GaAs基(GaAlIn)(AsNSb)低维材料及光电器件研究

牛智川

中国科学院半导体研究所

提　纲

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2、目前研究工作

　背景

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3、下一步研究方向

　微纳结构量子光源

　新型Sb化物红外光电材料

1、实验室简介

中国科学院半导体研究所

新型半导体光电材料

WWW.MBE-ISCAS.CN

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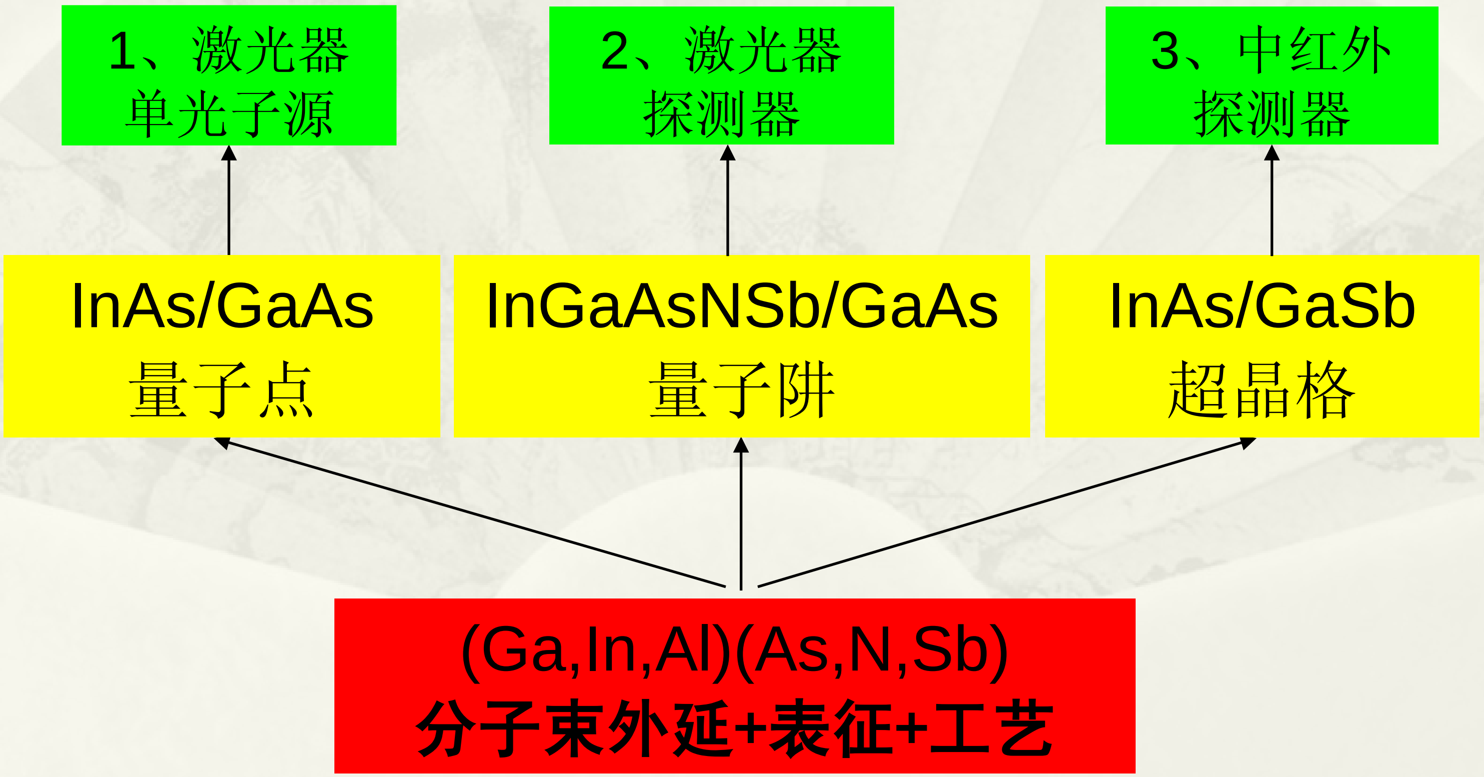
研究方向

以GaAs基(GaInAl)(AsNSb)量子点、量子阱、超晶格等低维结构为对象，研究其受限体系中光子、电子的量子物理效应，突破材料外延和结构制备关键技术，研制新型量子结构原型器件！



1、激光器
单光子源

2、激光器
探测器

3、中红外
探测器

InAs/GaAs
量子点

InGaAsNSb/GaAs
量子阱

InAs/GaSb
超晶格

(Ga,In,Al)(As,N,Sb)
分子束外延+表征+工艺

实验平台

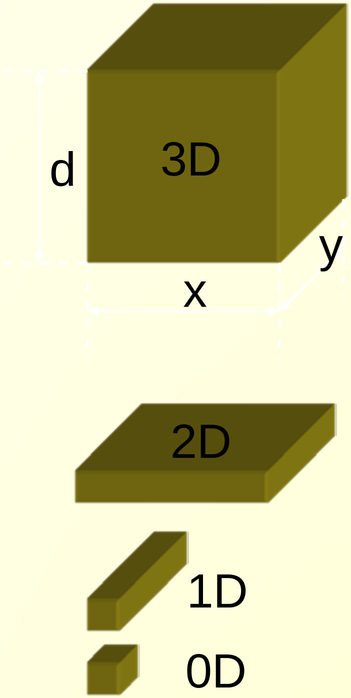
VEECO Gen II、VG V80 MkII 等 MBE 系统

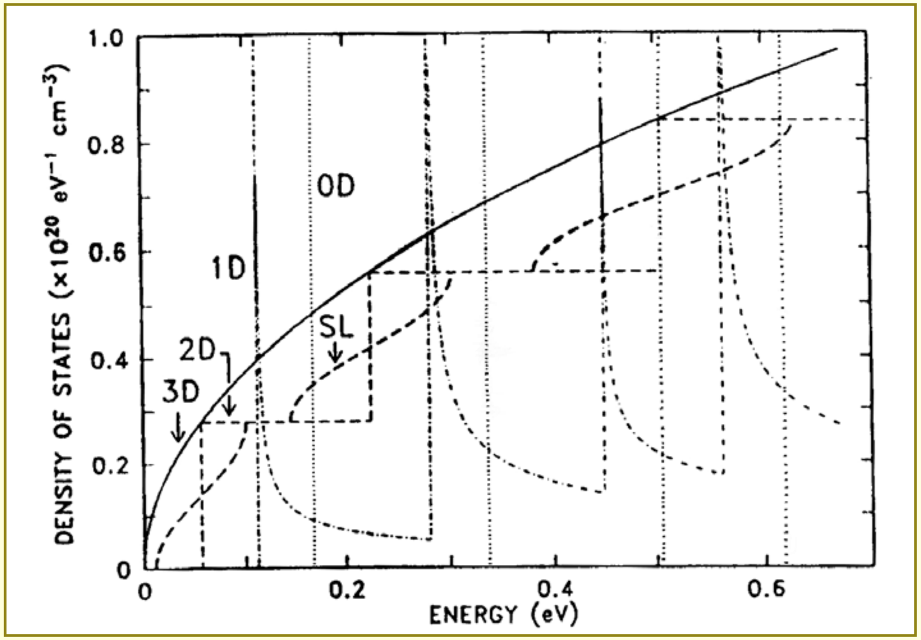
傅里叶光谱、HBT光谱、QE光谱、原子力显微镜、湿氮氧化

2、研究工作

背景
主要工作

半导体低维结构的优越性





不同维度纳米半导体电子态密度能谱分布

1、电子态密度能谱分布的浓缩、分立；

2、光和纳米低维结构的相互作用：多体关联效应和非线性光学效应变得越来越显著；

3、强量子封闭效应导致纳米半导体光电子器件的光增益增强、温度稳定性变好、阈值电流降低等性能质的改善；

4、纳米半导体微电子器件具有更高速、更低功耗等优越性

半导体低维材料制备与应用

早期半导体器件如DH激光器其核心结构尺度微米量级！

材料外延技术和纳米加工精度不断发展

利用超晶格概念、能带工程计算，可以设计生长制备多种纳米结构。

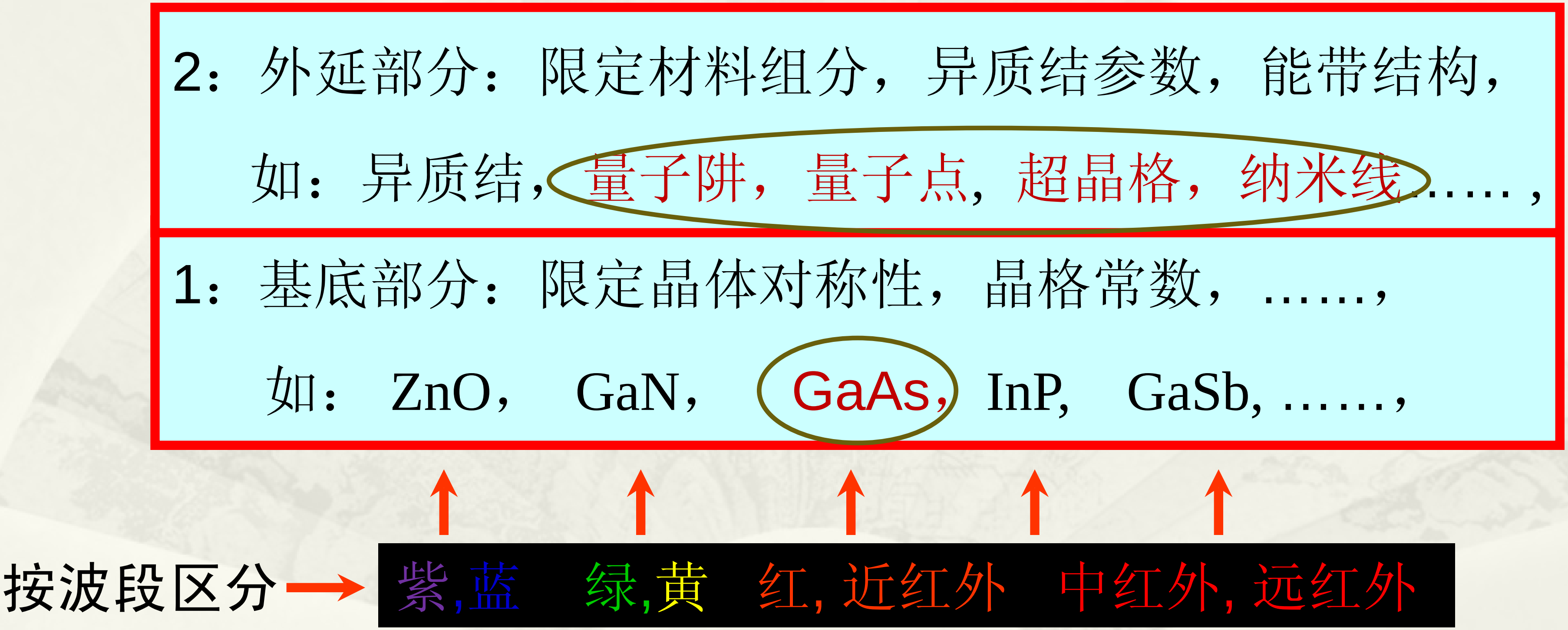
- 量子点
- 量子线
- 量子阱
- 超晶格
- …

光通信系统
1.31μm激光器

红外预警系统焦平面探测器

量子密码系统单光子发射源

化合物半导体材料与器件基本结构



2：外延部分：限定材料组分，异质结参数，能带结构，

如：异质结，量子阱，量子点，超晶格，纳米线……，

1：基底部分：限定晶体对称性，晶格常数，……，

如：ZnO，GaN，GaAs，InP，GaSb, ……，

按波段区分 → 紫,蓝　绿,黄　红, 近红外　中红外, 远红外

GaAs基半导体材料优越性及广泛应用

- 与同波段其他基底材料相比：
  GaAs基片成本更低
- 热导性好、温度稳定性高：
  器件特征温度大于 200 K
- 可直接生长GaAs/AlAs DBR:
  易于制备垂直工作集成器件
- 与Si基、GaAs基电学器件兼容：
  易于实现单片光电集成

垂直腔激光器

高 T_0 激光器

热光伏器件

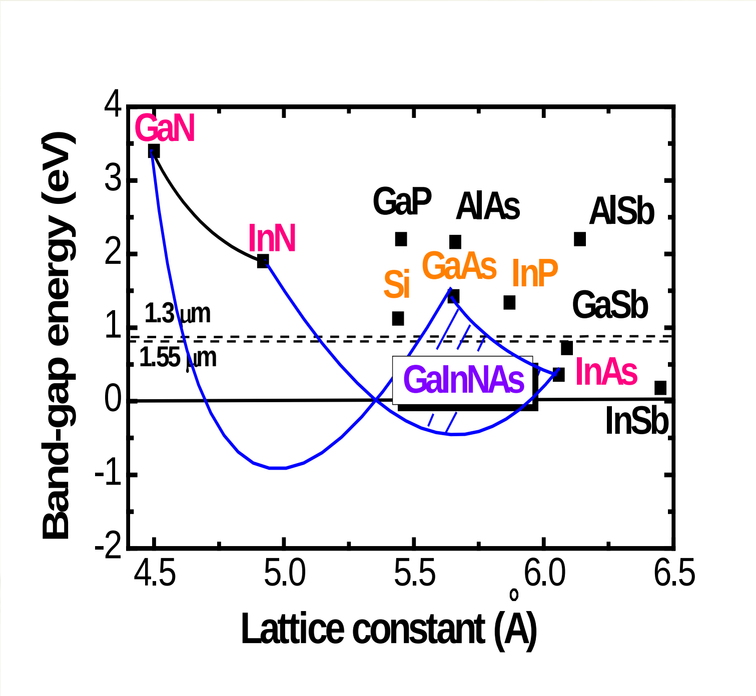
高效太阳电池

红外探测器

与硅集成

……

GaAs基半导体材料：晶格匹配/失配体系



匹配体系

1、AlGaAs、InGaAs 量子阱

2、GaInAsNSb 量子阱

失配体系

1、InAs 量子点

2、InGaAs 异变

3、InAs/GaSb 超晶格

外延部分： Ga (In)As(N,Sb)

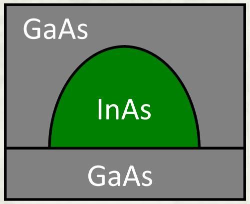
基底部分： GaAs

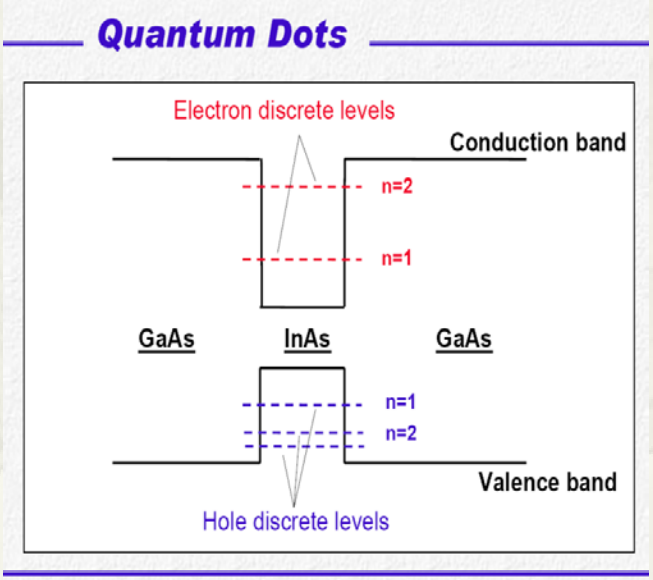
主要工作

1、InAs 自组织量子点材料与器件
2、InGaAs(NSb) 量子阱材料与器件
3、InAs/GaSb 超晶格材料与器件

1、InAs自组织量子点材料与器件

InAs自组织量子点，具有强的载流子量子限制效应，是可以人工制备的“类原子”结构，在半导体光电器件、固态量子信息器件潜在应用广泛！





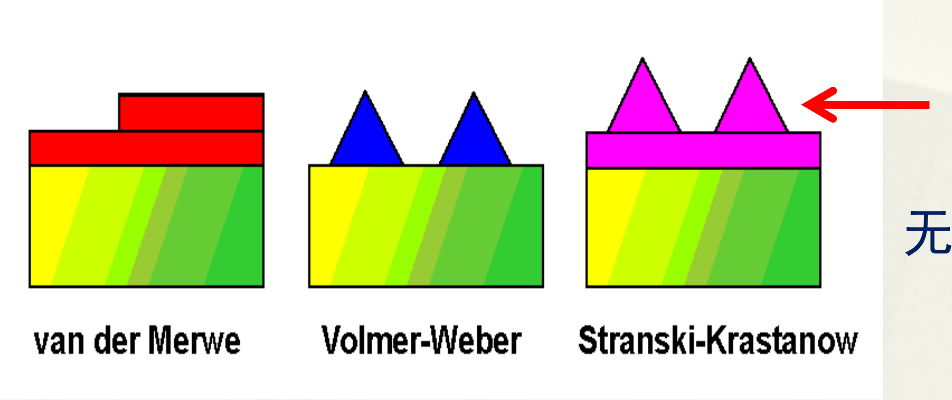
1.3微米波段长波长InAs量子点

通常1.3-1.5微米发光器件为InP基材料。克服其固有缺点的解决方法是采用GaAs基。

晶格匹配InGaAs量子阱上限波长是1.2微米左右，如何拓展其发光波长至1.3-1.5微米？

采用InAs/GaAs量子点是重要途径之一！

InAs自组织量子点外延生长方法

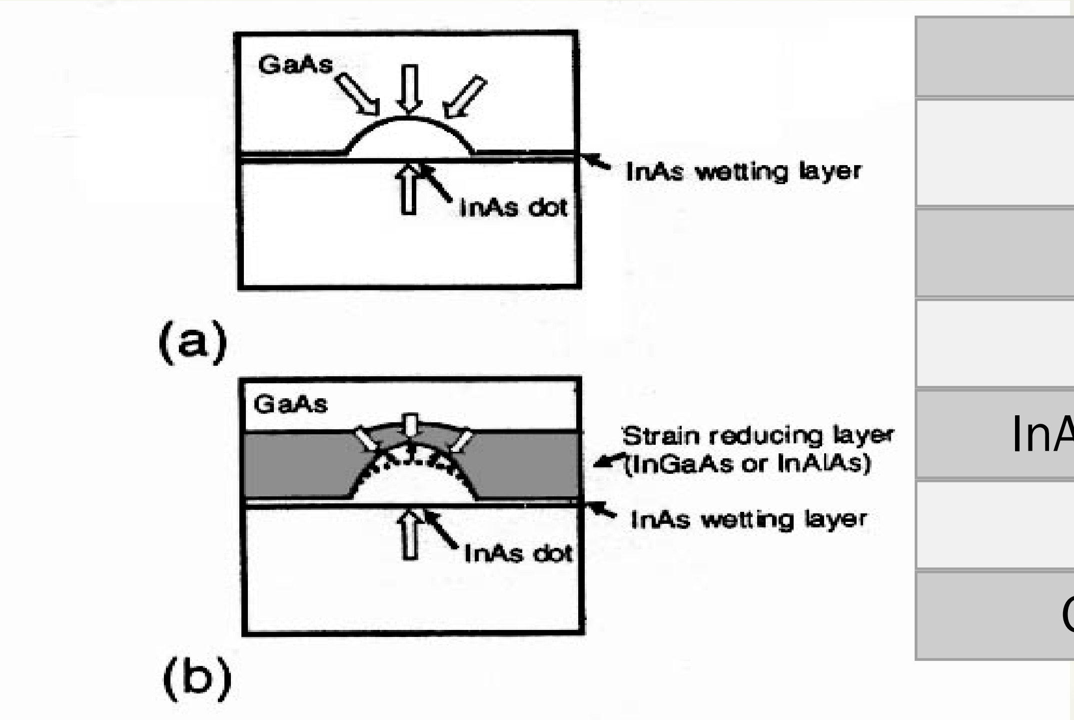


采用SK模式生长
InAs/GaAs量子点
无位错、光学性质好

自组织量子点生长主要问题：

1、均匀性，2、发光波长拓展，3、密度控制

1.3微米波段长波长量子点结构设计



量子点外延结构优化
GaAs cap
InGaAs cover
InAlAs cover
InAs QDs 亚单原子层循环
GaAs buffer
GaAs (001) substrates

亚单原子层循环生长，大幅度提高量子点均匀性

外延层结构

20nm GaAs cap

3nm $In_{0.2}Ga_{0.8}As$ cover

3ML AlAs cover

InAs QDs

500nm GaAs buffer

GaAs (001) substrates

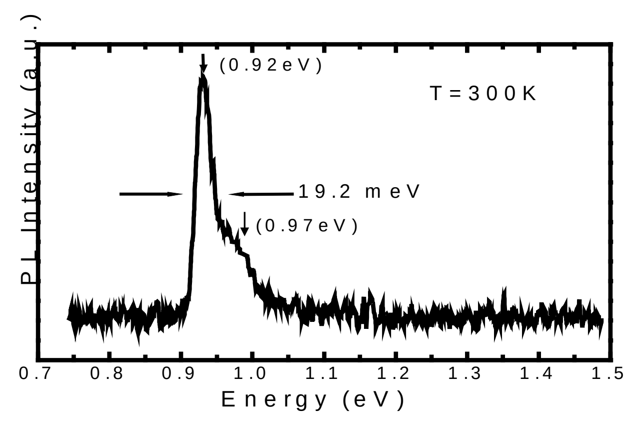
1、InAs 直接生长

2、亚单原子层InAs/GaAs交替

3、单原子层InAs/GaAs交替

4、多原子层InAs/GaAs交替

1.3微米InGaAs量子点室温PL谱
半峰宽减小到创纪录的19meV!



J. Crystal Growth, 220, 16(2000)
J.J. Appl. Phys., 39, 5076(2000)
J. Crystal Growth, 223, 363(2001)
J. Crystal Growth, 227, 1062(2001)
J.J. Appl. Phys., 42, 1154(2003)
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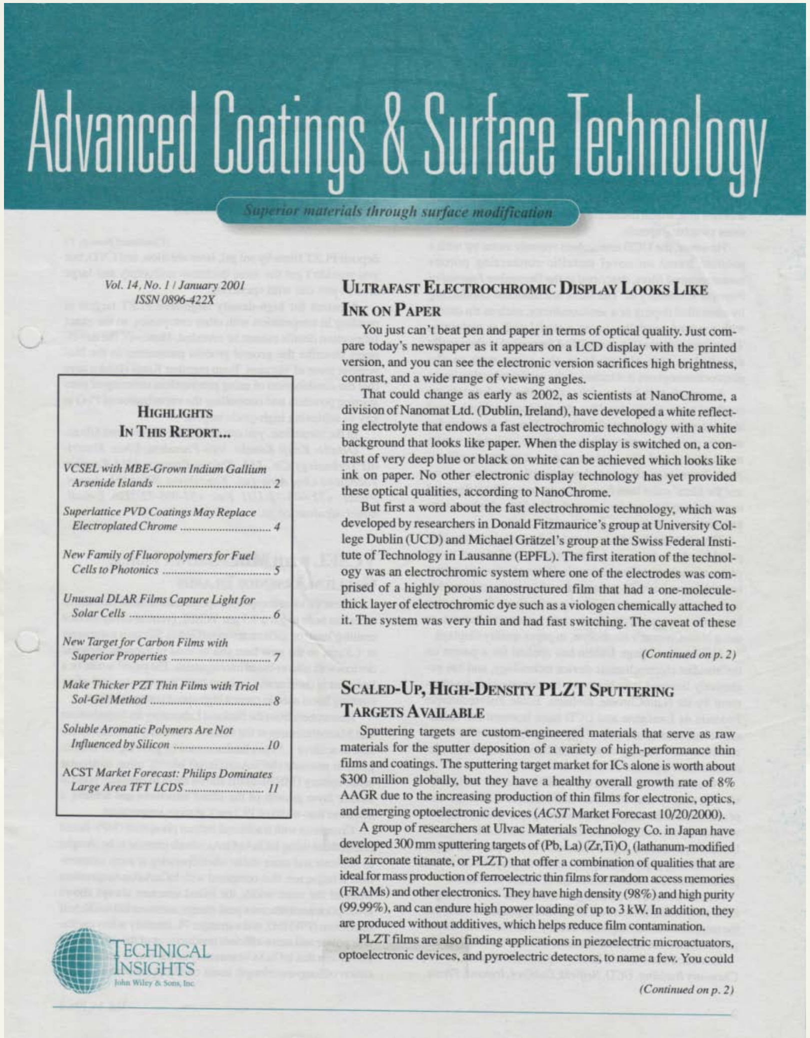


Advanced Coatings & Surface Technology
Superior materials through surface modification

Vol. 14, No. 1 / January 2001
ISSN 0896-422X

HIGHLIGHTS IN THIS REPORT...

ULTRAFAST ELECTROCHROMIC DISPLAY LOOKS LIKE INK ON PAPER

You just can't beat pen and paper in terms of optical quality. Just compare today's newspaper as it appears on a LCD display with the printed version, and you can see the electronic version sacrifices high brightness, contrast, and a wide range of viewing angles.

That could change as early as 2002, as scientists at NanoChrome, a division of Nanomat Ltd. (Dublin, Ireland), have developed a white reflecting electrolyte that endows a fast electrochromic technology with a white background that looks like paper. When the display is switched on, a contrast of very deep blue or black on white can be achieved which looks like ink on paper. No other electronic display technology has yet provided these optical qualities, according to NanoChrome.

But first a word about the fast electrochromic technology, which was developed by researchers in Donald Fitzmaurice's group at University College Dublin (UCD) and Michael Grätzel's group at the Swiss Federal Institute of Technology in Lausanne (EPFL). The first iteration of the technology was an electrochromic system where one of the electrodes was comprised of a highly porous nanostructured film that had a one-molecule-thick layer of electrochromic dye such as a viologen chemically attached to it. The system was very thin and had fast switching. The caveat of these

(Continued on p. 2)

SCALED-UP, HIGH-DENSITY PLZT SPUTTERING TARGETS AVAILABLE

Sputtering targets are custom-engineered materials that serve as raw materials for the sputter deposition of a variety of high-performance thin films and coatings. The sputtering target market for ICs alone is worth about $300 million globally, but they have a healthy overall growth rate of 8% AAGR due to the increasing production of thin films for electronic, optics, and emerging optoelectronic devices (*ACST* Market Forecast 10/20/2000).

A group of researchers at Ulvac Materials Technology Co. in Japan have developed 300 mm sputtering targets of (Pb, La) (Zr,Ti)O_3 (lathanum-modified lead zirconate titanate, or PLZT) that offer a combination of qualities that are ideal for mass production of ferroelectric thin films for random access memories (FRAMs) and other electronics. They have high density (98%) and high purity (99.99%), and can endure high power loading of up to 3 kW. In addition, they are produced without additives, which helps reduce film contamination.

PLZT films are also finding applications in piezoelectric microactuators, optoelectronic devices, and pyroelectric detectors, to name a few. You could

(Continued on p. 2)

TECHNICAL INSIGHTS
John Wiley & Sons, Inc.

ULTRAFAST ELECTROCHROMIC DISPLAY

(Continued from p. 1)

films was that only the dye could be attached to the electrode. The molecule needed to complete the electrochemical cell, known as the redox mediator, could not be effectively attached to it, which meant the films could not achieve maximum switching speeds.

However, the UCD researchers recently came up with a solution based on novel metallic conducting porous nanostructured films, described in the December *Journal of Physical Chemistry B*. The films are rendered conducting by controlled doping of a semiconductor, such as tin oxide, with a second carefully chosen material such as antimony. The redox mediator (e.g., a modified ferrocene) is chemically attached to this electrode in the same way as the electrochromophore is attached to the semiconducting layer.

As a result, both halves of the electrochemical system are confined to the electrodes. Plus, the conducting film is good at transporting charge out of the device. Since both molecules are now in direct contact with the electrode, switching can be much faster and the system shows a memory effect. NanoChrome recently reported switching times as low as 3 ms and the films' color lasts from hours to days without the need to maintain an external power supply. The films also have very low power requirements—4 mC/cm^2 for color.

The nanostructured films used in these systems are prepared by draw-down or screen printing techniques using pastes of nanocrystalline materials. Films of a few micrometers thickness have an enhanced surface area and provide high optical transparency. Consequently, the technology can be used in transparent devices such as fast smart windows, or using NanoChrome's electrolyte, in paper-quality displays.

University College Dublin has applied for a patent on the ultrafast electrochromic device technology, and has exclusively licensed it to Nanomat for commercial development by its NanoChrome division. École Polytechnique Fédérale de Lausanne and UCD have licensed the fundamental nanomaterials technology to NanoChrome for use in electrochromic display systems and NanoChrome has trademarked these systems as NanoChromics.

NanoChrome has carried out detailed materials cost analysis with display manufacturers and anticipates that the cost of manufacture for simple alphanumeric paper-quality displays will not significantly exceed that of low-cost LCD and will become equivalent at higher volumes. The company has hopes of introducing paper-quality electronic displays in 2002 and predicts a market value in the range of billion of dollars.

The entire suite of technologies is available for licensing to third-party manufacturers on terms and application areas that the manufacturer can negotiate directly with Nanomat. Strategic collaborations and joint ventures will also be considered.

Details: John Cashell, Managing Director, NanoChrome, Chemistry Building, UCD, Belfield, Dublin 4, Ireland. Phone: +353-1-706-7896. E-mail: nanochromics@nanomat.ie. URL: www.nanochrome.com; a-u.ac.jp/okuyamalab.

PLZT SPUTTERING TARGETS

(Continued from p. 1)

deposit PLZT films by sol gel, laser ablation, and CVD, but you wouldn't get the same thickness uniformity and large area as you can with sputtering.

A patent for high-density large-area PLZT targets is pending in cooperation with other companies, so the exact fabrication details cannot be revealed. However, the developers describe the general process parameters in the November issue of *Vacuum*. Team member Kouji Hidaka says that the combination of using pressureless sintering of pure starting powders and controlling the vaporization of PbO is key to achieving high-grade targets.

In the meantime, you can obtain the targets from Ulvac.

Details: Kouji Kaneko, Vice President, Ulvac Materials Technology Co., Ltd., Kyusyu Factory, 3313 Kamino, Yokogawa-cho, Aira-gun, Kagoshima 899-6301, Japan. Phone: +81-995-72-1111. Fax: +81-995-72-1126. E-mail: kaneko@ulvac.co.jp.

VCSEL WITH MBE-GROWN INDIUM GALLIUM ARSENIDE ISLANDS

One of the more competitive optical communications research races has been to get a 1.3 µm VCSEL (vertical cavity surface emitting laser) on gallium arsenide (GaAs). Silicon is transparent at 1.3 µm, so the new laser can be used to integrate photonic devices with silicon-based microsystems. The payoff would be a laser that is cheaper and easier to build than the standard edge-emitting lasers used in current high-speed communications.

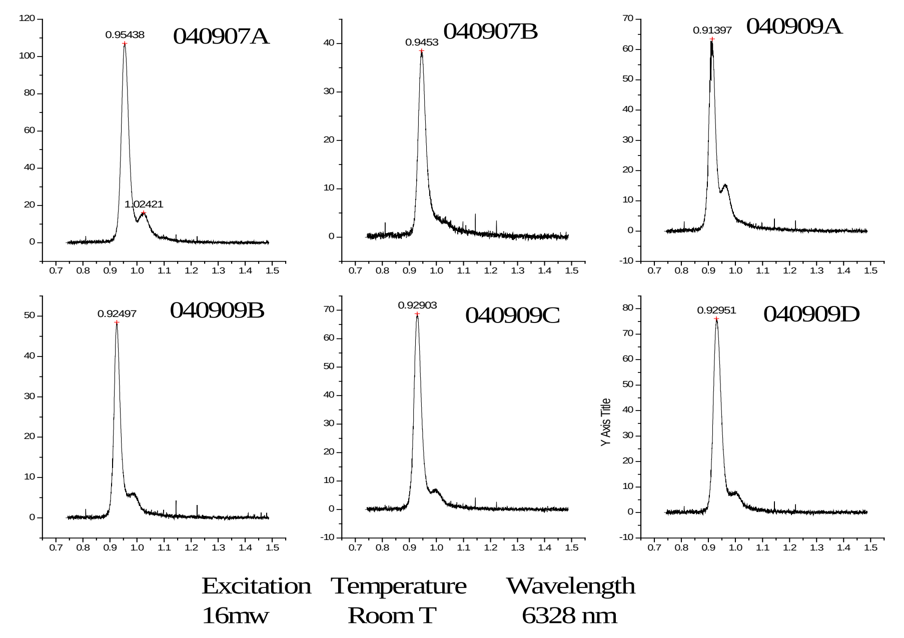
Researchers from the National Laboratory for Superlattices and Microstructures at the Chinese Academy of Sciences are able to achieve 1.35 µm luminescence by growing 3D indium gallium arsenide (InGaAs)/(GaAs) islands using molecular beam epitaxy (MBE). MBE allows them to carefully control atomic layer growth of the island structures and achieve a narrower line-width of 19.2 meV at room temperature.

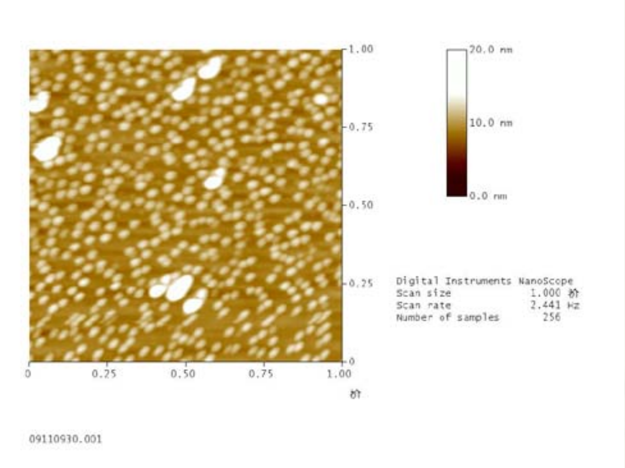
Compared with traditional indium phosphide (InP)- based lasers, those using InGaAs/GaAs islands promise to be cheaper to fabricate and more stable when operating at room temperature. It helps, too, that compared with InGaAs/GaAs quantum wells of the same width, the island structure always shows lower photoluminescence peak energy, narrower full-width half maximum (FWHM), and a stronger PL intensity at low excitation power and more efficient confinement of the carriers. All this means that InGaAs islands may be the way to go for fabrication of long-wavelength lasers on GaAs substrates.

设计InGaAs/InAs/InGaAs结构
解决1.3微米高密度量子点技术

QD 面密度 4.1E+10/cm2

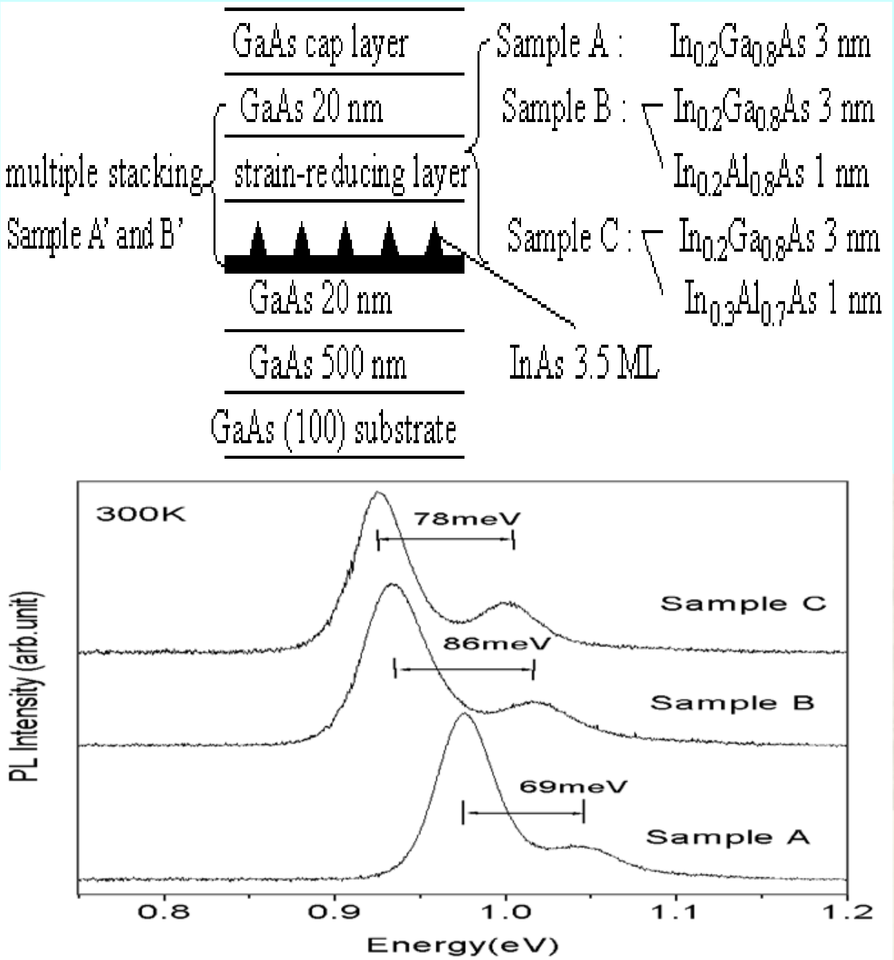
室温发光效率高、生长重复性好



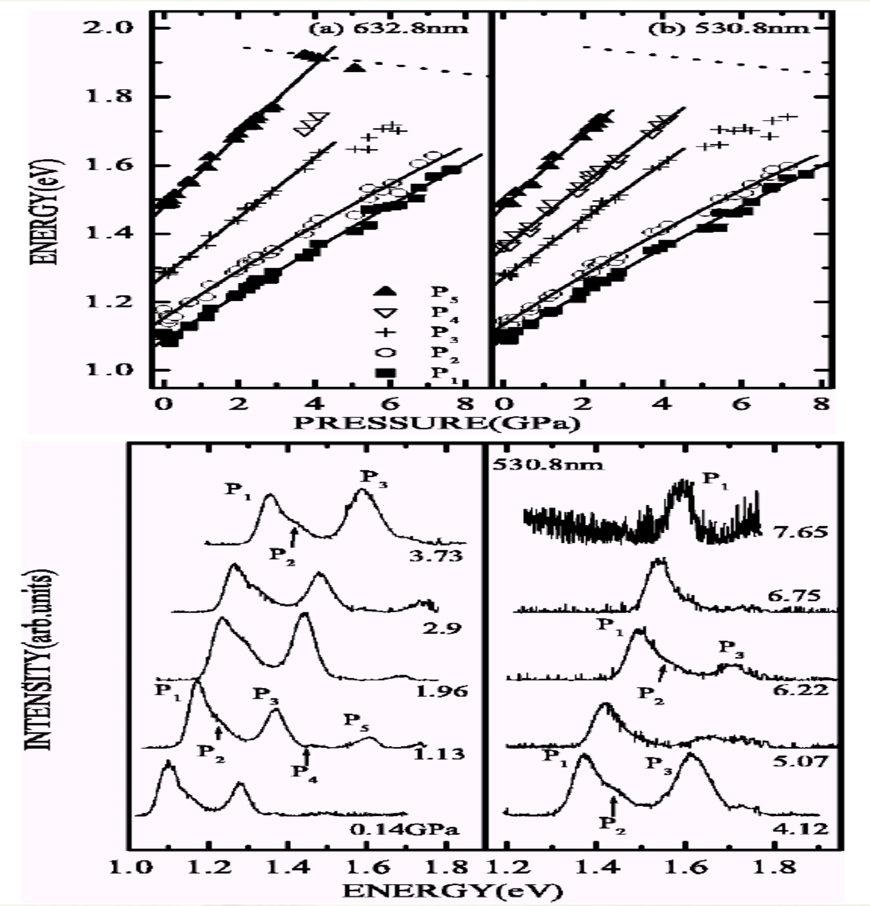


GaAs	Cap
InGaAs	QW
InAs	QD
GaAs	Buffer

1.3微米InAs量子点压力光谱：量子点压力系数

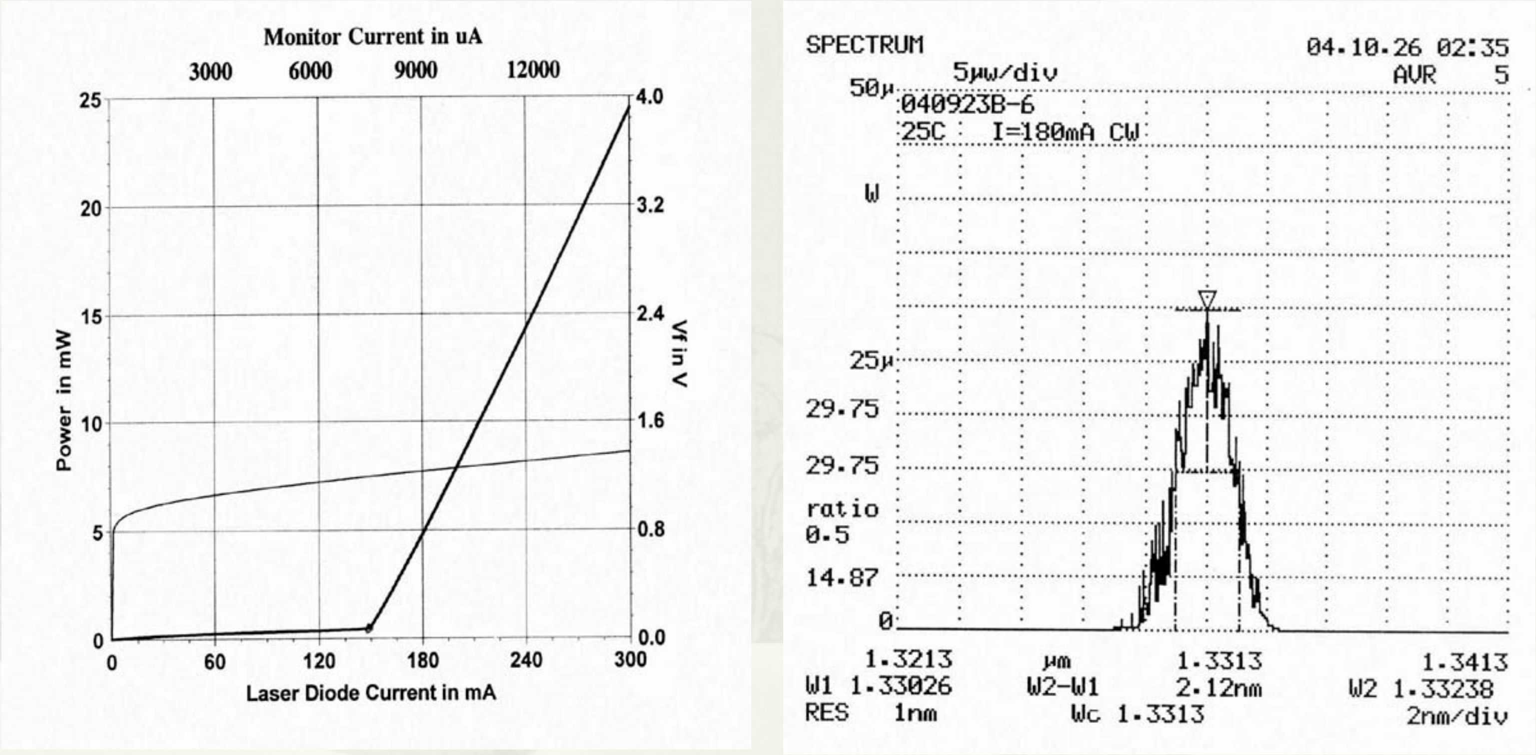


J. Phys.Conden. Mat. 15, 5383(2003)



J. Appl. Phys. 95, 933(2004)

GaAs基1.3微米量子点边发射激光器



室温基态激射1.33 微米，阈值电流密度:50Acm^{-2}/量子点层

1.3微米激光器研究工作受到权威刊物III-Vs评价

Optoelectronic News

- 22 November 2004 -

China's work on the GaAs gauntlet

A research group headed by Prof. Niu Zhichuan from the State Key Laboratory for Semiconductor Superlattice & Microstructures affiliated to the CAS Institute of Semiconductors has succeeded in developing a GaAs-based long-wavelength laser device: InAs/GaAs self-assembly quantum dot laser with lasing wavelength of 1.33μm under continuous-wave operation mode at room temperature.

Experts say this is the most important achievement in the field of GaAs-based near-infrared, long-wavelength materials and devices in China in recent years.

The most important kinds of GaAs-based semiconductor materials working for near-infrared wavelength from 1.2 to 1.7μm are in the form of InAs self-assembled quantum dots, GaInNAs and GaInNAsSb quantum wells.

The QD structures attract scientists as they excel in a high-speed operation with lower power consumption and new functions. The QWs are new multi-element compounds noted for their temperature stability. In recent years, these new semiconductor materials became a research focus in the most developed Western countries.

Since the end of the 1990s, a special research group headed by Prof. Niu at the CAS Institute of Semiconductors was funded for their work in the field. In order to speed up the research tempo, the team is composed of researchers from various fields ranging from material growth, physics analysis to device technology.

The first step for researchers in their success was the breakthrough attained before 2000 in the technology of MBE of the InAs-bsed quantum dots lasers for the 0.9-1.1 μm wavelengths.

By 2002, in the second stage, they succeeded in acquiring the 1.3μm QDs with high uniformity and high photoluminescence efficiency at room temperature.
The newest development over the last two years includes the solution of a knotty problem in the growth of such QDs with long wavelength and high-density over 4.0E+10/cm2, and the fabrication technology of InAs/GaAs QD lasers under continuous-wave operation mode

http://www.three-fives.com/optoelectronic_news/november04_opto_news/221104China_work_on_the_GaAs_gauntlet.htm 2005-10-15

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Chinese team produces quantum dot laser

23 November 2004

A team at the State Key Laboratory in China has fabricated a 1330 nm GaAs-based quantum dot laser that's capable of continuous-wave operation at room temperature.

Researchers at the State Key Laboratory for Semiconductor Superlattice and Microstructures have fabricated a long-wavelength GaAs-based quantum dot laser, according to a report from the Chinese Academy of Sciences.

The 1.33 μm laser, containing InAs quantum dots formed by a self-assembly process on a GaAs substrate, can operate in continuous-wave mode at room temperature.

Experts have touted the success of these quantum dot lasers, which are claimed to offer faster switching and lower power consumption than InP-based alternatives, as China's most important recent achievement in the field of GaAs-based long-wavelength devices.

The team's first significant breakthrough came over four years ago, when they fabricated MBE-grown InAs-based quantum dot lasers emitting in the 0.9-1.1 μm region.

By 2002 emission had been extended to 1.3 μm, and since then efforts have focused on increasing the emission wavelength to 1.35 μm, and achieving a quantum dot density of 4×10^{10} cm^{-2}.

The researchers are now improving the quantum-dot laser to a level that is suitable for practical applications. In addition, the team is investigating alternative materials systems, including GaInAs/GaAsSb lasers. These devices currently emit at 1.31 μm, but it is thought that this material system will allow emission wavelengths to be extended to 1.55 μm.

1. 3微米激光器研究工作受到英国IoP:
Institute of Physics，UK
专栏评价
（8/11/2004）

超晶格实验室的研究组研制成功1330nmGaAs基量子点激光器，它可以在室温下以连续激射模式工作

InAs量子点激光器研究发展

目前**1.3**微米量子点激光器研制技术已经成熟，器件性能：阈值电流、温度特性等优越性突出。

德国、日本、美国等几家公司在商品化器件研究方面走在前面。正在大力推广应用。

同时，基于**InAs**量子点的固态量子信息物理和器件研究处于热潮阶段！

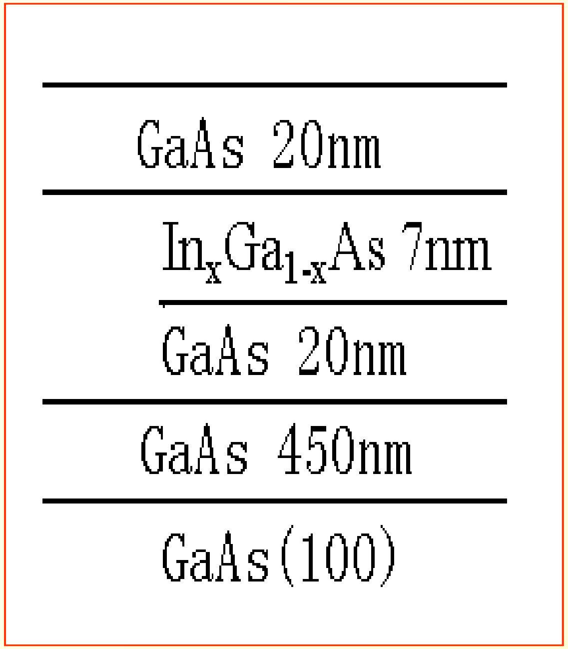
2、 InGaAs(NSb)量子阱材料与器件

晶格匹配InGaAs量子阱上限波长是1.2微米左右，如何拓展其发光波长至1.3-1.5微米？

采用量子点可以获得1.3微米发光，
引入N、Sb元素？或者异变结构？

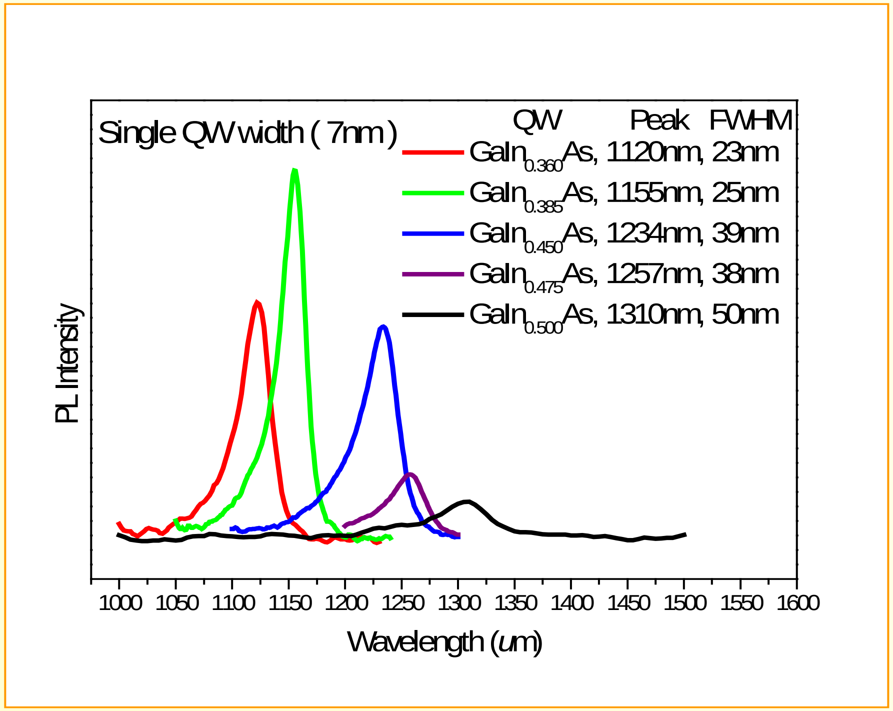
GaInNAsSb/GaNAs/GaAs量子阱

1、突破应变InGaAs/GaAs量子阱发光波长上限：1.26微米



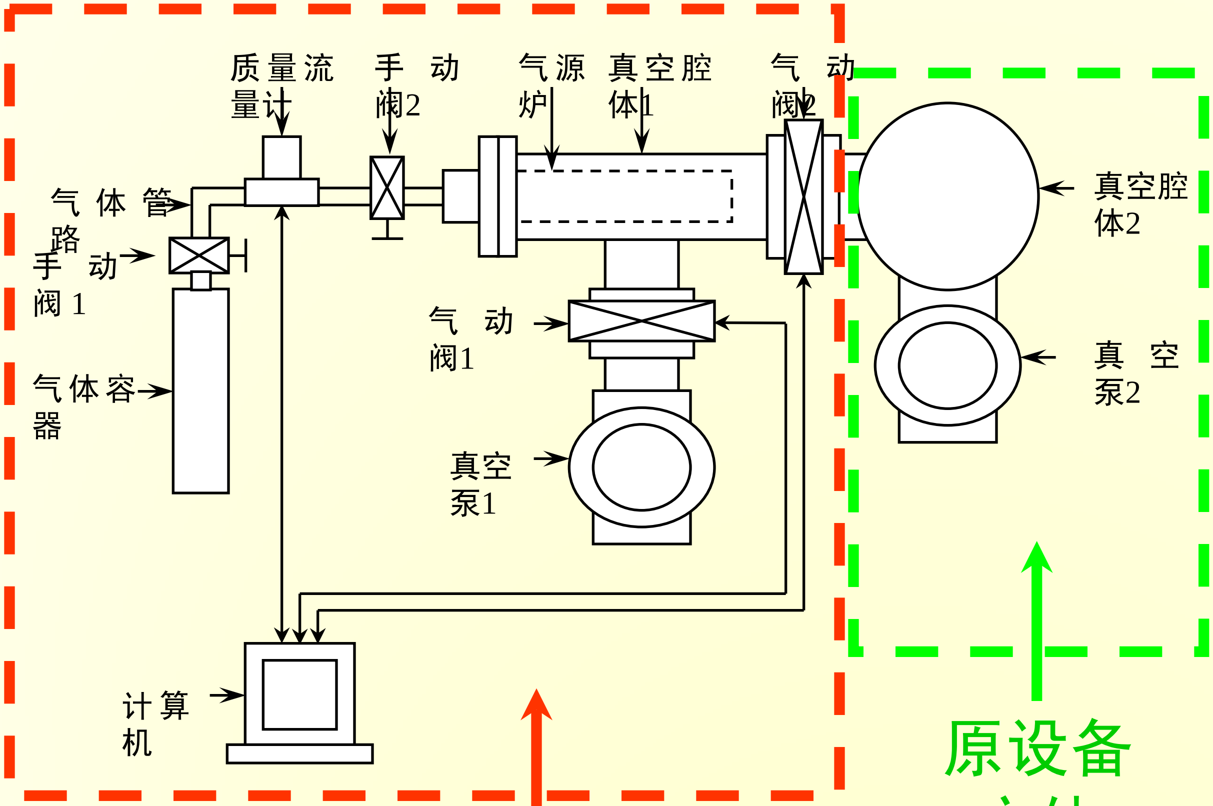
室温

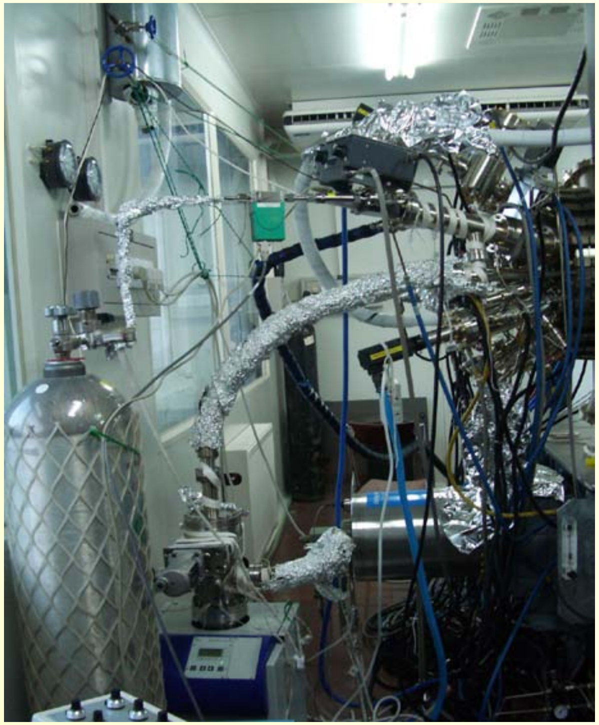
光荧光谱



专利：200310119746.6；2004 MBE国际会议 Late News 大会报告；Appl.Phys.Lett,84,5100(2004)。

发明“气态源瞬态控制装置”，解决了N控制难题！为含N、O、H等的化合物材料外延生长提供了普适解决方案





原设备主体

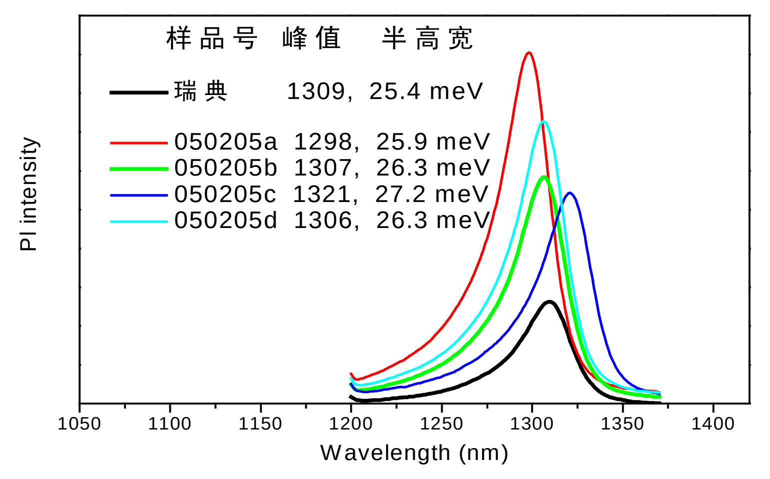
发明装置

1.3微米GaInAsN量子阱晶体质量、发光效率大幅度提高

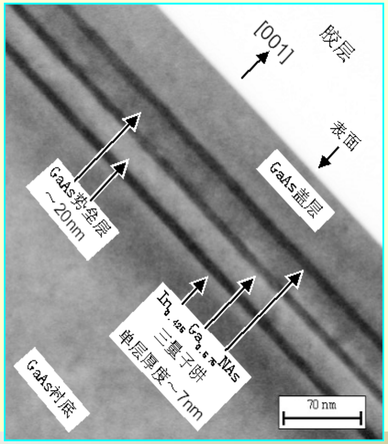
GaInNAs/GaAs量子阱室温光荧光谱对比:

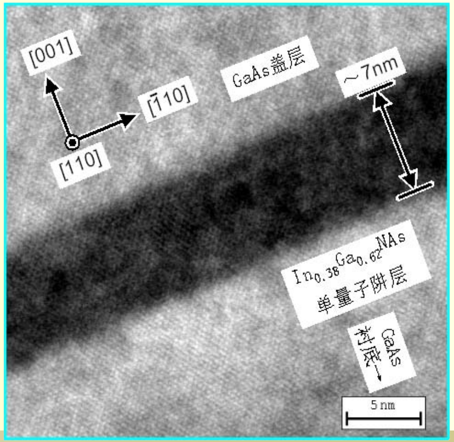
黑色谱线来自:
Photonics Lab.,
Chalmers University of Technology, SWEDEN

其余为本课题样品!



TEM验证GaInNAs量子阱晶体质量





APPL. PHYS. LETT. 87, 161911(2005)

大In组分GaInNAs量子阱N的应变补偿作用

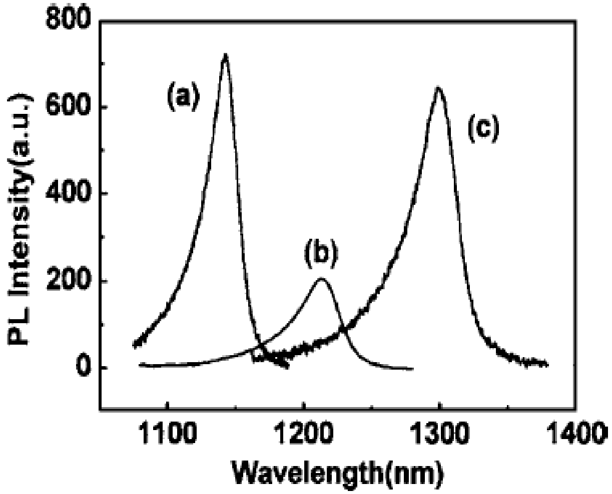


FIG. 3. RT-PL spectra of the GaIn(N)As/GaAs 3QWs at excitation power of 15 mW. (a) $In_{0.36}Ga_{0.64}As$ 7 nm/GaAs, (b) $In_{0.425}Ga_{0.575}As$ 7 nm/GaAs, and (c) $Ga_{0.575}In_{0.425}N_{0.01}As_{0.99}$ 6 nm/GaAs.

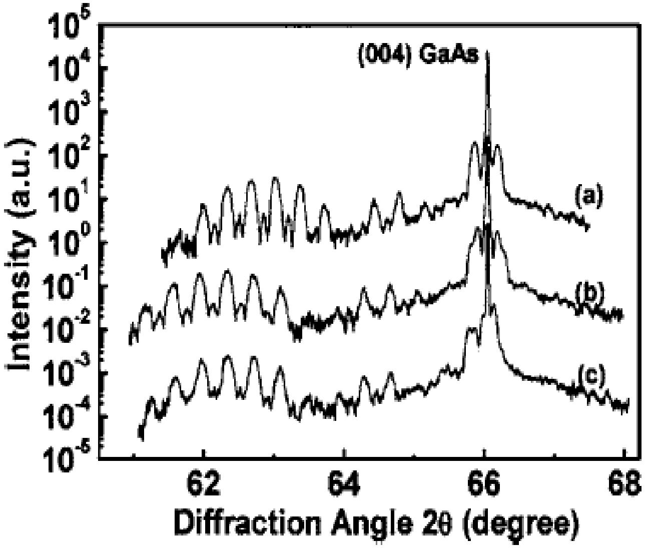


FIG. 2. Measured (004) x-ray rocking curves of the GaIn(N)As/GaAs 3QWs: (a) $In_{0.36}Ga_{0.64}As$ 7 nm/GaAs, (b) $Ga_{0.575}In_{0.425}N_{0.01}As_{0.99}$

为优化In、N配比，大幅度提高发光效率提供最新参考

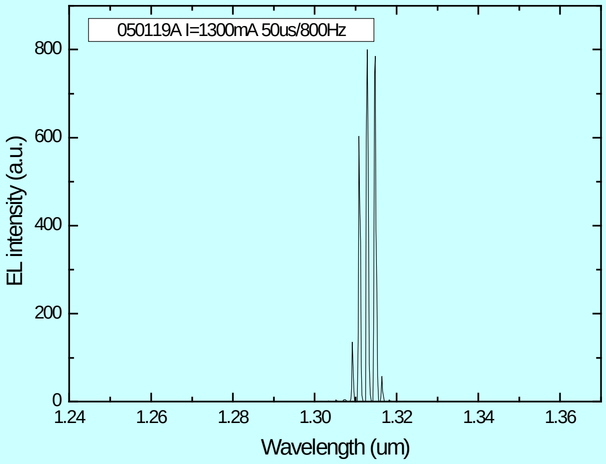
APPL. PHYS. LETT. 87, 161911(2005)

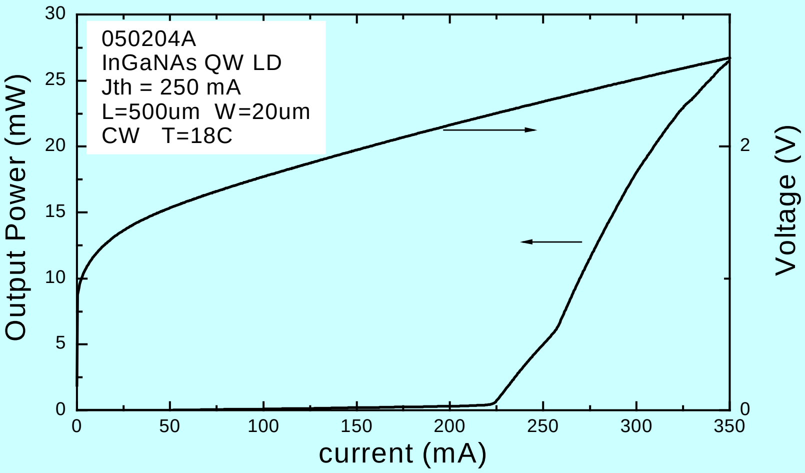
Phys. Sta. Sol.，3, 631 (2006)

研制成功 1.31微米GaInAsN 量子阱 边发射激光器实现室温连续激射

单量子阱、脊形波导条形
室温连续（CW）激射
阈值电流：250 mA

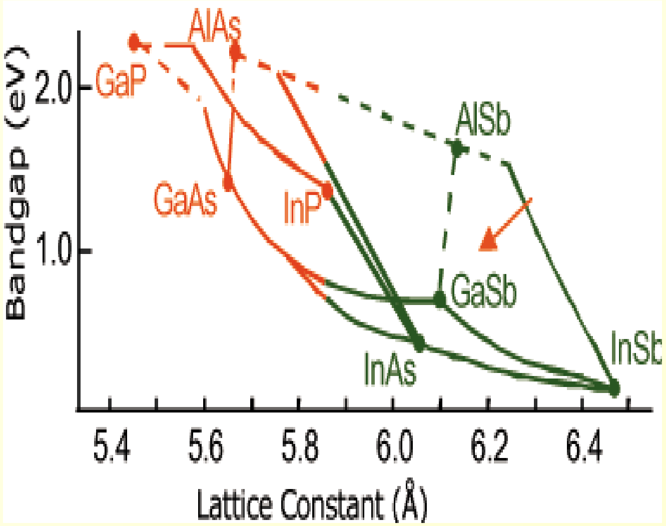
器件性能达到国
际较高水平！





拓展GaInNAs材料至1.55微米波段难度最大！

新方法－引入Sb元素



1、减小带隙

2、表面催化

→ 提高表面平整度

→ 提高 In 含量

→ 提高界面质量

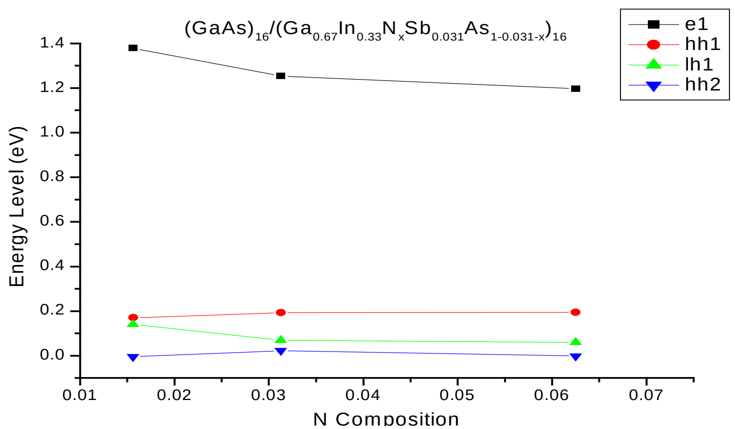
1、导带底电子态主要在N原子周围聚集，N原子减小光跃迁强度。

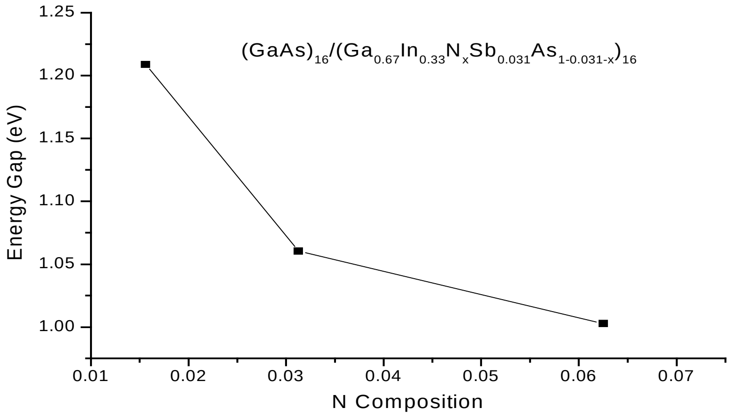
2、Sb原子也可以减小带隙，而对电子和空穴态约束不明显。

3、平行于超晶格平面的电子有效质量和GaAs相当，而垂直于超晶格平面的电子有效质量却非常小，利于高速光电子器件。

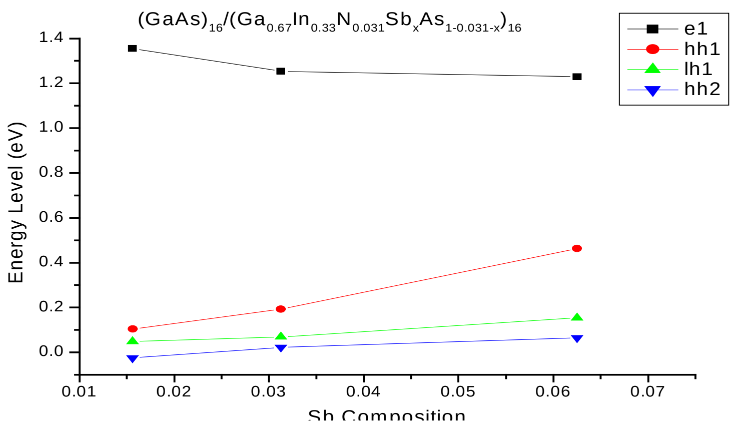
计算GaInAs(NSb)/GaAs超晶格能带结构参数

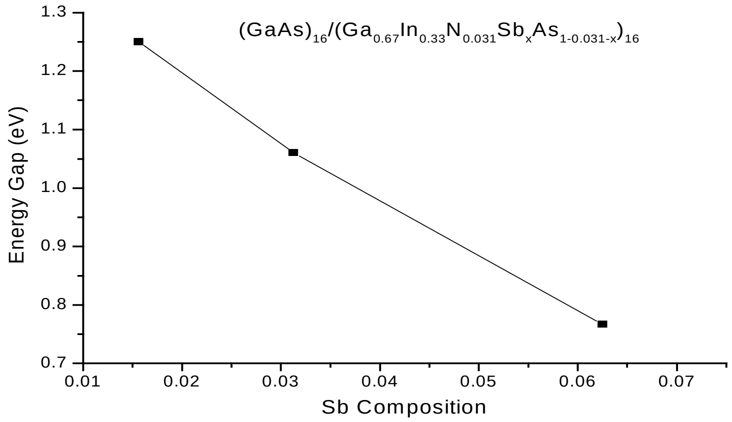
不同N含量 GaAs/GaInNSbAs 超晶格能级结构、带宽



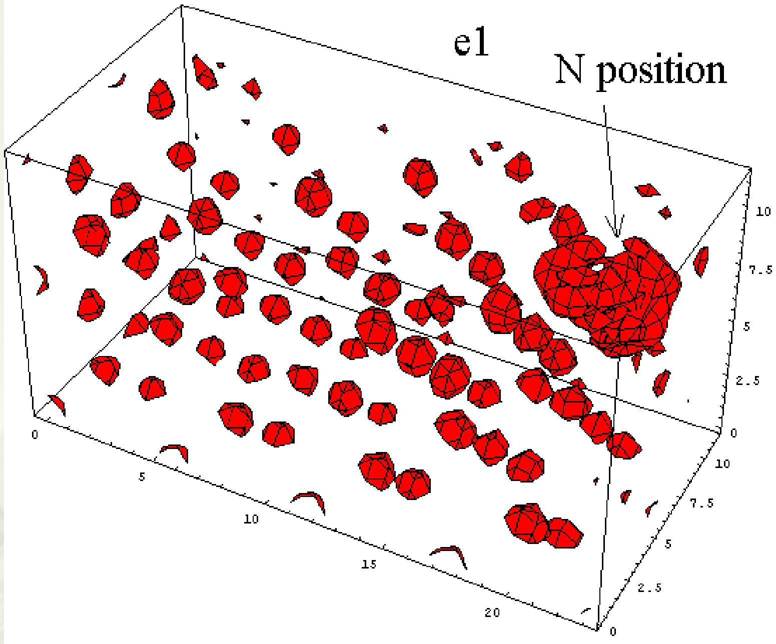


不同Sb含量的GaAs/GaInNSbAs 超晶格能级结构、带宽

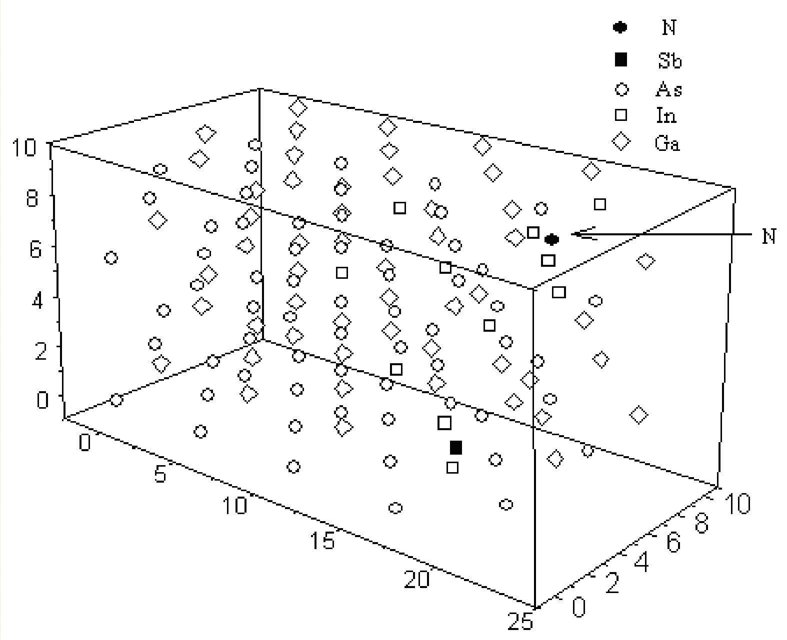




计算得到的$(GaAs)_4/(Ga_{0.67}In_{0.33}N_{0.031}Sb_{0.031}As_{0.938})_4$超晶格的电子态密度的等值面分布图，发现N原子周围电子局域化。



Isosurface plots of the charge densities of e1 state



Relaxed atomic position of the superlattices

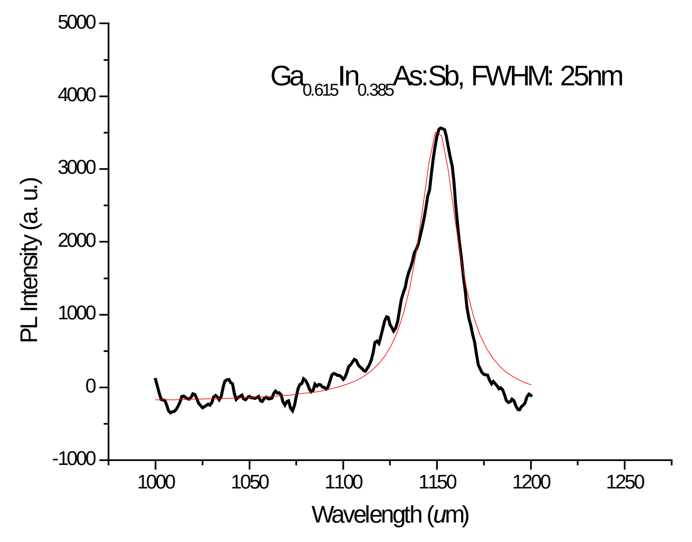
Phys. Rev. B, 68, 235326, 2003

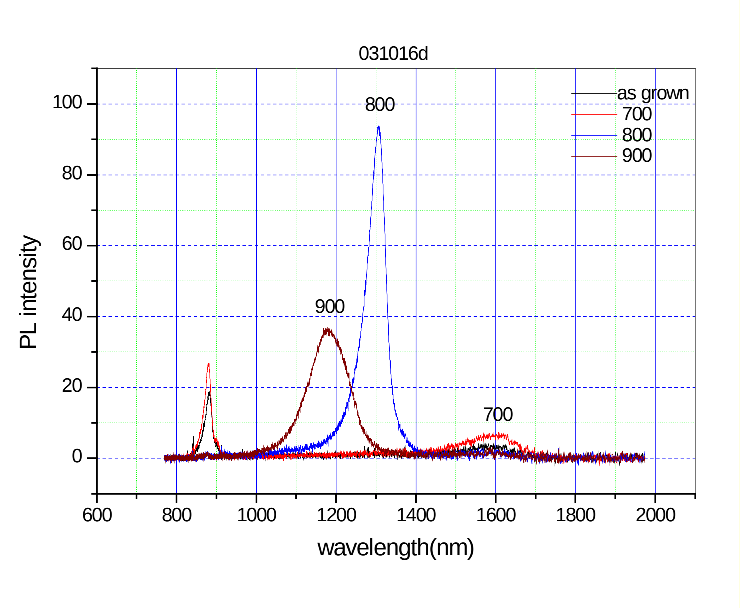
实验证明Sb可以有效提高长波长量子阱发光性能

Sb表面活化剂，有效提高
GaInAs量子阱发光性能

GaInAs:Sb/GaAs 3 QWs PL谱 FWHM 25 nm

退火进一步增加
GaInNAsSb量子阱发光强度、减小半高宽

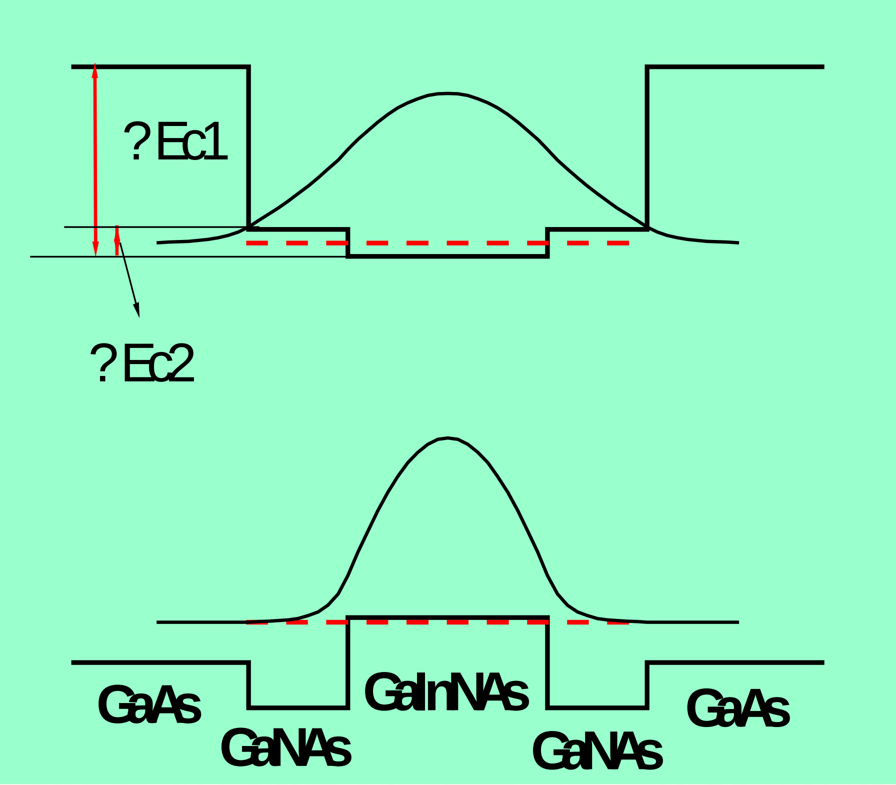




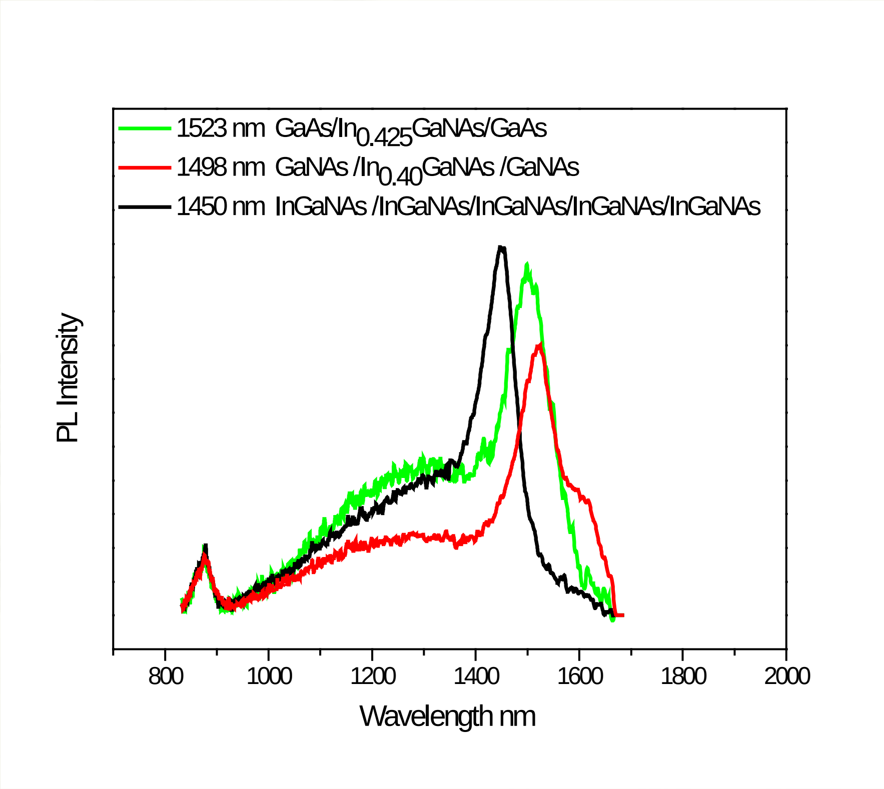
J. Appl. Phys. 99, 034903 (2006).

优化GaInNAsSb/GaNAs/GaAs 梯度势垒结构
－室温发光波长大幅度拓展至1.55 微米

结构设计

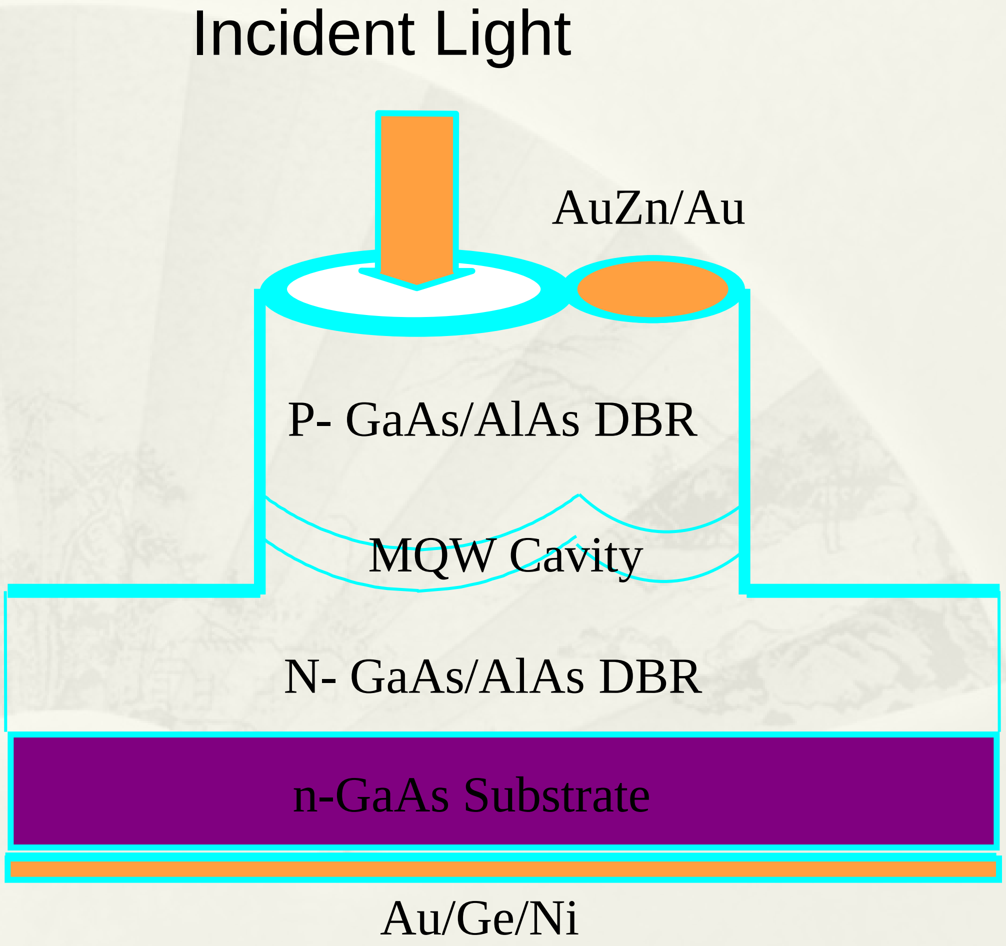


实验结果



1.55微米RCE谐振腔增强探测器

(8~16) X	GaAs	p	953 Å
	AlAs	p	1115 Å
	GaAs	i	1398 Å
3 X	GaAs	i	200 Å
	GaInNAs	i	70 Å
	GaAs	i	1598 Å
22 X	AlAs	n	1115 Å
	GaAs	n	953 Å
	AlAs	n	1115 Å
	GaAs buffer	n	5000 Å
	GaAs Substrate	n^+	



MQW

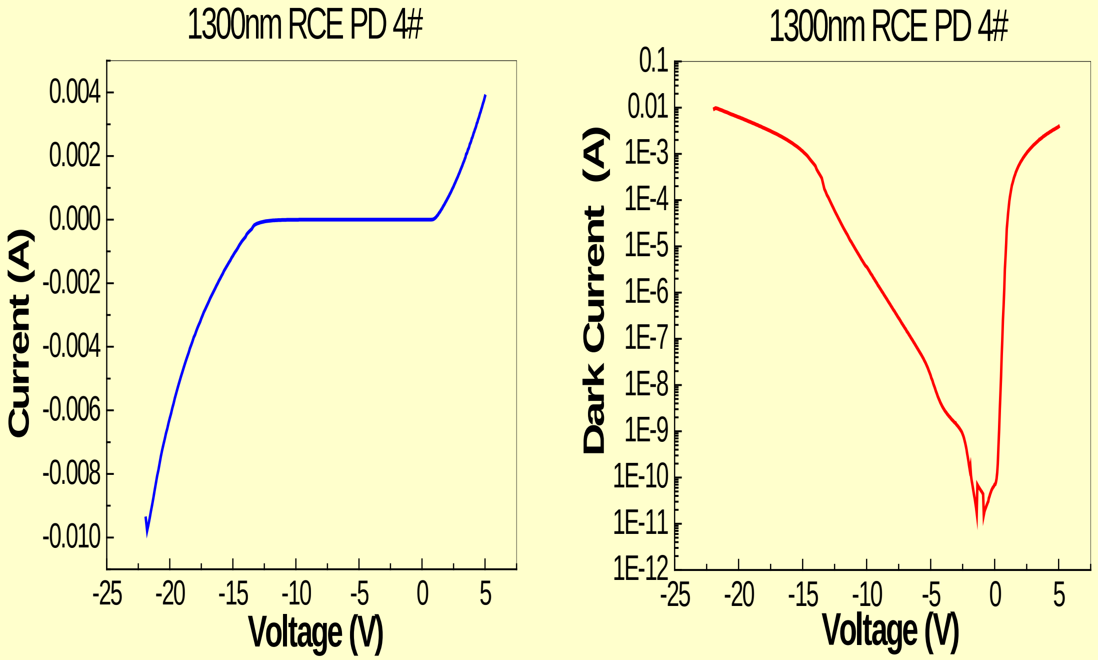
AlGaAs/GaAs： 850nm

GaInAs/GaAs： 980nm

GaInAs/GaAs： 1060nm

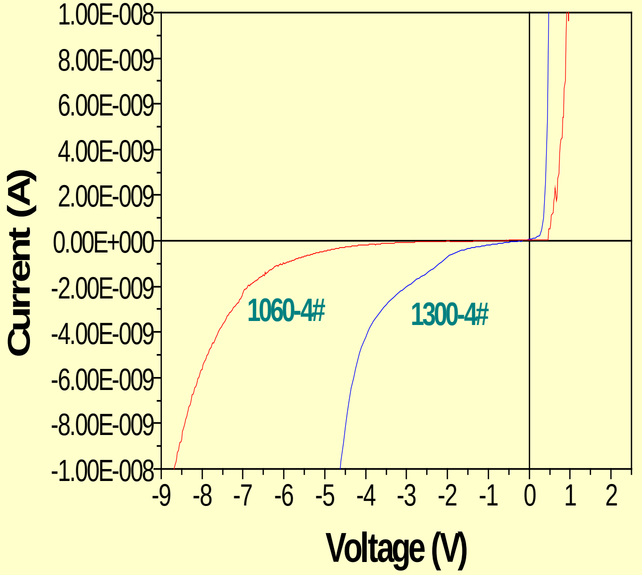
GaInNAs/GaAs： 1310nm

大偏压下RCE探测器的I-V特性

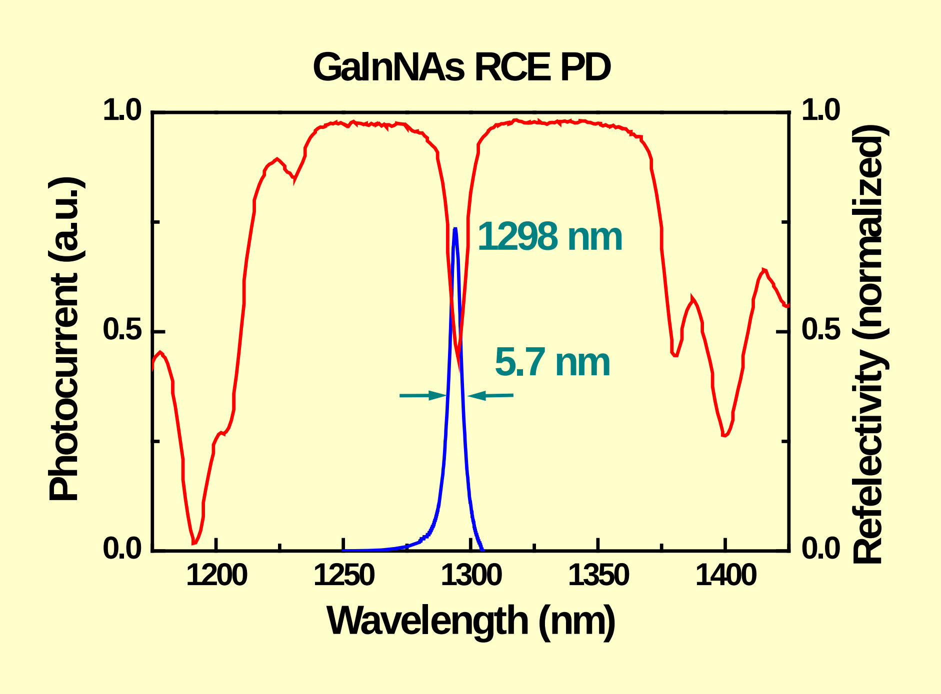


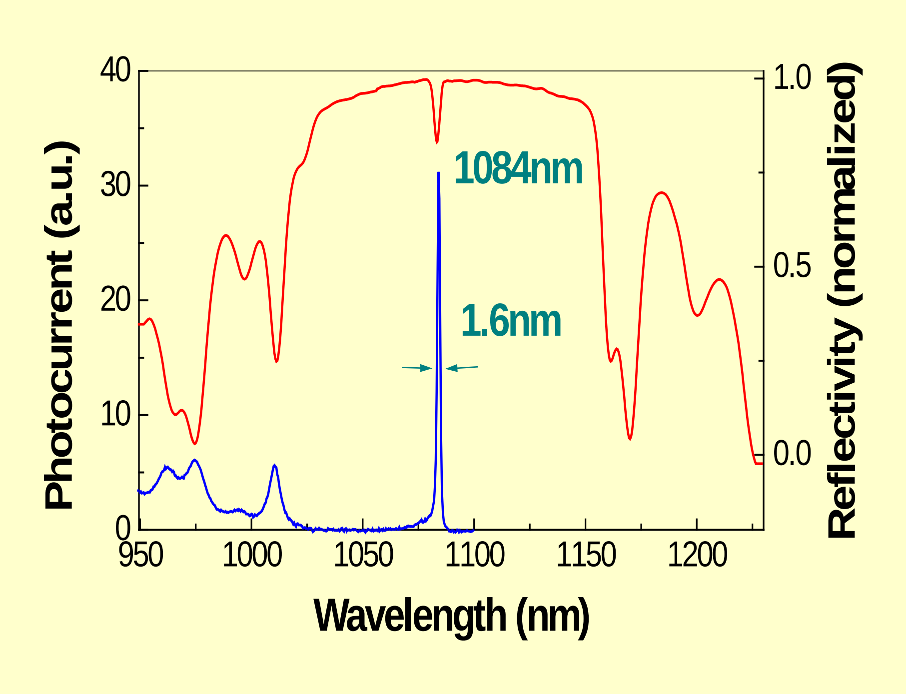
RCE器件有源层很薄，有着很小的暗电流、利于提高器件灵敏度。

RCE探测器的暗电流



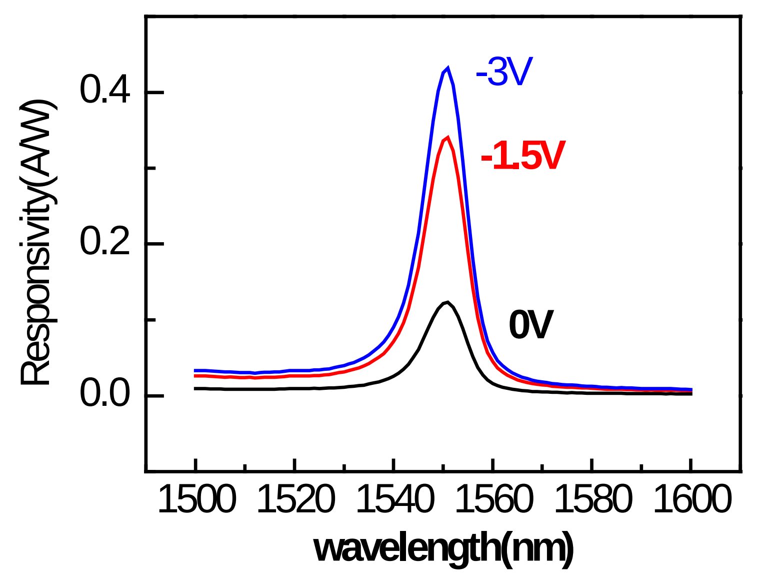
谐振腔增强探测器





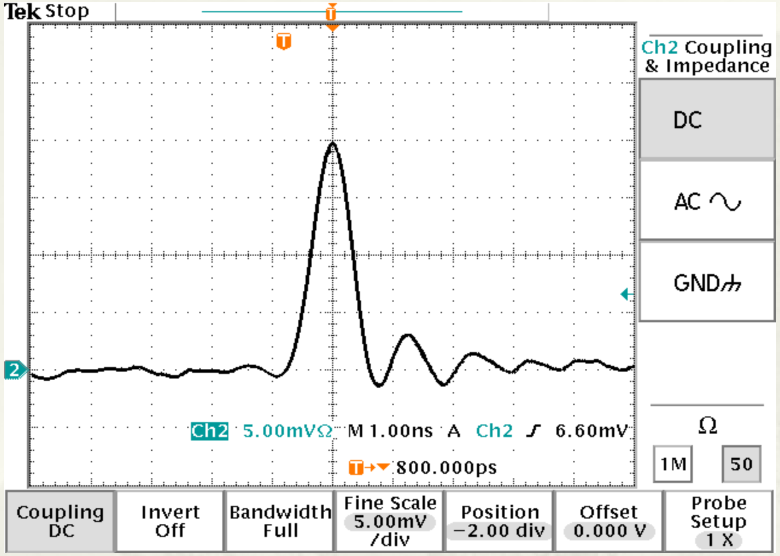
- 上下DBR的滤波作用使得器件只有在模式位置有强烈的吸收，高反带内的其他波长的光被全反射。模式位置是由器件的腔长来决定的，不同腔长的器件有着不同的响应波长。这是RCE器件的一大特色。

1.55微米高性能GaInAsN量子阱RCE探测器



Appl. Phys. Lett. 87，111105(2005)

1.55微米RCE-PD特性参数是目前最好结果



Ch2 5.00mVΩ M 1.00ns A Ch2 ∫ 6.60mV

800.000ps

Coupling DC

Invert Off

Bandwidth Full

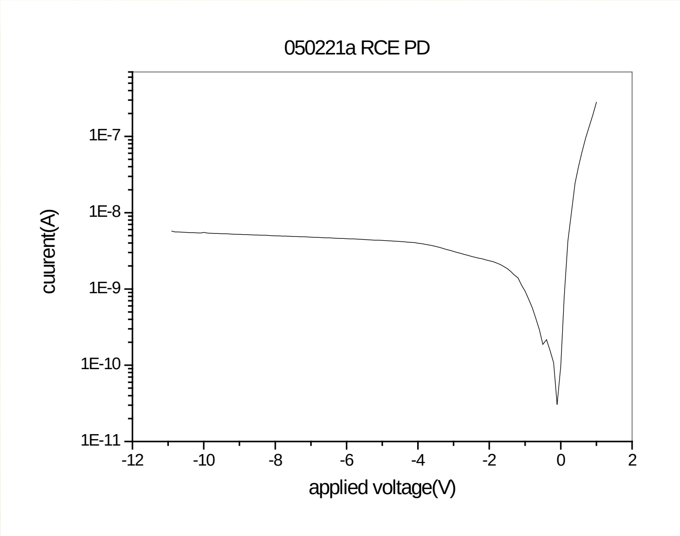
Fine Scale 5.00mV /div

Position −2.00 div

Offset 0.000 V

Probe Setup 1 X

RCE探测器响应时间

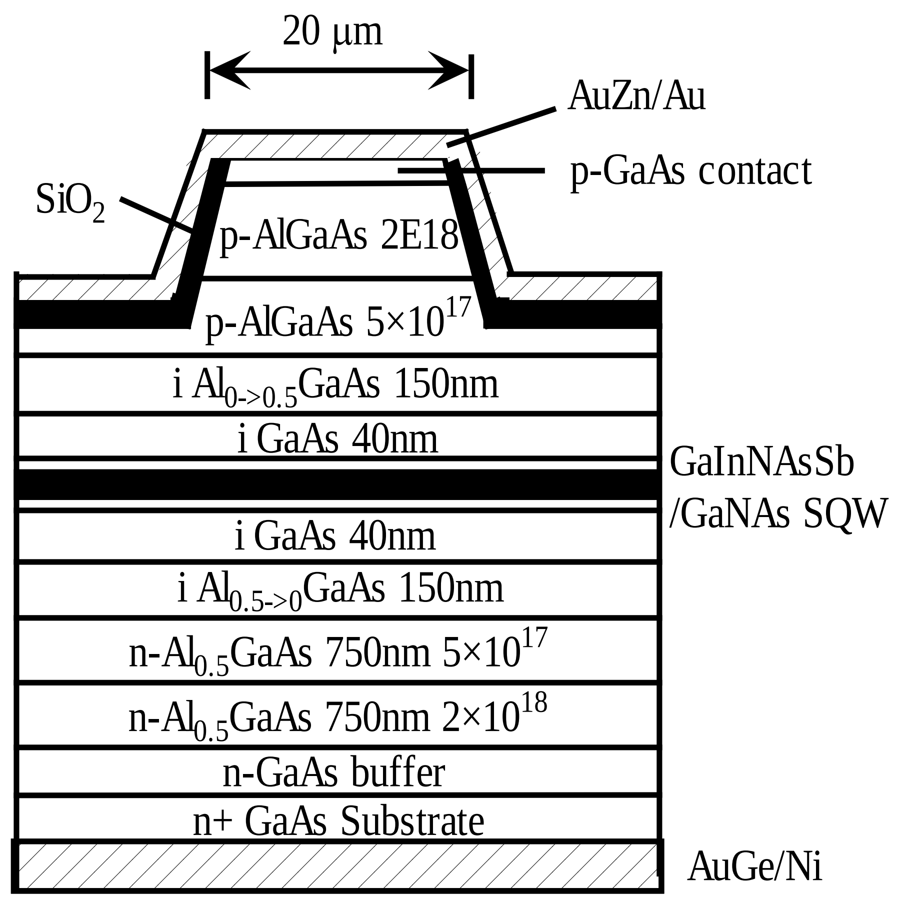


RCE探测器光电流响应谱

不同探测波长：1550,1300,1064,980 nm 基本光电参数：量子效率: 30 - 50%；选定波长: $\lambda_{0,}\Delta\lambda_{1/2}$（FWHM）≈1.6 -10nm；暗电流密度: ≈10^{-14}A/μm^2（零偏置）；响应时间: <ns量级（零偏置,大受光面）。

1.5微米边发射激光器

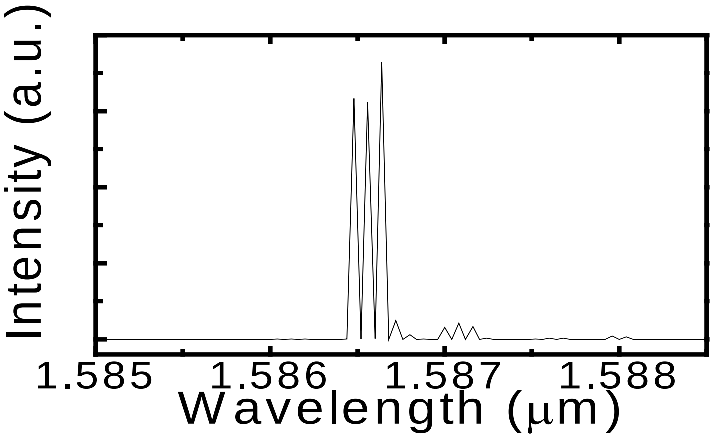
优化设计GaInAsNSb/GaNAs/GaAs
梯度单量子阱边发射激光器

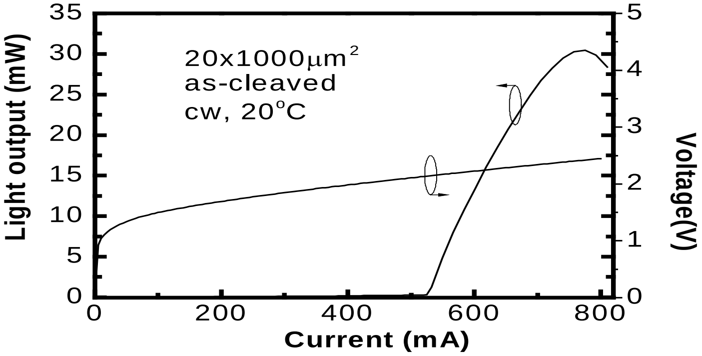


←

势垒GaNAs变温生长技术，大幅度改善界面质量

实现室温连续激射激光器





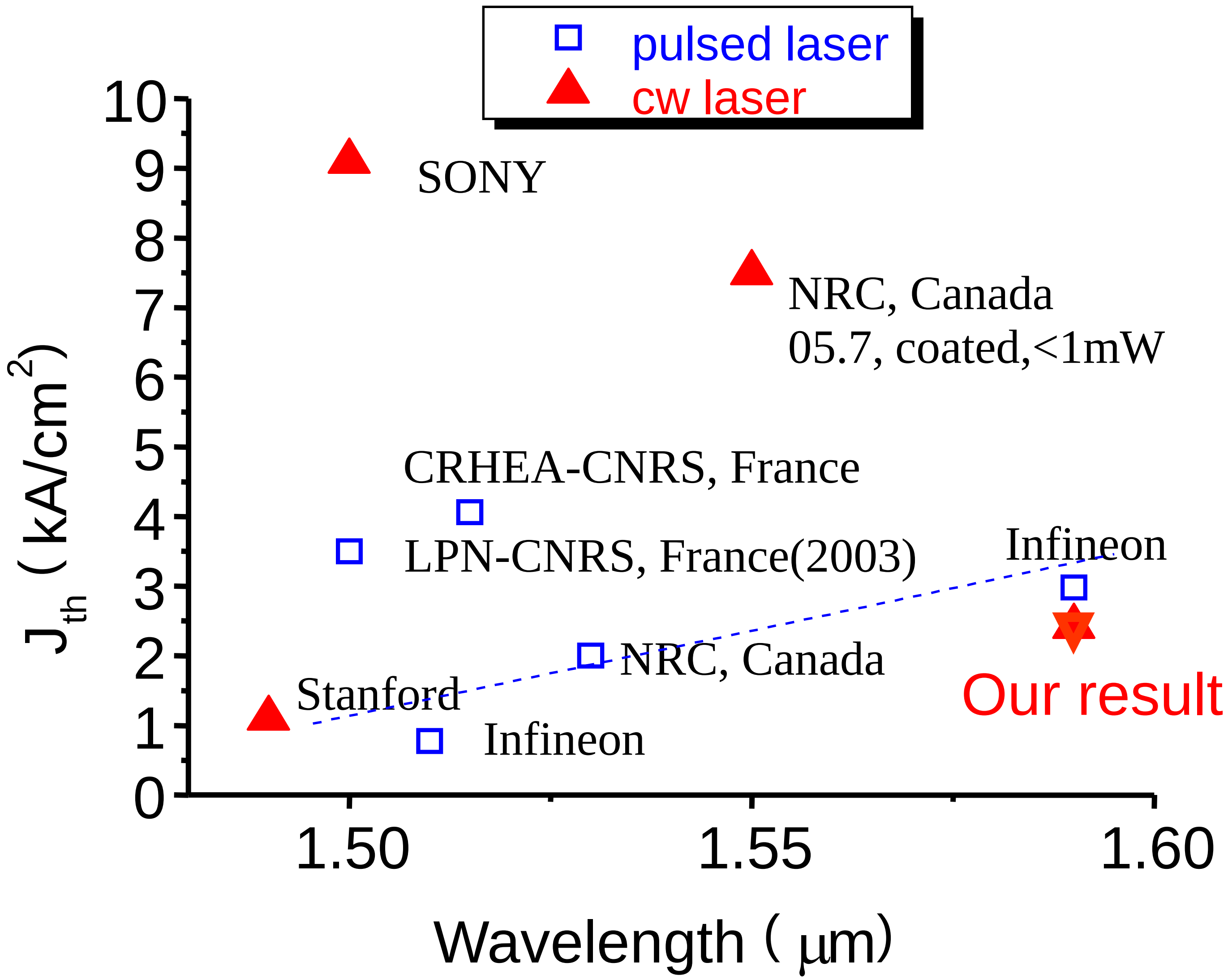
激射波长：1.59微米

阈值电流：2.6 kA/cm2

脊形结构：20 X 1000 um^2

FP谐振腔：端面自然解理

各研究小组在1.55微米波段LD器件结果对比



GaAs基1.59微米激光器受到关注和好评

A New GaAs-Based Long Wavelength Laser Diode Developed by CAS Scientists　　页码，1/18

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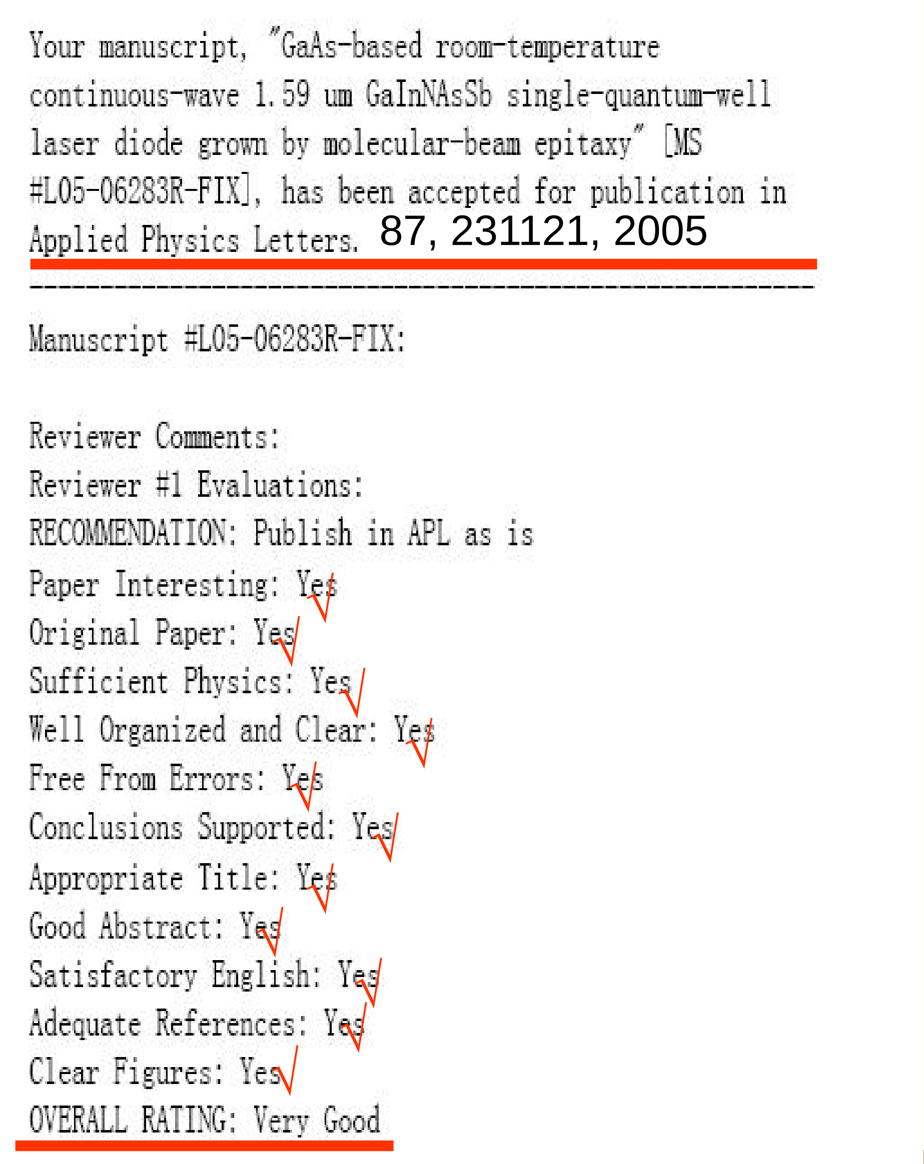
- Mitsui Chemicals to Launch Liquid EPDM
- Mittal Steel Company Acquires a 93% Stake in Kryvorizhstal in Ukraine

A New GaAs-Based Long Wavelength Laser Diode Developed by CAS Scientists

Researchers at the CAS Institute of Semiconductors (ISCAS) have made significant progress in their work on a new generation of the GaAs based long-wavelength laser device. Recently they have developed the world's first 1.586μm GaInNAsSb/GaNAs/GaAs single quantum well laser

http://www.azom.com/details.asp?newsID 4140　　2005-10-25



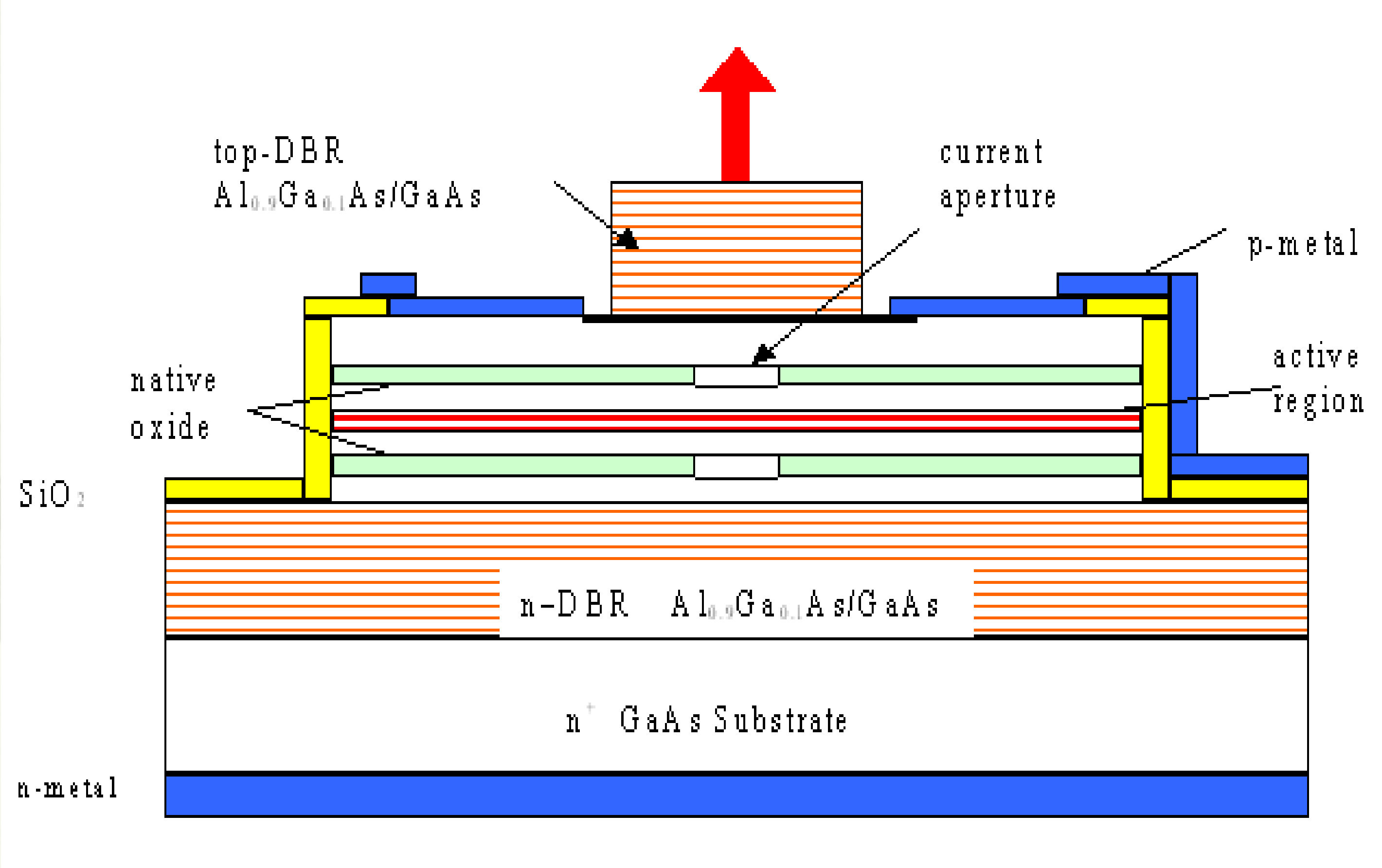
Your manuscript, "GaAs-based room-temperature continuous-wave 1.59 um GaInNAsSb single-quantum-well laser diode grown by molecular-beam epitaxy" [MS #L05-06283R-FIX], has been accepted for publication in Applied Physics Letters. 87, 231121, 2005

Manuscript #L05-06283R-FIX:

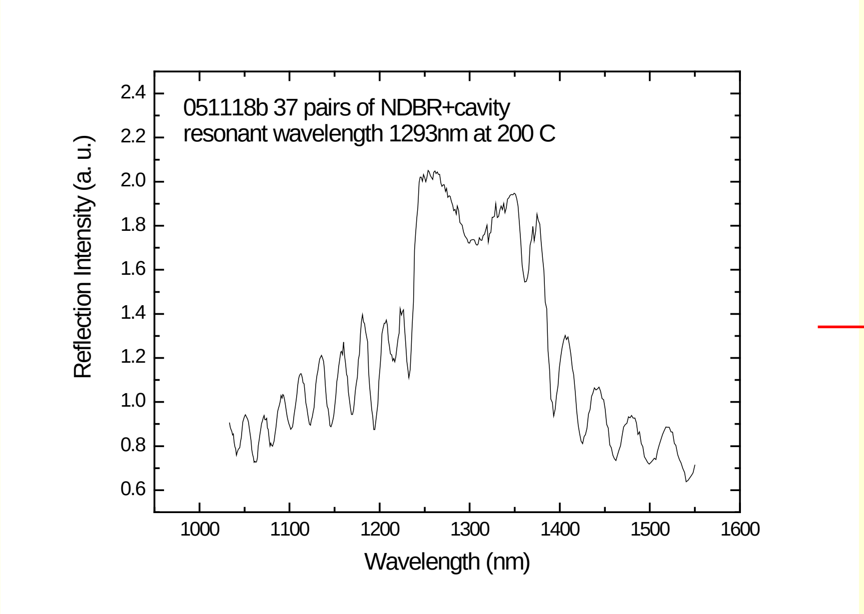
Reviewer Comments:
Reviewer #1 Evaluations:
RECOMMENDATION: Publish in APL as is
Paper Interesting: Yes √
Original Paper: Yes √
Sufficient Physics: Yes √
Well Organized and Clear: Yes √
Free From Errors: Yes √
Conclusions Supported: Yes √
Appropriate Title: Yes √
Good Abstract: Yes √
Satisfactory English: Yes √
Adequate References: Yes √
Clear Figures: Yes √
OVERALL RATING: Very Good

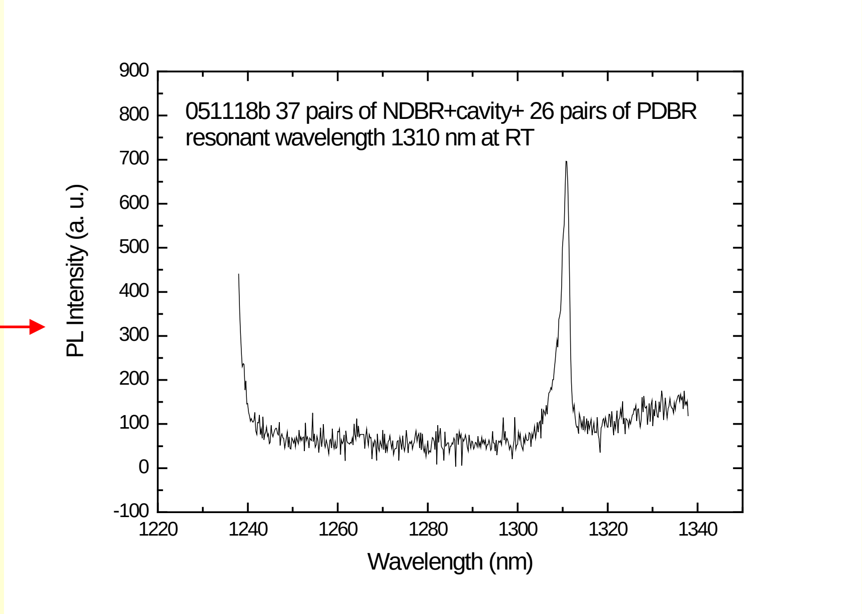
4、垂直腔面发射激光器

VCSEL器件结构

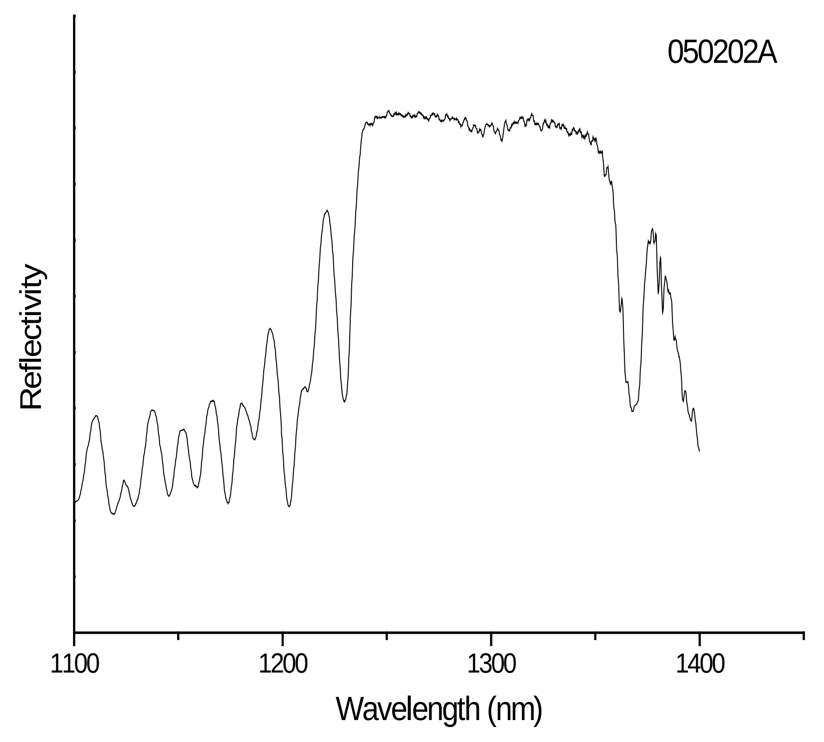


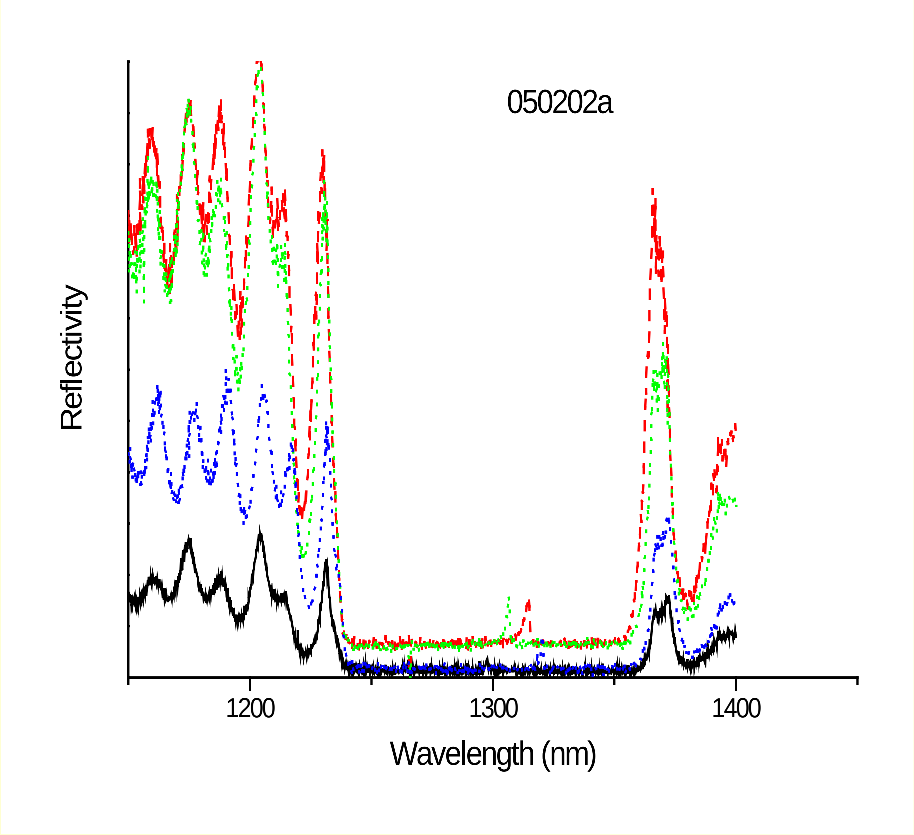
DBR－量子阱－VCSEL腔模中心波长的精确对准度、可控性大幅度提高



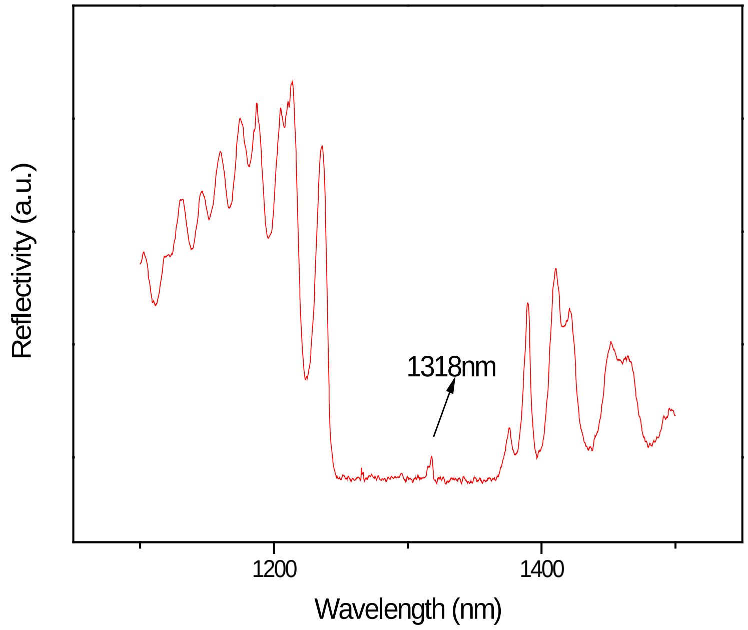


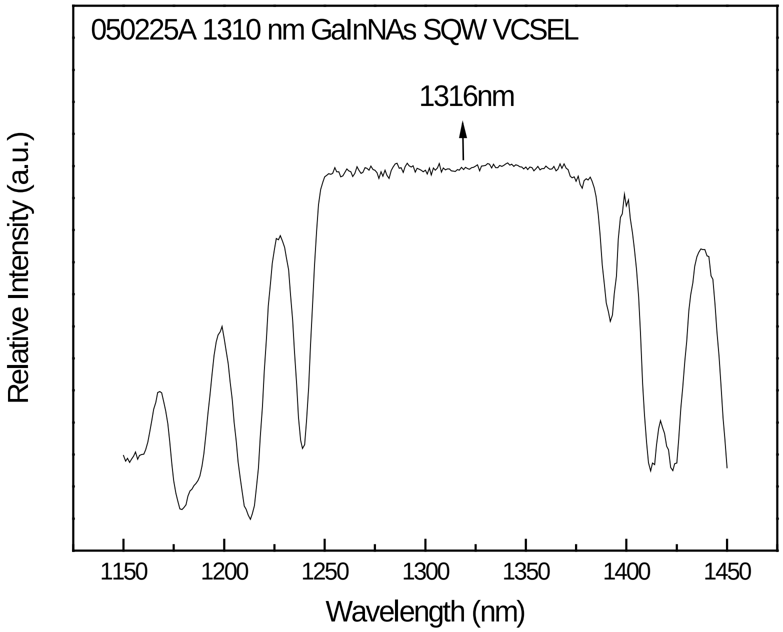
1.3微米VCSEL反射谱和室温PL谱（含1λ 等效腔长InGaAs/InAs/GaAs量子阱/量子点复合有源层）





1.3微米VCSEL反射谱和室温PL谱（含1λ 等效腔长 InGaNAs/GaAs量子阱有源层）





掌握湿氮氧化工艺

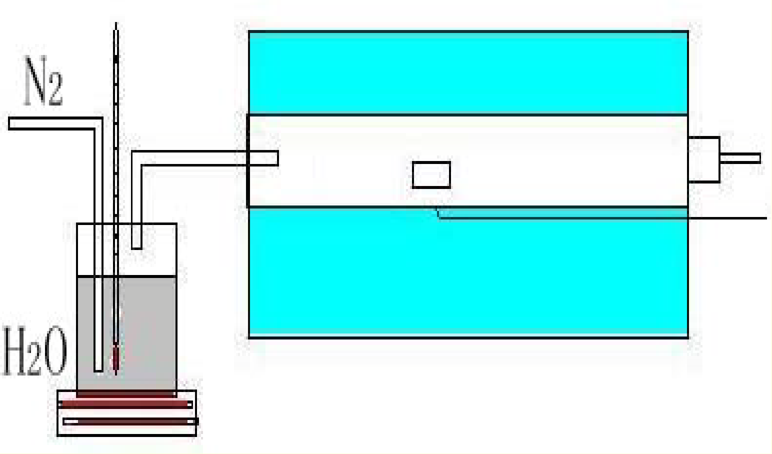
建立AlGaAs的湿氮氧化机理理论模型，摸清氧化参数对氧化层深度的较佳工艺条件。氧化均匀性、重复性很好！速度、氧化图形尺寸可控制在3－5微米。

AlAs氧化反应式：

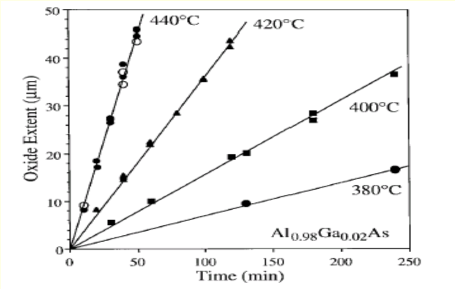
$2AlAs+6H_2O=Al_2O_3+As_2O_3+6H_2$

优化：温度、N2流量、水温、

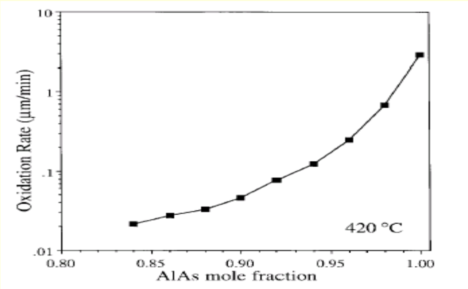
晶向、Al含量、厚度等参数



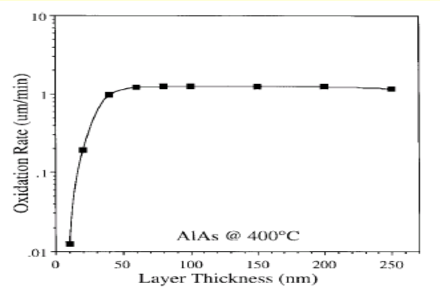
温度影响



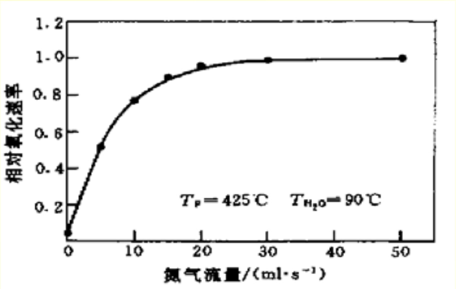
Al组分含量



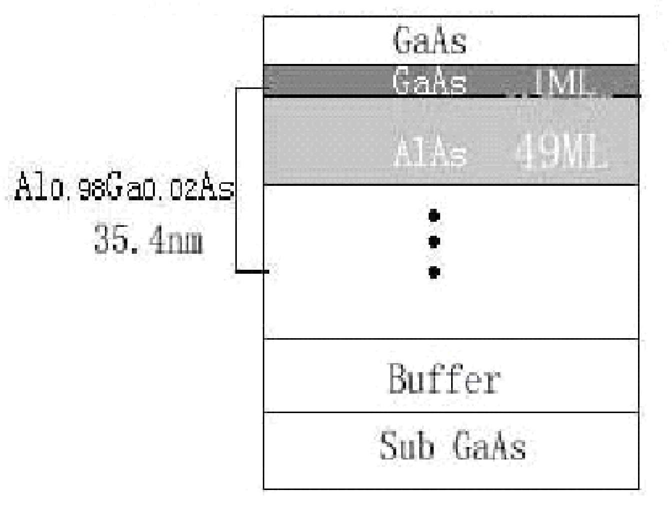
氧化层厚度



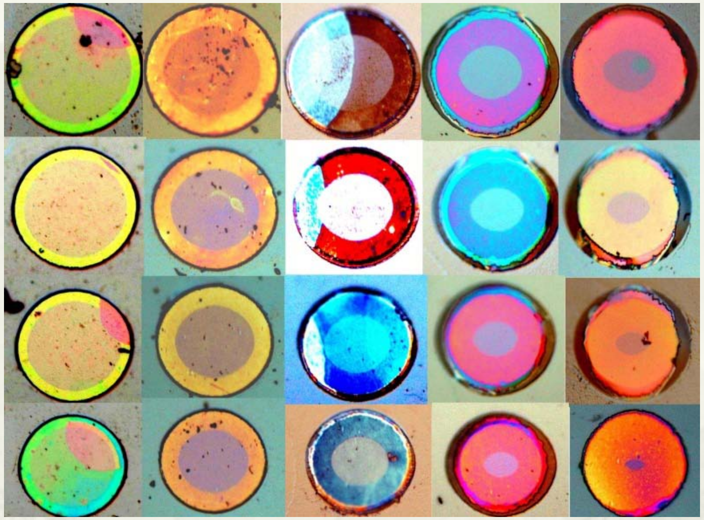
N_2气流量

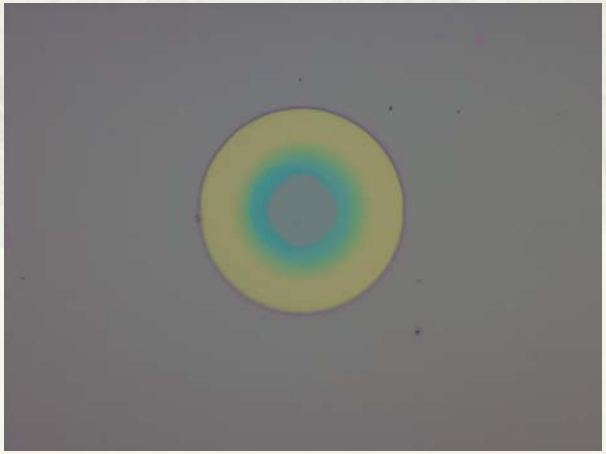


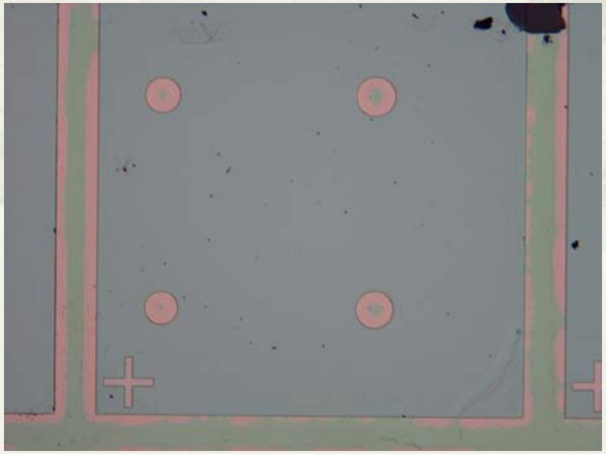
样品外延层结构



圆台形湿氮氧化俯视形貌图

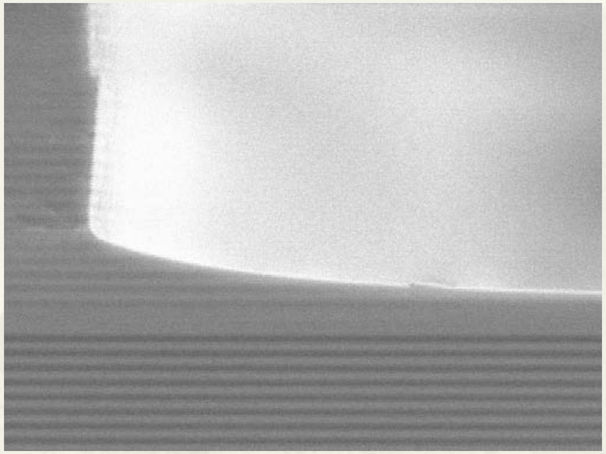




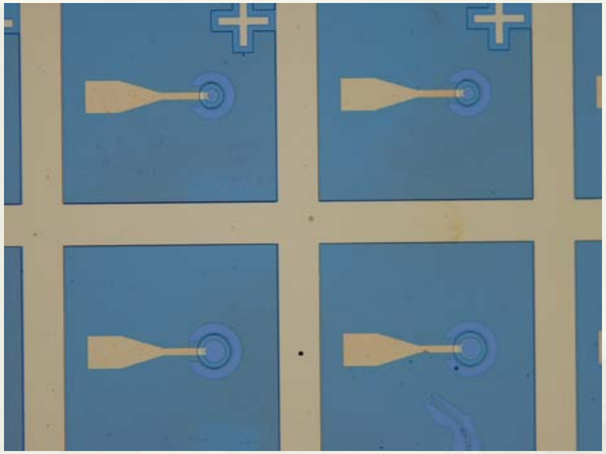


高精度台面刻蚀、电极制备、钝化工艺

VCSEL干法刻蚀SEM剖面图

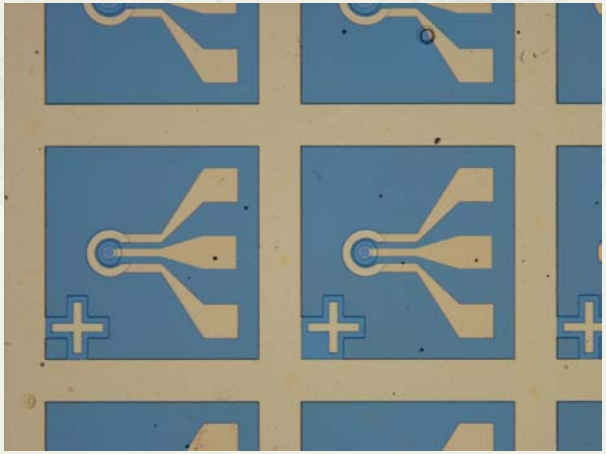


VCSEL 上下电极结构图形

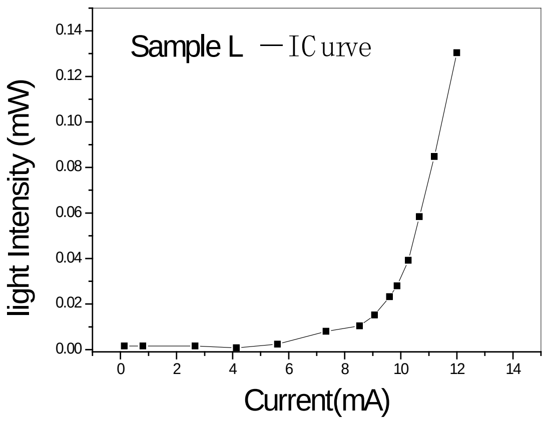


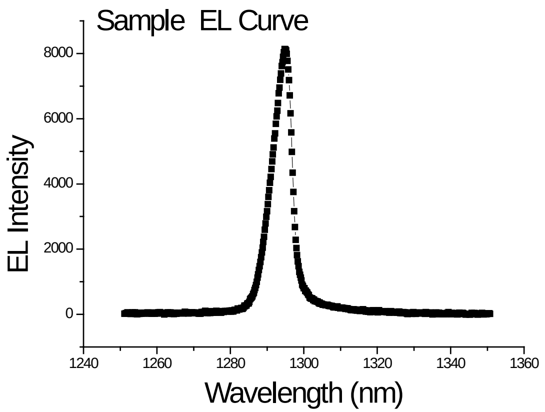
VCSEL湿法刻蚀SEM剖面图

VCSEL腔内电极结构图形



1.3微米GaInNAs量子阱VCSEL器件





室温激射，阈值电流小于10mA，
开启电压1－3V，功率几十微瓦

Standford大学长波长VCSEL激射谱线

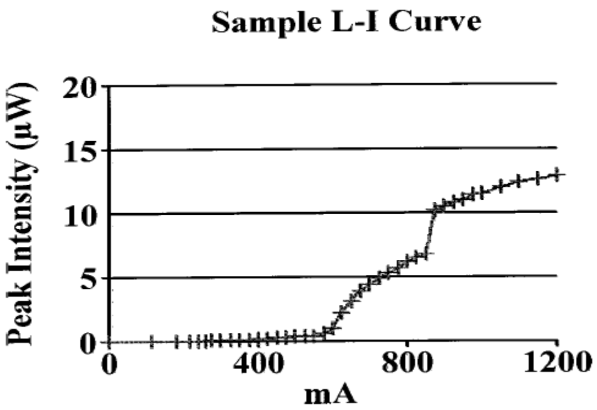


FIG. 3. Luminescence vs current curve. This particular device showed a kink at approximately 800 mA due to the onset of higher-order transverse modes.

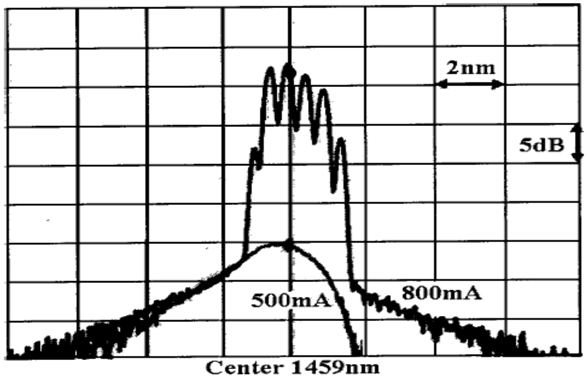


FIG. 2. Fiber-coupled spectrum of VCSEL pulsed at 500 mA (lower curve) and 800 mA (upper curve), showing onset of stimulated emission. Operated at 0.1% duty cycle and −10 °C, with 66 μm current aperture.

J. Vac. Sci. Technol. B,
22（3），1562（2004）

GaAs基近红外材料和器件研究获得好评

荣誉证书

北京市科学技术奖

为表彰在推动科学技术进步、对首都经济建设和社会发展作出贡献的集体和个人，特颁此证，以资鼓励。

获奖项目：新型GaInAs(NSb)低维半导体光电子材料与器件

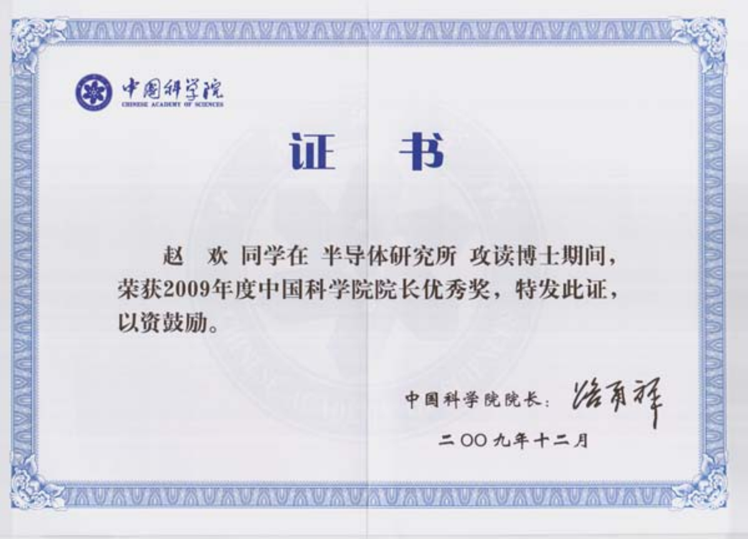
获奖等级：贰等奖

获奖单位：中国科学院半导体研究所、北京邮电大学

北京市人民政府

二〇〇八年十二月

NO. 2006基-2-001



中国科学院
CHINESE ACADEMY OF SCIENCES

证　书

赵　欢　同学在　半导体研究所　攻读博士期间，荣获2009年度中国科学院院长优秀奖，特发此证，以资鼓励。

中国科学院院长：路甬祥

二〇〇九年十二月

中国科学院

证　书

张石勇 同学在 半导体研究所 攻读研究生期间，荣获2006年度中国科学院院长优秀奖，特发此证，以资鼓励。

中国科学院院长：路甬祥

二〇〇六年七月

GaAs基长波长量子阱新结构

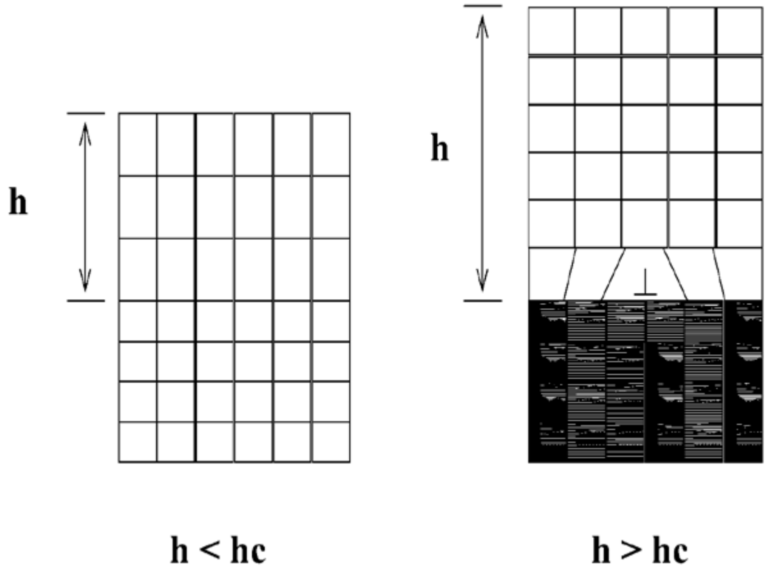
InAs量子点上限波长拓展受限?
掺N量子阱稳定性问题不易解决?

晶格失配体系材料的metamorphic生长技术
引起人们的高度关注！

GaAs基InGaAs异变材料

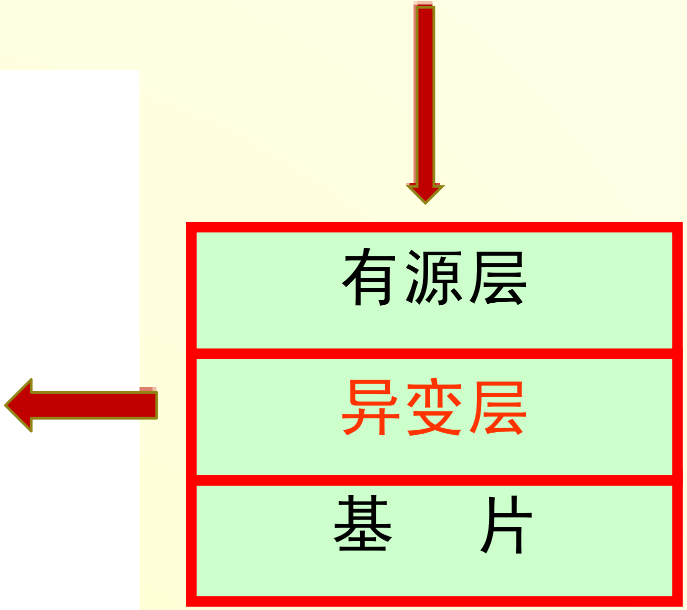
异变结构

异变器件



Pseudomorphic
赝变

Metamorphic
异变

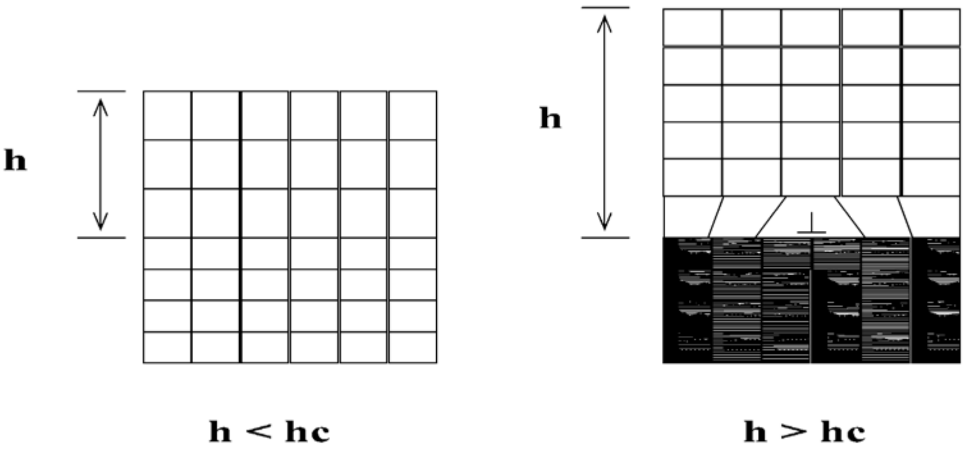


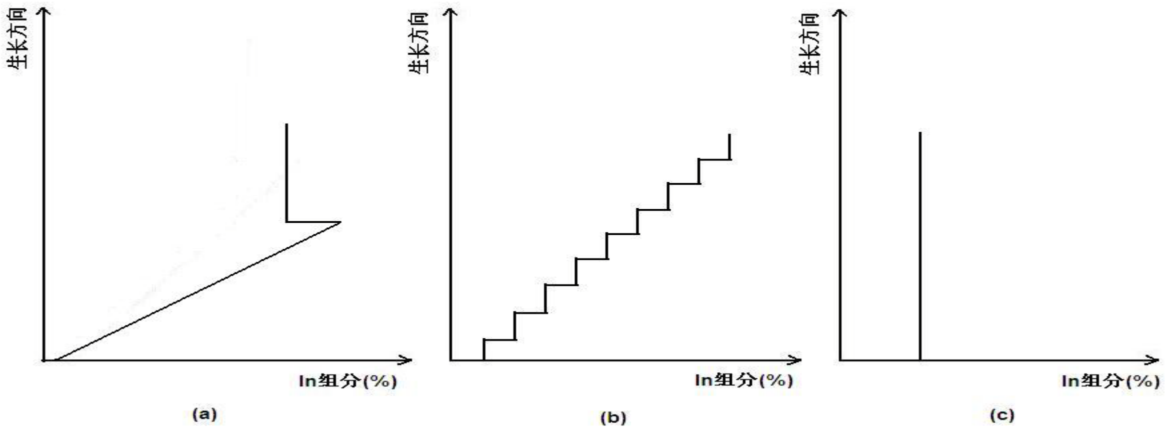
有源层

异变层

基　片

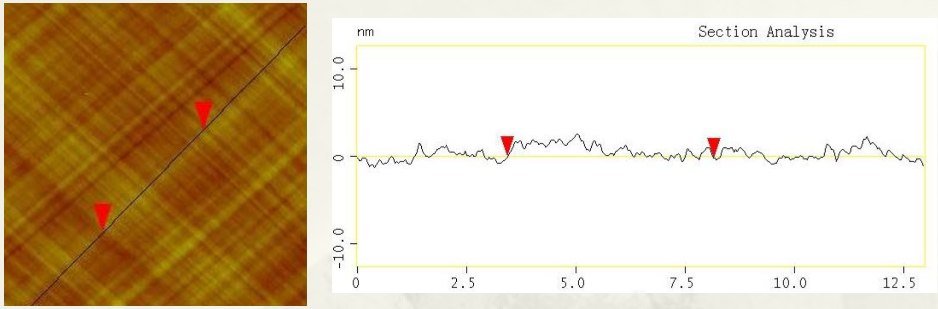
InGaAs/GaAs异变外延层In组分优化与控制



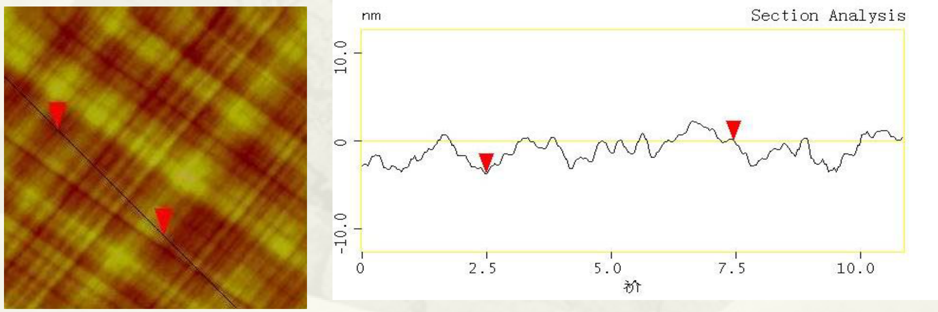


提出：源炉温度按照Arrhenius law: V=A exp (-B/T)指数变换方案，成功实现In组分的线性变化控制

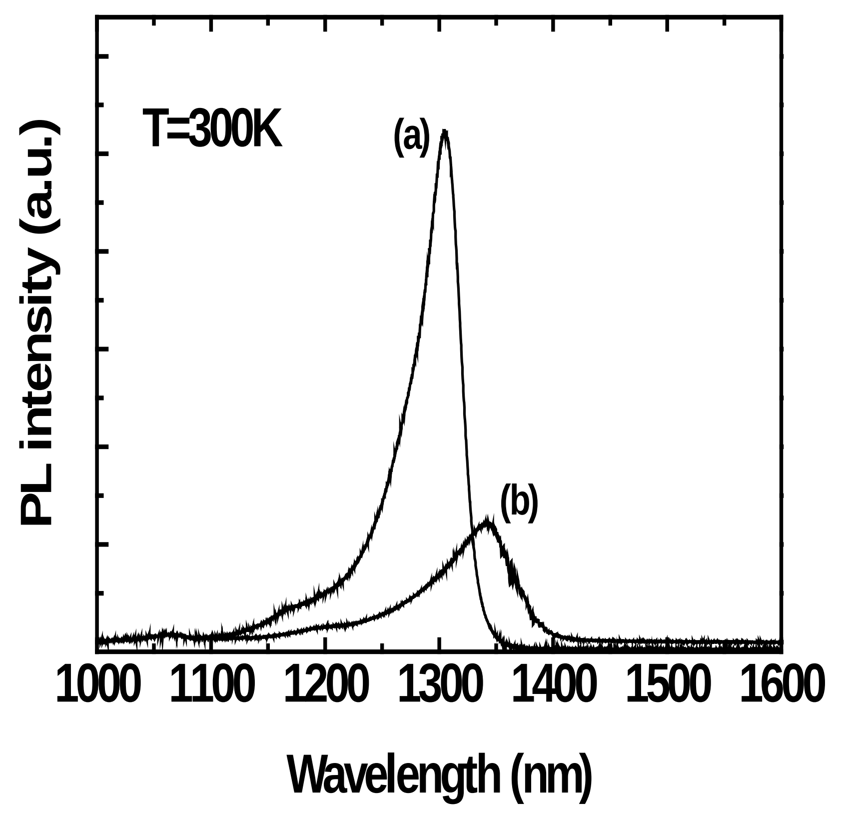
改善异变层表面平整度、提高量子阱发光效率



1 µm In(0.02 -- 0.25)GaAs, RMS=0.748nm,
In源温按照Arrhenius law指数变化



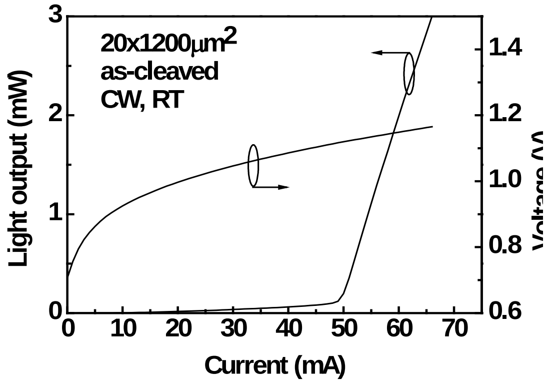
1 µm In(0.02 -- 0.25)GaAs, RMS=1.309 nm,
In源温按照线性变化

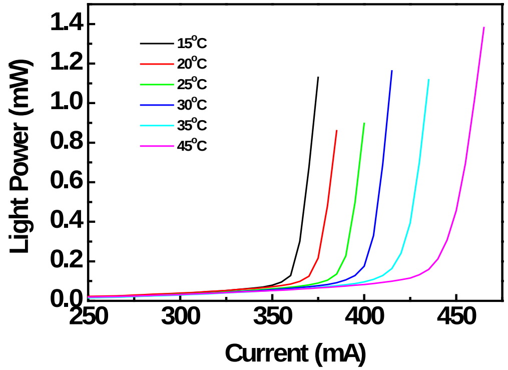


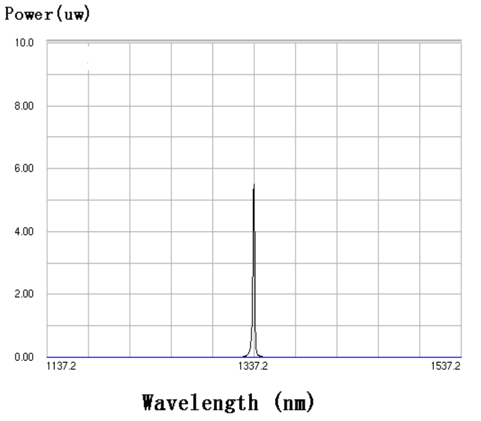
低阈值1.3微米InGaAs/GaAs异变量子阱激光器

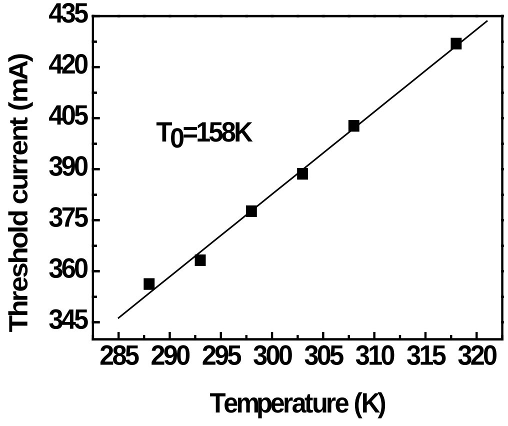
室温连续J_{th}=205A/cm2，特征温度158K, 效率: 0.17W/A

p-GaAs 10nm (Be: 1×10^{19} cm^{-3})
p-$In_{0.18}$GaAs 50nm (Be: 1×10^{19} cm^{-3})
p- $In_{0.18}$GaAs 200nm (Be: 5×10^{18} cm^{-3})
p-$In_{0.18}Al_{0.36\to0.2}$GaAs 200nm (Be: 2×10^{18} cm^{-3})
p- $In_{0.18}Al_{0.36}$GaAs 750nm (Be: 2×10^{18} cm^{-3})
p- $In_{0.18}Al_{0.36}$GaAs 750nm (Be: 1×10^{18} cm^{-3})
i-$In_{0.18}Al_{0.2\to0.36}$GaAs 200nm
i-$In_{0.18}$GaAs 100nm
i-$In_{0.47}$GaAs QW 7nm
i-$In_{0.18}$GaAs 100nm
i-$In_{0.18}Al_{0.36\to0.2}$GaAs 200nm
n-$In_{0.18}Al_{0.36}$GaAs 1500nm (Si: 1.4×10^{18} cm^{-3})
n-$In_{0.18}Al_{0.2\to0.36}$GaAs 200nm (Si: 1.4×10^{18} cm^{-3})
n-$In_{0.02\to0.25}$GaAs 1000nm (Si: 2×10^{18} cm^{-3})
n-GaAs buffer 300nm (Si: 2×$10^{18}$$cm^{-3}$)
n-GaAs substrate





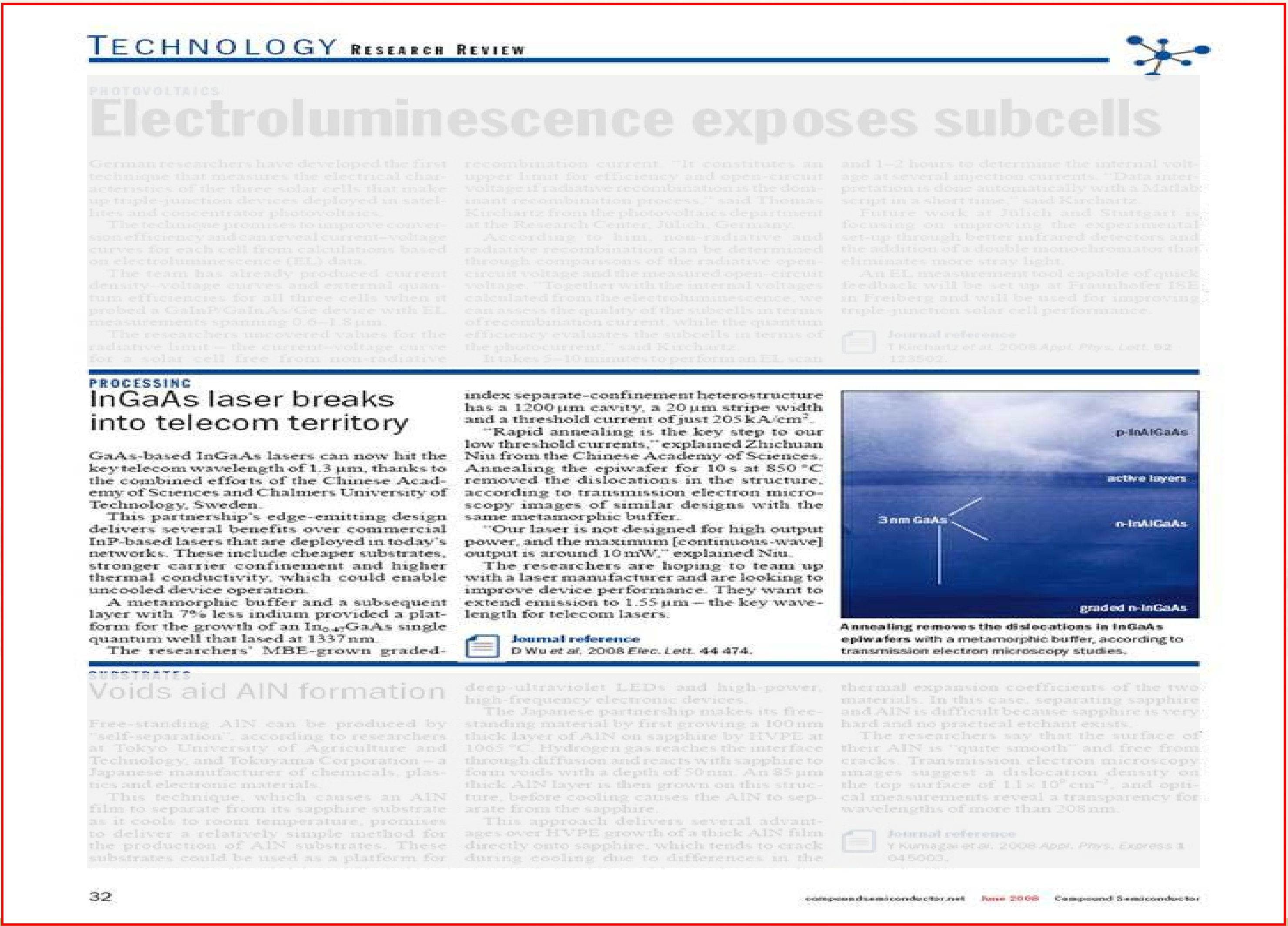




Electronics Letters,44,474 (2008)

2008年4月英国物理学会IOP《Compound Semiconductor》的报道

InGaAs laser breaks into telecom territory!



PHOTOVOLTAICS

Electroluminescence exposes subcells

German researchers have developed the first technique that measures the electrical characteristics of the three solar cells that make up triple-junction devices deployed in satellites and concentrator photovoltaics.

The technique promises to improve conversion efficiency and can reveal current–voltage curves for each cell from calculations based on electroluminescence (EL) data.

The team has already produced current density–voltage curves and external quantum efficiencies for all three cells when it probed a GaInP/GaInAs/Ge device with EL measurements spanning 0.6–1.8 µm.

The researchers uncovered values for the radiative limit – the current–voltage curve for a solar cell free from non-radiative recombination current. "It constitutes an upper limit for efficiency and open-circuit voltage if radiative recombination is the dominant recombination process," said Thomas Kirchartz from the photovoltaics department at the Research Center, Jülich, Germany.

According to him, non-radiative and radiative recombination can be determined through comparisons of the radiative open-circuit voltage and the measured open-circuit voltage. "Together with the internal voltages calculated from the electroluminescence, we can assess the quality of the subcells in terms of recombination current, while the quantum efficiency evaluates the subcells in terms of the photocurrent," said Kirchartz.

It takes 5–10 minutes to perform an EL scan and 1–2 hours to determine the internal voltage at several injection currents. "Data interpretation is done automatically with a Matlab script in a short time," said Kirchartz.

Future work at Jülich and Stuttgart is focusing on improving the experimental set-up through better infrared detectors and the addition of a double monochromator that eliminates more stray light.

An EL measurement tool capable of quick feedback will be set up at Fraunhofer ISE in Freiberg and will be used for improving triple-junction solar cell performance.

Journal reference
T Kirchartz *et al.* 2008 *Appl. Phys. Lett.* 92 123502.

PROCESSING

InGaAs laser breaks into telecom territory

GaAs-based InGaAs lasers can now hit the key telecom wavelength of 1.3 µm, thanks to the combined efforts of the Chinese Academy of Sciences and Chalmers University of Technology, Sweden.

This partnership's edge-emitting design delivers several benefits over commercial InP-based lasers that are deployed in today's networks. These include cheaper substrates, stronger carrier confinement and higher thermal conductivity, which could enable uncooled device operation.

A metamorphic buffer and a subsequent layer with 7% less indium provided a platform for the growth of an $In_{0.47}GaAs$ single quantum well that lased at 1337 nm.

The researchers' MBE-grown graded-index separate-confinement heterostructure has a 1200 µm cavity, a 20 µm stripe width and a threshold current of just 205 kA/cm^2.

"Rapid annealing is the key step to our low threshold currents," explained Zhichuan Niu from the Chinese Academy of Sciences. Annealing the epiwafer for 10 s at 850 °C removed the dislocations in the structure, according to transmission electron microscopy images of similar designs with the same metamorphic buffer.

"Our laser is not designed for high output power, and the maximum [continuous-wave] output is around 10 mW," explained Niu.

The researchers are hoping to team up with a laser manufacturer and are looking to improve device performance. They want to extend emission to 1.55 µm – the key wavelength for telecom lasers.

Journal reference
D Wu *et al.* 2008 *Elec. Lett.* 44 474.

Annealing removes the dislocations in InGaAs epiwafers with a metamorphic buffer, according to transmission electron microscopy studies.

SUBSTRATES

Voids aid AlN formation

Free-standing AlN can be produced by "self-separation", according to researchers at Tokyo University of Agriculture and Technology, and Tokuyama Corporation – a Japanese manufacturer of chemicals, plastics and electronic materials.

This technique, which causes an AlN film to separate from its sapphire substrate as it cools to room temperature, promises to deliver a relatively simple method for the production of AlN substrates. These substrates could be used as a platform for deep-ultraviolet LEDs and high-power, high-frequency electronic devices.

The Japanese partnership makes its free-standing material by first growing a 100 nm thick layer of AlN on sapphire by HVPE at 1065 °C. Hydrogen gas reaches the interface through diffusion and reacts with sapphire to form voids with a depth of 50 nm. An 85 µm thick AlN layer is then grown on this structure, before cooling causes the AlN to separate from the sapphire.

This approach delivers several advantages over HVPE growth of a thick AlN film directly onto sapphire, which tends to crack during cooling due to differences in the thermal expansion coefficients of the two materials. In this case, separating sapphire and AlN is difficult because sapphire is very hard and no practical etchant exists.

The researchers say that the surface of their AlN is "quite smooth" and free from cracks. Transmission electron microscopy images suggest a dislocation density on the top surface of $1.1 \times 10^{9}\,\text{cm}^{-2}$, and optical measurements reveal a transparency for wavelengths of more than 208 nm.

Journal reference
Y Kumagai *et al.* 2008 *Appl. Phys. Express* 1 045003.

1.55微米长波长InGaAs/GaAs异变量子阱

如何实现大In组分50%的InGaAs 异变材料外延？

创新方法：

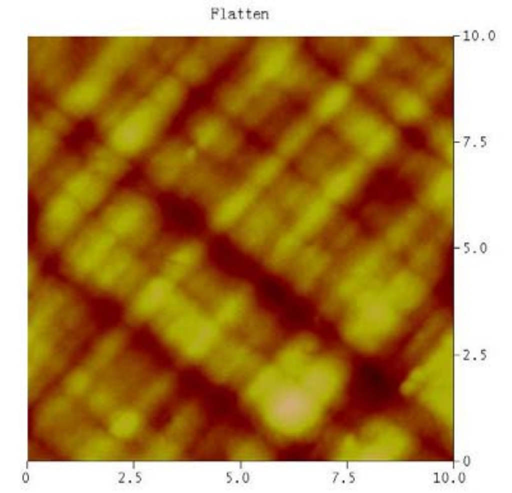
1、低温外延技术；

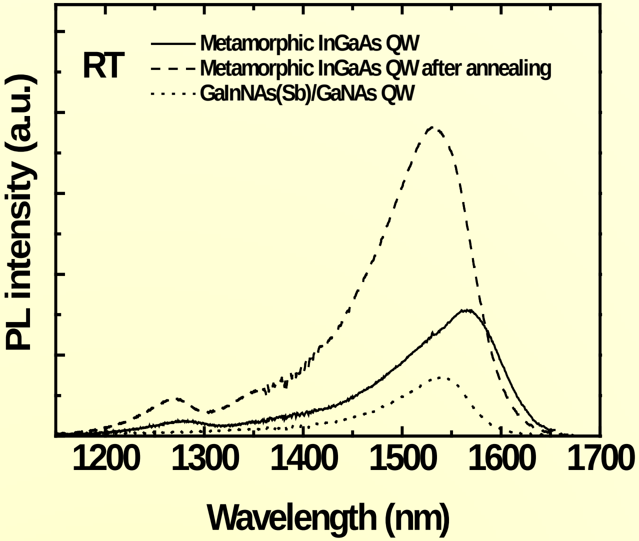
2、引入 GaAs 补偿；

3、采用 Sb 催化；

4、原位快速退火

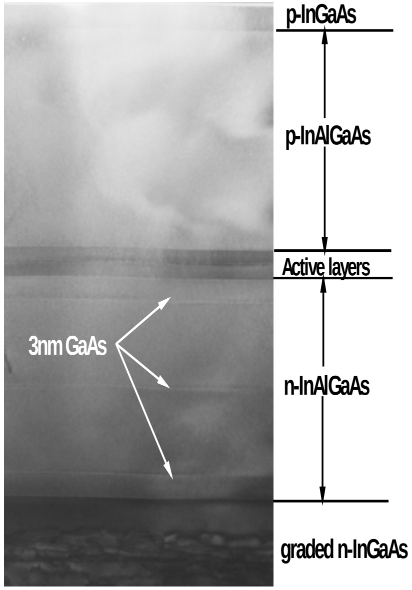
RMS＝2.840nm



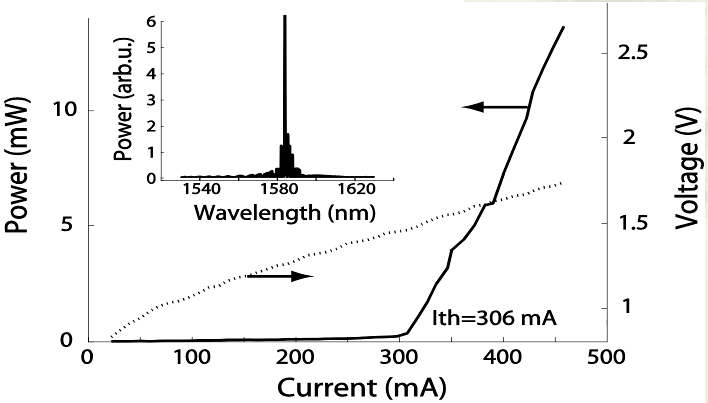


1.55 微米 InGaAs/GaAs 异变量子阱激光器

p-GaAs 10nm (Be: 1× $^{-3}$)
p-In$_{0.32}$GaAs (Sb:5E-9Torr) 50nm (Be: 1× $^{-3}$)
p- In$_{0.32}$GaAs (Sb:5E-9Torr) 200nm (Be: 5× $^{-3}$)
p-In$_{0.32}$Al$_{0.32->0.216}$GaAs (Sb:5E-9Torr) 200nm (Be: 2× $^{-3}$)
p- In$_{0.32}$Al$_{0.32}$GaAs (Sb:5E-9Torr) 750nm (Be: 2× $^{-3}$)
p- In$_{0.32}$Al$_{0.32}$GaAs (Sb:5E-9Torr) 750nm (Be: 5× $^{-3}$)
i-In$_{0.32}$Al$_{0.216->0.32}$GaAs (Sb:5E-9Torr) 200nm
i-GaAs 3nm
i-In$_{0.32}$GaAs (Sb:5E-9Torr) 100nm
i-In$_{0.6}$GaAs QW (Sb:5E-9Torr) 7nm
i-In$_{0.32}$GaAs (Sb:5E-9Torr) 130nm
i-GaAs 3nm
i-In$_{0.32}$Al$_{0.32->0.216}$GaAs (Sb:5E-9Torr) 200nm
n-GaAs 3nm
n-In$_{0.32}$Al$_{0.32}$GaAs (Sb:5E-9Torr) 750nm (Si: 4× $^{-3}$)
n-GaAs 3nm
n-In$_{0.32}$Al$_{0.32}$GaAs (Sb:5E-9Torr) 750nm (Si: 2× $^{-3}$)
n-GaAs 3nm
n-In$_{0.32}$Al$_{0.216->0.32}$GaAs (Sb:5E-9Torr) 200nm (Si: 2× $^{-3}$)
n-GaAs 3nm
n-In$_{0.02->0.39}$GaAs 1500nm (Si: 2× $^{-3}$)
n-GaAs buffer 300nm (Si: 2×$^{-3}$)
n-GaAs substrate



脊行波导结构：
50 x 1250 µm^2
波长：1584nm
阈值电流密度：
490A/cm^2



Appl. Phys. Lett, 91, 221101(2007)

2008年1月美国
《Laser Focus World》的报道

InGaAs QWs lasers provide alternative to 1.55 um GaAs based lasers

newsbreaks

InGaAs quantum-well lasers provide alternative to 1.55 µm GaAs-based lasers

Gallium arsenide (GaAs) lasers at 1.3 and 1.55 µm have received a lot of attention in the past several years for their potential as inexpensive, high-speed, uncooled sources for telecommunications. With careful optimization of metamorphic crystal growth, structure, and optical properties, researchers at Chalmers University of Technology (Gothenburg, Sweden) and the Chinese Academy of Sciences (Beijing, China) have demonstrated metamorphic 1.58 µm indium gallium arsenide (InGaAs) quantum-well lasers that may be a promising alternative to 1.55 µm GaAs-based lasers.

The metamorphic InGaAs quantum-well laser was grown by molecular beam epitaxy on an *n*-type GaAs substrate using a low growth temperature of 440°C and post growth rapid thermal annealing, using antimony as a surfactant and inserting thin GaAs smoothing layers. The resulting broad-area laser measured 50 × 1250 µm with a threshold current density of 490 A/cm² at room temperature under pulsed operation. The root-mean-square surface roughness of the 6-µm-thick laser structure, as measured by atomic-force microscope over 1 and 10 µm² areas, are 0.5 and 5.6 nm, respectively. *Contact Ivar Tångring at* ivar.tangring@mc2.chalmers.se.

Retinal flow cytometer tracks circulating blood cells

A retinal flow cytometer developed by researchers from the Wellman Center for Photomedicine at Massachusetts General Hospital and Harvard Medical School (Cambridge, MA) has demonstrated the potential to noninvasively monitor disease progression and enhance treatment by measuring blood flow in the eyes. The *in vivo* instrument is capable of continuous, real-time monitoring of fluorescently labeled blood cells as they circulate in retinal tissue at the back of the eye, eliminating the need to draw blood samples.

The cytometer improves cell-detection sensitivity by increasing sampling volume. Two phase-locked resonant galvanometer scanners steer the 635 nm beam at a rate of 4.8 kHz, creating a circular scan on the retina. Fluorescence is descanned by the resonant scanning mirrors and detected through a dichroic long-pass filter at 45° and through a 670 nm bandpass filter. A confocal pinhole in front of the photomultiplier tube rejects any out-of-focus signal. In feasibility experiments, the team monitored 1 million circulating cells in a mouse and were able to observe 250 cells/min.

According to the researchers, the ability to count circulating cells is important in diseases like multiple myeloma in which the number of cancer cells in the bloodstream can quickly change over time. The retinal flow cytometer could thus become a valuable tool in the development of better drugs and treatment strategies. *Contact Charles P. Lin* at lin@helix.mgh.harvard.edu.

Filters advance multispectral imaging

LaserFocusWorld

2008 Market Review and Forecast

2005 2006 2007 2008

n in nanoseconds

per Bragg gratings (FBGs) can be ap-
pulse picking in a fiber laser, among
have been used such as bending
stack, and using magnetic fields, these
l tuning speeds) and have mechanical
nt Research Centre of Photonics of the
Zhejiang University (Hangzhou, China),
nics Research Center (Kista, Sweden),
uctured fibers to cause high-speed

d to the electrodes—formed by pump-
er—which in turn heat up, expand, and induce birefringence changes in the
ringence causes two reflection peaks at different wavelengths correspond-
for the two orthogonal polarization modes in the fiber, allowing the grat-
29 ns. *Contact Walter Margulis at* walter.margulis@acreo.se.

Laser Focus World www.laserfocusworld.com January 2008 15

GaAs基长波长材料技术得到广泛应用

主要应用发展：

1、**HEMT**器件：异变外延技术

2、激光器件：**Sb**诱导改善界面

3、太阳能电池：异变层改善电流匹配

4、**GaInNAs**材料：电子自旋特性研究

3、下一步研究方向

微纳结构量子光源

新型Sb化物红外光电材料

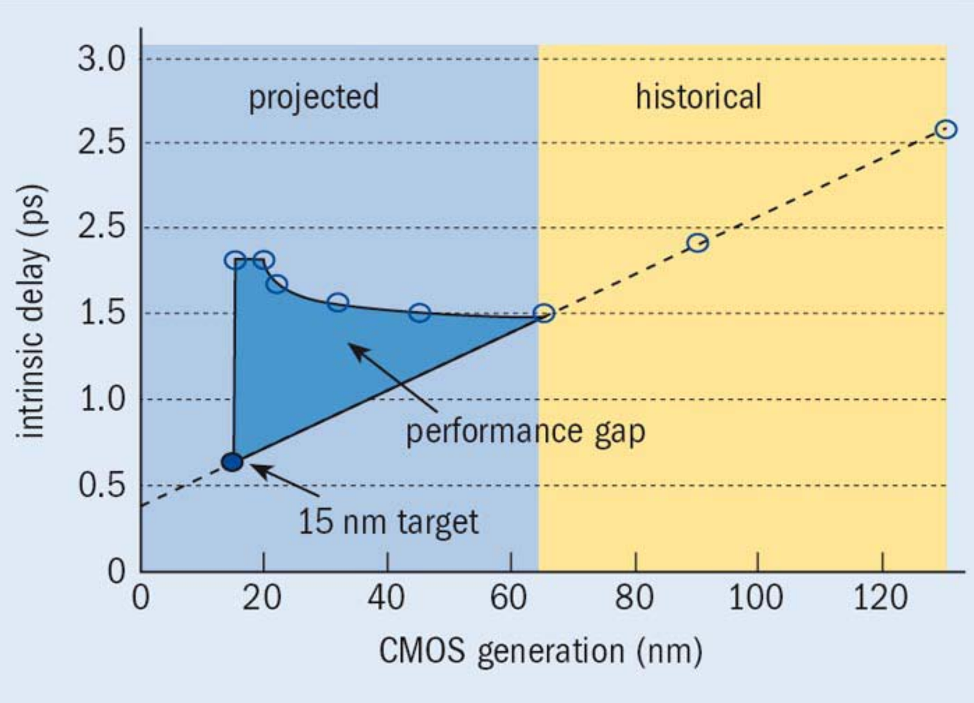
半导体技术进展速度出乎人的意料

22nm以下Si集成电路性能提升瓶颈

过去40年Si基 CMOS ICs技术获得巨大成功！依赖于高精度纳米加工技术及高质量的SiO_2/Si界面。07年后采用HfO_2高K介质与金属栅结构的32nm的Si电路实现量产。

当线宽降至15–22nm，SiO_2厚度薄到1.2nm时Si基ICs性能面临速率下降、漏电增加、功耗上升等瓶颈摩尔定律物理极限！

固有延迟时间和线宽的关系



Si电路线宽小于65nm电子固有延迟时间将不再按线宽线性减少而减小！（Antoniadis，MIT）

Si/Ge/III-V兼容材料：高迁移率+光互连

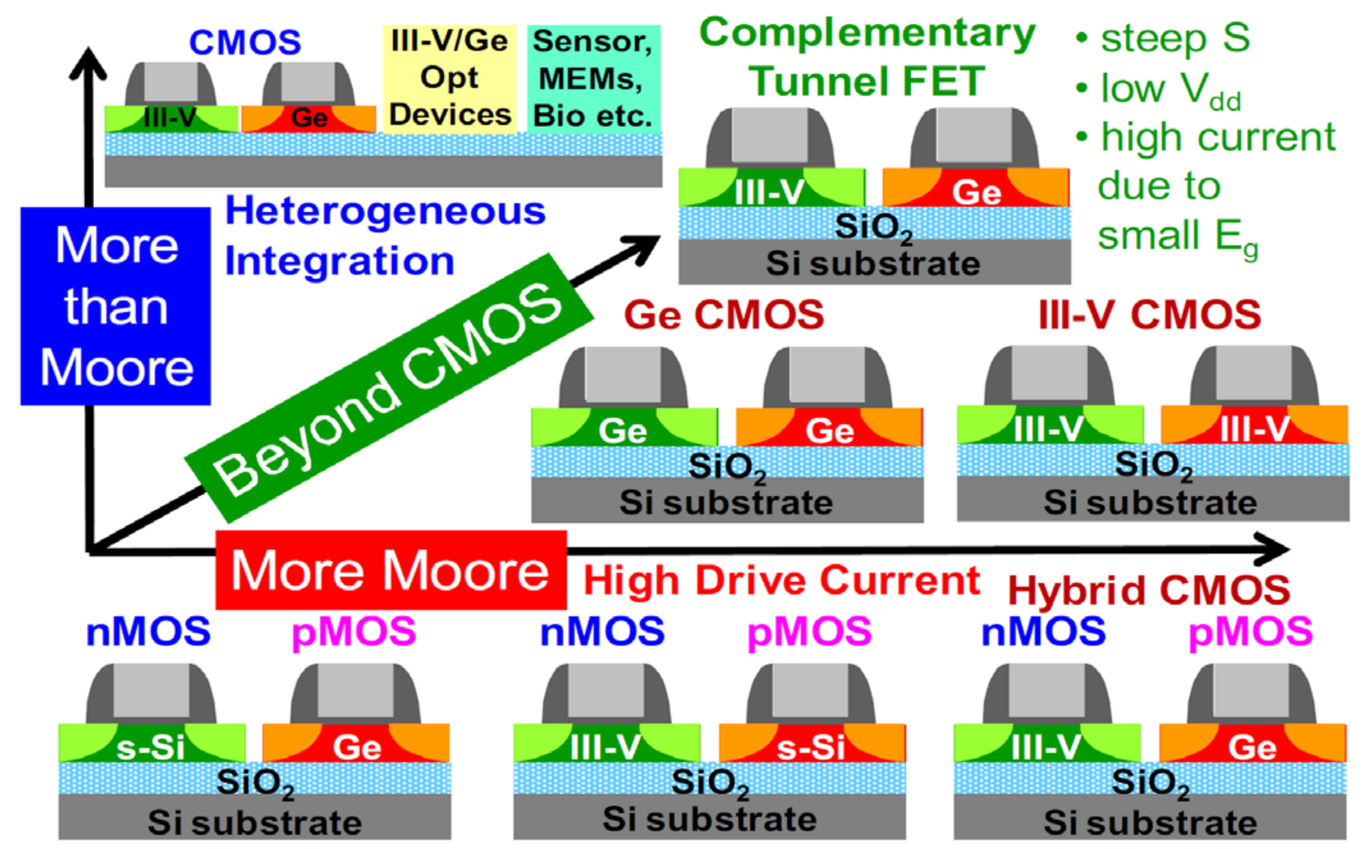
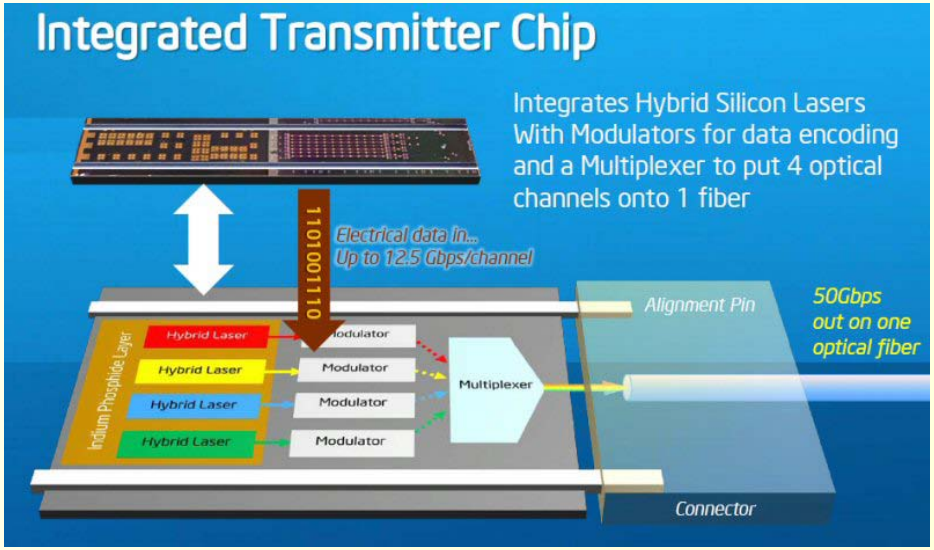


Fig. 1 Possible evolution scenario for III-V/Ge devices on Si platform through heterogeneous integration

Intel：光互连技术的最新进展

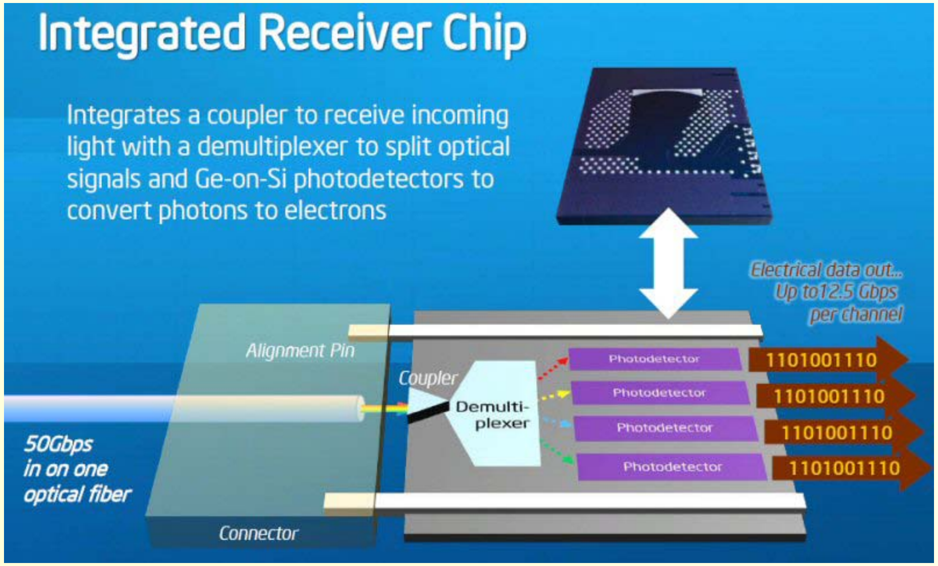


Integrated Transmitter Chip

Integrates Hybrid Silicon Lasers With Modulators for data encoding and a Multiplexer to put 4 optical channels onto 1 fiber

Electrical data in...
Up to 12.5 Gbps/channel

50Gbps out on one optical fiber

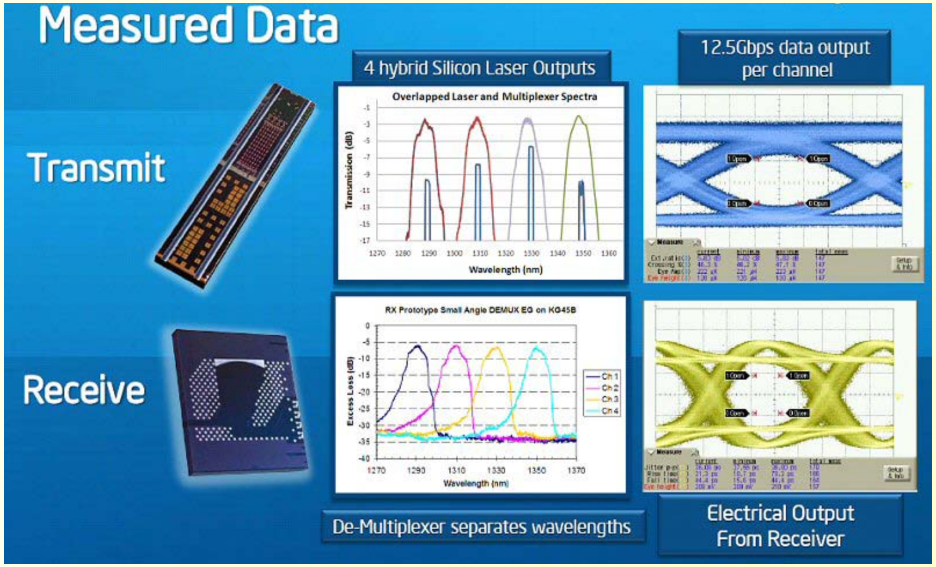


Integrated Receiver Chip

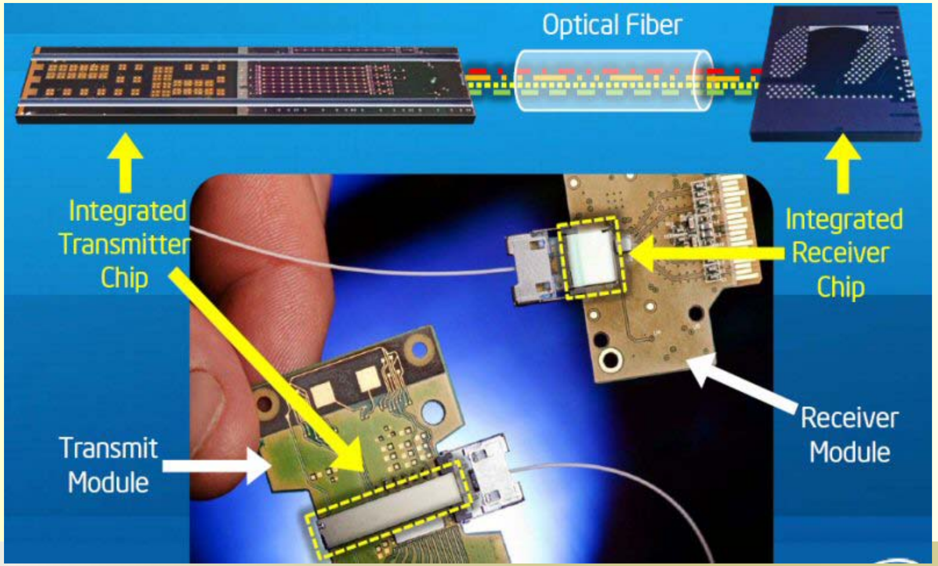
Integrates a coupler to receive incoming light with a demultiplexer to split optical signals and Ge-on-Si photodetectors to convert photons to electrons

Electrical data out...
Up to 12.5 Gbps per channel

50Gbps in on one optical fiber



Measured Data



1、采用光传输替代电传输?

2、采用高迁移率材料替代Si?

↓

1、微纳量子结构低功耗光源

2、下一代高迁移率Sb化物材料

采用光互连方案
光源器件的功耗过大是主要瓶颈

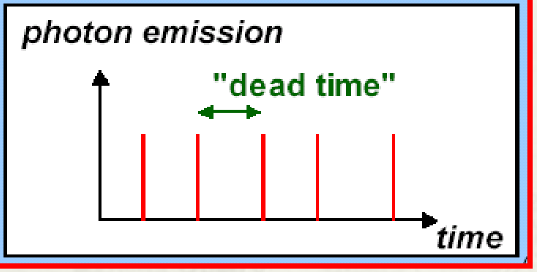
新型微纳（量子）结构光源

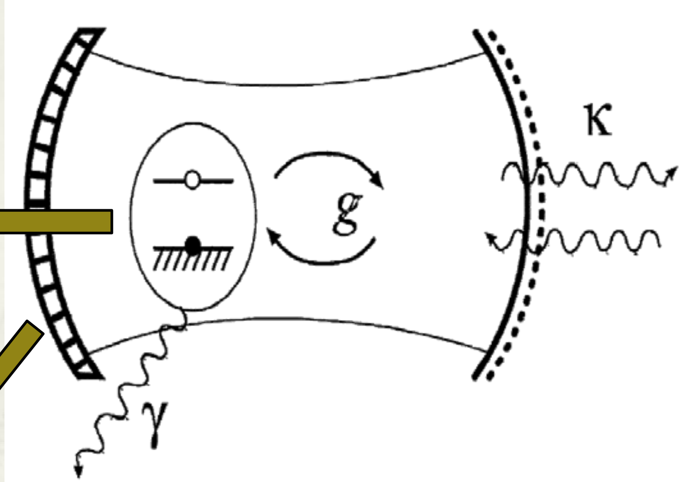
有源介质体积小：易泵浦，能耗低
输出光可控性：偏振度高
调制速度高

1、原子 = 极小有源介质
2、微腔 = 实现光辐射可控

$$\hat{H}_s = \underbrace{\frac{\hbar\omega_A}{2}\hat{\sigma}_z}_{\text{two-level atom}} + \underbrace{\hbar\omega_C\hat{b}^+\hat{b}}_{\text{free cavity field}} + \underbrace{i\hbar[g(r)\hat{b}^+\hat{\sigma}_- - g^*(r)\hat{b}\hat{\sigma}_+]}_{\text{atom-cavity interaction}}$$

原子是理想的二能级最小有源介质体系！





利用腔与原子的耦合效应，实现微腔对原子自发辐射调控，产生相干、单光子/纠缠光子。

γ → 原子辐射衰减速率

K→ 腔模衰减速率（腔镜损耗）

g → 腔模与原子耦合强度

$$g = \frac{\mu}{\hbar}\sqrt{\frac{\hbar\omega}{2\varepsilon_0\nu}}$$

- **Purcell效应对自发辐射耦合系数的影响**

  腔模对原子自发辐射几率的影响。自发辐射耦合系数反映了自发辐射耦合到一特定模式的比例。Purcell效应使得 $\beta \approx 1$ 微腔中原子的辐射光可以被腔全部收集并输出。

$$\beta = \frac{F_p}{1+F_p} \qquad F_p = \frac{3\lambda^3}{4\pi^2}\frac{Q}{V}$$

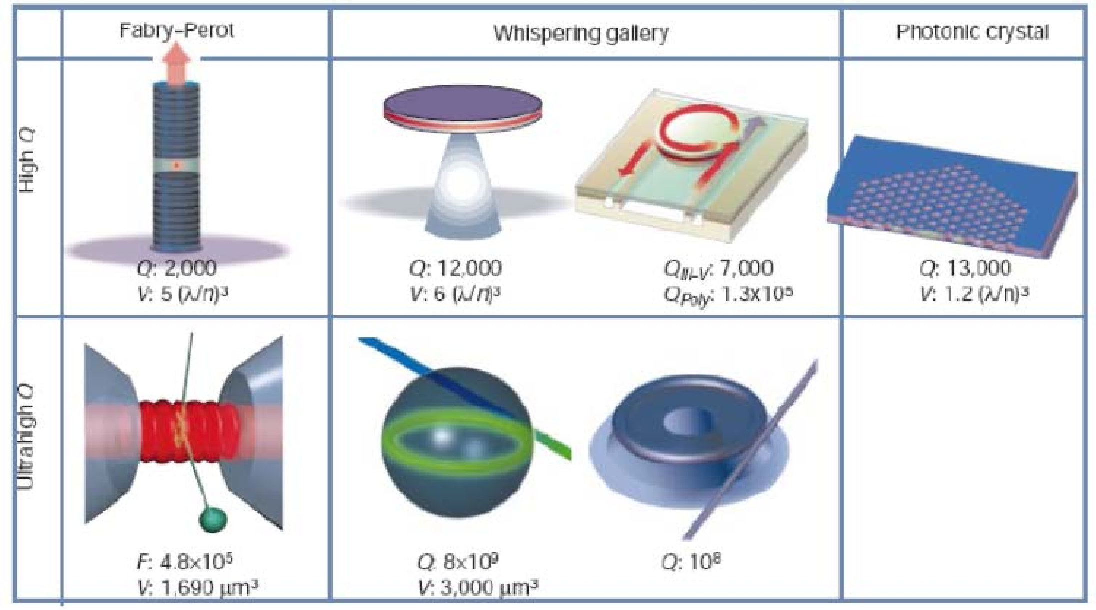
- **自发辐射跃迁时间**

  发射光子要求自发辐射跃迁时间小于光子失相时间（dephasing time）。对InAs量子点， 可长达1 ns，而失相时间约为0.9 ns（T =4 K下）。不满足要求，但量子点可充分利用微腔*Q*值，并获得高Purcell系数 使自发发射寿命缩短。

- **滤波效应（spectral filtering）**

  一次电流脉冲输入会使量子点中存在多个电子-空穴对，但前后不同时间复合发光的电子-空穴对所受库仑势影响不同，造成一个电脉冲时间内所发射的光子能量有微小差别 。为获得单光子，需要使用一高*Q*谐振腔对这些光子进行滤波 。

各种微腔结构



	Fabry–Perot	Whispering gallery		Photonic crystal
High Q	Q: 2,000 V: 5 $(\lambda/n)^3$	Q: 12,000 V: 6 $(\lambda/n)^3$	$Q_{III\text{-}V}$: 7,000 Q_{Poly}: 1.3×10^5	Q: 13,000 V: 1.2 $(\lambda/n)^3$
Ultrahigh Q	F: 4.8×10^5 V: 1,690 μm^3	Q: 8×10^9 V: 3,000 μm^3	Q: 10^8	

品质因子Q： $Q=\dfrac{W_{cav}}{P_{loss}/\omega}$ $\quad Q=\dfrac{\omega_0}{\Delta\omega}$

模式体积V： $V_{eff}=\dfrac{\int\varepsilon(\mathbf{r})\boldsymbol{E}^2(\mathbf{r})dV}{\left(\varepsilon(\mathbf{r})\boldsymbol{E}^2(\mathbf{r})\right)_{\max}}$

耦合强度g： $g=\dfrac{\mu}{\hbar}\sqrt{\dfrac{\hbar\omega}{2\varepsilon_0 v}}$ $\quad \gamma_0=\omega^3\mu^2\Big/3\pi\varepsilon_0\hbar c^3$ $\quad \gamma_{cav}=\omega\big/2Q$

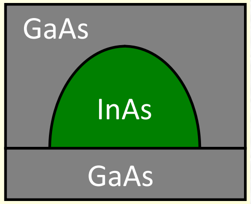
强耦合Rabi 振荡 $\quad g>\gamma_{cav},\gamma_0$ $\quad$ **弱耦合**Purcell效应 $\quad g<\gamma_{cav},\gamma_0$

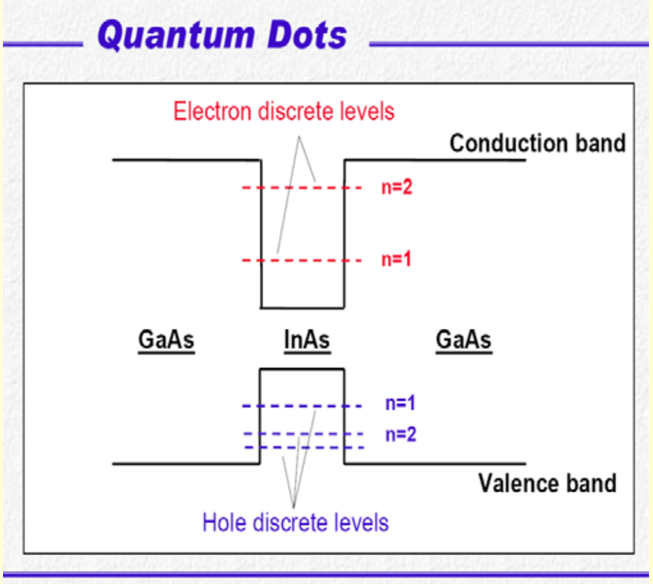
制备原子微腔结构光源的可行性方案

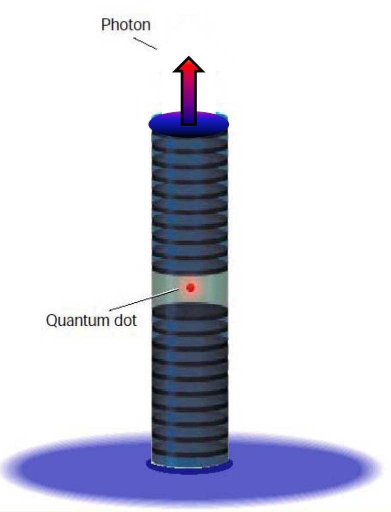
半导体量子点+布拉格微腔

半导体量子点—
人工“类原子”结构

分布布拉格反馈—
可控生长微腔结构



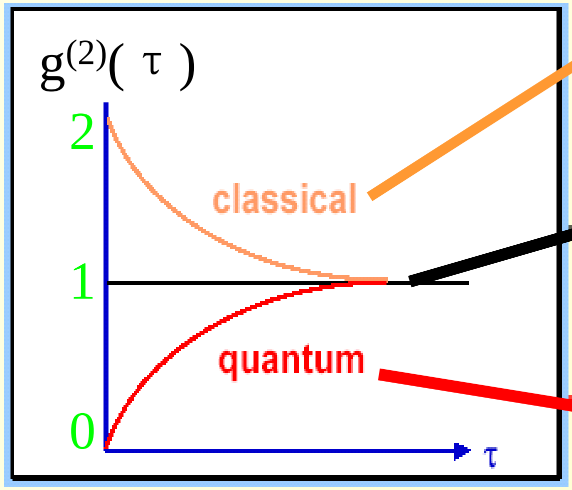




辐射光子的统计分布

服从二阶关联函数统计

$$g^{(2)}(\tau)=\frac{\langle I(t)I(t+\tau)\rangle}{\langle I(t)\rangle^2}$$

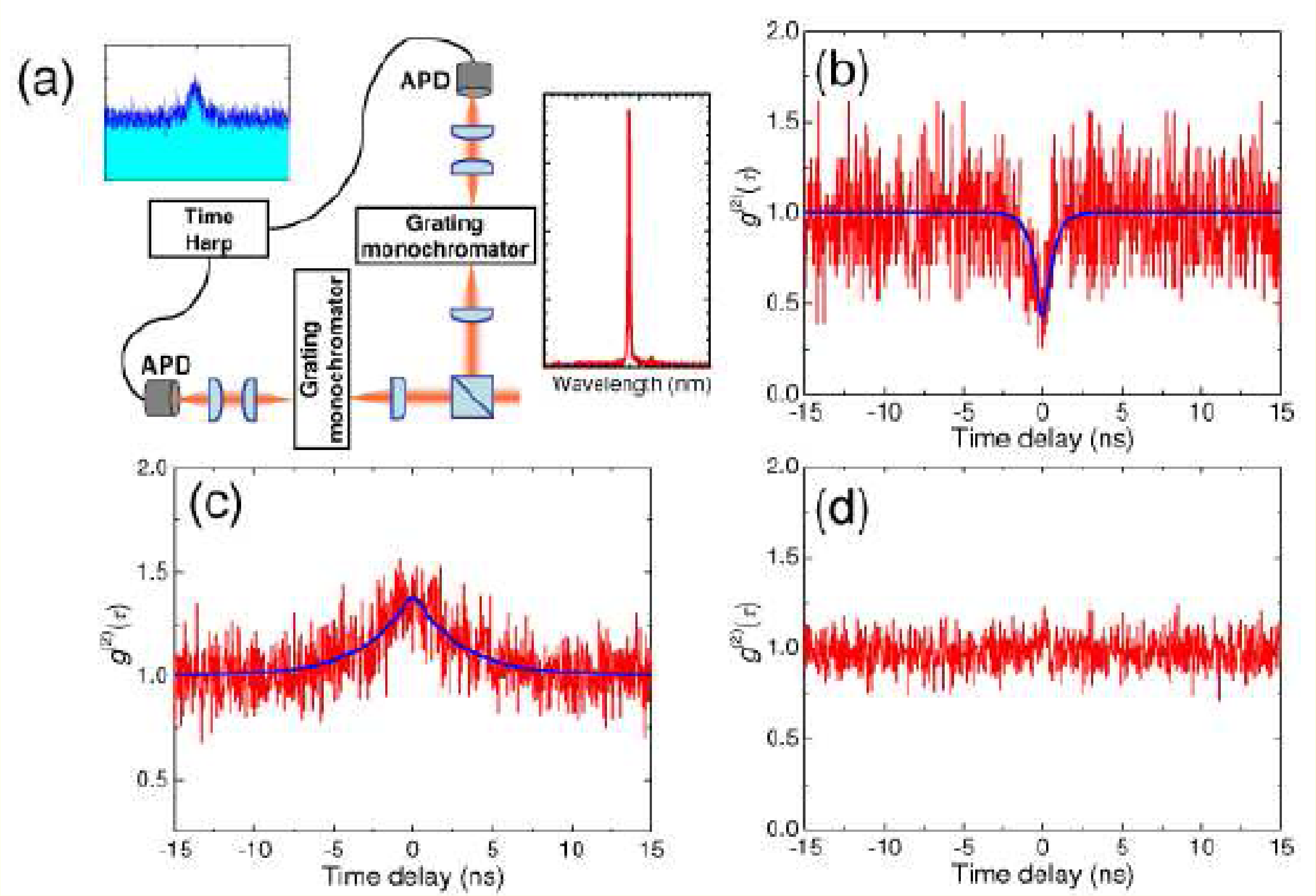


超泊松分布—经典态：光子数分布为聚束(photon bunching)态，光子趋向于成群出现。

泊松分布—相干态：光子记数随时间呈随机分布状态。

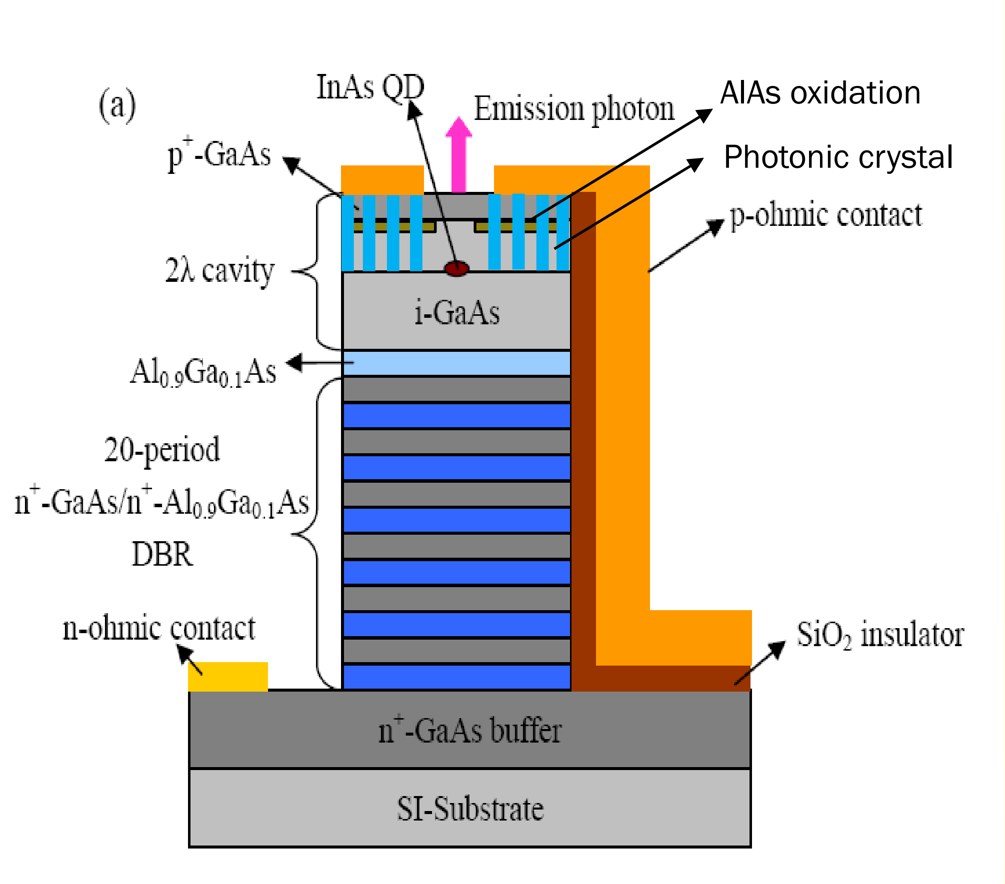
亚泊松分布—非经典态：光子呈现反聚束Anti bunching态，光场量子化—数态光场。

Hanbury Brown和Twiss （HBT）实验检测$g^{(2)}$态



随泵浦功率变化分别出现反聚束、聚束和相干光分布
（对应超泊松、亚泊松和泊松分布）

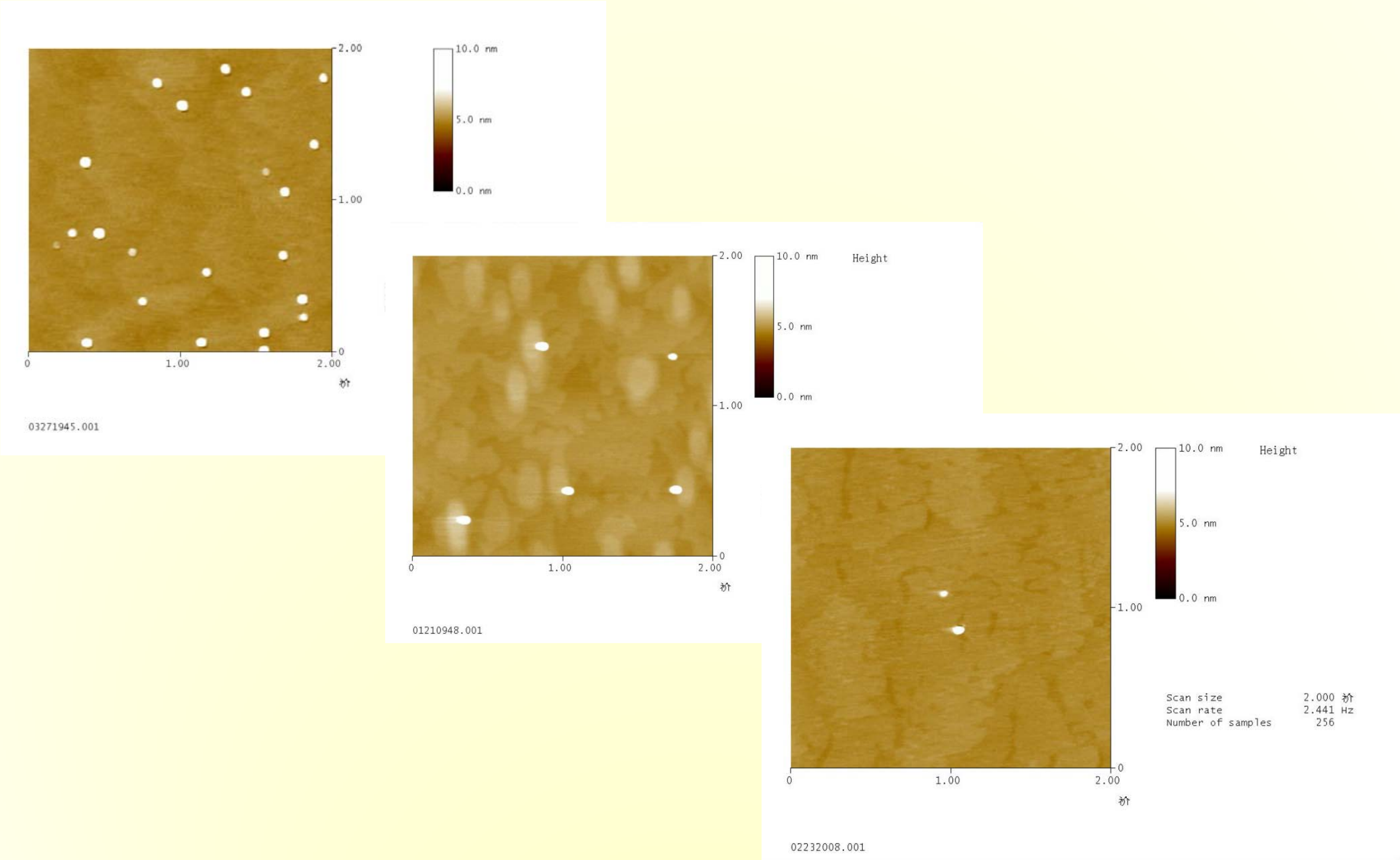
1、单量子点单光子发射器件



器件构成三要素

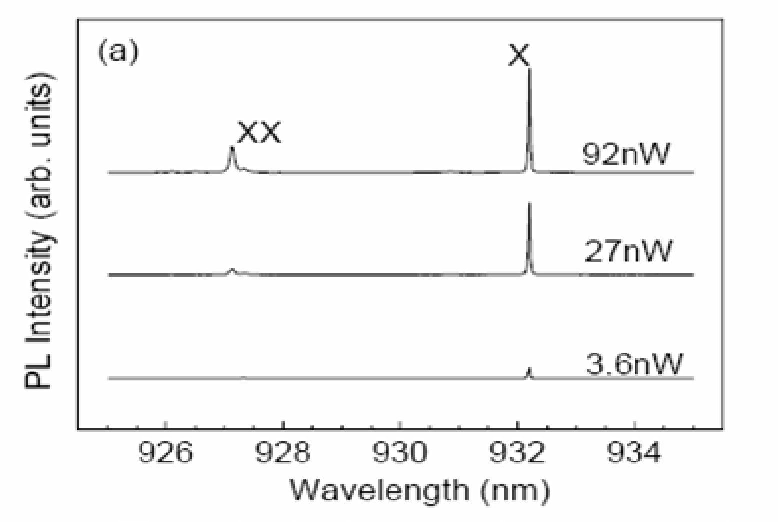
1. 量子点（二能级体系）
2. 微　腔（光学谐振腔）
3. 泵　浦（光或电注入）

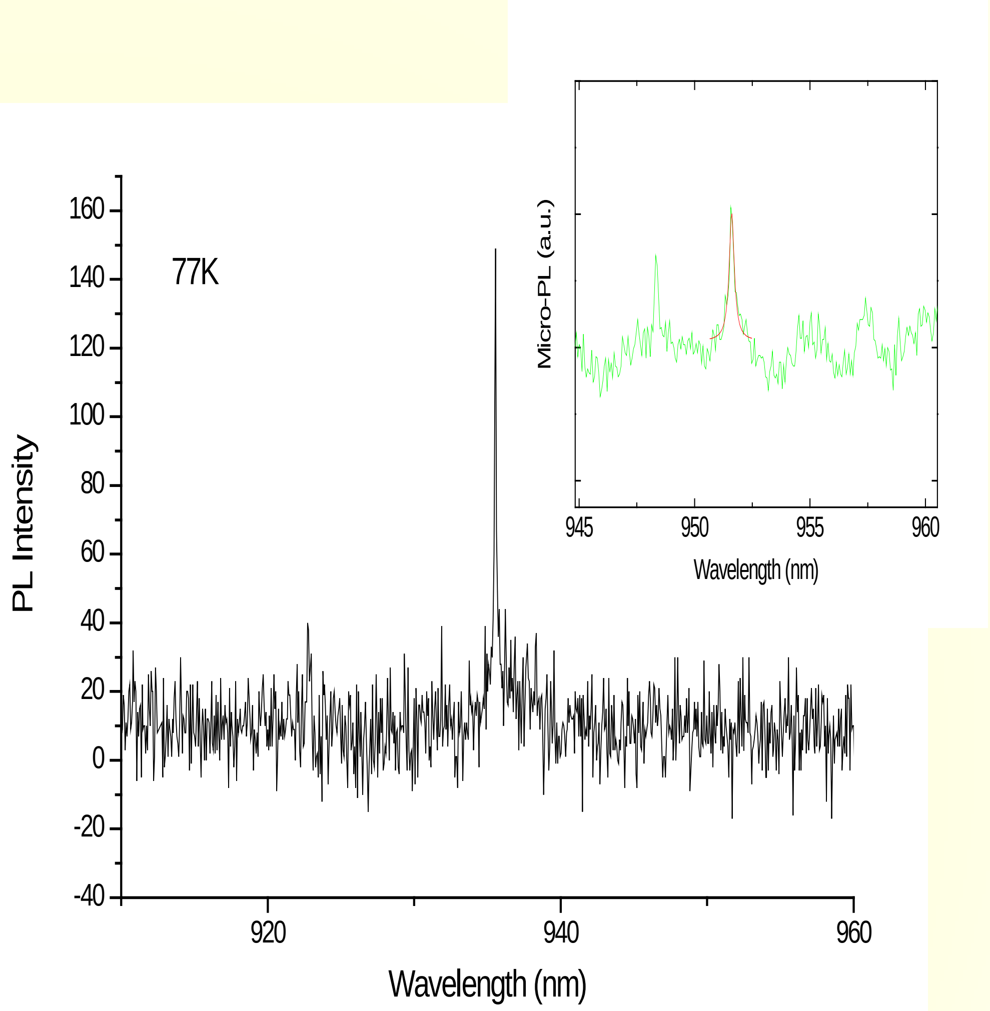
低密度InAs量子点外延技术



无需隔离制备工艺–直接分辨单量子点光谱

在77K温度下微区PL谱半宽约150ueV，与理论预测吻合。增加激发功率检测出单QD双激子峰。





量子点密度: 0.5个/um^2，表面覆盖[illegible]

单光子发射PIN器件特性参数

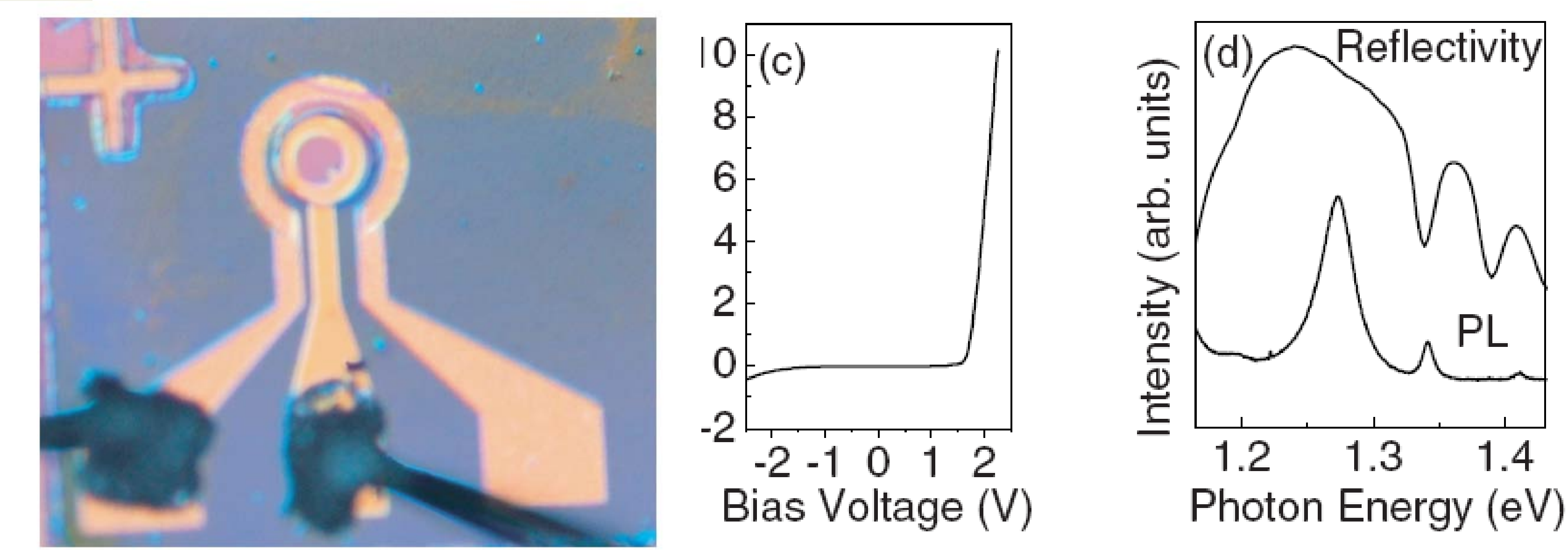
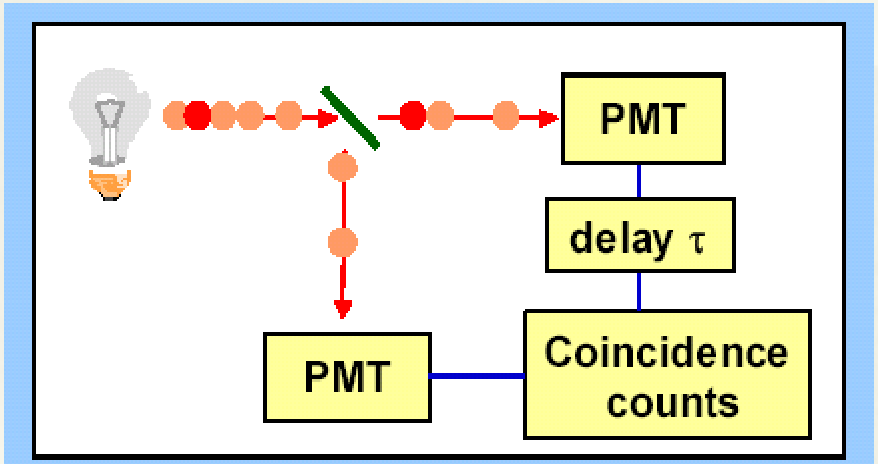


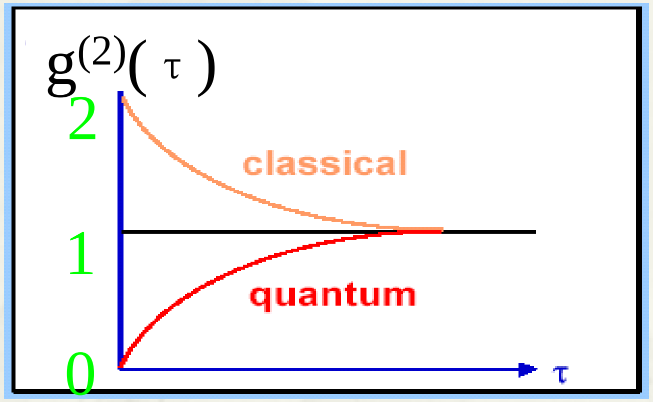
FIG. 1. (Color online) (a) Schematically vertical section of the diode. (b) Microscopic image of the diode. (c) Typical *I-V* character of the diode. (d) Reflectivity of the planer cavity and the PL of QD ensemble in the sample.

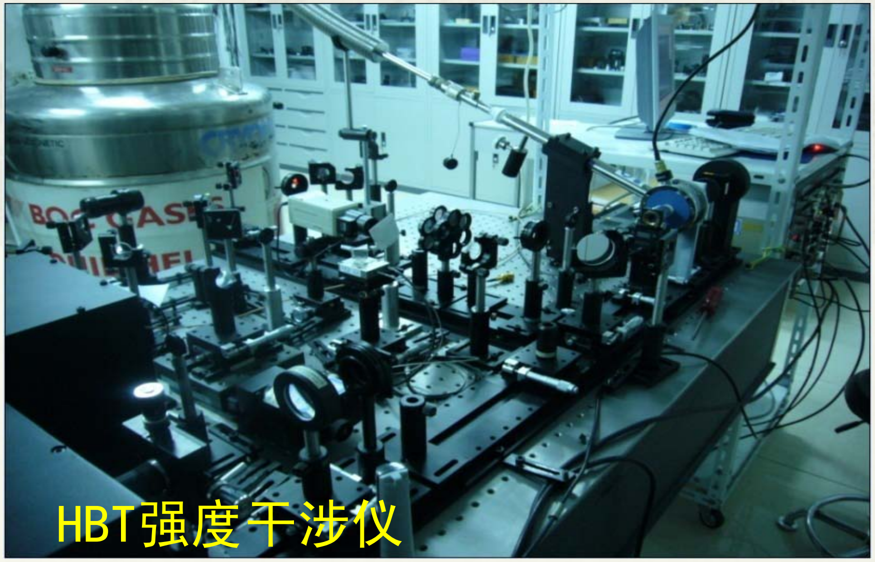
单光子发射二级强度时间关联HBT测试系统



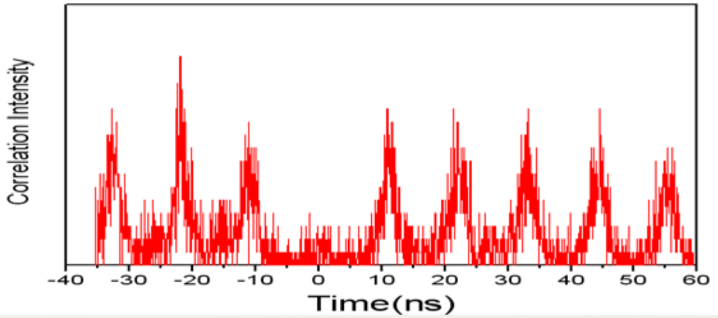
Hanbury Brown and Twiss experiment (1956)

$$g^{(2)}(\tau)=\frac{\langle I(t)I(t+\tau)\rangle}{\langle I(t)\rangle^2}$$





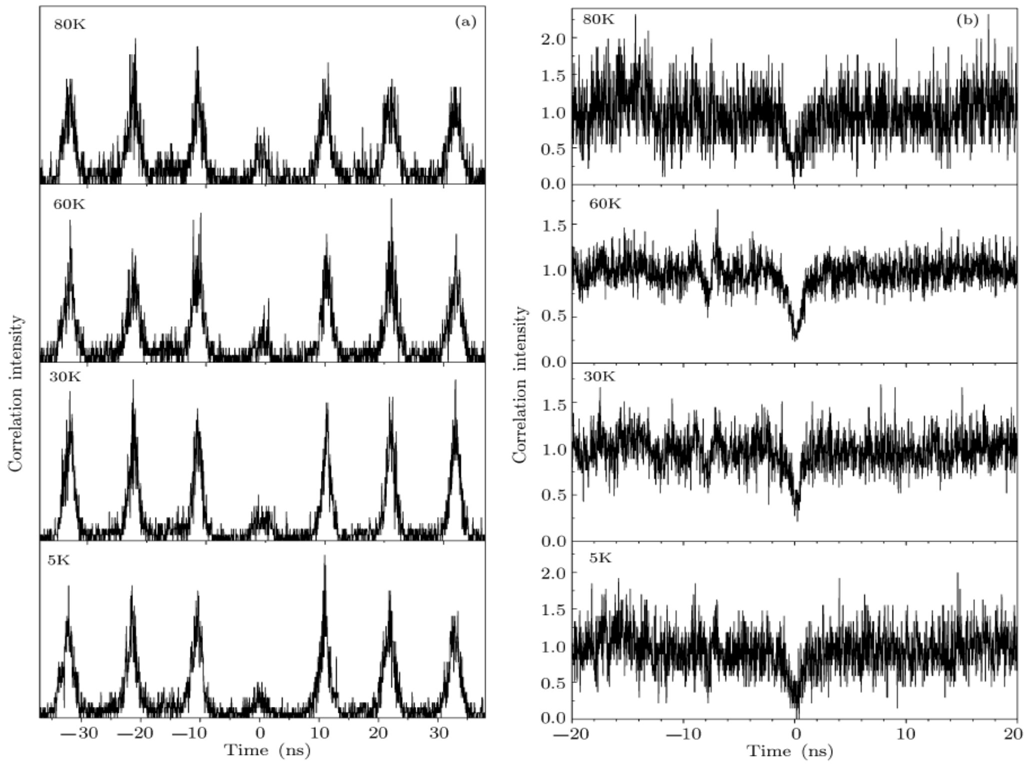
HBT强度干涉仪



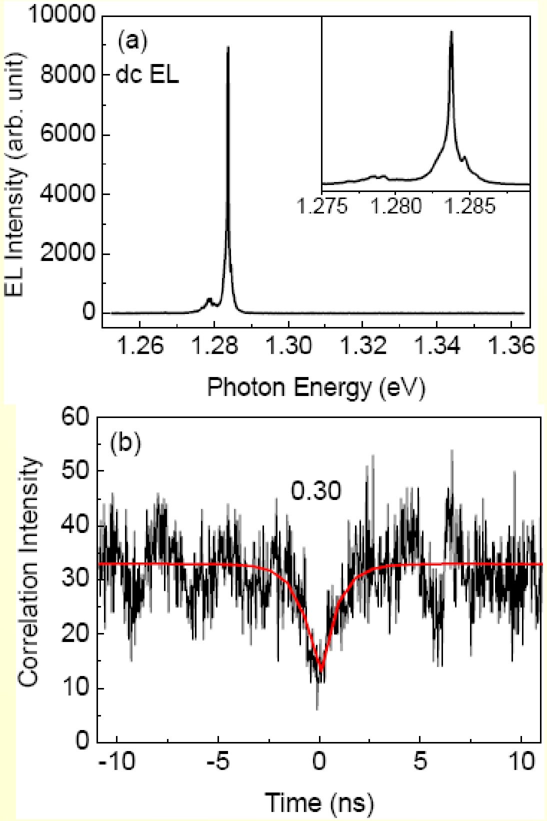
77K温度HBT谱

HBT测试结果-验证单光子发射性能

5-80K光激发



77K直流电激发

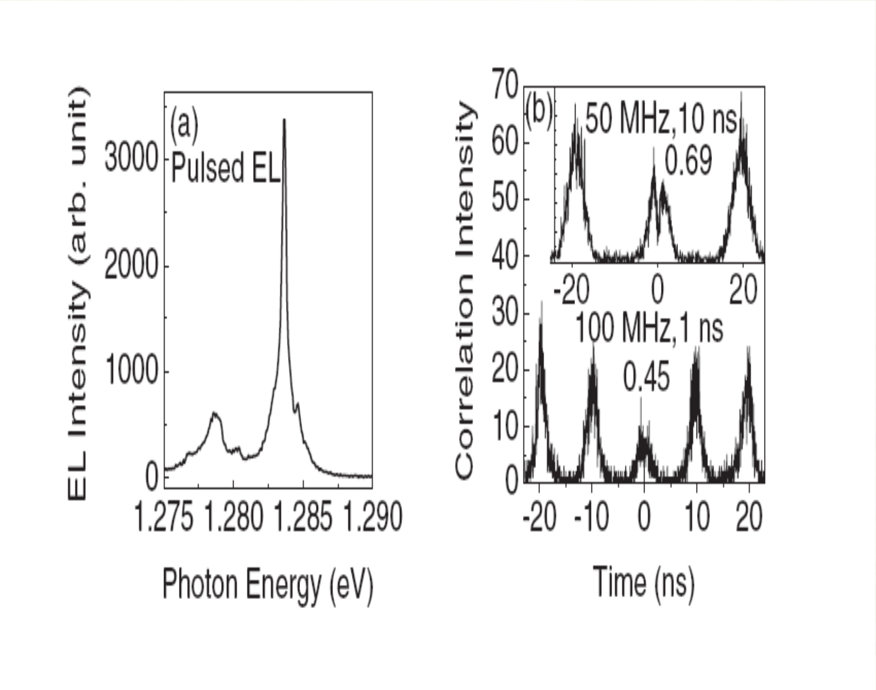


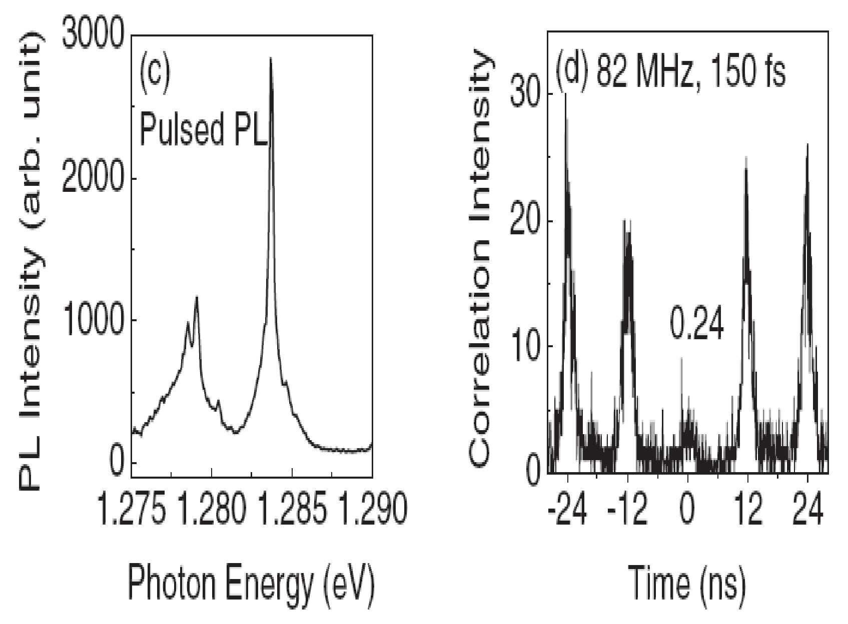
三因素造成 $g^{(2)}$ 大于零：HBT有限时间响应、APD暗计数、背景和相邻发光噪声

（a）电荧光谱
（b）二阶相关函数

液氮温度下脉冲电驱动单光子发射

Appl. Phys. Lett. 93, 101107(2008)





(a) EL 谱 脉冲电注入脉宽 1 ns.
(b) 脉冲EL(1ns脉宽)$g^2(t)$

(c) PL 谱线(激光脉宽150 fs）
(d) 脉冲PL二级关联函数 g^2t

第二部分 国家自然科学基金项目成果巡礼

2.10 半导体量子点单光子发射器件研究

量子保密通信是量子信息领域重要研究方向，单光子源器件是实现量子保密通信通信的核心器件。由于缺乏理想的单光子发射器件，目前的远距离量子密钥分发的实验结果原则上都有安全漏洞。如何得到一种稳定高效可靠的单光子源已经成为量子保密通信实用化的一个瓶颈。为解决上述科学难题，国家自然科学基金委以创新研究群体、杰出青年科学基金、重点项目和面上项目等多种形式对该领域进行了全方位、多层次的支持。最近，中国科学院半导体研究所超晶格国家重点实验室牛智川、孙宝权、李树深、夏建白等研究人员成功实现了量子点的单光子发射，相关研究成果在APL等重要刊物上发表论文二十多篇。主要成果为:

1．采用亚单原子层循环生长技术，制备出具有高发光效率的稀疏密度InAs/GaAs自组织量子点，其面密度可以控制在106/cm2－108/cm2，发光波长900－1300纳米。稀疏密度量子点材料的获得大幅度降低了隔离出单量子点的制备工艺难度，可以重复获得高质量单量子点，为单量子点的非经典光电效应的测试分析提供了材料基础。

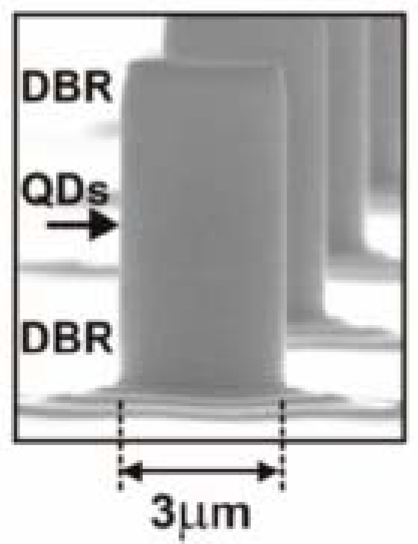
2．自主设计制备了分布布拉格反馈式平面微腔与InAs量子点耦合结构，建立了微腔反射中心波长原位检测和调整技术方法，实现了量子点发光波长的快速热退火调整，通过量子点和微腔光学模式的耦合，大幅度提高了单量子点的发光效率。

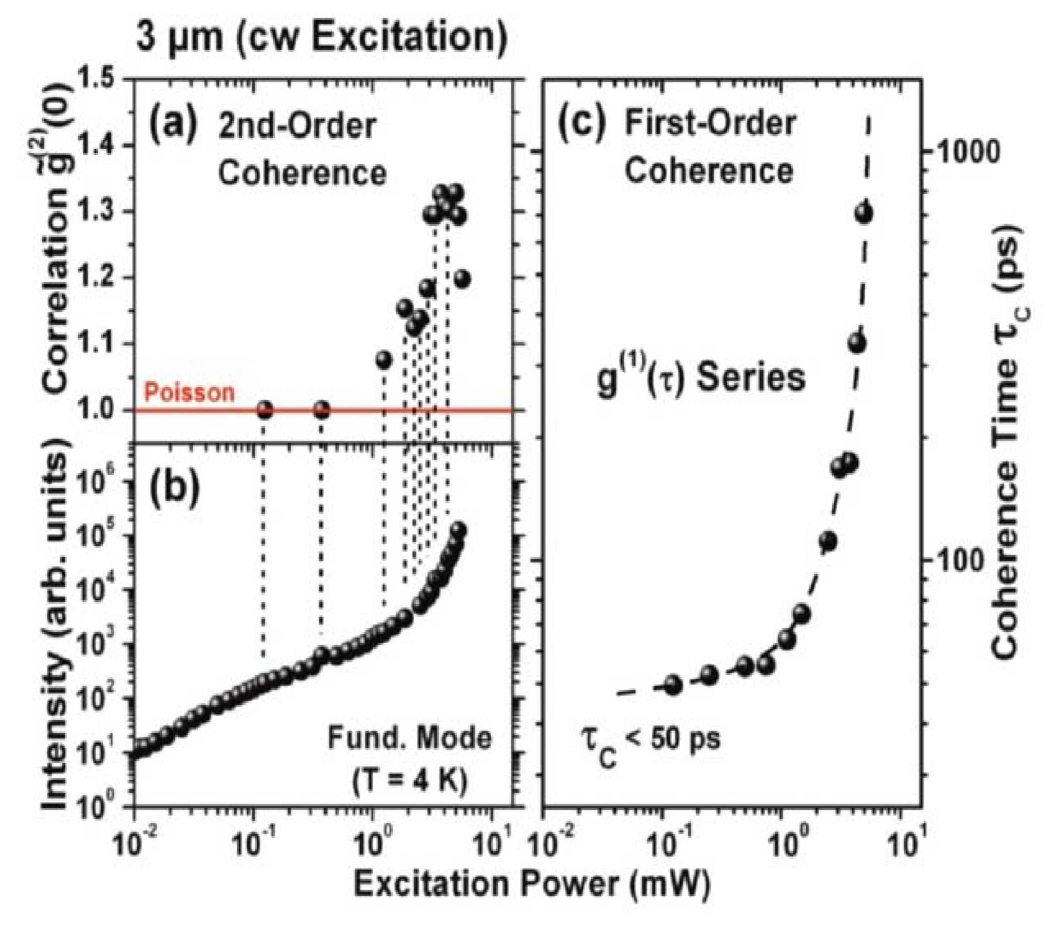
3．建立了激光非线性晶体参数下转换双光子纠缠态的关联性特性测试、纠缠光子杨氏干涉等HBT测试实验系统，建立了低温微区和时间分辨光谱测试系统，解决了单光子识别测试技术难题。

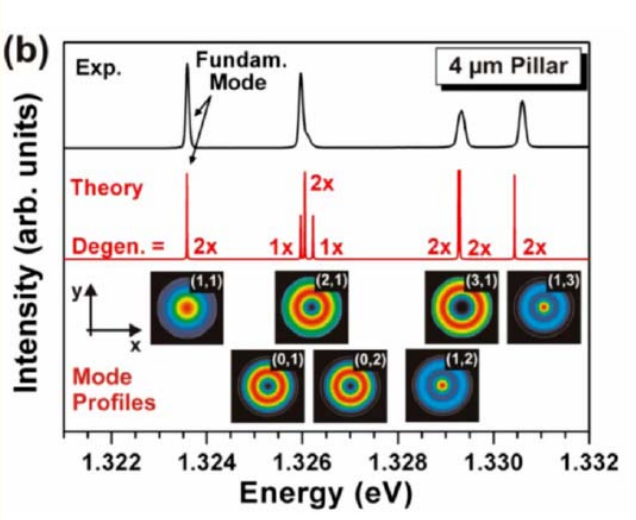
4．自主设计制备了电驱动微腔单量子点耦合单光子发射器件，实现了液氮温度下电驱动InAs量子点以及单光子发射，其中单光子发射波长965纳米，发射速率大于100KHz；该实验结果采用二级强度关联光荧光系统测试得到。

课题组首次实现的电驱动半导体量子点单光子发射，可为量子保密通信系统提供高性能的单光子源器件。 量子保密通信是量子信息领域重要研究方向，单光子源器件是实现量子保密通信通信的核心器件。

2、单量子点微腔激光器

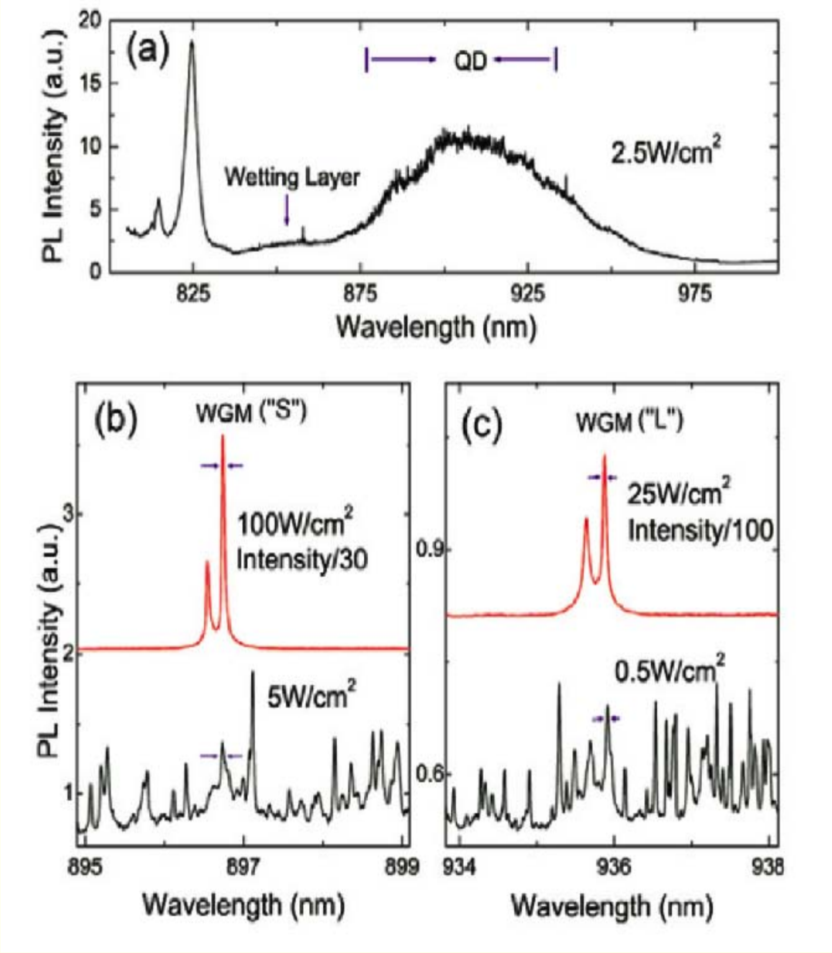


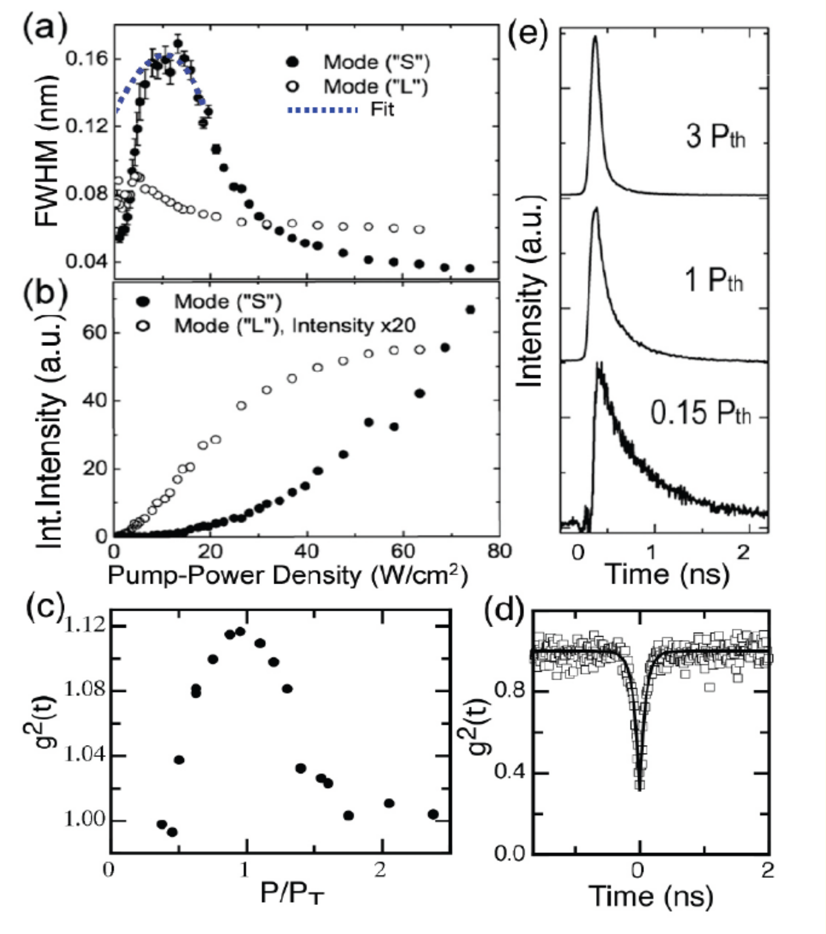




S. M. Ulrich等， PRL **98, 043906 (2007)**

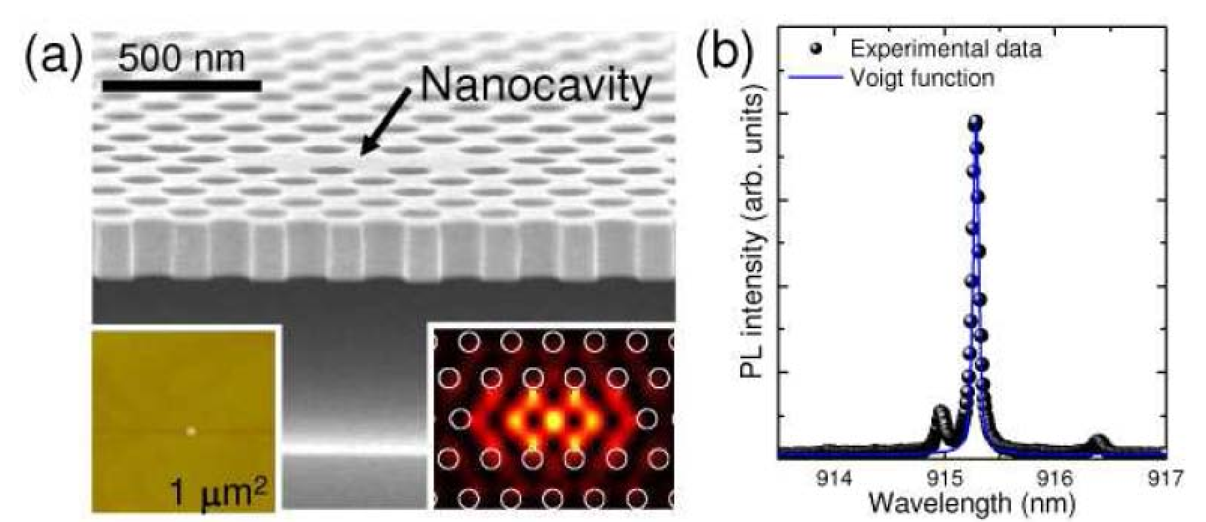
盘状状微腔单量子点激光器

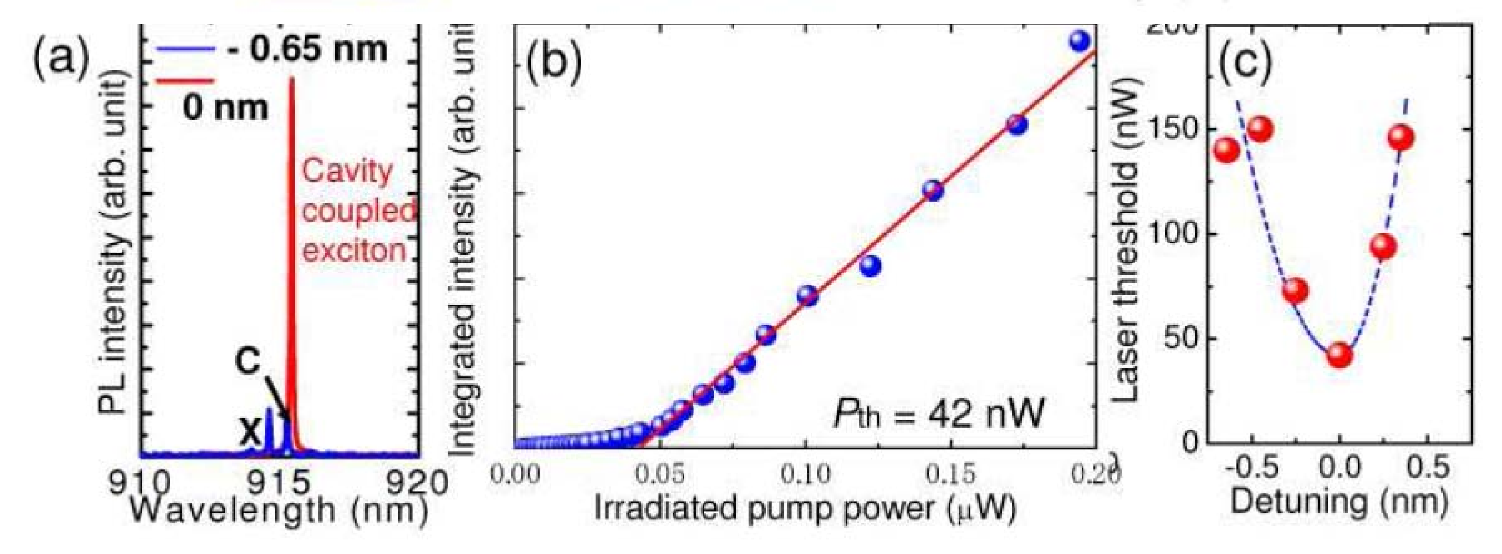




Z. G. Xie, PRL **98, 117401 (2007)**

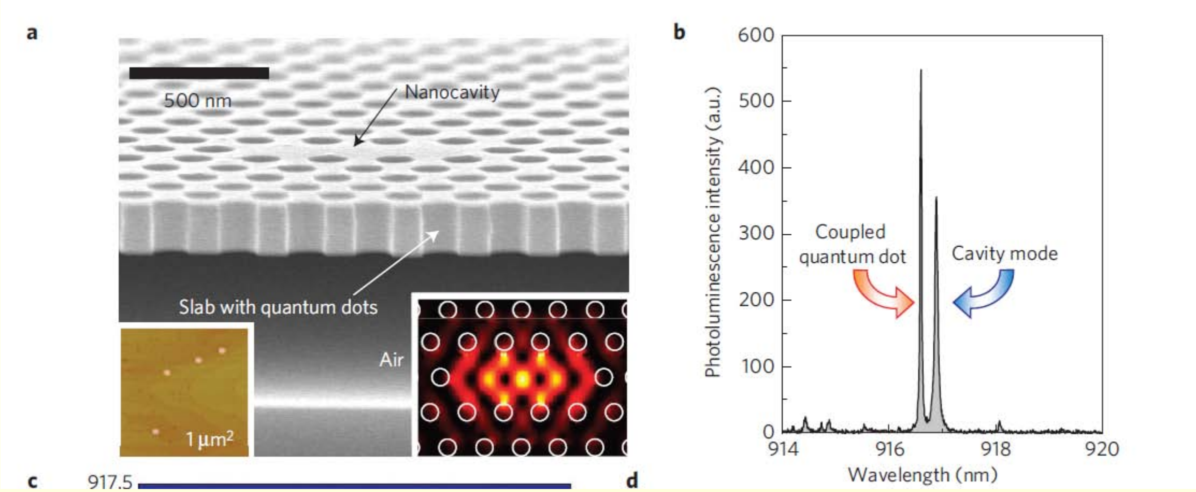
光子晶体微腔单量子点激光器

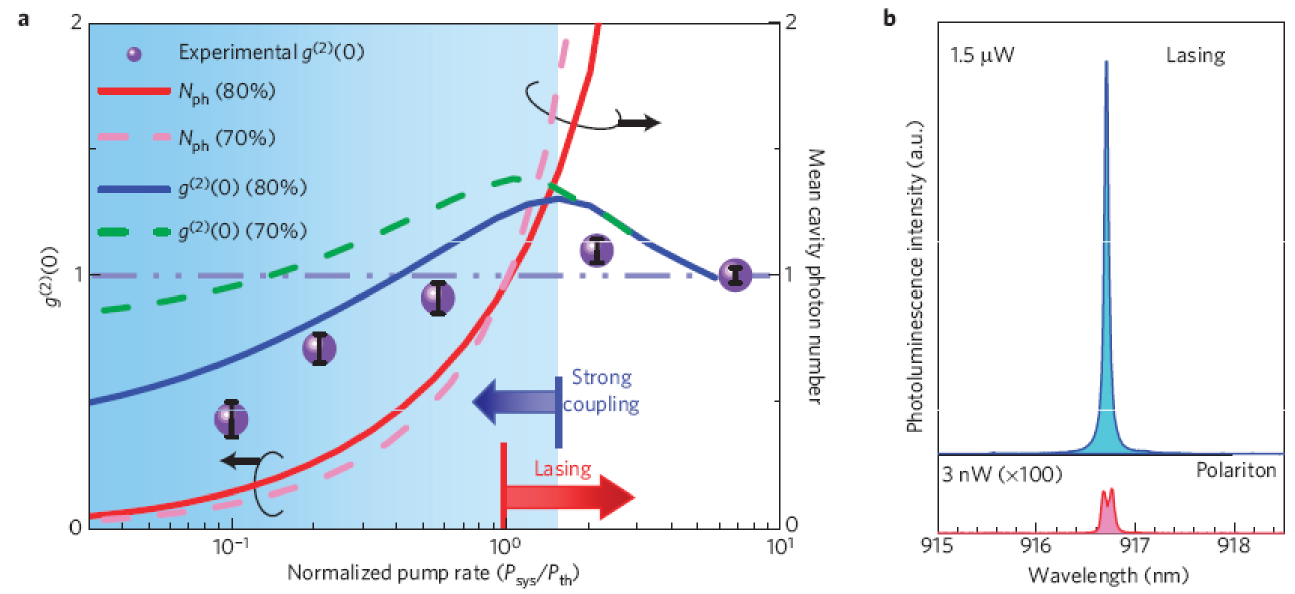




M. Nomura， Opt. Express 17, 15975–15982 (2009).

光子晶体微腔单量子点激光器

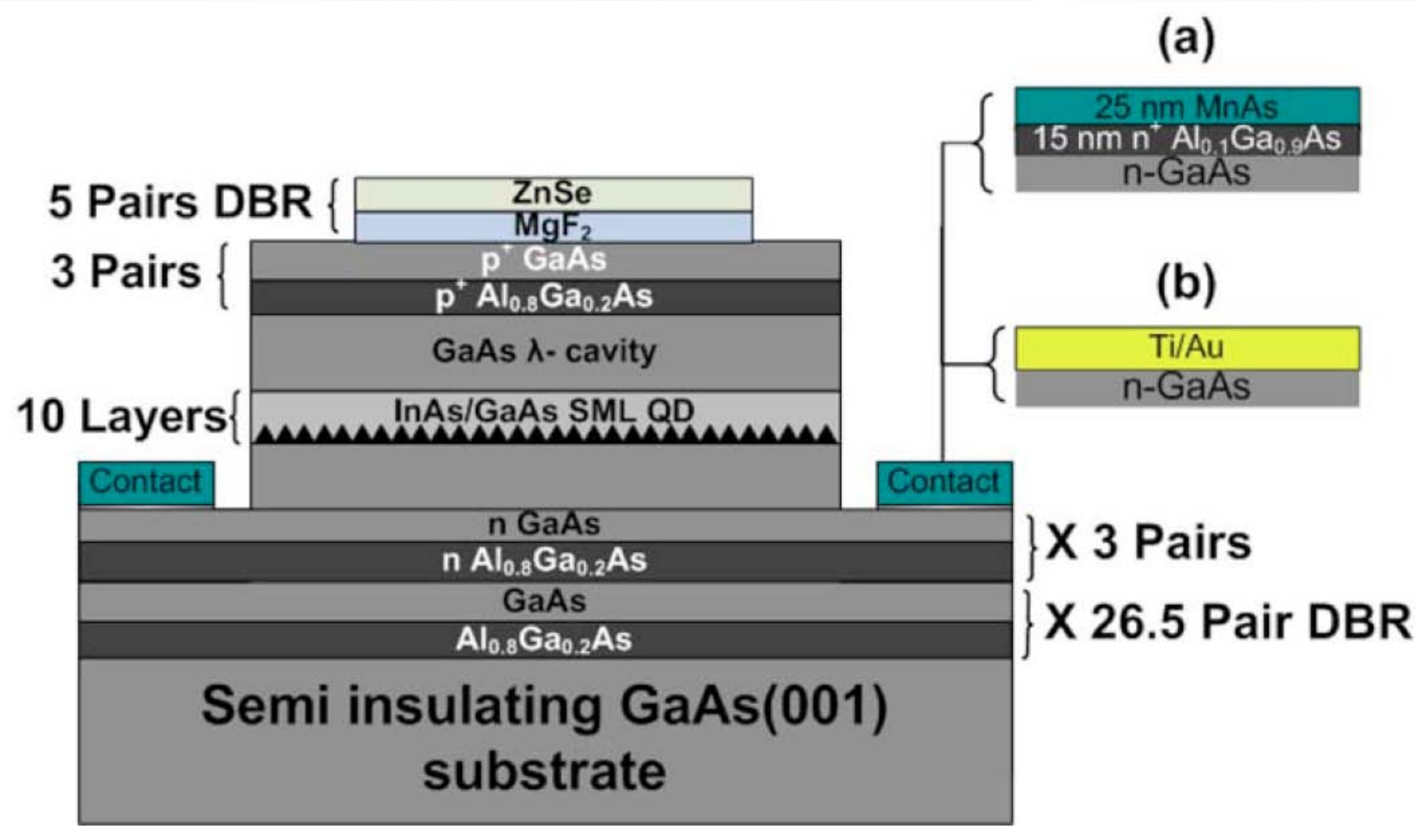




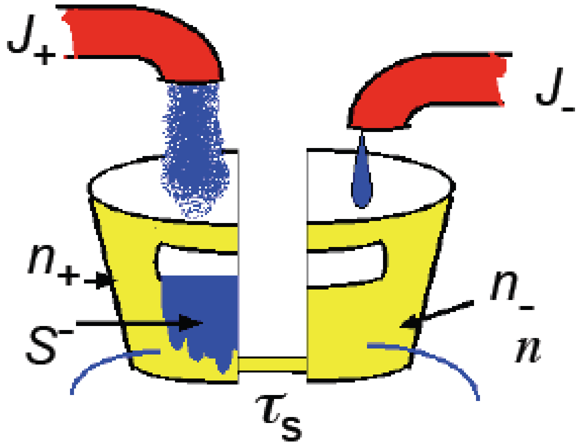
M. Nomura， NATURE PHYSICS， 6， 279（7, Feb. 2010）

3、量子点自旋激光器

QD-VCSEL + MnAs 磁性接触



自旋载流子注入激光速率方程



$J_{+/-}$	injection of spin up/down electrons
$n_{+/-}$	density of spin up/down electrons
$S^{-/+}$	density of left/right-polarized photons
τ_s	spin relaxation time

if only J_+ injection -> only 1/2 of the bucket needs to be filled -> threshold reduction!

$$\frac{d}{dt}n_\pm = J_\pm - g(\tfrac{3}{2}n_\pm + \tfrac{1}{2}n_\mp - n_{tran})S^\mp \mp (n_+ - n_-)/\tau_s^n - R_{sp}^\pm$$

$$\frac{d}{dt}S^\mp = \Gamma g(\tfrac{3}{2}n_\pm + \tfrac{1}{2}n_\mp - n_{tran})S^\mp - S^\mp/\tau_{ph}$$

J_+, n_+ couple to S^-

holes unpolarized + charge neutrality

$$g(n - n_{tran})S \rightarrow g(\tfrac{3}{2}n_\pm + \tfrac{1}{2}n_\mp - n_{tran})S^\mp$$

GaAs

Holes	$\sim 10^{-13}$ sec
Electrons	$\sim 10^{-9}$ sec

C. Gøthgen , R. Oszwałdowski, A. Petrou, I. Žutić, *Appl. Phys. Lett. 93, 042513 (2008)*

激光器双阈值 + 100%圆偏光输出

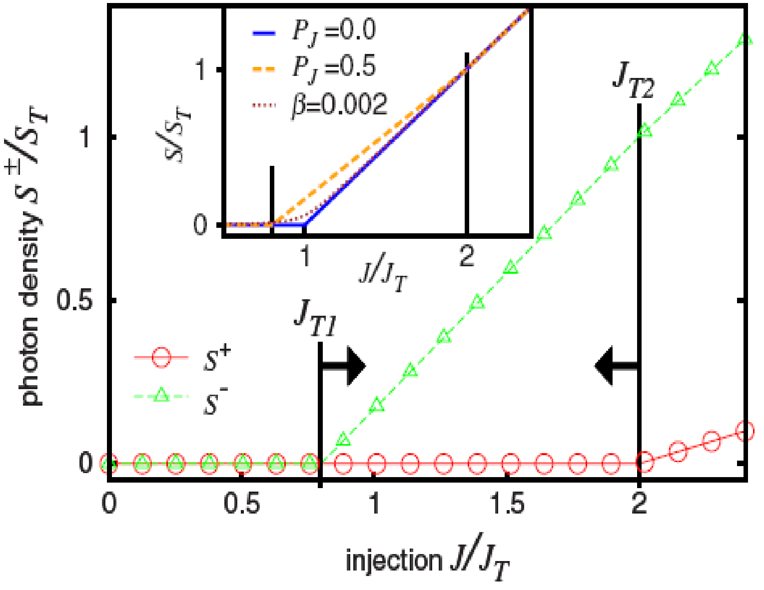


FIG. 1. (Color online) Photon densities of the left (S^-) and right (S^+) circularly polarized light as a function of electron current J with polarization P_J=0.5, infinite electron spin relaxation time, and LR. J is normalized to the unpolarized threshold current J_T, and $S^\pm$ is normalized to $S_T=J_T\Gamma\tau_{\text{ph}}$. The vertical lines indicate J_{T1} and J_{T2} thresholds, the arrows show their change when P_J is reduced. Inset: total photon density ($S=S^++S^-$) for unpolarized laser (P_J=0) and two spontaneous-emission coupling coefficients (β=0,0.002), as well as a spin laser with P_J=0.5 and β=0.

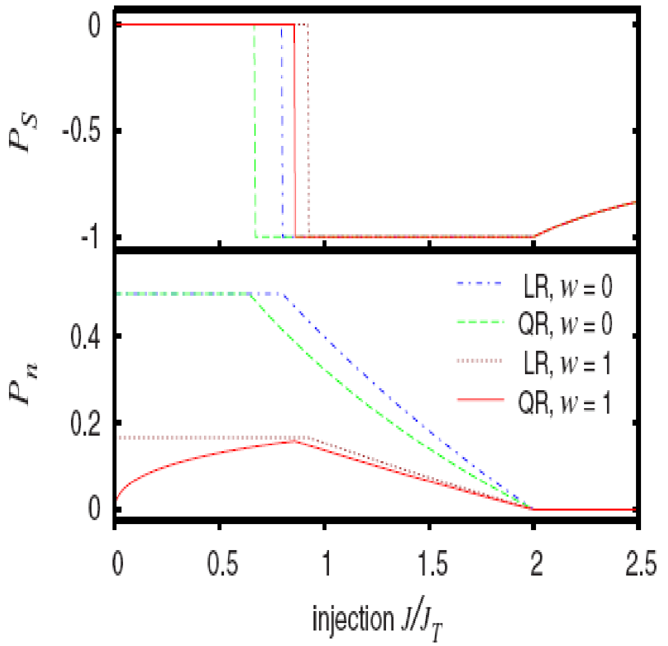


FIG. 2. (Color online) Electron (P_n) and photon (P_S) polarizations as a function of injection current J, with polarization P_J=0.5 and different ratios of recombination and electron spin relaxation time, w. LR and QR recombinations are shown. J is normalized to the unpolarized threshold J_T.

调制带宽增加

Modulation Response

$$\frac{\delta J(\omega)}{\delta S(\omega)} = |M(\omega)|e^{i\phi(\omega)}$$

Normalized Frequency Response

$$\frac{|M(\omega)|}{|M(0)|} = \frac{\omega_R^2}{[(\omega_R^2-\omega^2)^2+\gamma^2\omega^2]^{1/2}}$$

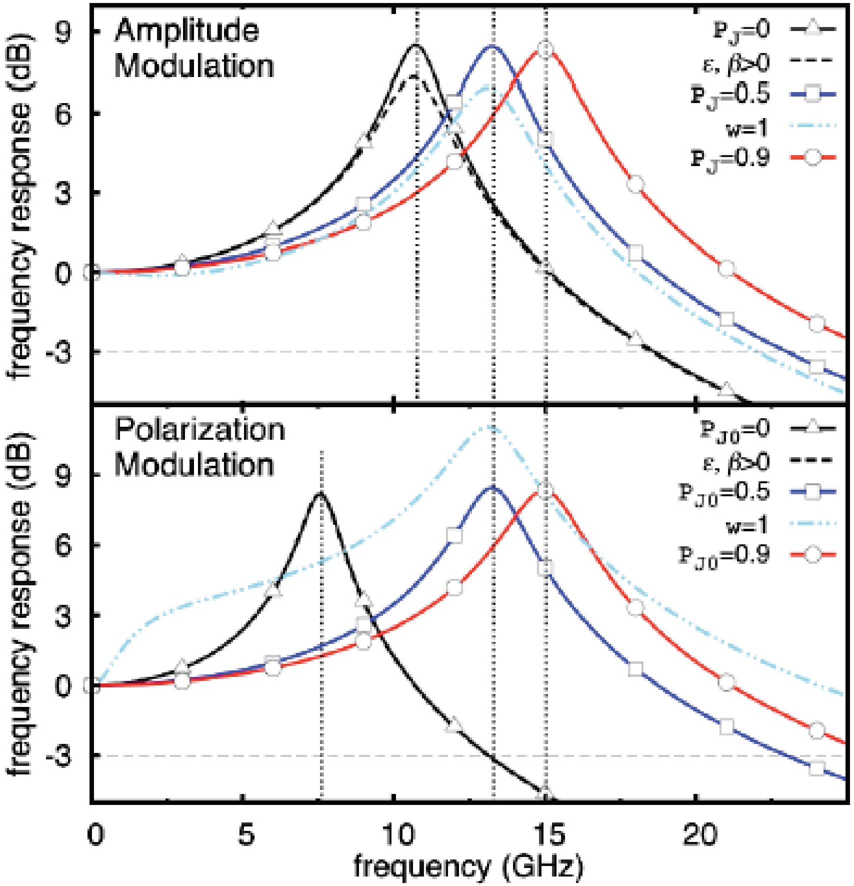
3-dB bandwidth $\sim \omega_R/2\pi$

$$\omega_R^2 = (3g_0\bar{S}_0/2\tau_{ph})$$

$$\sim (1+|P_{J0}|/2)$$

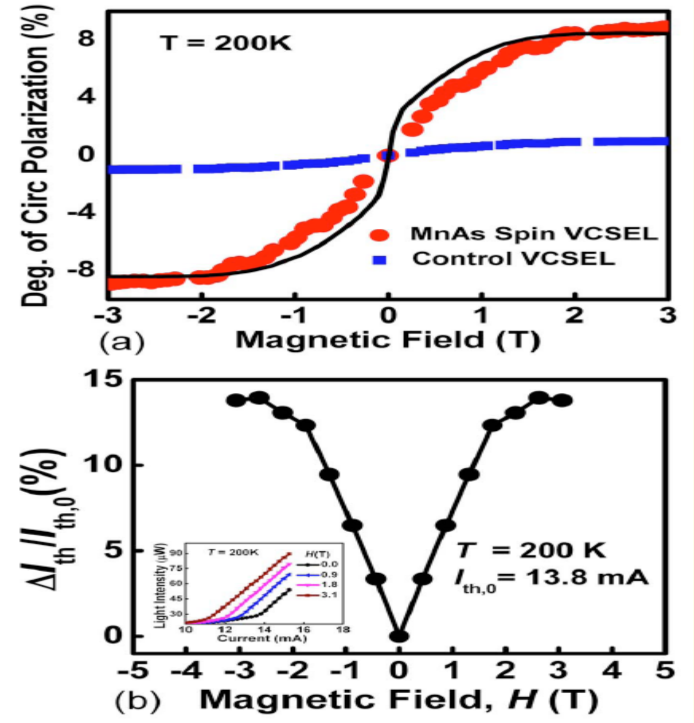
Steady-state threshold reduction

-> enhanced bandwidth

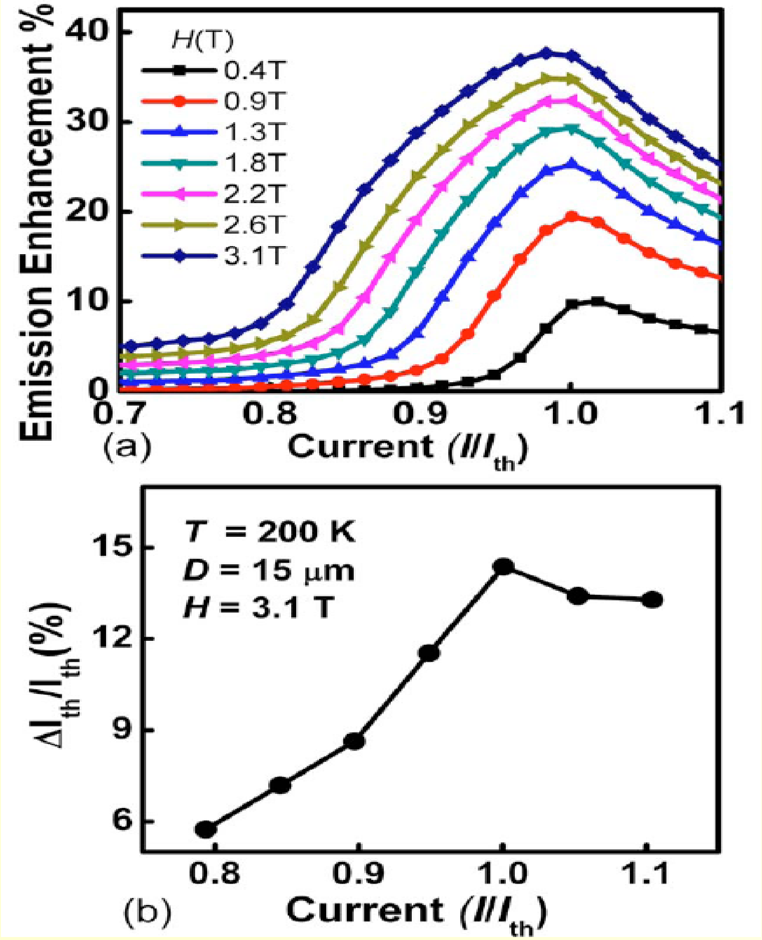


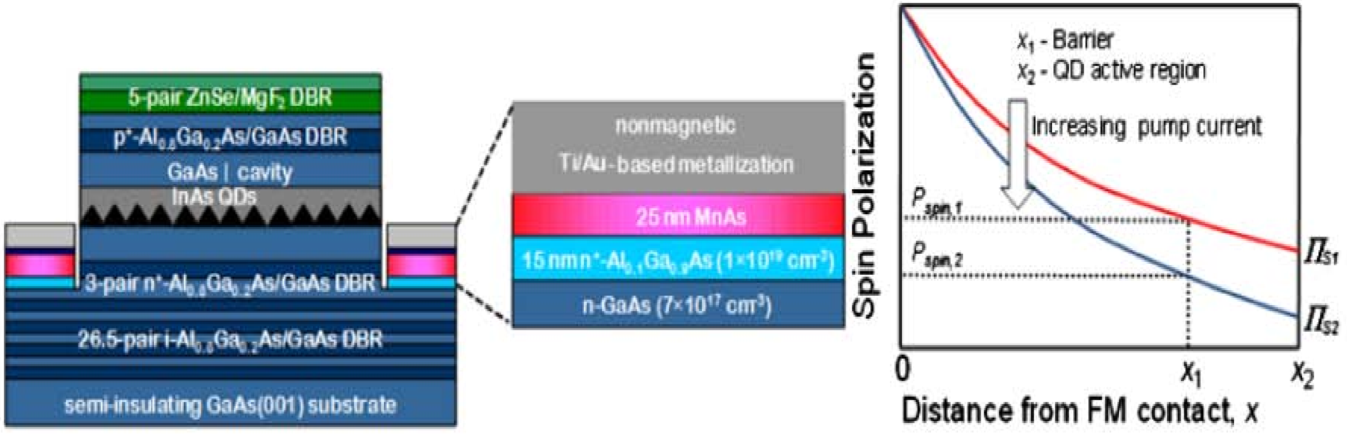
J. Lee, W. Falls, R. Oszwałdowski, I. Žutić, *preprint*

输出光圆偏度8%，阈值电流减小14%

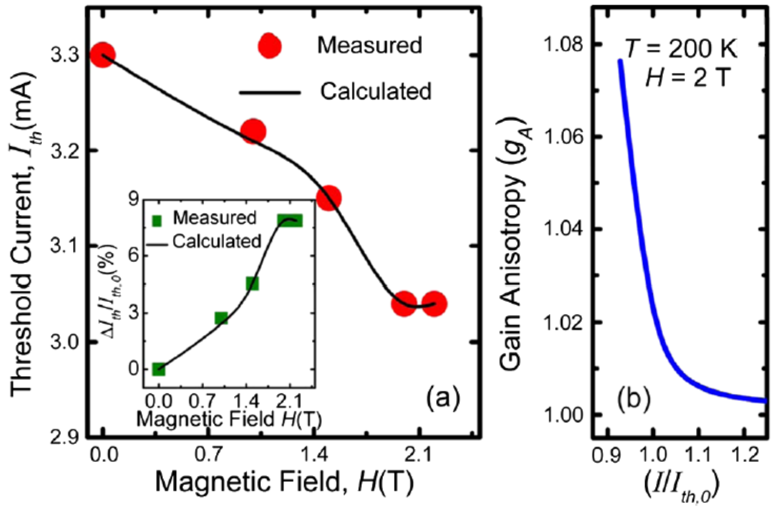


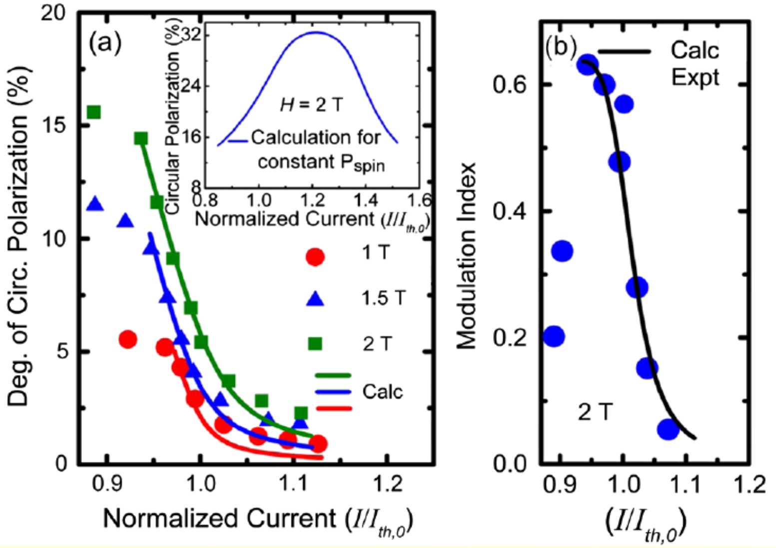
APL，92, 091119(2008)





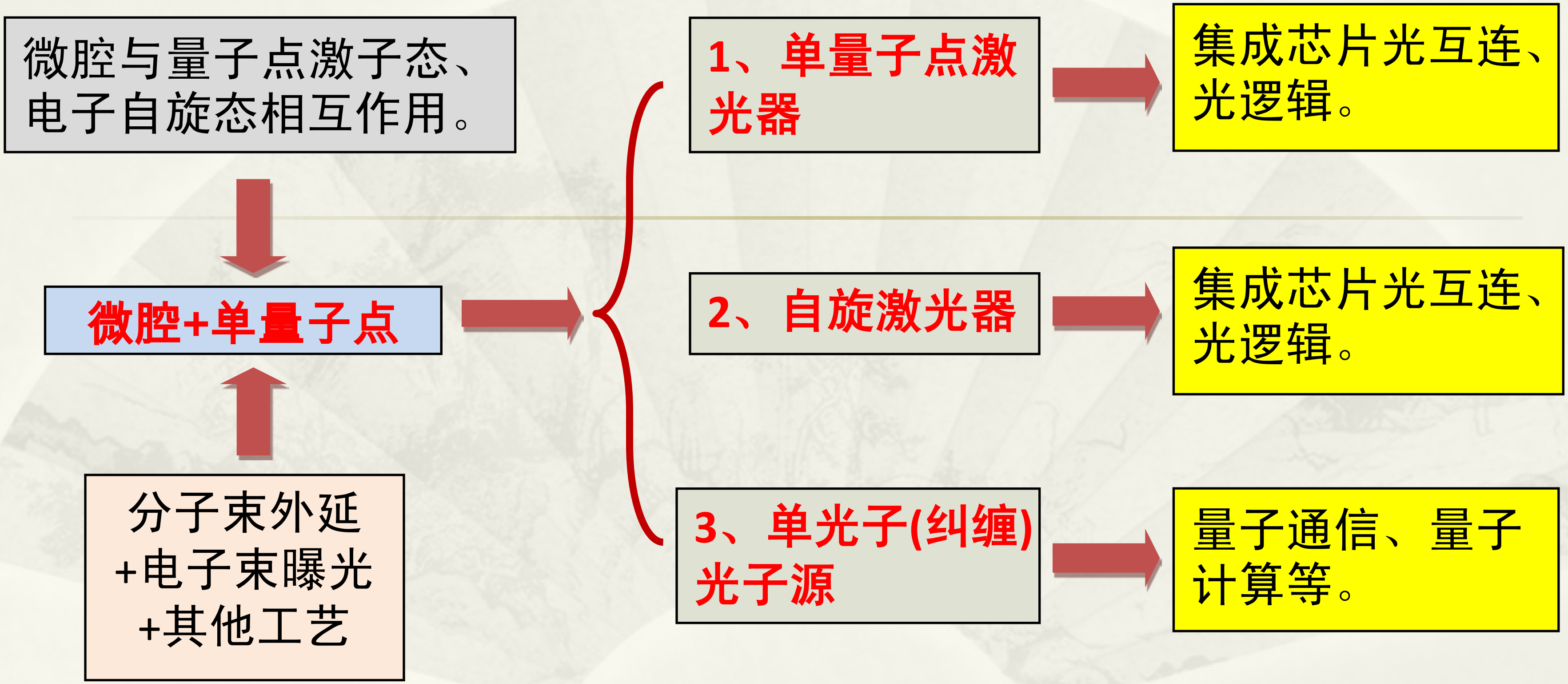
(a) (b)





PRL 102, 093904 (2009)

微纳结构量子光源研究方向



微腔与量子点激子态、电子自旋态相互作用。

微腔+单量子点

分子束外延
+电子束曝光
+其他工艺

1、单量子点激光器

集成芯片光互连、光逻辑。

2、自旋激光器

集成芯片光互连、光逻辑。

3、单光子(纠缠)光子源

量子通信、量子计算等。

1、采用光传输替代电传输?

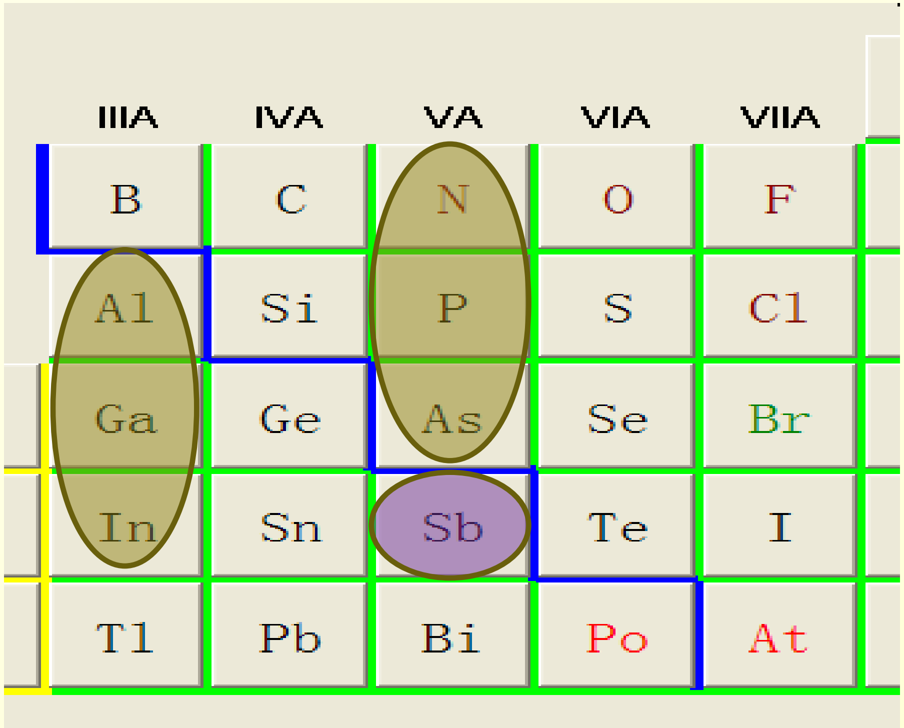
2、采用高迁移率材料替代Si?

↓

1、微纳量子结构低功耗光源

2、下一代高迁移率Sb化物材料

III-V族半导体材料研究新热点：Sb化物



IIIA	IVA	VA	VIA	VIIA
B	C	N	O	F
Al	Si	P	S	Cl
Ga	Ge	As	Se	Br
In	Sn	Sb	Te	I
Tl	Pb	Bi	Po	At

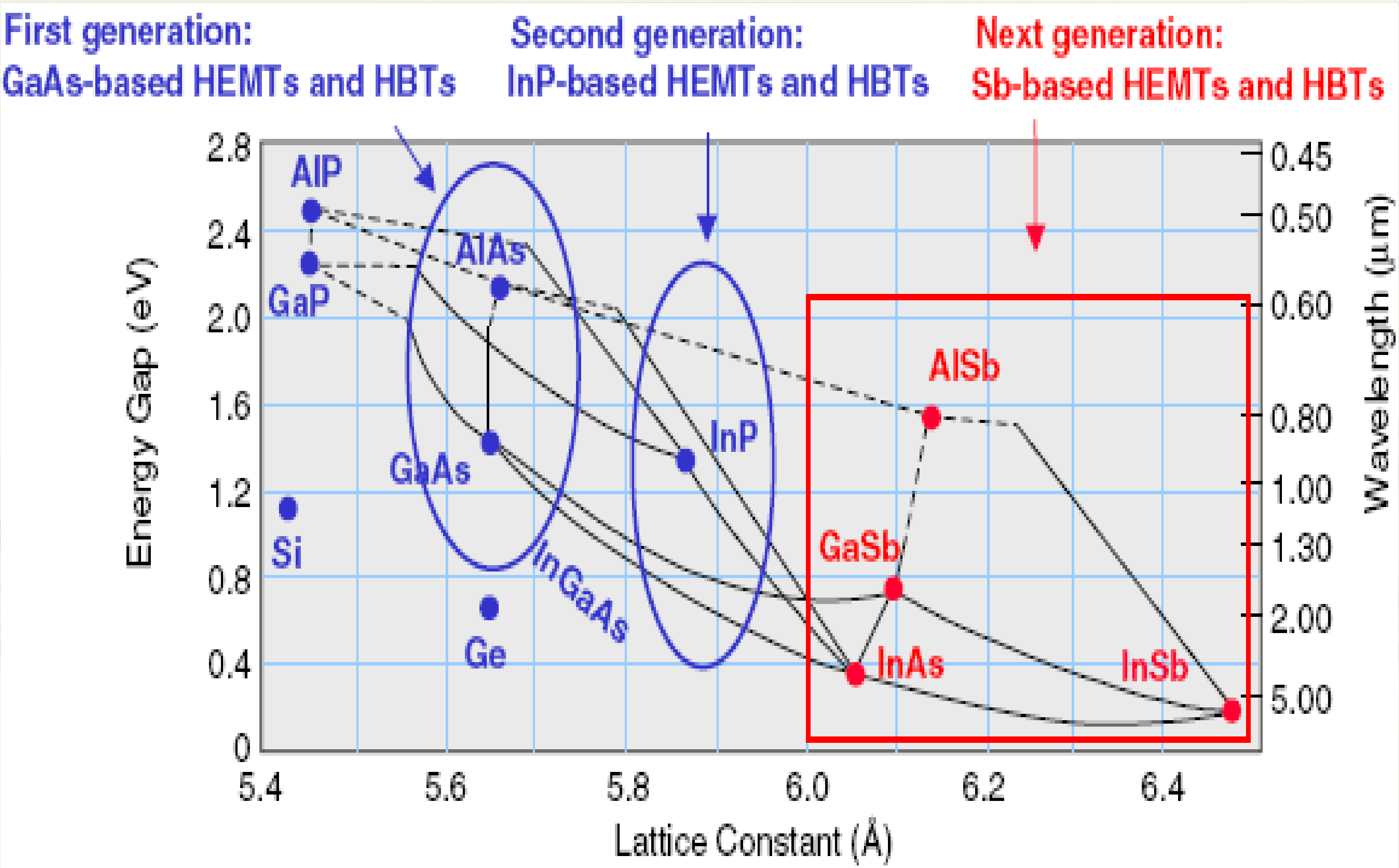
N 化物
As 化物
P 化物

Sb 化物

如： GaN， GaAs，InP， GaSb, ……，

按波段区分 蓝,绿,黄，红，近红外，红外，

III-V族电学材料与器件发展趋势


First generation:
GaAs-based HEMTs and HBTs

Second generation:
InP-based HEMTs and HBTs

Next generation:
Sb-based HEMTs and HBTs

Naval Research Laboratory，Solid-State Electronics 49 1875 (2005)

Sb化物电学特性

- **II（III）型能带结构**

  InAs与AlSb, GaSb之间存在II型能带结构，导带带隙差较大（InAs与AlSb之间为1.35eV）

- **电子迁移率极高**

  InAs~ 30000cm^2/Vs InSb~ 80000 cm^2/Vs。（300K）

- **功耗低**

  工作于Ka和W波段低噪声放大器（LNA）功耗不到同类型InP基器件的1/3

- **超高电子迁移率晶体管（HEMT）**
- **共振隧穿二极管（RTD）**
- **异质结双极型晶体管（HBT）**

第16届国际MBE会议
2010年8月22-27日，柏林

MBE 2010

16th International Conference on Molecular Beam Epitaxy

- **Start**
- General Information
- important Dates
- Program
- Scope
- Registration and Abstract Submission
- Conference Proceedings
- Exhibiton Sponsors
- Venue
- Accommodation
- Excursion
- Travel Information
- Contact

The international conference for all aspects of MBE growth as well as science, technology and application of epitaxial hetero- and nanostructures

Date: August, 22nd - August 27th

Venue: The Conference Venue is located in the Center of Berlin

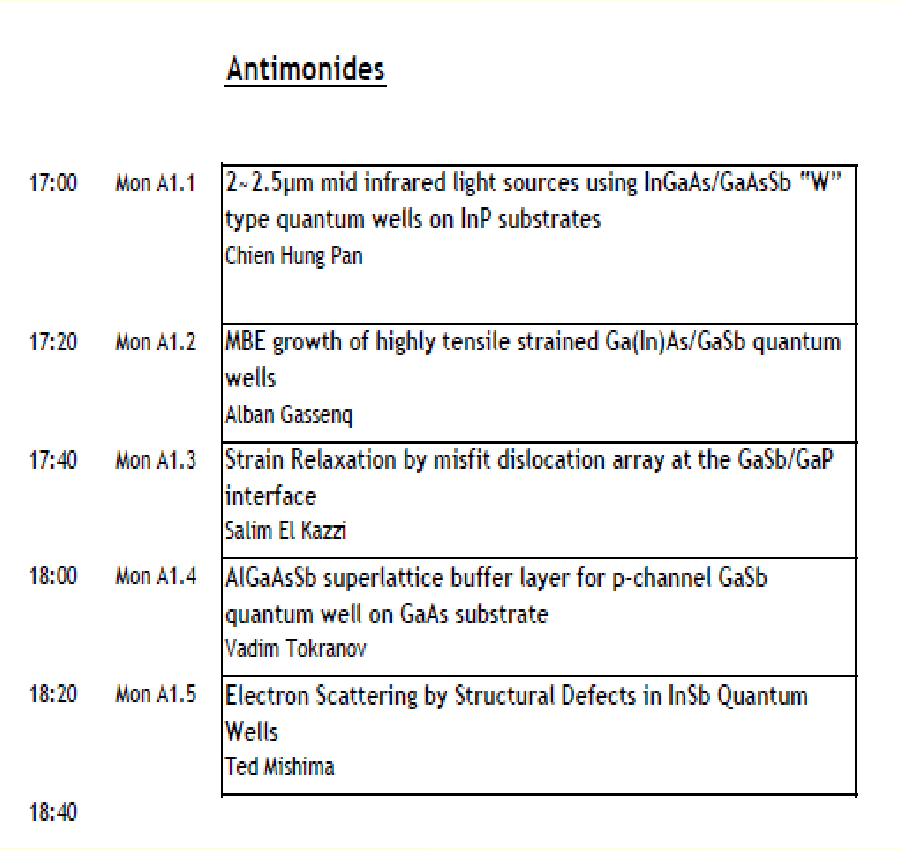
Humboldt-Universität zu Berlin, Unter den Linden
bcc Berliner Congress Center, Alexanderplatz

Organized by:

Prof. Dr. H. Riechert
(Paul-Drude-Institut, Berlin, Germany)

Prof. Dr. W. T. Masselink

Paul-Drude-Institut für Festkörperelektronik

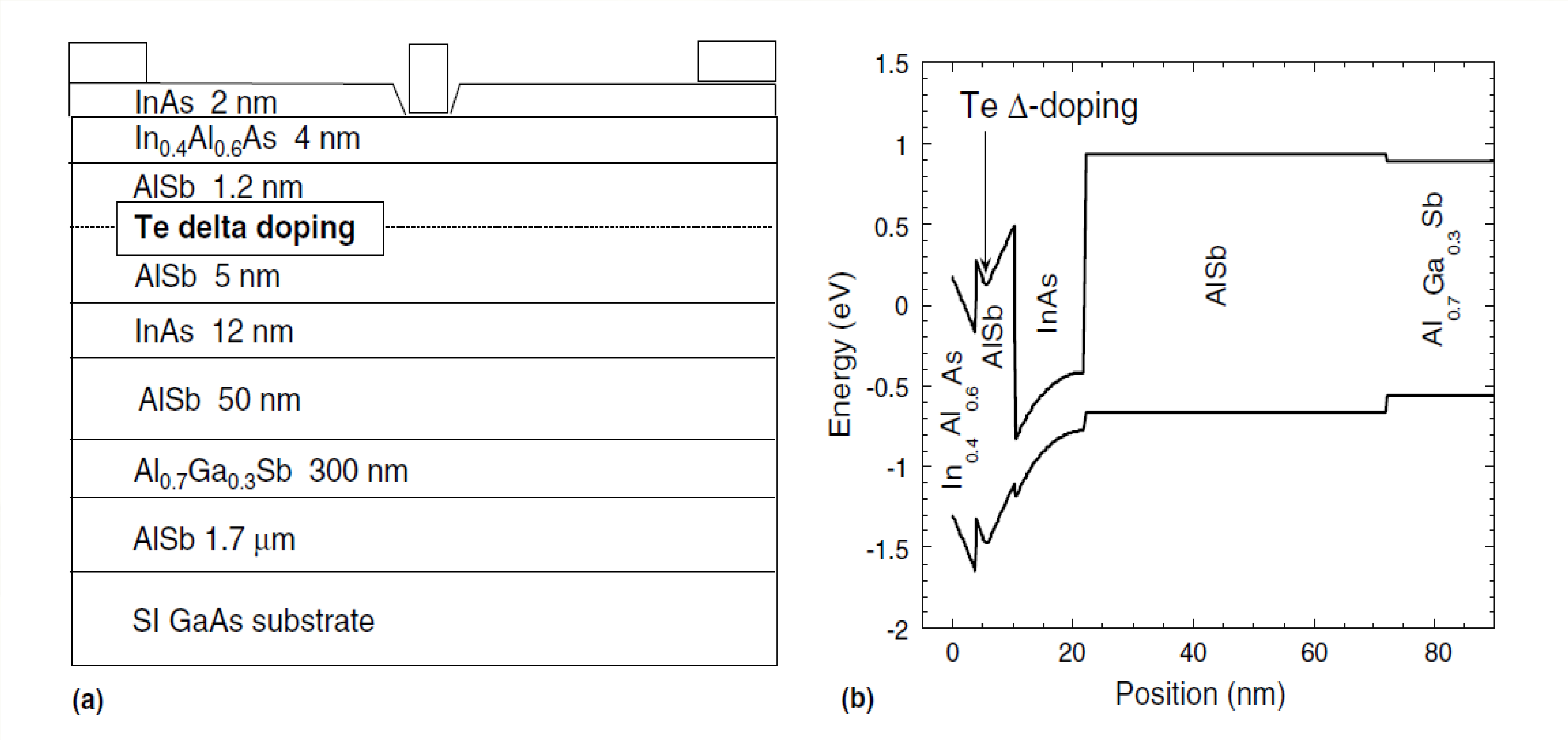


Antimonides

17:00	Mon A1.1	2~2.5μm mid infrared light sources using InGaAs/GaAsSb "W" type quantum wells on InP substrates Chien Hung Pan
17:20	Mon A1.2	MBE growth of highly tensile strained Ga(In)As/GaSb quantum wells Alban Gasseng
17:40	Mon A1.3	Strain Relaxation by misfit dislocation array at the GaSb/GaP interface Salim El Kazzi
18:00	Mon A1.4	AlGaAsSb superlattice buffer layer for p-channel GaSb quantum well on GaAs substrate Vadim Tokranov
18:20	Mon A1.5	Electron Scattering by Structural Defects in InSb Quantum Wells Ted Mishima
18:40		

350篇论文首次组织Sb化物专场

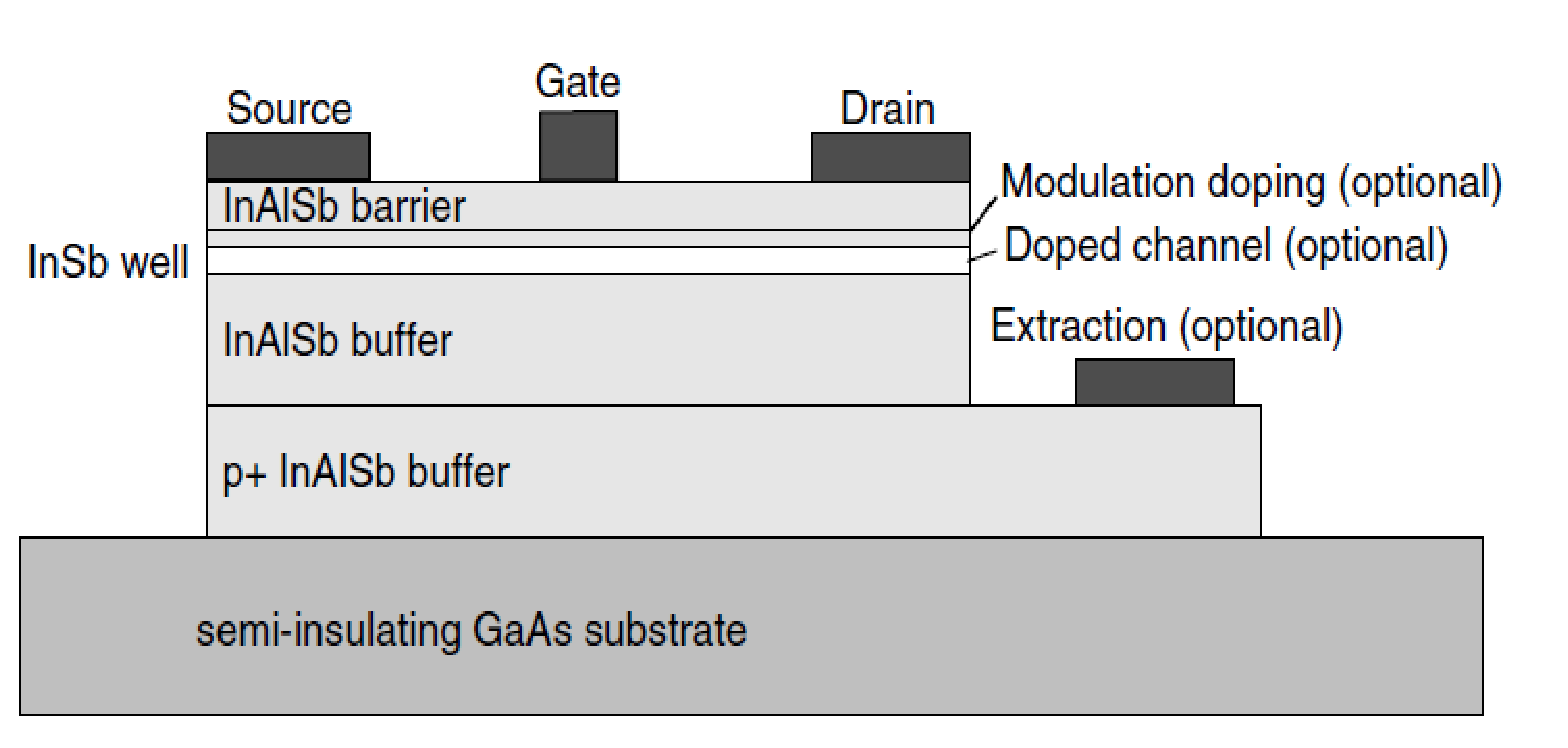
HEMT异质结与能带结构



异质结结构

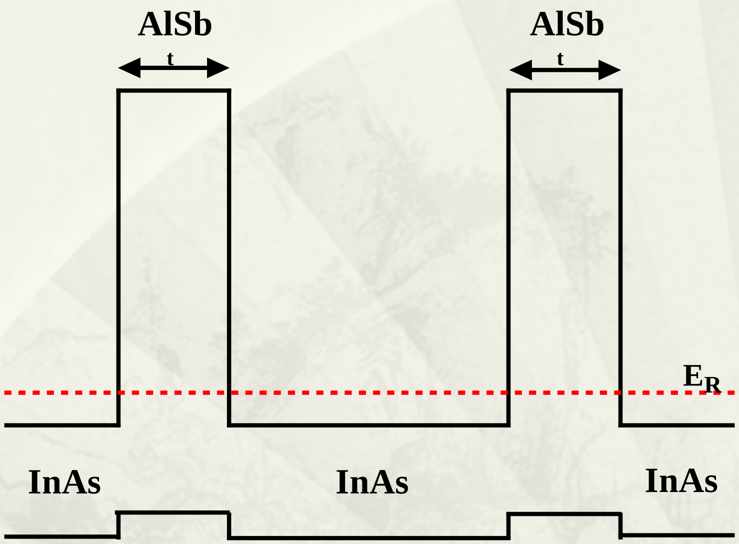
能带结构

InSb量子阱 HEMT

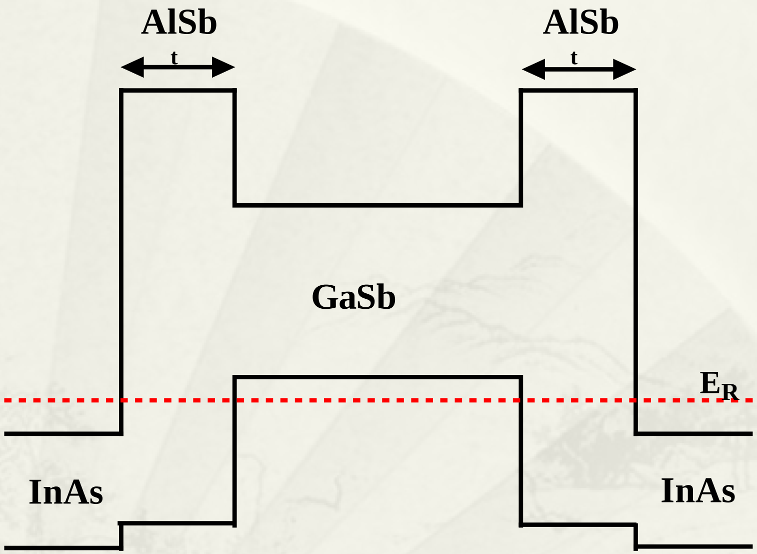


室温下的InSb HEMT迁移率达到40000cm²/V·s

Sb基共振隧穿二极管

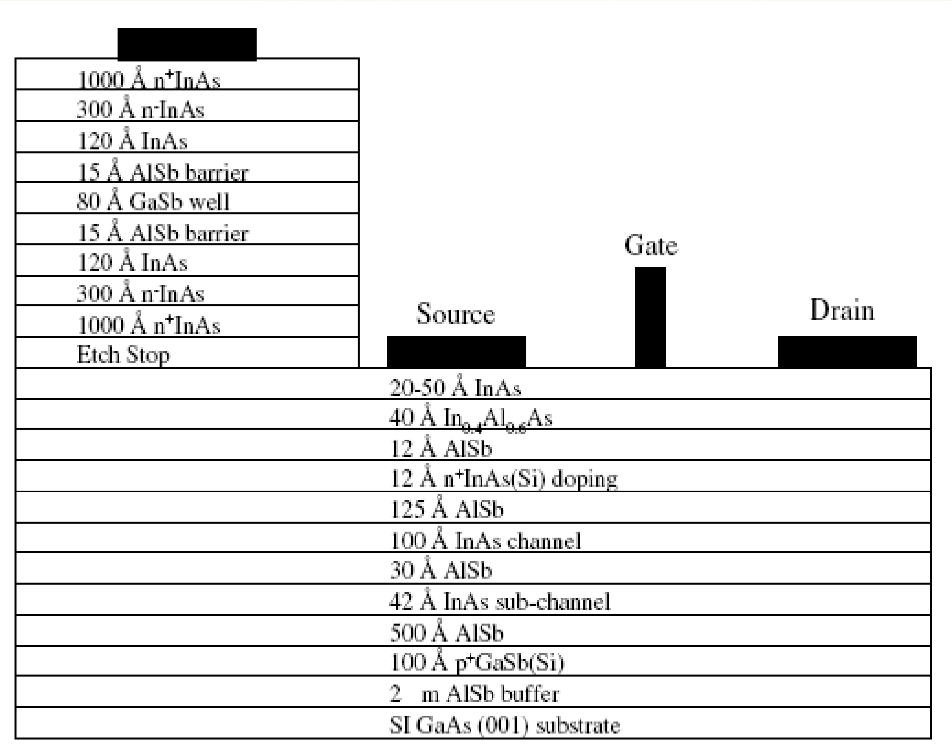


共振隧穿二极管（RTD）



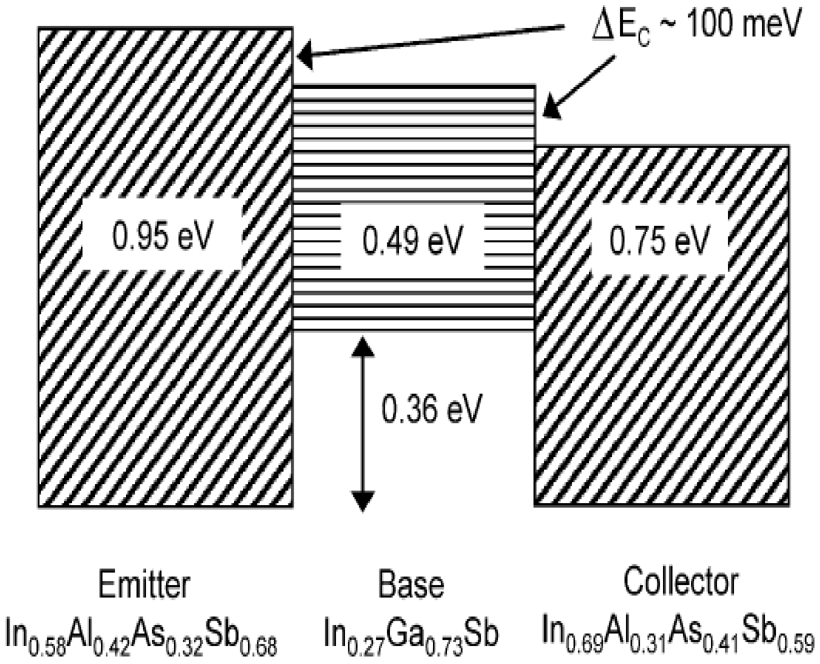
带间共振隧穿二极管（RITD）

Sb基RITD与HEMT集成

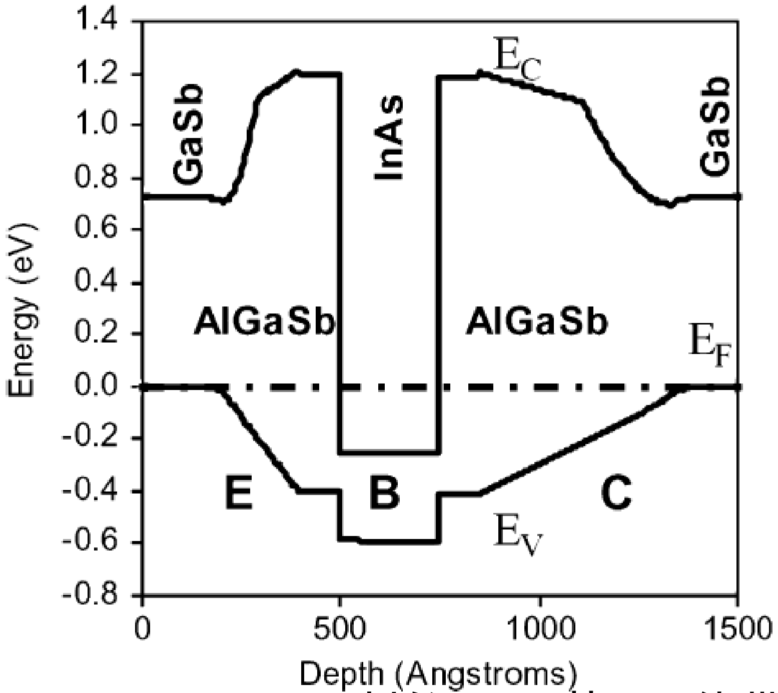


美国海军实验室利用RITD和HEMT集成将有可能为移动通讯设备提供功耗非常小的电子元器件。（Solid-State Electronics 49 1875 (2005)）

GaSb衬底上的Sb化物HBT



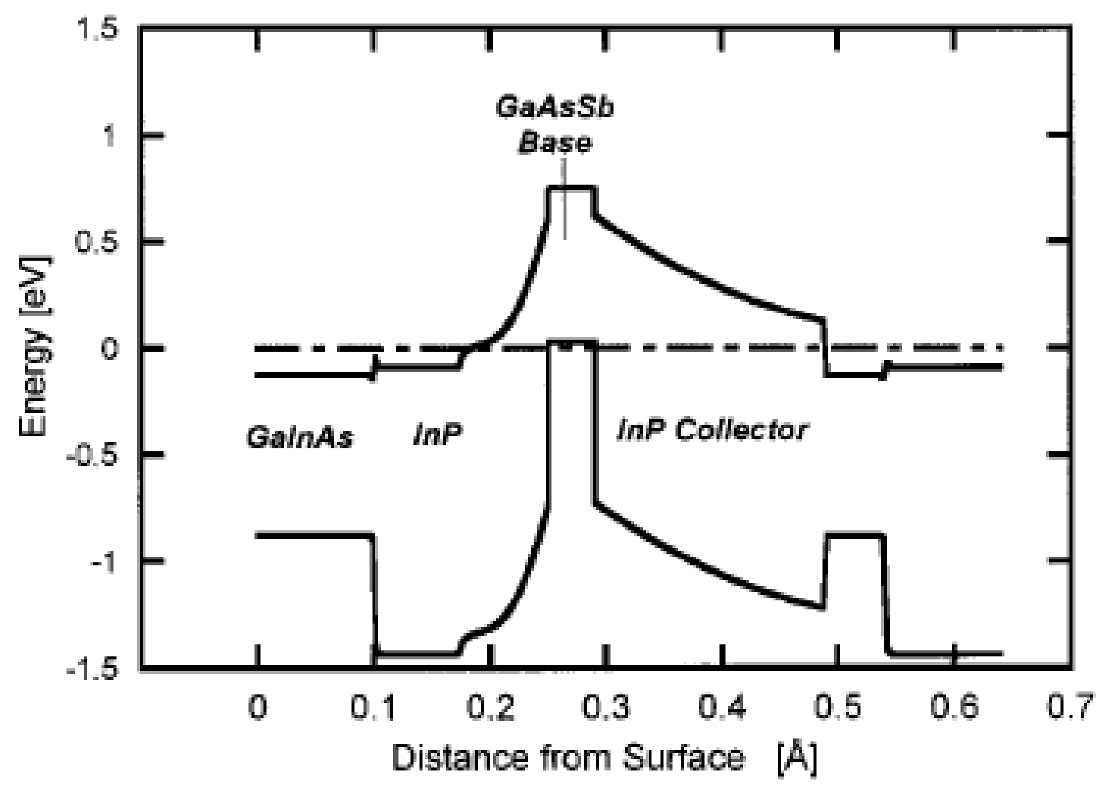
美国海军实验室GaSb基HBT能带结构



Rockwell公司研制的GaSb基HBT能带结构，V_{BE}为0.2V。

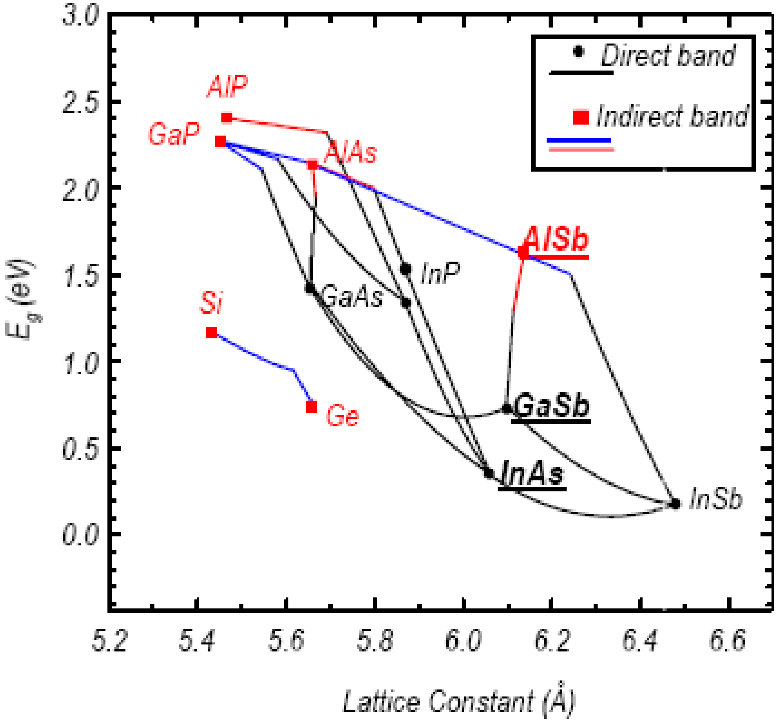
较小的基区和发射极间电压意味着较大的收集极电流
这有利于器件高频和低功耗工作

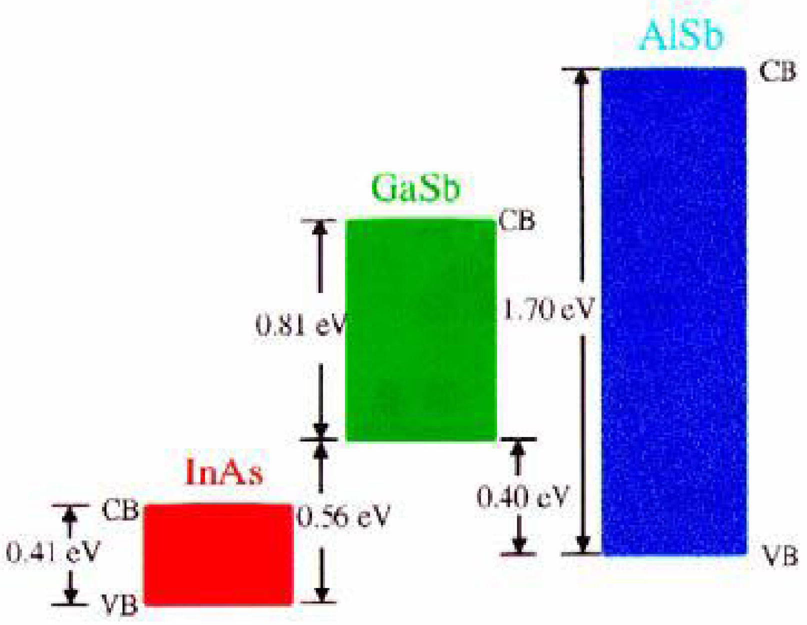
InP衬底上的Sb化物HBT



采用GaAsSb材料取代InP基HBT中的InGaAs基区以减小收集极电流阻碍

Sb化物：第三代红外光电器件





第十届国际中红外材料与器件会议
2010年9月5-9日，上海

10th International Conference on

Mid-Infrared

Optoelectronics:

Materials and Devices

September 5 – 9, 2010

Shanghai, China

PROGRAM AND ABSTRACTS

Organized by :Shanghai Institute of Microsystem and Information Technology,Chinese Academy of Sciences

State Key Laboratory of Functional Materials for Informatics,China

聚集了国际红外领域的著名小组：

美国西北大学：M. Nazeghi

美国海军实验室：J. Meyer

瑞士ETH Zurich：J. Faist

德国弗朗和费、肖特基研究所

法国CNRS研究所：A. Baranov

法国Montpellier大学：E. Tournie

加拿大NRC-IMS：H. C. Liu

俄罗斯Ioffe 研究所

1/3论文为Sb化物

Sb化物激光器研究

QW、SL、QCL、VCSEL、VECSEL
主要波段2-3微米、3-4微米、5微米
发光功率几十毫瓦、几瓦、十瓦以上都有报道

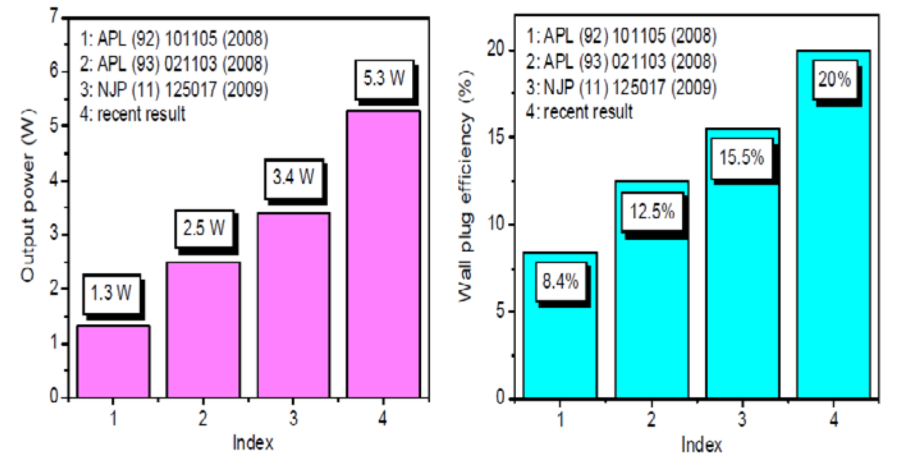


Fig. 2. Steady improvement of output power (left) and wall plug efficiency (right) of quantum casc lasers around 4.7 μm in room temperature continuous wave operation.

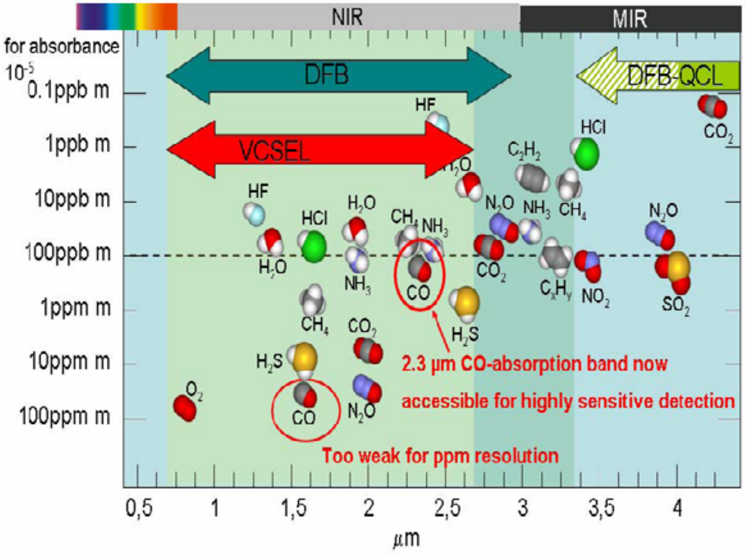
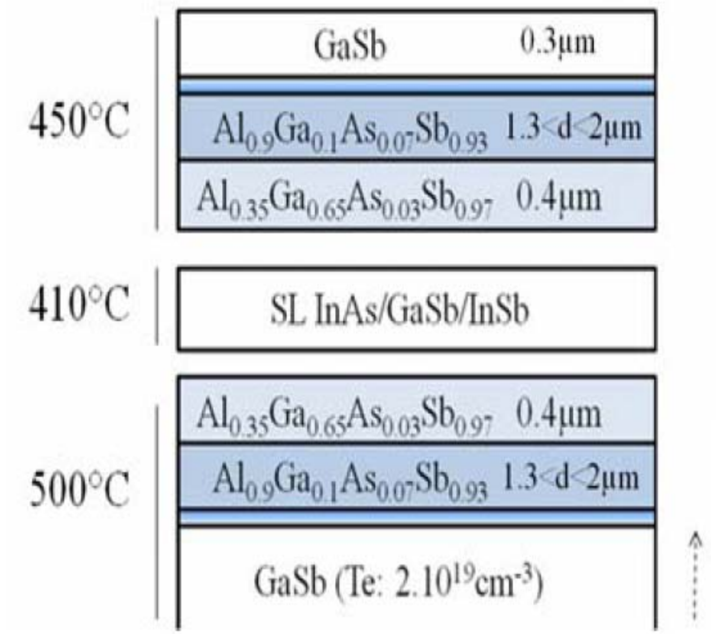


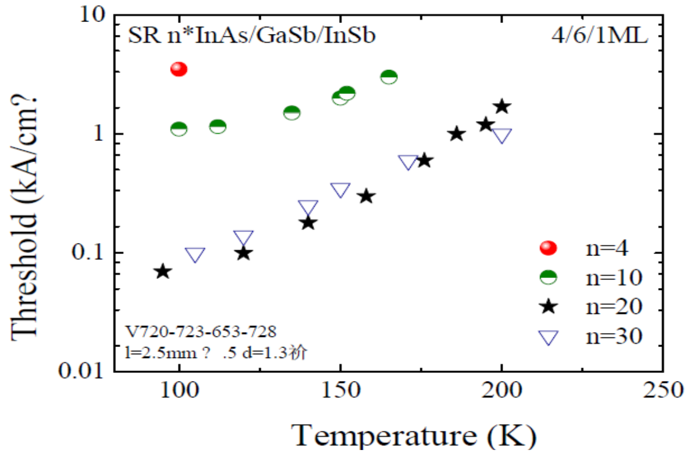
Fig.1: Detection limit as function of wavelength for several technically relevant gases.

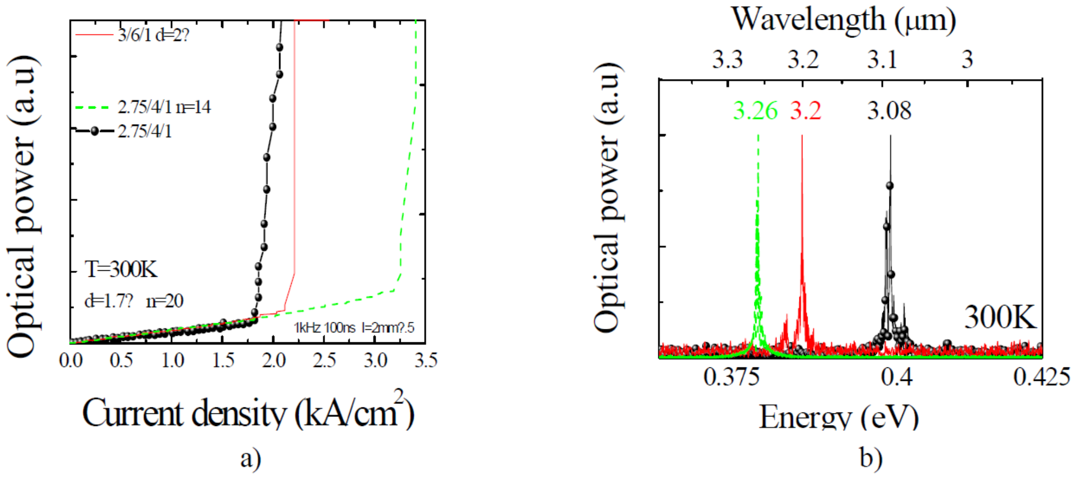
3微米II型超晶格激光器进展

A. Gassenq*, L. Cerutti, E. Tournié

Institut d'Electronique du Sud, Université Montpellier 2, UMR CNRS 5214,
Place Eugène Bataillon, CC 067, F-34095 cedex 5 Montpellier (France)



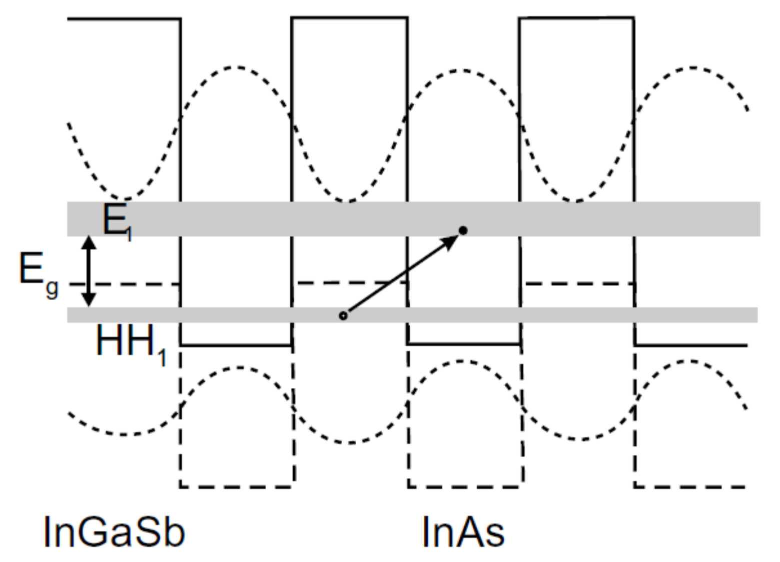




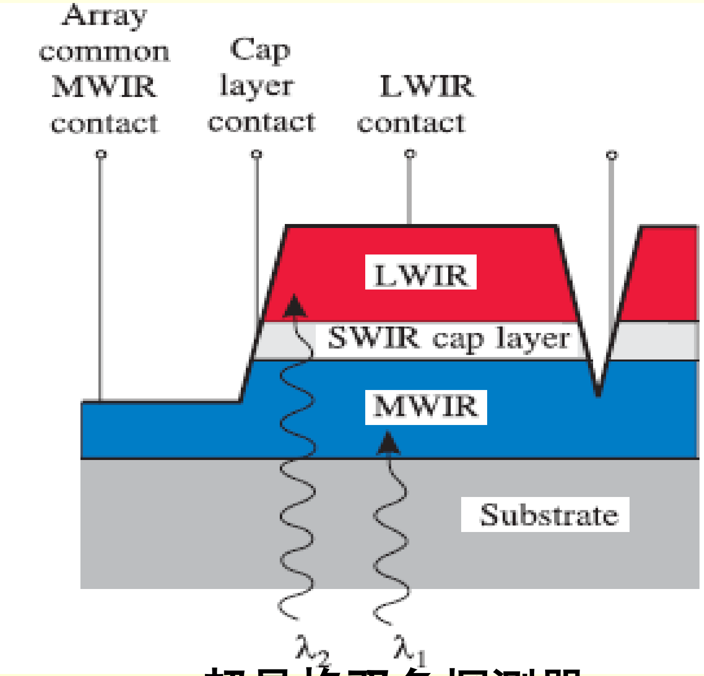
a) b)

Figure 3: a) P(I) curve and b) laser spectra for various SPSL lasers

InAs/GaSb II型能带超晶格红外探测器

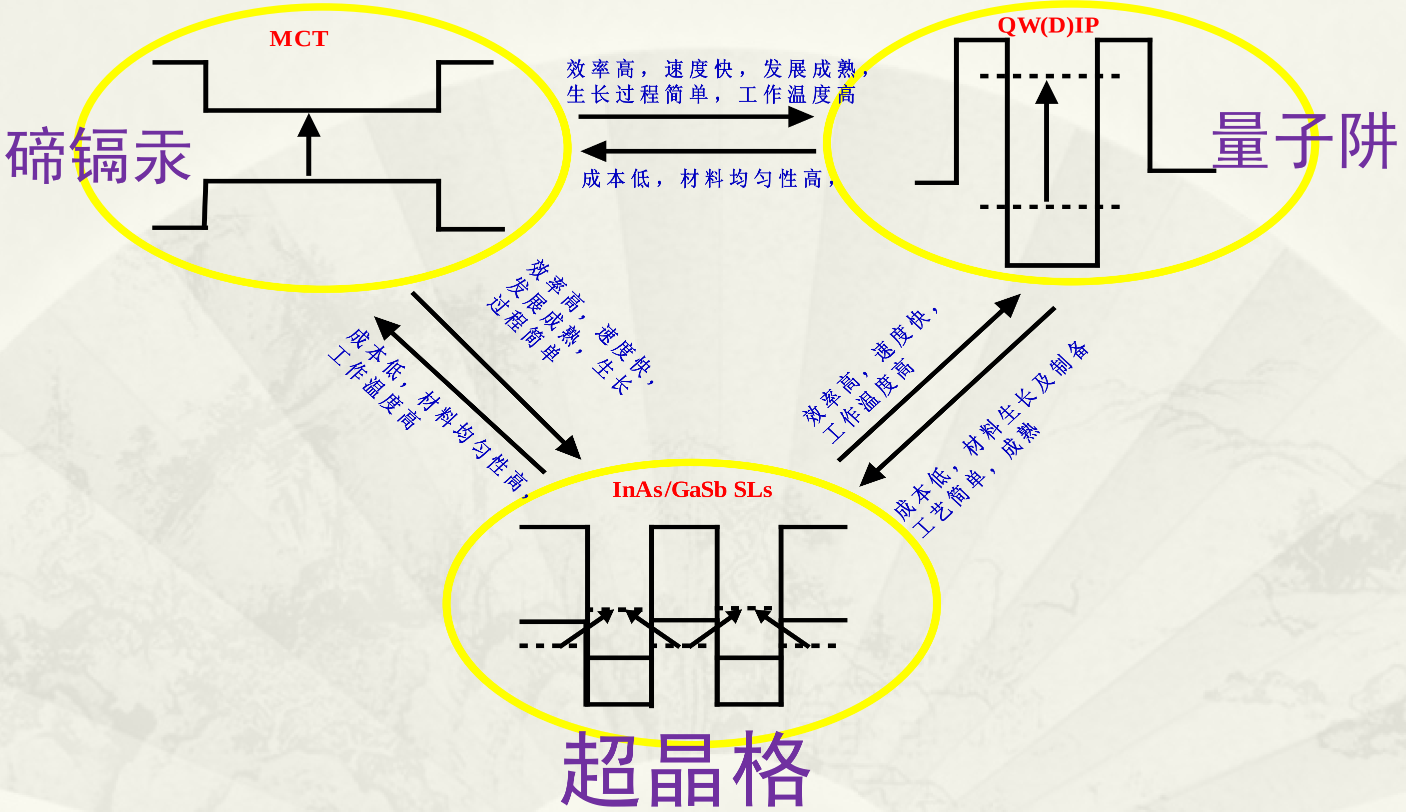


超晶格微带间吸收跃迁



超晶格双色探测器

红外探测器材料对比-InAs/GaSb超晶格优点突出



MCT

碲镉汞

QW(D)IP

量子阱

InAs/GaSb SLs

超晶格

效率高，速度快，发展成熟，
生长过程简单，工作温度高

成本低，材料均匀性高，

效率高，速度快，
发展成熟，生长
过程简单

成本低，材料均匀性高，
工作温度高

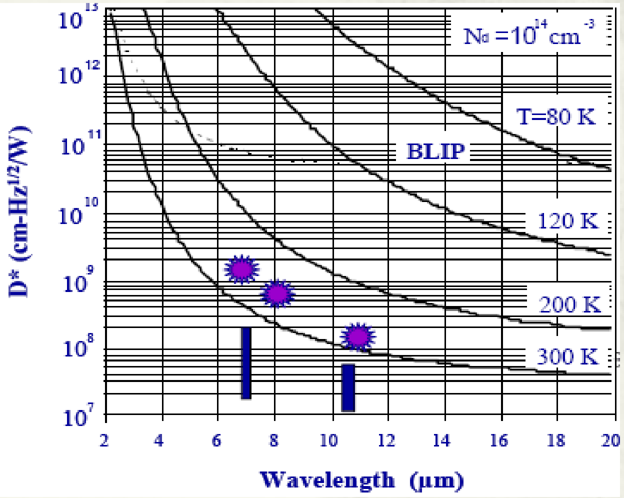
效率高，速度快，
工作温度高

成本低，材料生长及制备
工艺简单，成熟

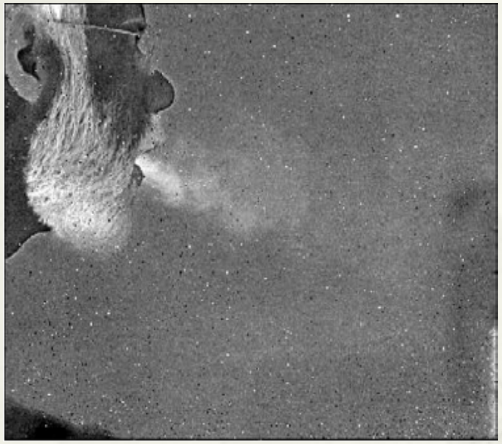
- **II型**InAs与GaSb超晶格，电子和空穴分别限制，
- **红外探测波段范围大：**2-30微米，抑制俄歇复合暗电流

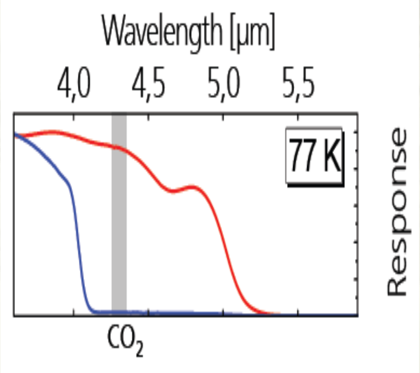
国际重要研究单位

- 美国西北大学、新墨西哥大学
- 美国海军、空军、喷气推进实验室
- 美国Raytheon vision system公司
- 德国Fraunhofer研究所
- 俄国Ioffe研究所



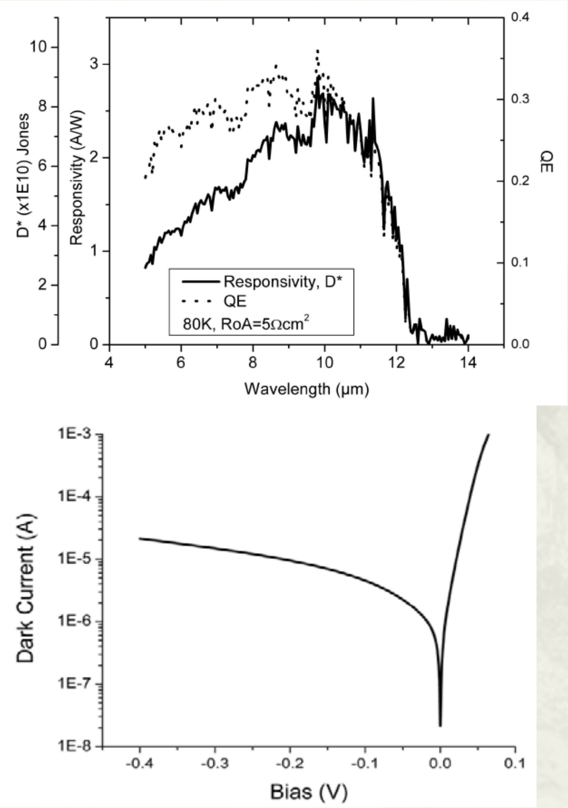
✸ InAs/GaSb超晶格
▌ HgCdTe
美国西北大学



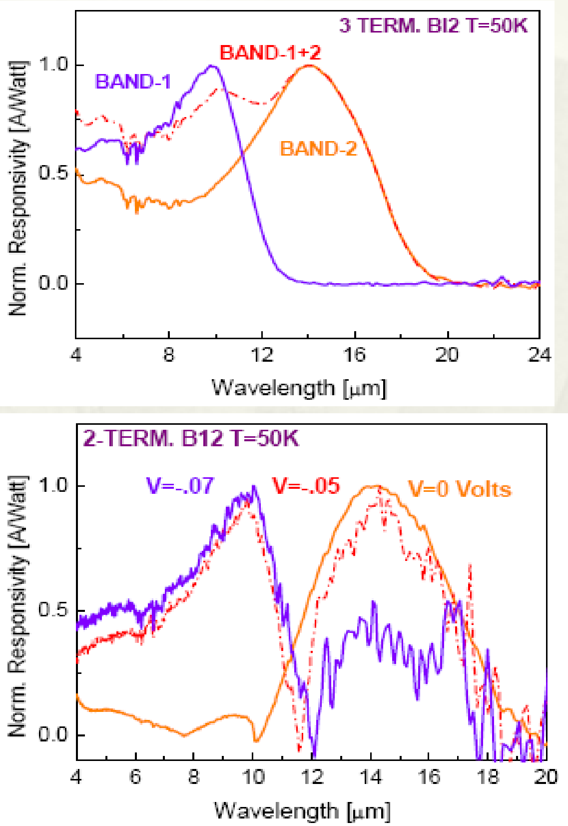


夫朗荷费：NETD=22.2mK(3-4μm)
/11.7mK(4-5mK) @ F#/2.0, 2.8ms

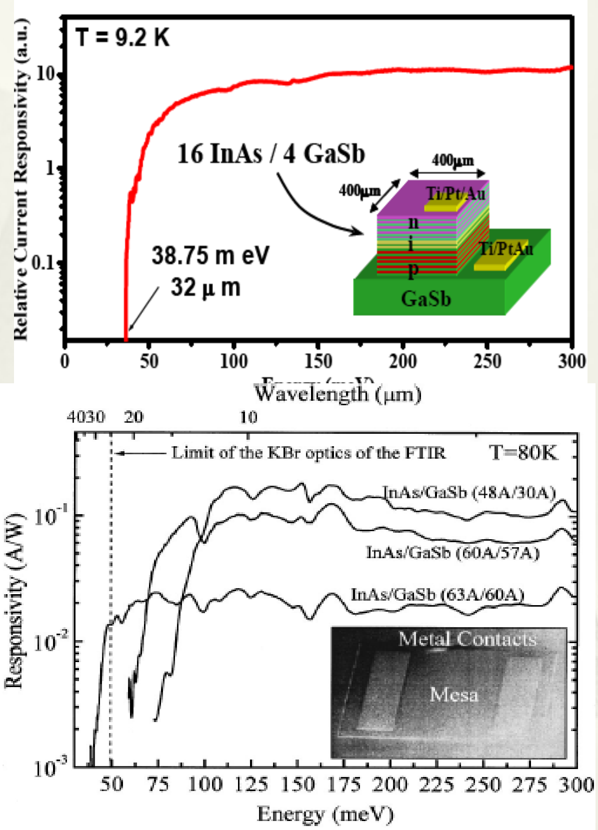
甚长波InAs/GaSb探测器研究引人关注



10-11μm效率
美国喷气实验室



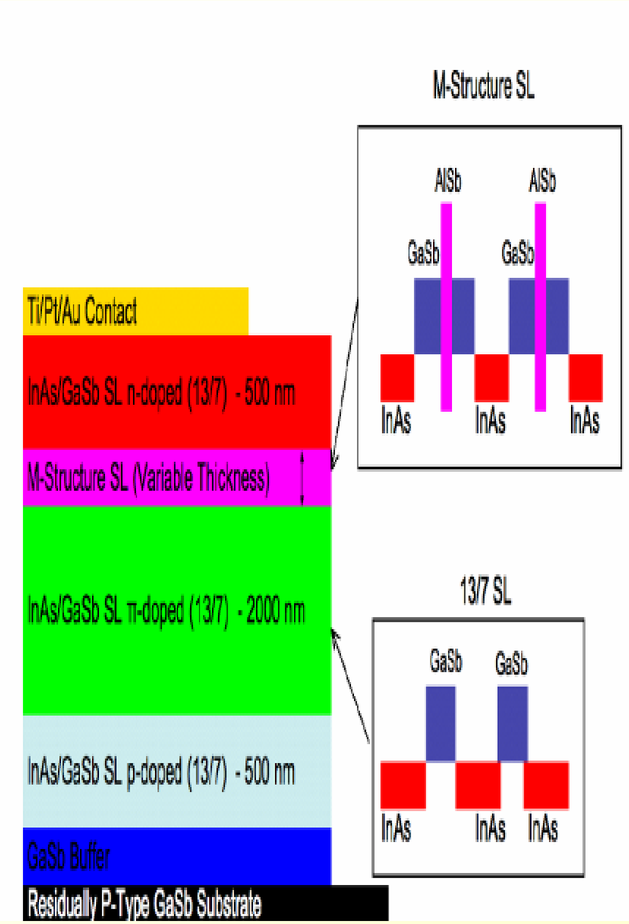
12-16微米
美国海军实验室



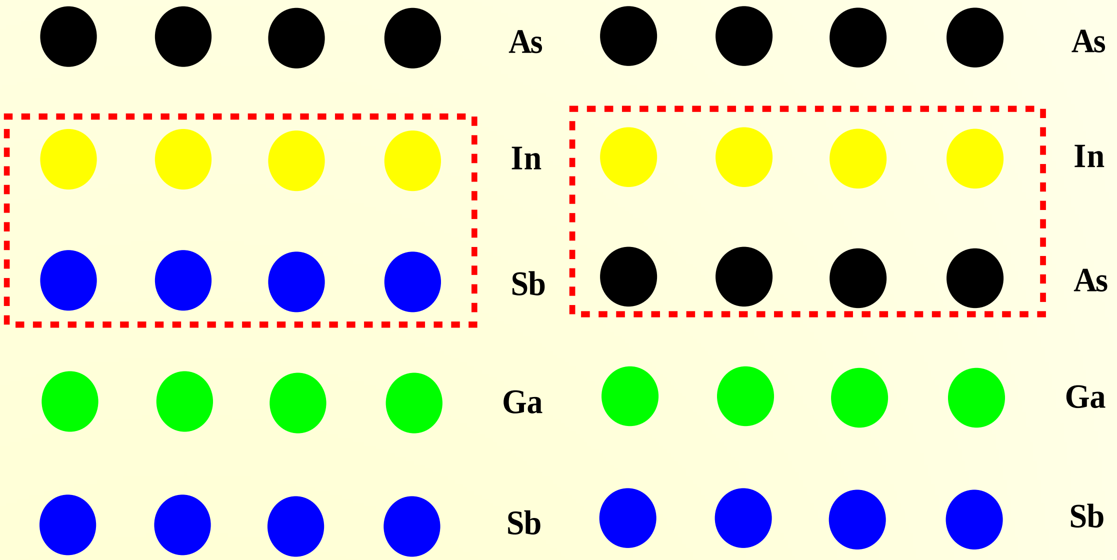
截止波长>30微米
美国西北大学

2005年起开展InAs/GaSb材料生长研究

能带设计

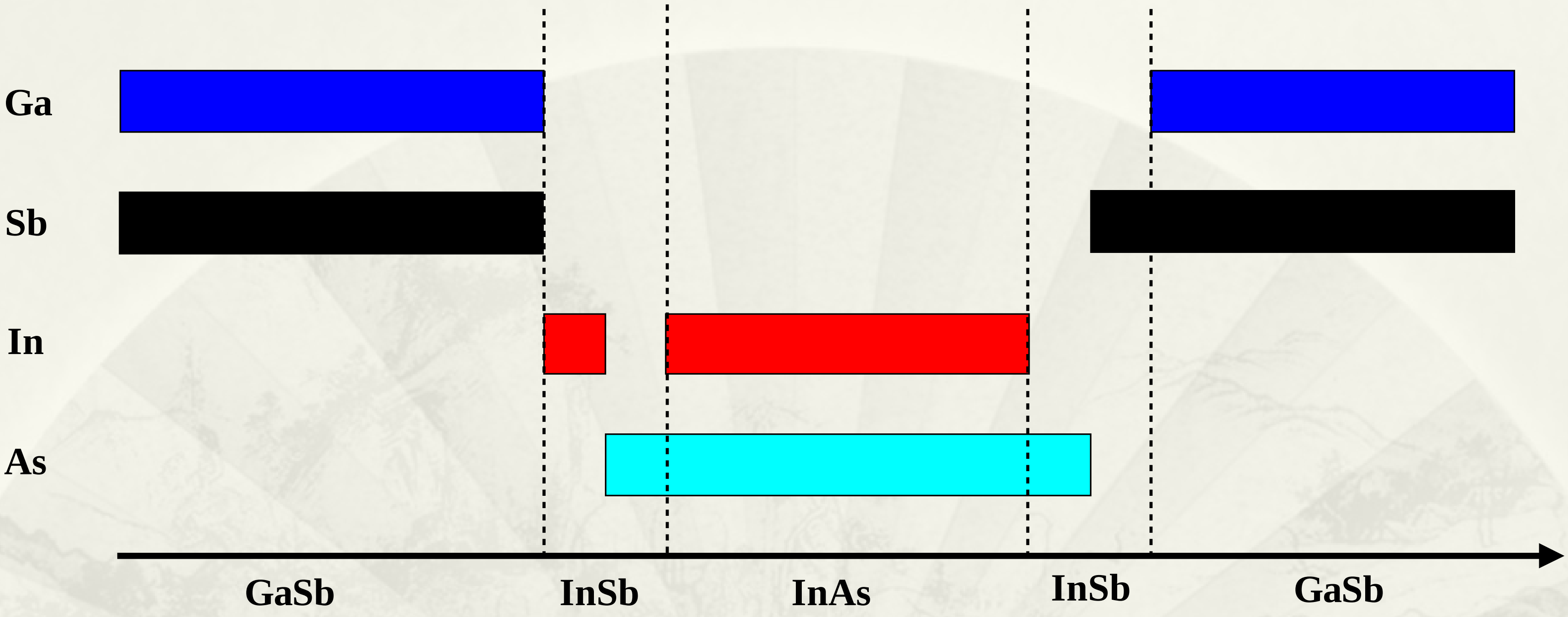


超晶格异质界面类型



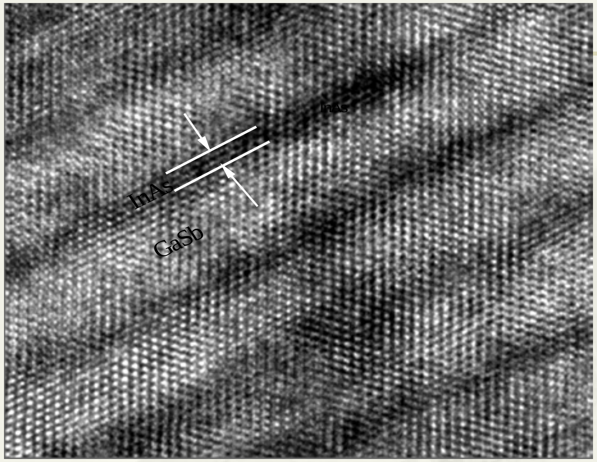
InAs / InSb /GaSb	InAs /GaAs /GaSb
A 6.06Å /6.48Å/6.09Å	a 6.06Å/5.65Å/6.09Å
Δa/a -0.6%/ 6% / 0	Δa/a -0.6%/-8%/ 0

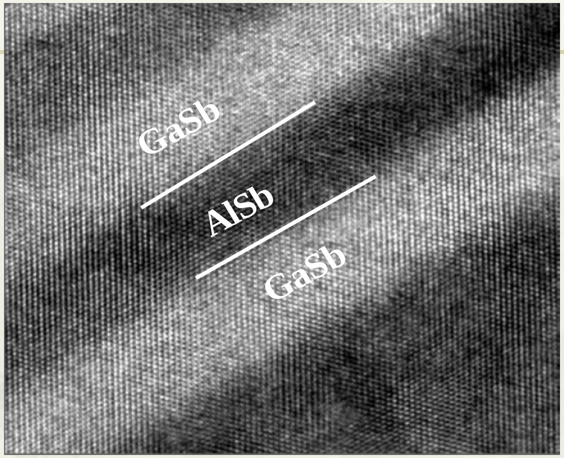
2007年突破超晶格界面控制技术难题



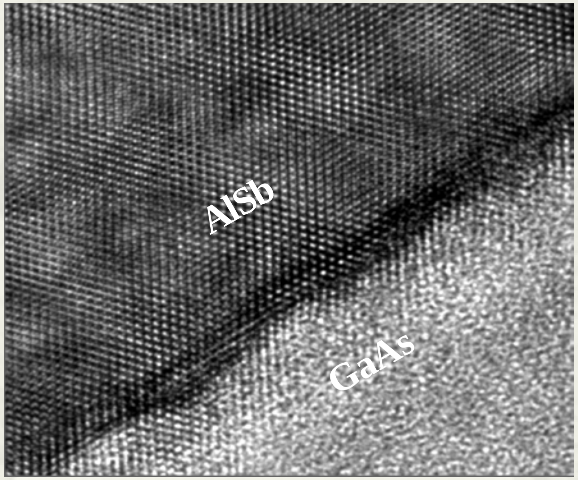
通过在GaSb表面淀积一层In原子，确保GaSb与InAs间界面为InSb。防止生长InAs层初始阶段As将GaSb中的Sb置换而形成GaAs界面！

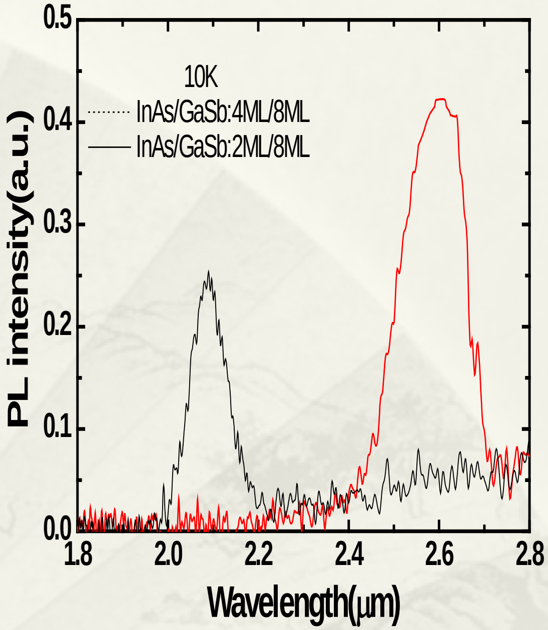
获得GaAs基高质量InAs/GaSb超晶格





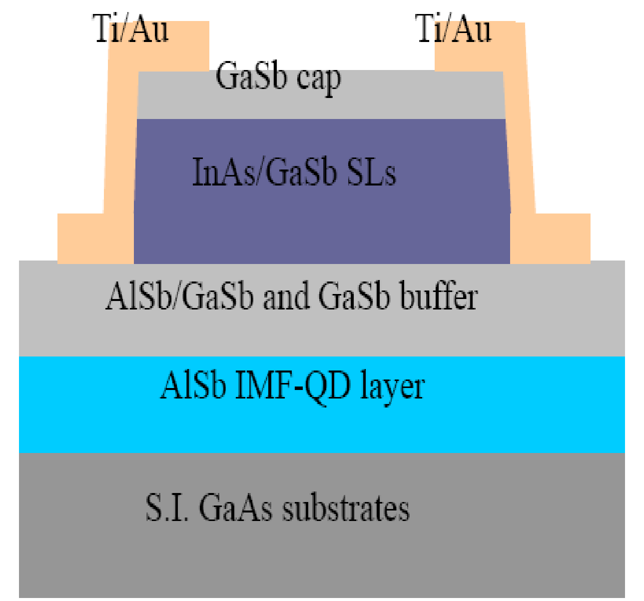
InAs/GaSb 超晶格	AlSb/GaSb 超晶格
	AlSb/GaAs 界面

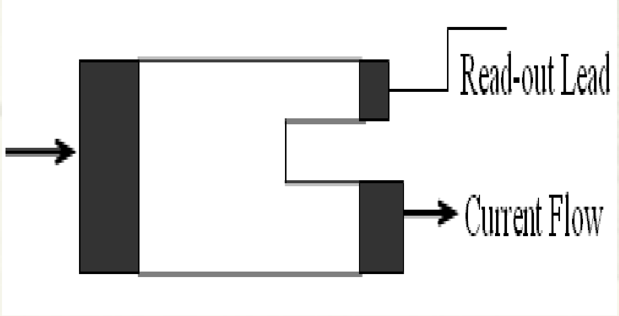


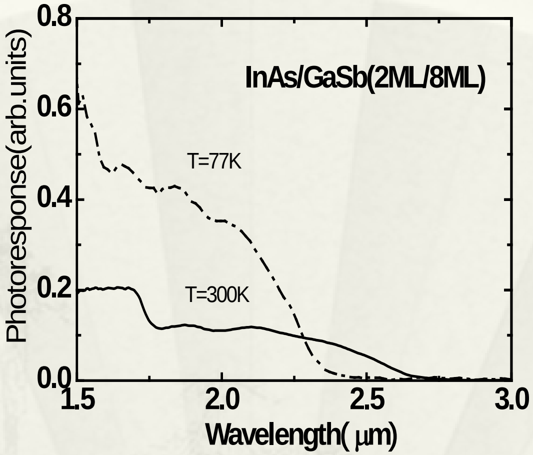


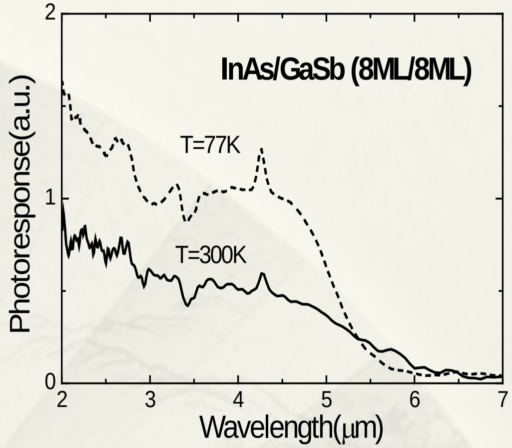
JPD: Applied Physics, 40, 1080(2007)
JPD: Applied Physics, 40, 6690(2007)

研制成功2-5微米InAs/GaSb光导型探测器









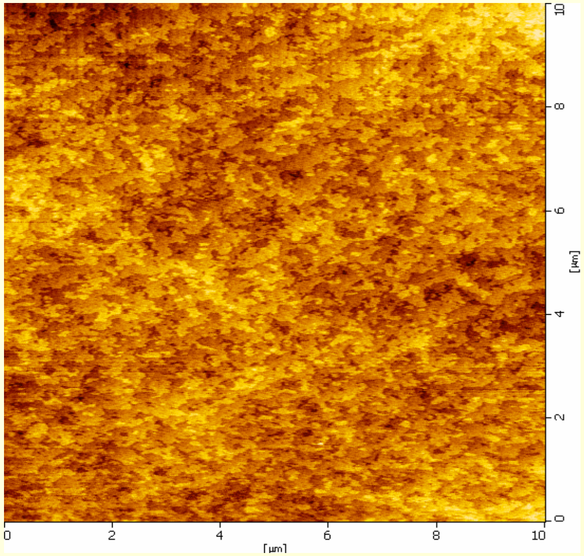
	77K	300K
λ_{cut} (μm)	2.15	2.45
D^* (cmHz$^{1/2}$/W)	4x10^9	2x10^8
R_v (V/W)	1400	30

	77K	300K
λ_{cut} (μm)	5.05	5.40
D^* (cmHz$^{1/2}$/W)	2x10^9	
R_v (V/W)	1800	

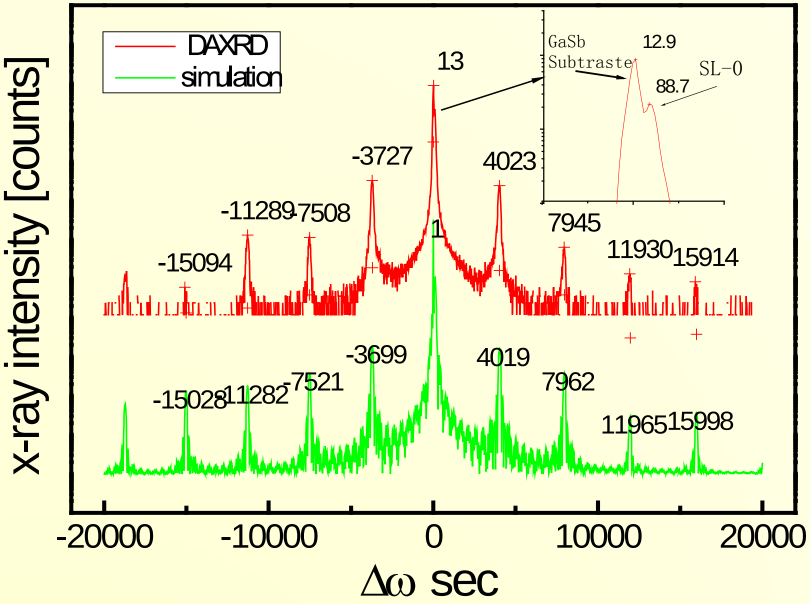
Chin. Phys. Lett. 26(2), 028102(2009)

获得GaSb基高质量InAs/GaSb超晶格

表面平整、界面清晰



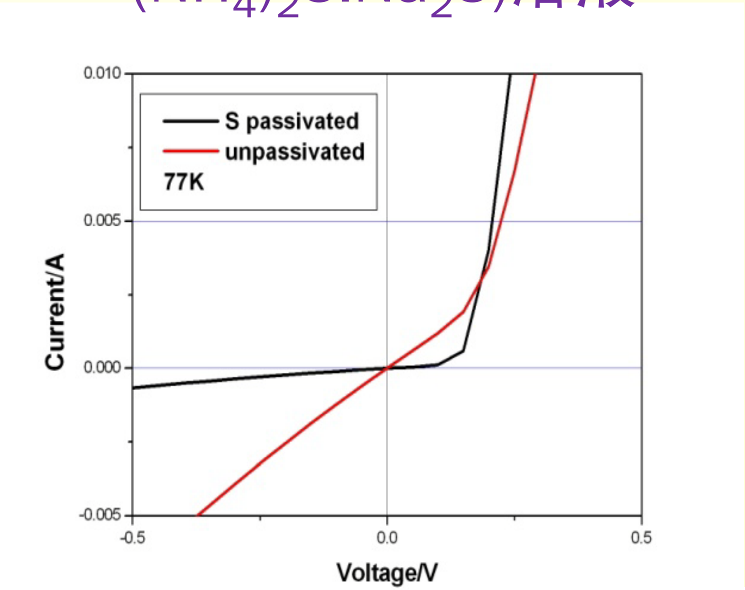
320周期InAs(8ML)/GaSb(8ML)超晶格表面原子力形貌。扫描面积：10μm X 10μm



320周期InAs(8ML)/GaSb(8ML)超晶格X射线衍射曲线。插图为超晶格零级峰与衬底峰。

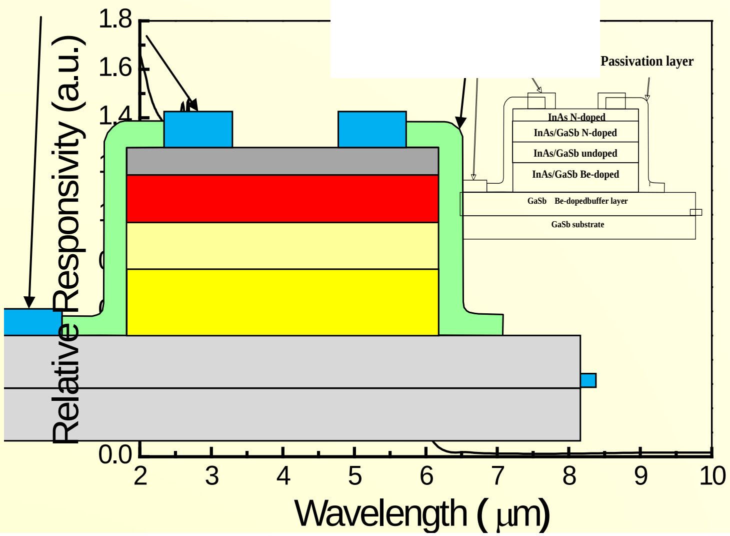
研制成功2-5微米InAs/GaSb光伏型探测器

S化工艺改善IV特性
$(NH_4)_2S$:Na_2S)溶液



InAs(8ML)/GaSb(8ML)超晶格探测器硫化前后I V特性曲线。

探测率D*达到
1.6×10^{10} (cmHz$^{1/2}$/W)



InAs(8ML)/GaSb(8ML)超晶格探测器光电谱插图为探测器结构图

Infrared Phys. & Technology, 52 (4): 124(2009)
J. Infrared Millimeter Waves, 28, 165(2009)

谢 谢