Silicon photonics:
Optical modulation in silicon platform

Laurent Vivien,
Institut d’Electronique Fondamentale, CNRS UMR 8622, Université Paris Sud, 91405 Orsay Cedex, France

http://silicon-photonics.ief.u-psud.fr/
The Institute for Fundamental Electronics

IEF is a joint research unit between CNRS and University of Paris Sud

135 CNRS researchers, professors and lecturers, technical staff

+100 PhD students, Post-Doc and visitors

~ 400 students undergoing training within IEF's ground

Spintronics and Si-based Nano-electronics

Micro-Nano systems and systems

Photonics

University Technology Center (CTU) MINERVE

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University Technology Center

IEF-MINERVE member of The French Network on “Basic Technological Research” (RTB)

University Technology Centre (1000 m²):

Photolithography:
- 2-sided UV lithography with wafer bonding
- Deep UV lithography (248 nm)
- 2 e-beams (Raith150 and 100keV nanobeam)
- Laser

Etching:
- Wet etching (KOH, TMAH, …)
- Dry etching:
  - fluoride gases RIE (2 systems)
  - ICP Si deep etching
  - IBE
  - O2 plasma etching
  - Chloride gases RIE

...
Data centers

Interconnects

Free space communications

FTTH

i-Sicret

Environment

Chemical/Biological sensors

Military

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Silicon photonic building blocks

Off-chip III-V laser

On-chip III-V laser on Si

Germanium photodetector

Optical coupler

Germanium-based laser

Emitter
Laser → Modulator

Receiver
Detector

“Silicon” modulator

Input waveguide

10 µm

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Passive photonic devices

Waveguides

WDM

Beam splitter

Strip WG

Electric field

Strip WG

Slot WG

PC

8 µm

14 µm

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Ge waveguide photodetector

Over 50GHz @ 0V

Dark current: ~1nA

40 Gbit/s @ -1V
Optical modulation

- Optical intensity
- Electrical driver
- Optical modulator
- Modulated optical intensity

**Electroabsorption**
Absorption coefficient variation under an electric field
- Intensity modulation

**Electrorefraction**
Refractive index variation under an electric field
- Phase modulation
- Interferometer
- Intensity modulation
## Figures of Merit

- **MD**: Modulation Depth - %
- **Extinction ratio (ER)** - dB
- **Insertion loss** - dB

### Distinction between $I_{\text{min}}$ and $I_{\text{max}}$

$$\text{MD} = \frac{I_{\text{max}}}{I_{\text{min}}} - 1$$

$$\text{ER} = 10 \log_{10} \frac{I_{\text{max}}}{I_{\text{min}}}$$

- **Output optical intensity**
  $$I_{\text{out}} = I_{\text{in}} \times \text{MD}$$

- **Input optical intensity**
  $$I_{\text{in}} = I_{\text{out}} / \text{MD}$$

### Figures of Merit

- **$V_{\pi}L_{\pi}$**: Modulation efficiency
- **IL**: Insertion loss
- **$f_c$**: -3dB bandwidth
- **ER**: Extinction ratio ratio
- **Voltage swing**
- **Power consumption**

### Insertion loss - dB

$$P = 10 \log \left( \frac{I_0}{I_{\text{max}}} \right)$$
What are the limitations of the modulator speed?

- Intrinsic speed
  - Physical phenomenon limitation

- RC time constant
  - Electrical circuit limitation

- RF signal propagation
  - Impedance adaptation
  - Matching of electrical and optical velocities
Optical modulation

Optical intensity

Electrical driver

Optical modulator

Modulated optical intensity

Optical modulation

Electroabsorption

Absorption coefficient variation under an electric field

Intensity modulation

Electrorefraction

Refractive index variation under an electric field

Phase modulation

interferometer

Intensity modulation
Thermo-optic effect

- Thermo-optic coefficient
  - √ In silicon
  - 2.10^{-4} K^{-1} at 1.55µm

Δn = \frac{dn}{dT} \Delta T

- Demonstration of silicon optical modulator:
  - Bandwidth limited to few 100 kHz


Thermal effect can be a parasitic effect for high speed optical modulators.

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Electro-optic effect

Nonlinear Polarization:

\[ \vec{P}(t) = \chi^{(1)} \vec{E}(t) + \chi^{(2)} \vec{E}^2(t) + \chi^{(3)} \vec{E}^3(t) + \cdots \]

- √ **Pockels effect:**
  - Linear electrooptic effect

- √ **Wavelength conversion**
  - Second Harmonic Generation (SHG)

- √ **Kerr effect:**
  - Nonlinear electrooptic effect

- √ **Wavelength conversion**
  - Four wave mixing (FWM)

Silicon is a centro-symmetric material! Weak effect in silicon to be efficient for modulation

\[
 n_2^{Si} \sim 10^{-14} \text{ cm}^2 / \text{W} \quad \Rightarrow \quad n_2^{glass} \sim 10^{-16} \text{ cm}^2 / \text{W}
\]
Electro-optic effect

Nonlinear Polarization:

\[ \tilde{P}(t) = \chi^{(1)} \tilde{E}(t) + \chi^{(2)} \tilde{E}^2(t) + \chi^{(3)} \tilde{E}^3(t) + \cdots \]

- Pockels effect: \( \chi^{(1)} \)
- Linear electro-optic effect
- Wavelength conversion
  - Second Harmonic Generation (SHG)

Without straining layer
- Linear electro-optic effect
- Break the symmetry of silicon crystal

With straining layer
- Strained silicon photonics

Mach-Zehnder modulator based on Pockels effect

**Pockel’s effect:**
- Bottom of waveguide fixed and top is strained
- SiN induces strain all around the waveguide
- Thermal annealing

**Conditions to achieve strain:**
- Bottom of waveguide fixed and top is strained
- SiN induces strain all around the waveguide
- Thermal annealing

Bartos Chmielak et al. (2011) Opt. Express
Mach-Zehnder modulator based on Pockels effect

Pockel’s effect:

- Intrinsically high speed
- Field effect – no capacitance
  - Low power consumption
- Low bias swing
- Low insertion loss
  - No doped regions

Still weak effect and high voltage BUT promising for the development of low power consumption devices

- Intrinsically high speed
- Field effect – no capacitance
  - Low power consumption
- Low bias swing
- Low insertion loss
  - No doped regions
Free carrier density variation in silicon

- Refractive index and optical absorption are modified by free-carrier concentration variations (Kramers-Kröning related):
  - Plasma dispersion effect

![Graph showing free carrier density variation](image)

Free electrons

Free holes

Electro-refraction effect:

\[ \Delta n = -8.8 \times 10^{-22} \Delta N - 8.5 \times 10^{-18} \Delta P^{0.8} \]

Refractive index variation

Effective index variation of the guided optical mode

Phase variation

Interferometers

Optical intensity variation
What are the possibilities to obtain a free carrier concentration variation in silicon-based materials?

- Carrier injection in pin diode under forward bias voltage
- Carrier accumulation in metal-oxide-semiconductor (MOS) capacitors
- Carrier depletion in a pin diode under reverse bias voltage
Optical modulators based on carrier depletion

- **Phase shifters:**
  - PN diode
  - Interleaved PN diode
  - PIN diode
  - PIPIN diode
  - MOS Capacitor

- **Interferometers**
  - Ring resonator
  - Mach-Zehnder
  - Photonic crystals
Carrier depletion optical modulator

Lateral pn diode

Interleaved pn diode
From the idea to the final device

Structure design
- MATLAB

Structure definition
- MESH

Electrical simulation
- DESSIS

Optical simulation
- SolverFDM

Device model
- MATLAB

Couplers

10 parameters need for optimization

Optimization

ISE DESSIS
- Drift-diffusion
- SRH, Auger

DC, AC and Time

Effective index, loss

\[ \Delta n = -8.8 \times 10^{-22} \Delta N - 8.5 \times 10^{-18} \Delta P^{0.8} \]

\[ \Delta \alpha = 8.5 \times 10^{-18} \Delta N + 6.0 \times 10^{-18} \Delta P \]

Layout

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Carrier depletion Si optical modulator

Europe: Univ. Paris Sud, CEA Leti, Univ. of Southampton…
Asia: A*Star, Petra, AIST, Chinese Academy of Sciences, Samsung Electronics, Tokyo Institute of Technology …
North America: Intel, IBM, Cornell, Luxtera, Lightwire, Kotura, Oracle …
Silicon photonics on 300 mm platform

Optical modulators

Mach-Zehnder Interferometer

Length = 950 μm

Interleaved pn diode

\[ V_{\pi} L_{\pi} = 2.4 \text{ V.cm} \]

Insertion loss = 4 dB

-3dB cut-off frequency > 20 GHz

ER \sim 8 \text{ dB} @ 40 \text{ Gbit/s}
40Gbit/s optical link

External laser

PRBS generator
RF cable
RF driver
RF cable

40Gbit/s Si modulator

Optical fiber

RF cable

40Gbit/s Ge photodetector
RF cable

Sampling oscilloscope

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Short distance and high volume applications (electrical bottleneck)

Main challenges:
- Driving voltage of modulator
- Power consumption

ITRS Roadmap: Optical interconnect
- (…) A large variety of CMOS compatible modulators have been proposed in the literature (…)
- “The primary challenges for optical interconnects at the present time are producing cost effective, low power components.”

Optical interconnects

Data-center
Power consumption

Mach Zehnder modulators
~ 3 pJ/bit

Ring resonator modulators
~ 0.5 to 1 pJ/bit

For emitters and short optical links:
~100 fJ/bit down to fJ/bit
(D.A.B. Miller, Opt Exp., 2012)

How do we reduce the power consumption?
Power consumption

- **Reduction of capacitance of device**
  - ✓ Slow-wave photonic crystals for reducing the length
  - ✓ Small radius Ring Modulators

- **Improvement of the modulation efficiency**
  - ✓ Improve efficiency of Si modulator
  - ✓ MZM or EAM Hybrid modulator (ie III-V modulator on Si)
  - ✓ Ge EAM modulators
    - Franz-Keldysh effect in bulk material
    - Quantum Confined Stark Effect in quantum wells
Absorption edge in QW structures is more abrupt than in bulk material.

- $E_0 = \frac{hc}{\lambda_0}$
- $E_0$ depends on the quantum well thickness
  - Adjustment of the wavelength is possible

Ge/SiGe quantum well structures
Epitaxial growth by LEPECVD

- Growth of Ge/SiGe multiple quantum wells

**LEPECVD**
Low energy plasma enhanced chemical vapor deposition

- Relaxed buffer graded from Si to Si$_{0.1}$Ge$_{0.9}$ buffer layer
- Si(100)

Low dislocation density - Best possible device performance

- Temperatures down to 400°C

L-NESS
Como, Italy

Low energy plasma enhanced chemical vapor deposition

- LEPECVD
Low energy plasma enhanced chemical vapor deposition

- Low-rate growth (~0.3 nm/s) for optimum layer and interface control
- High-rate growth (5–10 nm/s) for maximum efficiency
- Temperatures down to 400°C
Device processing

1. Mesa etching
   - n layer
   - Ge MQWs
   - p-type SiGe layer
   - Relaxed and graded Buffer
   - Silicon substrate

2. Etching of P-type layer
   - n layer
   - Ge MQWs
   - p-type SiGe layer
   - Relaxed and graded Buffer
   - Silicon substrate

3. SiO$_2$/Si$_3$N$_4$ Deposition and Patterning

4. Metallization: Lift off

5. Deep Etch for waveguide characterization
Electroabsorption modulator

20 Ge/SiGe QW

P. Chaisakul et al., Optics Express (2012).
Static performance: optical transmission

~7.5 \times 10^4 \text{ V/cm} ~ 6 \times 10^4 \text{ V/cm} ~ 4.5 \times 10^4 \text{ V/cm} ~ 3 \times 10^4 \text{ V/cm}

Bias from 0 to 5V:
- Extinction Ratio (ER) > 6 dB for 20 nm range
- Insertion Loss (IL): 5 to 15 dB

1V swing  2V swing

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Frequency response

Network Analyzer System

Optical receiver

RF Output

Optical receiver input

A single mode fiber

Objective

50GHz Lightwave Test set

Optical fiber

Polarization controller

Tunable Laser

DC bias

Bias Tee

V+V-a

V+a

DC+RF

Lensed fiber

Polarization maintaining fiber

Frequency response

Normalized optical output (dB)

Measured

Fit

23 GHz

Frequency (GHz)

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Energy consumption

Energy to charge the device
\[
\text{Energy/\text{bit}} = \frac{1}{4} \left( CV_{pp} \right)^2
\]

Energy dissipation of photocurrent
\[
\text{Energy/\text{bit}} = \frac{1}{B} (I_{ph} V_{bias})
\]

C \approx 62 \text{ fF} \rightarrow \text{Energy/\text{bit}} = 70 \text{ fJ/\text{bit}}

(for a voltage swing of 1 V, 20 Gbps, 0.5 mW input power)
The absorption edge shifted to 0.8 eV (quantum confinement + strain). QCSE observed. Fabry-Perot (FP) fringes observed at energy lower than the absorption edge.

One order of magnitude higher than carrier depletion effect in silicon.
Overlap factor optimization

<table>
<thead>
<tr>
<th>Overlap factor</th>
<th>ER</th>
<th>Length</th>
<th>IL</th>
</tr>
</thead>
<tbody>
<tr>
<td>10%</td>
<td>10 dB</td>
<td>120µm</td>
<td>8dB</td>
</tr>
<tr>
<td>20%</td>
<td>10 dB</td>
<td>60µm</td>
<td>6.4dB</td>
</tr>
<tr>
<td>30%</td>
<td>10 dB</td>
<td>40µm</td>
<td>5.9dB</td>
</tr>
</tbody>
</table>

12% overlap factor between the optical mode and MQWs

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Integrated circuits based on Ge/SiGe QW?

**Schematic description**

- **Doped-N Si$_{0.1}$Ge$_{0.9}$**
- Si$_{0.1}$Ge$_{0.9}$
- QWs
- Si$_{0.1}$Ge$_{0.9}$
- **Doped-P Si$_{0.1}$Ge$_{0.9}$**
- 2 µm Si$_{0.1}$Ge$_{0.9}$ relaxed buffer
- 13 µm thick gradual buffer from Si to Si$_{0.1}$Ge$_{0.9}$
- Si

**The real scale**

- 2 µm Si$_{0.1}$Ge$_{0.9}$ relaxed buffer
- 13 µm thick gradual buffer from Si to Si$_{0.1}$Ge$_{0.9}$
- Si

**Challenge:** coupling the light from silicon to Ge/SiGe QW
1st option: waveguide in the relaxed SiGe layer (thanks to the graded buffer)

Ge concentration in the waveguide: trade-off between
- Strain compensation
- Optical loss

P. Chaisakul et al, submitted

Optical loss of each device, including input/output coupling with Si_{0.16}Ge_{0.84} waveguide < 5dB
2\textsuperscript{nd} option: decrease the thickness of the buffer layer
Challenge: keeping homogeneous and high quality layers

Thick gradual buffer from Si to Si\textsubscript{0.1}Ge\textsubscript{0.9}

Ge/SiGe modulator integrated with SOI: estimated performance:
Extinction ratio = 7.7 dB, loss = 4 dB

M-S. Rouifed et al, submitted
Power consumption evolution

Carrier depletion modulator MZi
Energy/bit ~ 5 pJ/bit

Ring resonator modulator
Energy/bit ~ 0.7 pJ/bit

EA Ge/SiGe modulator
energy/bit ~ 0.07 pJ/bit

Strained modulator

Ultra low power consumption modulator
energy/bit ~ few fJ/bit
Electronic – Photonic convergence
Photonics-electronics integration

Front-end fabrication

😊 Very low parasitics
⚠️ Custom SOI, specific libraries
⚠️ process co-integration
Photonics-electronics integration

Front-end fabrication

- Very low parasitics
- Custom SOI, specific libraries
- process co-integration

Back-end fabrication

- On top of CMOS or in metal layers
- Serial process
- Compound yield
- Thermal budget < 400C

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Photonics-electronics integration

Front-end fabrication

- Very low parasitics
- Custom SOI, specific libraries
- Process co-integration

Back-end fabrication

- On top of CMOS or in metal layers
- Serial process
- Compound yield
- Thermal budget < 400°C

3D integration

- Separate processes
- No change in CMOS Front-End
- No thermal budget!
- Other layers: MEMS, antennas
- Higher (but reasonable) parasitics

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HELIOS
Photonics Electronics functional integration on CMOS

Plat4M
photonic libraries and technology for manufacturing

SASER
Safe and Secure European Routing

CARTOON
Carbon nanotube photonic devices on silicon

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Silicon photonics: 
Optical modulation and detection

L. Vivien, 
D. Marris-Morini, G. Rasigade, L. Virot*, M. Ziebell, D. Perez-Galacho, P. Chaisakul, 
M-S. Rouifed, P. Crozat, P. Damas, E. Cassan 
D. Bouville, S. Edmond, X. Le Roux

Institut d’Electronique Fondamentale, CNRS UMR 8622, 
Université Paris Sud, 91405 Orsay Cedex, France

http://silicon-photonics.ief.u-psud.fr/

J-M. Fédéli, S, Olivier, Jean Michel Hartmann

CEA-LETI, Minatec 17 rue des Martyrs, 38054 Grenoble cedex 9, France

G. Isella, D. Chrastina, J. Frigerio

L-NESS, Politecnico di Milano, Polo di Como, Via Anzani 42, I-22100 Como, Italy

C. Baudot, F. Boeuf

STMicroelectronics, Silicon Technology Development, Crolles, France