The Past, Present, and Future of Silicon Photonics

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Outline

- Introduction
- A glance at history
- Present achievements (2006)
- Future Prospects

Introduction

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The Past, Present, and Future of Silicon Photonics

Richard Soref, *Life Fellow, IEEE*

(Invited Paper)

- Ph.D. degree in electrical engineering from Stanford Univ.
- 1964-1965: Staff member at MIT Lincoln Lab.
- 1965-1983: Staff member at Sperry Research Center
- 1983~ : Research scientist at U.S. Air Force Research Lab.

☞ *Four-decade career in photonics research*

The preliminary results indicate that

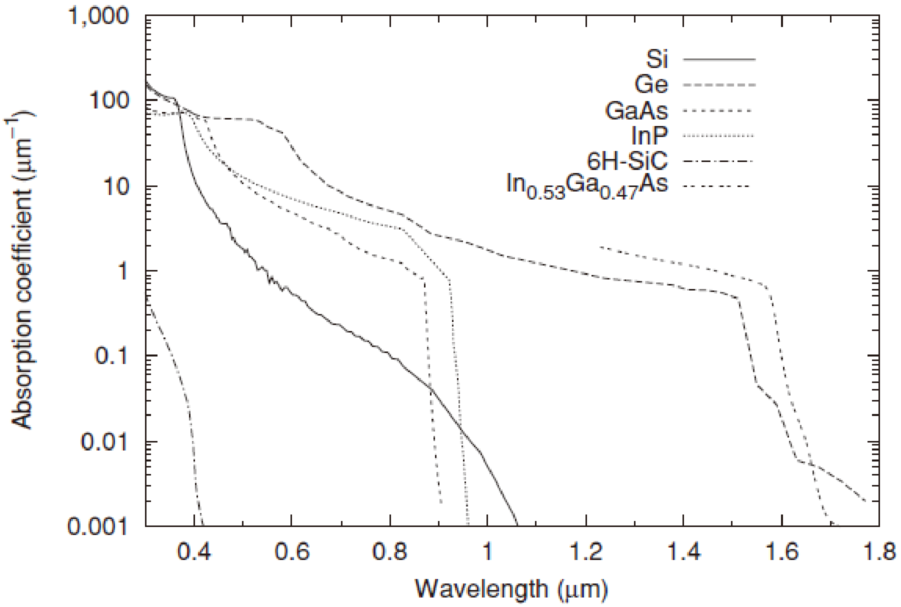
the silicon photonics is truly CMOS compatible!

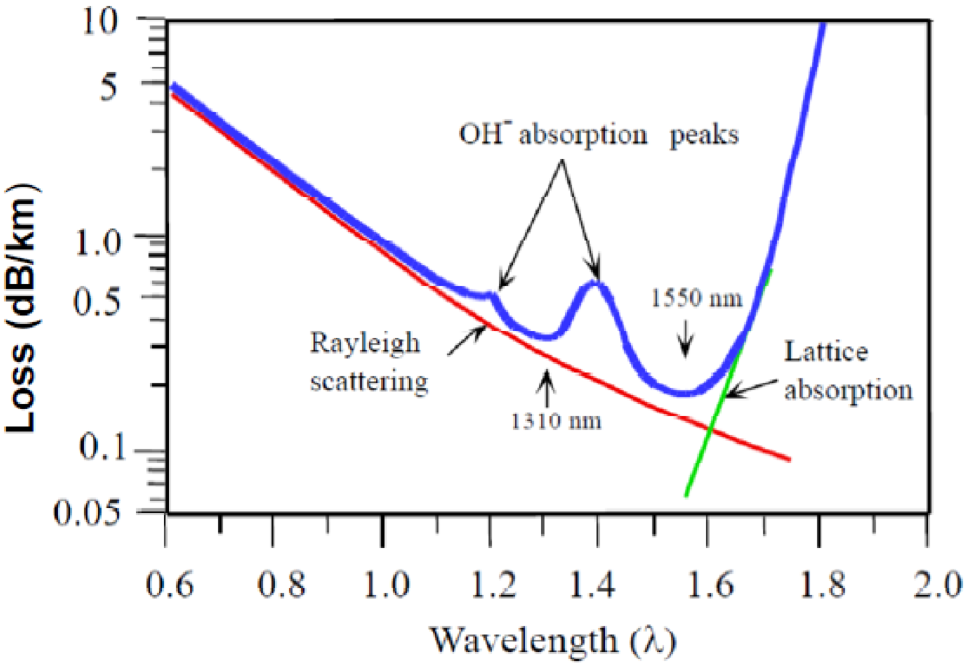
A Glance at History

• Silicon photodiodes are excellent detectors at wavelengths shorter than 1.2 um, however, telecommunication occurs beyond 1.2 um.

• Silicon can be a waveguide medium for the 1.3- and 1.55-um fiber-optic transmission wavelengths.

• Silicon substrate can be a platform for the visible and 850-nm.





A Glance at History

- 1985: Optoelectronic (OE) integration upon silicon has been a prime motivation
- 1990s: Progress on OE integration, SiGe/Si infrared sensors, etc.
  lack of light sources (silicon LEDs/lasers) → skepticism for monolithic on-chip integration
- 2004: * Group IV Photonics – first ongoing global meeting devoted solely to silicon photonics
  * EU – Silicon Heterostructure Intersubband Emitter (SHINE) program
  * Univ. teams (funded by the Air Force Office of Scientific Research) – electrically pumped 1.55-um silicon-based lasers
  * Defense Advanced Research Projects Agency (DARPA) – electronic and photonic integrated circuits (EPIC) in silicon

Present Achievements (2006)

• Development of high-volume optoelectronic integrated circuit (OEIC) chips and practical photonic ICs

• Optical interconnects: rack-to-rack, board-to-board, chip-to-chip, intra-chip

• Potential uses of silicon photonics

- photonic interconnects, data communication, telecommunication, signal processing, switched networks, imaging, display, radio frequency/wireless photonics, electronic warfare, photonics for millimeter-wave/microwave/radio-frequency systems, bionics, optical storage, etc.

→ Recent explosion in Si photonics

Present Achievements

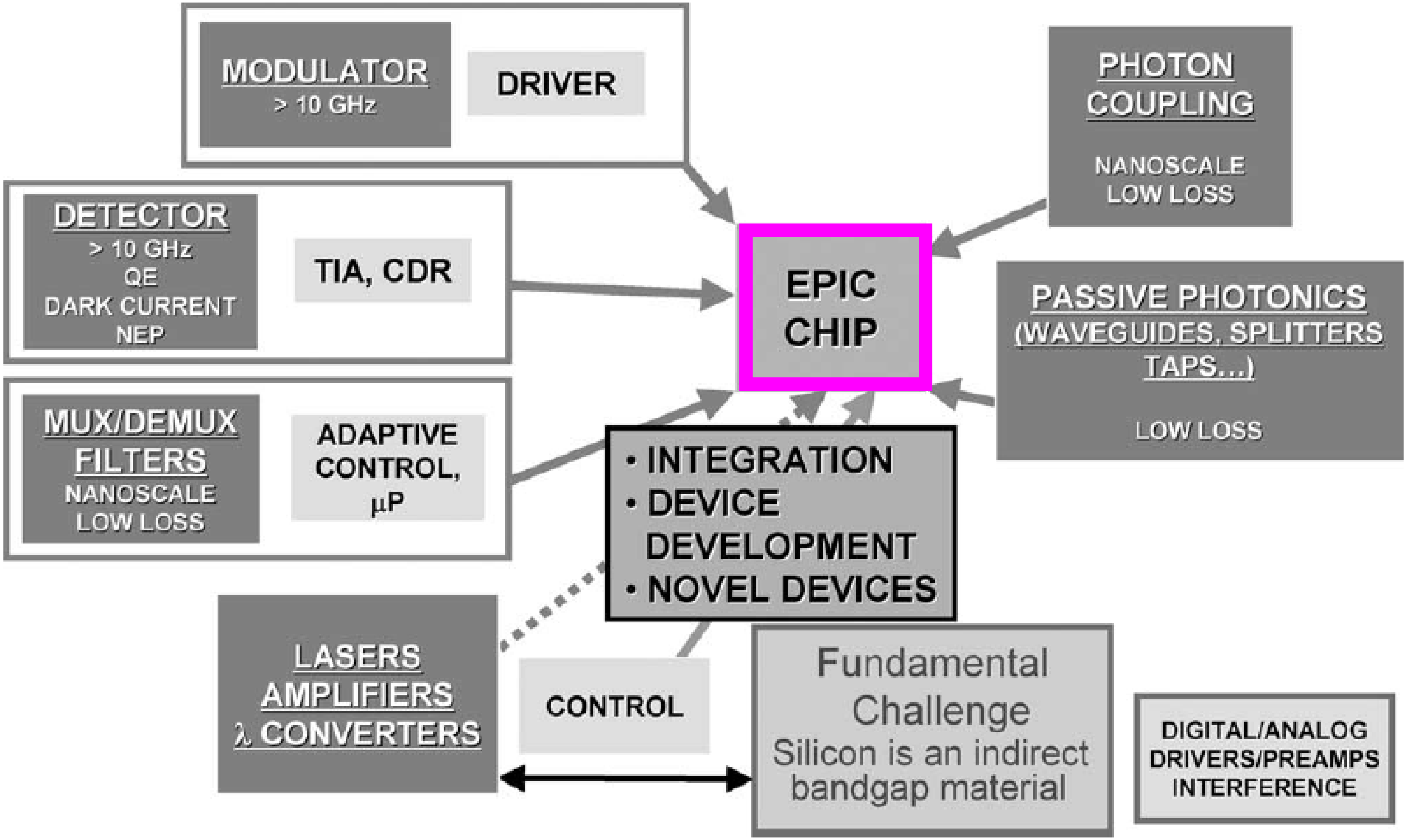
A. Electronic and Photonic Integration
B. Silicon Raman Lasers
C. Erbium-Silicon Lasers
D. Ultrafast Group IV Electrooptical Modulators
E. Direct-Bandgap SiGeSn/Ge/GeSn Heterostructure/QW Devices
F. Electrically Pumped Group IV Laser for 1.2-1.6 um
G. Hybrid Integration of III-V Lasers on Si
H. Active Microresonator Devices
I. PhC Devices
J. Plasmon Optics
K. The Long-Wave Infrared (LWIR) Paradigm for Silicon Integrated Photonics
L. Nonlinear Optical (NLO) Devices

A) Electronic and Photonic Integration

• Organizations investigating electronic and photonic integration

- BAE Systems team: electronic warfare application-specific EPIC
- Luxtera team: CMOS photonics technology
- Lincoln Lab. team: high-resolution optical sampling technology
- California Institute of Technology: optical signal amplification in silicon
- UCLA: nonlinear silicon photonics
- Translucent: low-cost buried photonic layer beneath CMOS
- University of Michigan: CMOS-compatible quantum dot lasers grown directly on Si/SiGe
- Stanford University: germanium quantum wells on silicon substrate for optical modulation
- Brown University: all-silicon periodic nanometric superlattices toward a silicon laser

A) Electronic and Photonic Integration



• EPIC (electrical and photonic integrated circuits) challenge

A) Electronic and Photonic Integration

- A few EPIC results from 2004 to 2006
- Luxtera team

  - developing chips in 130-nm SOI CMOS foundry

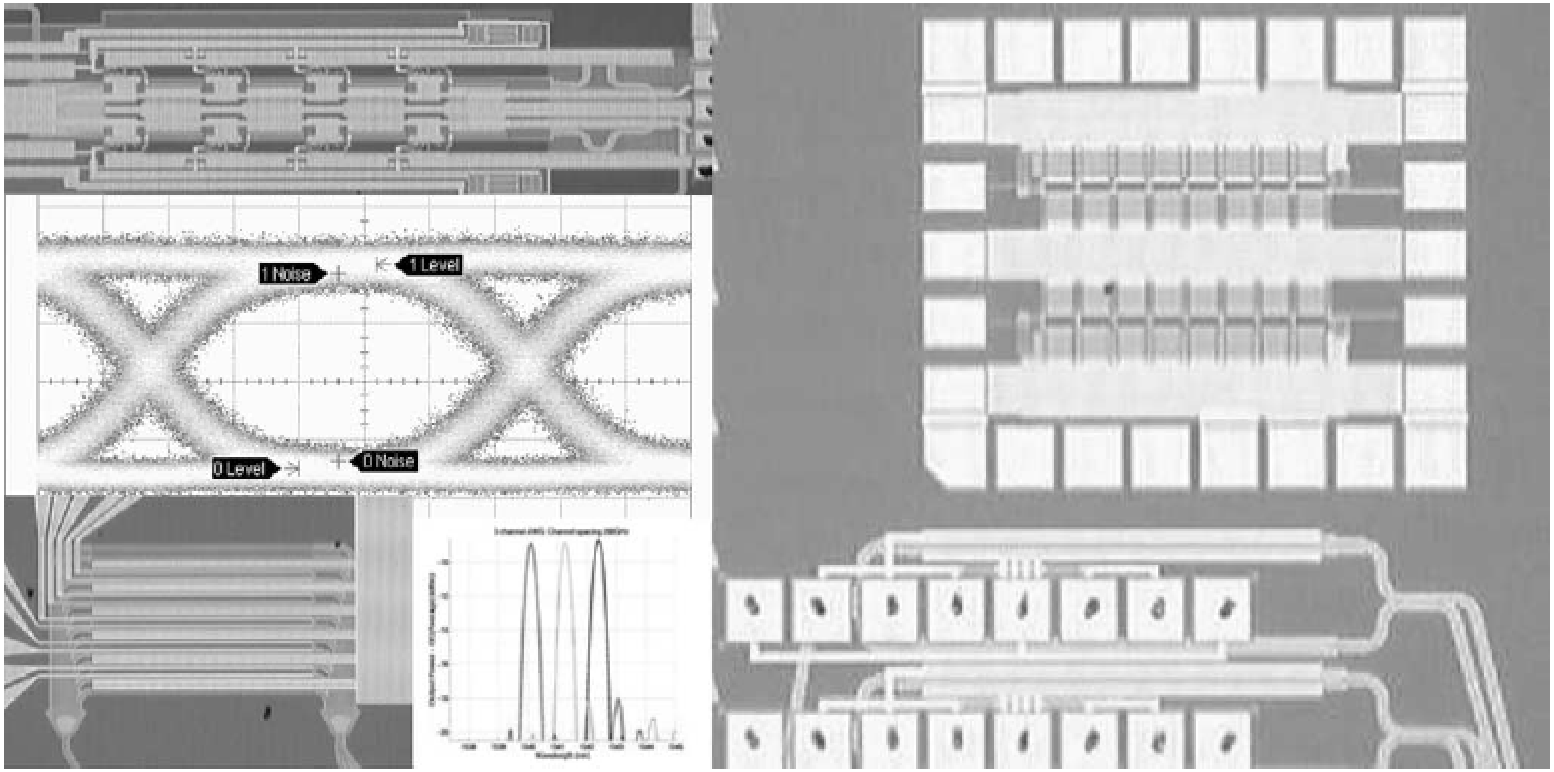
  - 10-Gb/s fiber-optic transceiver OE chip: a silicon 10-Gb/s modulator, a filp-chip bounded 1.55-um III-V laser diode, a high-speed Ge-on-Si photodiode, a low-speed photodiode, and an efficient fiber-to-waveguide coupler

  - monolithically joined to CMOS drivers, controllers, and transimpedance amplifiers (TIAs)

  - test monolithic OE chips containing about 100 photonic components and 200,000 transistors

A) Electronic and Photonic Integration

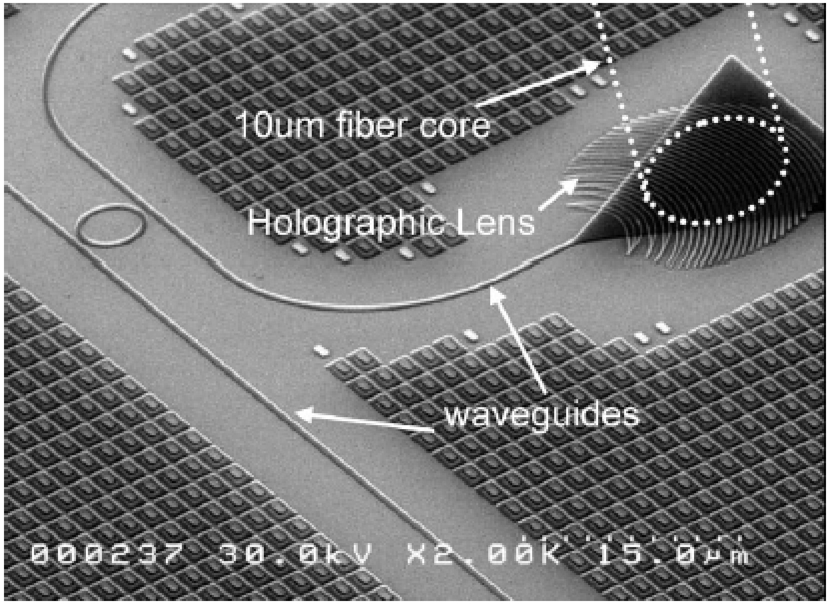
- Luxtera team



• 10-Gb/s 1.55-um electro-optical modulator, electrically trimmed wavelength division multiplexing filter, RF amplifier, and two 1 by 2 electro-optical switches.

A) Electronic and Photonic Integration

• Luxtera team



• Microscope photographs of SOI integrated-photonic test network including microring filter and fiber-to-waveguide coupler

• 1.55-um optical coupling between single-mode fiber and SOI strip waveguide

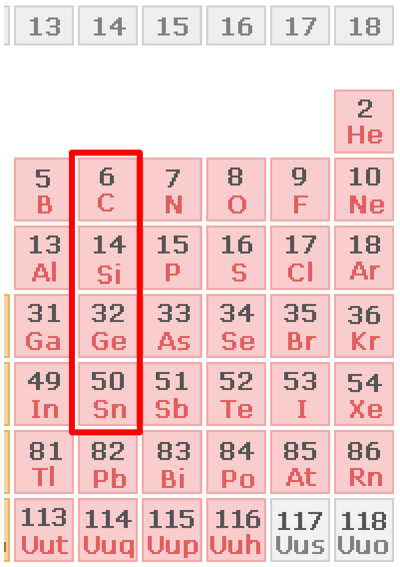
B/C) Silicon Raman/Erbium-Silicon Lasers

- Development of the silicon Raman lasers
  - UCLA, Intel Corporation
  - fully integrateable
  - low gain
  - performance improvements needed
  - needed for optical pumping (it takes a laser to make a laser)

- Development of the Erbium-Silicon lasers
  - Electrically pumped lasers
  - more desirable in OE chips

D) Ultrafast Group IV Electrooptical Modulators

- Using Group IV materials: carbon, silicon, stannum, etc.
  - optically driven SOI plasma-effect modulator; 20-ps rates
  - carrier-injected split-ridge waveguide modulator in double SOI; 24 GHz
  - silicon Mach–Zehnder modulator; 6-10-Gb/s data transmission
  - a sub-micron depletion-type photonic modulator in SOI; 3-7-ps rates
  - SOI-waveguided modulator; 10 Gb/s
  - germanium quantum-well modulator on silicon
  - electroabsorption modulator (EAM)



E) Direct-Bandgap SiGeSn/Ge/GeSn Heterostructure/QW Devices

• for direct band-to-band photonic devices

• many possibilities for direct-gap conduction-to-valence photonic devices
- laser diodes, LEDs, photodetectors, and modulators

• operating in the near- and midinfrared regions

- SnGe on Si for strain-balanced Ge/SnGe quantum well heterostructures

- Si–Ge–Sn semiconductors on Si(100) via Sn

- Si-based Ge/GeSn multiple quantum wells (MQWs)

• Critical challenge for this technology: compatible with a CMOS foundry?

F) Electrically Pumped Group IV Laser for 1.2-1.6 um
G) Hybrid Integration of III-V Lasers on Si

- IV-IV lasers

  - Electrically pumped Group IV semiconductor micro-ring laser

  - Stimulated emission in a nanostructured silicon pn junction diode using current injection

  - Stimulated emission in periodic nanopatterned silicon

- III-V lasers: integrating of III-V laser diodes on silicon

  - Electrically pumped hybrid AlGaInAs-silicon evanescent laser

  - CMOS-compatible quantum-dot lasers grown directly on Si/SiGe

→ Most manufacturable method / lowest cost per performance

H) Active Microresonator Devices

• Miniaturization: to reduce the “footprint” of silicon photonic components

→larger scale of on-chip integration

• Resonators can form the basis of a laser, a light emitter, a photodetector, a modulator, or a spatial routing switch.

- active microring modulator
- 10-Gb/s intensity modulator in an SOI microring
- silicon microring optical routing switches
- electro-optical and optical–optical switching of dual microring resonator waveguide systems
- dual-microring-resonator cross-connect switches and modulators

I) PhC Devices

• Photonic crystal (PhC) can yield devices with unique properties

- negative-refraction lenses, superprisms, sharp waveguide bends, all-optical buffer memories, dynamic dispersion compensators, nanoscale 3-D point-defect resonators, etc.

• Active devices are feasible using PhC.

- silicon-based PhC laser diode
- silicon PhC line-defect waveguides
- SOI PhC line-defect waveguides

→ PhC devices can be made in a CMOS facility.

→ PhC devices can be a part of the high-performance OEIC in future

J) Plasmon Optics

- Plasmon optics can open a new domain for integrated photonics based on:

1) compact, low-power optical devices
2) optical imaging systems with nanometer-scale resolution
3) enhanced light emission from active photonic devices via coupling to surface plasmons
4) coupling from dielectric (fiber and SOI waveguide) photonics to plasmonic devices

K) The Long-Wave Infrared (LWIR) Paradigm for Silicon Integrated Photonics

• Opportunities for sensing, communications, signal processing, missile detection, tracking, and imaging in the “wide infrared,” expecially in the 3-5 and 8-14 um windows, in a band near 20 um, and in the 30-100-um “terahertz” range.

• Si-based OEICs can operate at a wavelength anywhere from 1.2 to 100 um.

- Silicon waveguides with low propagation loss for wide infrared:
  * silicon rib-membrane for 1.2-6.0 and 24-100 um
  * germanium rib on silicon for 1.9-14 um
  * Si-based air-filled hollow-core channel waveguide for 1.2-100 um

- long-wave Si-based photodetectors, modulators, and light emitter

L) Nonlinear Optical (NLO) Devices

- Nonlinear optical effects in silicon are relatively strong.
  - Franz-Keldysh shift
  - Kerr effect
  - stimulated Raman scattering
  - coherent anti-Stokes Raman scattering
  - two-photon absorption
  - intensity-dependent refractive index
  - four-wave mixing

Future Prospects

1) True OE integration on CMOS in a stable 130-nm or 90-nm commercial process
2) Hundreds of photonic components and more than a million transistors on a monolithic OE chip
3) Cost-effective fiber-optic links using Si OE transceivers at 10-100 Gb/s
4) Fast, cost-effective optical interconnection of computer chips
5) Integrated Ge-on-Si photodiodes as the 1.55 um detectors-of-choice in PICs and OEICs
6) A room-temperature electrically pumped Ge/Si laser
7) A well-developed Ge/GeSn technology-both MQWs and heterodiodes-that includes 1.55-um band-to-band laser diodes, LEDs, modulators, and photodetectors

Future Prospects

8) Silicon laser diodes that rely upon Erbium ions
9) Integration of silicon PhC devices into high-performance silicon photonic circuits
10) Development of practical Si-based Group IV components for the wide infrared spectrum stretching beyond 1.6 um out to 100 um-components
11) Ultrasmall, nanophotonic Ge-in-Si p-i-n lasers, modulators, and detectors
12) Si-based photonic devices utilizing Group IV quantum dots or QWs

Thank you!

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