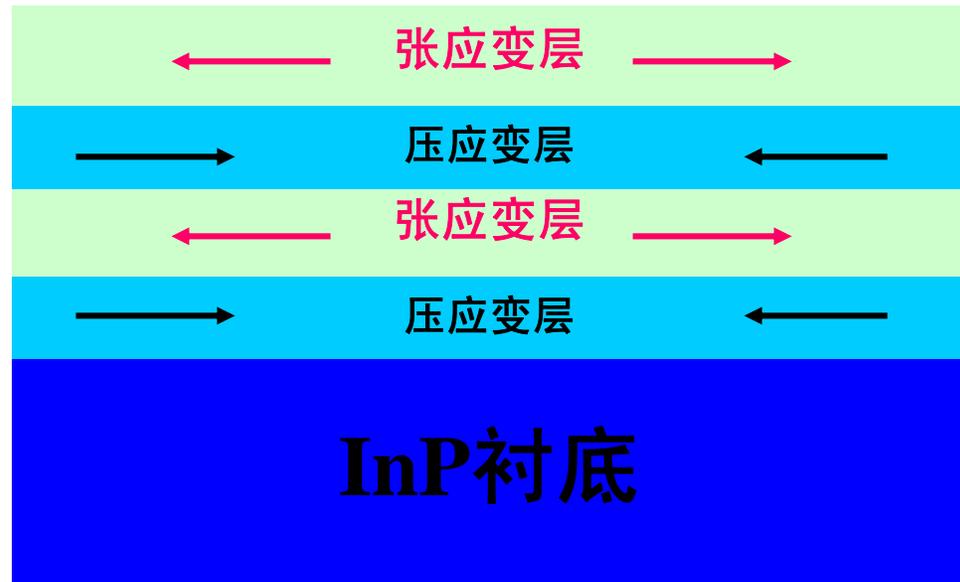
晶格匹配



$X > 0.53$ 压应变



克服应力积累



张应变与压应变相互补偿!

提高材料的容错能力



$$x = 0.532 + 7.2 \Delta a_{\perp} / a_s$$



$$y = 0.523 + 7.4 \Delta a_{\perp} / a_s$$

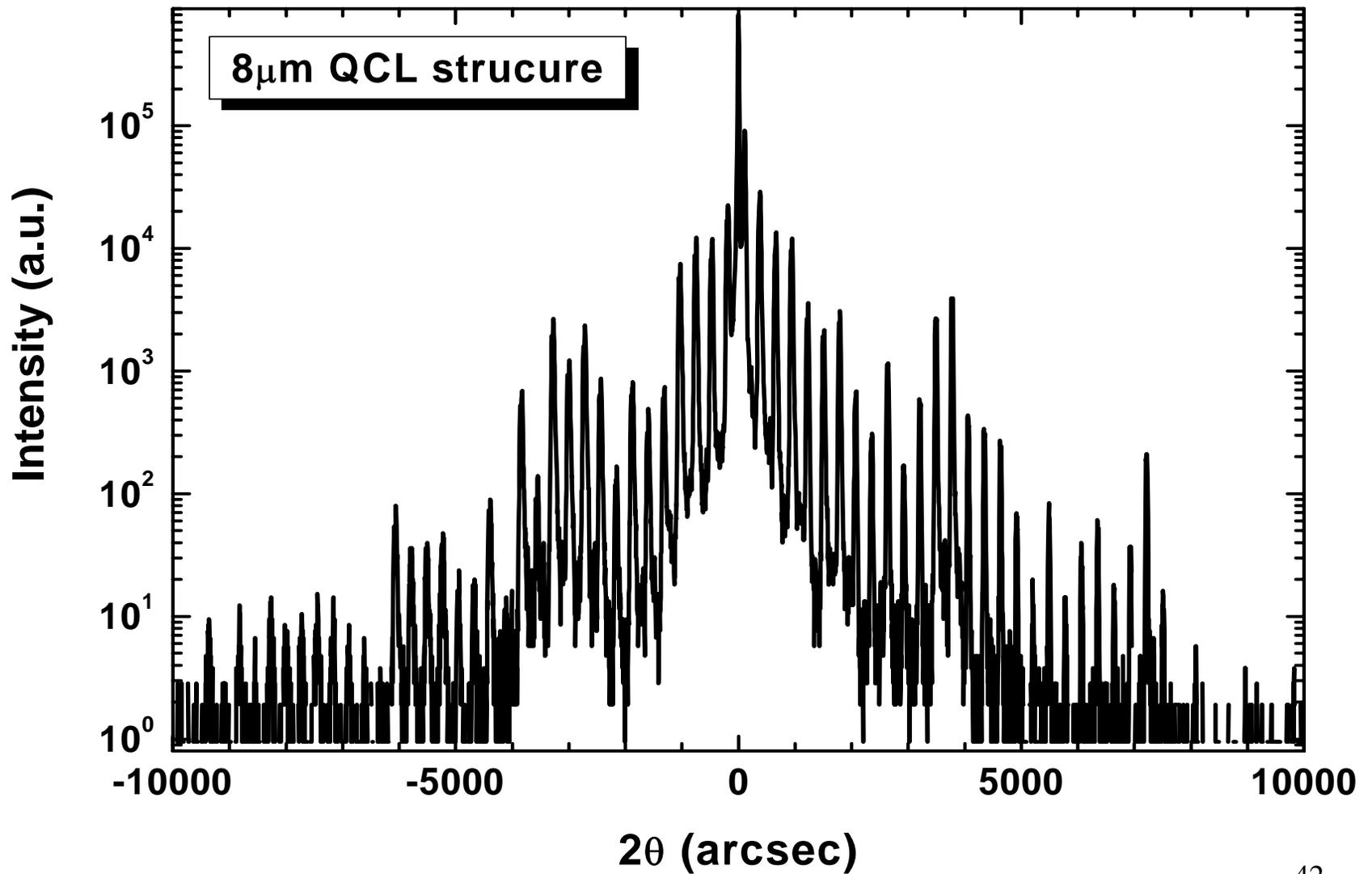
束流**1%涨落**将产生 **7×10^{-4}** 的晶格失配度，要生长总层厚为**4-5 μm** 左右的器件结构，在**6小时**生长过程中**保证束流的涨落小于1%几乎是不可能的。**

对超薄层构成的多层结构，采用**张应变与压应变相互补偿**的巧妙思路可以使整体结构的失配度控制在很小范围，**降低了材料制备难度。**

QCL structure

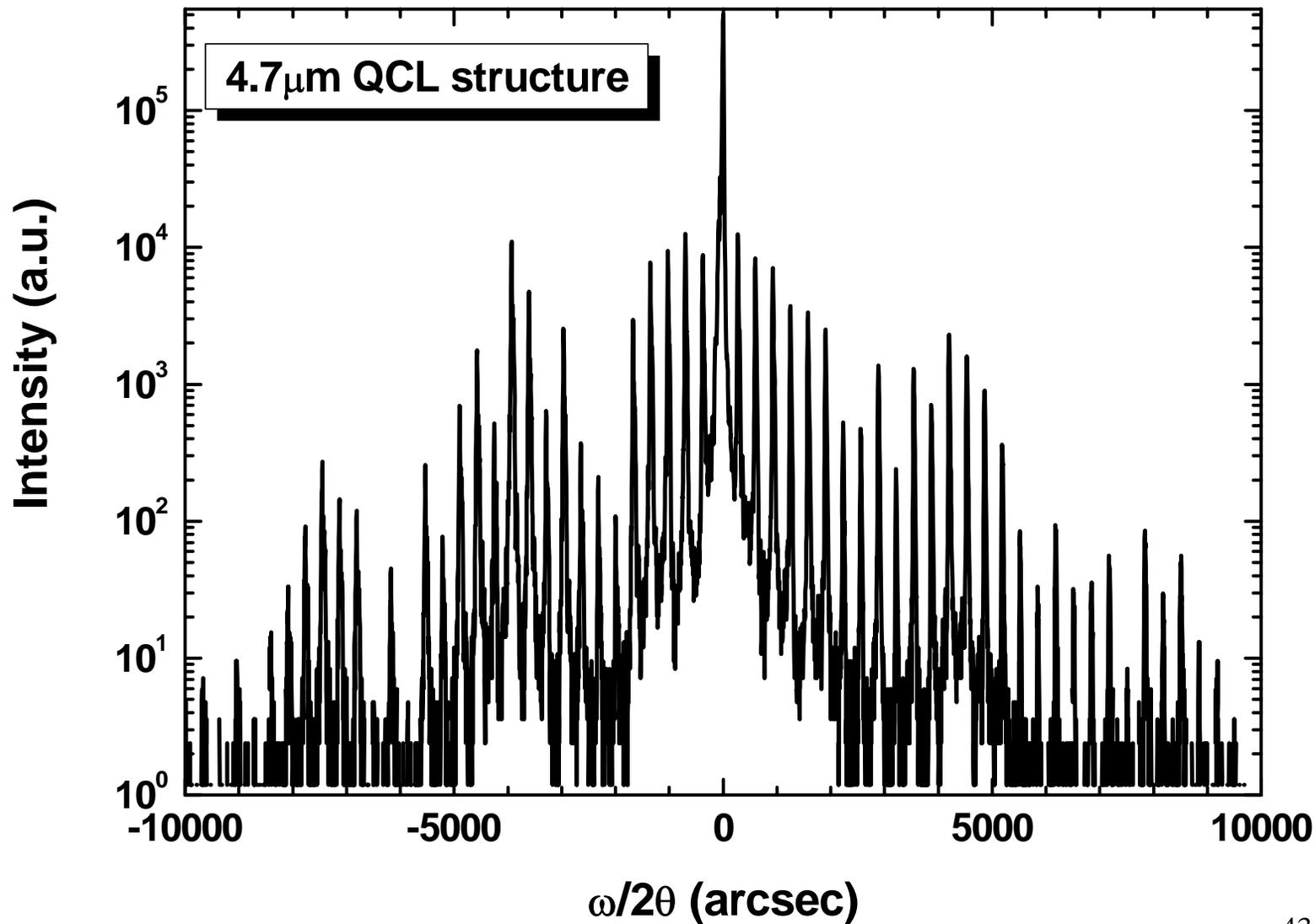
InGaAs	$5 \times 10^{18} \text{ cm}^{-3}$	400nm
InP	$5 \times 10^{18} \text{ cm}^{-3}$ $1 \times 10^{17} \text{ cm}^{-3}$ ↑	2500nm
InGaAs	$1 \times 10^{17} \text{ cm}^{-3}$	350nm
(Active + Injector)	$\times 30$	
InGaAs	$1 \times 10^{17} \text{ cm}^{-3}$	300nm
InP substrate	n-doped	

$\text{In}_{0.6}\text{Ga}_{0.4}\text{As}/\text{In}_{0.38}\text{Al}_{0.62}\text{As}$ 全结构 QCL



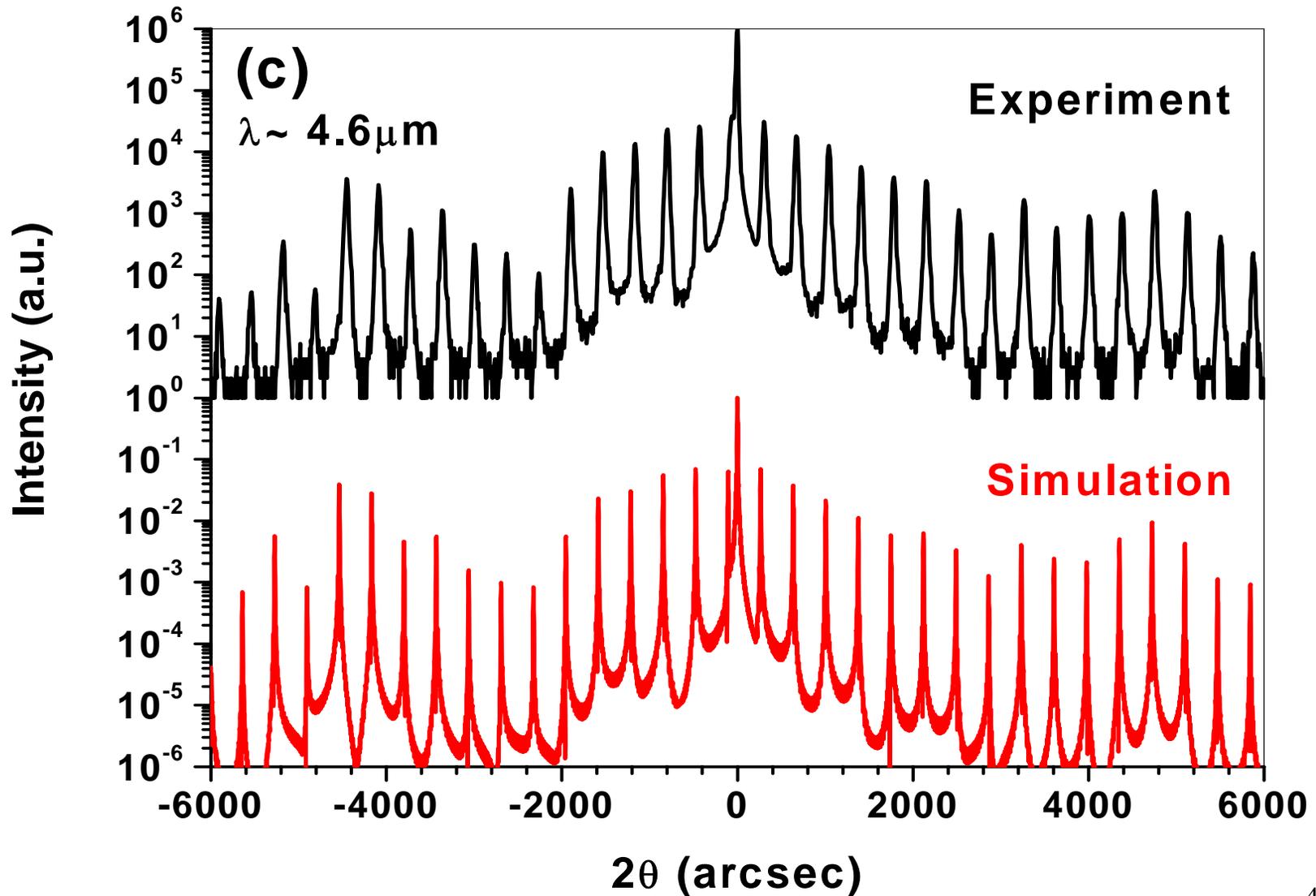
DXRD results

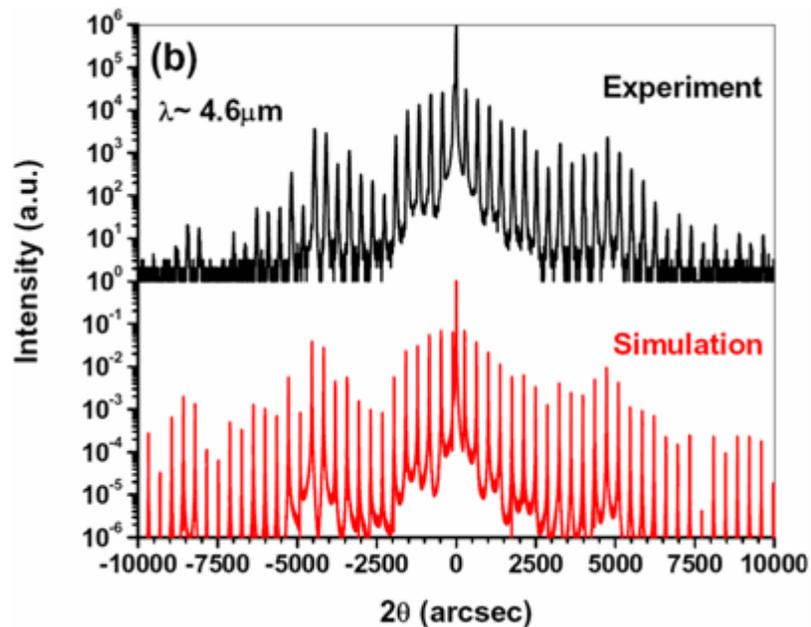
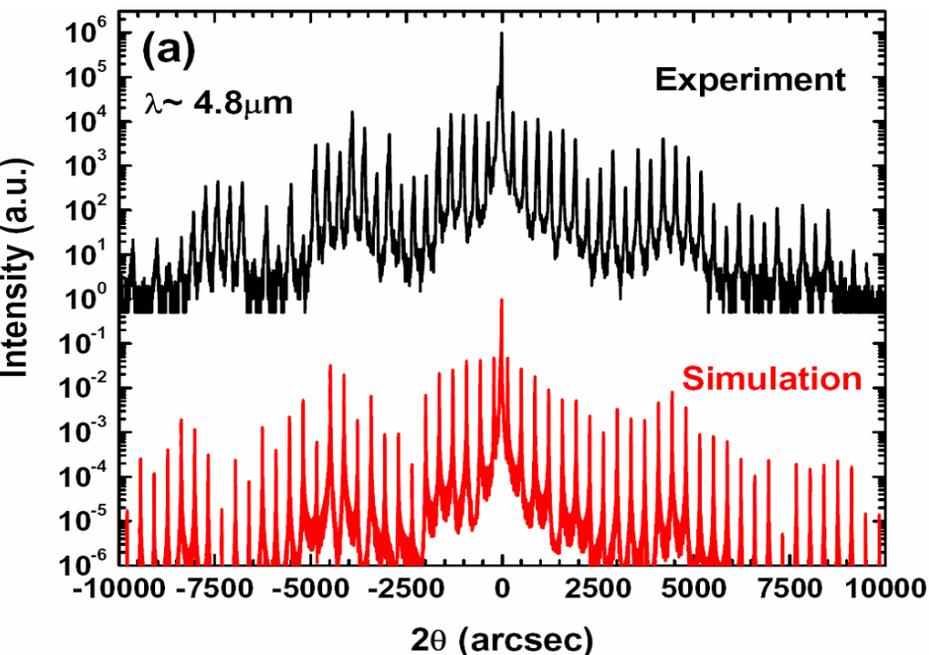
$\text{In}_{0.669}\text{Ga}_{0.331}\text{As}/\text{In}_{0.362}\text{Al}_{0.638}\text{As}$ 全结构 QCL



DXRD results

QCL materials

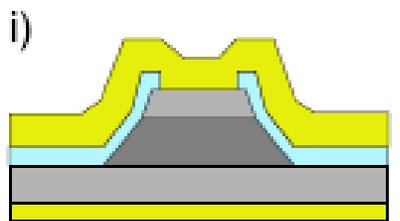
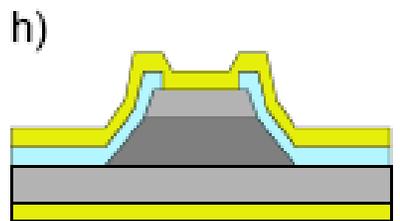
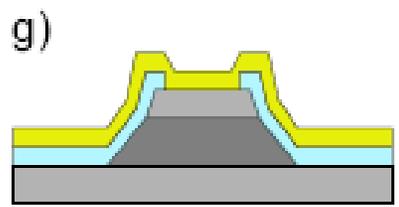
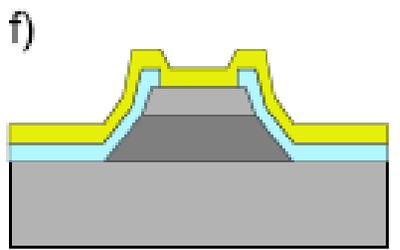
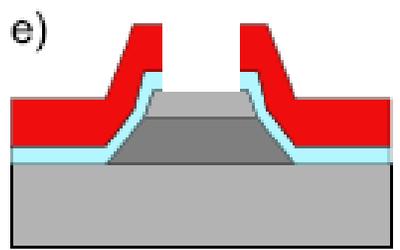
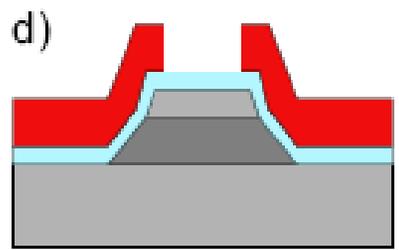
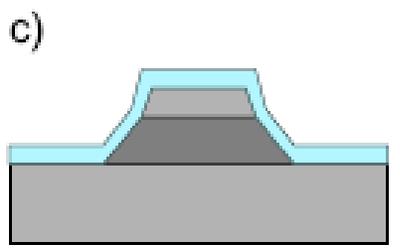
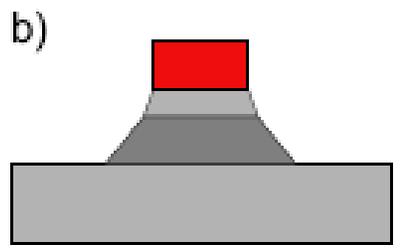
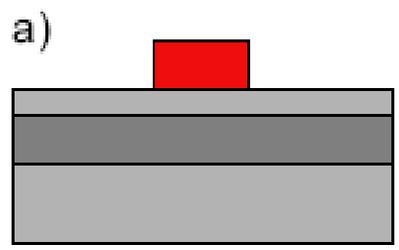


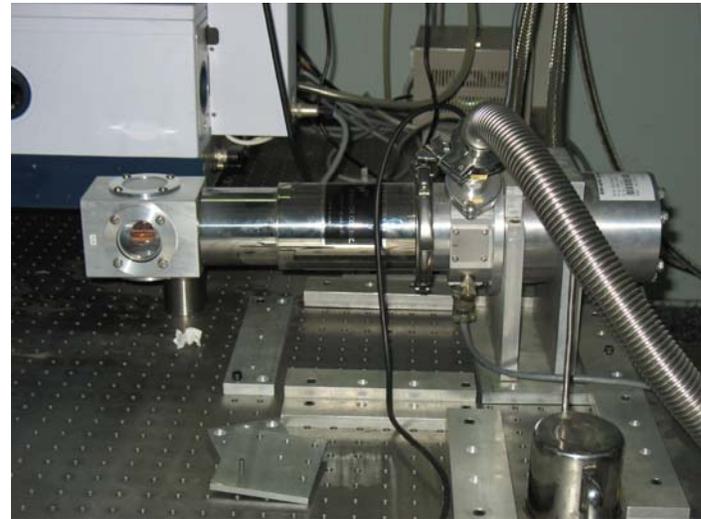
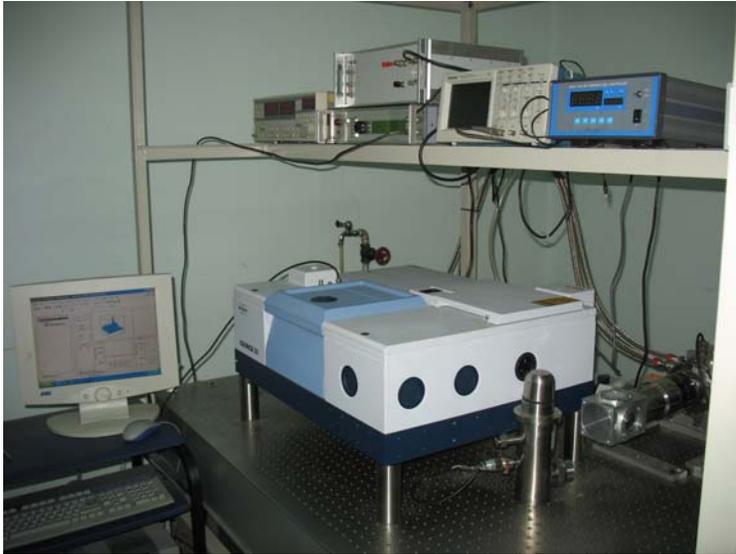


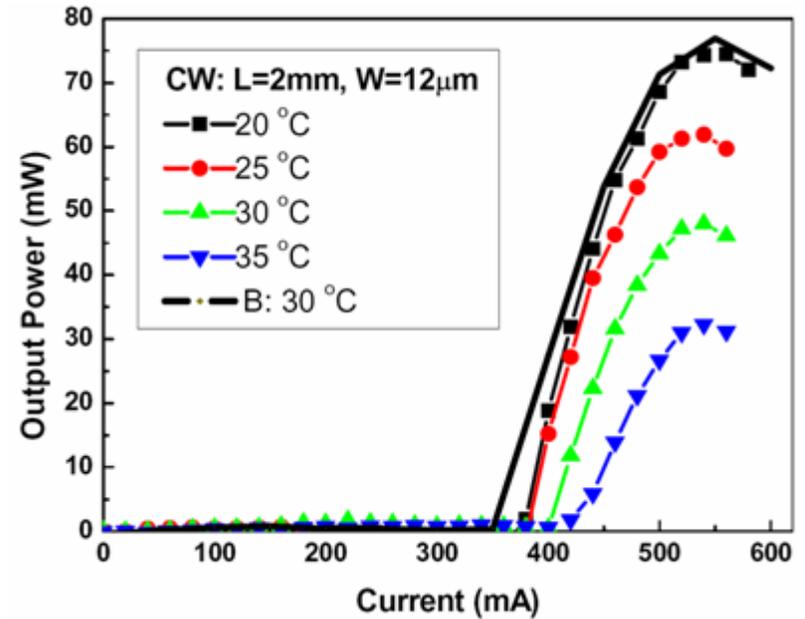
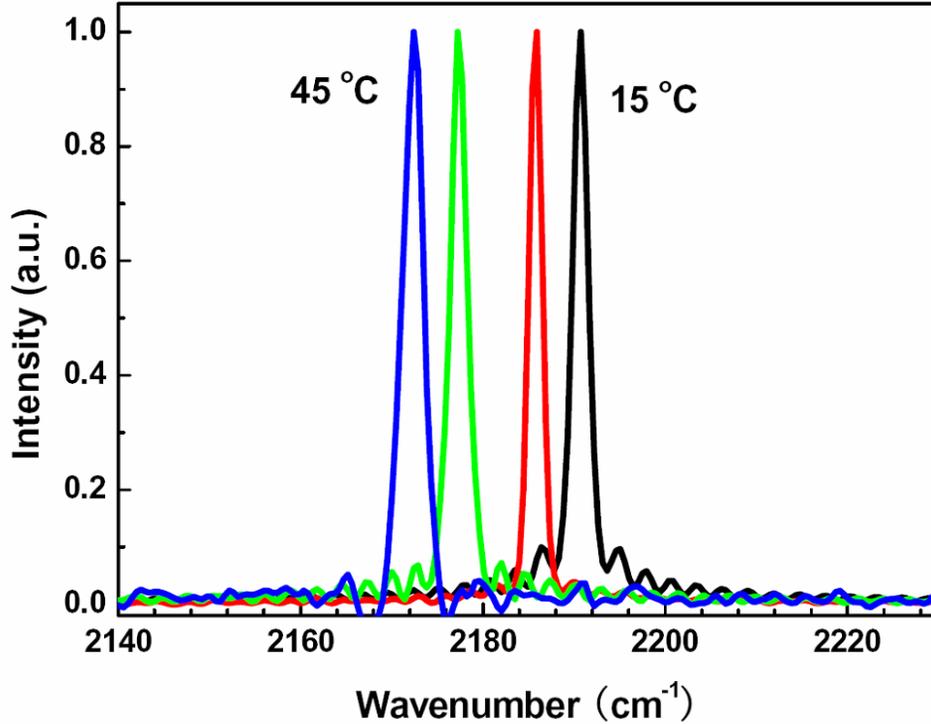
外延生长的4.8 μm 、4.6 μm 应变补偿QCL全器件结构典型双晶X射线双晶衍射结果，双晶X射线衍射的卫星峰超过60级。

$$\Lambda = \frac{(i - j)\lambda}{2(\sin \theta_i - \sin \theta_j)}$$

器件工艺

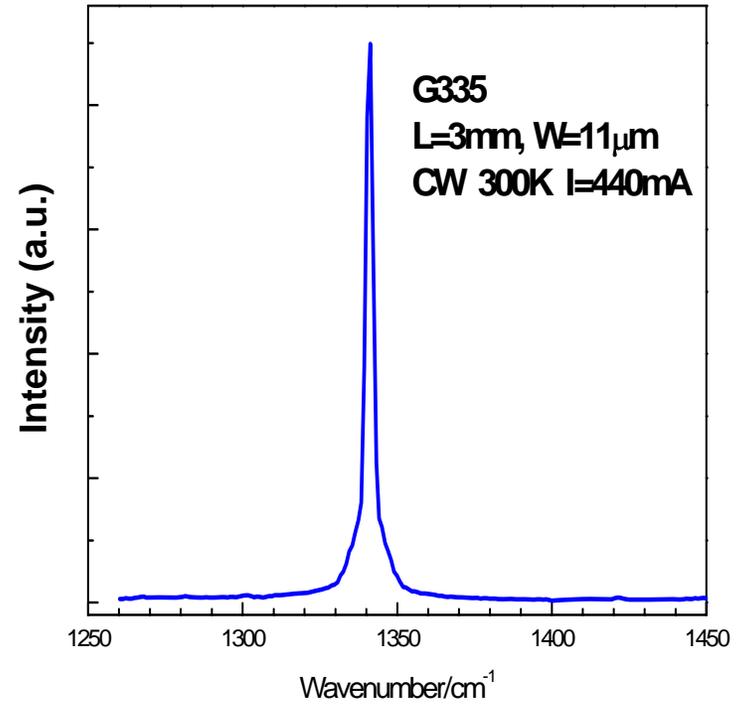
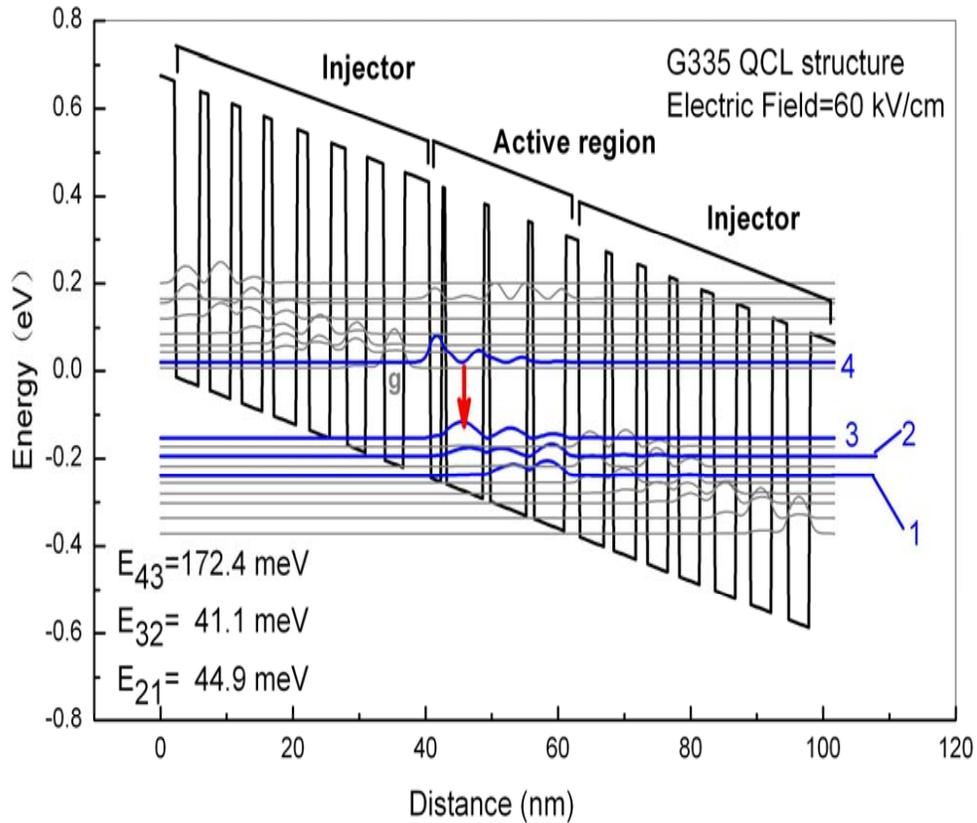






波长 $\lambda \sim 4.6$ 微米应变补偿QCL室温连续激光谱(左)、室温连续工作的电流-输出功率曲线(右)。激光器大小: $2\text{mm} \times 12\mu\text{m}$

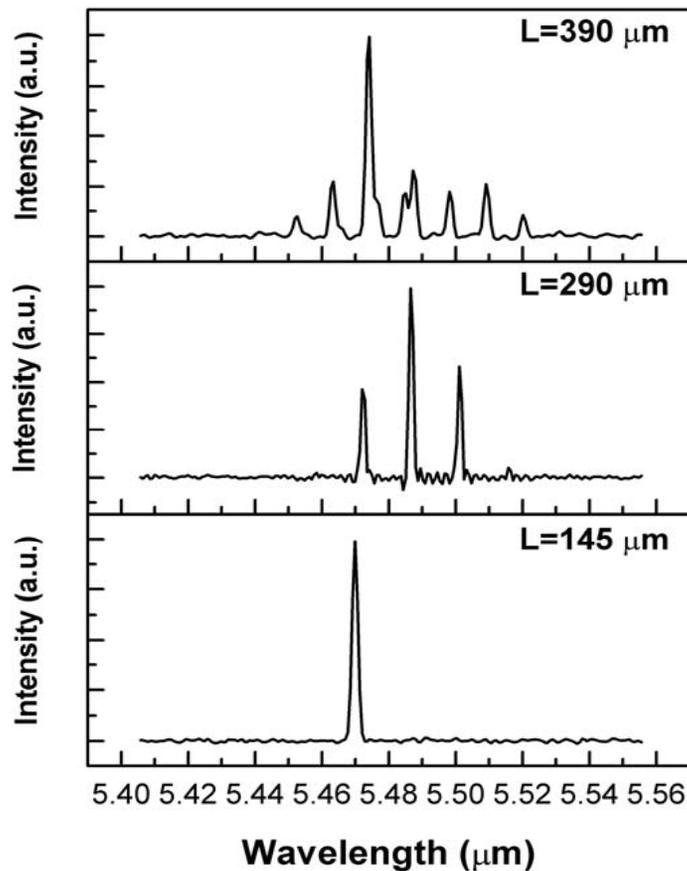
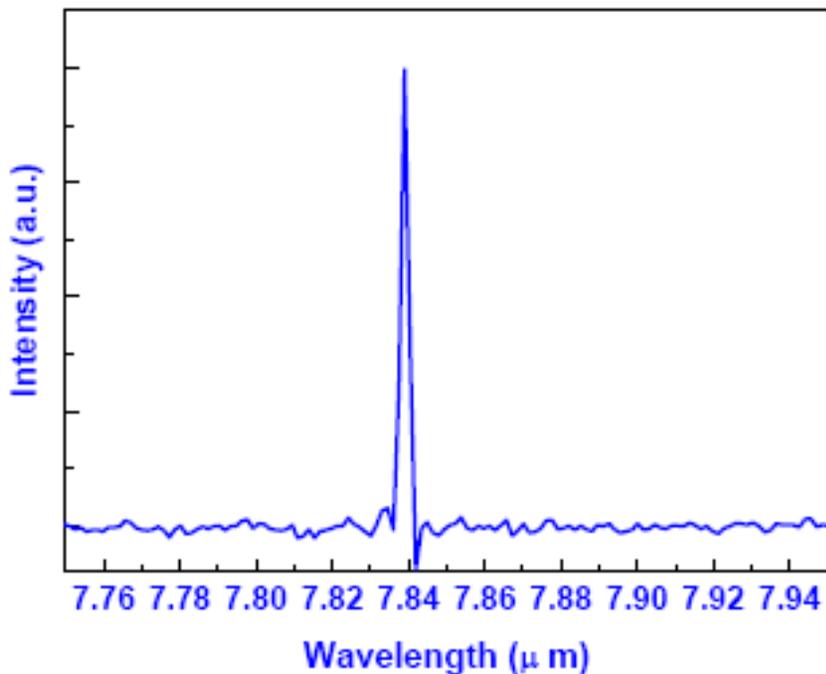
室温连续工作 $\lambda \sim 7.4\mu\text{m}$



常规Fabry-Pérot腔量子级联激光器的光谱为多纵模工作。而在一些特殊应用中要求激光器能够实现窄线宽、单纵模、波长连续可调谐。

如何实现单模工作？

短腔单模QCLs

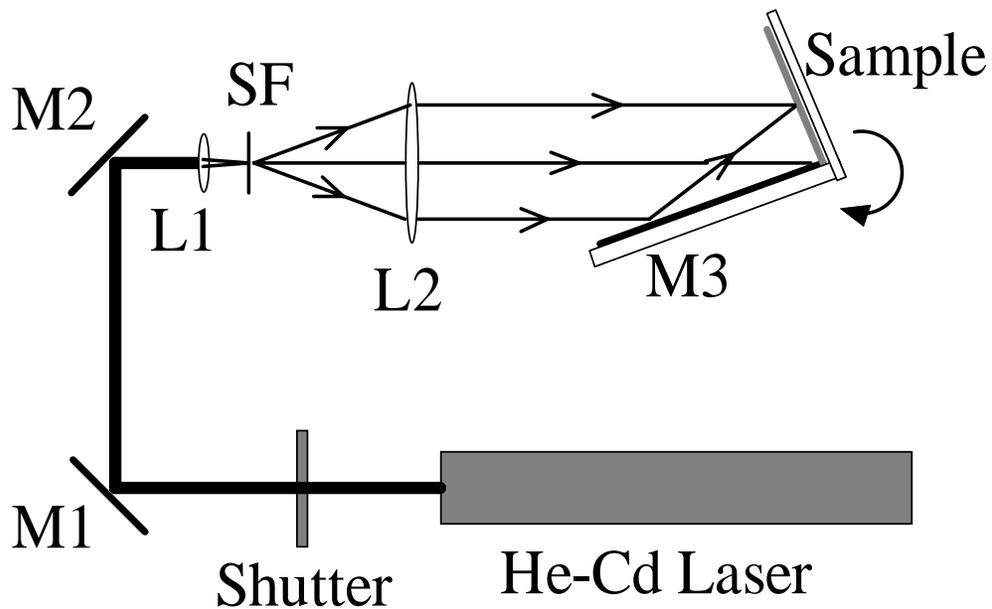


由于增益区很小，能够实现激射是很不容易的。短腔结构解决了分布反馈QCL工艺复杂、微腔QCL出光方向难以控制问题。

纵模间距:

$$d\lambda_0 = \frac{\lambda_0^2}{2nL}$$

DFB-QCLs、光子晶体DFB-QCLs



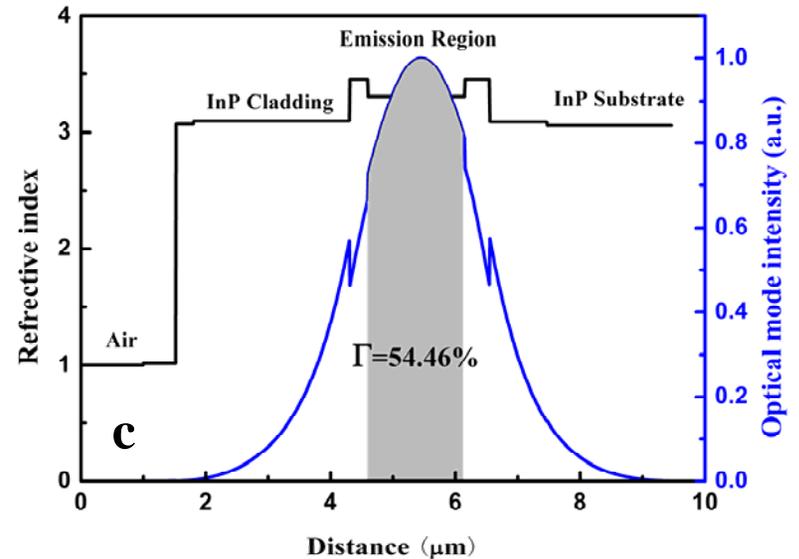
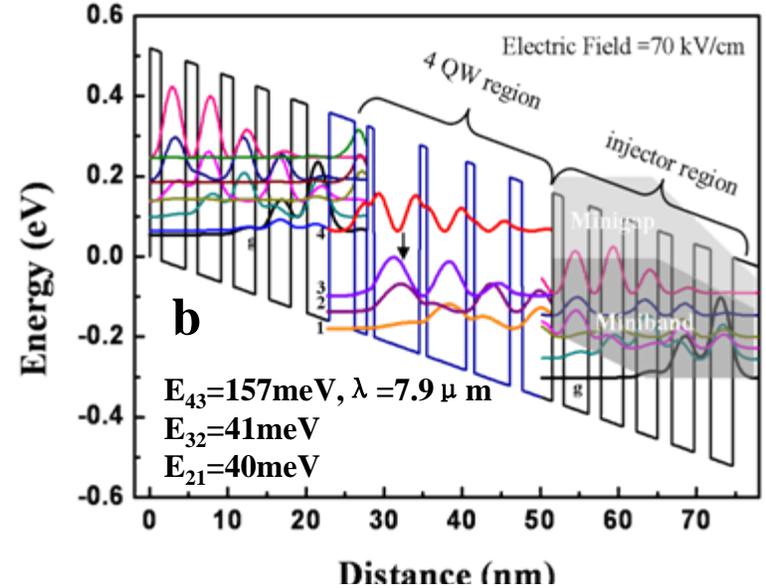
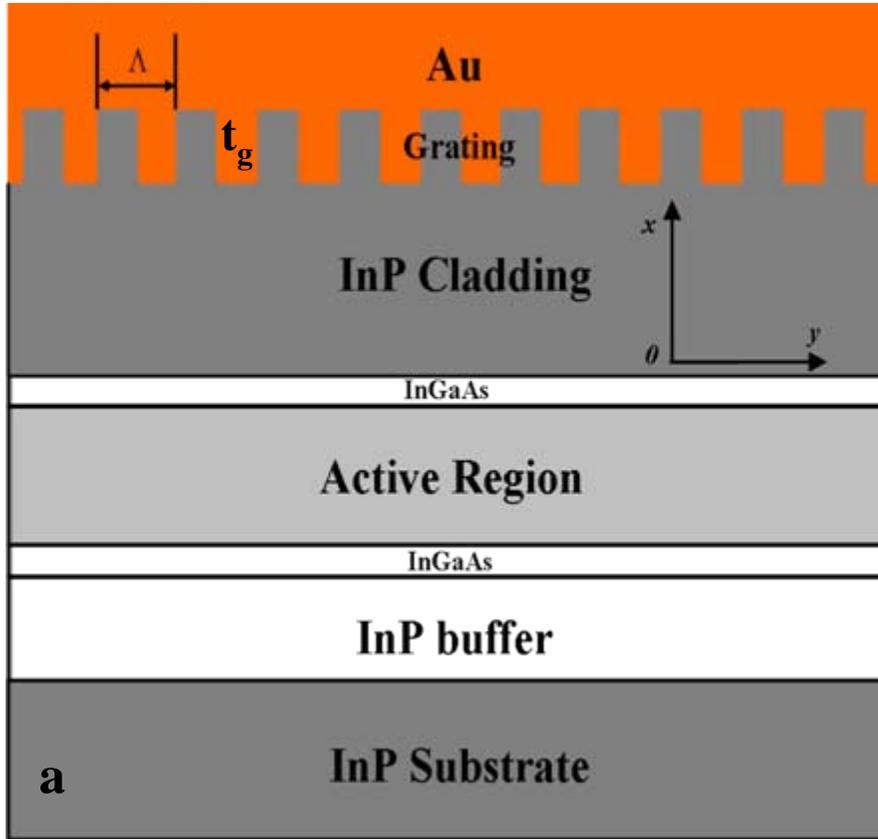
全息曝光系统光路图

激光器波长: 441.6 nm

全息曝光系统照片

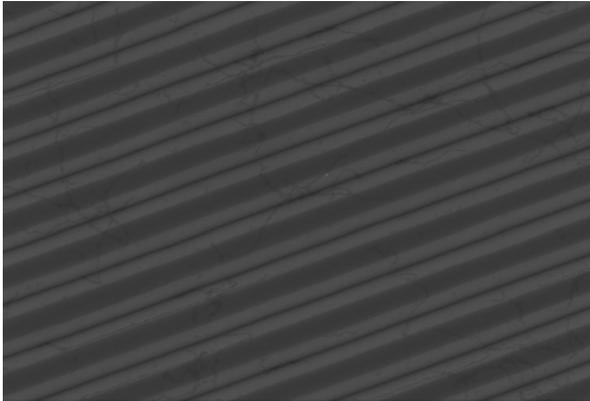


DFB-QCL有源区及波导结构

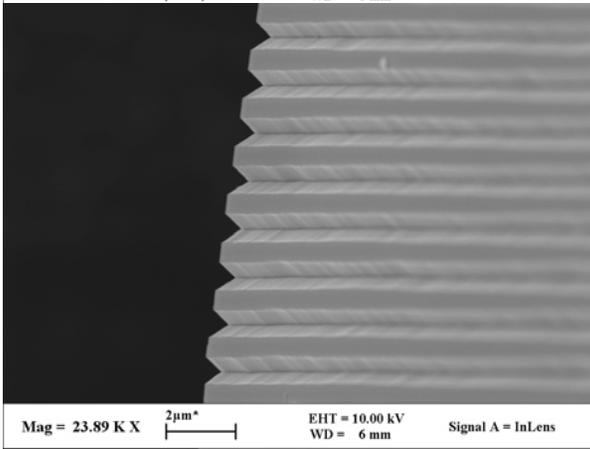


- a:** 波导结构示意图
- b:** 双声子共振结构能带图
- c:** 一维模式分布

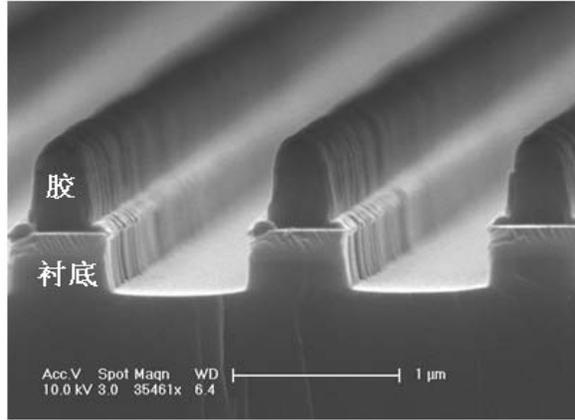
光栅刻蚀



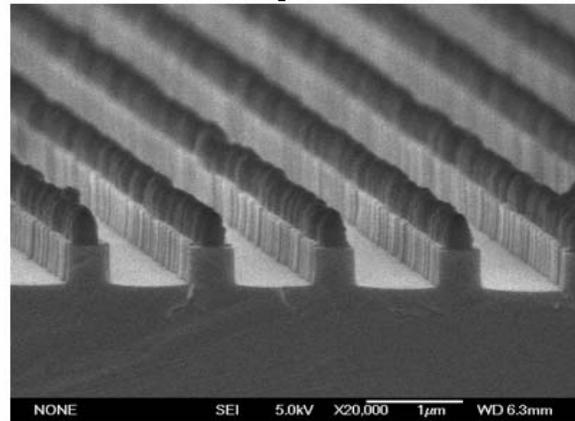
Mag = 25.00 K X 1 μ m* EHT = 10.00 kV Signal A = InLens
WD = 6 mm



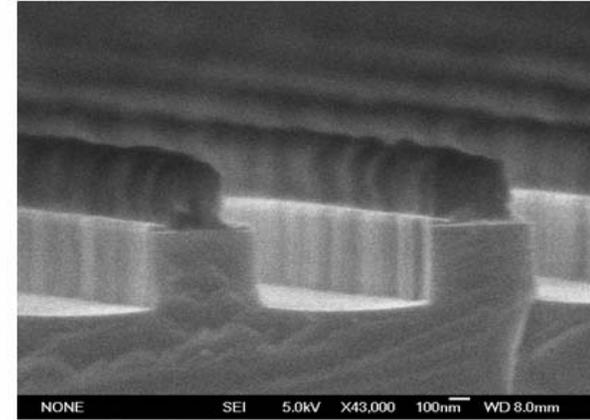
Mag = 23.89 K X 2 μ m* EHT = 10.00 kV Signal A = InLens
WD = 6 mm



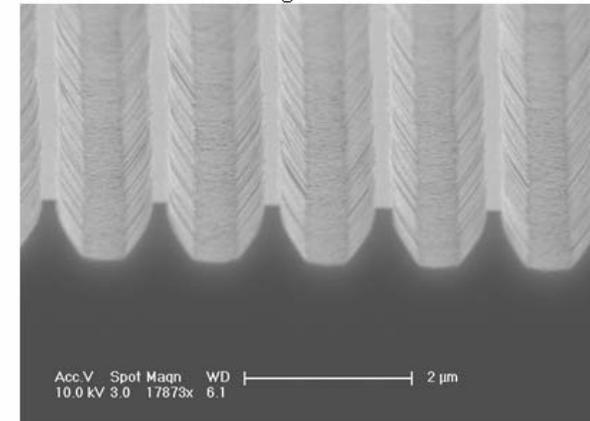
time=4.5 min, $t_g=380$ nm, dc=39 %
Acc.V Spot Magn WD |-----| 1 μ m
10.0 kV 3.0 35461x 6.4



time=6.5 min, $t_g=450$ nm, dc=32 %
NONE SEI 5.0kV X20,000 1 μ m WD 6.3mm



time=5.0 min, $t_g=410$ nm, dc=38 %
NONE SEI 5.0kV X43,000 100nm WD 8.0mm



time=7.0 min, $t_g=670$ nm, dc=23 %
Acc.V Spot Magn WD |-----| 2 μ m
10.0 kV 3.0 17873x 6.1

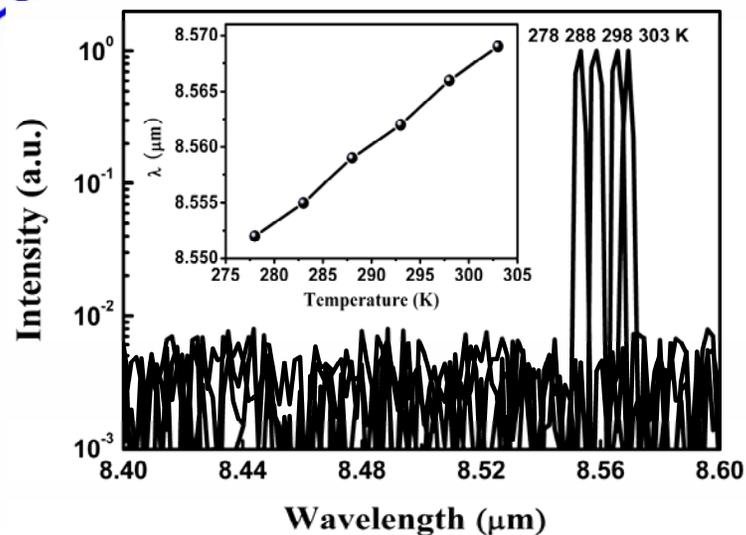
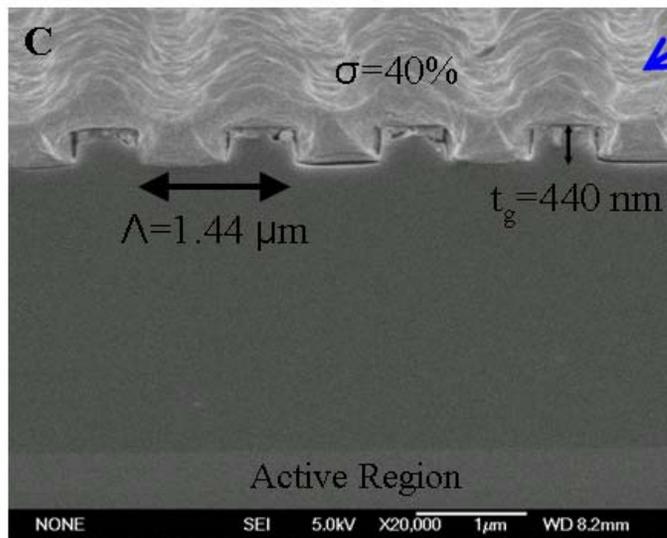
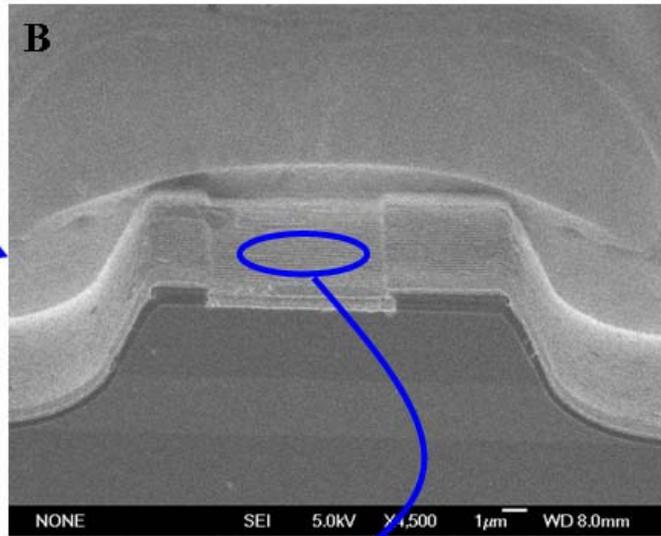
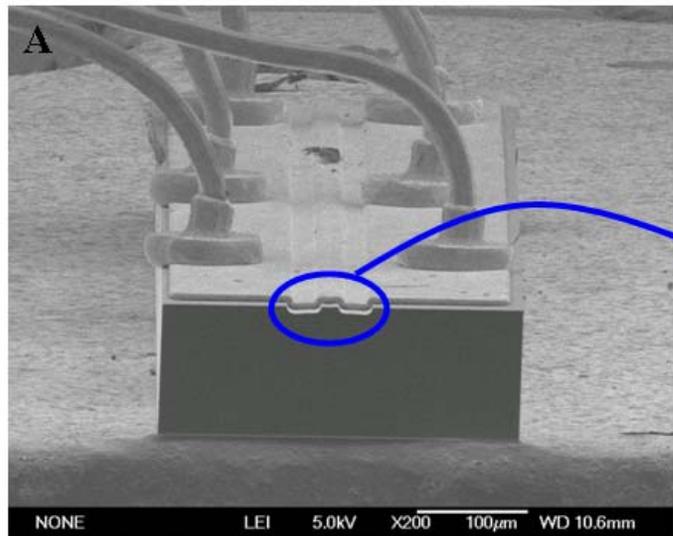
Wet Etch

HBr: HNO₃: H₂O=1: 1: 20

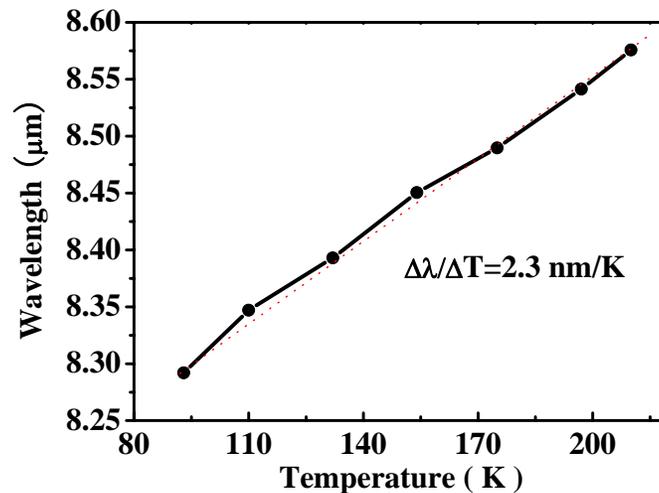
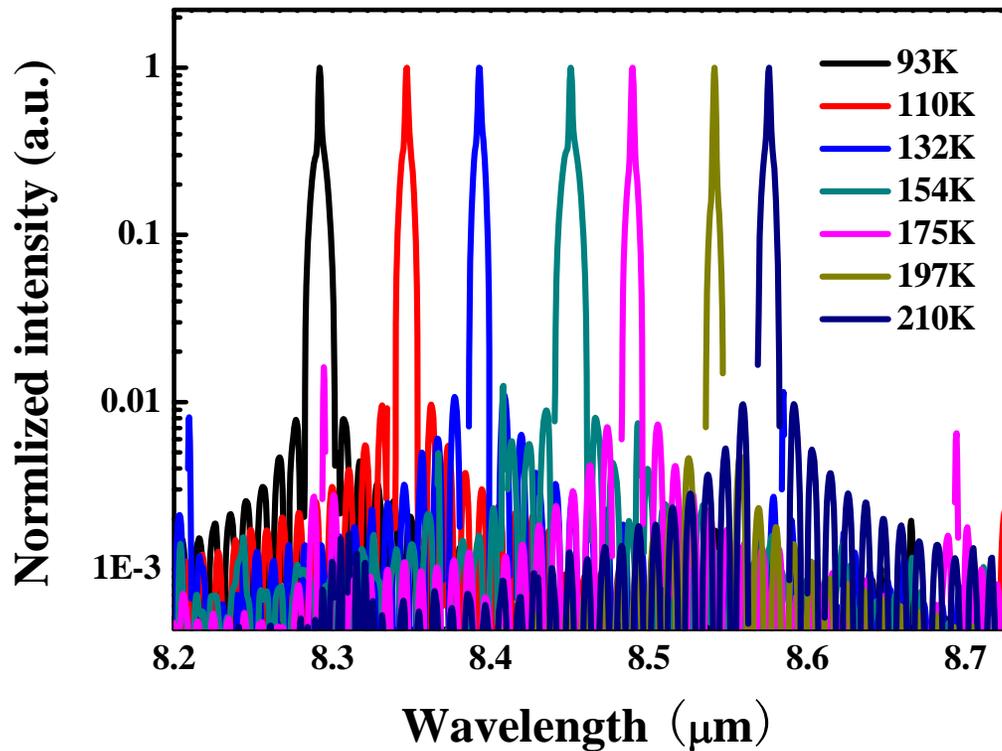
RIE Dry Etch

Ar₂: CH₄: H₂=5: 18: 45

室温工作表面金属光栅DFB-QCL

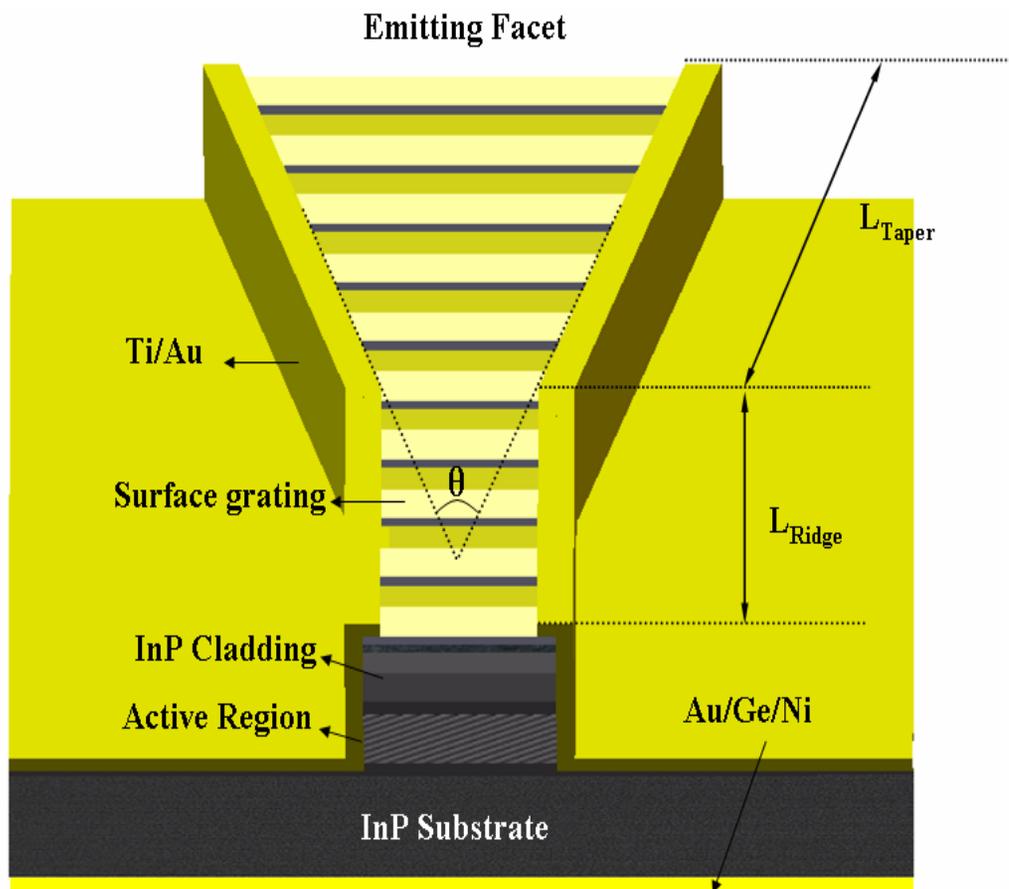


掩埋光栅DFB-QCLs的连续工作



最近：室温CW外腔调谐单模QCLs

锥形DFB结构的优点



DFB光栅



锥形波导

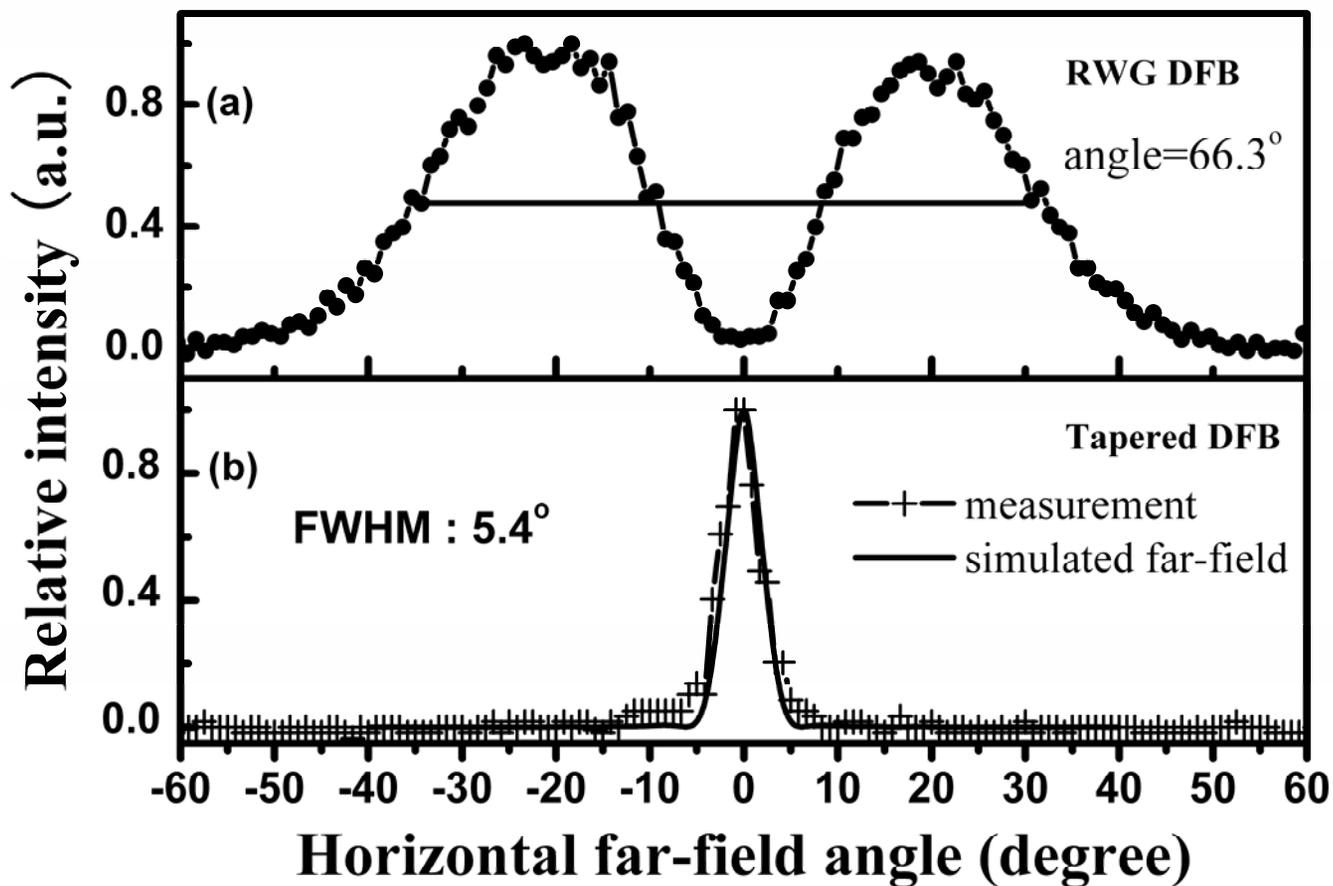


单纵模工作

改善远场

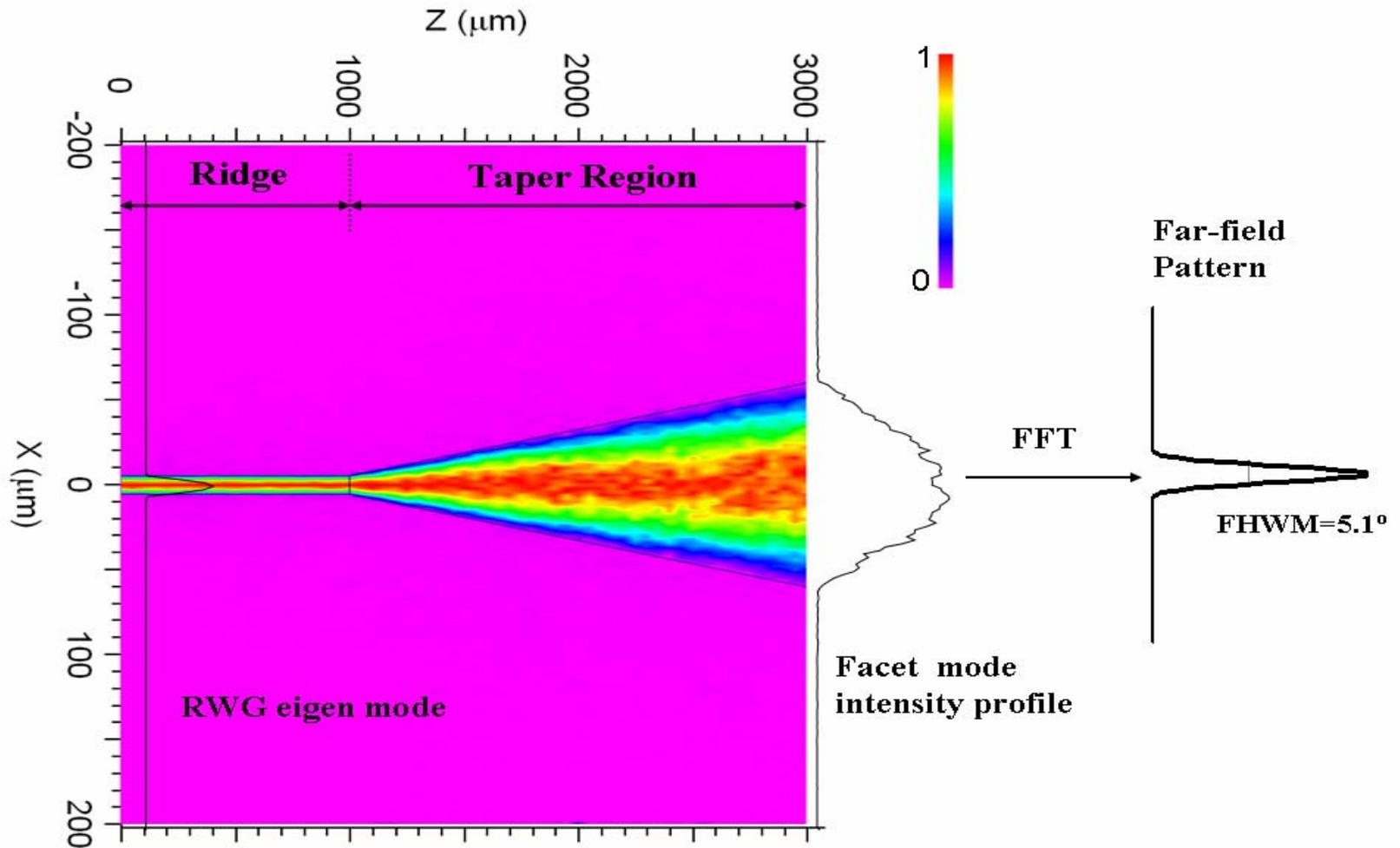
增加功率

锥形DFB远场特性

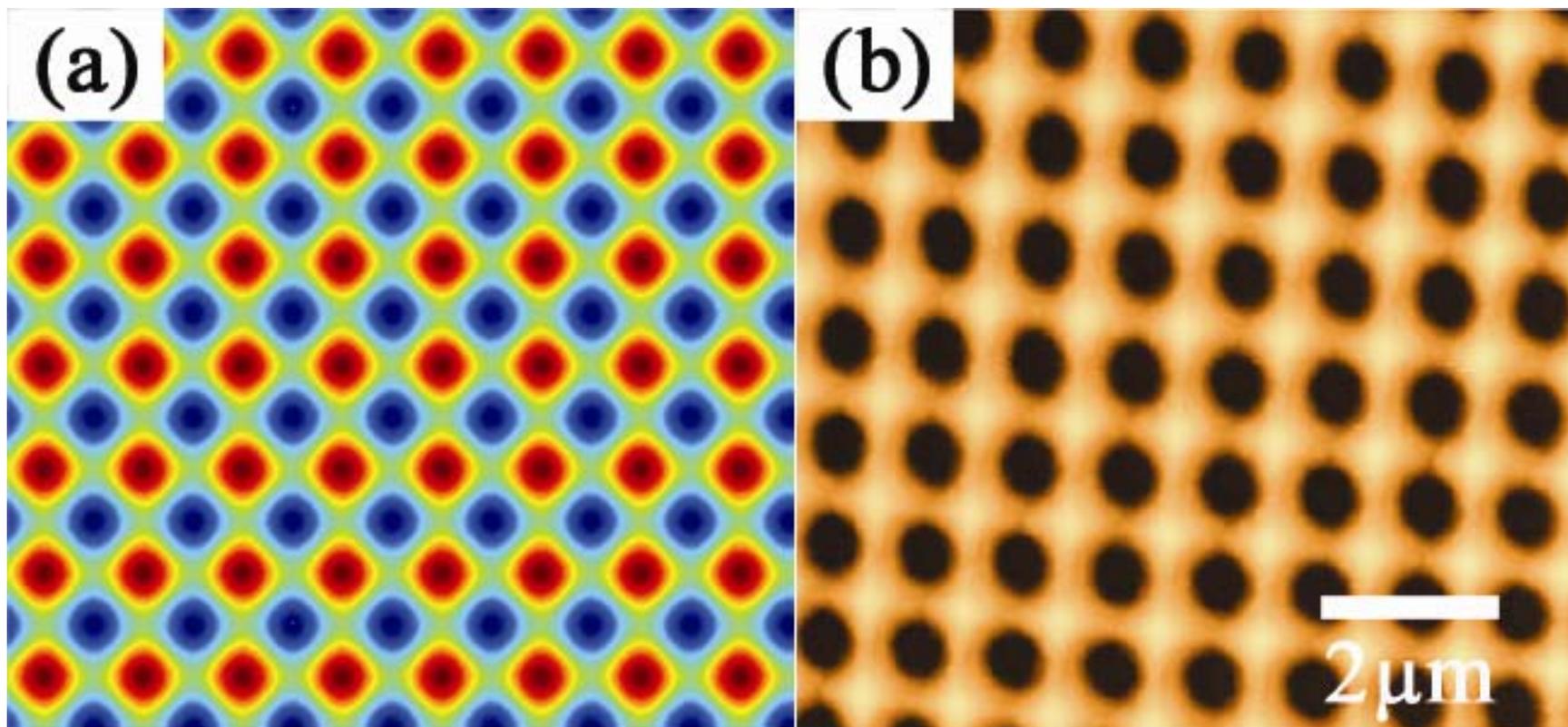


单纵模输出

锥形DFB-QCL水平远场模拟

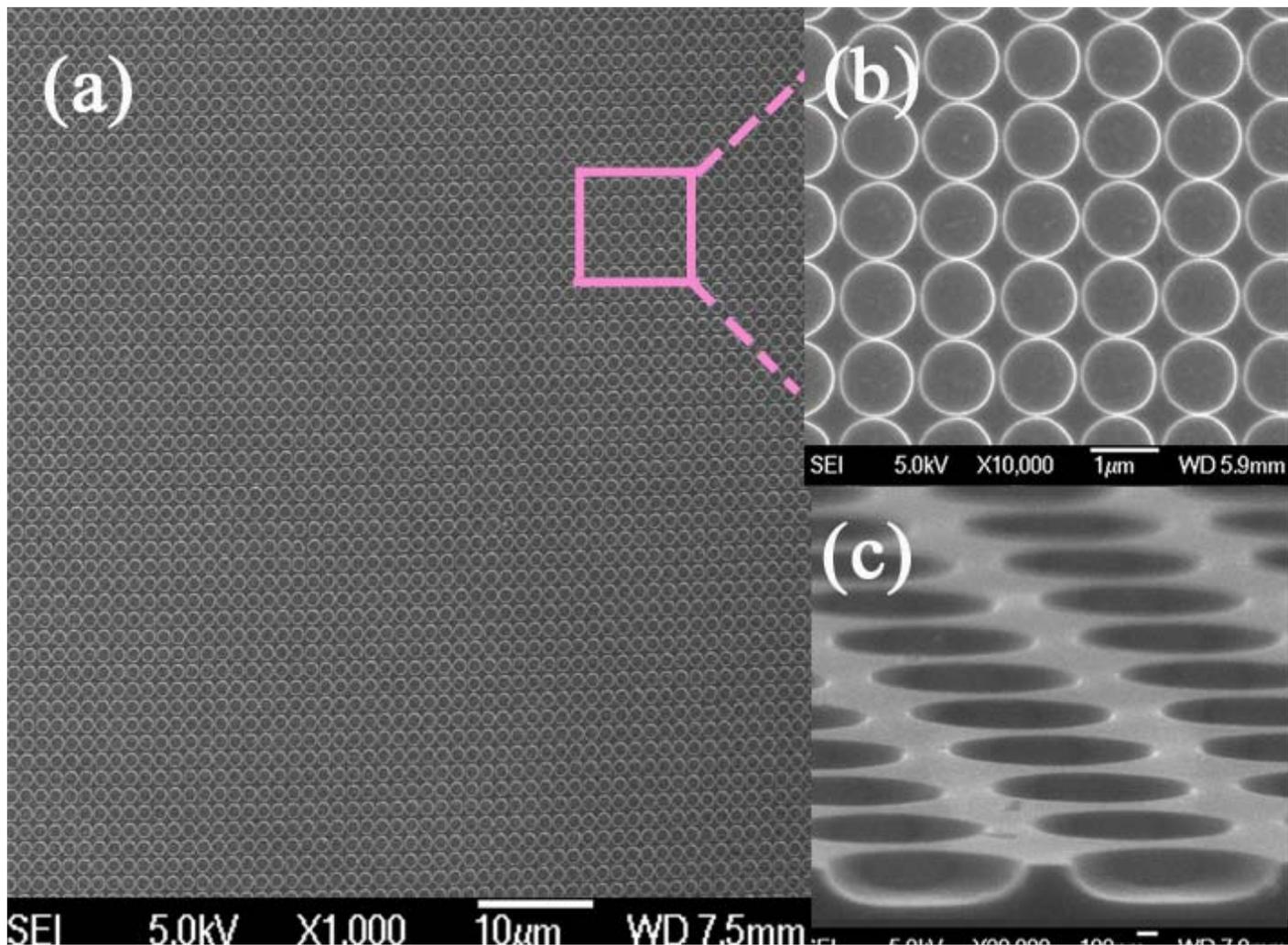


表面二维光子晶体DFB-QCL



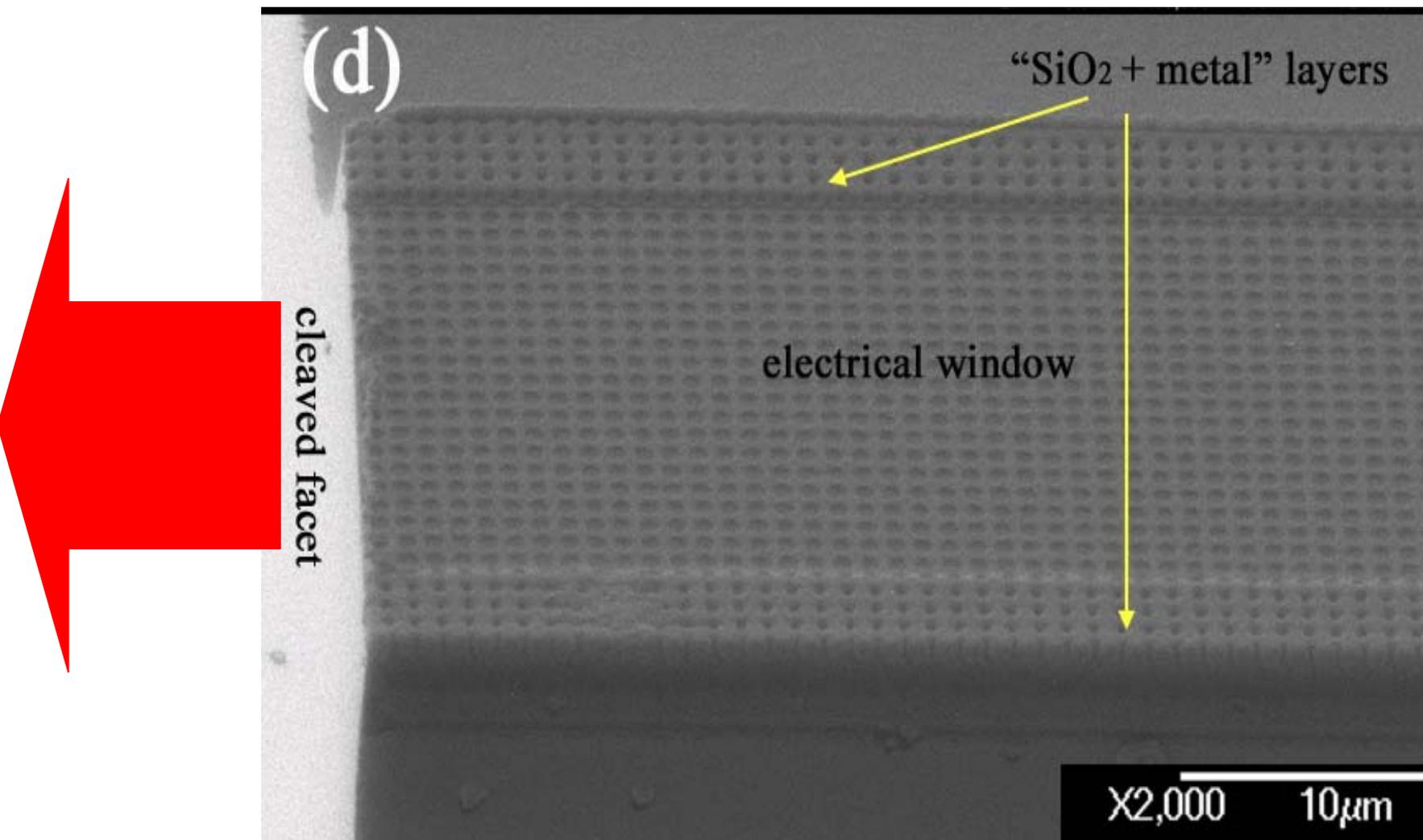
全息方法制备2D光子晶体点阵

表面二维光子晶体DFB-QCL



湿法腐蚀后，波导结构上二维光子晶体形貌

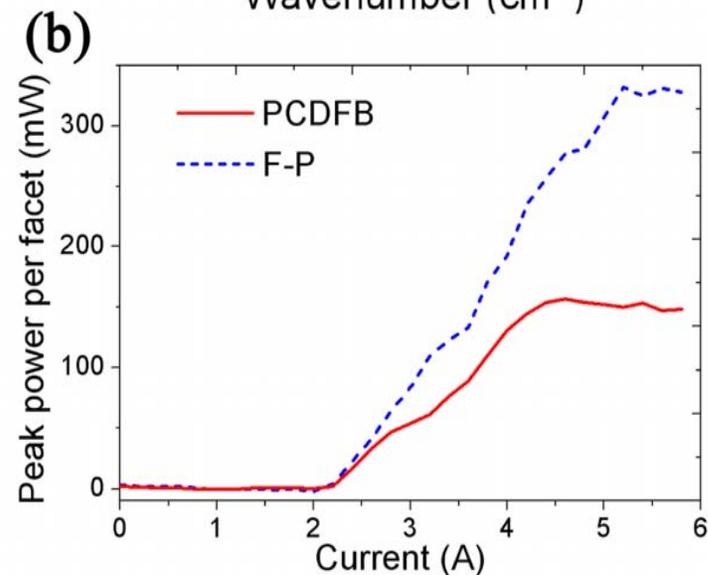
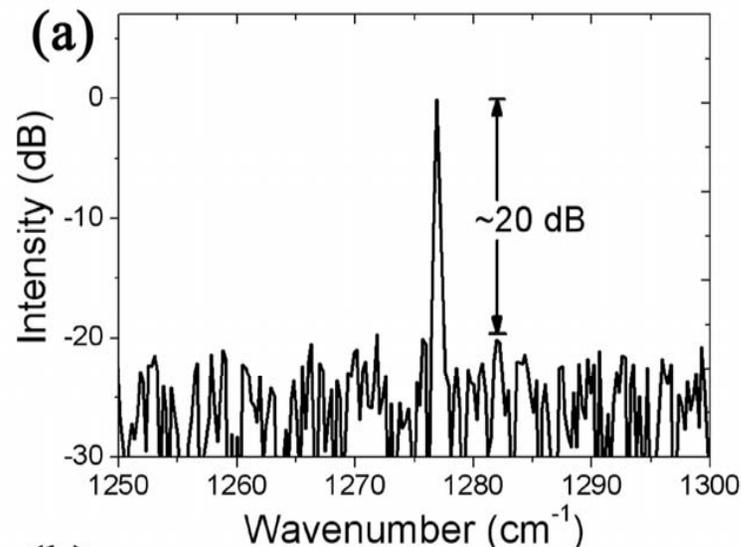
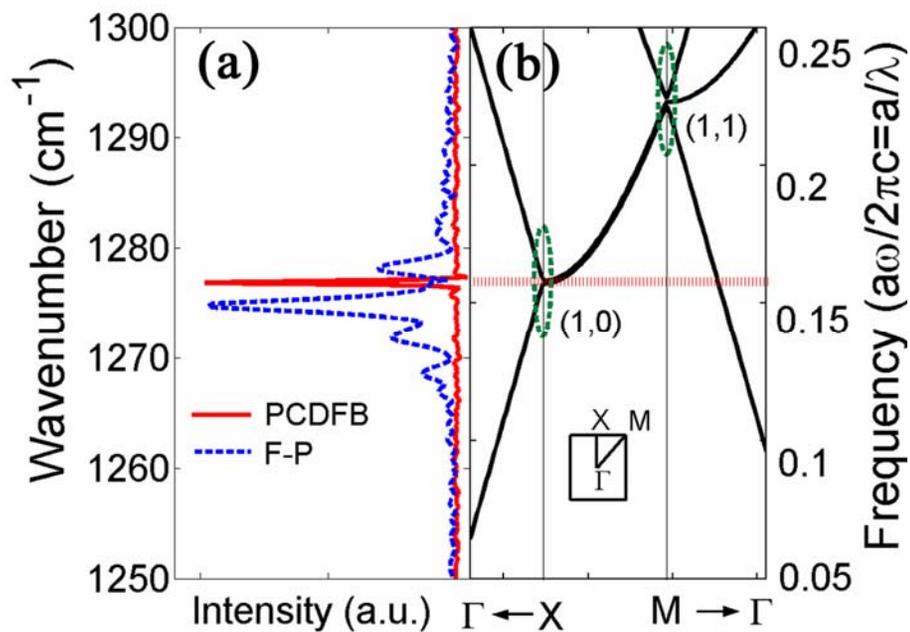
表面二维光子晶体DFB-QCL



二维光子晶体DFB-QCL器件形貌

Electronics Letters 45, 53(2009)

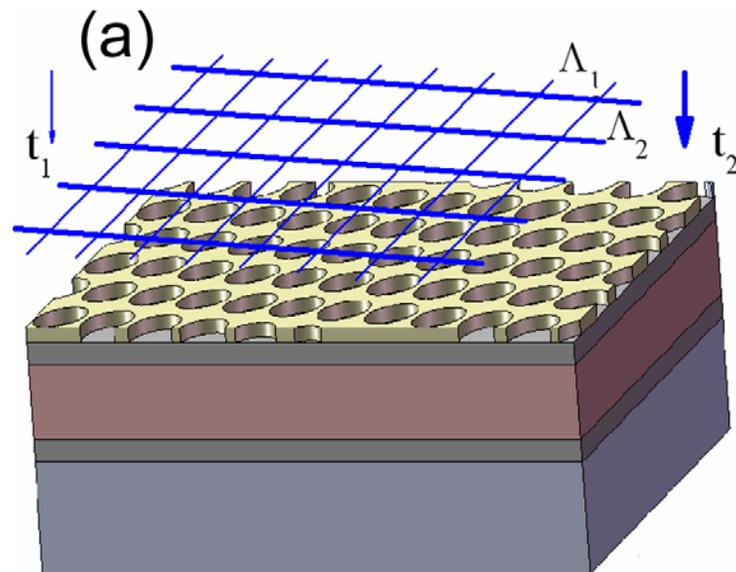
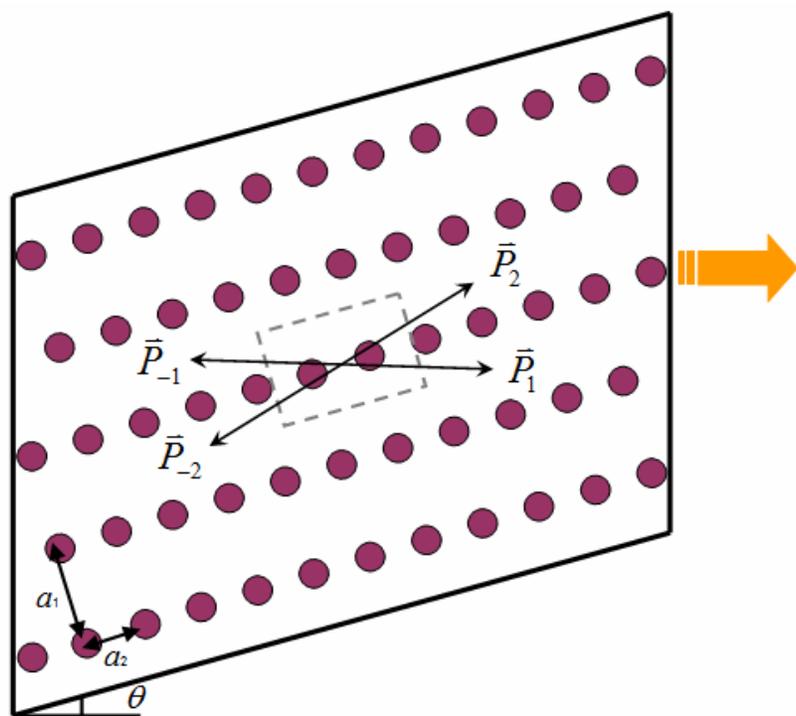
表面二维光子晶体DFB-QCL



上图(a)PCDFB-QCL与相应的FP-QCL光谱; (b)二维光子晶体的能带图。

右图(a) 高分辨的PCDFB-QCL光谱; (b)PCDFB-QCL与相应的FP-QCL输出功率随注入电流的变化。

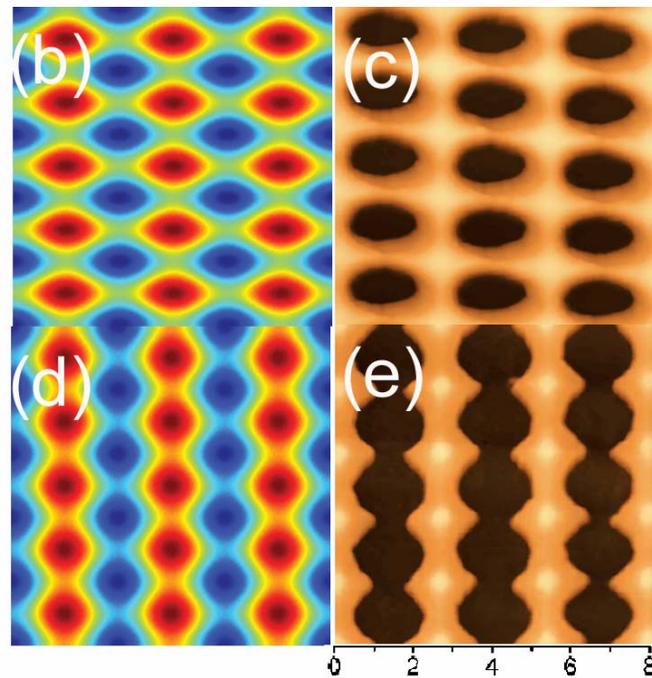
斜角二维光子晶体DFB-QCL



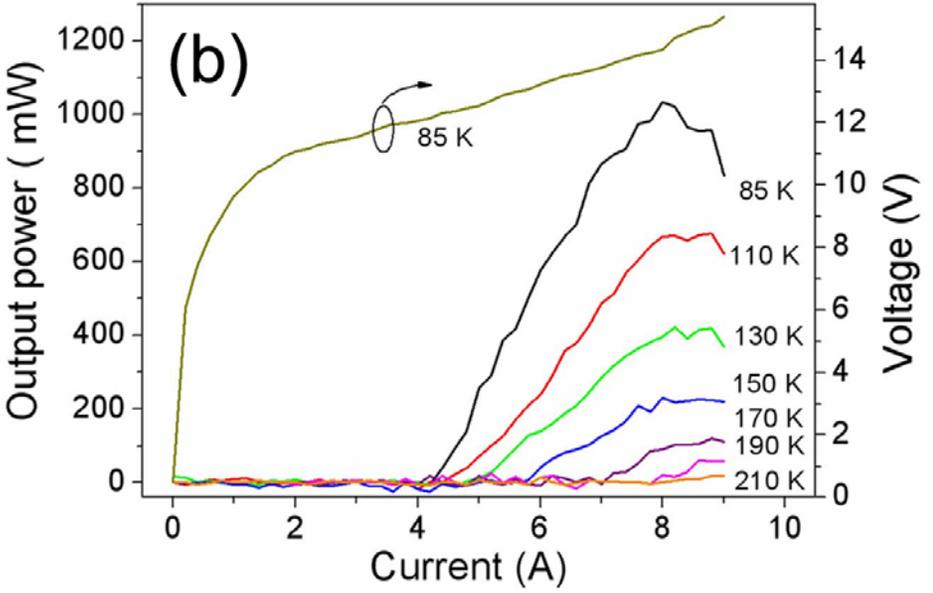
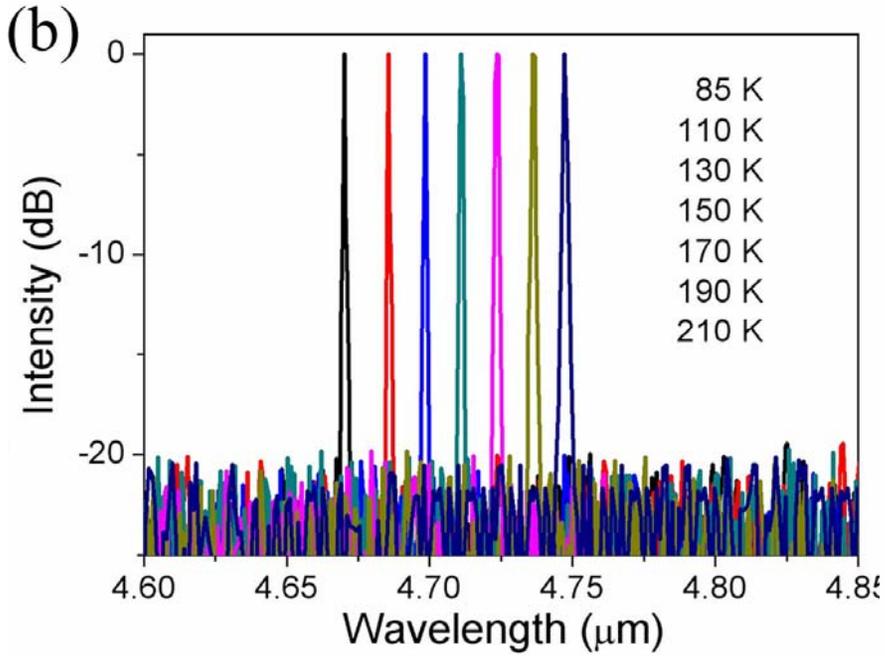
将二维点阵套刻在波导上，利用(1,2)级耦合机制，形成二维分布反馈结构；腔面与点阵成 θ 角度，可得到单模工作和近衍射极限的远场分布。

$t_1/t_2=1$

$t_1/t_2=3$

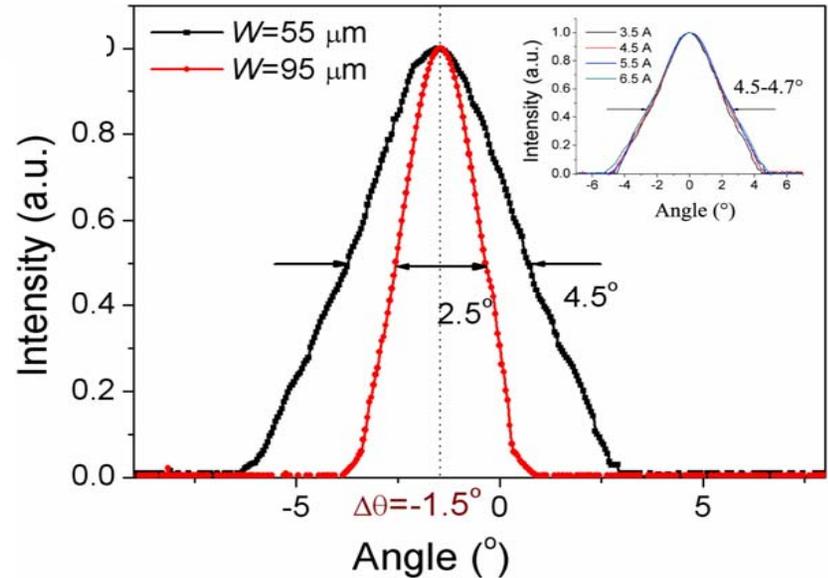


斜角二维光子晶体DFB-QCL

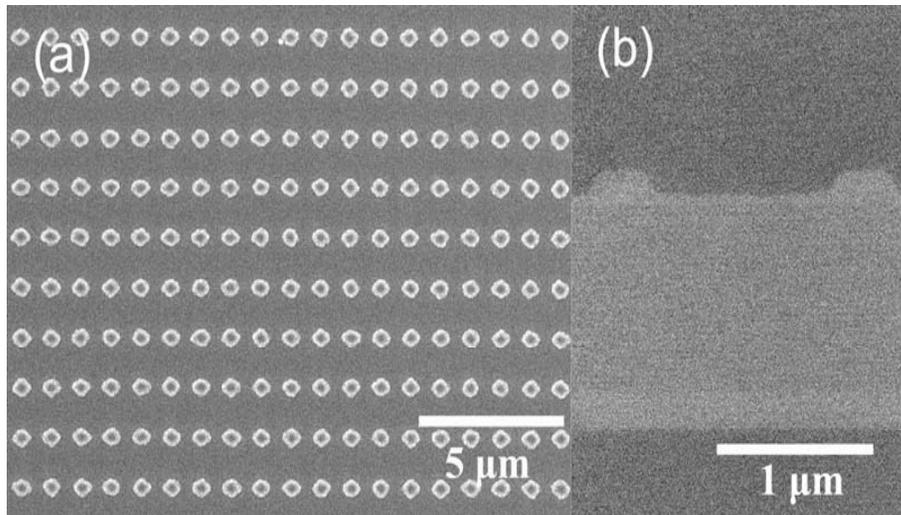
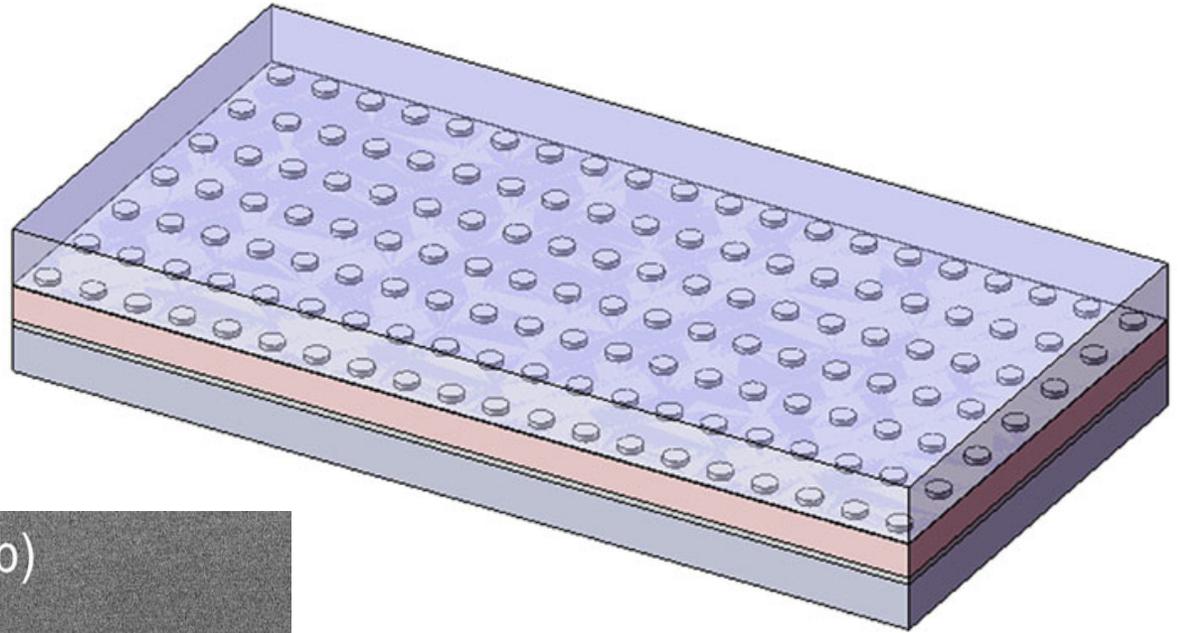


单模、近衍射极限

$$\phi \geq \sin^{-1}(\lambda / (2n_{eff} W))$$

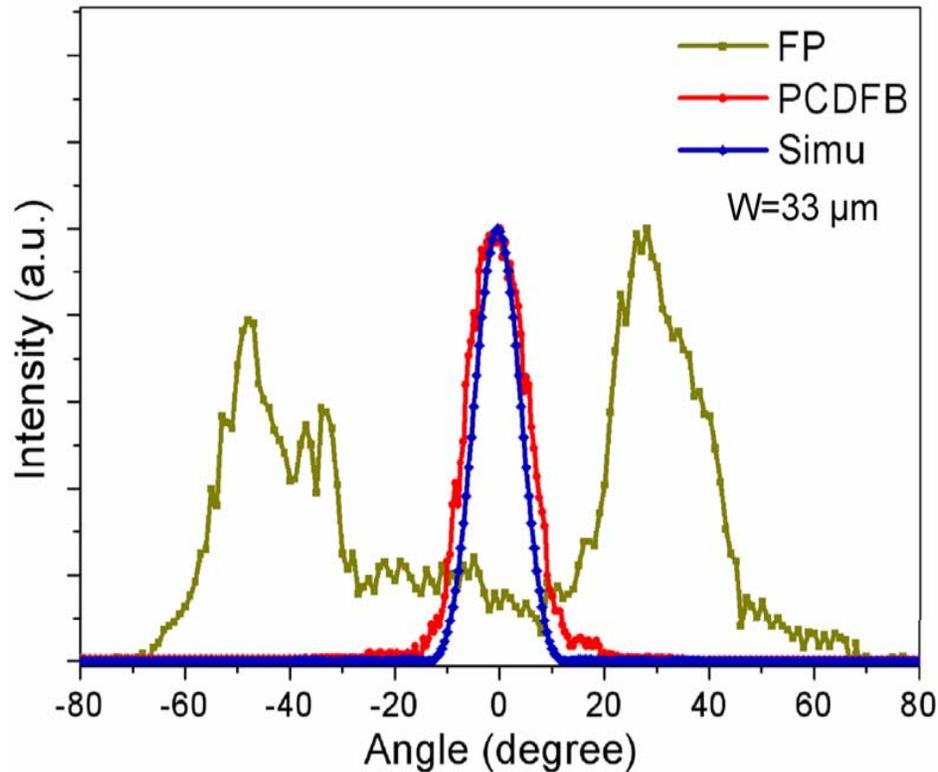


直角二维光子晶体DFB-QCL

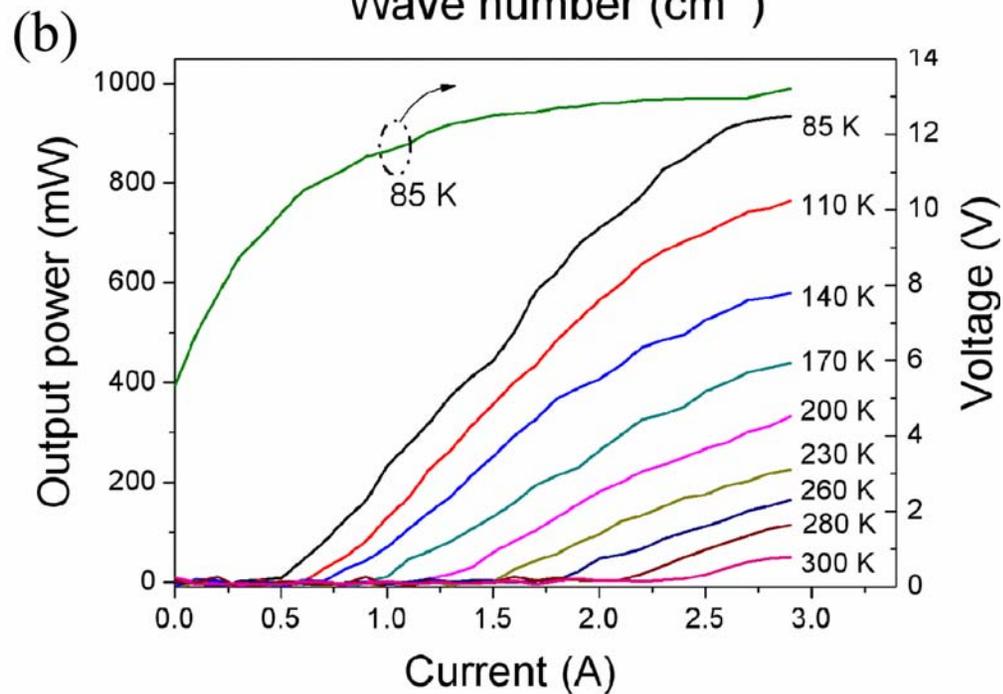
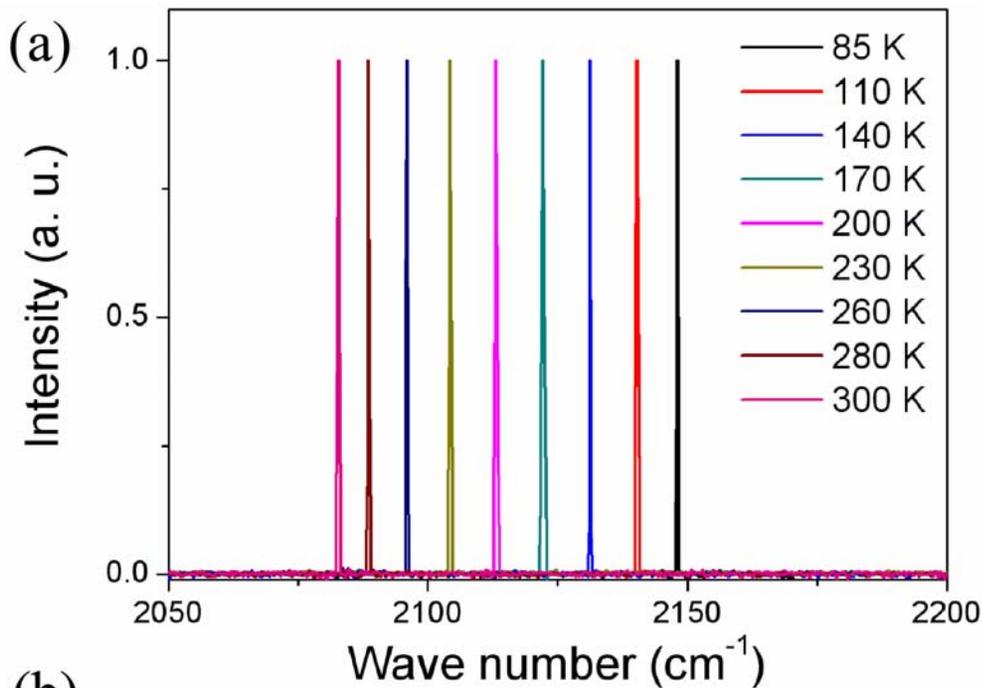


点阵PC平行于解理面
Appl. Phys. Lett. 96, 1(2010)

直角二维光子晶体DFB-QCL

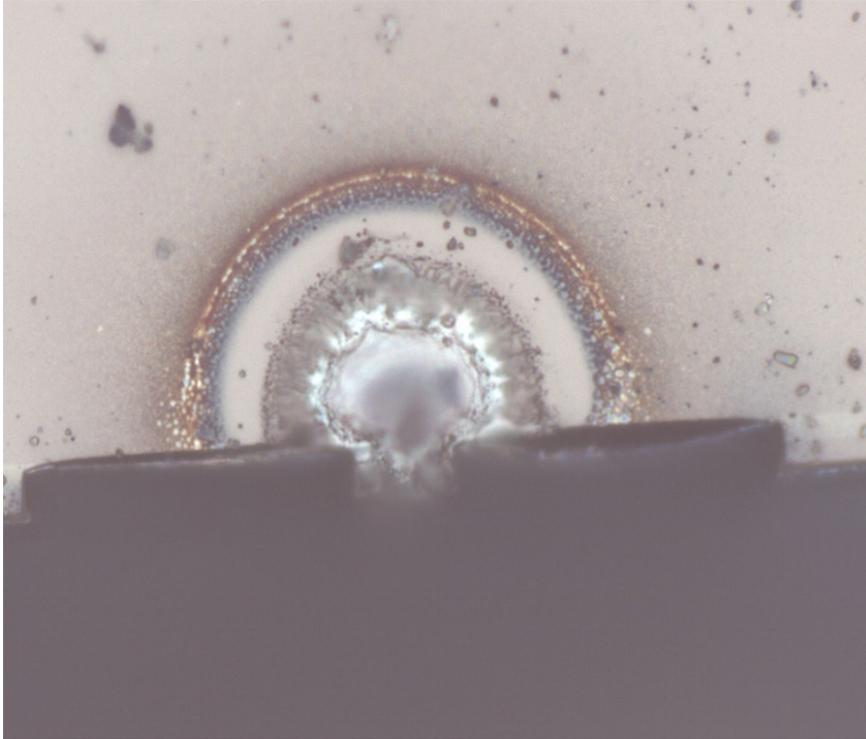


由于有效的二维DFB机制，直腔器件的光束质量大为改善，其远场发散角为 12° ，远小于FP腔的 93° 发散角，与最小发散角 10.5° 相比，可认为直腔PCDFB QCLs得到了近衍射极限的光束质量。

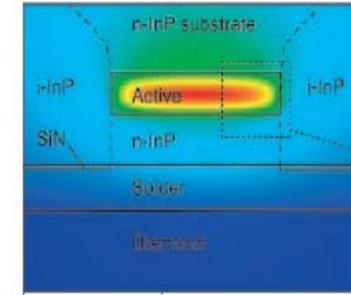


室温工作的
 激射波长4.7
 微米的近衍
 射极限的单
 模光子晶体
 分布反馈-
 QCL

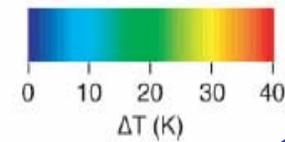
QCL失效特征



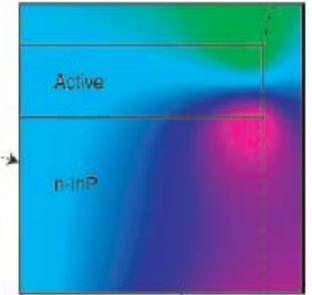
B) Temperature



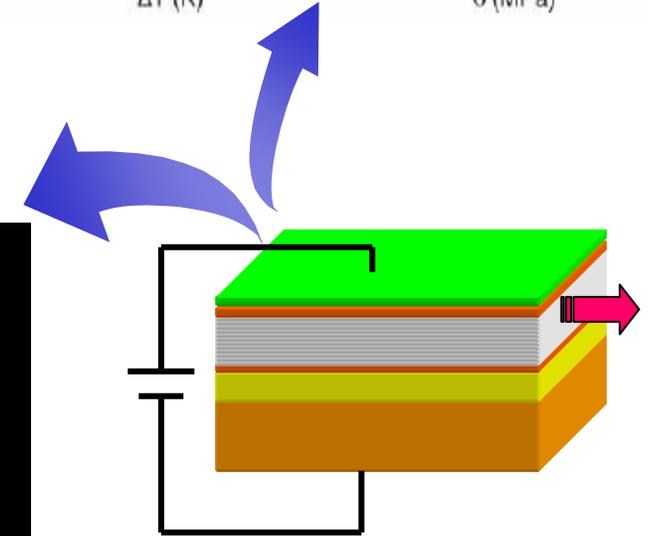
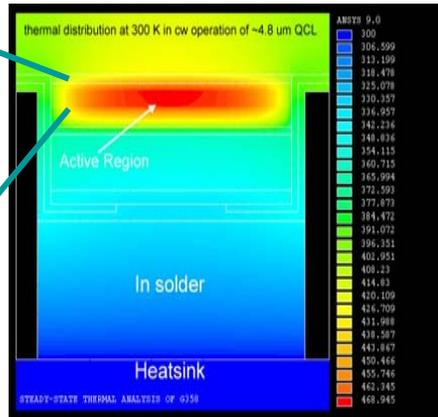
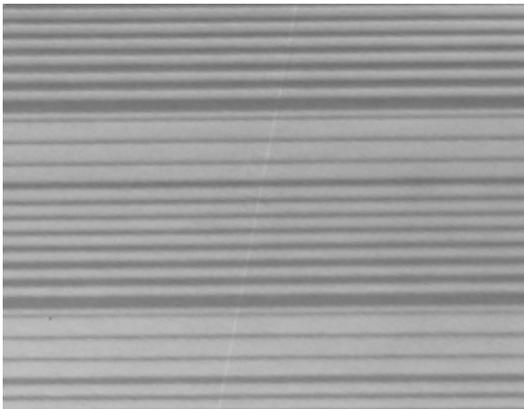
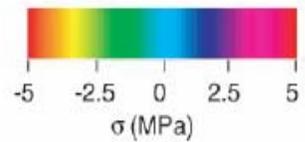
10 μ m



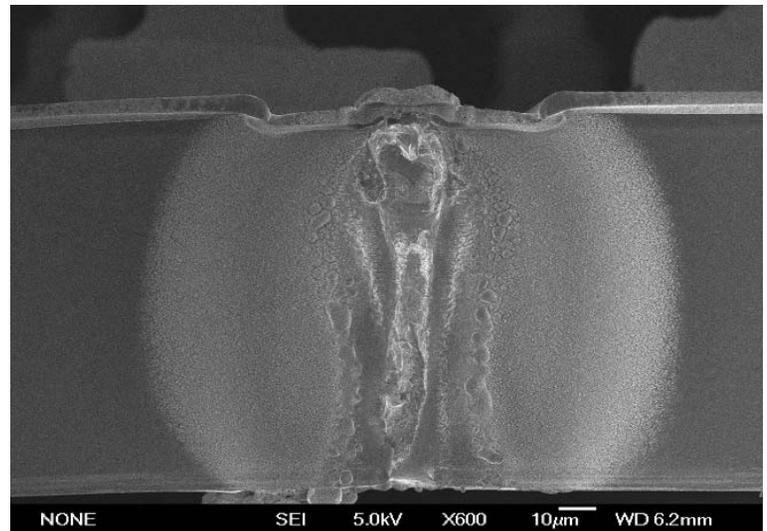
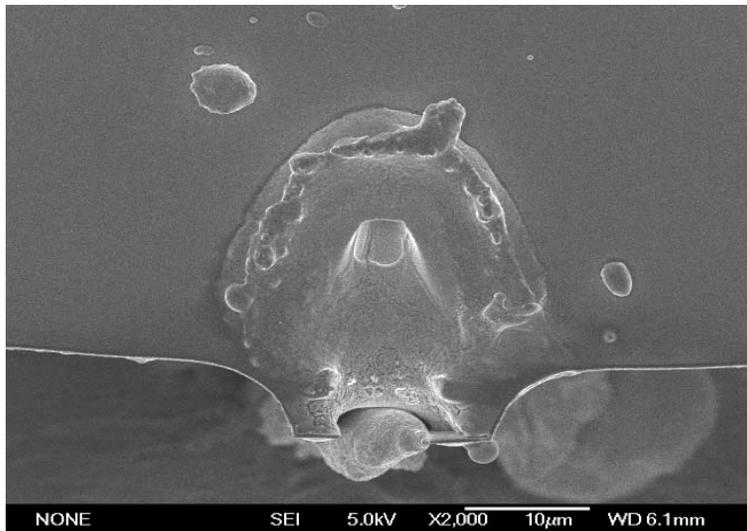
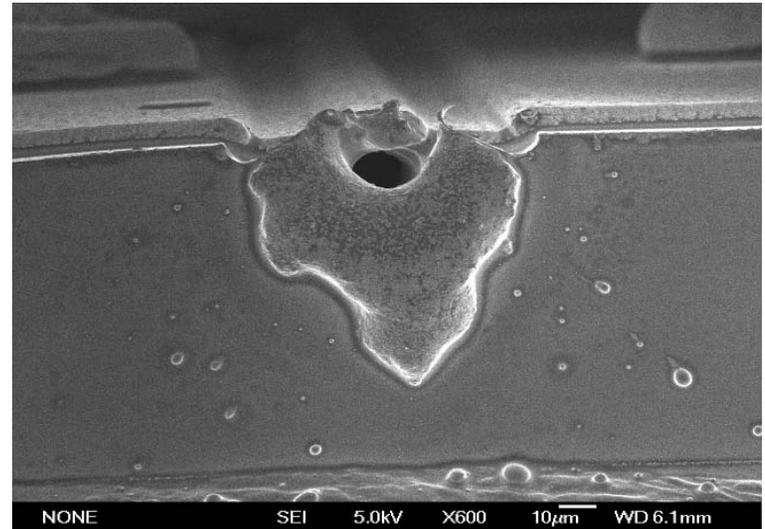
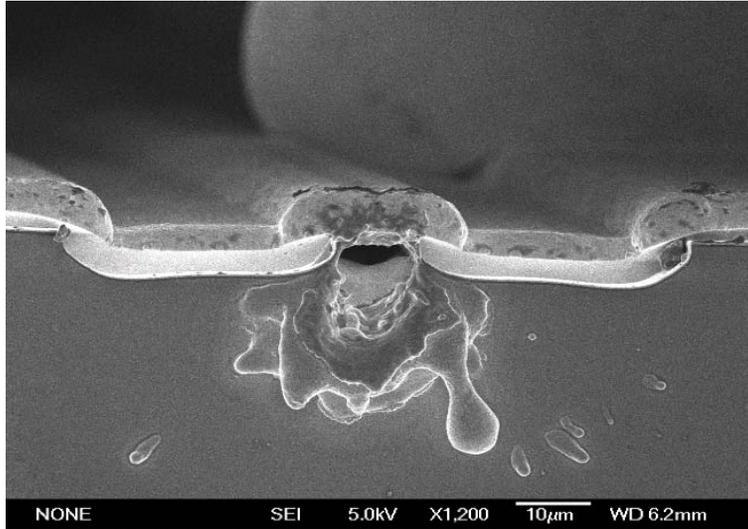
C) Shear stress



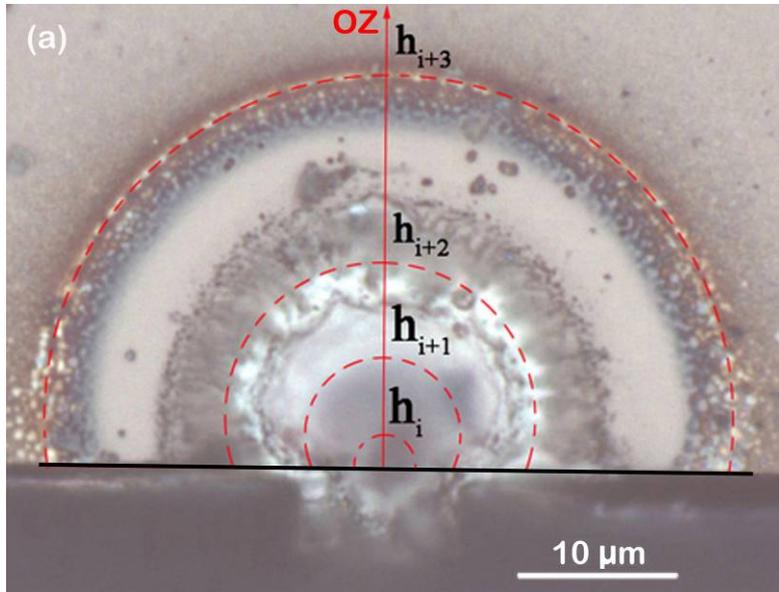
2 μ m



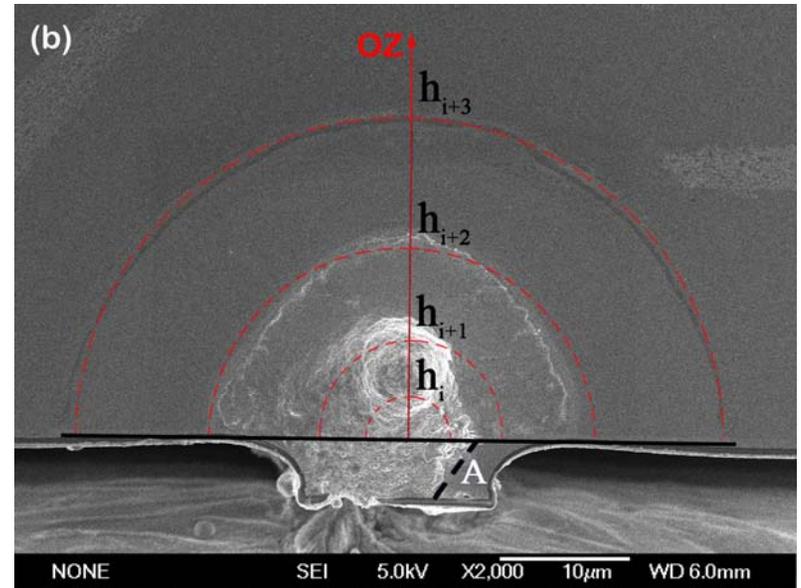
QCL失效特征



腔面损伤

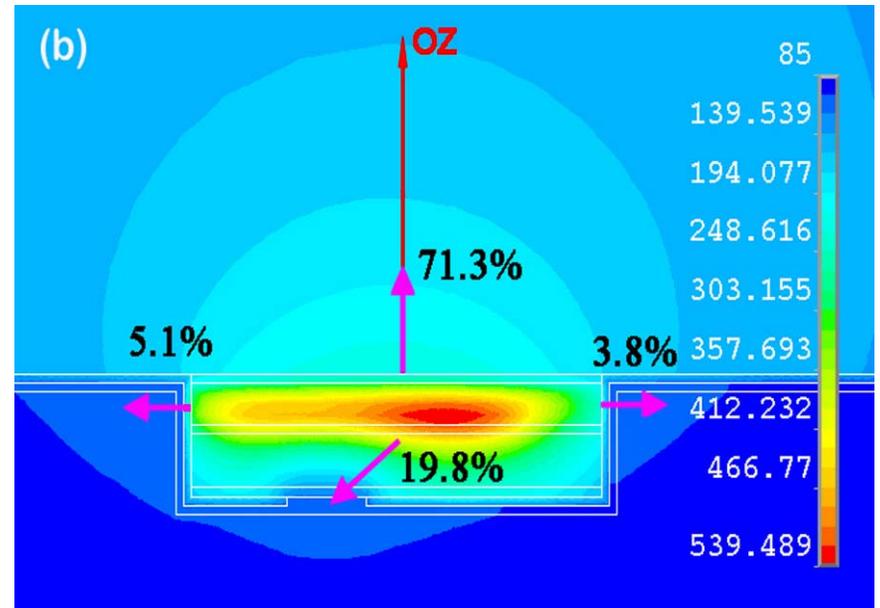
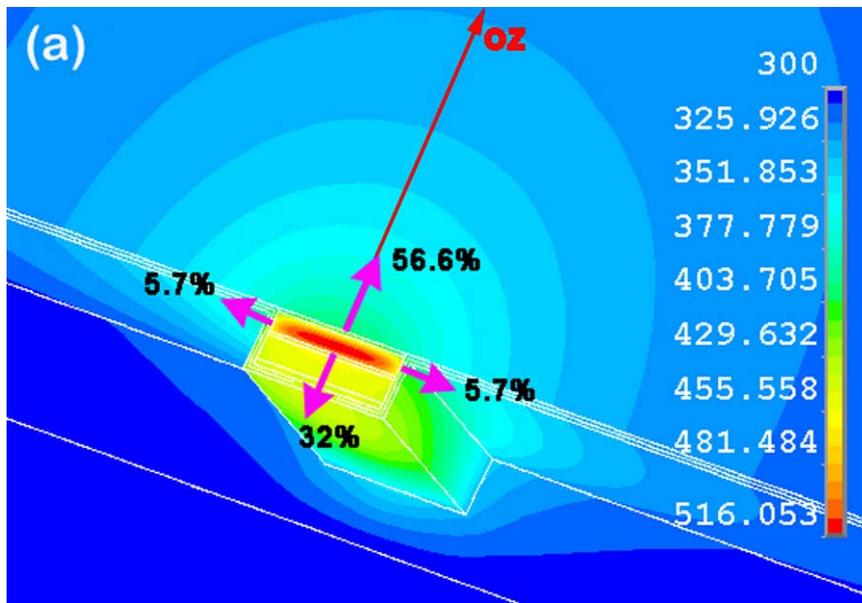


(a) G358



(b) G085

其腔面损伤都在衬底上呈现同心半圆环状损伤带；
损伤严重部位不在有源区、而在衬底上；
损伤过程是多级顺序的。



管芯灾变失效时的热模拟结果： (a) G358, (b) G085

力学平衡模型：

$$F_H = G \frac{1+\nu}{1-\nu} bhf$$

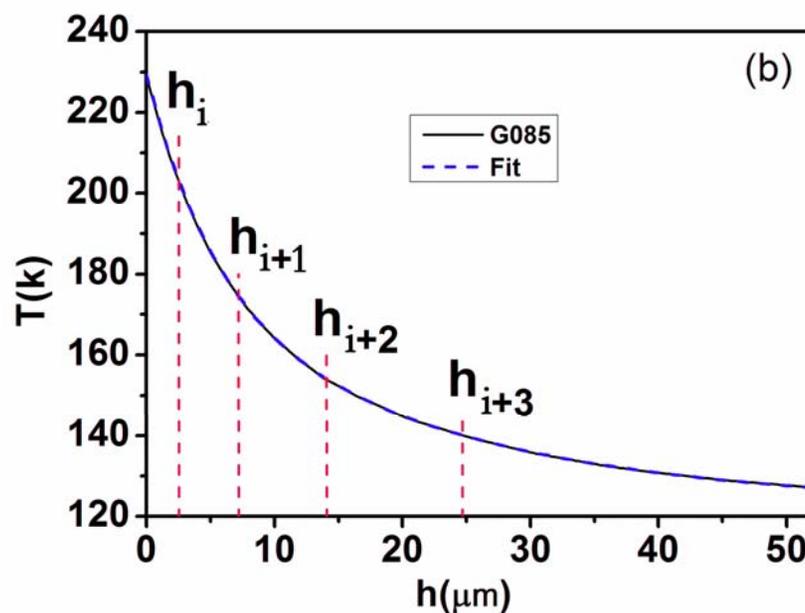
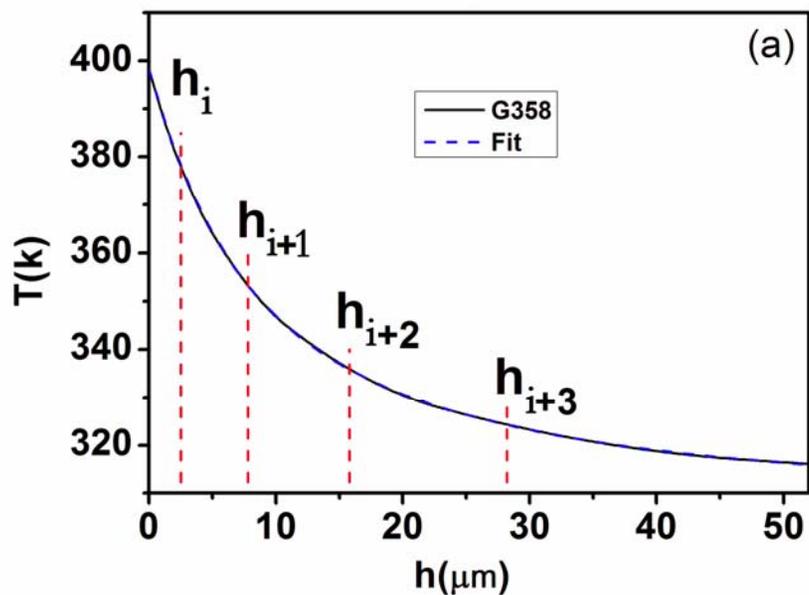
$$F_D = \frac{Gb^2}{4\pi(1-\nu)} \left[\ln \frac{h}{b} + 1 \right]$$

热晶格失配模型：

$$F_H = G \frac{1+\nu}{1-\nu} b \int_{h_i}^{h_{i+1}} f dh$$

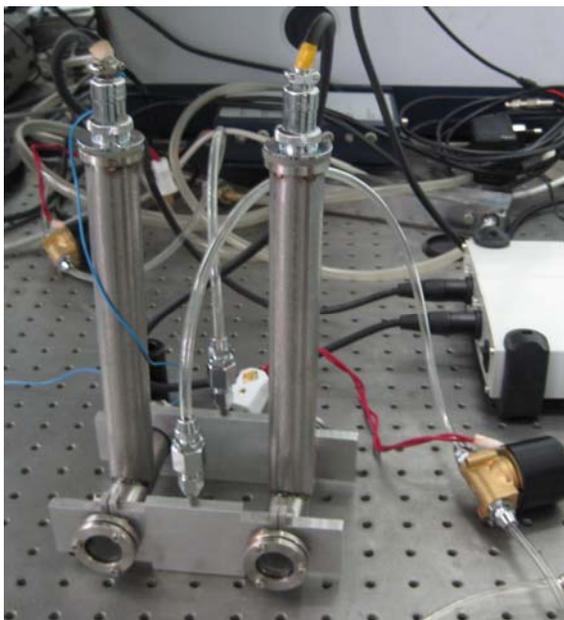
$$F_D = \frac{Gb^2}{4\pi(1-\nu)} \left[\ln \frac{h_{i+1} - h_i}{b} + 1 \right]$$

给定 h_i
获得 $h_{i\pm 1}$



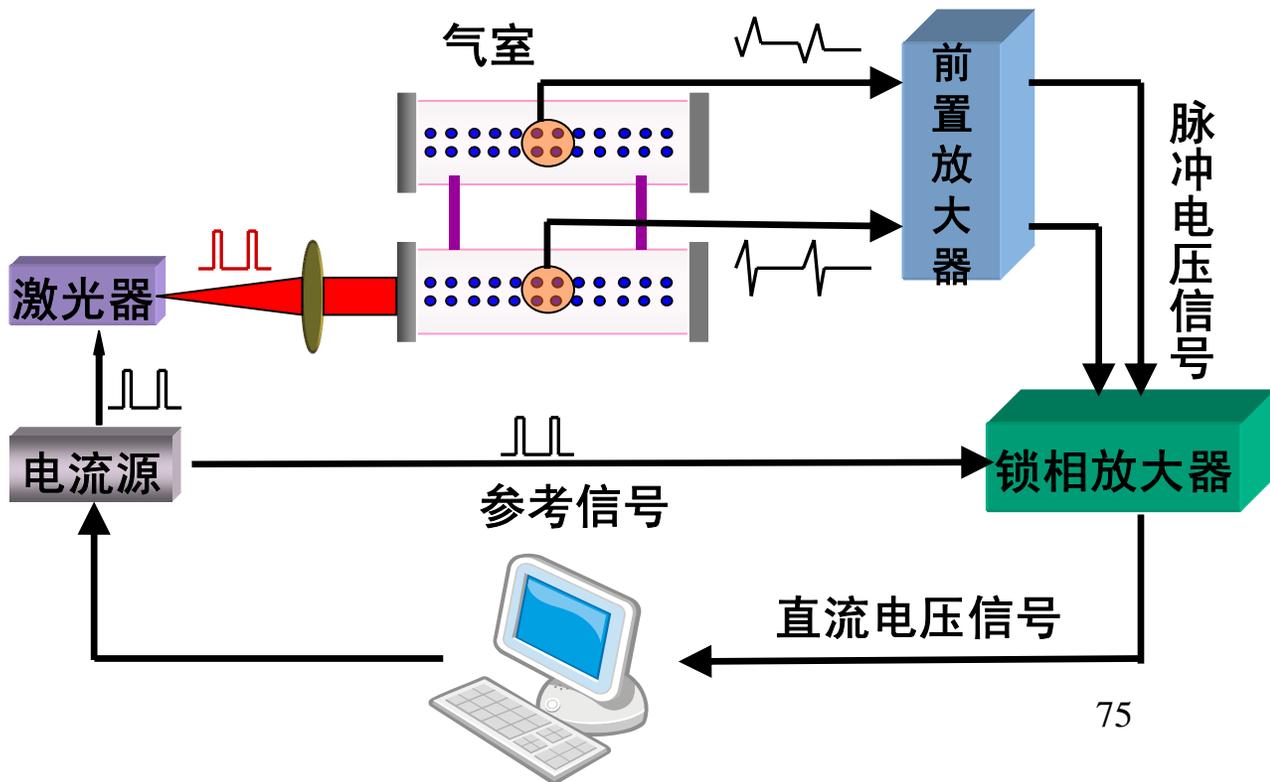
OZ轴上的温度分布： (a) G358, (b) G085

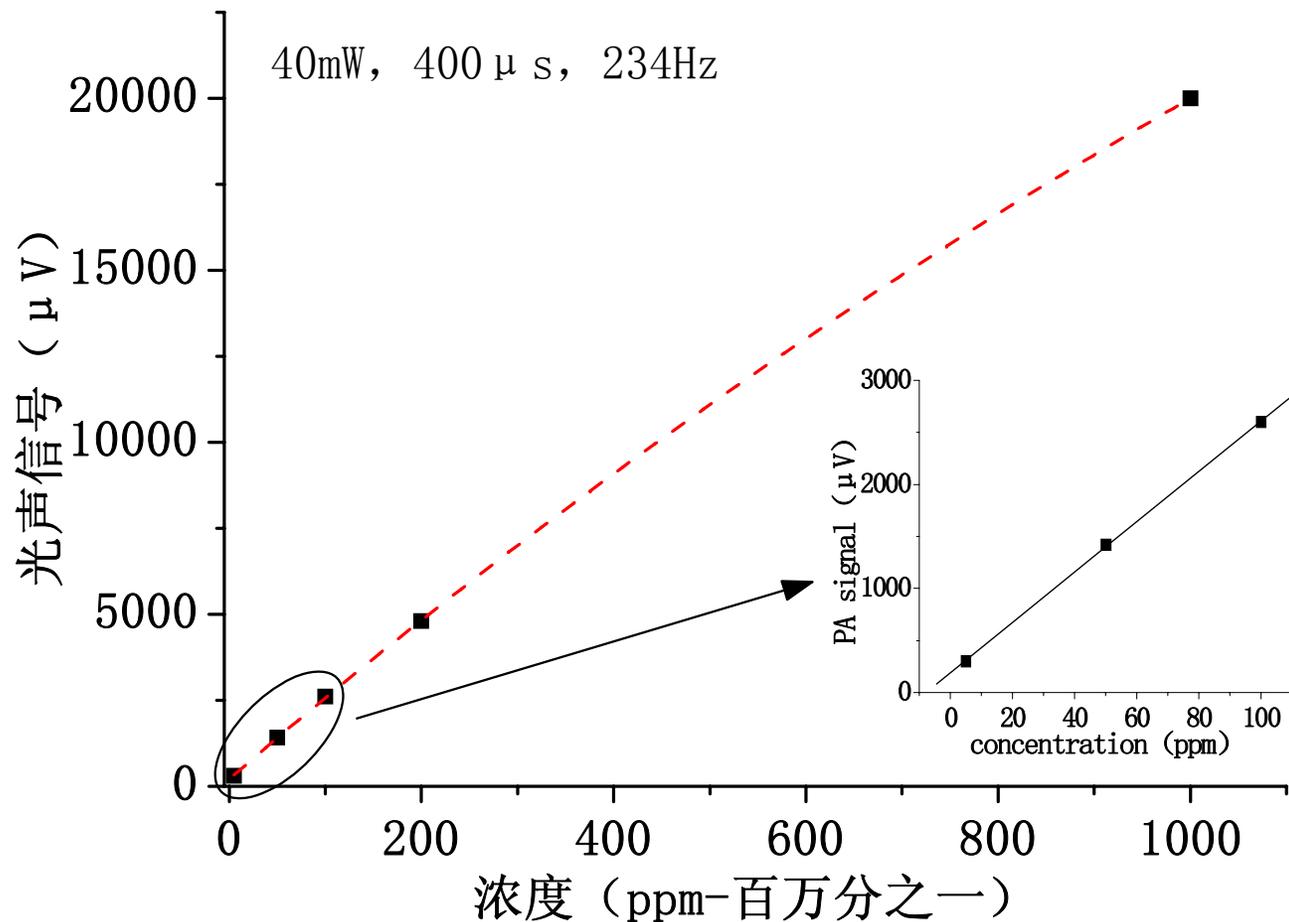
气体检测应用



气室照片

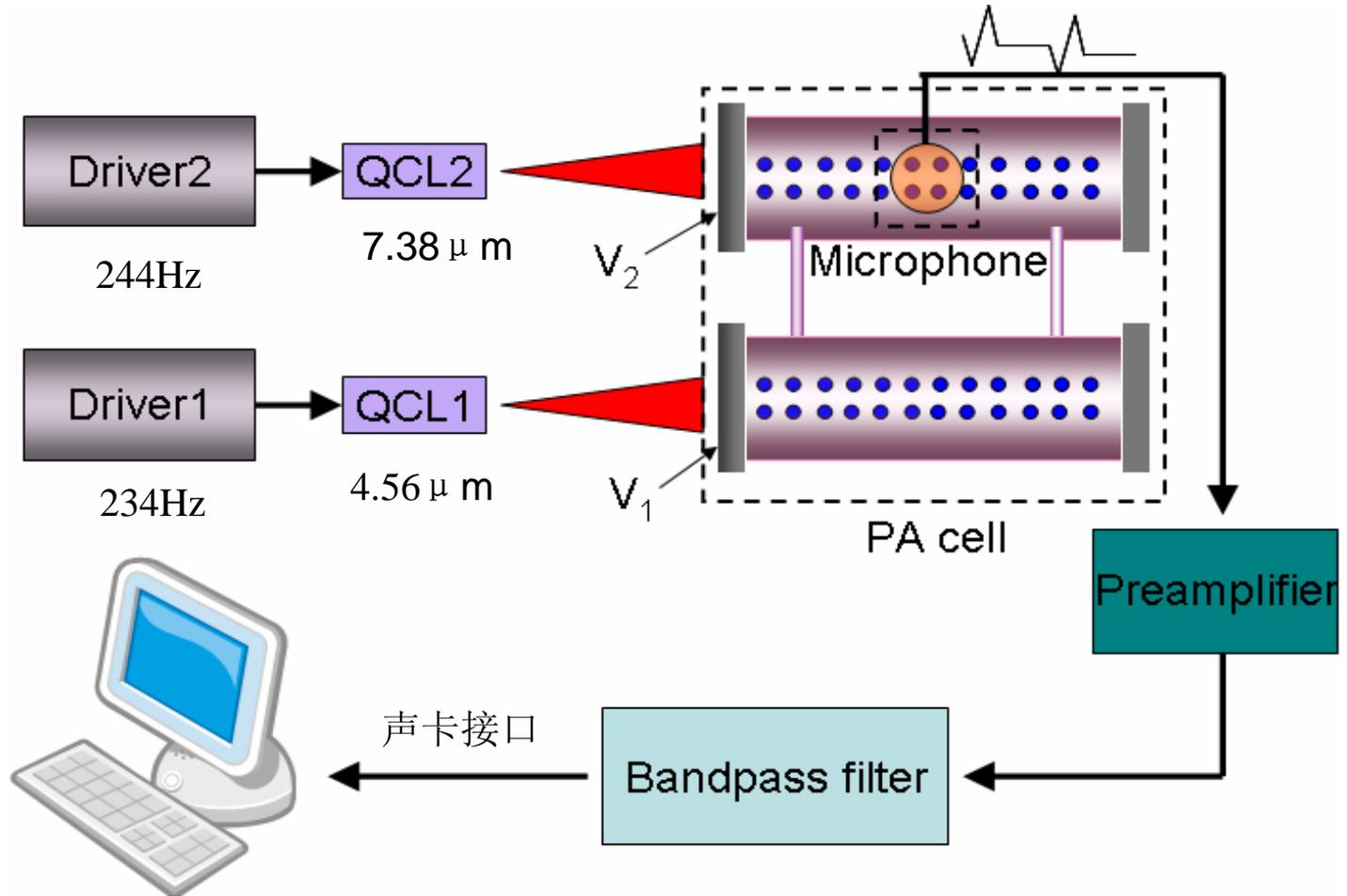
光声效应检测SO₂气体装置图





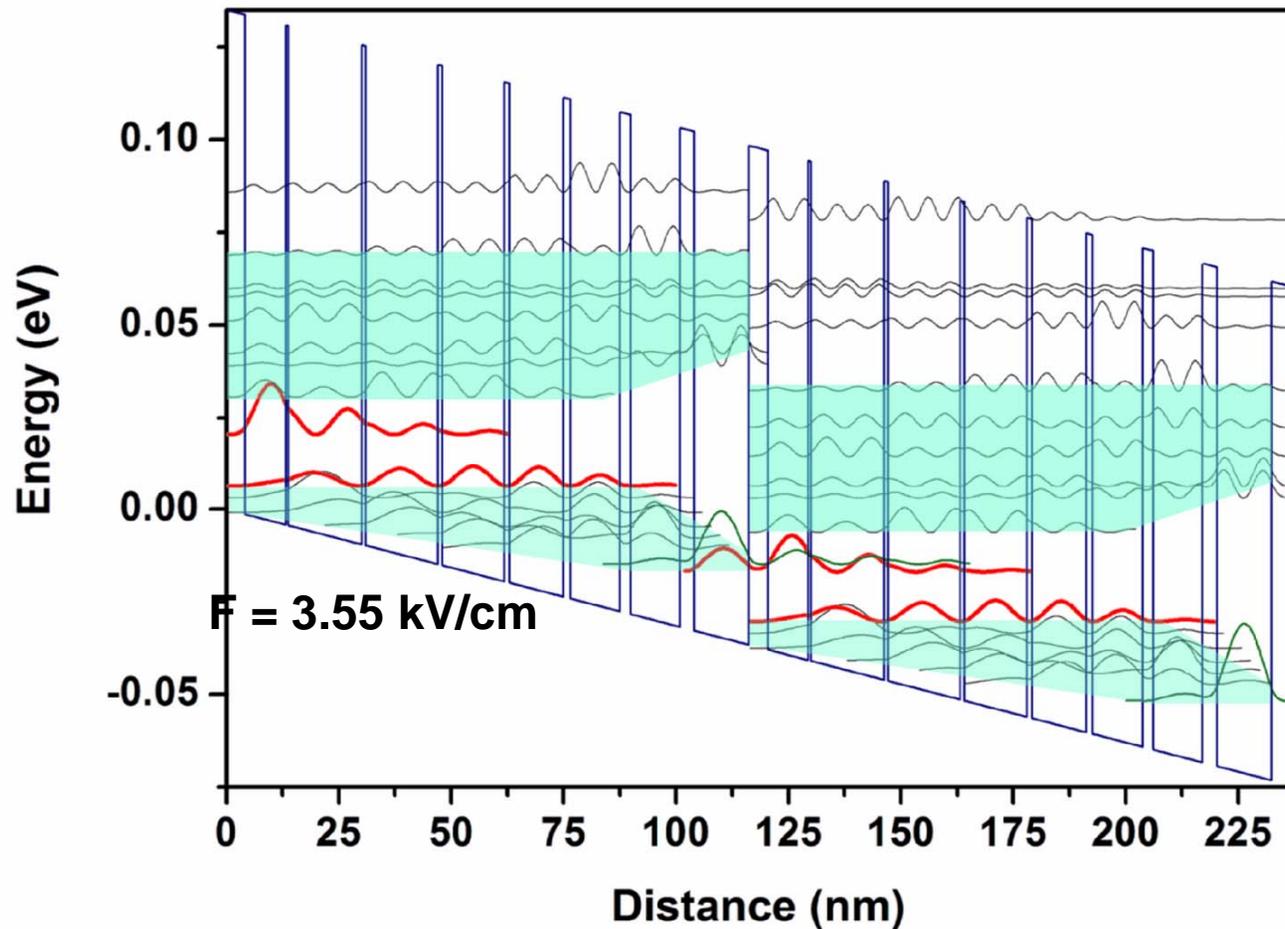
二氧化硫探测极限为167ppb (十亿分之一)

多种气体检测装置图

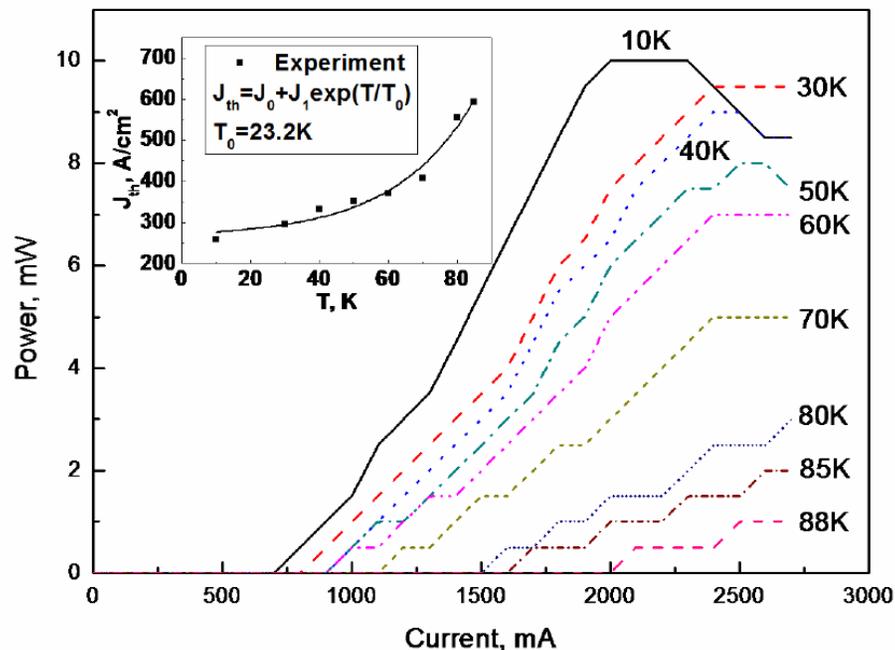
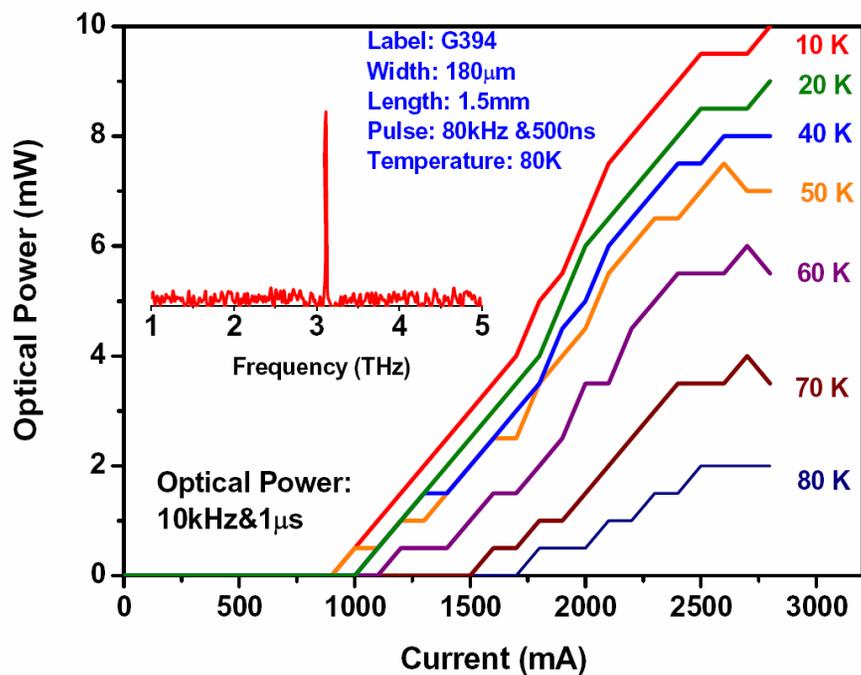


THz-QCL研制

3THz量子级联激光器—束缚-连续有源区

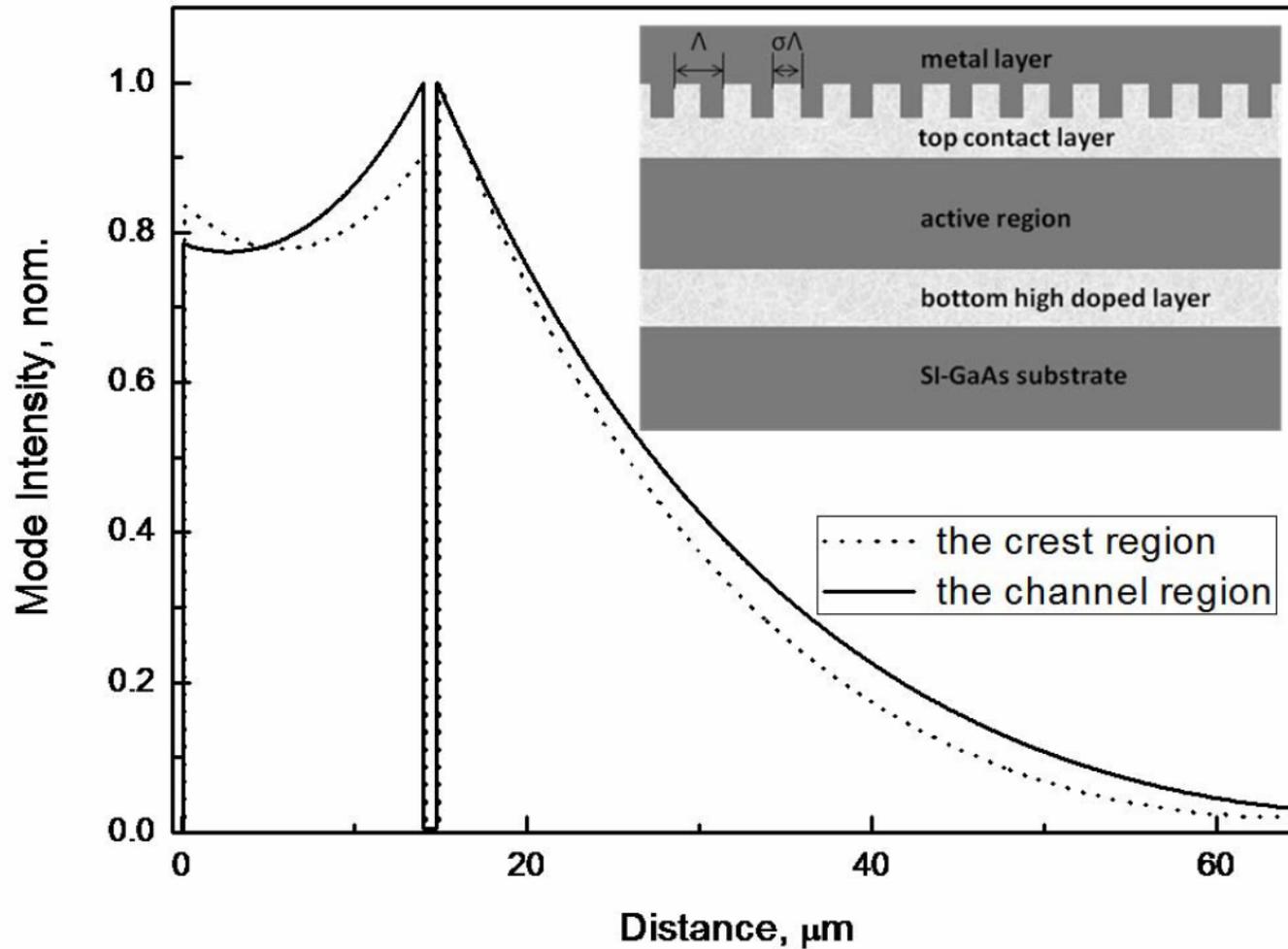


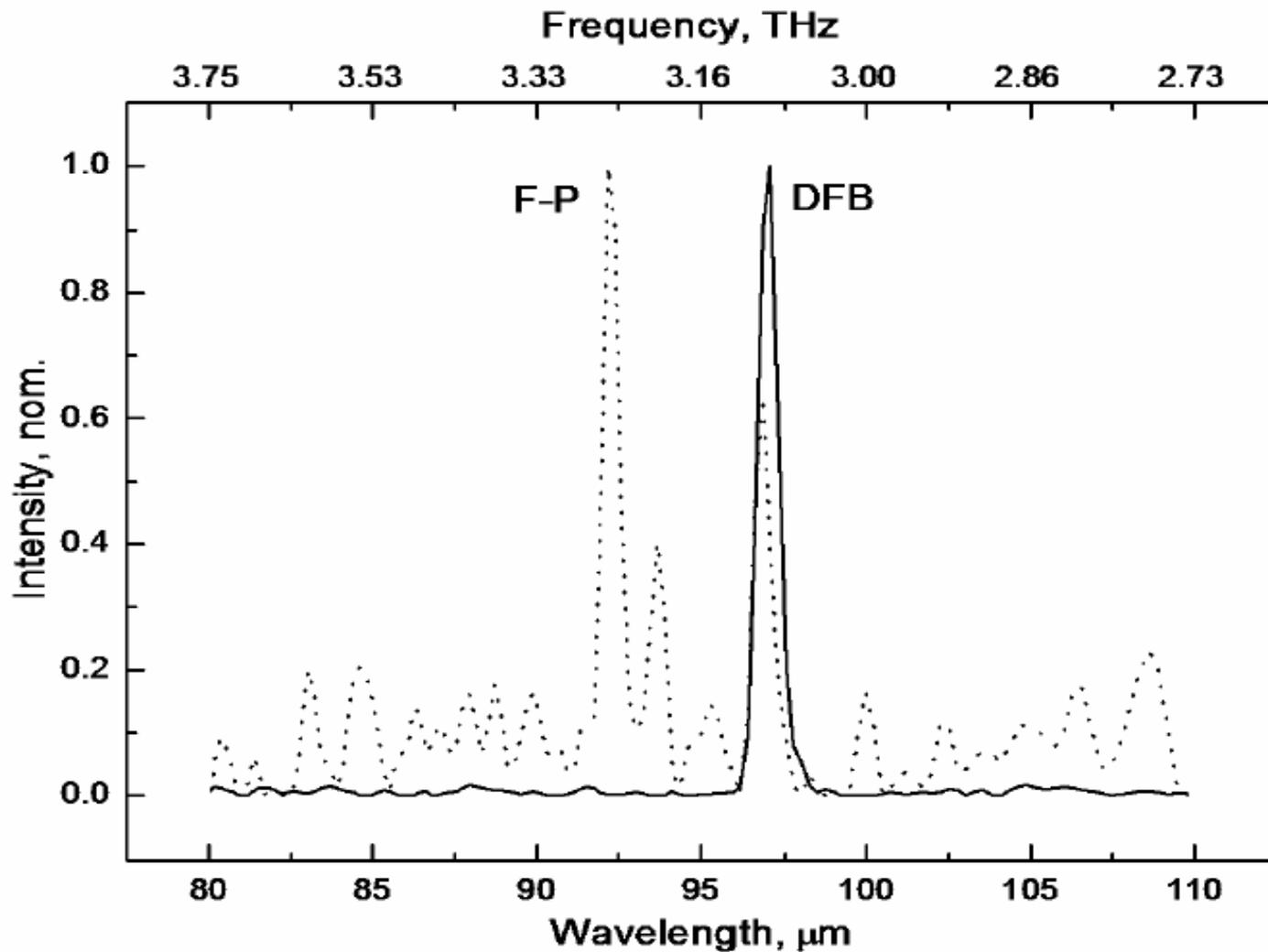
利用2006年生长的材料研制出频率3THz的量子级联激光器，工作温度达到88K



最近：工作温度大于90K、低温功率14mW。

分布反馈THz-QCL研制





DFB THz-QCL, 激光波长97微米。(2006年外延片)。

Electron. Lett. 46(19)_ 1340(2010)

小结

红外量子级联激光器(QCL)是十几年来才发展起来的新型红外量子器件，是以半导体低维结构材料为基础、在纳米尺度内基于量子工程设计的、具有级联特征的、光电性能可调控的人工材料。QCLs具有小型、大功率、高速响应、可集成等特点，在环境、医学、缉毒反恐、红外制导、深空探测等方面具有广泛的应用前景。

半导体所研制一系列 $\text{In}_x\text{Ga}_{1-x}\text{As}/\text{In}_y\text{Al}_{1-y}\text{As}$ QCLs:
室温工作: $3.5\mu\text{m}$, $4.6\mu\text{m}$, $4.7\mu\text{m}$, $4.8\mu\text{m}$, $5.2\mu\text{m}$,
 $5.5\mu\text{m}$, $5.7\mu\text{m}$, $7.4\mu\text{m}$, $7.8\mu\text{m}$, $8.9\mu\text{m}$.

室温连续 $4.6\mu\text{m}$, $7.4\mu\text{m}$.

室温连续工作外腔调谐单模QCLs

短腔长单模QCLs;

表面光栅、垂直面发射、锥形DFB-QCLs;

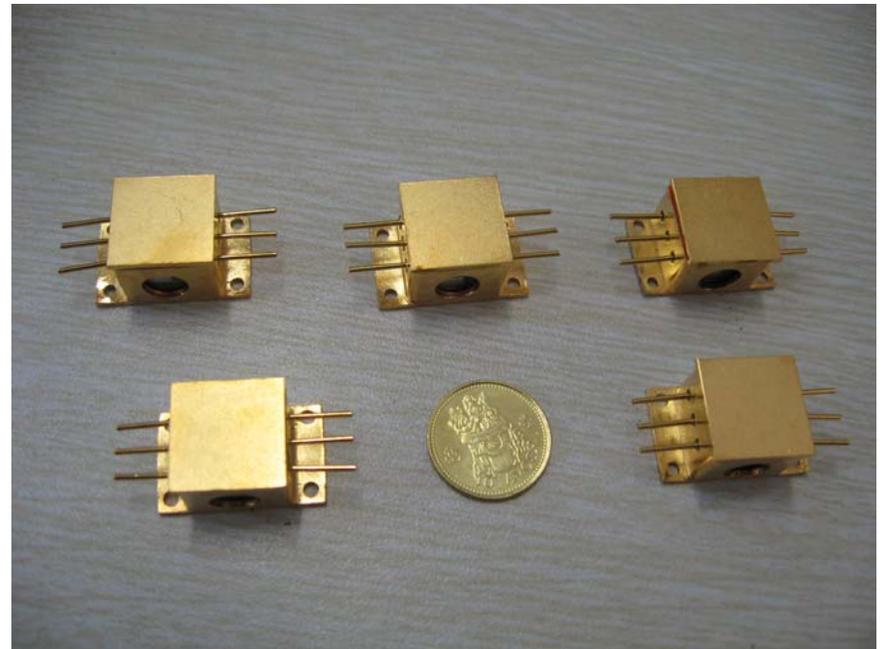
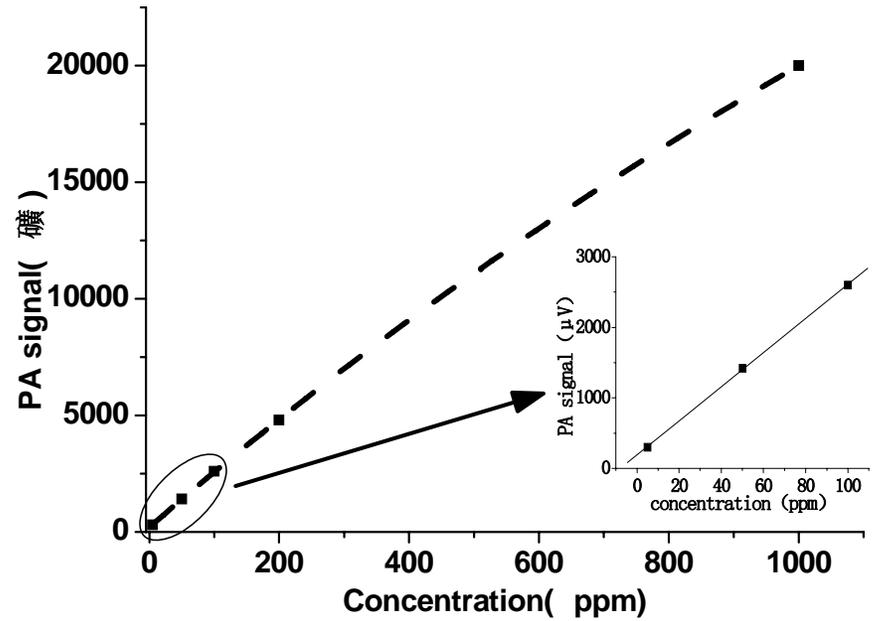
光子晶体分布反馈QCL;

GaAs/AlGaAs QCLs: 一系列 $9.1\text{--}11.4\mu\text{m}$

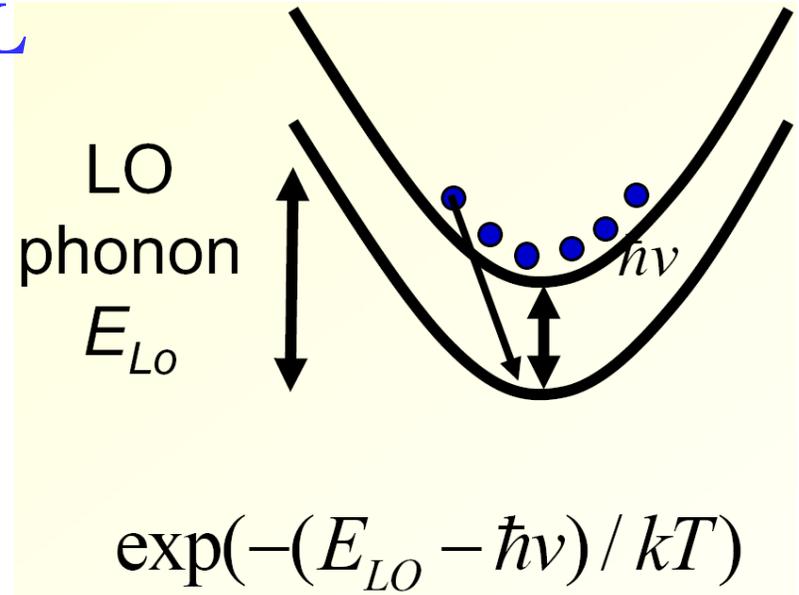
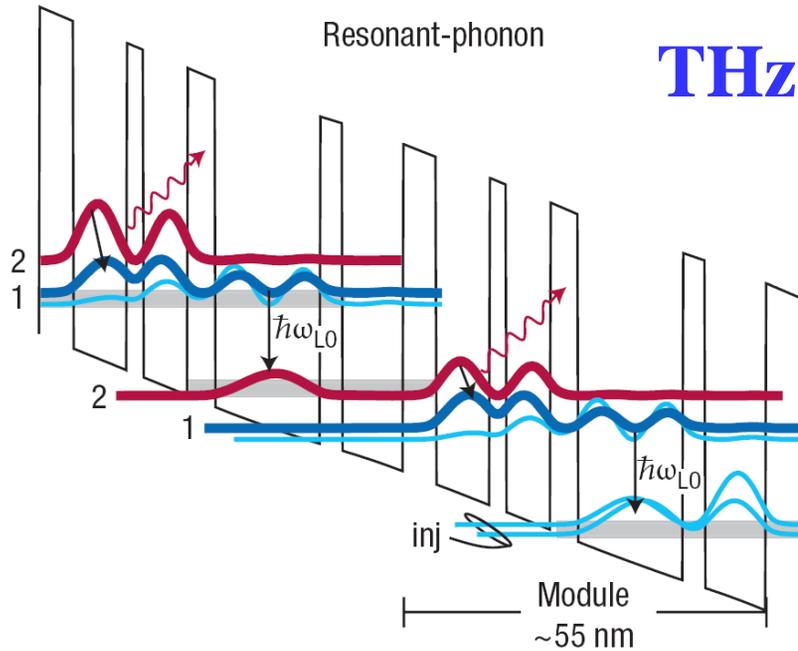
THz-QCLs、功率 14mW 。

气体检测演示

提供QCL器件



THz-QCL



Challenges and Frontier :

- (1). GaN材料体系QCLs? 短波、THz-QCL
- (2). Surface plasmonic structures
- (3). 有源区, 是否有新的设计思路?

量子理论

驱动红外技术发展