Advanced Germanium p-i-n and Avalanche Photodetectors for Low-power Optical Interconnects

Hongtao Chen
Supervisor: Prof. Gunther Roelkens, Dr. Joris Van Campenhout
Motivation → Low-power optical interconnects

Global data center and cloud IP traffic

Mega-scale cloud data centers

Optical interconnects in data center
A commercial optical transceiver cartoon
High Sensitivity Optical Receiver to Improve Power efficiency

*Power efficiency, pJ/bit (4λ×20 Gb/s)

High bandwidth, high responsivity photodetectors enabling high sensitivity optical receiver to improve optical transceiver link power efficiency.


"HOTONICS RESEARCH GROUP"
Imec’s silicon photonics platform

- **State-of-the-art R&D platform** for advanced device and system R&D
- **200 mm** SOI wafers, 220 nm top Si, 160 nm polySi
- Integration Flow based on a **130-nm CMOS node/toolset** augmented with **100% selective Ge epitaxy module**
- **193-nm lithography** for critical waveguide patterning steps.
- Available for **bilateral development on demand** and through **MPW service** (ePIXfab)
Outline

- Motivation
- Si-contacted Ge p-i-n Photodetectors
  - 400nm-Ge Si-LPIN GePD
  - 160nm-Ge Si-LPIN GePD
- Low-voltage Ge Avalanche Photodetectors
  - 400nm-Ge VPIN GeAPD
  - 185nm-Ge VPIN GeAPD
- Summary
Ge-on-Si Waveguide p-i-n photodetectors

Ge-on-Si WG photodetector

Light transmission

Photo-carriers generation & collection

Responsivity

O/E bandwidth

Dark current

Photodetector performance metrics
Responsivity

- The capability of a p-i-n photodetector to convert an optical signal into a photocurrent,
- The ratio of the generated photocurrent and incident optical power,

☐ Light absorption
☐ Photo-carriers collection

\[ R = \eta \frac{q}{h \cdot f} \approx \eta \frac{\lambda (\mu m)}{1.23985 (\mu m)} (A/W) \]

Responsivity as a function of wavelength

Quantum efficiency
Optical frequency
Dark current

The small electric current that flows through a p-i-n photodetector when no photons are entering the device

- Diffusion current
- SRH leakage current
  - Material defects
  - Ge passivation

A typical photodiode I-V characteristic

SRH leakage current source modeling

Ge-on-Si SEM graph
O/E bandwidth

The capability of a p-i-n photodetector to respond to a fast modulated optical signal.

- Transit time
- RC-constant

bit ‘1’

bit ‘0’

An ideal OOK modulated optical signal

Optical  Electrical

p-i-n photodetector model
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400 nm-Ge Si-LPIN GePD

- Higher responsivity
- Higher O/E bandwidth
- Lower dark current

Si-LPIN GePD:
- BOX
- Ge
- Si

BL-VPIN GePD (for reference)
Static, Small & Large-signal Measurement Data at 1550 nm

**Static I-V & responsivity**

- **Si-LPIN GePD**:
  - Photocurrent: 11 nA
  - Dark current: 3.3 nA

- **BL-VPIN GePD**:
  - Photocurrent: 0.5 A/W
  - Dark current: 11 nA

**Small-signal $S_{21}$ curves**

- **Si-LPIN GePD**:
  - 3 GHz: 38 dBm
  - 20 GHz: 41 dBm
  - 27 GHz: 44 dBm

- **BL-VPIN GePD**:
  - >50 GHz: 44 dBm
  - 36 GHz: 47 dBm

**Table: @-1 V, 1550 nm**

<table>
<thead>
<tr>
<th></th>
<th>Si-LPIN GePD</th>
<th>BL-VPIN GePD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Responsivity</td>
<td>&gt;1 A/W</td>
<td>0.45 A/W</td>
</tr>
<tr>
<td>Dark current</td>
<td>3 nA</td>
<td>11 nA</td>
</tr>
<tr>
<td>O/E bandwidth</td>
<td>20 GHz</td>
<td>&gt;50 GHz</td>
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28 Gb/s OOK-NRZ eye
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160nm-Ge Si-LPIN GePD

Thinner Ge layer

3-D & cross sectional schematic

- $|E| > 1 \times 10^4$ V/cm at -1 V bias
- Shorter transit distance compared to 400nm-Ge device
- Higher O/E bandwidth expected
- High responsivity & Low dark current
Static and Small-signal Measurement Data

I-V characteristics

Responsivity at -1 V

C-band

O/E Bandwidth

(a) 1550 nm
Light current
Dark current

1310 nm

45 GHz
> 67 GHz
67 GHz
> 50 GHz

2.4 nA
3.6 nA

(b) 1550 nm

44 GHz
> 67 GHz
1310 nm

-3 V
-2 V
-1 V

3-dB O/E bandwidth (GHz)

Input optical power (mW)

Wavelength (nm)

Responsivity (A/W)

(a) 1550 nm

(b) 1310 nm

O-band

Dark current
Light current

45 GHz
> 50 GHz
7 GHz

50 GHz

40
45
50
55
60
65
70

0 10 20 30 40 50

0 V
-1 V
-2 V

Input optical power (mW)

Wavelength (nm)

Responsivity (A/W)

RF power (dBm)

Frequency (GHz)

RF power (dBm)

Frequency (GHz)

RF power (dBm)

Frequency (GHz)
Large-signal Data Reception Measurement

*Generating 80 Gb/s modulated optical signal through Optical Time Domain Multiplexing

- PRBS, \((2^{31}-1)\)
- MLL: mode-lock laser
- 10 GHz MLL
- 10 Gb/s MZM
- 50ps
- 25ps

* Implemented in DTU Fotonik, Denmark
Large-signal Data Reception Measurement

80 Gb/s eye diagrams

Eye height: 57.3 mV

Eye height: 75.4 mV

100 Gb/s eye diagrams

Eye height: 34 mV

Eye height: 51 mV

Clear open eye diagrams obtained at 100 Gb/s
Ge p-i-n PD: Benchmark

Responsivity V.S. O/E Bandwidth

Dark current V.S. O/E Bandwidth
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Pursuing Even Higher Sensitivity By Leveraging Avalanche Multiplication

\[ Q = \frac{I_1 - I_0}{2i_n} \]

\[ \sigma = i_n \]

Basis optical receiver model

Optical receiver (p-i-n PD):

\[ \frac{S}{N} = \frac{S_0}{2 \cdot q \cdot I_0 \cdot B + N_0} \]

Noise power from Linear Channel

- Avalanche gain
- Excess noise factor

Optical receiver (APD):

\[ \frac{S}{N} = \frac{S_0}{2 \cdot q \cdot I_0 \cdot B \cdot F(M) + \frac{N_0}{M^2}} \]

- Excess noise factor
- Avalanche gain
- Gain-bandwidth product

*Eduard Sackinger, Broadband Circuits for Optical Communications.*
Avalanche gain

Impact ionization coefficient:
- \( \alpha \), electrons; \( \beta \), holes
- the number of electron-hole pairs generated by a carrier per unit distance traveled
Gain-bandwidth product $\leftrightarrow$ build-up time

- RC-constant
- Transit time

O/E bandwidth as a function of gain

*Modeled Bandwidth v.s. Gain

$M, \frac{\alpha_n}{\alpha_p}$

*Simon M. Sze, Physics of Semiconductor Devices
Excess noise factor

Bulk material avalanche noise properties

\[
\langle i_S \rangle^2 = 2 \times q \times I_0 \times M^2 \times F(M) \times B
\]

- Noise current power
- Gain
- Excess noise factor

Avalanche sensitivity improvement

\[ k = \frac{\alpha}{\beta} \]
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400 nm-Ge VPIN GeAPD

3-D & cross sectional schematic

- $|E| \sim 2 \times 10^5$ V/cm confined in the bottom 200 nm Ge layer at -5.5 V bias,
  - Strong avalanche multiplication expected,
Static & Small-signal Measurement Data

Raw $S_{21}$ param. curves, 1550 nm

Strong avalanche multiplication occurs at -5.9 V
- Gain of 10.2,
- Bandwidth of 10.4 GHz
- Gain-bandwidth product, 106 GHz

Extracted from raw $S_{21}$ curves
Optical Receiver Sensitivity Measurement Data

- Custom TIA design from INTEC_design,
- 130 nm SiGe BiCMOS technology,
- 1.2 μA input referred (RMS) noise current at 10 Gb/s,
- \((2^{31}-1)\) PRBS NRZ modulation
- Operate at 1550 nm,
- Commercial LA used after TIA,

\[ \text{BER} = 1 \times 10^{-12} \]

- 5.8 dB avalanche sensitivity improvement at -5.9 V APD bias
- -23.2 dBm absolute sensitivity

* X. Yin et al., IEEE ISSCC Dig. Tech. Papers, 416 (2012).
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185 nm-Ge VPIN GeAPD

3-D and cross sectional schematic

→ Better avalanche performance expected

Doping & electric field distribution
Avalanche performance

185nm Ge APD

400nm Ge APD
Avalanche performance

### Avalanche gain

- **185nm Ge APD**
  - Gain of 10 at -5 V
  - Voltage (V) vs. Gain (1)
  - Gain of 2 at -5 V

- **400nm Ge APD**
  - Gain of 2 at -5 V
  - Voltage (V) vs. Gain (1)

### O/E bandwidth v.s. gain

- 18 GHz at gain of 10
- Voltage (V) vs. Bandwidth (GHz)

### Excess noise factor

- k ~0.2
- k = 0.1
- k = 0.3
- k = 0.5
- k = 0.7
- k = 0.9
- k ~0.6
Optical Receiver Sensitivity Measurement Data

- Custom TIA design from INTEC_design
- 130-nm SiGe BiCMOS technology
- 2 μA input referred (RMS) noise current at 20 Gb/s
- (2^{31}-1) PRBS NRZ modulation
- Operate at 1310 nm

- 6.2 dB avalanche sensitivity improvement at 20 Gb/s
- Absolute sensitivity -17.4 dBm

Ge APD: Benchmark

Sensitivity (dBm)

-30
-25
-20
-15
-10

Operation voltage (V)

-5  -10  -15  -20  -25  -30

INTEL, Y.Kang, Nat. Photonics 3 (2009)

HP labs, Z.Huang (2016)


This work, 400nm-Ge

This work, 185nm-Ge


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Summary

- **High performance Ge p-i-n PD demonstrated,**

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<thead>
<tr>
<th>-1 V</th>
<th>Responsivity (A/W)</th>
<th>O/E bandwidth (GHz)</th>
<th>Dark current</th>
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<tbody>
<tr>
<td></td>
<td>1550 nm 1310 nm</td>
<td>1550 nm 1310 nm</td>
<td></td>
</tr>
<tr>
<td>400-nm Ge</td>
<td>&gt; 1 A/W in the C-band</td>
<td>20 NA</td>
<td>3 nA</td>
</tr>
<tr>
<td>160-nm Ge</td>
<td>0.74 0.92</td>
<td>67 44</td>
<td>3 nA</td>
</tr>
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- **Low-voltage Ge APD demonstrated,**

<table>
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<th>Gain·bandwidth product (GHz)</th>
<th>Avalanche sensitivity improvement (dB)</th>
<th>Absolute sensitivity (dBm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>* 400-nm Ge</td>
<td>100</td>
<td>5.8</td>
<td>-23.2</td>
</tr>
<tr>
<td>**185-nm Ge</td>
<td>140</td>
<td>6.2</td>
<td>-17.4</td>
</tr>
</tbody>
</table>

**- 10 Gb/s at -5.9 V APD bias (1550 nm)
- TIA input referred (RMS) noise current, 1.2 μA;**

**- 20 Gb/s at -5 V APD bias (1310 nm)
- TIA input referred (RMS) noise current, 2.0 μA;**
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  - Joris Van Campenhout, Peter Verheyen, Geert Hellings, Jeroen De Coster, Guy Lepage, ...

- Photonics Research Group Team

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