硅基光子学的新进展

Recent Progresses of Si-Based Photonics

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OUTLINE

1. Introduction
2. Si-based light emitter
   - *a. Stimulated emission from Si nanostructure*
   - *b. CW Raman Si Laser*
3. Si-based photodetector
   - *a. SiGe/Si MQW RCE photodetector*
   - *b. SOI-based InGaAs photodetector*
4. SOI optical wave guiding devices
   - *a. Optical modulator*
   - *b. Optical filter*
   - *c. Optical switch*
5. Summary

光子学

- *从物理学的角度看，光子学是研究光子的产生和运动特性、光子同物质的相互作用及其应用的一门前沿学科。*
- *从工程技术的角度看，光子学是研究作为信息和能量载体所赋予的特性、运动行为及其应用的一门工程技术。*

信息光子学　固体光子学

- *在信息领域，将光子看作信息载体，研究光子的产生和运动特性，这种专门研究光子的信息功能和应用的新型科学便是信息光子学。*
- *专门以固体材料为介质，研究光子载体在固体介质中的产生、运动、控制、操作，研究光子同固体物质的相互作用及其应用，这种专门研究固体中的光子性能的新型科学便是固体光子学。*
- *半导体光子学:以半导体材料为介质的光子学。研究半导体中光的产生、传输、控制和探测特性。*

Three Major Inventions in Optics

- Laser
- Low-loss Optical Fiber
- Semiconductor photonic Devices

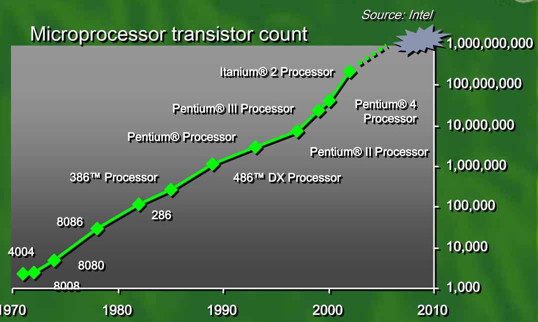
Three "T" of Information Society

信息社会中的三"T"

"T": tera (10^{12})

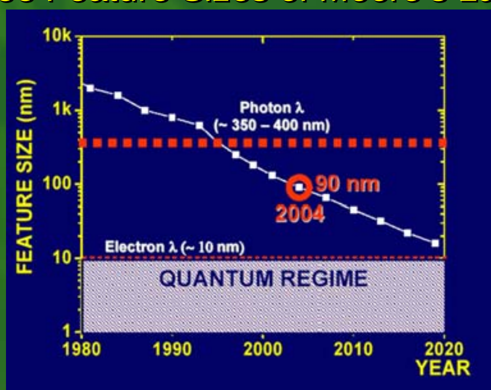
1. Calculation rate of computer
   计算机计算速度 1T bit/sec.
2. Transmission rate of optical fiber communication
   光纤通信传输速度 1T bit/sec.
3. Recordation density of optical disc
   光盘记录密度 1T bit/inch^2

Moore's Law



~ 1 Billion transistors by 2nd half of decade

Tree Feature Sizes of Moore's Law

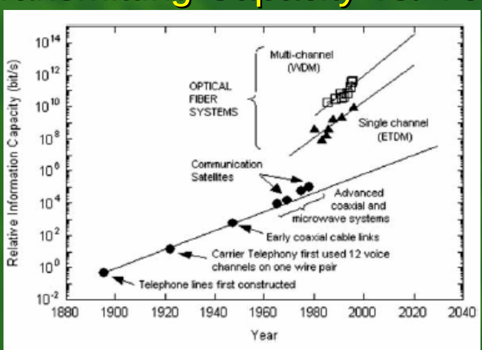


信息科学五十年前后对比

年份	1950	2000	前后变化
电子器件尺寸	晶体管发明不久,尚无可靠产品,微小型电子管体积>0.6cm³	VLSI 中每个器件平均体积<10⁻⁸cm³	缩小 10⁸ 倍
电子器件功耗	>50mW	<10nW	缩小 10⁷ 倍
集成度	无	>10⁸ 器件	>10⁸ 倍
门电路延迟时间	~μs	~0.1ns	加快数万倍
计算机速度	~10² 次/秒	~10¹² 次/秒	增加 10¹⁰ 倍

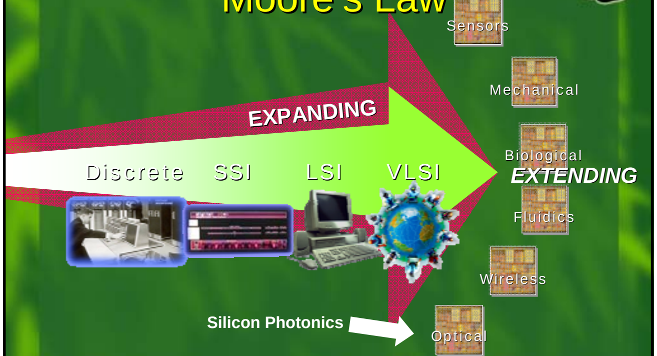
引自 王守觉院士的学术报告

Transmitting Capacity vs. Year



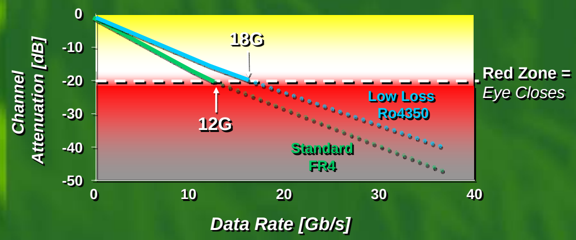
C. H. Fine, Optoelectronic Industry Association

Extending and Expanding Moore's Law



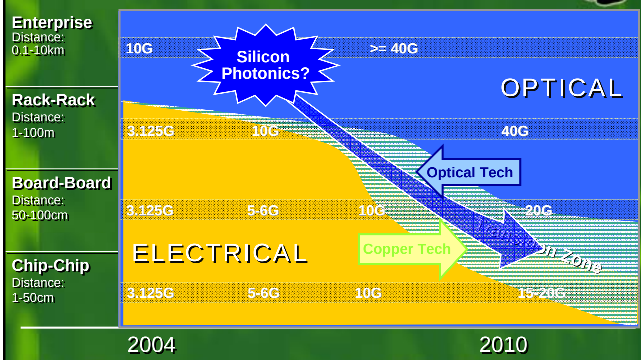
Copper Approaching Limits

Simulation of 20" server channel transmitter w/ equalization



Copper scaling more challenging.
Headroom getting squeezed.

Electrical to Optical



Requirements for "Siliconizing" Photonics

REQUIREMENT	SOLUTION
1. Light Source*	Low-cost External Laser
2. Guide Light	Si-on-Insulator (SOI) WG
3. Fast Modulation	Si MOS Capacitor Device
4. Light Detection	Si Based Photodetector
5. Low-cost Assembly	Si Passive Alignment
6. Intelligence	Si CMOS Circuitry

*Light amplification/laser — Stimulated Raman scattering

UHV/CVD System

Progresses in the last 3 years

2003	PBG WG <25dB/cm IBM	Raman Stimulated Scattering UCLA	Wavelength Conversion UCLA	PBG WG <7dB IBM, FESTA, NTT	DGADC Surrey	
2004	30GHz SiGe PD IBM	GHz-MOS Modulator Intel	Raman Net Fulsed Gain Ientel, Cornell UCLA, CUHK	CW Gain in photonic wire: Columbia University	Gain in tapered waveguides Tech. University Hamburg	Polarisation independent ring resonator Surrey
2005	Raman laser direct electrical switching UCLA	First CW Raman Laser Intel	Lossless modulator Intel	Low loss Si nanowires Columbia Cornell IBM, NTT	10GBit/s Modulator Intel	Single mode equation for small waveguides Surrey

2005 FGP (Four Group Photonics)
Terahertz and Mid-IR Sources, Optoelectronic Integration, Photonic Crystals, Light Sources, Modulators & Switches, Photodetectors, Waveguides, Lasers

Why SOI?

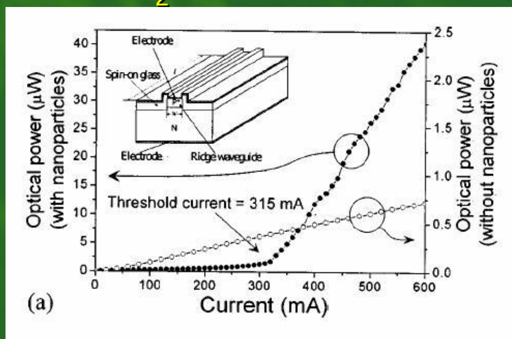
Advantage	Disadvantage
• SOI wafers available • Transparent for light 1.3μm & 1.55 μm • Large refraction difference between Si and SiO_2 • Compatible with CMOS technique • Large thermal conductivity • Possible for integrating multiple optical devices	• Without Pockels effect • Slow modulation mechanism • Small size for single-mode waveguide • Limited optical confinement of rib waveguide with large cross section • Large coupling loss between waveguide and fiber • Large reflection loss when coupling

SOI-based photonics is potential to converge computing and communications

SOI-based Photonicc Devices

- " A High-Speed Silicon Optical Modulator based a Metal-on-Semiconductor Capacitor"
  SOI+CMOS, Ridge waveguide structure, 1 GHz
  *A. Liu, et. Al., Nature, Feb. 22, 2004: **427**, 616-618*
- "High speed silicon Mach-Zehnder modulator"
  a silicon modulator with an intrinsic bandwidth of 10 GHz and data transmission from 6 Gbps to 10 Gbps.
  *L. Liao, et. al., OPTICS EXPRESS, 2005 , **13**(8) , 3129-3135*
- "Stimulation Emmission in a Nanostructured Silicon *pn* Junction Diode Using Current Injection"
  Nanostructure, pn juncture, Current Injection
  λ: 1.2μm, E: 1.1eV
  *M. J. Chen, et. al., Appl. Phys. Lett., 2004: **54**(12), 2163-2165.*
- "A Continuous-wave Raman Silicon Laser"
  p-i-n diode embedded in Si waveguide, Cavity: multilater dielectric films. CW operation: Milestone for Si-based optoelectronic devices
  *H. Rong, et. al., Nature, Feb. 17, 2005: **433**, 725-727.*

Silicon *pn* Junction Diode with Si/SiO_2/Si Nanostructures



*M. J. Chen, et. al., Appl. Phys. Lett., March 22, 2004: **54**(12), 2163-2165*

A Continuous-wave Raman Si Laser

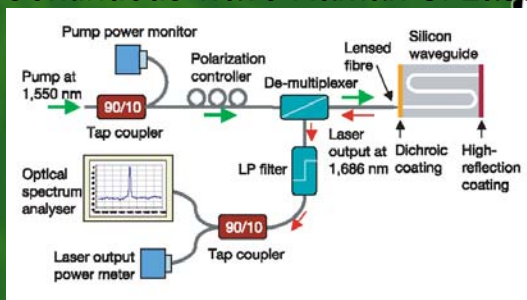
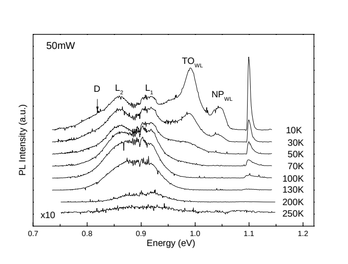
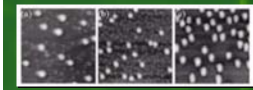


Figure 2 Schematic set-up of the silicon Raman laser experiment. See main text for details.

*H. Rong, et. al., Nature, Feb. 17, 2005: **433**, 725-727.*

PL Spectra of Ten-bilayer Sample of Ge/Si (001) Islands

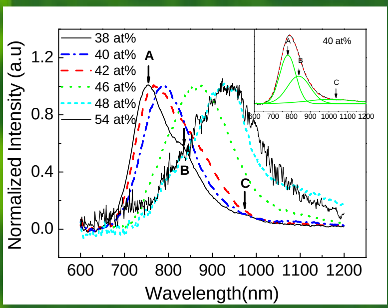




Sample No. 545
λ= 514.5 nm
P = 50mW/mm^2
Ge detector 1.099eV
Si Sub. TO Peak,
NP$_{WL}$+TO$_{WL}$ wetting layers
L1+L2 NP TO from Ge islands

- The study demonstrated that the underlying Ge_xSi_{1-x} layers took part in the formation of Ge islands partly.
- PL spectra showed that photoluminescence from Ge islands is stronger than that from Ge grown Si directly.

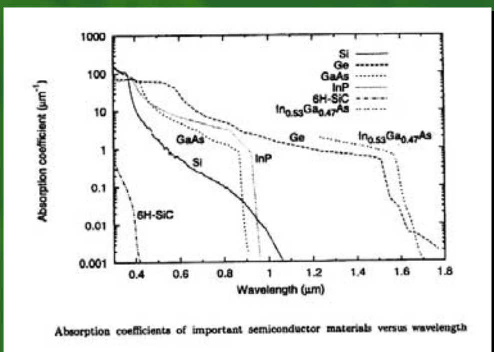
PL Spectra of Silicon Rich Silica (SRO) with Different Si Concentration



1, radiation of Si NC.
2, interface state recombination.
3, localized state transitions in α Si clusters.

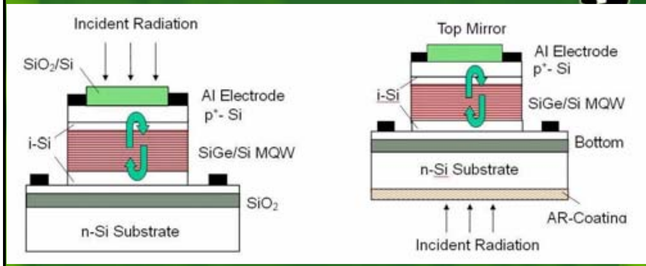
X. X. Wang, J. G. Zhang, et. al., "Origin and evolution of photolumines-cence from Si nanocrystals embedded in a SiO_2 matrix", PHYSICAL REVIEW B 72, 195313 , 2005.

α of different materials



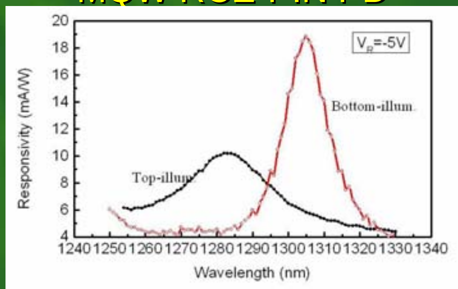
Absorption coefficients of important semiconductor materials versus wavelength

Top- and bottom-illuminated RCE-PD



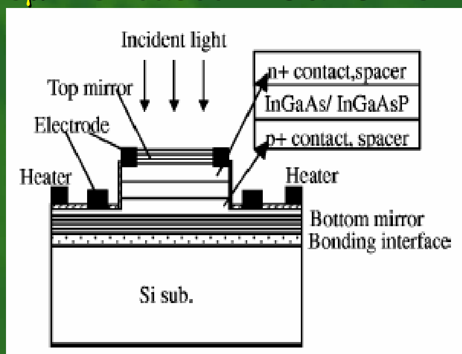
(a) Si/SiO$_2$ interface in the SOI and a stack of Si/SiO$_2$ DBR films on the epitaxial wafer as the bottom and top mirrors.
(b) Bottom mirror is also Si/SiO$_2$ DBR films on Si substrate.
Bonding technique to combine wafer A (SiGe/Si MQW grown on Si) and wafer B (Si/SiO$_2$ DBR films deposited on Si) together.

Responsivity Spectra of SiGe MQW RCE-PIN PD

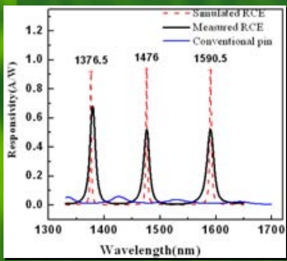


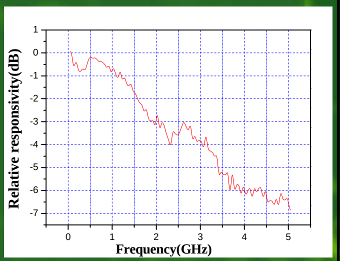
- Top-incident PD: R=10.4mA/W, FWHM=32nm at 1.283μm, V_R=-5V.
- Bottom-incident PD, R=19mA/W, FWHM=14nm at 1.305μm,V_R=-5V.
- The peak responsivity increases with reverse voltage.

1.55μm Si-based InGaAs RCE-PD



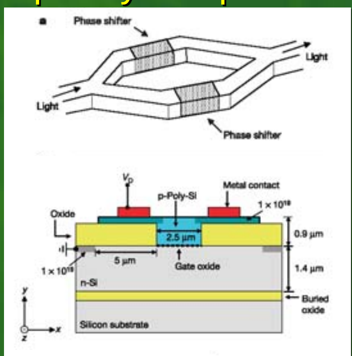
Response of Si-based InGaAs RCE-PD





λ_0 = 1590.5nm, FWHM<12.5nm,
R = 0.48A/W, η ~ 44% at 0V,
f_{3dB}=1.8GHz.

High Frequency Si Optical Modulator



A. Liu, et. al., Nature, Feb. 22, 2004: ***427****, 616-618*

High frequency Si optical Modulator

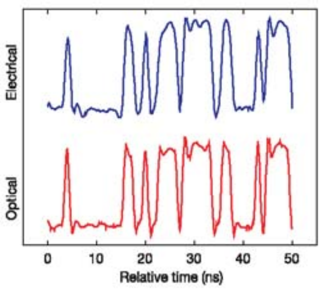
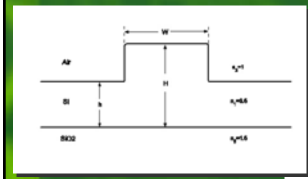
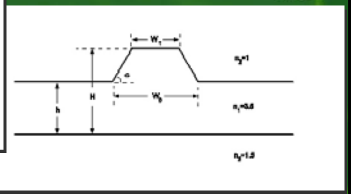


Figure 5 Pseudorandom bit sequence of a silicon Mach–Zehnder interferometer modulator containing a single 2.5-mm-long MOS capacitor phase shifter in one arm at a data bit rate of 1 Gbit s^{-1}.

SOI Rib Waveguide



Rectangular Cross Section



Terraced Cross Section

Numerical Simulation for SOI Waveguide

Beam propagation method：semi-vectorial BPM. Applied in simulation of straight waveguides.

Effective index method: Applied in simulation of S-bend waveguides.

Single Mode Conditions of SOI Rib Waveguides

$$t \le 0.3 + \frac{r}{\sqrt{1-r^2}}, \qquad r > 0.5$$

R.A. Soref, J. Schmidtchen, K. Petermann, IEEE J. Quantum Electro., 1991, 27(8):1971-1974.

$$t \le \frac{r}{\sqrt{1-r^2}} \qquad r > 0.5$$

S. P. Pogossian, L. Vescan, and A. Vonsovici, J. Lightwave Technol. , 1998, 16(10):1851-1853.

t=W/H，r=h/H，W、H and *h* is the width, height, and slab height, respectively.

Single Mode Condition for Rib Waveguide

Rectangular Cross Section:

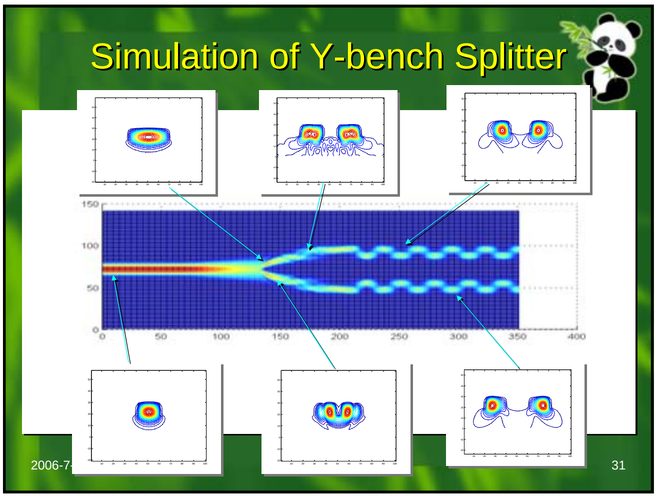
$$t \le 0.29 + \frac{r}{\sqrt{1-0.97r^2}}, \qquad r > 0.5$$

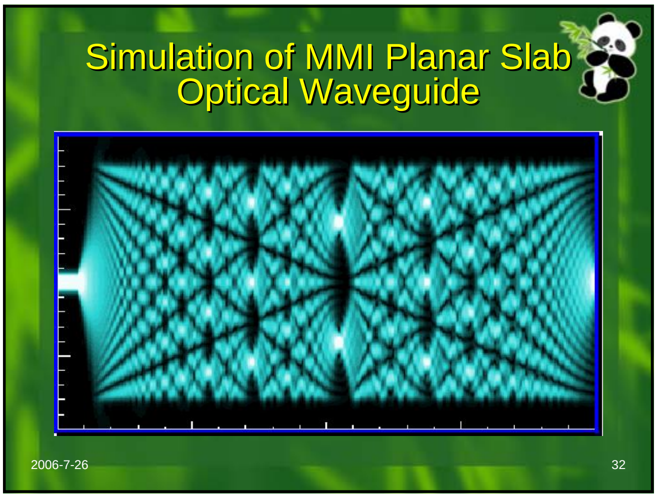
Terraced Cross Section:

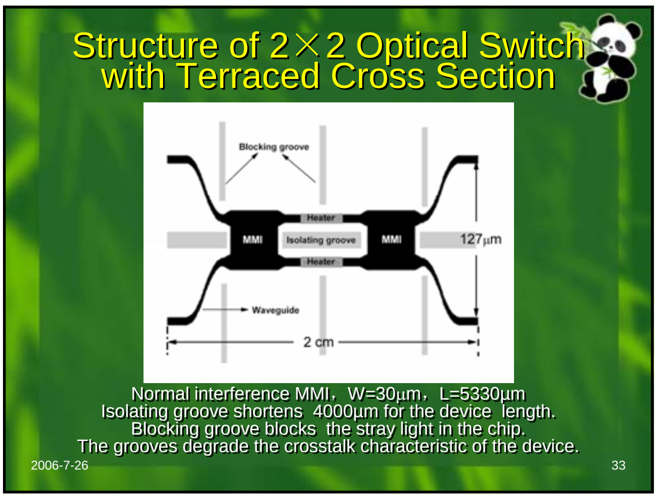
$$t \le -1.12 + \frac{0.63r}{\sqrt{1-1.03r^2}} + 2.04r, \qquad r > 0.5$$

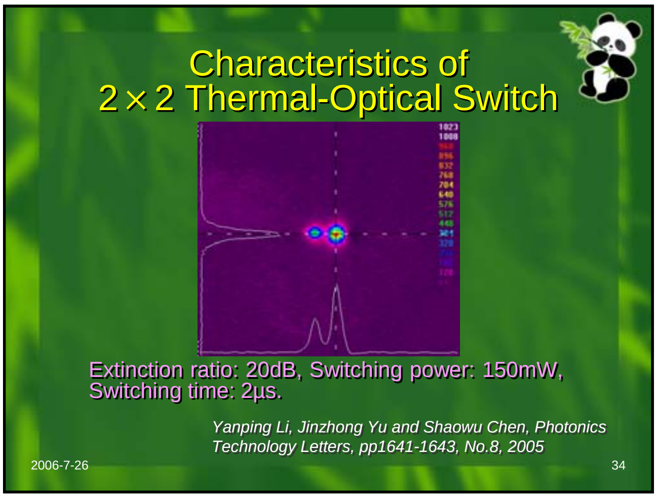
Were $t=W_t/H$，$r=h/H$

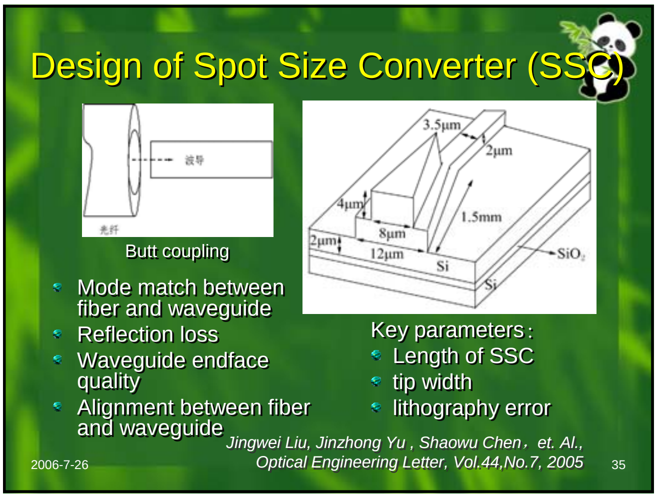
Jinzhong Yu, Saowu Chen, Jinsong Xia, et. Al., Science in China Ser. F Information Science, 2005 Vol. 48 No. 2, 234-246.

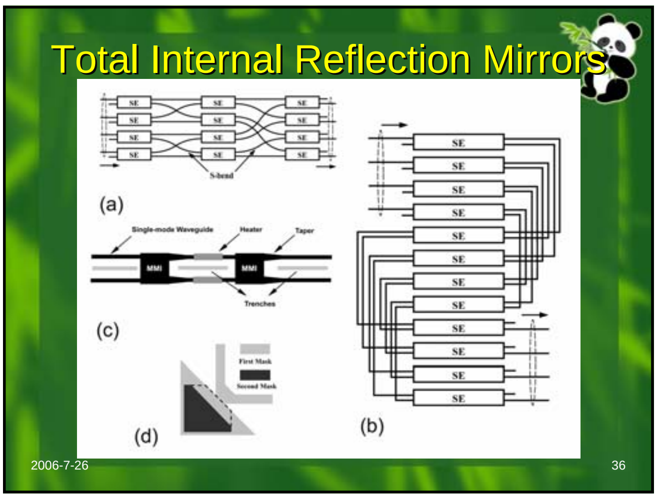

Simulation of Y-bench Splitter
2006-7-
31


Simulation of MMI Planar Slab Optical Waveguide
2006-7-26
32

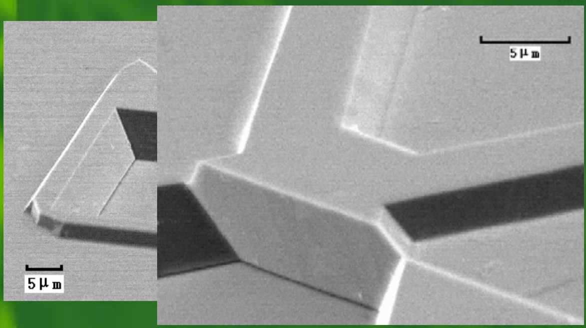

Structure of 2×2 Optical Switch with Terraced Cross Section
Blocking groove
Heater
MMI
Isolating groove
MMI
Heater
127μm
Waveguide
2 cm
Normal interference MMI，W=30μm，L=5330μm
Isolating groove shortens 4000μm for the device length.
Blocking groove blocks the stray light in the chip.
The grooves degrade the crosstalk characteristic of the device.
2006-7-26
33


Characteristics of 2×2 Thermal-Optical Switch
Extinction ratio: 20dB, Switching power: 150mW,
Switching time: 2μs.
Yanping Li, Jinzhong Yu and Shaowu Chen, Photonics Technology Letters, pp1641-1643, No.8, 2005
2006-7-26
34


Design of Spot Size Converter (SSC)
光纤
波导
Butt coupling
3.5μm
2μm
4μm
1.5mm
8μm
2μm
12μm
Si
SiO2
Si
Mode match between fiber and waveguide
Reflection loss
Waveguide endface quality
Alignment between fiber and waveguide
Key parameters:
Length of SSC
tip width
lithography error
Jingwei Liu, Jinzhong Yu , Shaowu Chen，et. Al., Optical Engineering Letter, Vol.44,No.7, 2005
2006-7-26
35


Total Internal Reflection Mirrors
SE
S-bend
(a)
Single-mode Waveguide
Heater
Taper
MMI
MMI
Trenches
(c)
First Mask
Second Mask
(d)
(b)
2006-7-26
36

Total Internal Reflection Mirrors



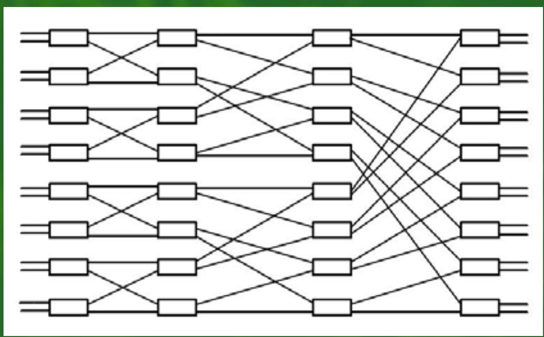
SOI photonic wires

Group	Date	h [nm]	w [nm]	loss [dB/cm]	BOX [um]	top clad	Fab.
IMEC	Apr. '04	220	500	2.4	1	no	DUV
IBM	Apr. '04	220	445	3.6	2	no	EBeam
Cornell	Aug. '03	270	470	5.0	3	no	EBeam
NTT	Feb. '05	200	400	2.8	3	yes	EBeam
Yokohama	Dec. '02	320	400	105.0	1	no	EBeam
MIT	Dec.'01	200	500	32.0	1	yes	G-line
LETI / LPM	Apr. '05	300	300	15.0	1	yes	DUV
		200	500	5.0			
Columbia	Oct. 03	260	600	110.0	1	yes	EBeam
NEC	Oct.04	300	300	19.0	1	yes	EBeam

(Table partly from Vlasov, McNab, Opt. Expr. '04, pp1630)

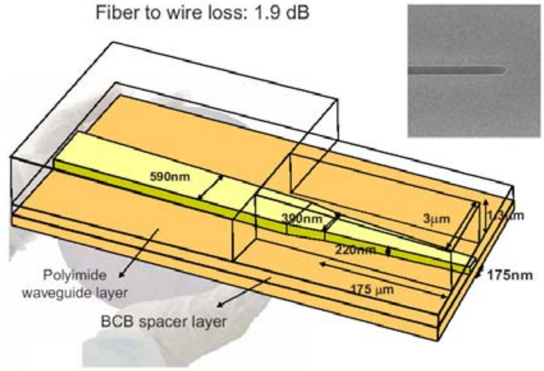
 Photonics Research Group

16×16 Thermo-optic Switch Matrix Architecture



Fiber to wire coupler design

Fiber to wire loss: 1.9 dB



Blocking 16×16 SOI Optical Switch Matrix

16×16 switch matrix:
- *32 switch cells.*
- *4-stage interconnections.*
- *Size: 4.5cm × 0.215cm.*

2×2 switch cell: 0.6cm × 20μm.
Insertion loss: 21.7~27.1dB.
crosstalk: -12.6~-33.2dB.
extinction ratio: 13.8~22.3dB.
power consumption : ~200mW.
rise and fall time: 2.1μs & 2.3μs.

Jinzhong Yu, Shaowu Chen, Zhiyong Li, et. al., "SOI Optical Switch Matrix Integrated with Spot Size Converter (SSC)", to be published in 2006 International Conference on Four Group Photonics.

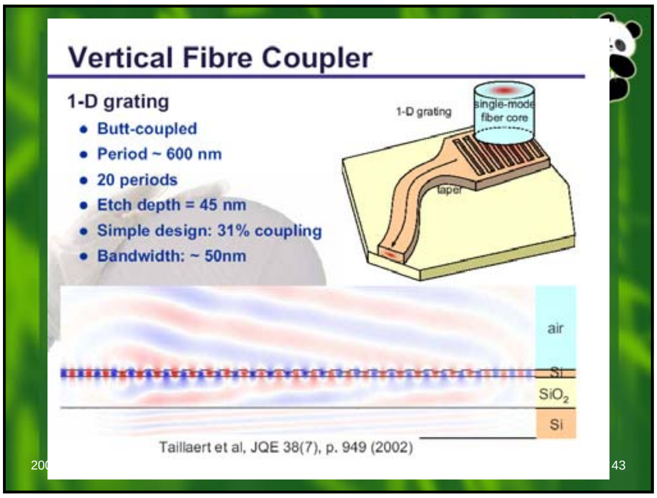
Single Mode Conditions of Nanowire Waveguides

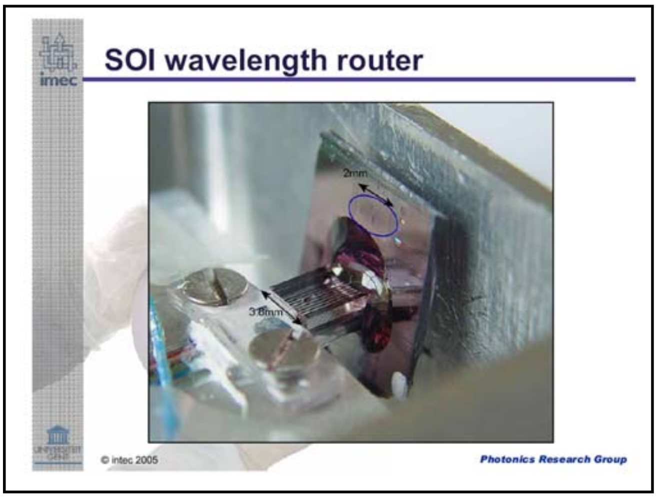
$$\frac{W}{H} \le 0.05 + \frac{(0.94+0.25H)r}{\sqrt{1-r^2}}$$

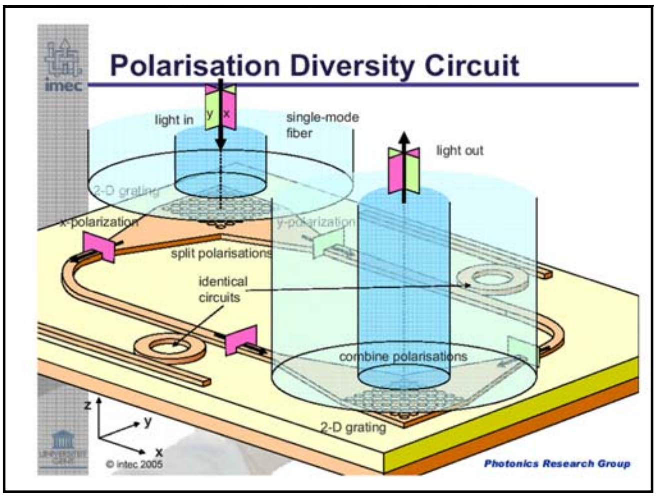
$$0.3 < r < 0.5$$

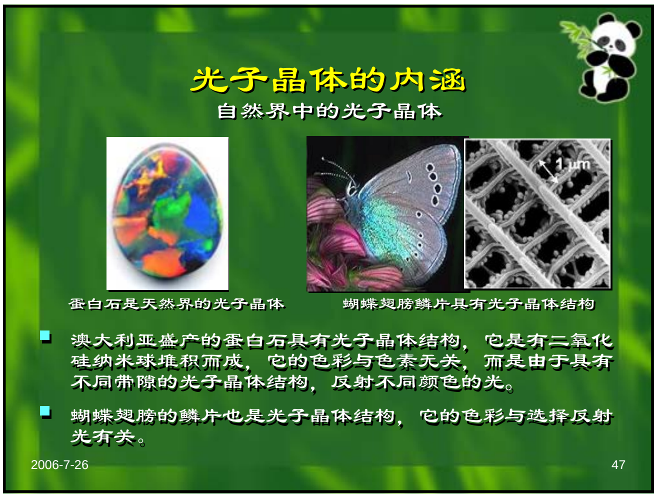
$$1.0\mu m \le H \le 1.5\mu m$$

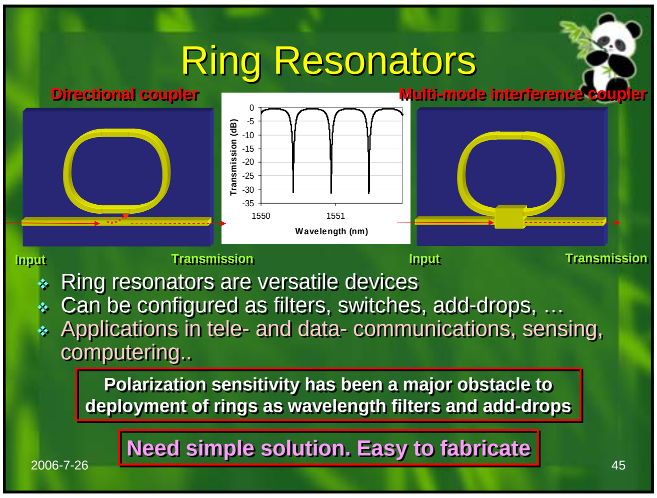
S. P. Chan et al. Single-mode and polarization-independent silicon-on-insulator waveguides with small cross section. J. Lightwave Technol., 23(6):2103-2111, 2005


Vertical Fibre Coupler
1-D grating
Butt-coupled
Period ~ 600 nm
20 periods
Etch depth = 45 nm
Simple design: 31% coupling
Bandwidth: ~ 50nm
1-D grating
single-mode fiber core
taper
air
Si
SiO2
Si
Taillaert et al, JQE 38(7), p. 949 (2002)
43


imec
SOI wavelength router
2mm
3.6mm
© intec 2005
Photonics Research Group


imec
Polarisation Diversity Circuit
light in
single-mode fiber
light out
2-D grating
x-polarization
y-polarization
split polarisations
identical circuits
combine polarisations
2-D grating
© intec 2005
Photonics Research Group


光子晶体的内涵
自然界中的光子晶体
1 μm
蛋白石是天然界的光子晶体
蝴蝶翅膀鳞片具有光子晶体结构
澳大利亚盛产的蛋白石具有光子晶体结构，它是有二氧化硅纳米球堆积而成，它的色彩与色素无关，而是由于具有不同带隙的光子晶体结构，反射不同颜色的光。
蝴蝶翅膀的鳞片也是光子晶体结构，它的色彩与选择反射光有关。
2006-7-26
47


Ring Resonators
Directional coupler
Multi-mode interference coupler
Transmission (dB)
Wavelength (nm)
Input
Transmission
Input
Transmission
Ring resonators are versatile devices
Can be configured as filters, switches, add-drops, …
Applications in tele- and data- communications, sensing, computering..
Polarization sensitivity has been a major obstacle to deployment of rings as wavelength filters and add-drops
Need simple solution. Easy to fabricate
2006-7-26
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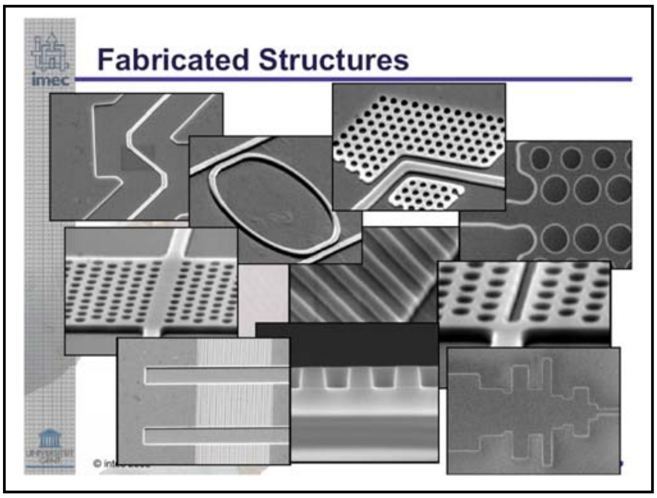
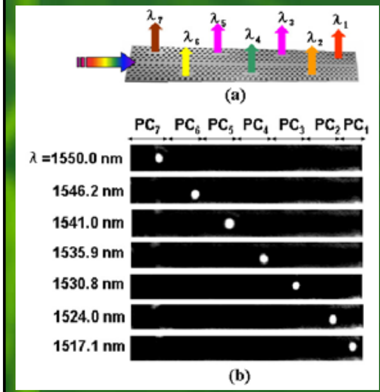
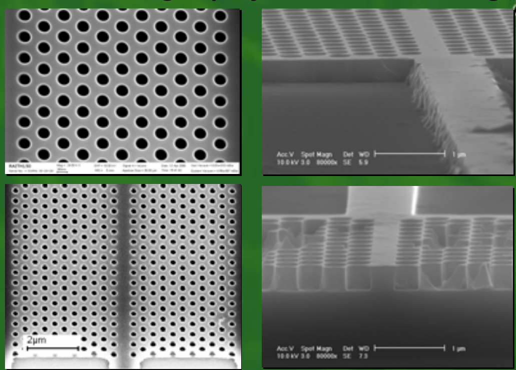

imec
Fabricated Structures



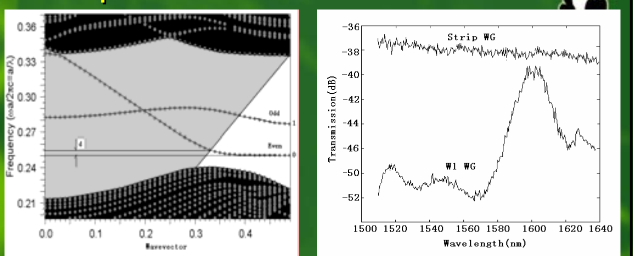
(a)Photonic-nanostructure device based on in-plane hetero photonic crystals, where in-plane arrays of photonic crystals with different lattice constant (1.25nm) are integrated.

(b) multi-channel drop (add) operation.

EB Lithography & ICP Etching



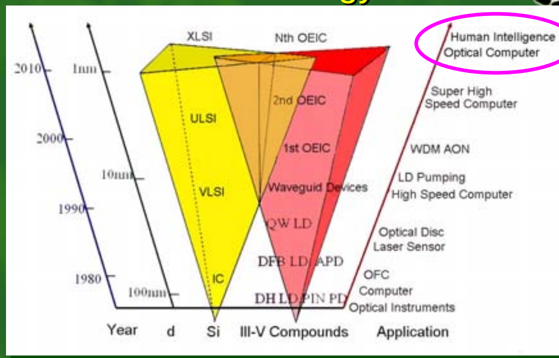
Experimental Result of SOI-PC



理论计算取r/a=140/400 (nm)，相应的波长范围:1563－1602nm，实验测出的范围约是1585－1615nm.出现了明显的传输区与截止区。

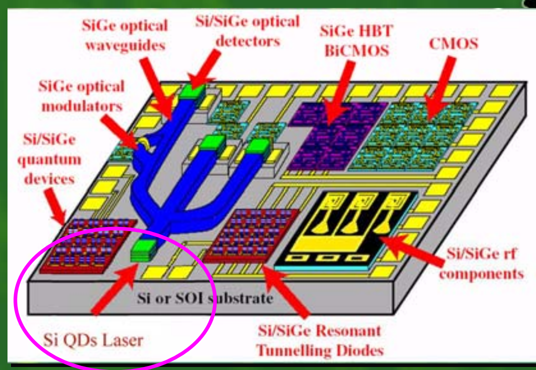
- photonic-nanostructure devices can be indeed realized.
- Nanocavities with ultrahigh *Q* factor of 600,000.
- Apllication in various fields including quantum communication and computing, bio and accurate environmental monitors.

Tendency of Semiconductor Technology



余金中：半导体光电子技术，2003，化工出版社

Si-based OEIC



Summary

- Si , SiGe and SOI are the promoting materials for Si-based photonic devices.
- The progress of Si photonics in recent years has been significant and rapid.
- The current trend of shrinking device dimensions raises important design and strategy issues.
- With the recent developments, Si super-chip now seems within reach.
- There are a long way to go for Si-based PIC (photonic integrated circuit), but potential for it is available and the future is bright !

"It is a great time to be working on Silicon Photonics."

—Prof. Graham T Reed

(Advanced Technology Institute, University of Surrey, UK)