Silicon Nanophotonics

- 现代工程与应用科学学院
- 2020-4-22

主要内容

- 简介
- 器件及应用
- 小结

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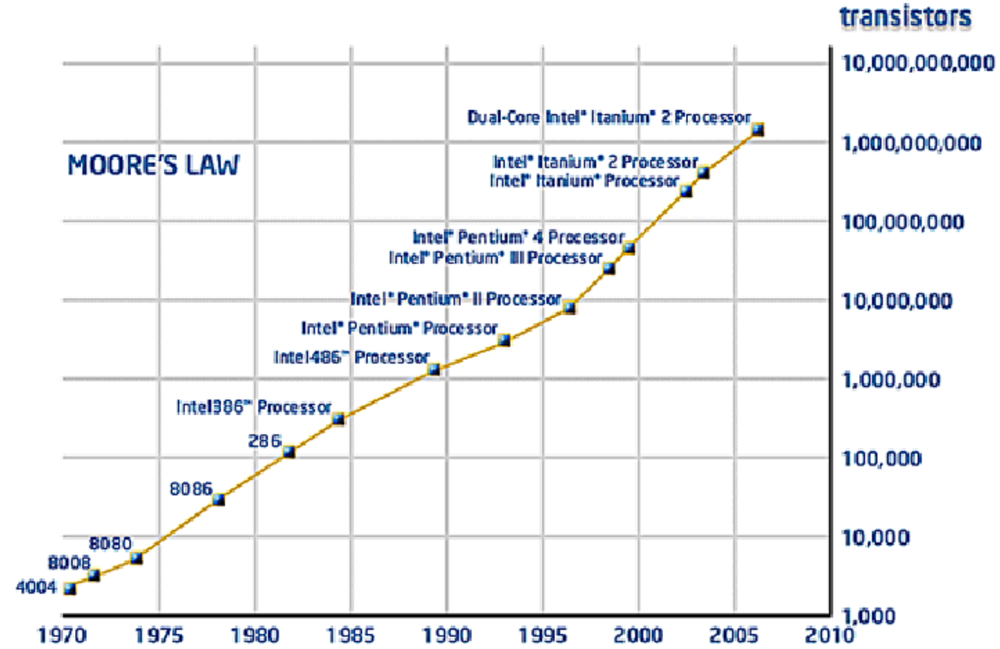
简介

背景介绍



摩尔定律

1984 J.P. Goodman提出光互联(Ge, InP, GaAs，Si…）

Si光互联可能是最有前景的方法

- 制备工艺与微电子工艺兼容
- 成本低
- 在通信波段损耗低
- 折射率高(3.4) → 小尺寸
- ⋮

简介

早期工作

IEEE JOURNAL OF QUANTUM ELECTRONICS, VOL. QE-22, NO. 6, JUNE 1986

All-Silicon Active and Passive Guided-Wave Components for $\lambda = 1.3$ and $1.6\ \mu m$

RICHARD A. SOREF, SENIOR MEMBER, IEEE, AND JOSEPH P. LORENZO

Loss: 5-20 dB/cm

OPTICAL CHANNEL WAVEGUIDES IN SILICON DIFFUSED FROM GeSi ALLOY

Indexing terms: Optoelectronics, Optical waveguides, Silicon

A technique for fabricating low-loss and polarisation-independent channel waveguides in silicon is reported. The waveguides are obtained by Ge-indiffusion using either a GeSi alloy or a system of alternating Ge and Si layers. Typical fabrication parameters for single-mode waveguides are given.

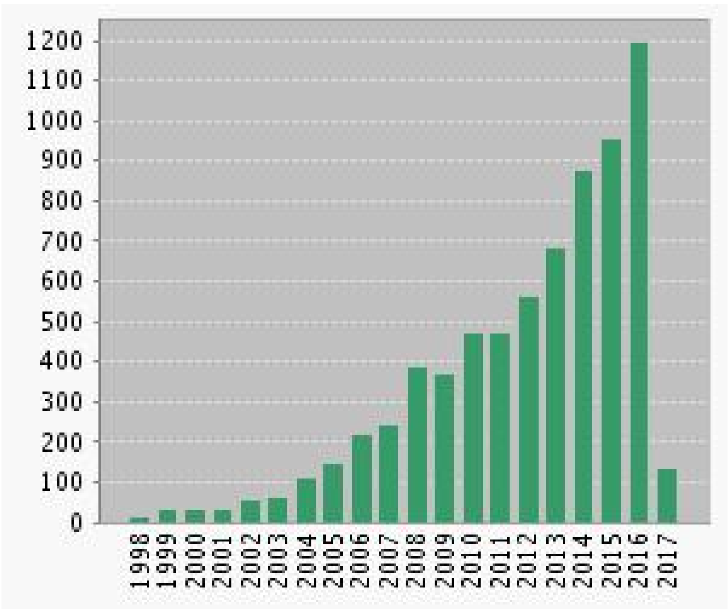
Loss: 4 dB/cm

ELECTRONICS LETTERS 26th October 1989 Vol. 25 No. 22

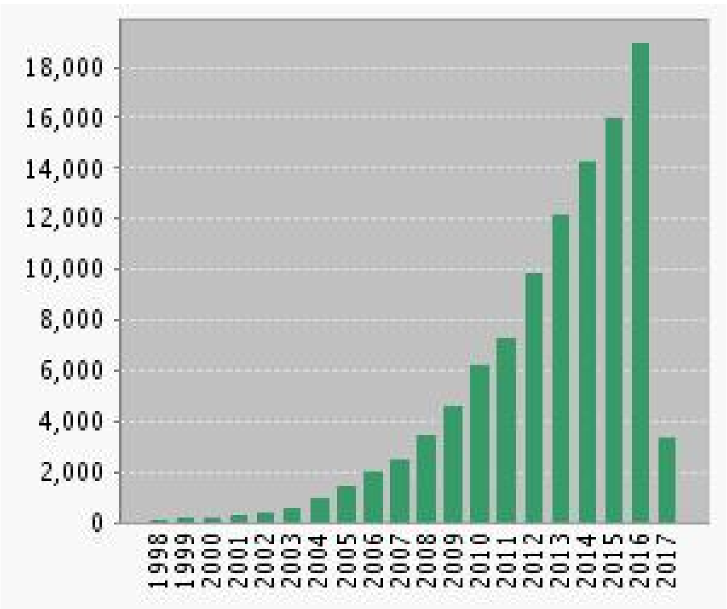
简介

研究现状

每年出版的文献数



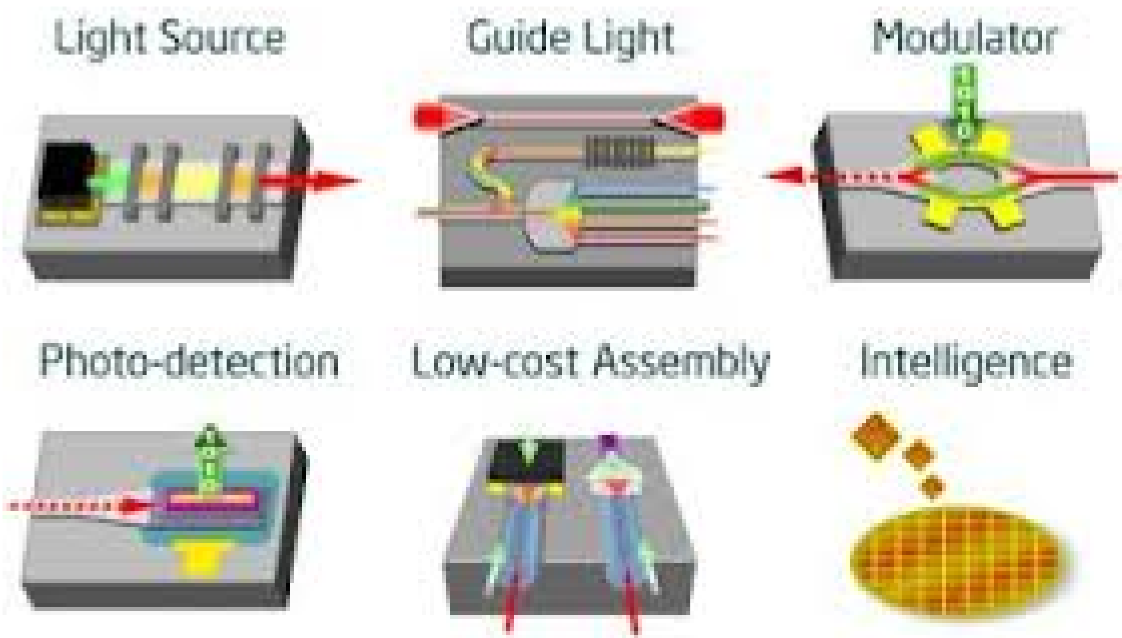
每年的引文数



关键词：Silicon Photonics (ISI Web of Knowledge)

简介

Building blocks



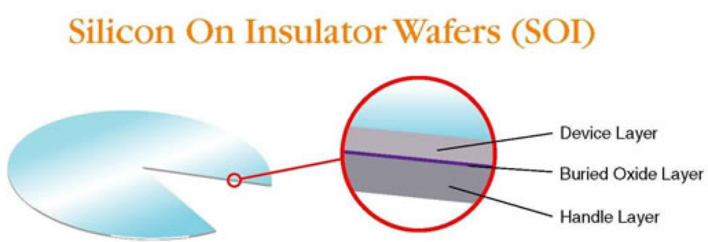
Intel

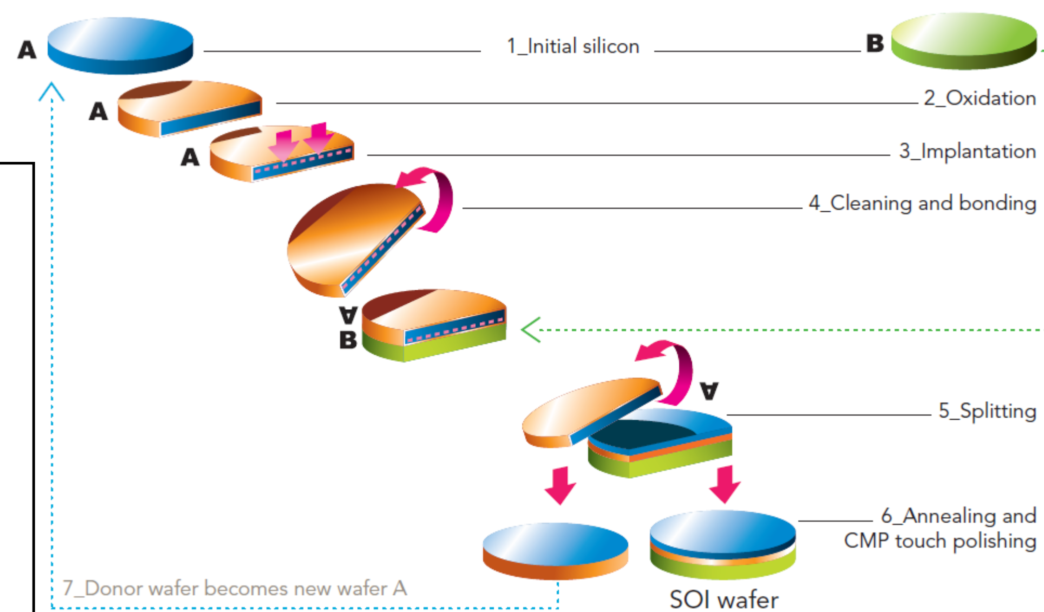
主要内容

- 简介
- 器件及应用
- 小结

器件及应用

SOI wafer





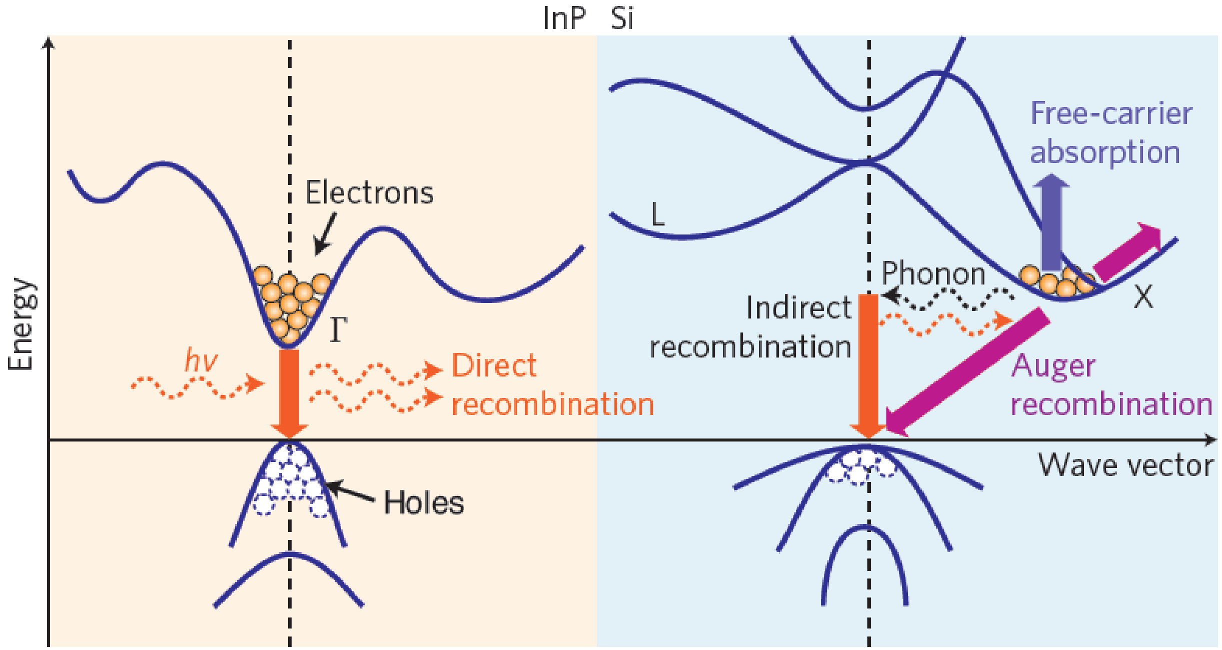
Smart Cut™

Soitec

器件及应用

光源–硅基激光

硅的局限
（最大问题）



Energy band diagrams in InP and silicon crystals

解决方法　　拉曼激光，外延生产、复合结构

D. Liang et. al., Nat. Photon. **4**, 511 (2010).

器件及应用

光源–硅基激光

拉曼激光

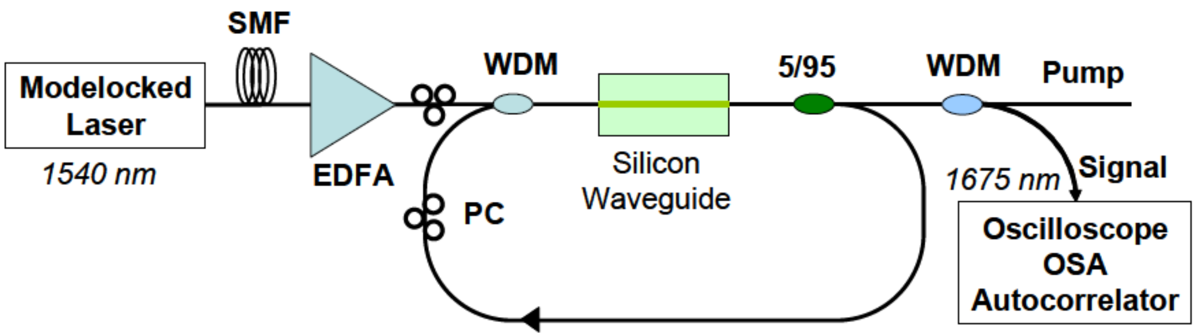
Demonstration of a silicon Raman laser

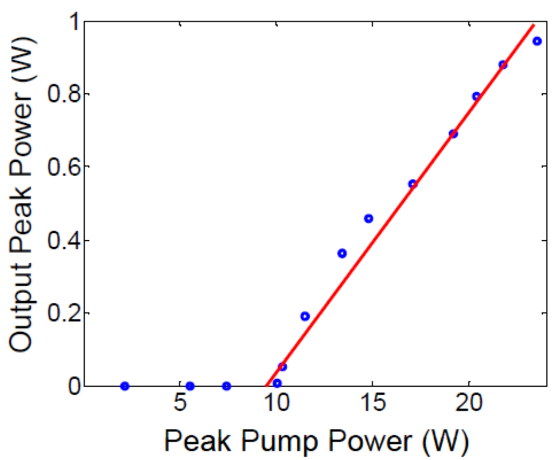
Ozdal Boyraz and Bahram Jalali

Optoelectronic Circuits and Systems Laboratory
University of California, Los Angeles
Los Angeles, CA 90095-1594

2004.10

第一个硅拉曼激光





Cavity length: 8 m
Pump：30 ps, 25 MHz
Threshold: 9 W peak power

O. Boyraz et. al., Opt. Express **12**, 5269 (2004).

器件及应用

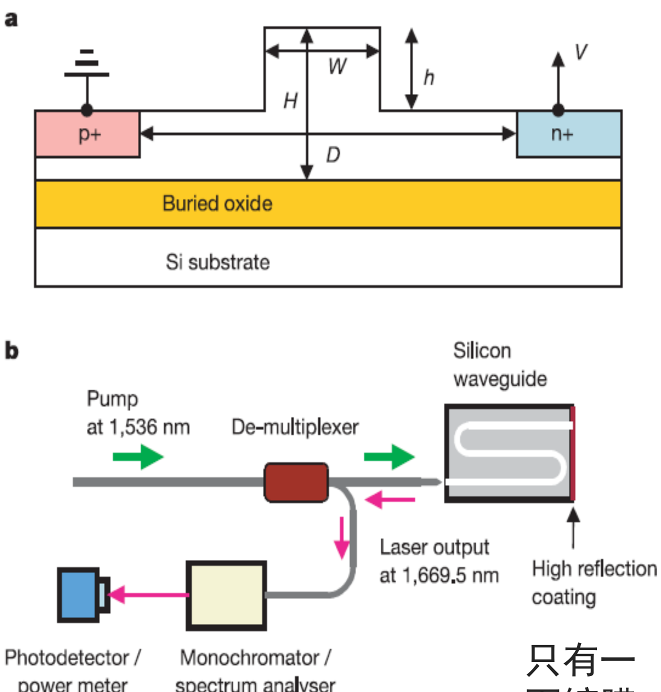
光源–硅基激光

拉曼激光

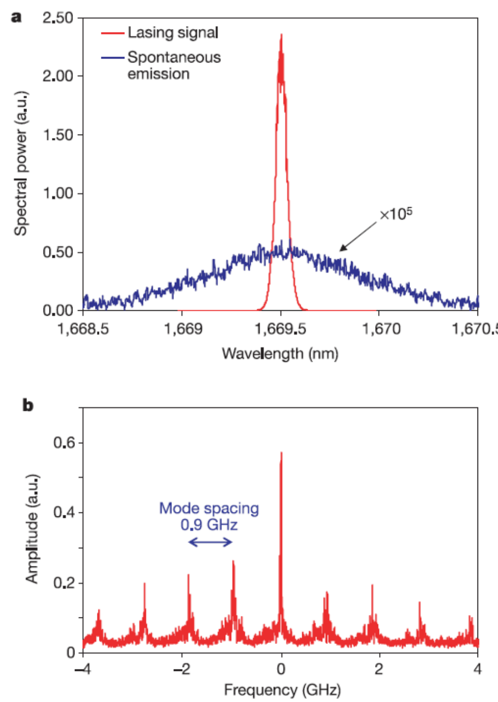
An all-silicon Raman laser

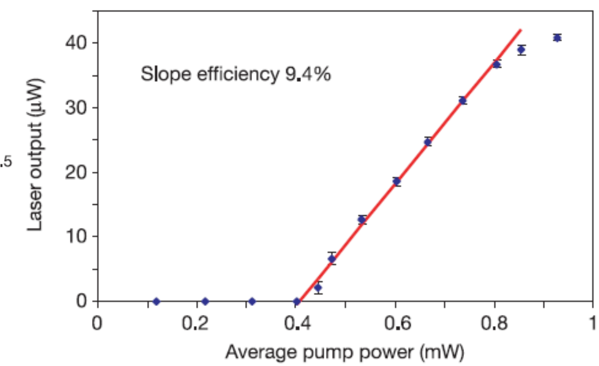
Haisheng Rong[1], Ansheng Liu[1], Richard Jones[1], Oded Cohen[2], Dani Hak[2], Remus Nicolaescu[1], Alexander Fang[1] & Mario Paniccia[1]

2005.1



只有一面镀膜





Cavity length: 4.8 cm

Pulse pump: 130 ns, 10 KHz

H. Rong et. al., Natute **433**, 292 (2005).

器件及应用

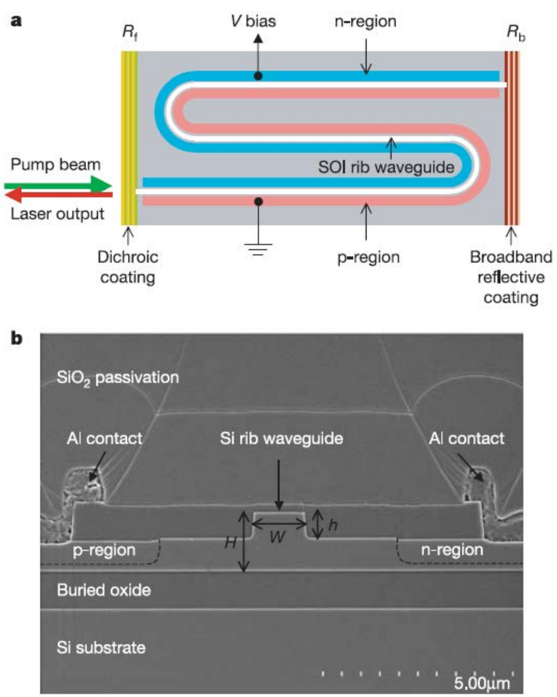
光源-硅基激光

拉曼激光

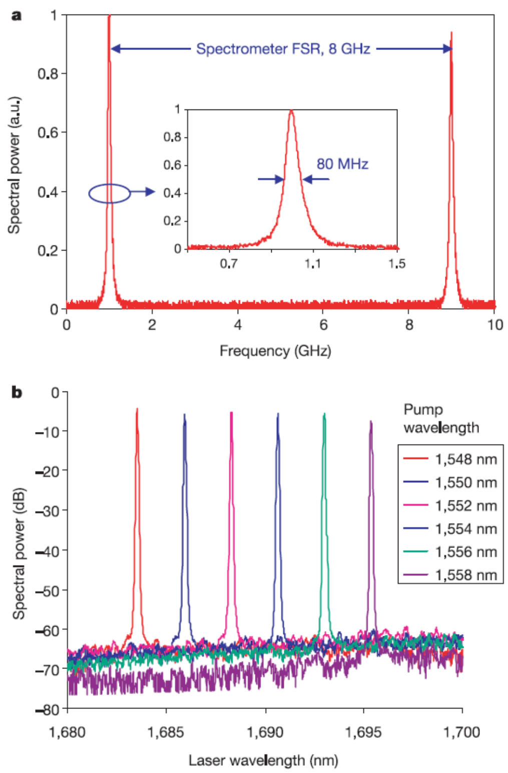
A continuous-wave Raman silicon laser

2005.2

Haisheng Rong[1], Richard Jones[1], Ansheng Liu[1], Oded Cohen[2], Dani Hak[2], Alexander Fang[1] & Mario Paniccia[1]



Cavity length: 4.8 cm



Threshold: 180 mW

H. Rong et. al., Natute **433**, 725 (2005).

器件及应用

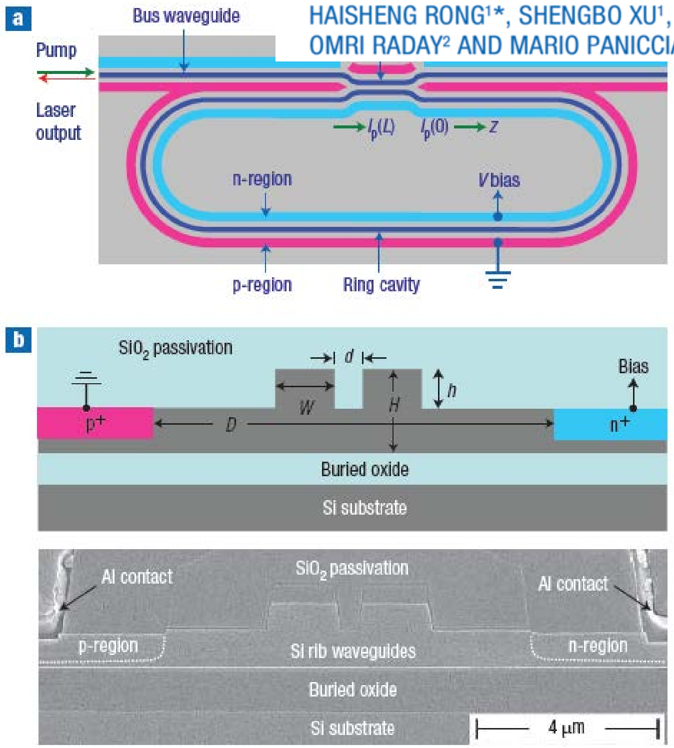
光源–硅基激光

拉曼激光

Low-threshold continuous-wave Raman silicon laser

2007.4

HAISHENG RONG[1]*, SHENGBO XU[1], YING-HAO
OMRI RADAY[2] AND MARIO PANICCIA[1]



Cavity length: 3.0, 1.5 cm

Pump light: On resonance

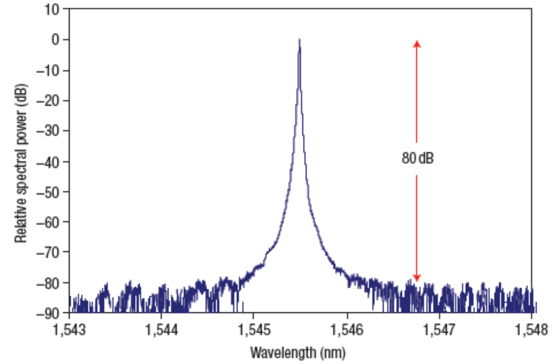
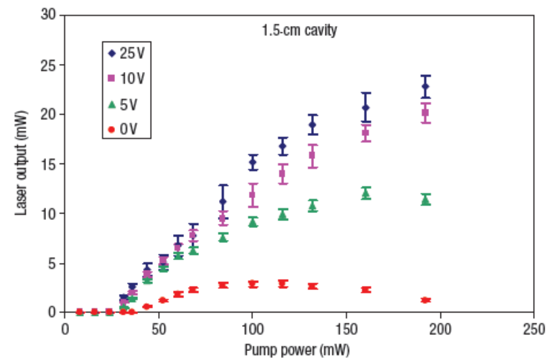


Figure 5 Raman silicon laser spectrum. The laser spectrum was measured with a grating-based optical spectrum analyser with a resolution of 0.01 nm, showing single-mode lasing with side-mode suppression of >80 dB.

Threshold: ～20 mW



H. Rong et. al., Nat. Photon. **1**, 232 (2007).

器件及应用

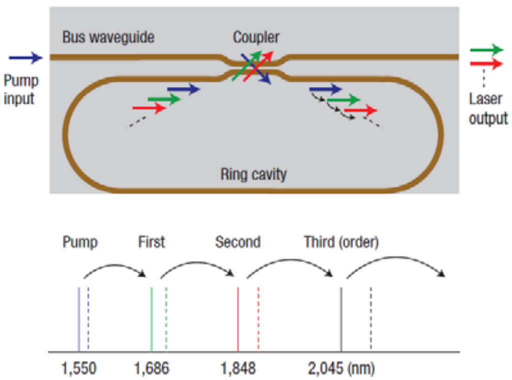
光源–硅基激光

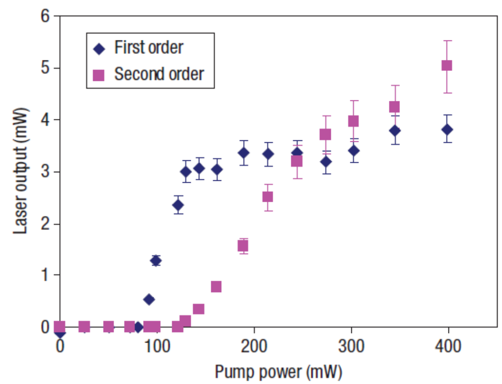
拉曼激光

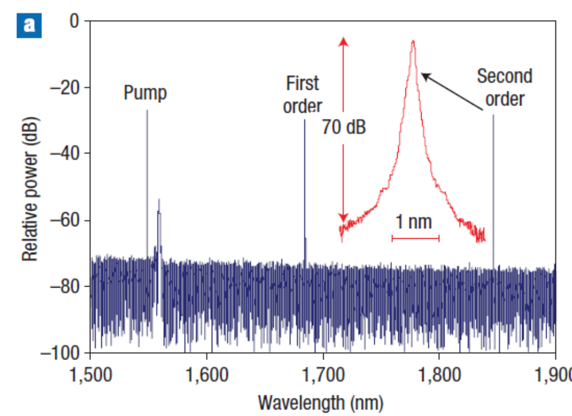
2008.3

A cascaded silicon Raman laser

HAISHENG RONG[1]*, SHENGBO XU[1], ODED COHEN[2], OMRI RADAY[2], MINDY LEE[1], VANESSA SIH[1] AND MARIO PANICCIA[1]







Cavity length: 3.0 cm
Q: $3.4*10^6$

Threshold: 80 mW, first order raman
120 mW, second order raman

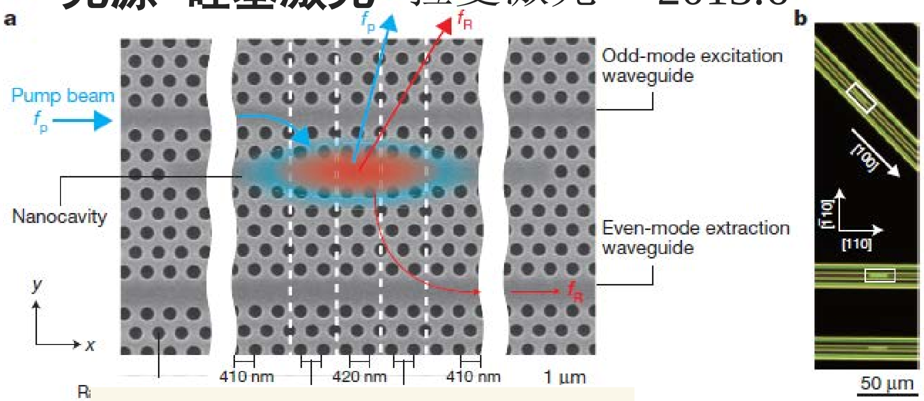
Near to mid-IR

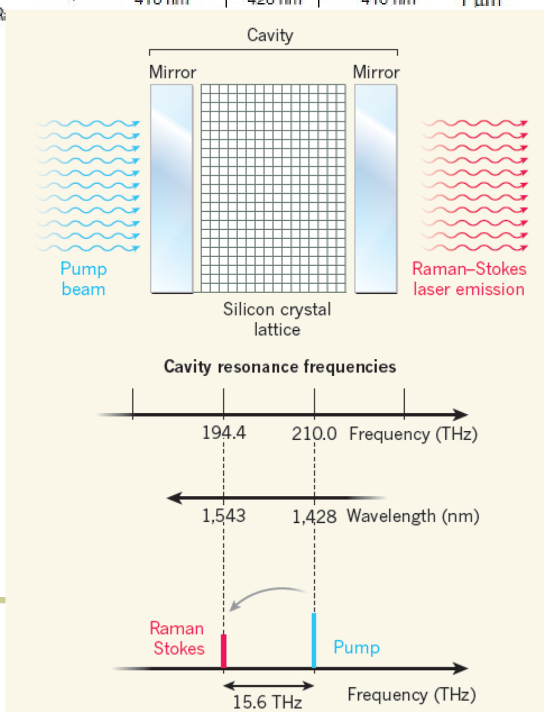
Pump light: On resonance

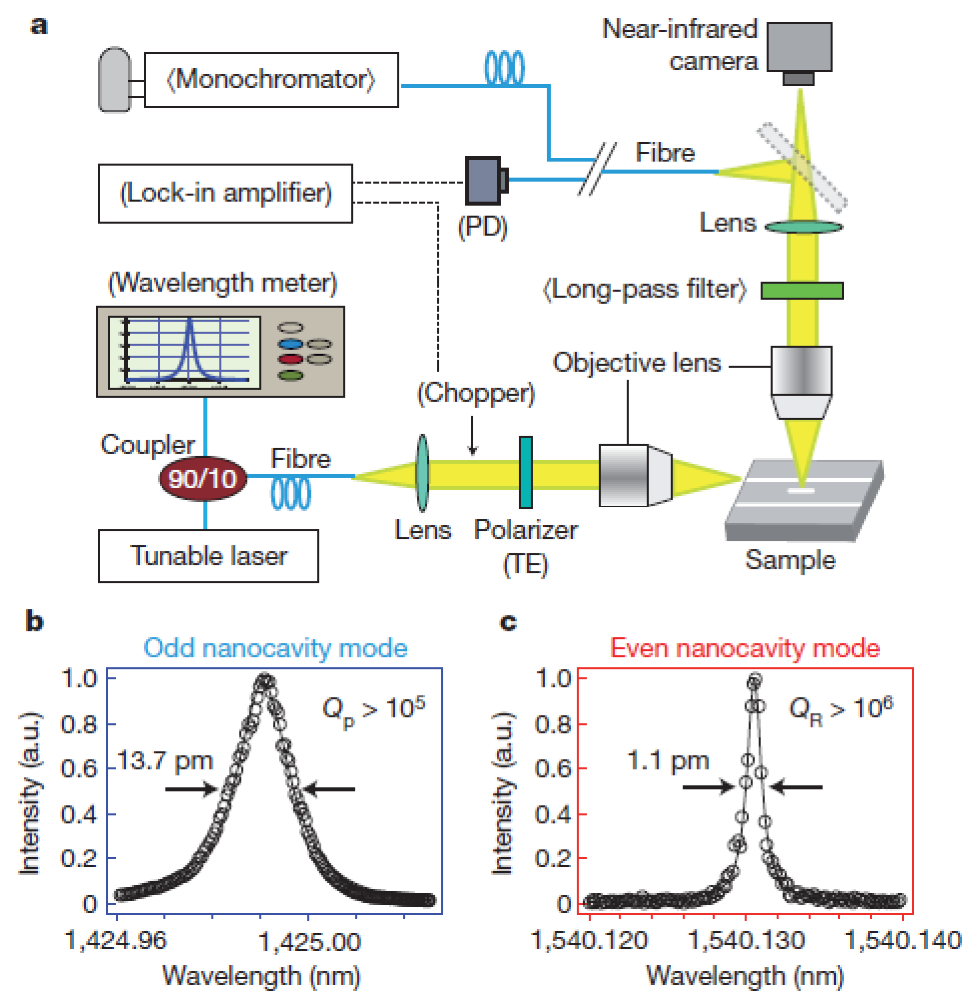
H. Rong et. al., Nat. Photon. **2**, 170 (2008).

器件及应用

光源–硅基激光　拉曼激光　2013.6





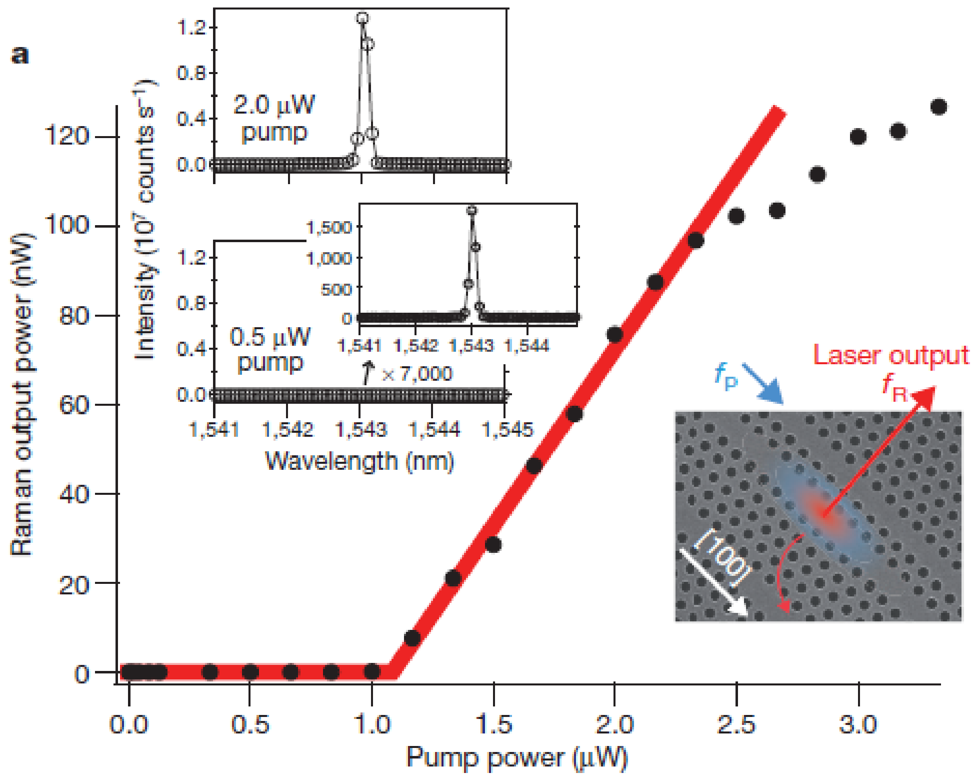


Y. Takahashi et. al., Nature. **498**, 470 (2013).

器件及应用

光源–硅基激光

拉曼激光



Threshold: ～1 μW

Y. Takahashi et. al., Nature. **498**, 470 (2013).

器件及应用

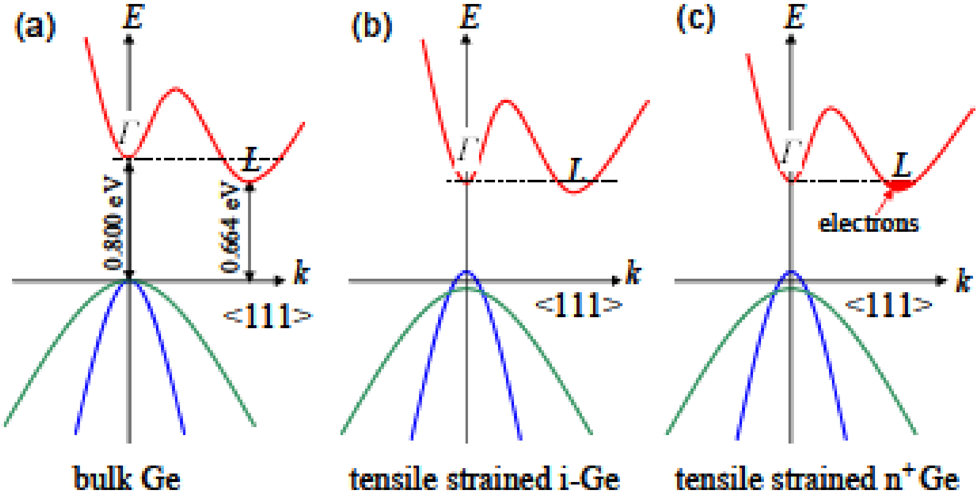
光源–硅基激光

Ge-on-Si laser

Energy band engineering of Ge

Direct- and Indirect-Bandgap Semiconductors

Semiconductors for which the conduction-band minimum energy and the valence-band maximum energy correspond to the same value of the wavenumber k (same momentum) are called **direct-bandgap** materials. Semiconductors for which this is not the case are known as **indirect-bandgap** materials.



Difference: 136 meV

Reduce: 115 meV

Heavy n-doping

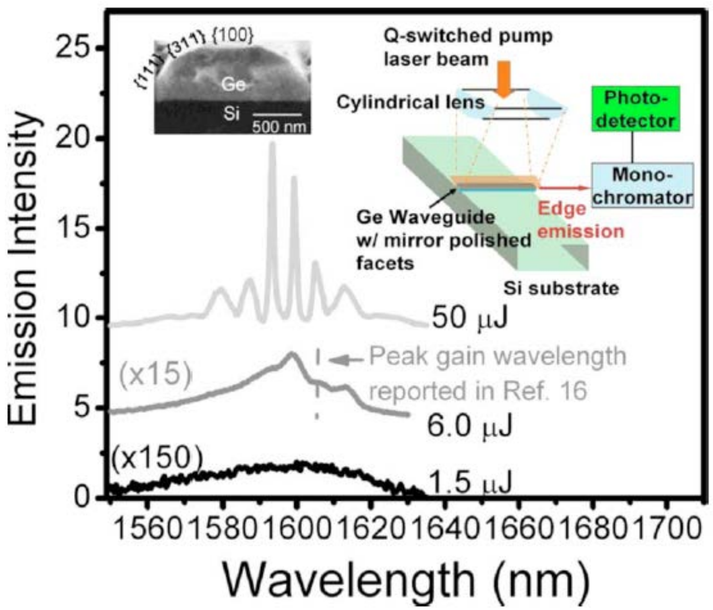
J. Liu et. al., Opt. Express. **15**, 11272 (2007).

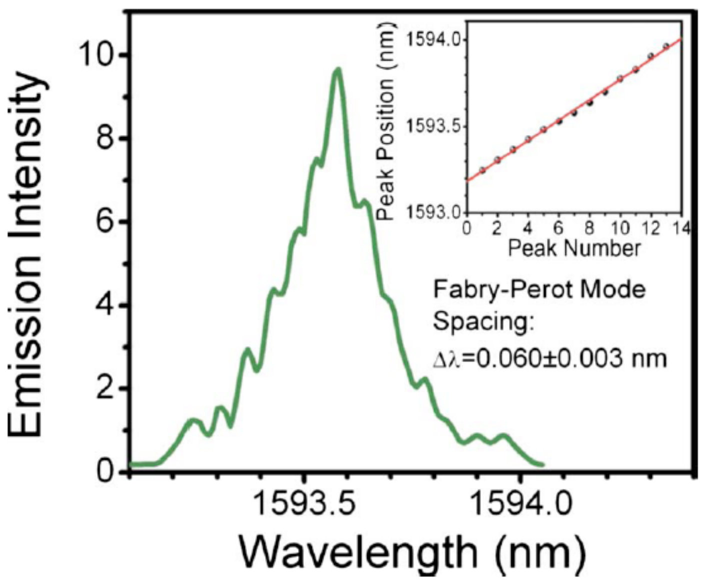
器件及应用

光源–硅基激光

Ge-on-Si laser

Ge-on-Si laser operating at room temperature





Pump: 1064 nm,1.5 ns, 1 kHz

Threshold: 30 kW/cm^2

J. Liu et. al., Opt. Lett. **35**, 679 (2010).

器件及应用

光源–硅基激光

Ge-on-Si laser

An electrically pumped germanium laser

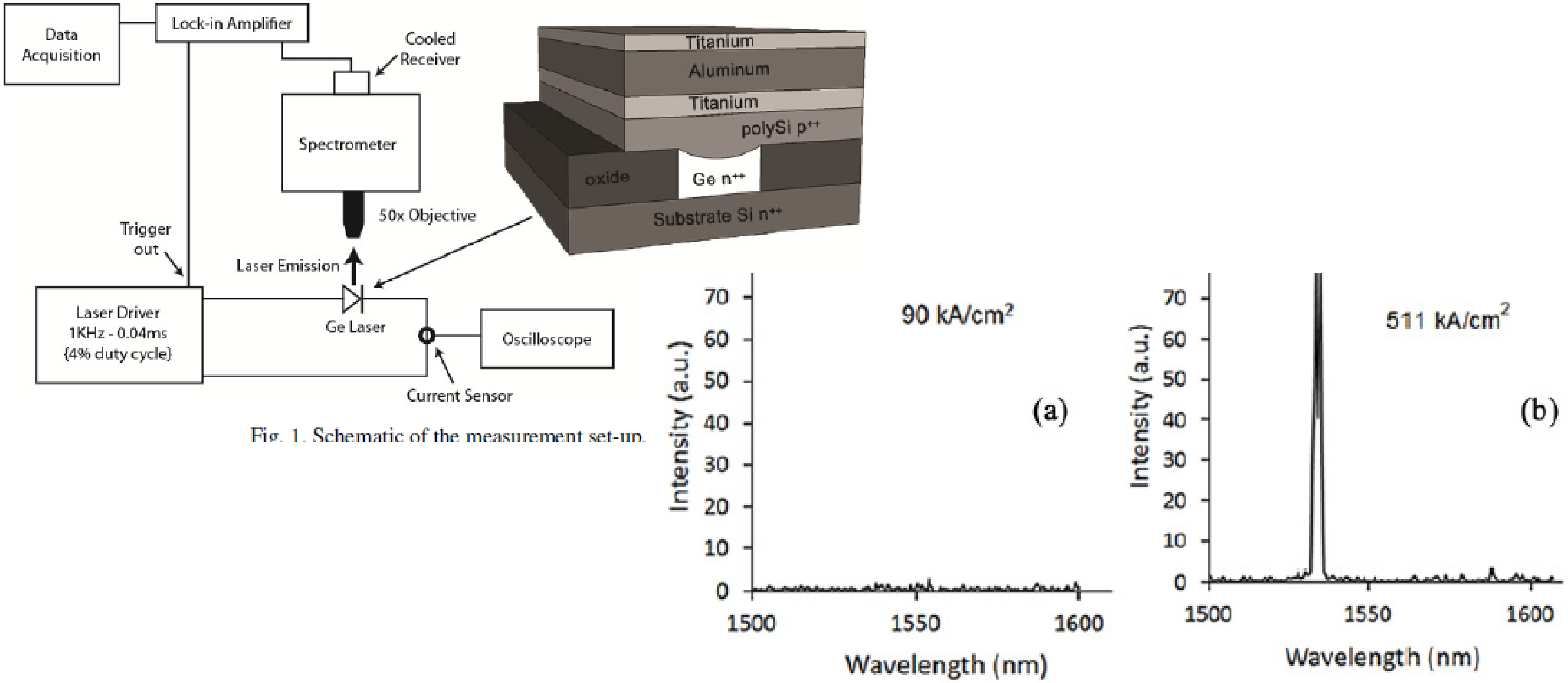
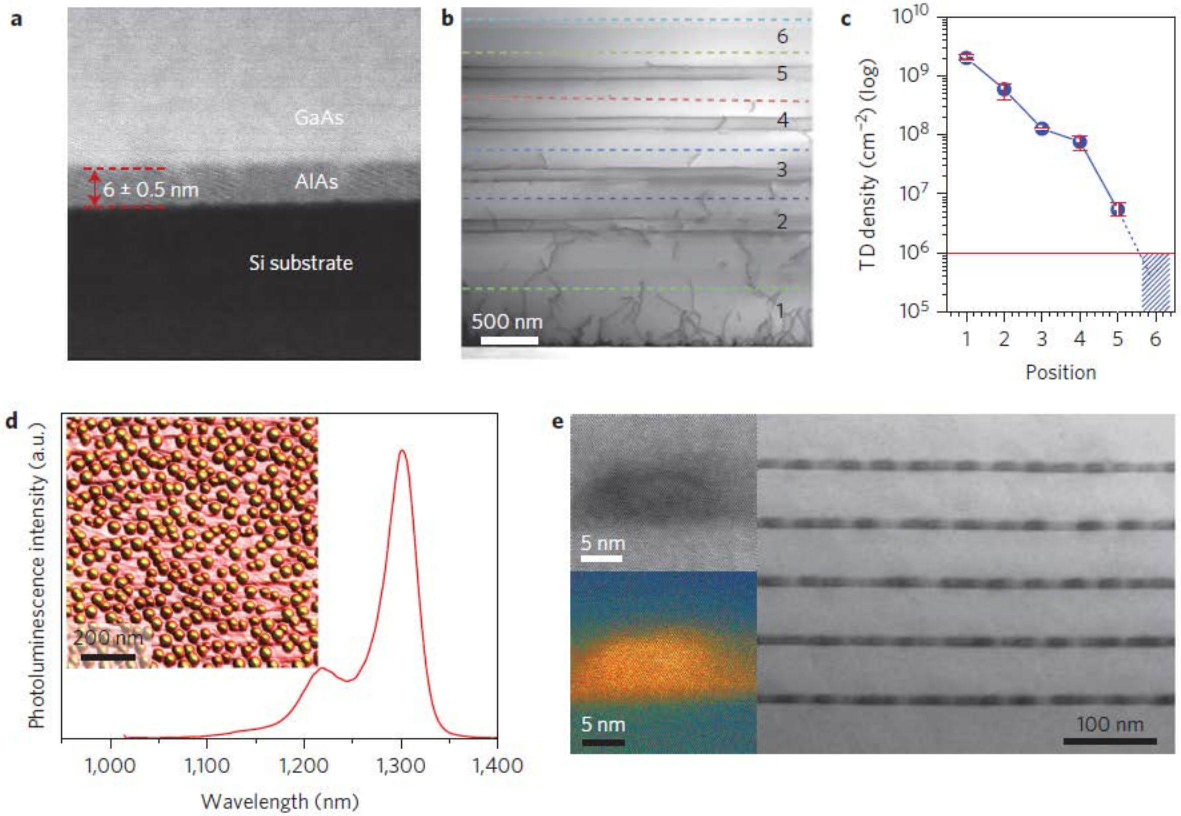


Fig. 1. Schematic of the measurement set-up.

R. E. Camacho-Aguilera et. al., Opt. Express. **20**, 11316 (2012).

器件及应用

光源-直接生长的量子点激光器

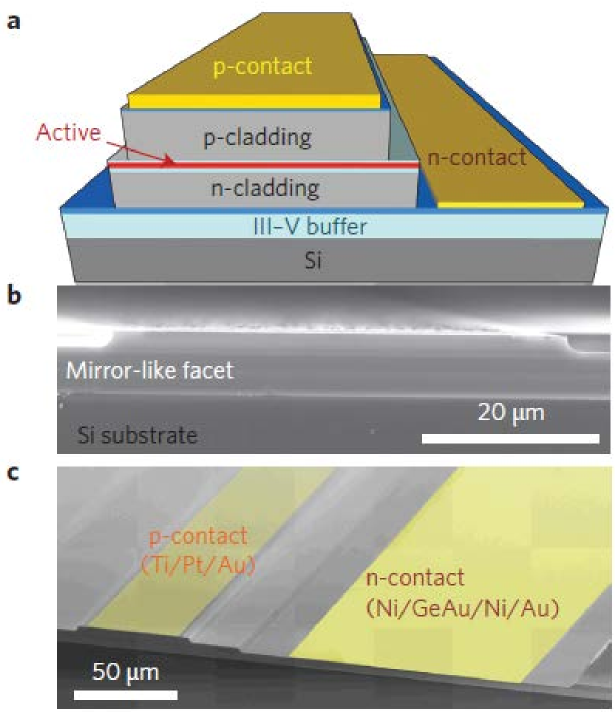


Epitaxial growth and structural characterization of QD lasers.

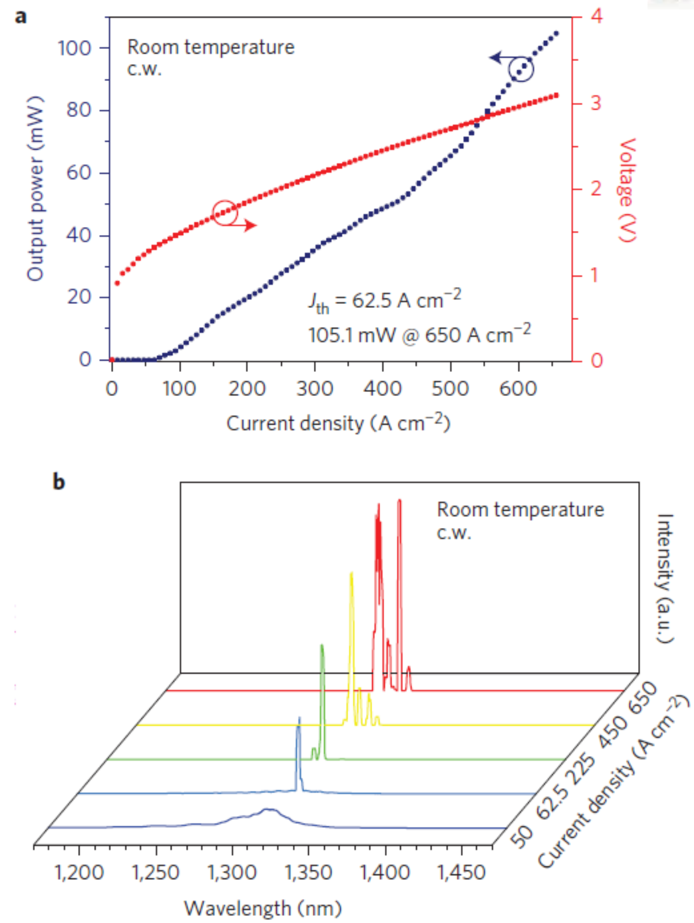
S. Chen et. al., Nat. Photon. **10**, 307 (2016).

器件及应用

光源-直接生长的量子点激光器



Fabricated III-V laser directly grown on a silicon substrate

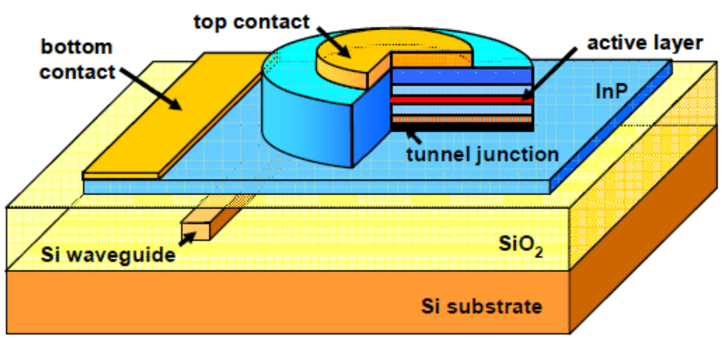


Silicon laser performance characterization

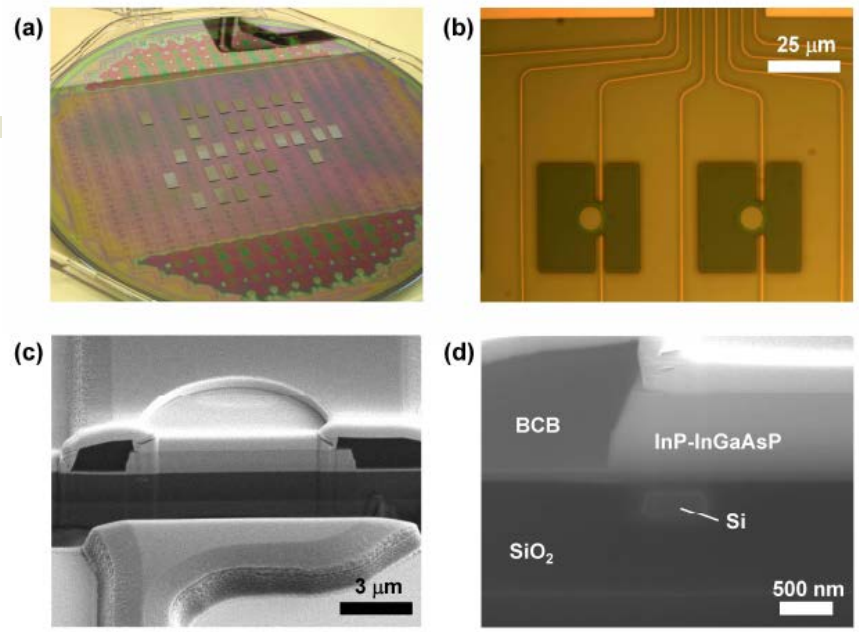
S. Chen et. al., Nat. Photon. **10**, 307 (2016).

器件及应用

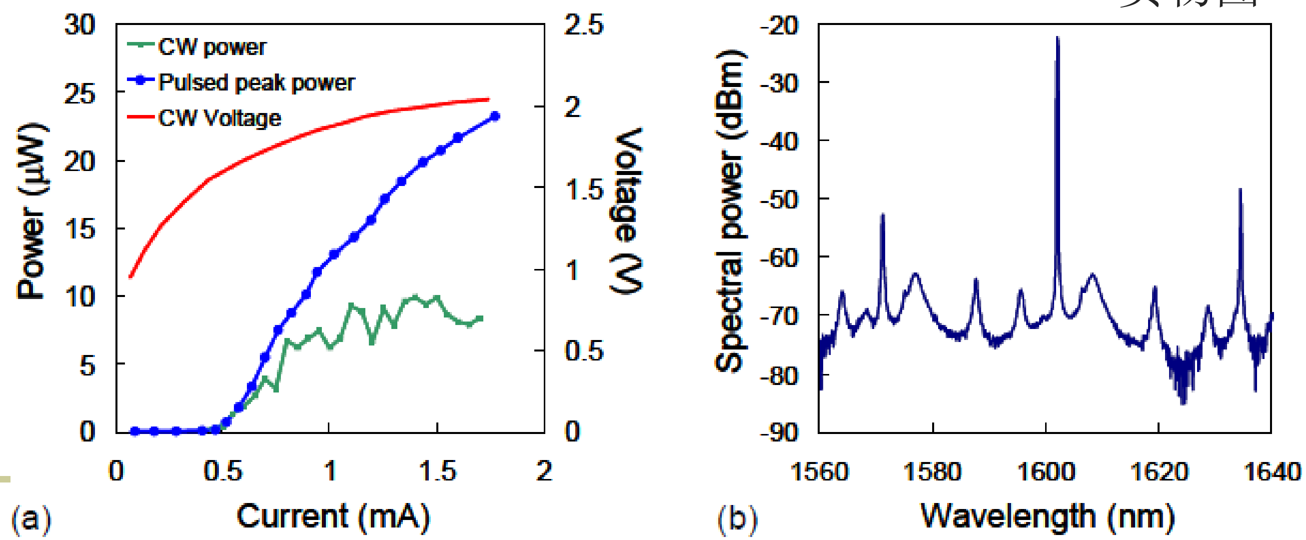
光源-复合激光器



示意图



实物图



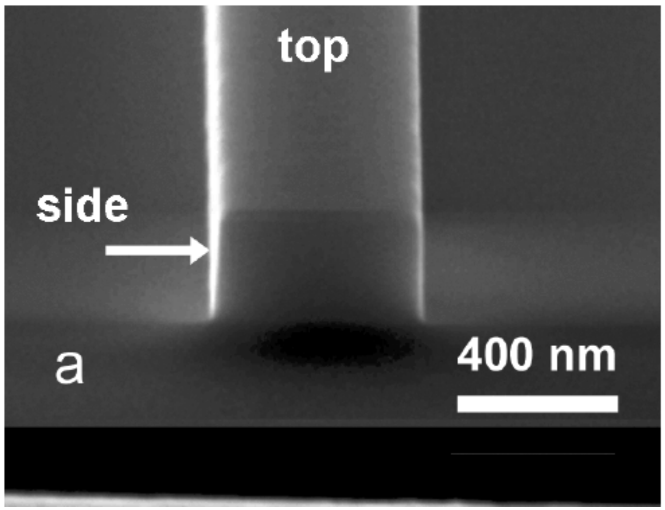
激光特性

J. V. Campenhout et. al., Opt. Express. **15**, 6744 (2007).

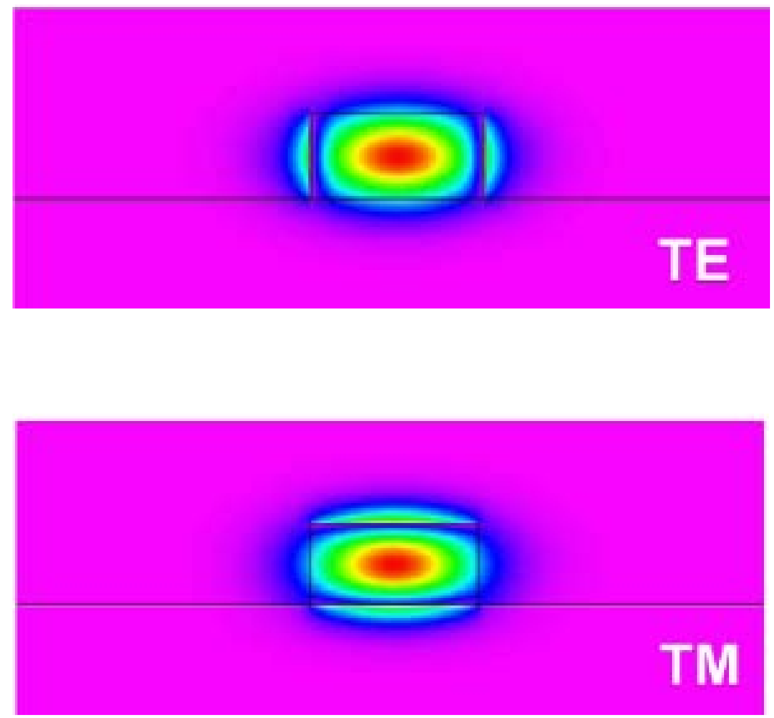
器件及应用

硅基光波导

Silicon waveguide or SOI waveguide



SEM照片



电场分布

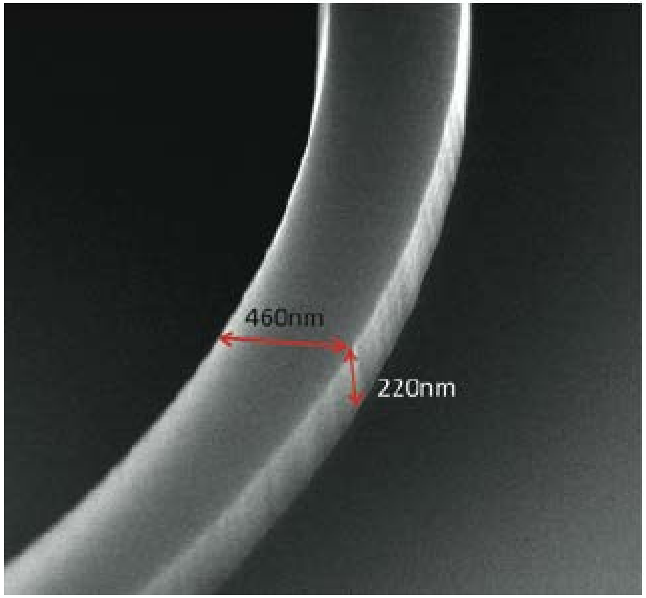
Fabrication: e-beam or optical lighography + reactive ion etching

Y. A. Vlasov et. al., Opt. Express. **12**, 1622 (2004).

器件及应用

硅基光波导

损耗



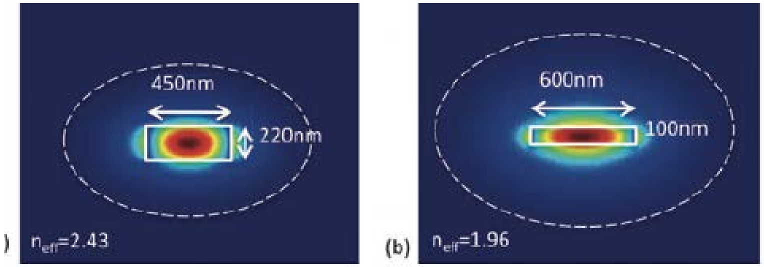
SEM照片

损耗主要来自侧壁粗糙度

减低损耗的办法：

1. 减小侧壁的粗糙度；

2. 优化波导结构，波导模场与侧壁的相互作用

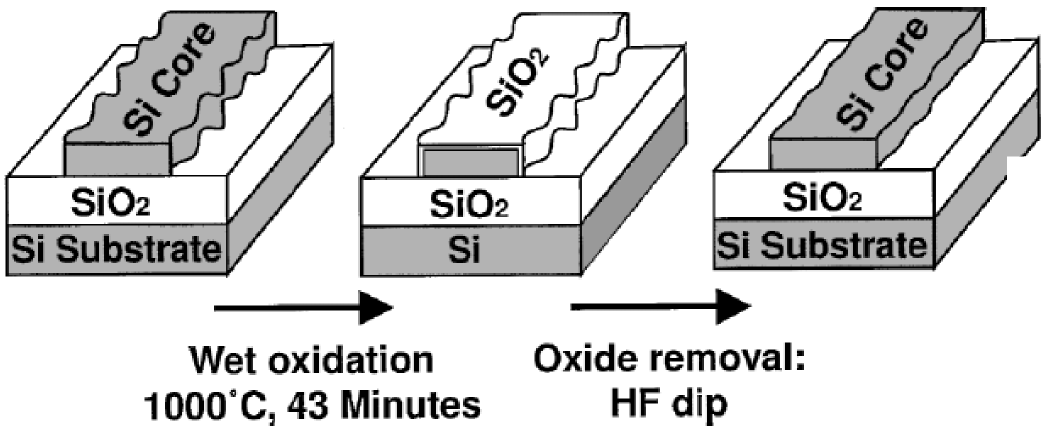


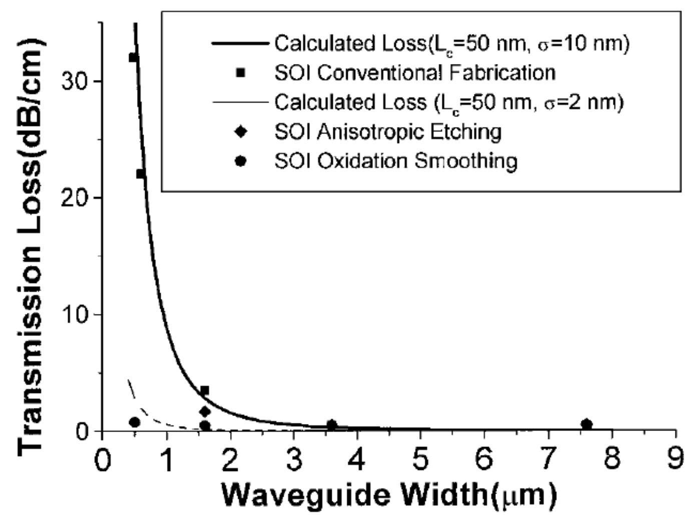
W. Bogaert et. al., Laser Photon. Rev. **6**, 47 (2004).

器件及应用

硅基光波导

Fabrication of ultralow-loss Si/SiO_2 waveguides by roughness reduction





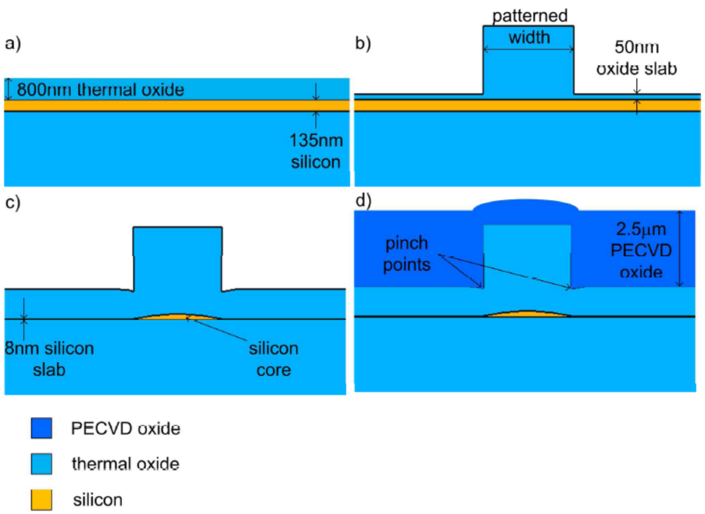
320 dB/m → 80 dB/m

K. K. Lee et. al., Opt. Lett. **26**, 1888 (2001).

器件及应用

硅基光波导

Low loss etchless silicon photonic waveguides



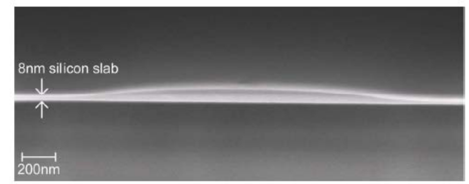
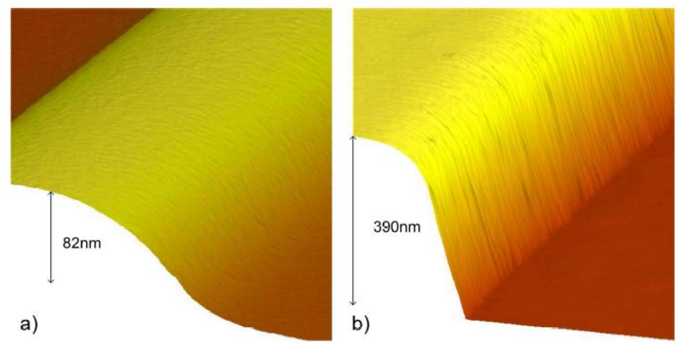
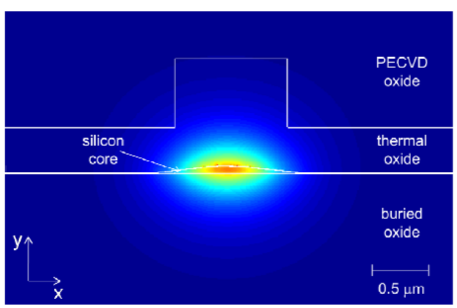


Fig. 3. Cross-section SEM image of an etchless waveguide.





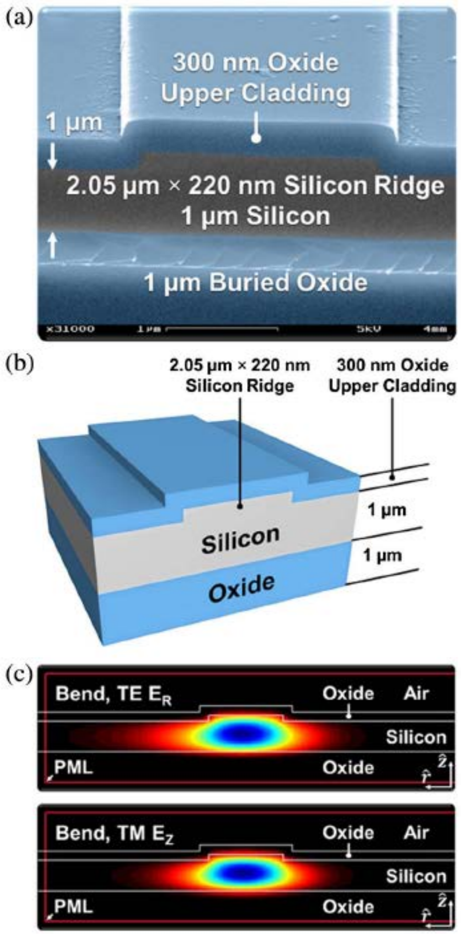
α= 30 dB/m

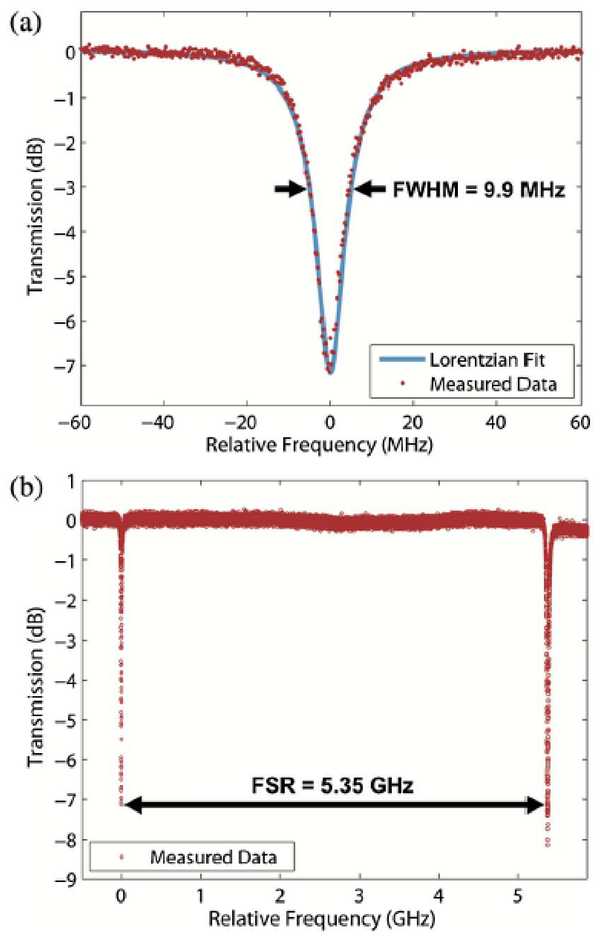
J. Cardenas et. al., Opt. Express. **17**, 4752 (2009).

器件及应用

硅基光波导

Ultralow-loss silicon ring resonators





$Q = 2.7 \times 10^7$

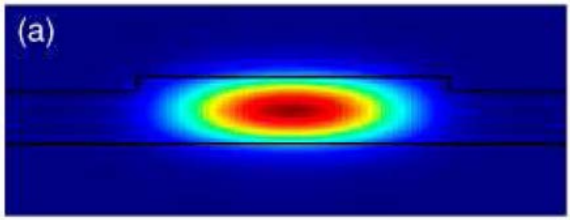
$\alpha = 2.7$ dB/m

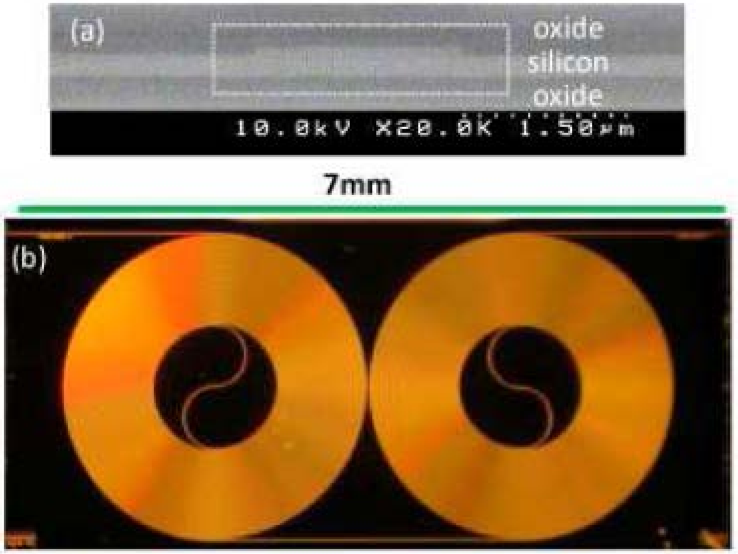
Record!

A. Biberman et. al., Opt. Lett. **26**, 4236 (2012).

器件及应用

硅基光波导





α= 27.4 dB/m

P. Dong et. al., Opt. Express. **18**, 14474 (2010).

Record!

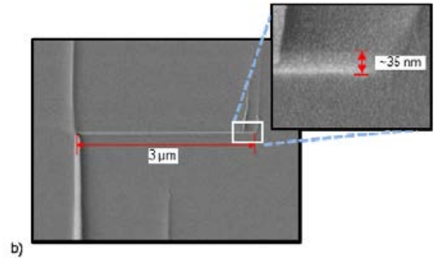
α= 2.6 dB/m

G. Li et. al., Opt. Express. **20**, 12035 (2012).

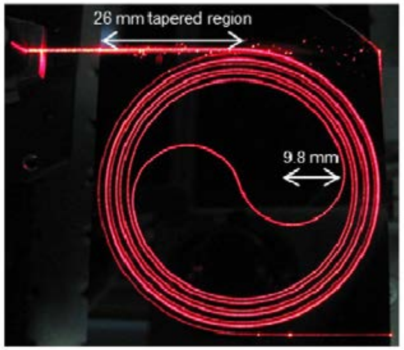
器件及应用

硅基光波导

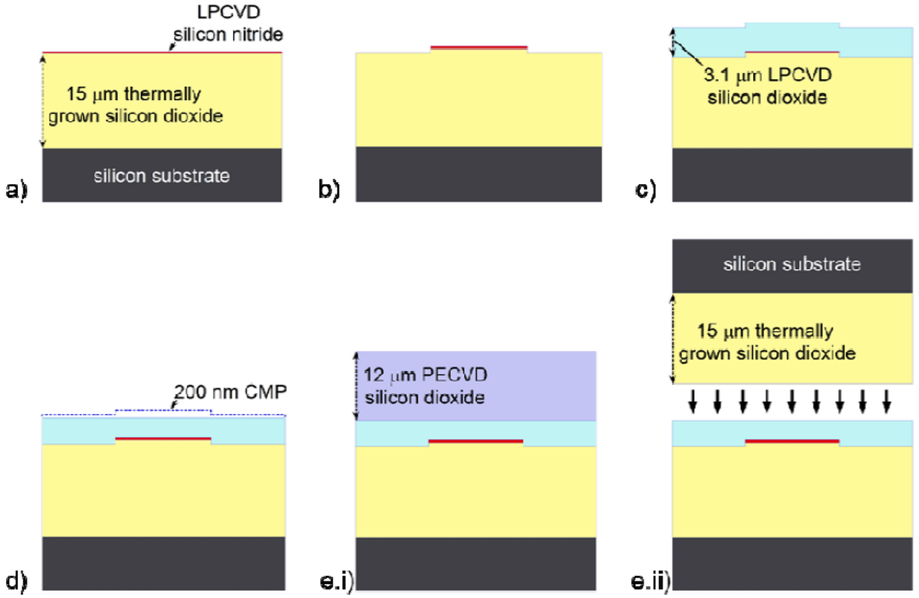
氮化硅光波导-1

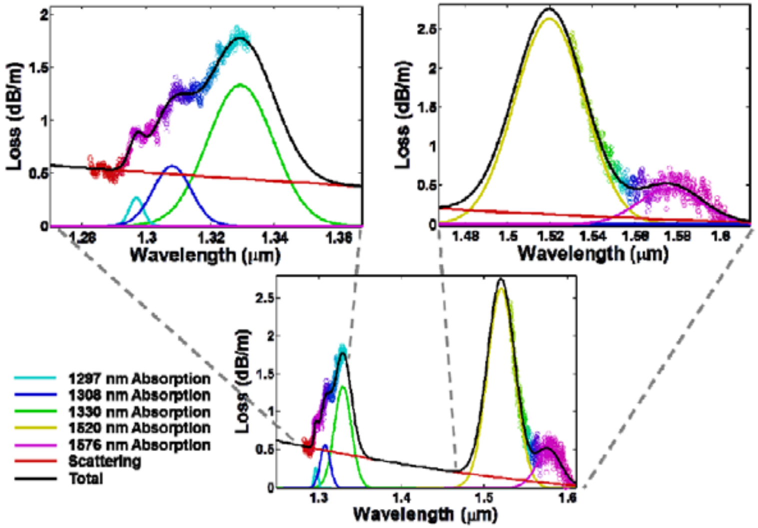


Si_3N_4 thickness:35 nm



Length：1m





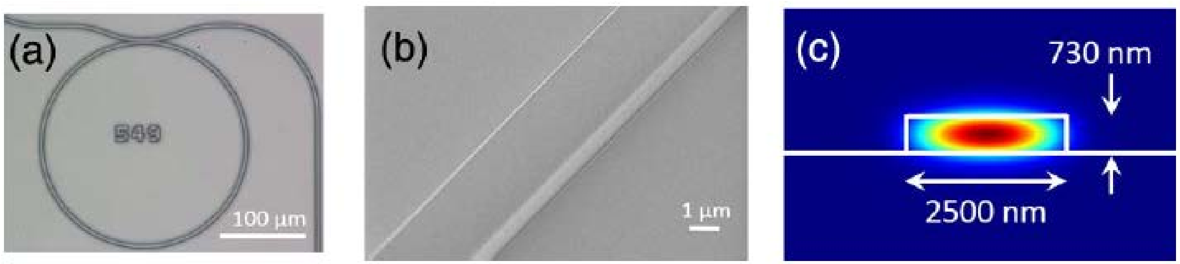
α= 0.045 dB/m @1580 nm

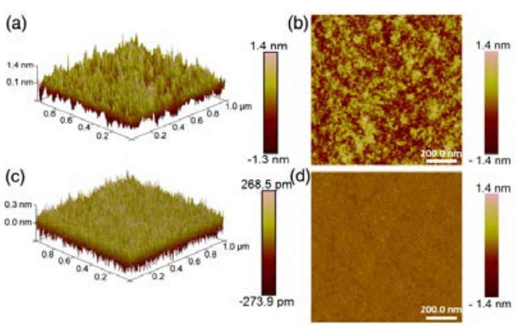
J. F. Bauters et. al., *Opt. Express*. **19**, 24090 (2011).

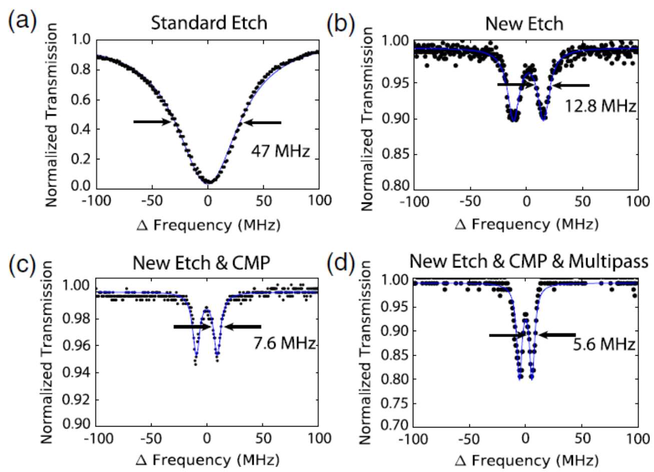
器件及应用

硅基光波导

氮化硅光波导-1







$Q=3.7\times10^7$

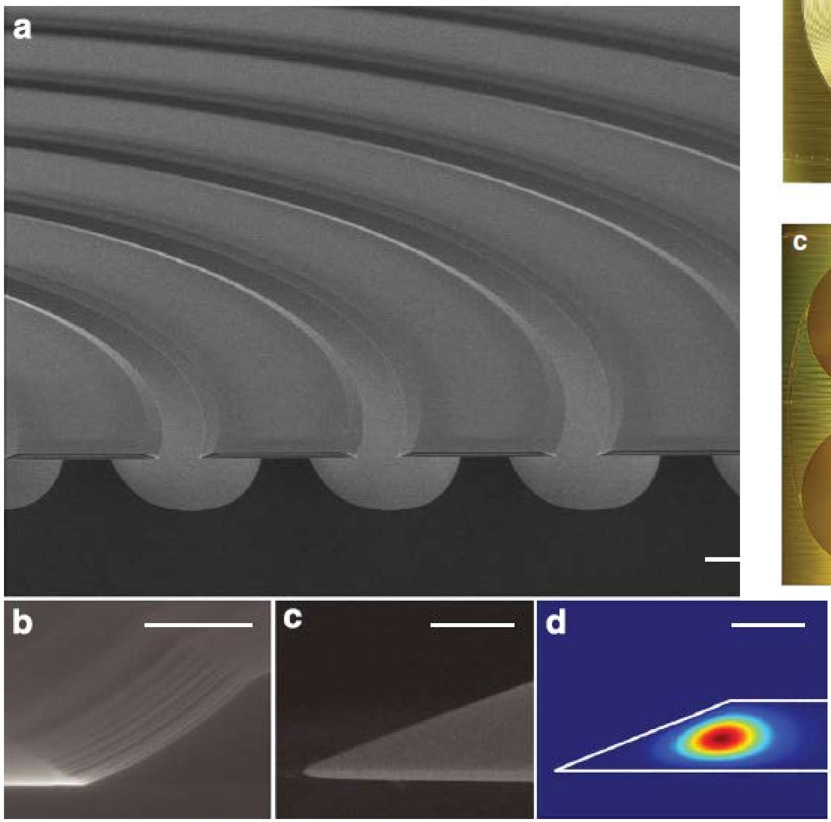
$\alpha= 0.8$ dB/m

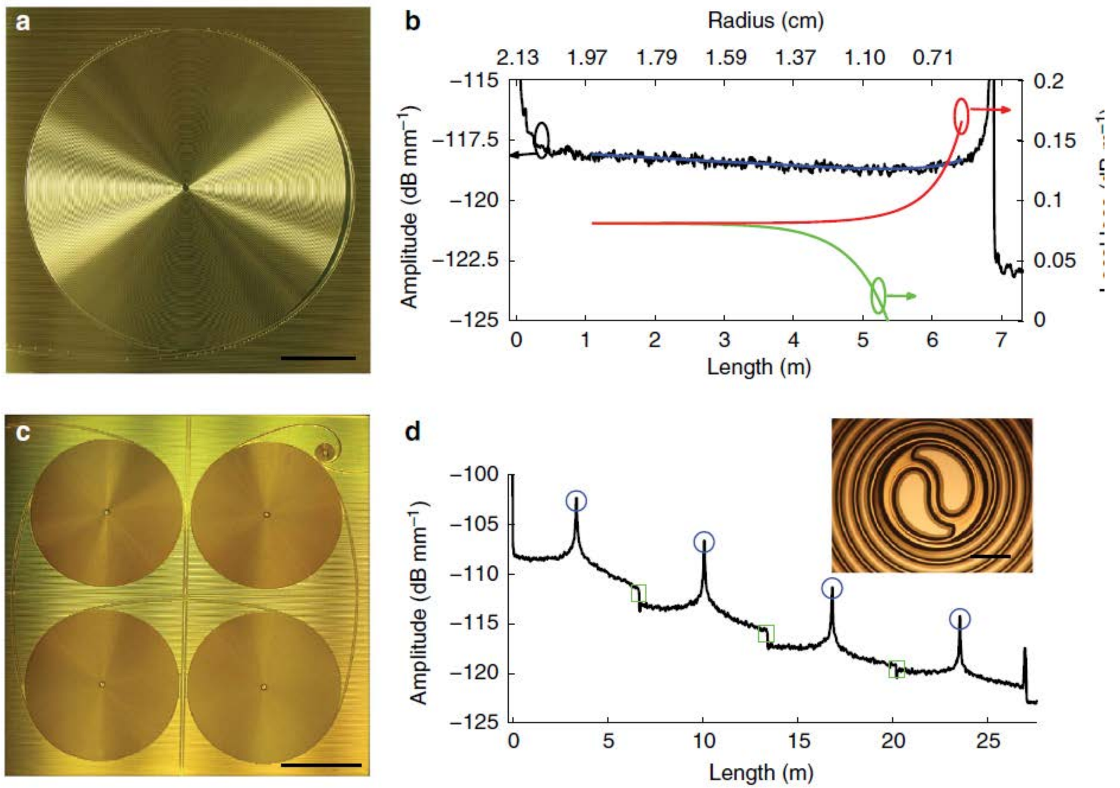
X. Ji et. al., *Optica* **4**, 619 (2017).

器件及应用

硅基光波导

氧化硅回音
壁模光波导





$\alpha = 0.08 \pm 0.01$ dB/m
L= 27 m

H. Lee, et. al., Nat. Commun.**3**, 867 (2012).