OPTICAL COUPLING OF SOI WAVEGUIDES AND III-V PHOTODETECTORS

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Outline

- Background and motivation
- Coupling light from fiber to silicon waveguides
  - Principle of grating couplers
- Photodiode design
  - Photodiode design for high speed
  - Prism coupling
  - Evanescent coupling
- Fabrication
  - Prism photodiode fabrication
  - Heterogeneous integration
- Performance
  - Prism photodiodes, discrete and integrated (OTUS)
  - Heterogeneously integrated photodiodes (BOOM)
- Conclusion
Background: Integrated optics

**SOI platform**

- light wave guiding and processing (optics - interference)
- CMOS technology

SOI waveguides:

- 2.0 µm, 3.5 µm
- 200 nm, 500 nm

**III/V oe-devices**

- light detection, modulation and generation (applied Quantum Theory)
- wavelength range: 1.3 µm … 1.5 µm (fibre based telecommunication)

- InP, InGaAsP, InAlGaAs, InGaAs on InP

Waveguides, photodiodes, modulators:
- Mach-Zehnder (MZI),
- electro-absorption (EAM),
- semiconductor amplifiers (SOA)
- lasers and integrated devices
Motivation

“micro”-waveguides:

“nano”-waveguides:

How?

SOI platform

III/V oe-devices

hybrid integration

Integration, optical coupling
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Coupling light into Si “nano” waveguides

Grating fiber couplers

single-mode fibre
adiabatic taper (>150µm)
to integrated circuit
10µm wide waveguide

Efficiency

- Standard: 31 %  
- With poly-silicon overlay: 68 %  
  D. Vermeulen, GFP09, PD1
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III-V Photodiodes

planar type

mesa type

\[ P_{\text{opt}}^{\text{in}} \]
How to make a high-speed PD

Bandwidth is depending on: (K. Kato, 1993.)

- The time it takes a carrier to drift across the depletion region

\[ f_t = \frac{3.5v}{\pi d} \]

\( v \) = average speed holes and electrons
\( d \) = thickness intrinsic layer

- The time it takes to charge and discharge the capacitance of the diode

\[ f_{RC} = \frac{1}{2\pi C(R_{load} + R_{contact})} \]

\( C \) = capacitance
\( R \) = resistance

\[ C = \frac{\varepsilon_0 \varepsilon_r A}{d} \]

\( A \) = area
\( d \) = thickness intrinsic layer
\( \varepsilon_r \) = relative permittivity
\( k \) = contact resistance (Ohm.m²)

However: \( C \) is determined by active area and parasitics

Total 3-dB bandwidth:

\[ \frac{1}{f_{3dB}^2} = \frac{1}{f_t^2} + \frac{1}{f_{RC}^2} \]
Requirements:

- Compatible architectures (fabrication, integration)
- Effective optical coupling (high responsivity)
- Suitable for 10 Gb/s operation
- Independent of polarization and wavelength
Principle of evanescent coupling

• Coupled mode theory: power transfer from Si waveguide into III-V absorption layer

• For large & fast power transfer
  • Similar phase velocity → small phase mismatch
  • Large mode overlap → thin bonding layer

• Power transferred into the III-V layer is absorbed

Example evanescently coupled PD:
Power transfer from silicon layer to III-V layer
Increase high-speed performance

- Optimize trade-off RC-limit and transit-limit
  - Find optimum absorption layer thickness \( d \)

- Optimize silicon waveguide for phase matching
  - High responsivity:
    - minimized metal contact absorption
  - Fast absorption:
    - short detector length for lower capacitance
Example: Simulating TM detector
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Fabrication – processing steps

Standard photodiode processing sequence

+ BCB prism fabrication as add-on:

① BCB layer deposition and curing

② Lithography to produce a tapered resist mask (providing sliding mask technique)

③ Relief transfer into BCB layer by RIE process (O₂ containing plasma)

→ Advantage: “custom-made” prism shapes available
Fabrication of photodiode chips - results

Chip footprint: 500 x 500 µm²

BCB prism

p-pad

height / µm

scan length / µm

n-pad

p-pad

n-pad

BCB prism

input facet

W = 60 µm  L = 40 µm  H = 6.5 µm
Photodiode design evanescent coupling

Old design

New design: the helmet

Improvement in responsivity by minimizing absorption in contact metal and p-doped InGaAs

Z. Sheng, GFP, 2009
Heterogeneous integration

SOI-wafer

Planarization (BCB)

Bonding III-V die

Substrate Removal

Pattern definition

III-V processing
Heterogeneous integration examples

- Two unprocessed BCB bonded InP-based epitaxial layers (3 x 3 mm²) on top of an SOI substrate

- Cross-section SEM picture of a III-V film (after substrate removal) bonded on SOI using a 100 nm BCB layer
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Photodiode performance – discrete chips (1)

Low dark currents
High breakdown voltages

I / A

PD#2a
40-40-C4
60-40-C8
90-40-I23

U / V
High responsivity

Discrete PD: 60 x 40 µm² @ 1550 nm

- TE
- TM, as measured
- TE, TM, adjusted for reflection loss at prism input facet

h = 6.5 µm
Weak dependence on wavelength and polarization
Photodiode performance – discrete chips (4)

PD 60-40 discrete, bias: -20 V

Bandwidth suitable for 10 Gb/s operation

\[ f_{-3dB} = 9 \text{ GHz} \]
Demands on optical coupling:

- high responsivity independent on
  - wavelength
  - polarization
  - waveguide position
- high bandwidth for 10 Gb/s operation
Weak dependence on wavelength and polarization

- Photodiode performance – chips on SOI (1)

Simulation @ 1550 nm

Responsivity / A/W

PD integrated with SOI w.g.
discrete PD

TE
TM

Wavelength / nm

0.55
0.60
0.65
0.70
0.75
0.80
0.85

1510
1520
1530
1540
1550
1560
1570
Effective and homogeneous optical coupling with SOI waveguide array.
Degradation of bandwidth due to connection via RF line on low resistivity SOI.
OTUS channel wavelength filter

3 filter stages:

1st SOA array
2nd SOA array
3rd SOA array

optical signal in

AWG “fine”
1st AWG “coarse”
2nd AWG “coarse”
w.g. combiner

electrical signal out

2 filter stages:

cyclic AWG 1
1 channel in p channels out T_{AWG1}

SOA array 1
p channels
> 1 ns switching time P_{SOA1} / T_{SOA1}

SOA array 2
p channels in p channels out T_{AWG2}

> 1 ns switching time P_{SOA2} / T_{SOA2}

combiner
p channels in 1 channel out T_{comb}
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BOOM: Photodetector results

- High responsivity (1.1 A/W @ 1550 nm or 88 % quantum efficiency)
- Covering the whole S, C and L communication band
- Very low dark current 10 pA (needs very low bias voltage)

Top view (before final metallization)

Z. Sheng, OpEx, vol 18(2), 2010
Increase high-speed performance

Performance is polarization dependent

- Thin InGaAs: TE higher responsivity & faster power transfer
- Thick InGaAs:
  - TM has a faster power transfer
  - Both polarizations have higher responsivity
BOOM: UDWDM Demultiplexer

- Design: 4-channel demultiplexer
  - Fiber couplers to couple light in
  - Double microring for higher roll-off
  - Heaters for fine-tuning

- Fabrication underway

Input fiber coupler

High-speed PD spec: 10GHz
Conclusion

- Successful integration of InP based photodiodes with SOI waveguides via two approaches: prism coupling and evanescent coupling.

- Prism coupling via a BCB prism as add-on on standard photodiode structure: effective, easy to fabricate.

- Evanescent coupling via InGaAs dies, heterogeneously integrated on top of SOI “nano” waveguides: effective, more sophisticated design and technology.

- Both approaches show high responsivity with low dependence on wavelength, suitable for 10 Gb/s operation.
Acknowledgement

This work has been funded by:

**Optical Technologies for Ultra-fast Processing**

European Space Agency (ESA) under ESTEC contract No 20174/06/NL/PM (OTUS, ARTES5)

**Terabit-on-chip:**

*Micro- and Nano-scale silicon photonic integrated components and sub-systems enabling Tb/s-capacity, scalable and fully integrated photonic routers*

European Commission, STREP - 7th framework programme (ICT-2007-2, Contract no. 224375)

With special thanks to Klemens Janiak