PHOTONICS RESEARCH GROUP

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

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DATA

PayPal

PAYPAL PROCESSES OVER $315M IN PAYMENTS PER DAY

FACEBOOK'S HADOOP CLUSTER CONTAINS OVER 100 PB OF DATA

NETFLIX STREAMS OVER 1 BILLION HOURS OF VIDEO MONTHLY

AMAZON OWNS THE 3 LARGEST LINUX DBs WITH DATA STORES UP TO 24.7 TB

DATA CENTER TO END USER TRAFFIC WILL BE 561 EB IN 2013

72 HOURS OF VIDEO ARE UPLOADED TO YOUTUBE EVERY MINUTE

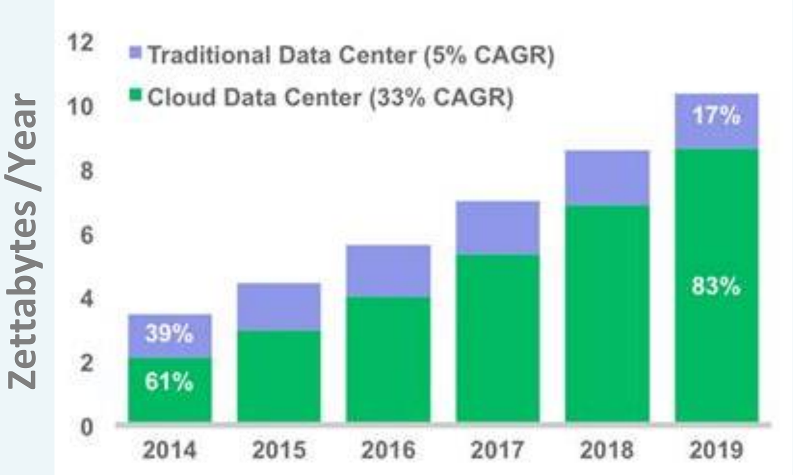
AMAZON CLOUD HANDLES 500,000 TRANSACTIONS PER SECOND

EBAY PROCESSES OVER 1 BILLION TRANSACTIONS DAILY

350 MILLION IMAGES UPLOADED DAILY TO FACEBOOK

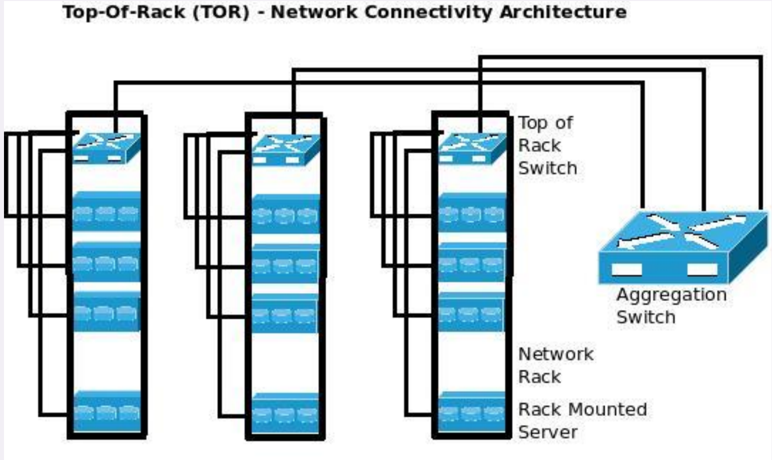
400,000,000 TWEETS PER DAY ON Twitter

Motivation → Low-power optical interconnects

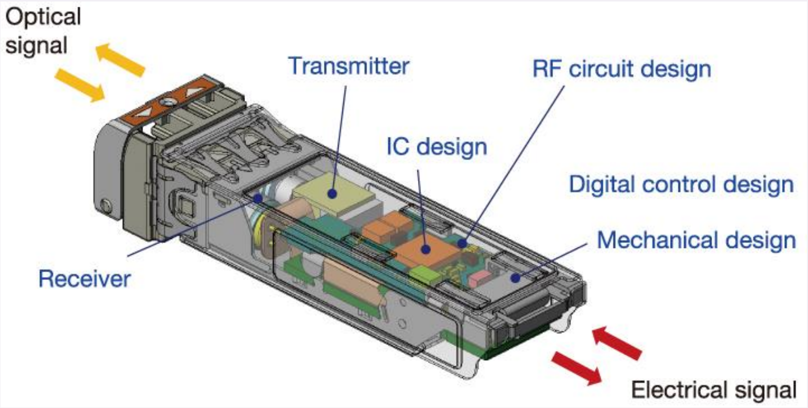


Global data center and cloud IP traffic
Source: Cisco Global Cloud Index, 2014–2019.

Mega-scale cloud data centers

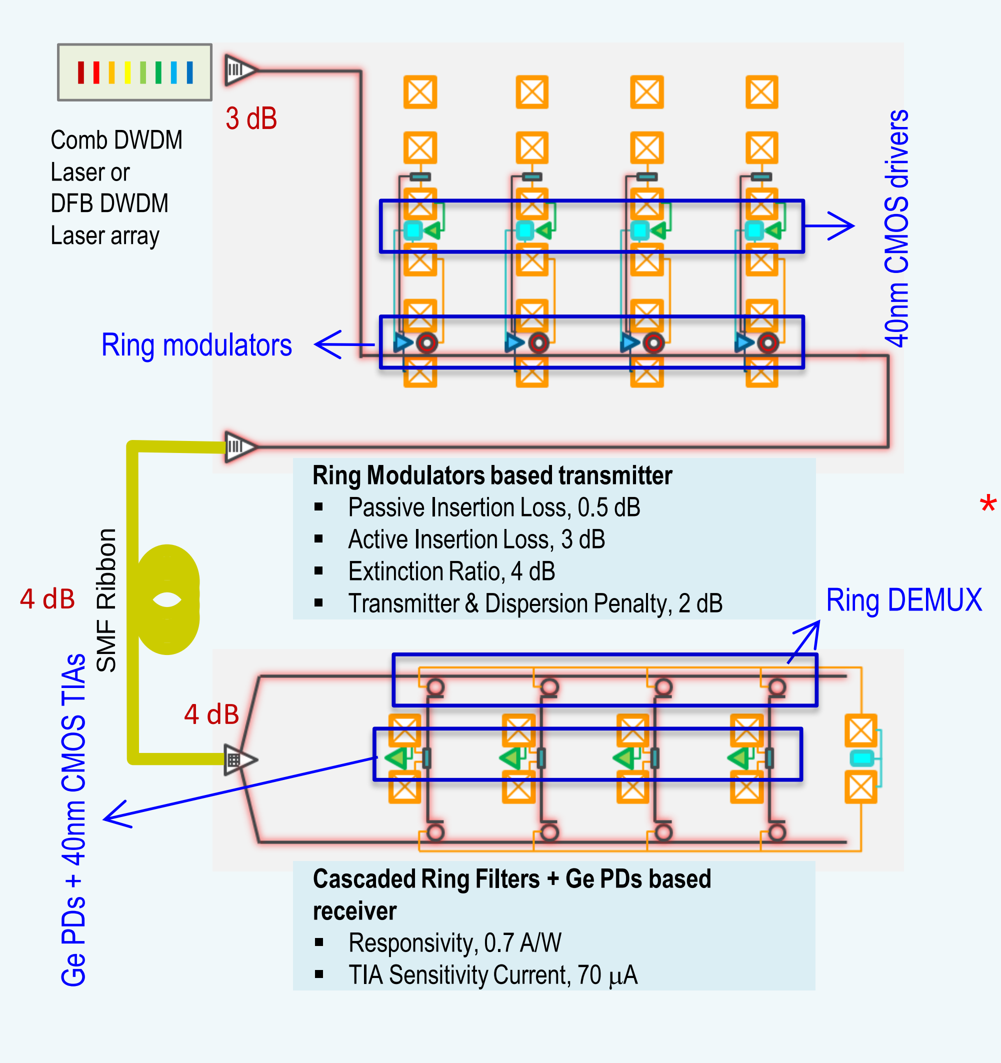


Optical interconnects in data center



A commercial optical transceiver cartoon

High Sensitivity Optical Receiver to Improve Power efficiency



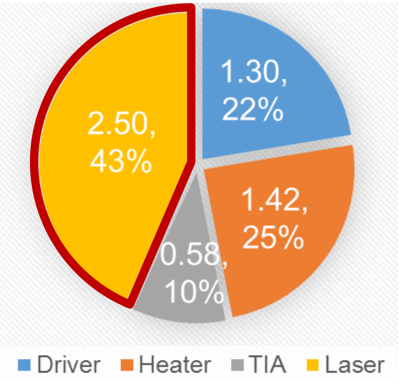
Ring Modulators based transmitter

- Passive Insertion Loss, 0.5 dB
- Active Insertion Loss, 3 dB
- Extinction Ratio, 4 dB
- Transmitter & Dispersion Penalty, 2 dB

Cascaded Ring Filters + Ge PDs based receiver

- Responsivity, 0.7 A/W
- TIA Sensitivity Current, 70 μA

CMOS 4λ-CWDM OOK optical transceiver

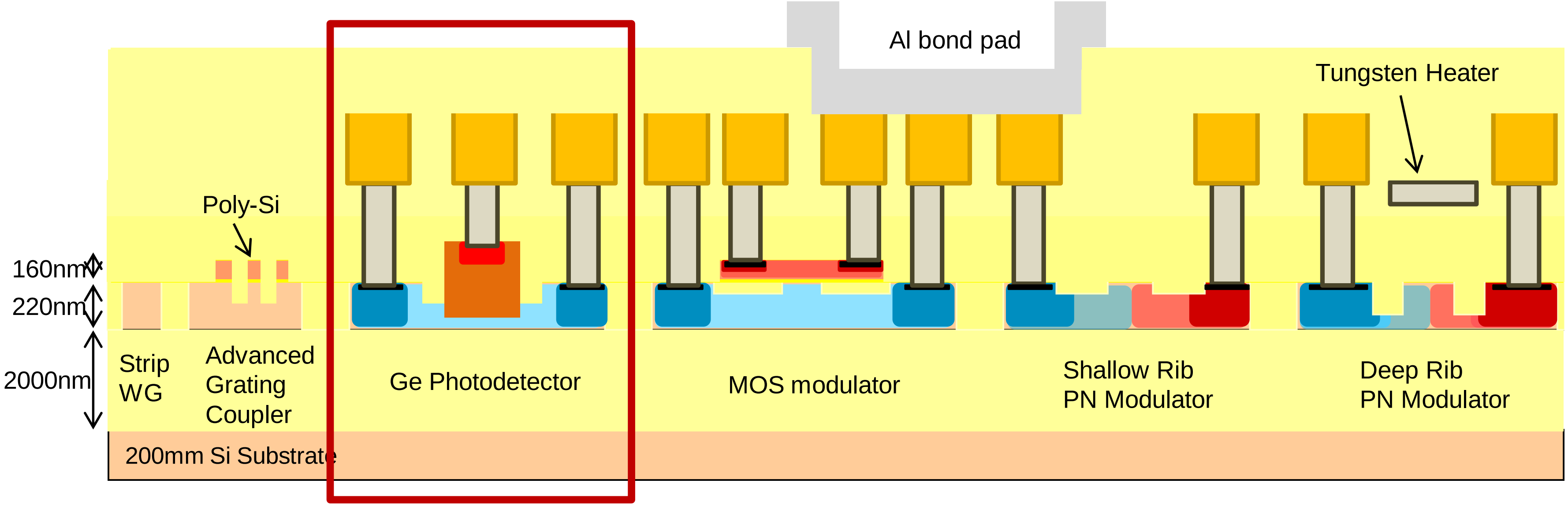


*Power efficiency, pJ/bit (4λ×20 Gb/s)

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

*M. Rakowski, et al, "A 4x20Gb/s WDM Ring-based Hybrid CMOS Silicon Photonics Transceiver", *ISSCC*, 408 (2015).

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

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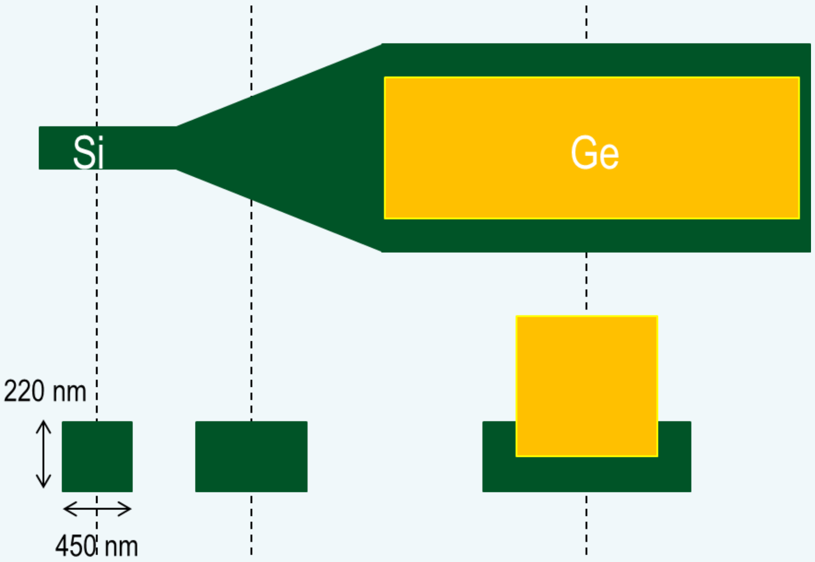
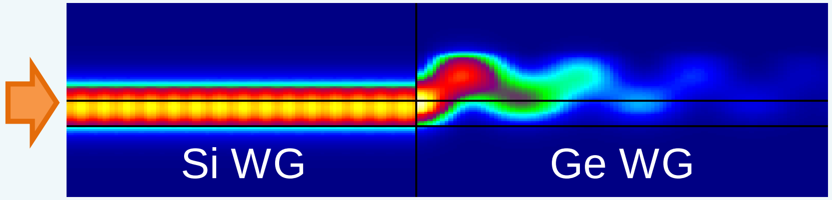
- Si-contacted Ge p-i-n Photodetectors
    - 400nm-Ge Si-LPIN GePD
    - 160nm-Ge Si-LPIN GePD
- Low-voltage Ge Avalanche Photodetectors
    - 400nm-Ge VPIN GeAPD
    - 185nm-Ge VPIN GeAPD
- Summary

Ge-on-Si Waveguide p-i-n photodetectors



Ge-on-Si WG photodetector



Light transmission

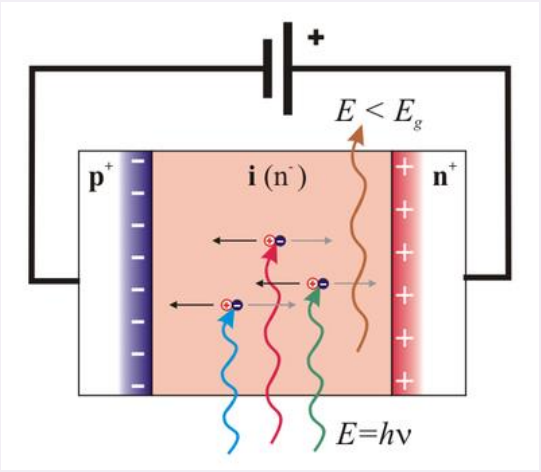
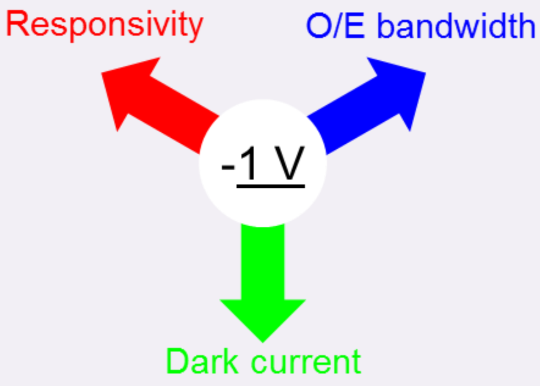


Photo-carriers generation & collection



Responsivity

O/E bandwidth

-1 V

Dark current

Photodetector performance metrics

Responsivity

$$R = \eta \frac{q}{h \cdot f} \approx \eta \frac{\lambda_{(\mu m)}}{1.23985_{(\mu m)}} (A/W)$$

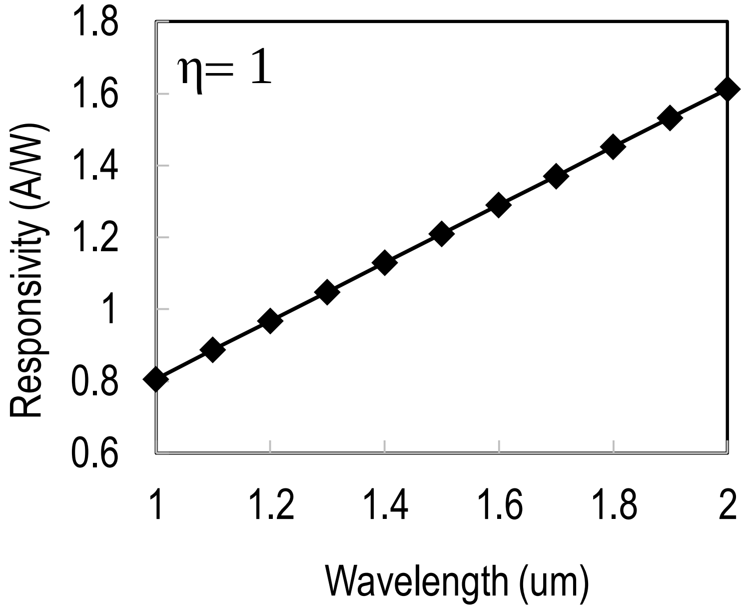
Quantum efficiency

Optical frequency

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

☐ Light absorption

☐ Photo-carriers collection

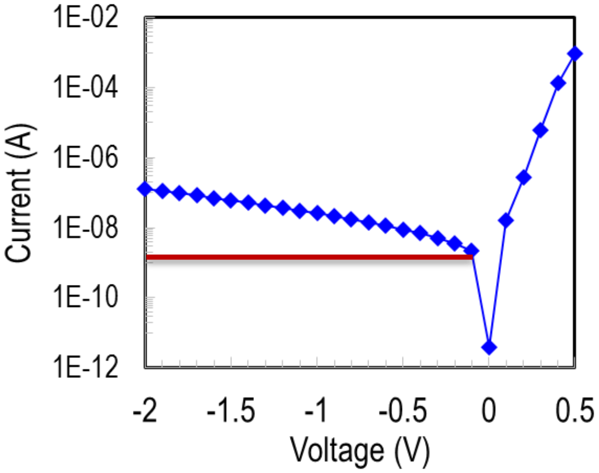


Responsivity as a function of wavelength

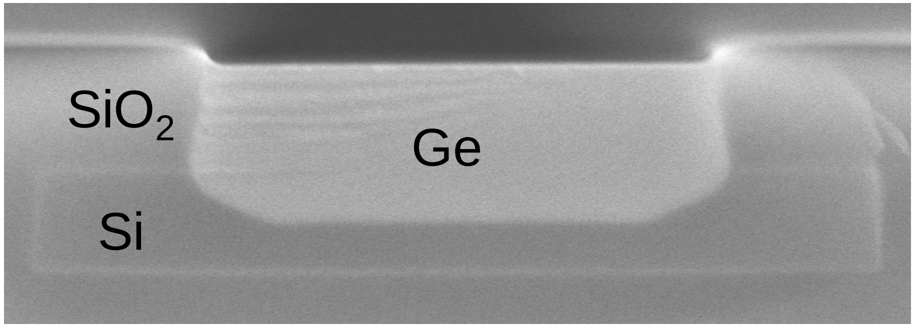
Dark current

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

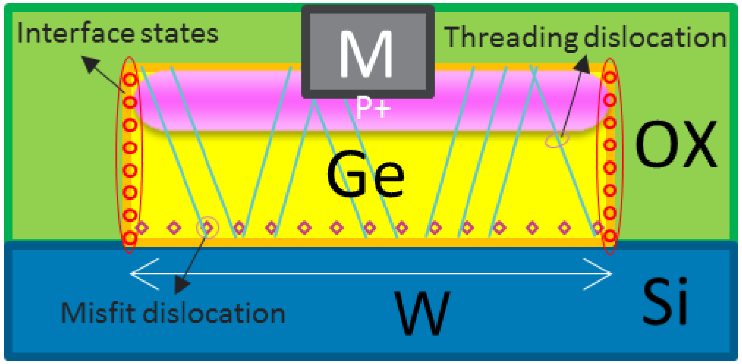
- Diffusion current
- SRH leakage current
    - Material defects
    - Ge passivation



A typical photodiode I-V characteristic



Ge-on-Si SEM graph

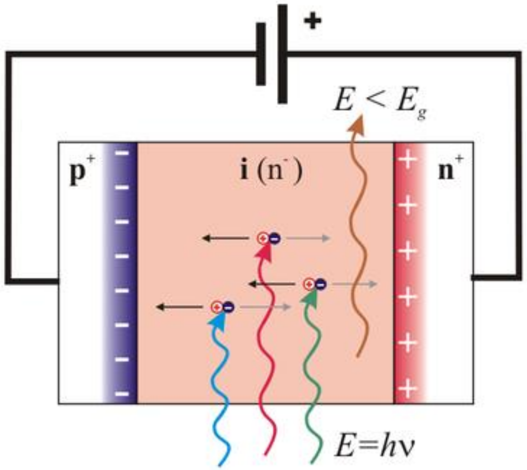


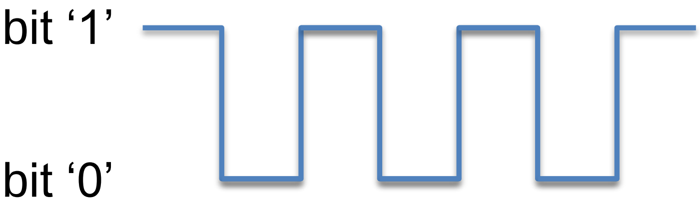
SRH leakage current source modeling

O/E bandwidth

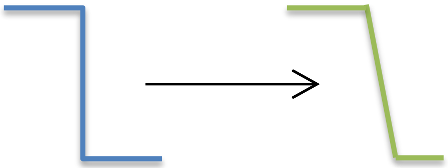
The capability of a p-i-n photodetector to respond to a fast modulated optical signal.

- Transit time
- RC-constant

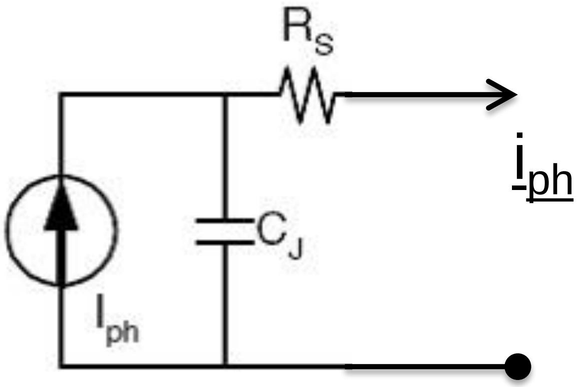




An ideal OOK modulated optical signal



Optical Electrical



p-i-n photodetector model

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- Si-contacted Ge p-i-n Photodetectors
    - 400nm-Ge Si-LPIN GePD
    - 160nm-Ge Si-LPIN GePD
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    - 185nm-Ge VPIN GeAPD
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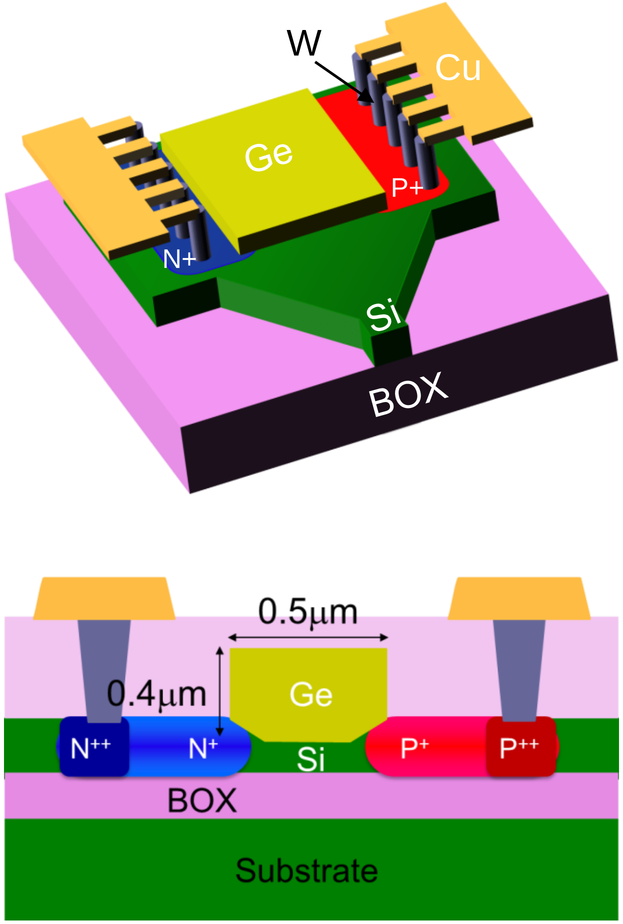
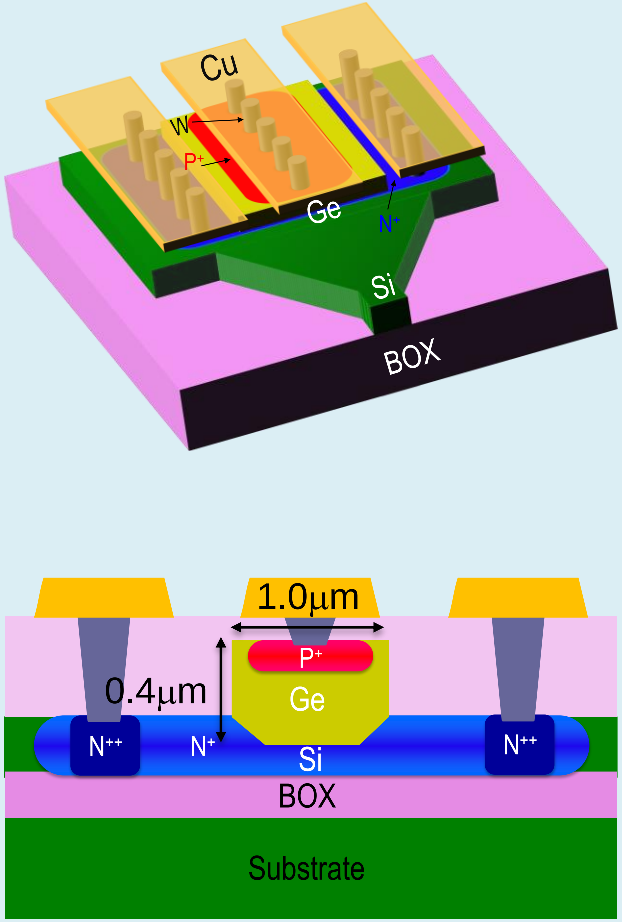
400 nm-Ge Si-LPIN GePD



Si-LPIN GePD



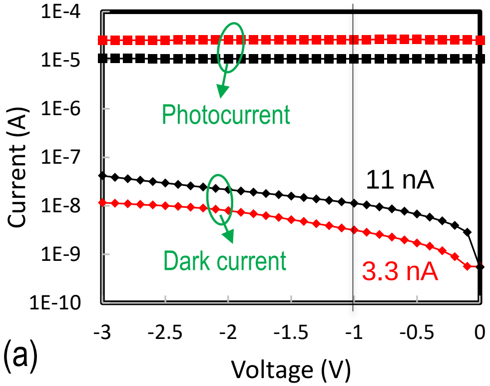
BL-VPIN GePD (for reference)

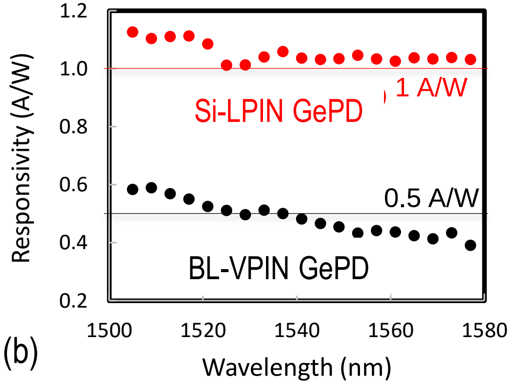
Si-LPIN GePD:

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

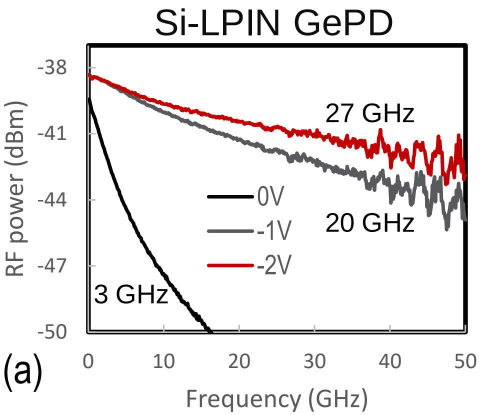
Static, Small & Large-signal Measurement Data at 1550 nm

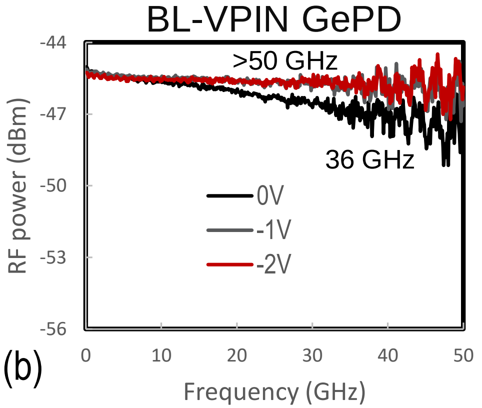
Static I-V & responsivity





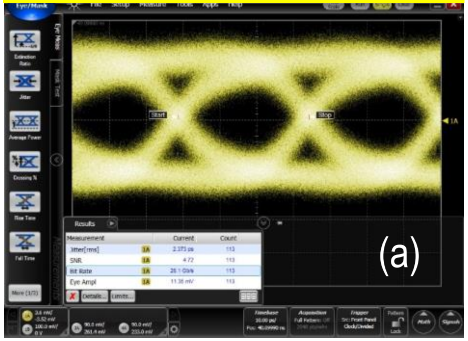
Small-signal S_{21} curves



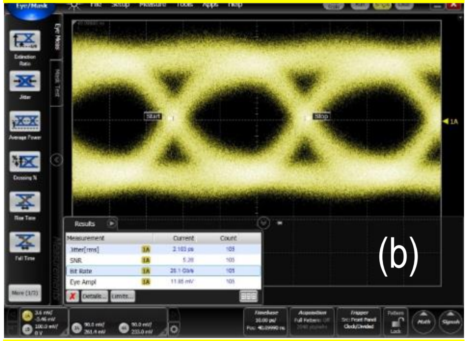


@-1 V, 1550nm	Si-LPIN GePD	BL-VPIN GePD
Responsivity	>1 A/W	0.45 A/W
Dark current	3 nA	11 nA
O/E bandwidth	20 GHz	>50 GHz

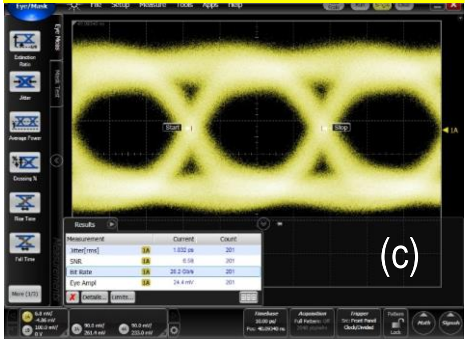
Si-LPIN GePD at -1 V



Si-LPIN GePD at -2 V



BL-VPIN GePD at -1 V



28 Gb/s OOK-NRZ eye

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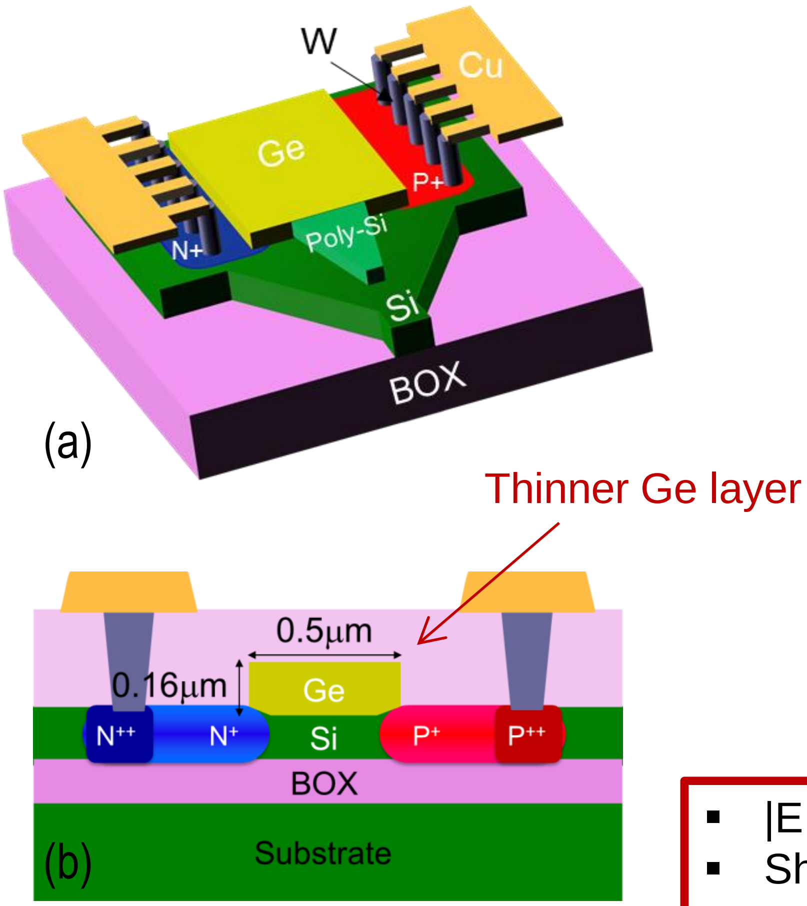
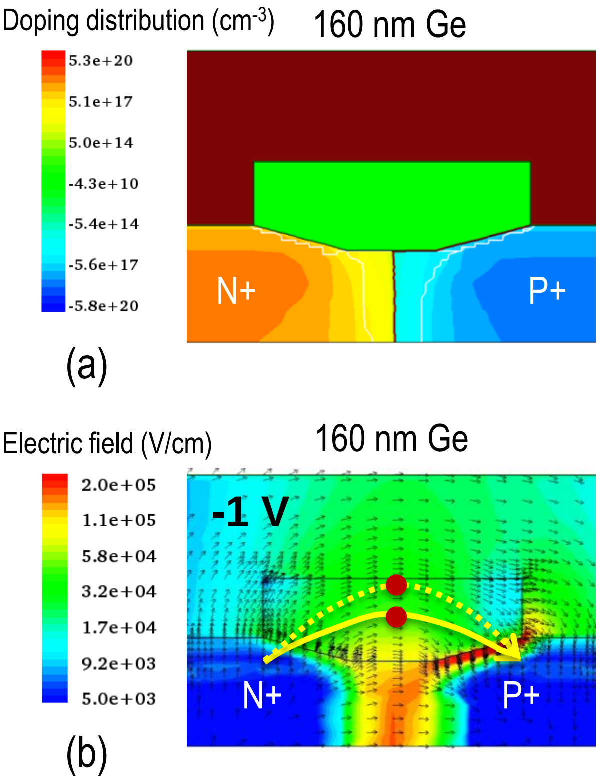
160nm-Ge Si-LPIN GePD



Thinner Ge layer

3-D & cross sectional schematic



Doping & electric field distribution

- $|E| > 1 \times 10^4$ V/cm at -1 V bias
- Shorter transit distance compared to 400nm-Ge device

→ Higher O/E bandwidth expected

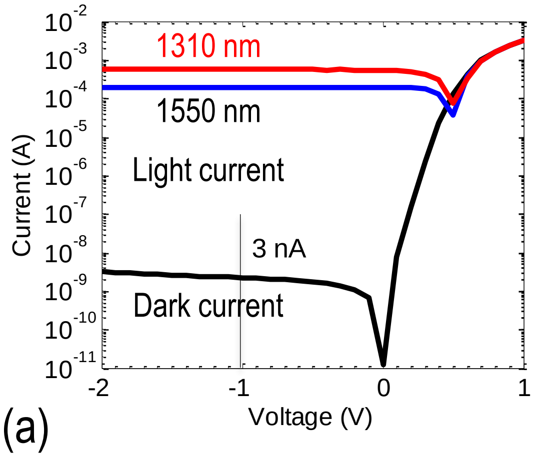
☐ High responsivity & Low dark current

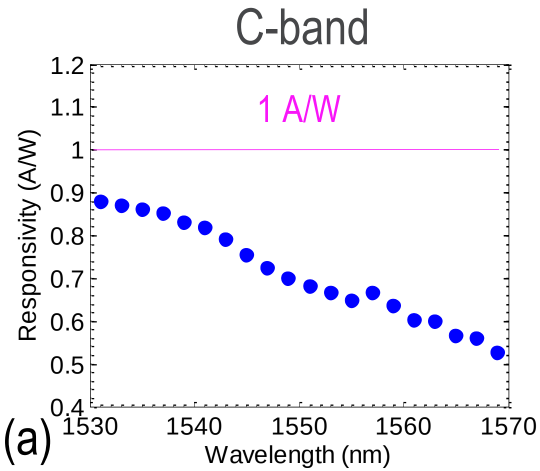
Static and Small-signal Measurement Data

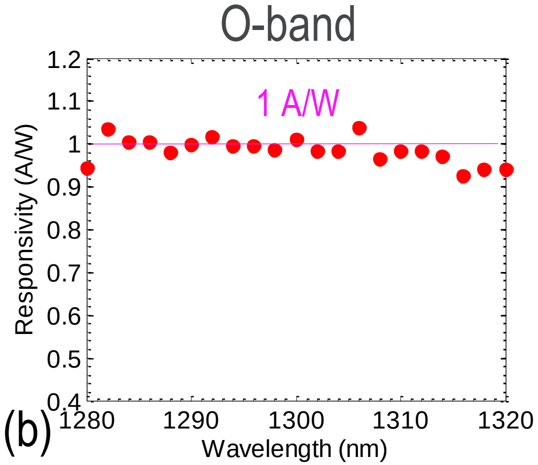
I-V characteristics

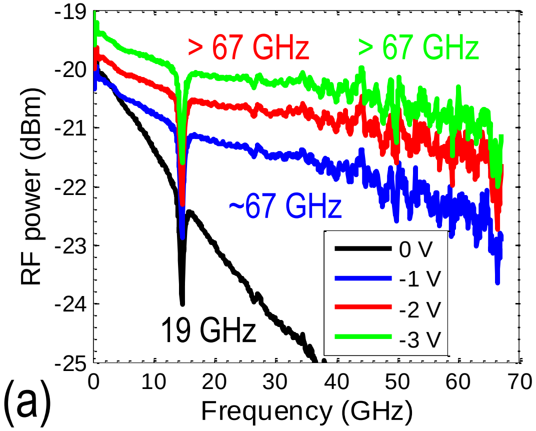
Responsivity at -1 V

O/E Bandwidth



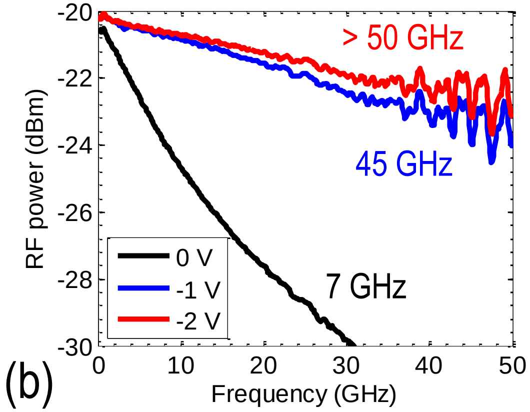






67 GHz S_{21} meas. at 1550 nm

1310 nm

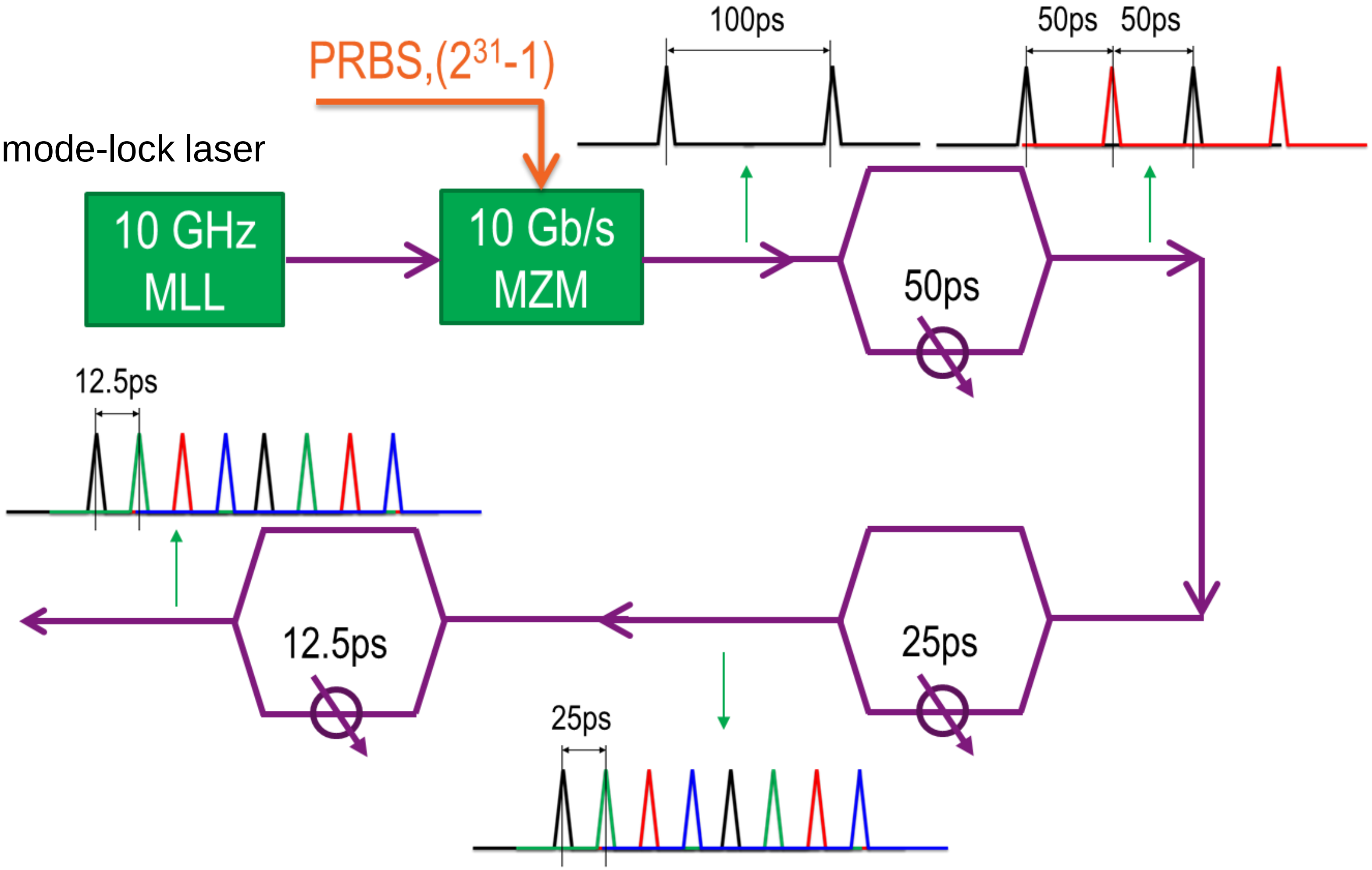


50 GHz S_{21} measurement

Large-signal Data Reception Measurement

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

MLL: mode-lock laser



*Implemented in DTU Fotonik, Denmark

Large-signal Data Reception Measurement

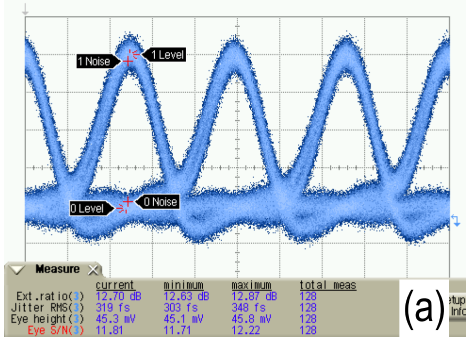
70 GHz comerc. PD

(u2t XPDV-3120R)

at -1 V

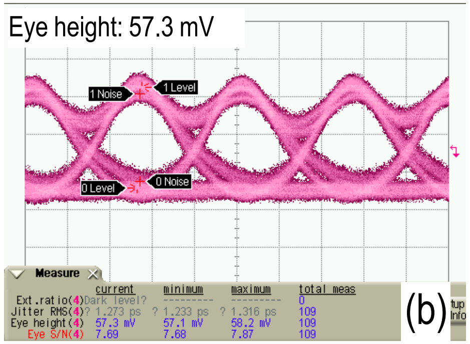
at -2 V

80 Gb/s eye diagrams



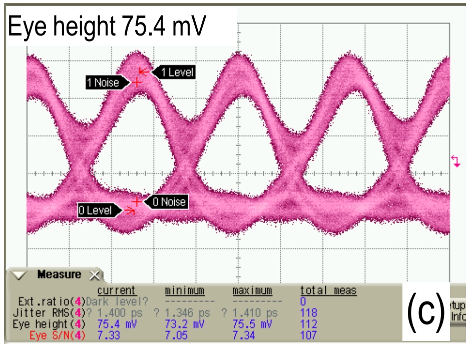
	current	minimum	maximum	total meas
Ext.ratio(3)	12.70 dB	12.63 dB	12.87 dB	128
Jitter RMS(3)	319 fs	303 fs	348 fs	128
Eye height(3)	45.3 mV	45.1 mV	45.8 mV	128
Eye S/N(3)	11.81	11.71	12.22	128

Eye height: 57.3 mV



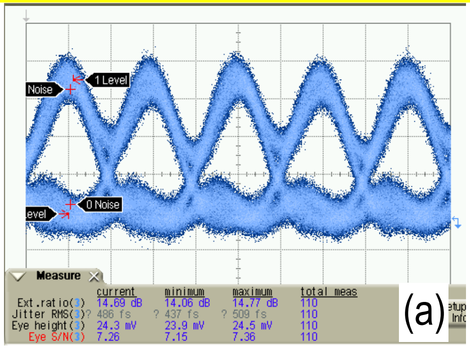
	current	minimum	maximum	total meas
Ext.ratio(4)	Dark level?	---------	---------	0
Jitter RMS(4)	? 1.273 ps	? 1.233 ps	? 1.316 ps	109
Eye height(4)	57.3 mV	57.1 mV	58.2 mV	109
Eye S/N(4)	7.69	7.68	7.87	109

Eye height 75.4 mV



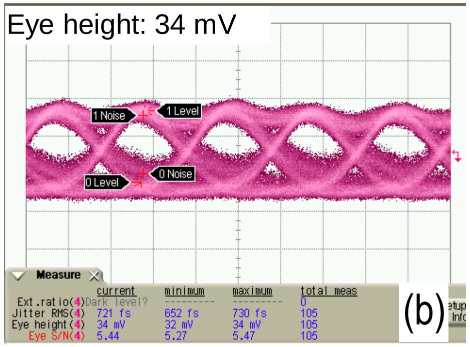
	current	minimum	maximum	total meas
Ext.ratio(4)	Dark level?	---------	---------	0
Jitter RMS(4)	? 1.400 ps	? 1.346 ps	? 1.410 ps	118
Eye height(4)	75.4 mV	73.2 mV	75.5 mV	112
Eye S/N(4)	7.33	7.05	7.34	107

100 Gb/s eye diagrams



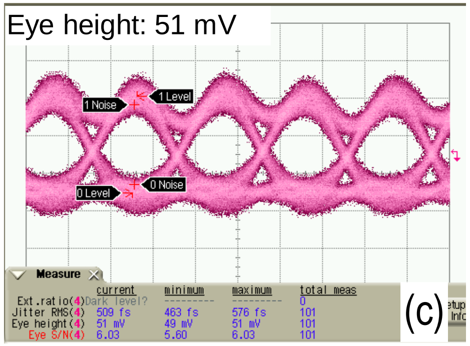
	current	minimum	maximum	total meas
Ext.ratio(3)	14.69 dB	14.06 dB	14.77 dB	110
Jitter RMS(3)	? 486 fs	? 437 fs	? 509 fs	110
Eye height(3)	24.3 mV	23.9 mV	24.5 mV	110
Eye S/N(3)	7.26	7.15	7.36	110

Eye height: 34 mV



	current	minimum	maximum	total meas
Ext.ratio(4)	Dark level?	---------	---------	0
Jitter RMS(4)	721 fs	652 fs	730 fs	105
Eye height(4)	34 mV	32 mV	34 mV	105
Eye S/N(4)	5.44	5.27	5.47	105

Eye height: 51 mV

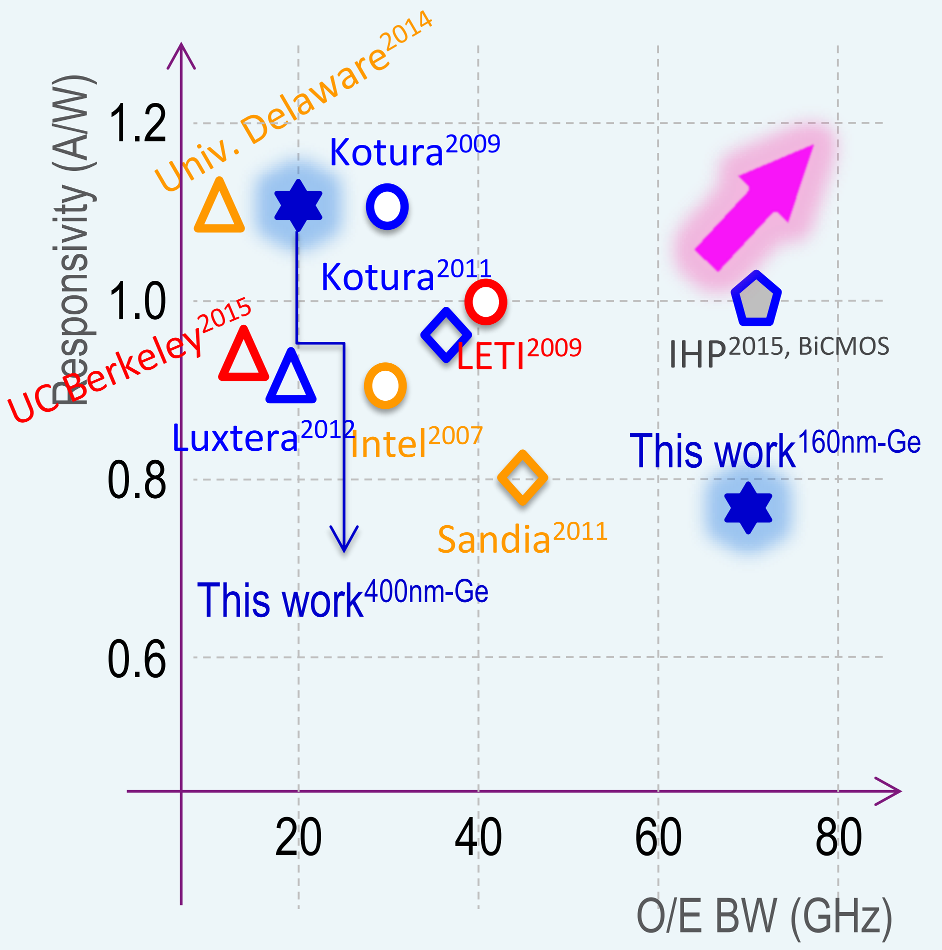


	current	minimum	maximum	total meas
Ext.ratio(4)	Dark level?	---------	---------	0
Jitter RMS(4)	509 fs	463 fs	576 fs	101
Eye height(4)	51 mV	49 mV	51 mV	101
Eye S/N(4)	6.03	5.60	6.03	101

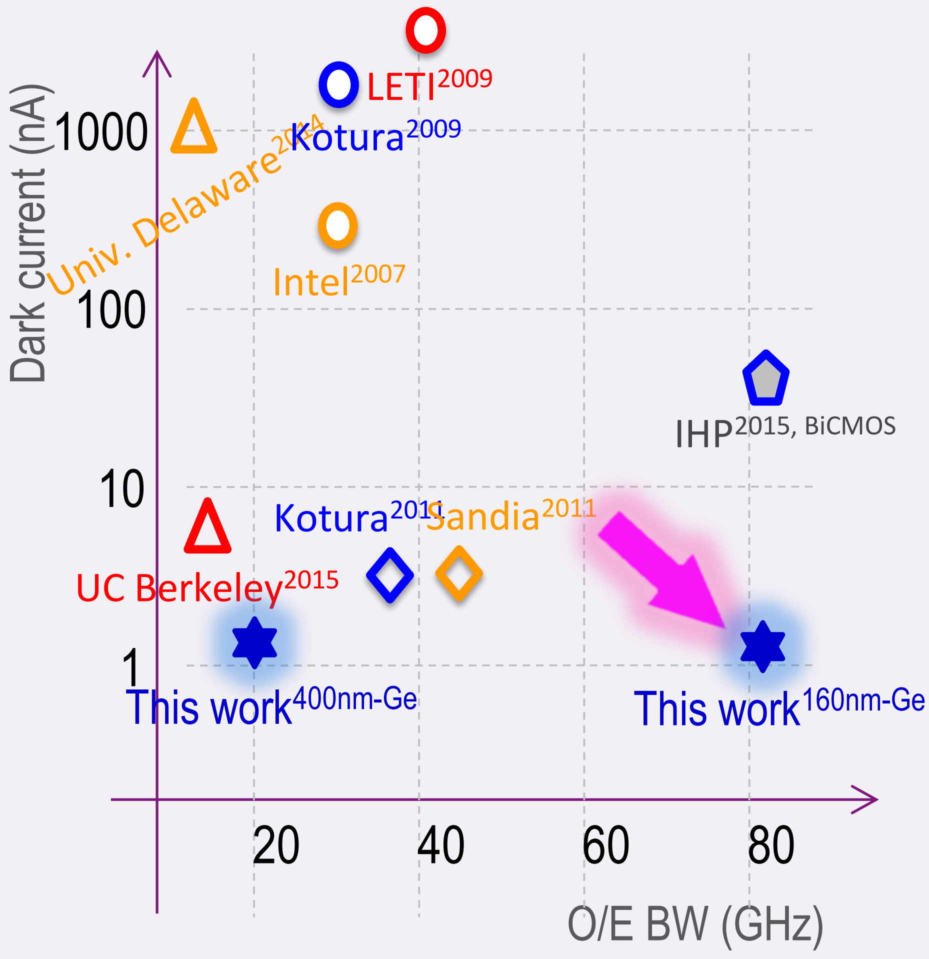
Clear open eye diagrams obtained at 100 Gb/s

Ge p-i-n PD: Benchmark

▬ -1 V ▬ -2 V ▬ >-2 V



Responsivity V.S. O/E Bandwidth



Dark current V.S. O/E Bandwidth

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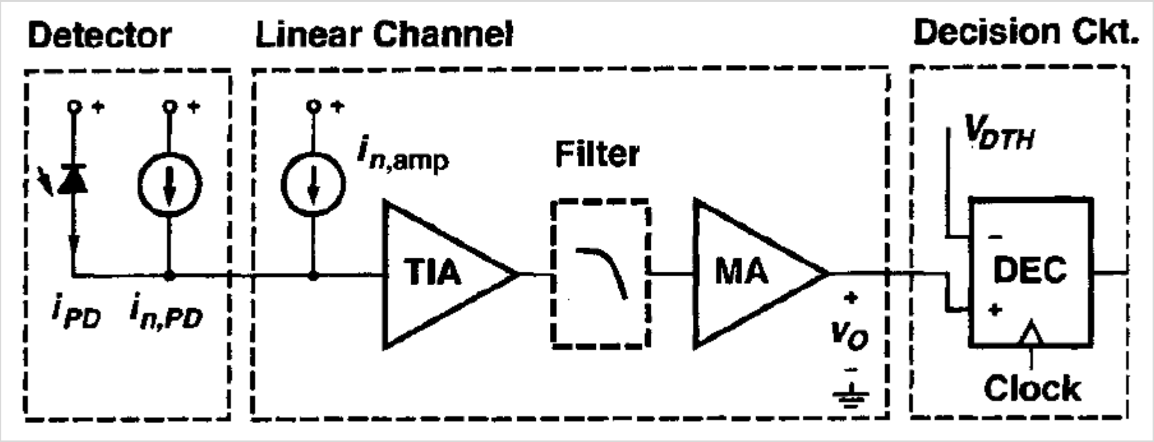
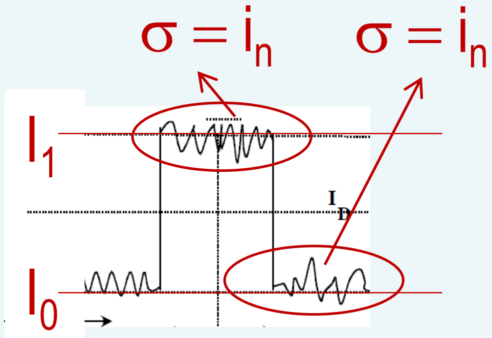
Pursuing Even Higher Sensitivity By Leveraging Avalanche Multiplication



*Basis optical receiver model



$Q = (I_1 - I_0) / 2*i_n$

Optical receiver (p-i-n PD):

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

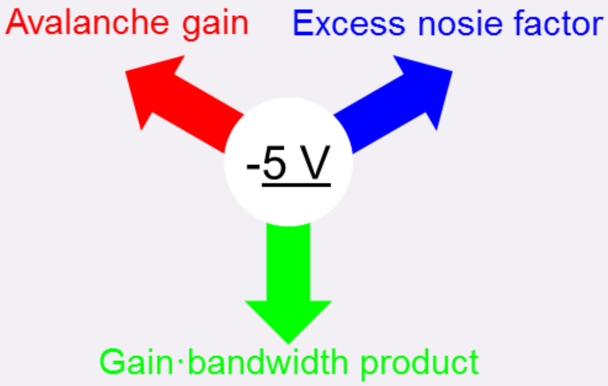
Noise power from Linear Channel

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



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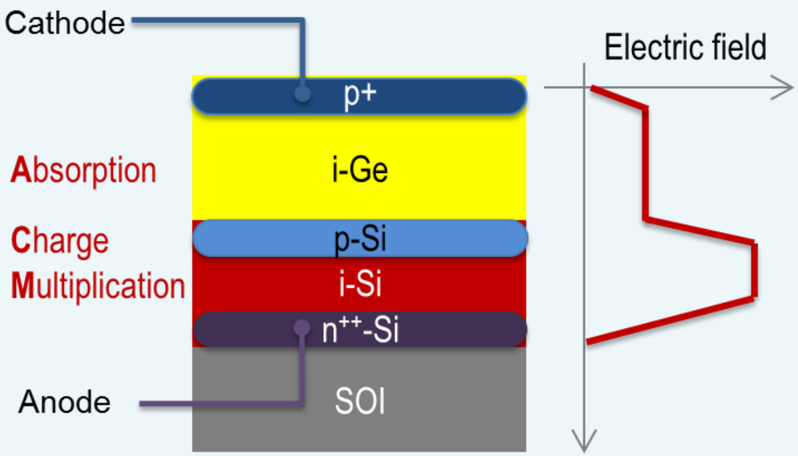
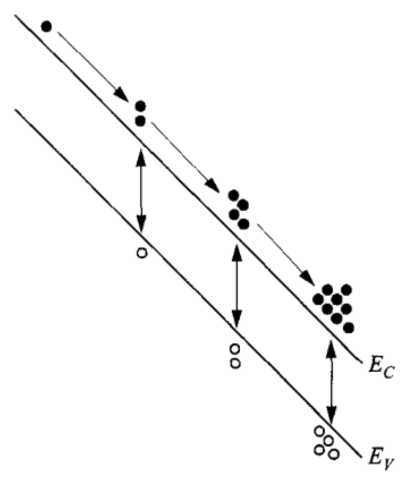
*Eduard Sackinger, Broadband Circuits for Optical Communications.

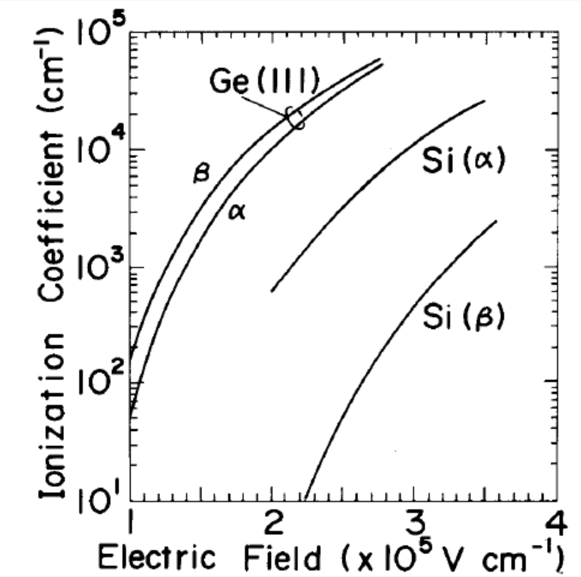
Avalanche gain



S-A-C-M Ge/Si Avalanche Photodiode



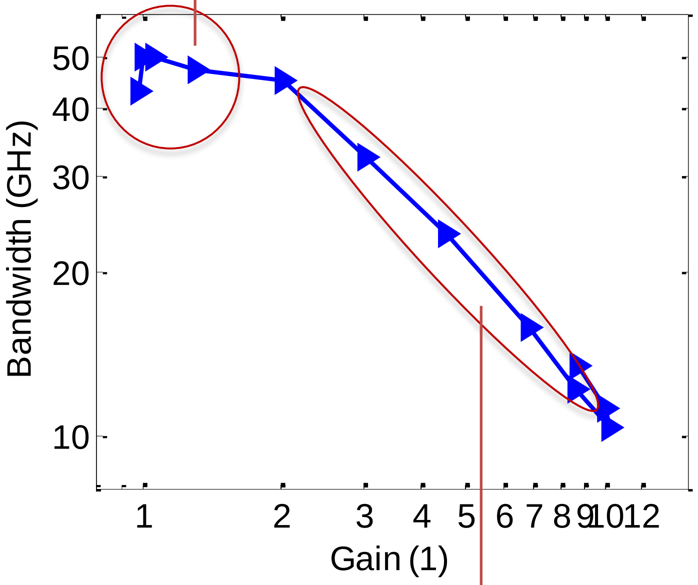
Impact ionization



Impact ionization coefficient:
(α, electrons; β, holes)
- the number of electron-hole pairs generated by a carrier per unit distance traveled

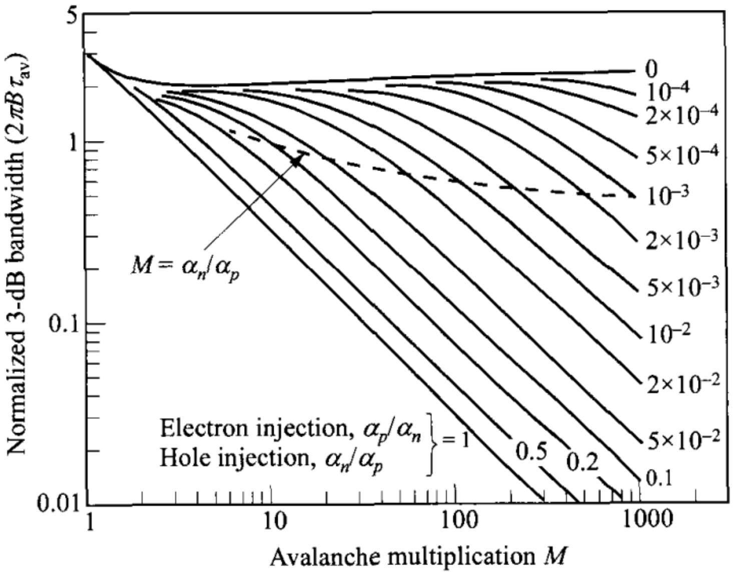
Gain·bandwidth product ← build-up time

- RC-constant
- Transit time



Avalanche build-up time

O/E bandwidth as a function of gain

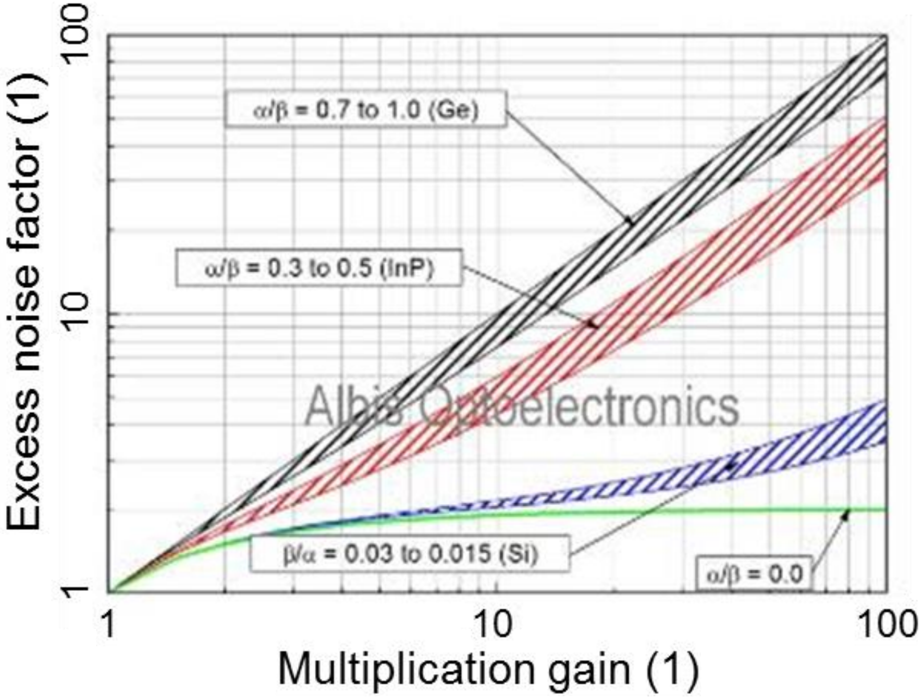


*Modeled Bandwidth v.s. Gain

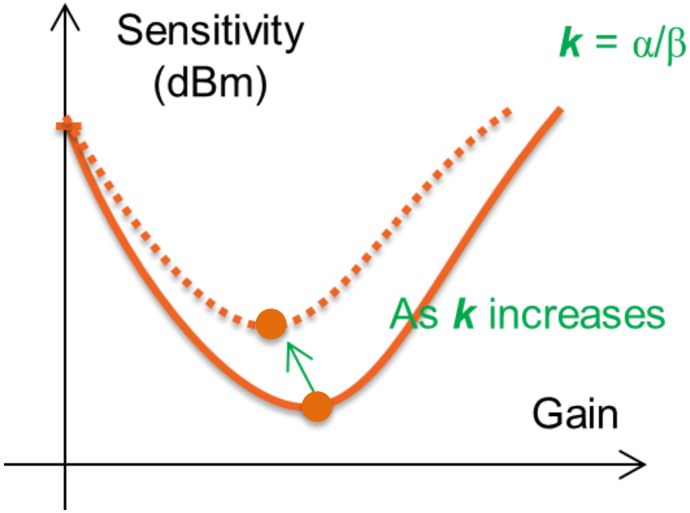
$M, \alpha_n/\alpha_p$

*Simon M. Sze, Physics of Semiconductor Devices

Excess noise factor



Bulk material avalanche noise properties



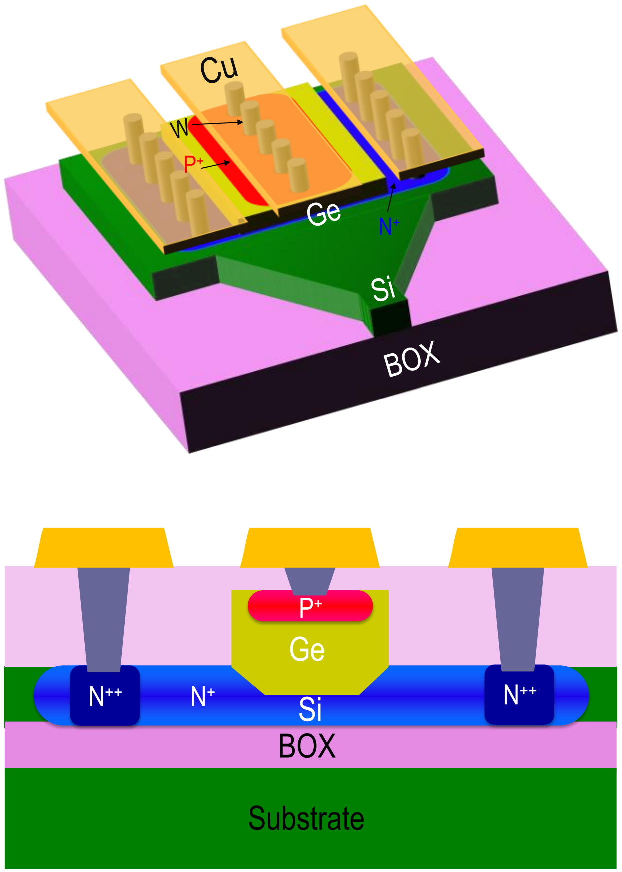
Avalanche sensitivity improvement

$$\underbrace{\langle i_S \rangle^2}_{\text{Noise current power}} = 2 \times q \times I_0 \times \underbrace{M^2}_{\text{Gain}} \times \underbrace{F(M)}_{\text{Excess noise factor}} \times B$$

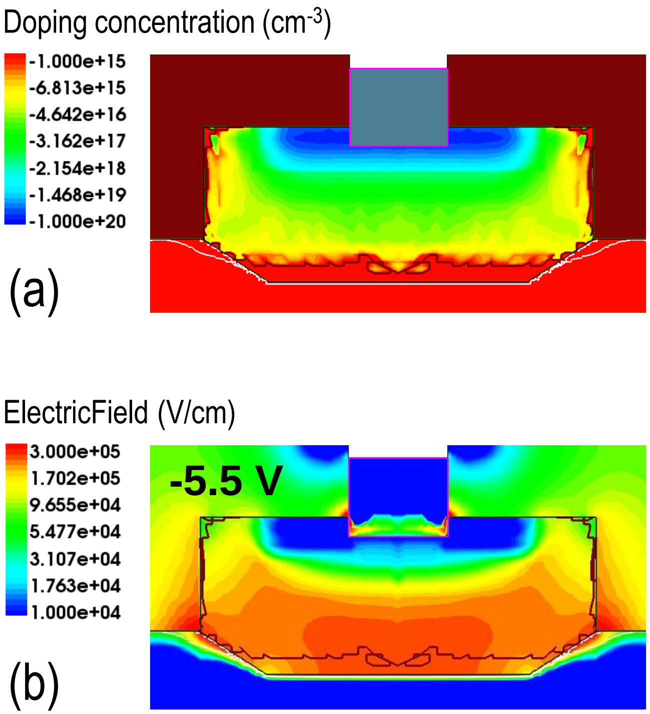
Outline

- 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

400 nm-Ge VPIN GeAPD



3-D & cross sectional schematic

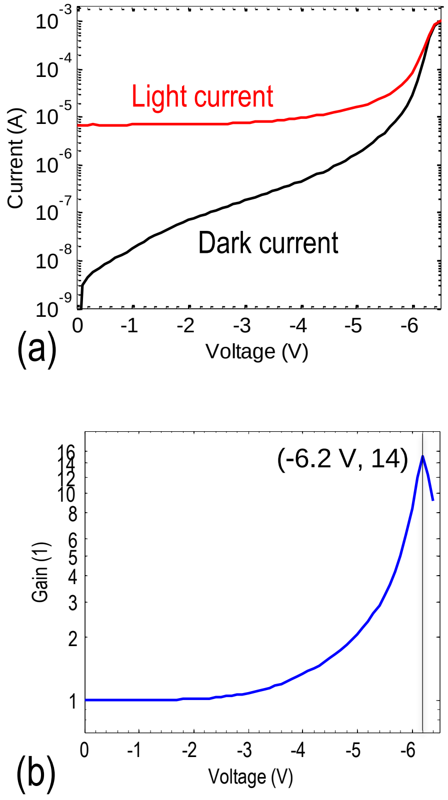


Doping & electric field distribution

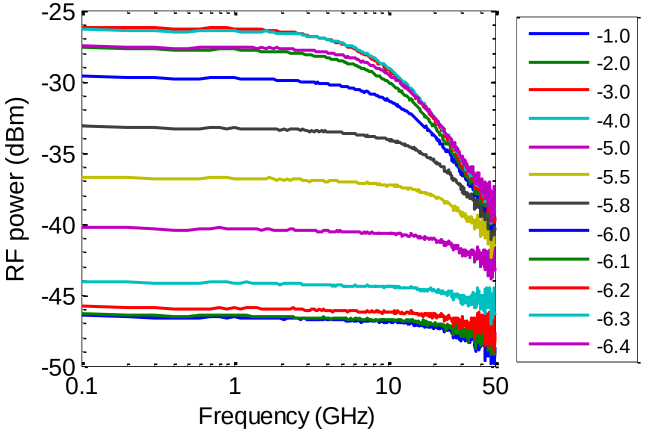
- $|E| \sim 2\times10^5$ V/cm confined in the bottom 200 nm Ge layer at -5.5 V bias,

→ Strong avalanche multiplication expected,

Static & Small-signal Measurement Data



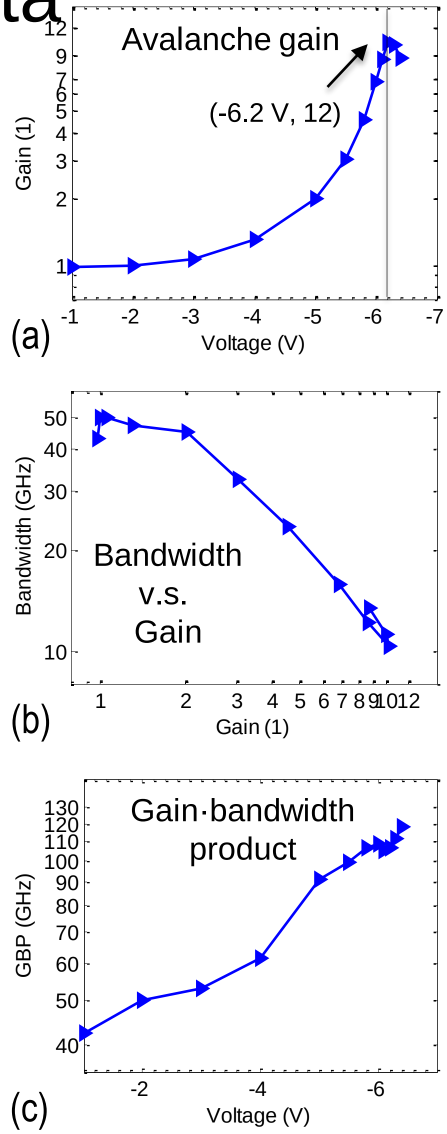
Static I-V characteristics, 1550 nm



Raw S_{21} param. curves, 1550 nm

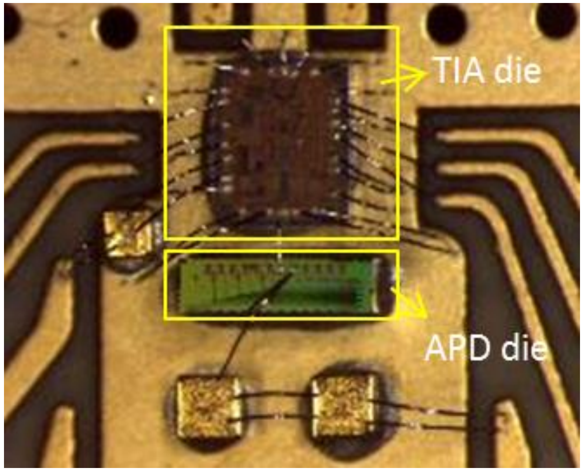
Strong avalanche multiplication occurs at -5.9 V

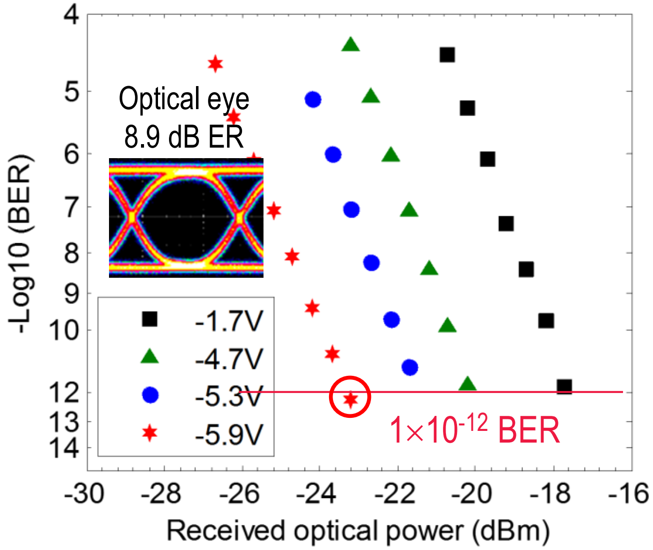
- Gain of 10.2,
- Bandwidth of 10.4 GHz
- Gain·banwdith product, 106 GHz

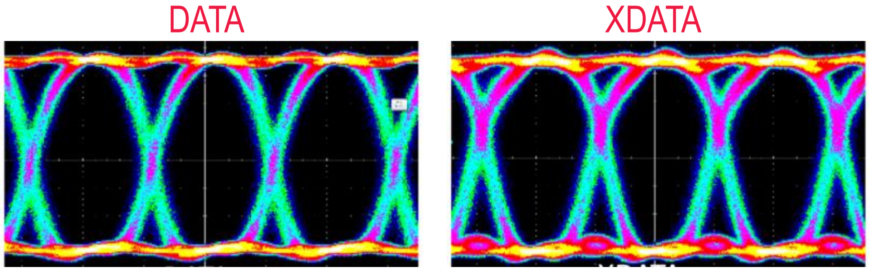


Extracted from raw S_{21} curves

Optical Receiver Sensitivity Measurement Data







10 Gb/s bit error ratios for various bias voltages

- *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,

- 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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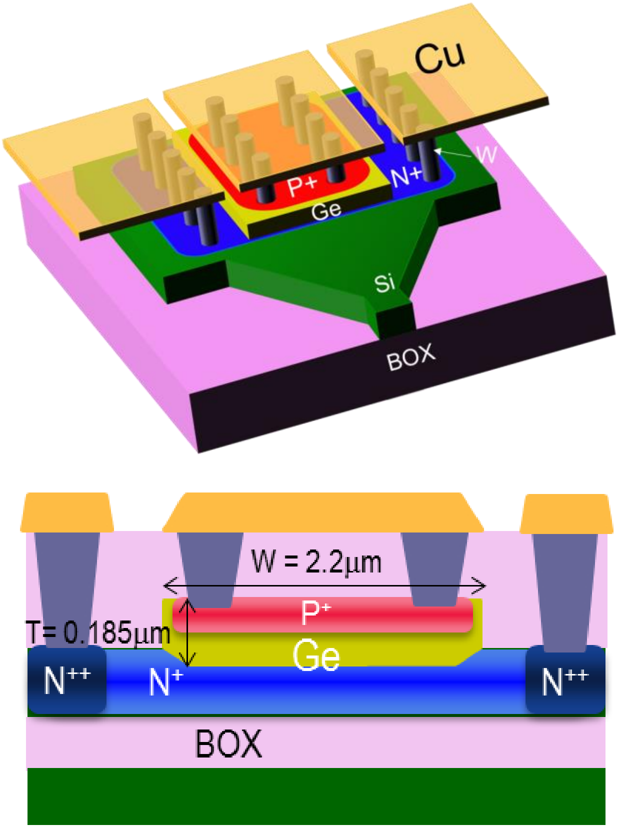
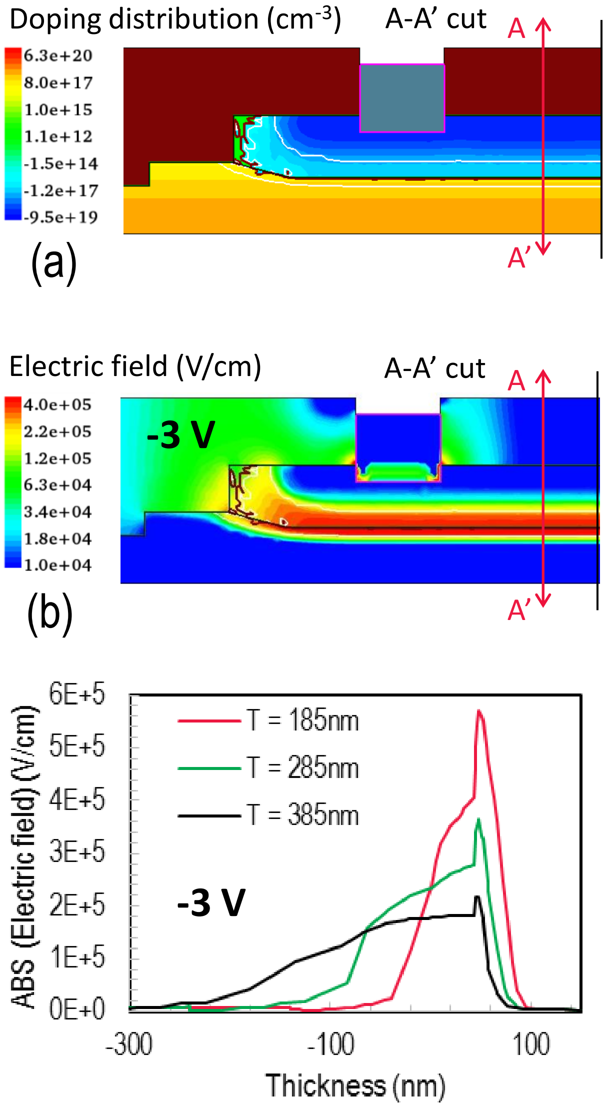
185 nm-Ge VPIN GeAPD



3-D and cross sectional schematic

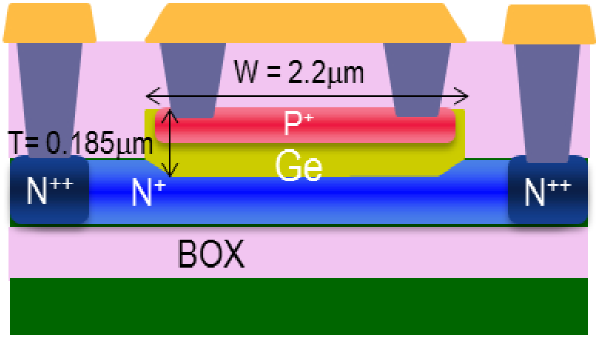
→ Better avalanche performance expected



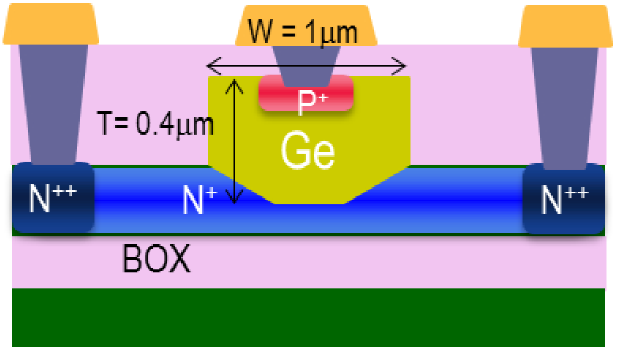
Doping & electric field distribution

Avalanche performance

185nm
Ge
APD



400nm
Ge
APD



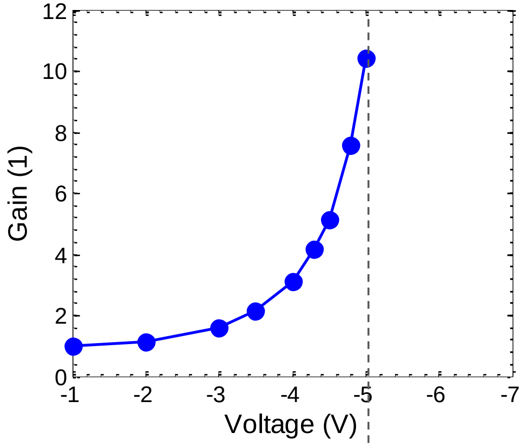
Avalanche performance

Avalanche gain

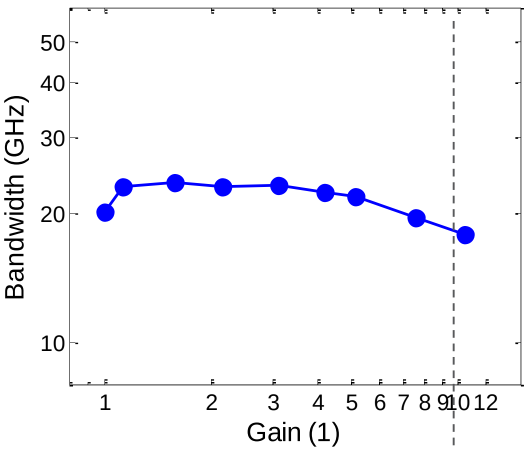
O/E bandwidth v.s. gain

Excess noise factor

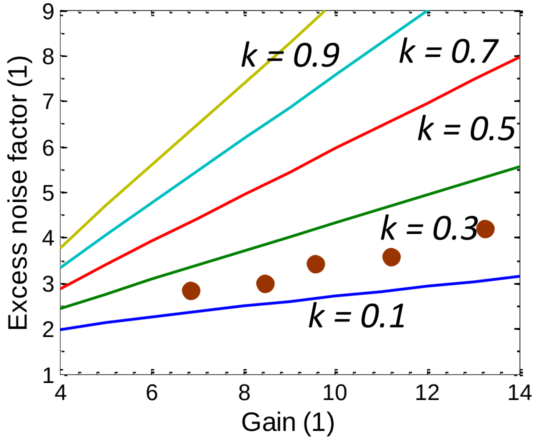
185nm
Ge
APD



Gain of 10 at -5 V

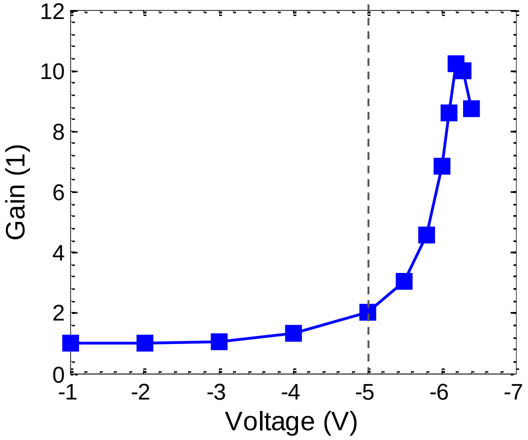


18 GHz at gain of 10

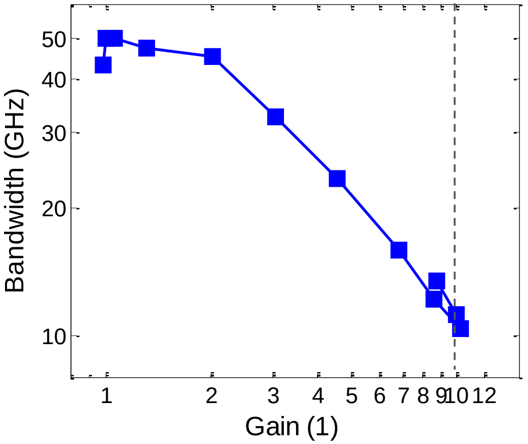


k ~0.2

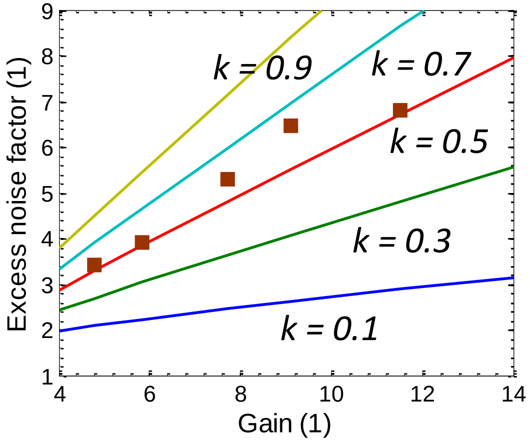
400nm
Ge
APD



Gain of 2 at -5 V

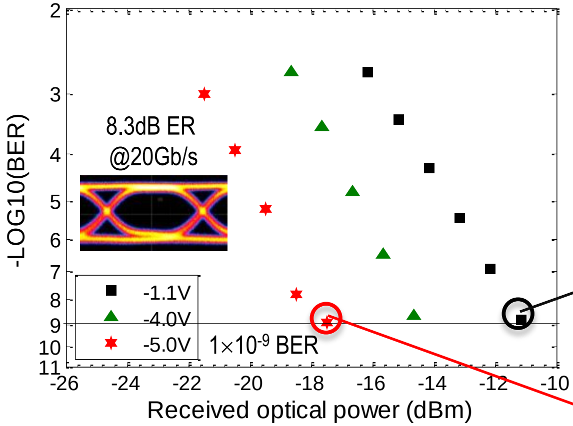


10 GHz at gain of 10



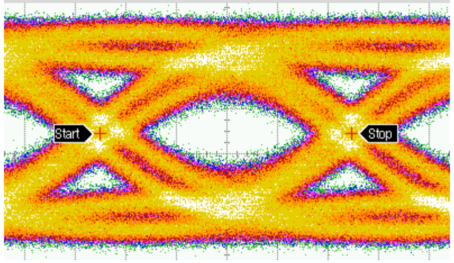
k ~0.6

Optical Receiver Sensitivity Measurement Data

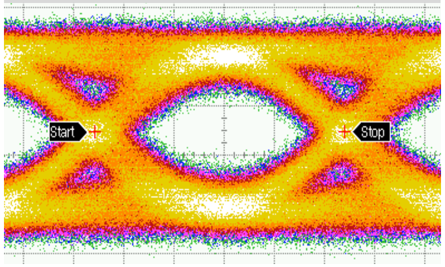


Bit error ratio data at 20 Gb/s

Input optical power, -11.2dBm



Input optical power, -17.4dBm

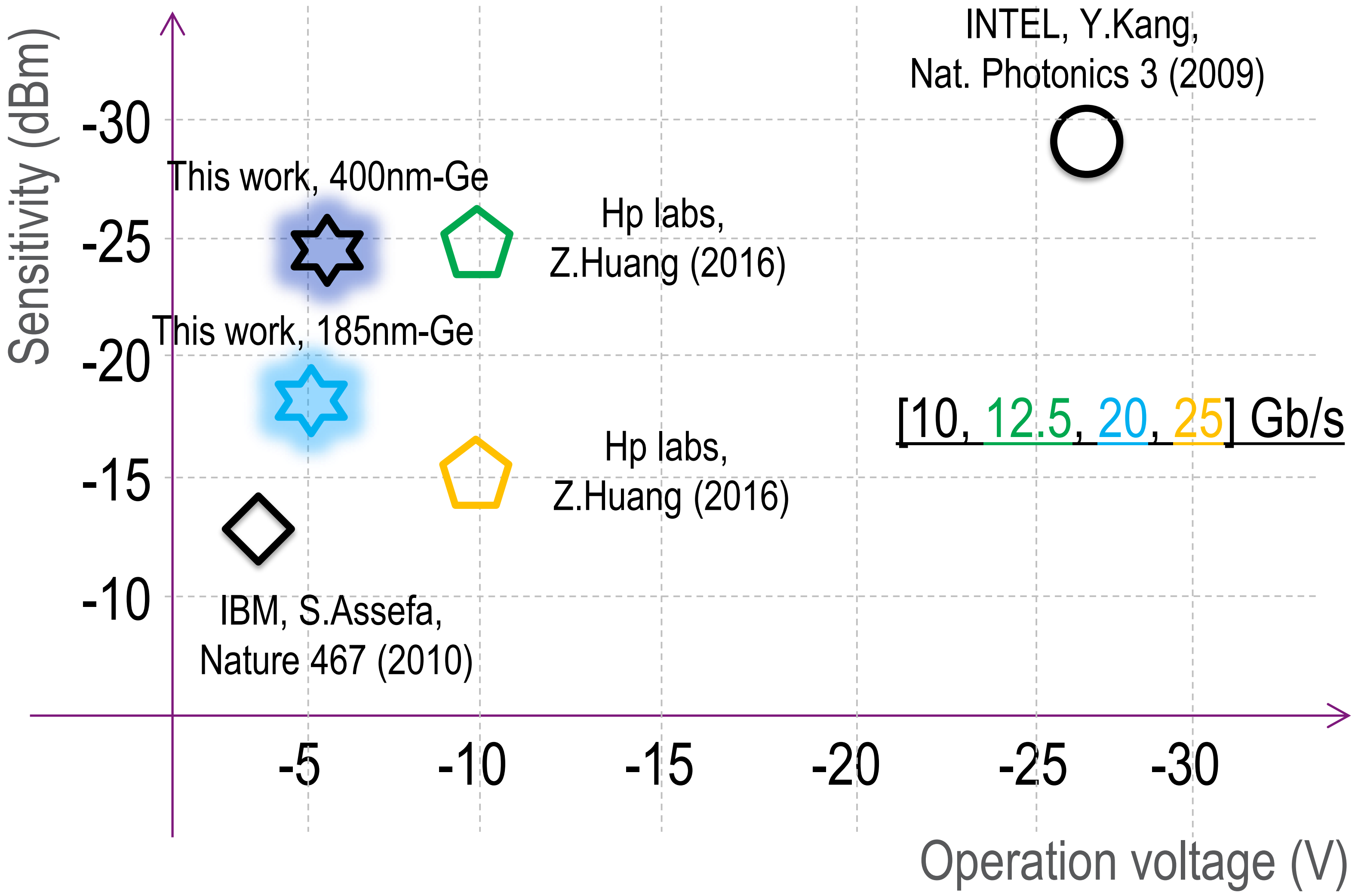


- *Custom TIA design from INTEC_design
- ✓ 130-nm SiGe BiCMOS technology
- ✓ 2 μA input referred (RMS) noise current at 20 Gb/s
- $(2^{31}-1)$ PRBS NRZ modulation
- Operate at 1310 nm

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

*B. Moeneclaey, et al., IEEE PTL, 27(13), 1375 (2015)

Ge APD: Benchmark



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  - 400nm-Ge VPIN GeAPD
  - 185nm-Ge VPIN GeAPD
- Summary

Summary

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

-1 V	Responsivity (A/W)		O/E bandwidth (GHz)		Dark current
	1550 nm	1310 nm	1550 nm	1310 nm	
400-nm Ge	> 1 A/W in the C-band		20	NA	3 nA
160-nm Ge	0.74	0.92	67	44	3 nA

- Low-voltage Ge APD demonstrated,

	Gain·bandwidth product (GHz)	Avalanche sensitivity improvement (dB)	Absolute sensitivity (dBm)
*400-nm Ge	100	5.8	-23.2
**185-nm Ge	140	6.2	-17.4

*- 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;

Acknowledgement

- IMEC Si photonics Team,
  - Joris Van Campenhout, Peter Verheyen, Geert Hellings, Jeroen De Coster, Guy Lepage, ...

- Photonics Research Group Team

- Intec Design Team,
  - Jochem Verbist, Bart Moeneclaey, Xin Yin (Scott), Johan Bauwelinck,