Advanced Germanium Devices for Optical Interconnects

Srinivasan Ashwyn Srinivasan

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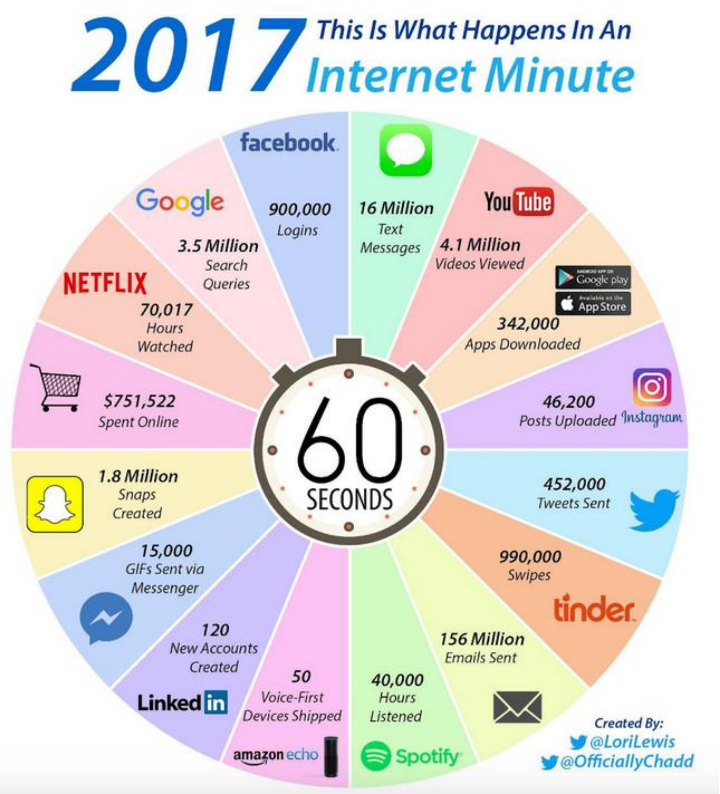
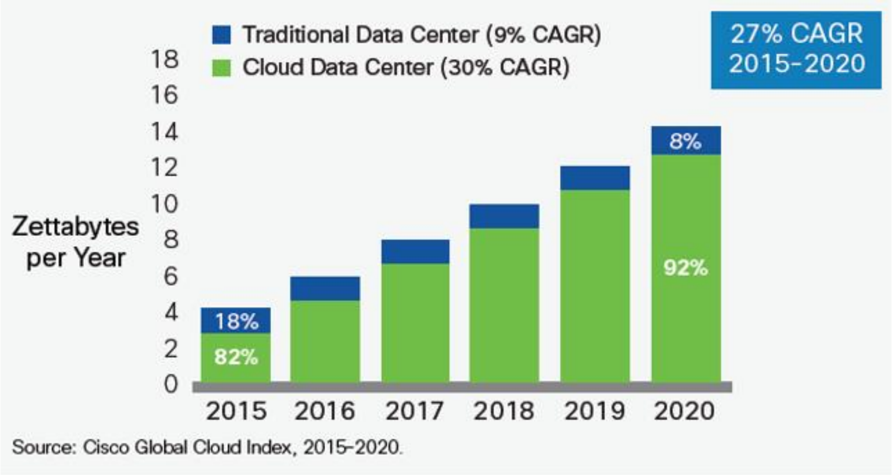
Internet Protocol Traffic





1000 MB	1 Gigabyte
1000 GB	1 Terabyte
1000 TB	1 Petabyte
1000 PB	1 Exabyte
1000 EB	1 Zettabyte

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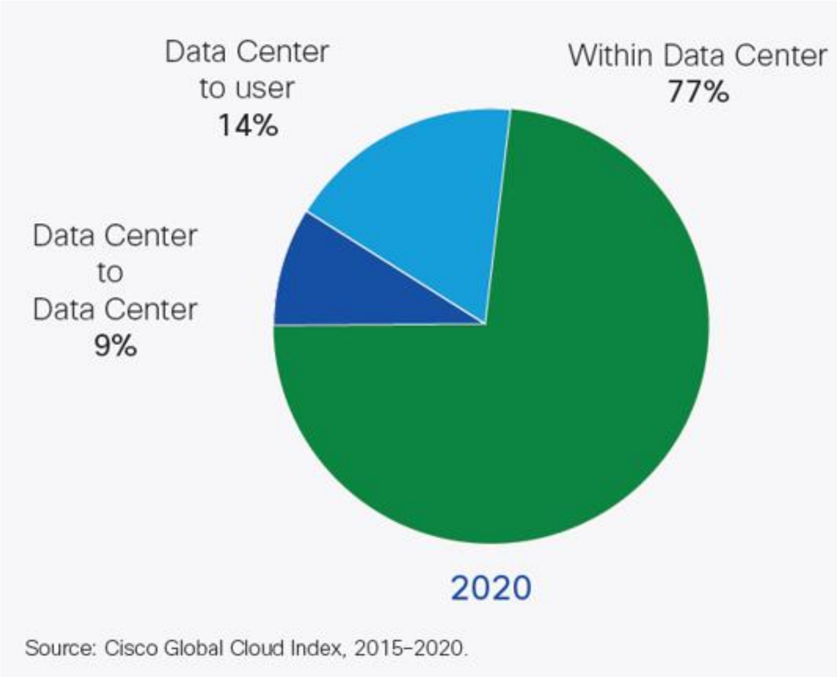
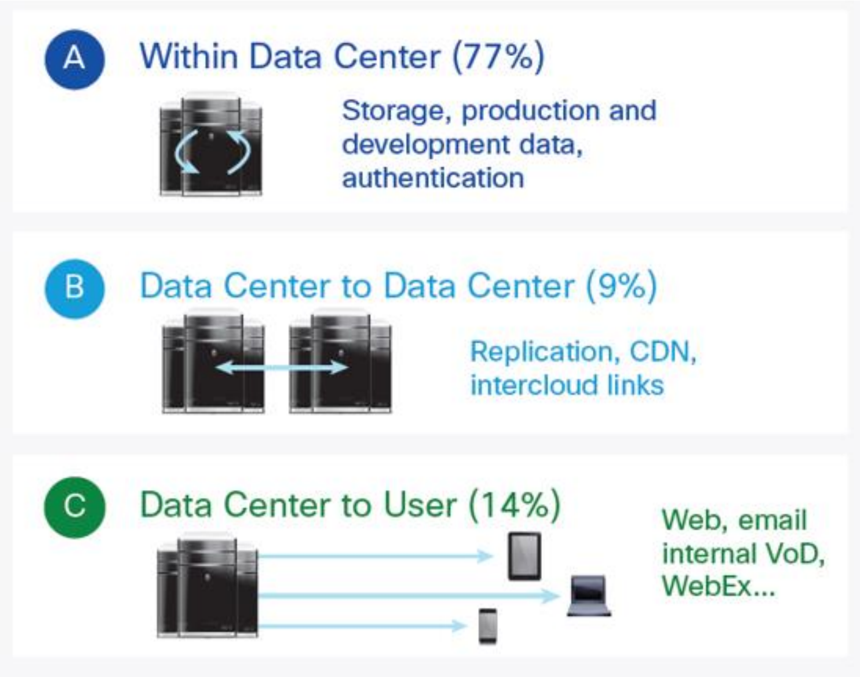
Kachris, C., & Tomkos, I. (2012). A survey on optical interconnects for data centers. *IEEE Communications Surveys & Tutorials*, *14*(4), 1021-1036.

Cisco Global Cloud Index, Forecast and Methodology for 2015-2020, 2016.

INTERNET PROTOCOL TRAFFIC





Cisco Global Cloud Index, Forecast and Methodology for 2015-2020, 2016.

Data Center: Google, Mayes County, Oklahoma, US

150×240 m^2 =
5× Anfield
(Liverpool FC)

CHALLENGES IN THE DESIGN OF THE DATA CENTERS

Speed/ Latency

1. Computation speed
2. Interconnection speed

0.5s delay

Google 20% ↓

0.1s delay

amazon 1% ↓

Asghari, M., & Krishnamoorthy, A. V. (2011). Silicon photonics: Energy-efficient communication. *Nature photonics*, *5*(5), 268.

Challenges in the design of the data centers

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1. Computation speed
2. Interconnection speed

Cost

1. Equipment costs
2. Administering the data centers

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amazon 1% ↓

Krishnamoorthy, A. V., Goossen, K. W., Jan, W., Zheng, X., Ho, R., Li, G., ... & Schwetman, H. (2011). Progress in low-power switched optical interconnects. *IEEE Journal of selected topics in quantum electronics*, *17*(2), 357-376.

Asghari, M., & Krishnamoorthy, A. V. (2011). Silicon photonics: Energy-efficient communication. *Nature photonics*, *5*(5), 268.

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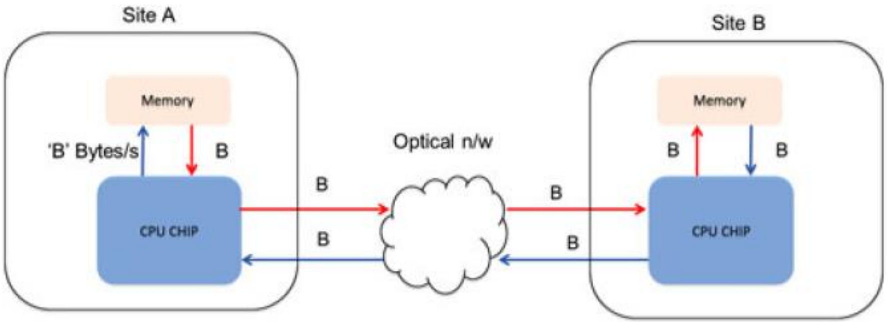
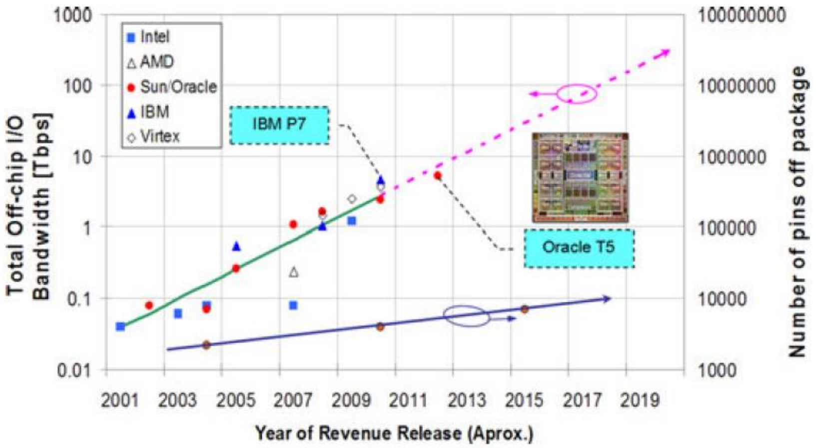
Power Consumption

1. Compute node
2. Data storage node
3. Switch node
4. Heating, ventilation and air conditioning (HVAC)

https://www.independent.co.uk/environment/global-warming-data-centres-to-consume-three-times-as-much-energy-in-next-decade-experts-warn-a6830086.html

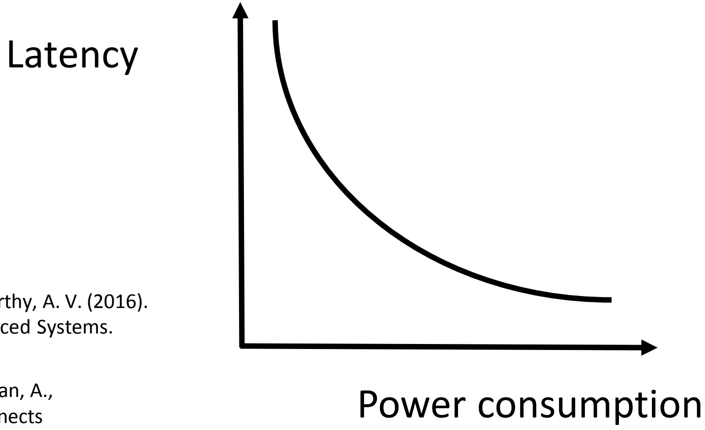
ELECTRICAL INTERCONNECTS





For long distance communication (> 3 m), power consumption is significant due to:

1) Skin effect losses
2) Dielectric losses



Schwetman, H., Patel, A., Robinson, L., Zheng, X., Wood, A., & Krishnamoorthy, A. V. (2016). An Energy-Efficient Optical Interconnect Architecture for Bandwidth-Balanced Systems. *Journal of Lightwave Technology*, *34*(12), 2905-2919.

Krishnamoorthy, A. V., Thacker, H. D., Torudbakken, O., Müller, S., Srinivasan, A., Decker, P. J., ... & Dignum, M. (2017). From Chip to Cloud: Optical Interconnects in Engineered Systems. *Journal of Lightwave Technology*, *35*(15), 3103-3115.

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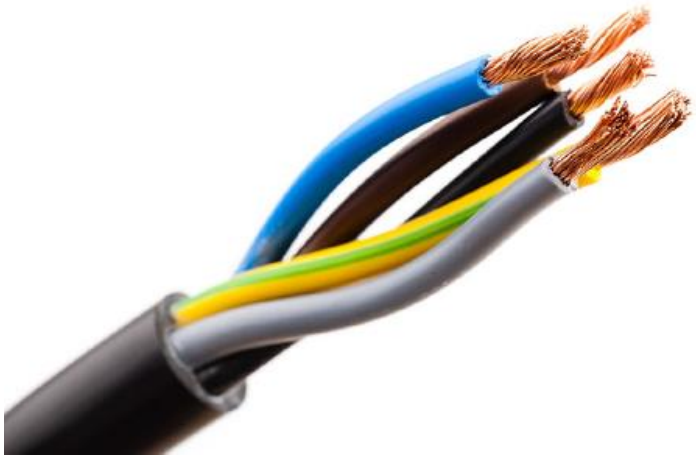
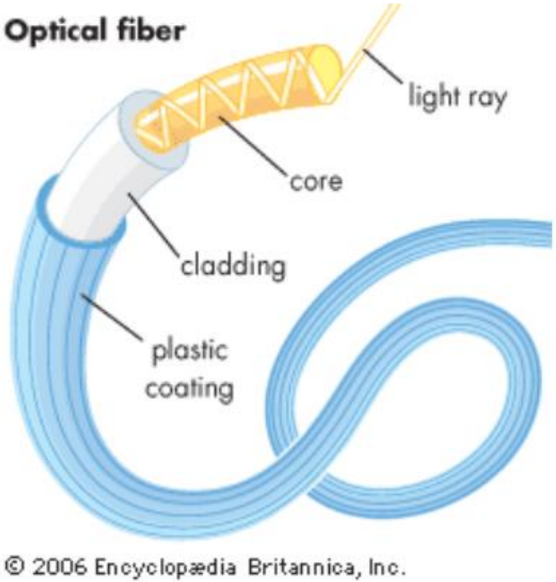
ELECTRICAL → OPTICAL INTERCONNECTS





Requirements for optical interconnects:

High Speed	Low equipment Cost	Low Power Consumption	High Temp operation
100-400 Gbps	<1 $/Gbps	<10 pJ/bit	Large optical bandwidth of individual devices

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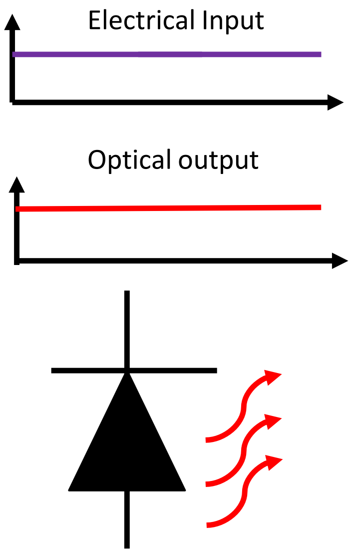
Robert Blum, *Silicon Photonics and the future of optical connectivity in the data center*, ECOC, 2016.

Optical Interconnect

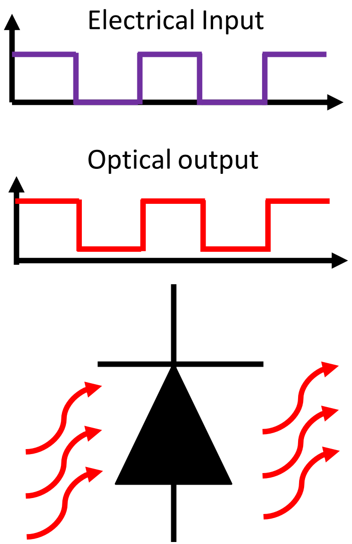
Light, instead of electricity, is used to carry information

Light source



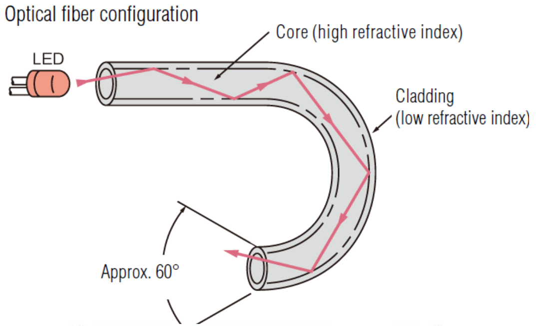
Let there be light!!!

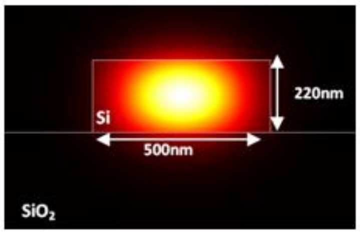
Modulator



Convert electrical signal to optical signal.

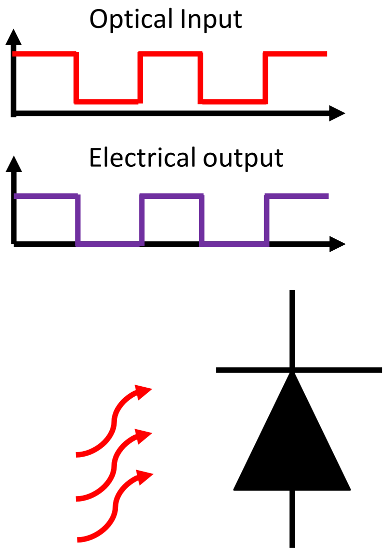
Transport medium





Manipulate light by routing/filtering.
Medium for light propagation

Photodetector



Convert optical signal to electrical signal.

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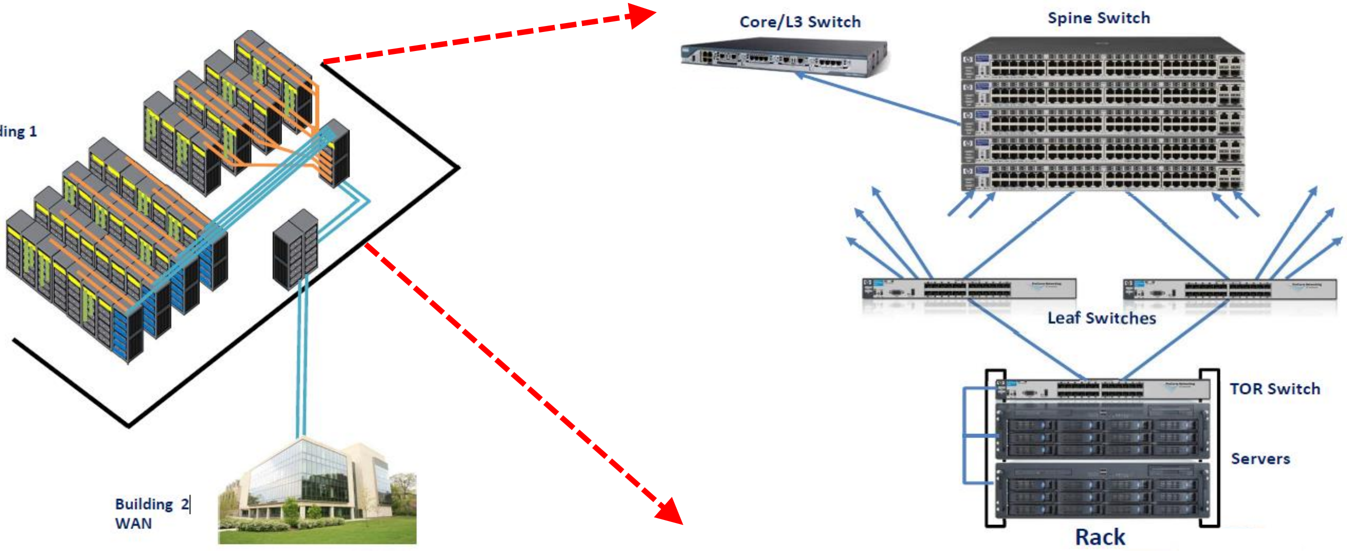
MMF- Multi mode fiber
SMF - Single mode fiber

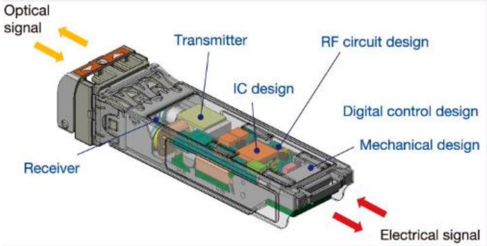
Optical Interconnects in Data Centers



	Server to TOR (<3 m)	TOR to Leaf (3-20 m)	Leaf to Spine (400-2000 m)	Spine to Core (500-2000 m)
Deployed today	10G Cu	40G MMF	40G MMF	40G SMF
Being upgraded	25G Cu	100G SMF	100G SMF	100G SMF
For future	50/100G Cu	400G SMF	400G SMF	400G SMF

Brad Booth and Tom Issenhuth, *Global Networking Services: Objectives to Support Cloud Scale Data Center Design*, 2013.

OPTICAL TRANSCEIVER



Optical transceiver → Optical transmitter and receiver
A component used to transmit-receive optical signals.

100GbE QSFP28
PSM4

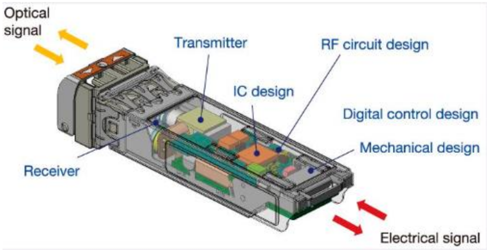
100GbE QSFP28
CWDM4

100GbE QSFP28
PSM4

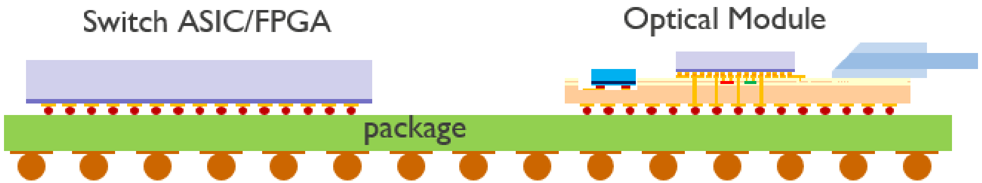
100GbE QSFP28
CWDM4

OPTICAL TRANSCEIVER

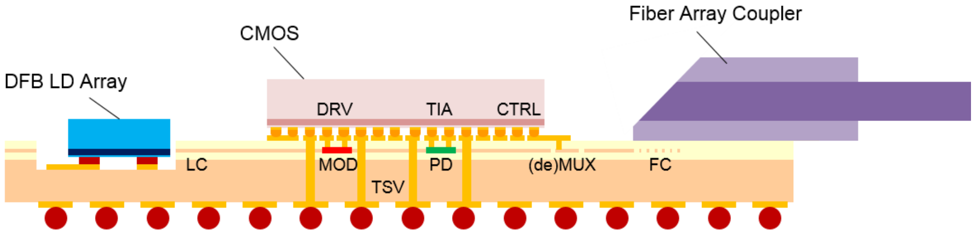
Cartoon



Cross-section



Optical Module



DFB LD Array	Laser array
LC	Light coupler
MOD	Modulator
PD	Photodetector
(de)MUX	(de)Multiplexer
FC	Fiber coupler
TSV	Through Silicon Vias
DRV	Electrical driver
TIA	Transimpedance Amplifier
CTRL	Controller circuit

Light source

Modulator

Transport medium

Photodetector

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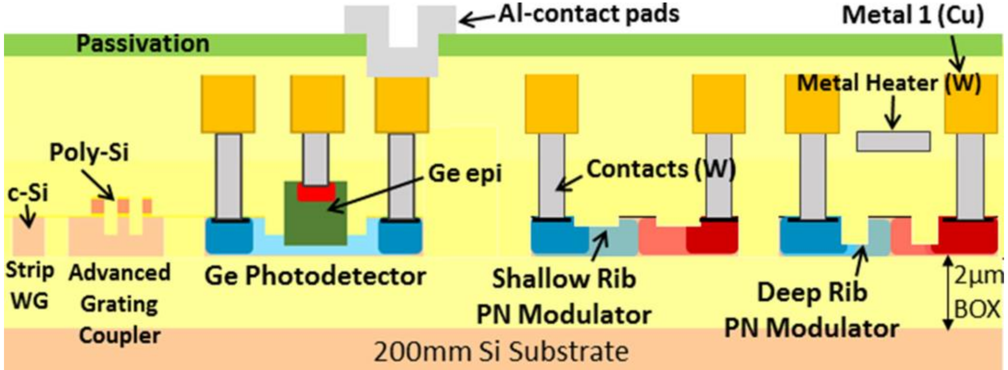
Michal Rakowski, Silicon Photonics Platform for 50G Optical Interconnects, In Photonics Summit and Workshop 2017.

SILICON PHOTONICS

Material platform based on Si to realize optical transceivers



imec's 200mm Silicon photonics platform

Pantouvaki, M., Srinivasan, ... & Absil, P. (2017). *Journal of Lightwave Technology*, *35*(4), 631-638.

Devices	Material	Status
Photodetector	Ge	Yes
Micro Ring modulator (MRR)	Si	Yes
Mach Zehnder Modulator (MZM)	Si	Yes
Grating couplers/ Light coupler/ Fiber couplers	Si	Yes
(de)MUX filters	Si	Yes
Light source (Laser diode)	??	None

Need for monolithically integrated light source!!

GERMANIUM DEVICES FOR OPTICAL INTERCONNECTS

Active medium	Temp (K)	J_{th} (P_{th}) – current density	λ(nm)
III-V Quantum dot	300	< 1 kA/cm^2	1310
P-doped Ge	300	280-510 kA/cm^2	1576-1650

Modulators	Opt. BW	Speed	Power consumption
Si MZM	> 80 nm	22 GHz	750 fJ/bit
Si MRR	< 0.2 nm	47 GHz	12.8 fJ/bit
Ge FKE EAM	~ 30 nm	40 GHz	60 fJ/bit
Ge QCSE EAM	~ 20 nm	23 GHz	16 fJ/bit

Evaluate Ge modulators and Ge Laser Diodes are technologically viable for Optical Interconnect applications while addressing:

1) Power consumption:
   a) <50 fJ/bit for Ge modulator
   b) <10 kA/cm^2 for Ge laser
2) Speed:
   a) ≥50 GHz
3) Operating wavelength:
   a) C and L band
   b) If feasible, O band

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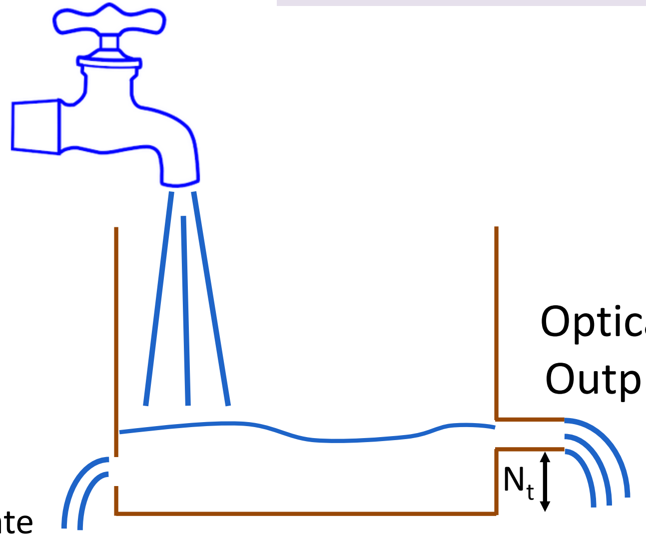
Wirths, S., Geiger, R., Von Den Driesch, ... & Sigg, H. (2015). *Nature photonics*, *9*(2), 88.
Camacho-Aguilera, R. E., et al. Optics Express, 20(10), 11316–20, 2012.
Bao, S., Kim, D., ... & Wang, H. (2017). *Nature communications*, *8*(1), 1845.
O. Chaisakul, (2013). *Science and Technology of advanced materials*, 15(1):014601.
Pantouvaki, M., Srinivasan, ... & Absil, P. (2017). *Journal of Lightwave Technology*, *35*(4), 631-638.
Feng, D.,... & Asghari, M. (2013). *IEEE Journal of Selected Topics in Quantum Electronics*, *19*(6), 64-73.

Light emission from Direct bandgap material

Longer lifetime → Increased light emission

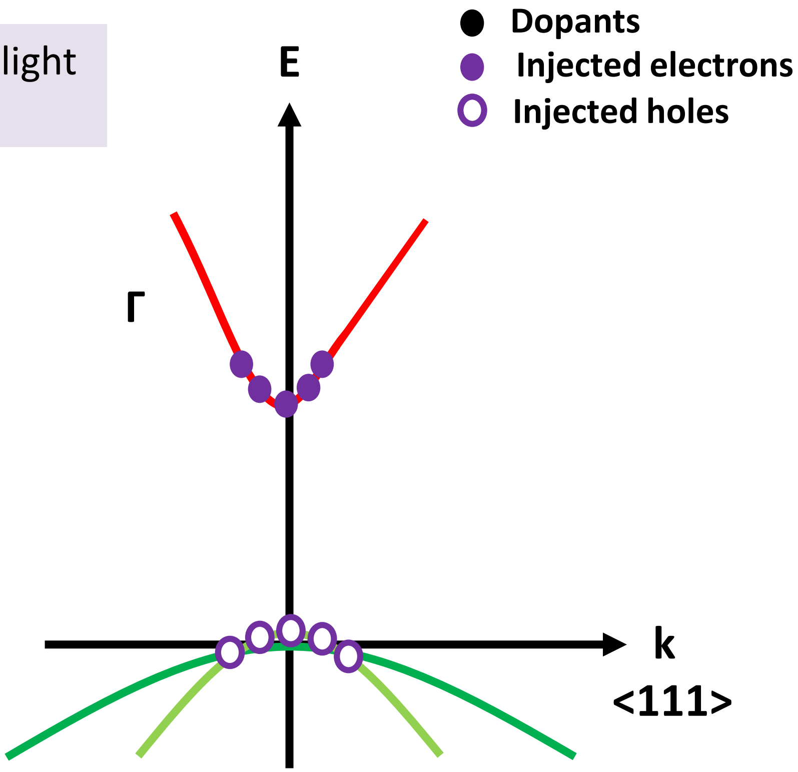
Electrical Input



Optical Output

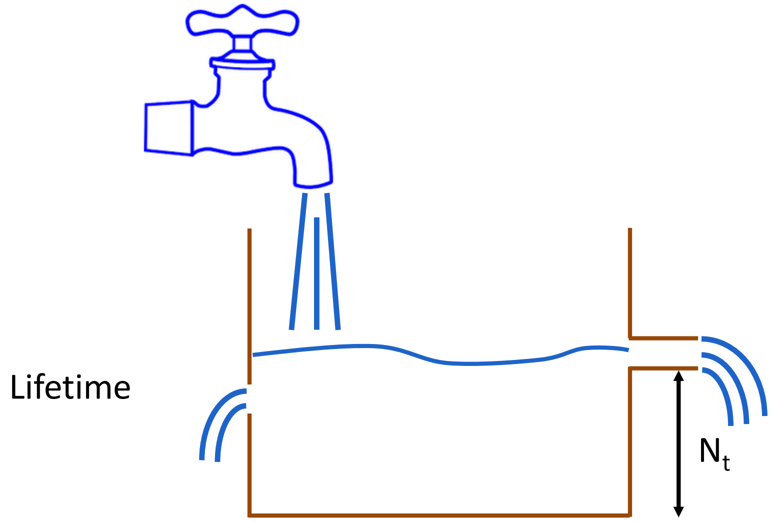
Spontaneous + Nonradiative recombination rate
➔ Lifetime

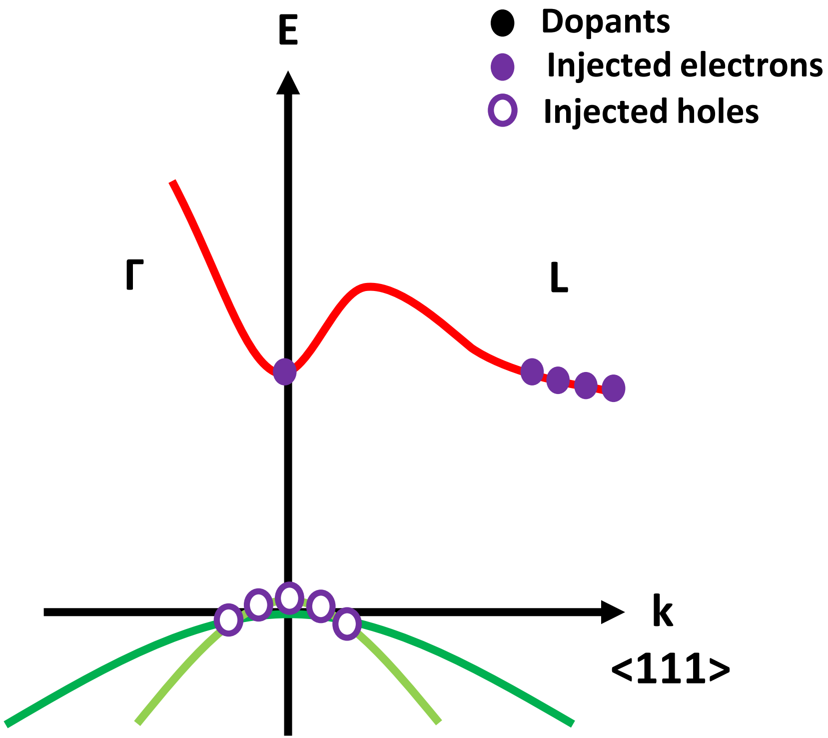
Water bucket analogy



Ideal direct bandgap material

LIGHT EMISSION EFFICIENCY FROM UNDOPED GE



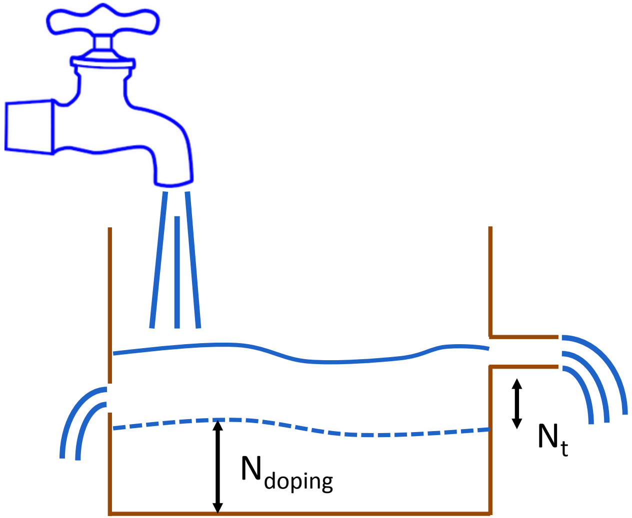


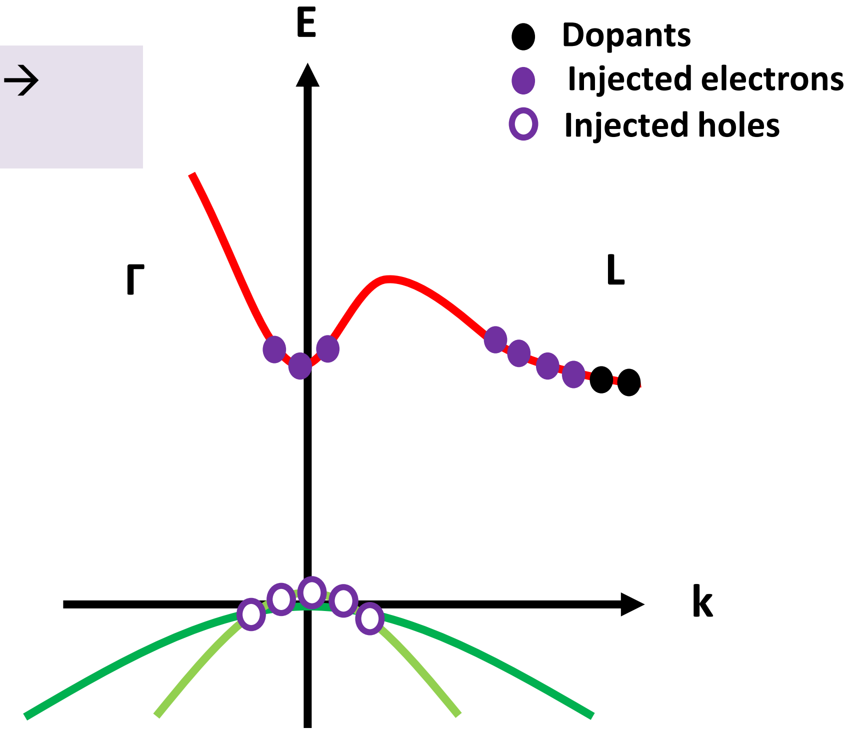
Undoped and unstrained Ge

LIGHT EMISSION EFFICIENCY FROM DOPED GE

High doping, longer lifetime →
Increased light emission

Lifetime

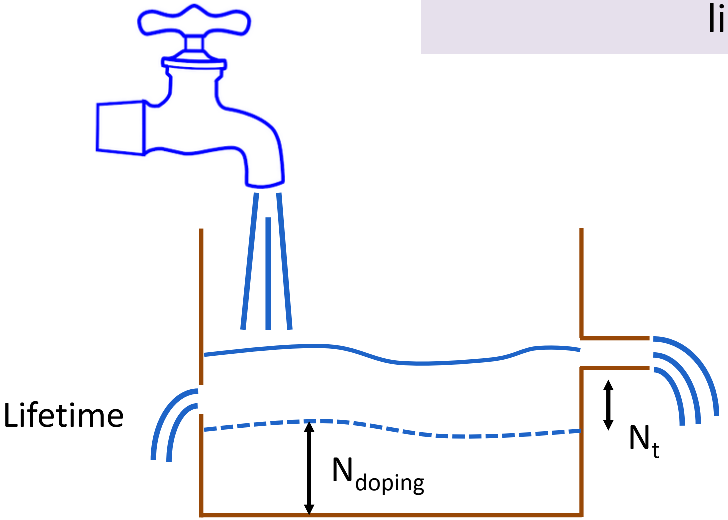


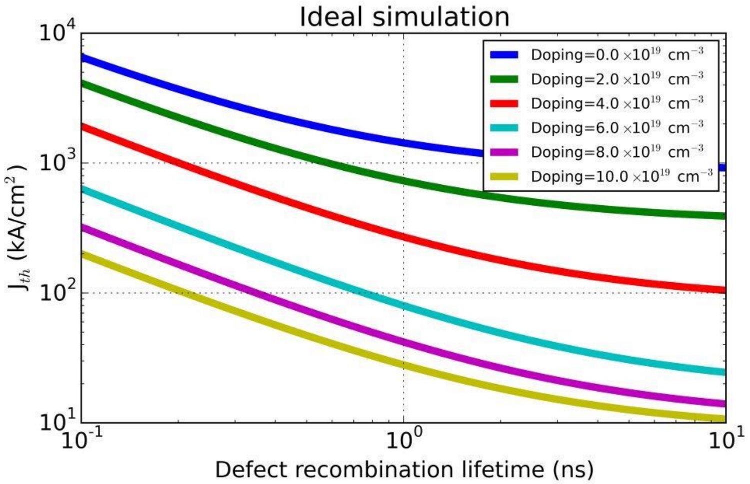


0.2 % biaxially strained and n-type doped Ge

GE LASER: REQUIREMENTS

High doping, longer lifetime → Increased light emission





Design target for $J_{th} < 10$ kA/cm^2:

1. Lifetime > 10 ns.
2. Doping level as high as 1×10^{20} cm^{-3}.

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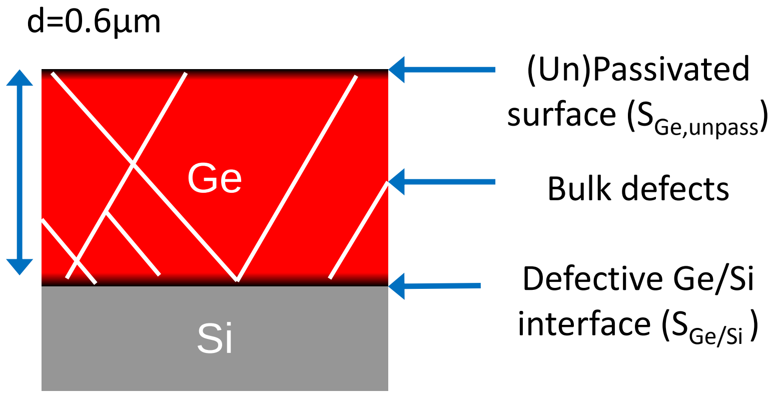
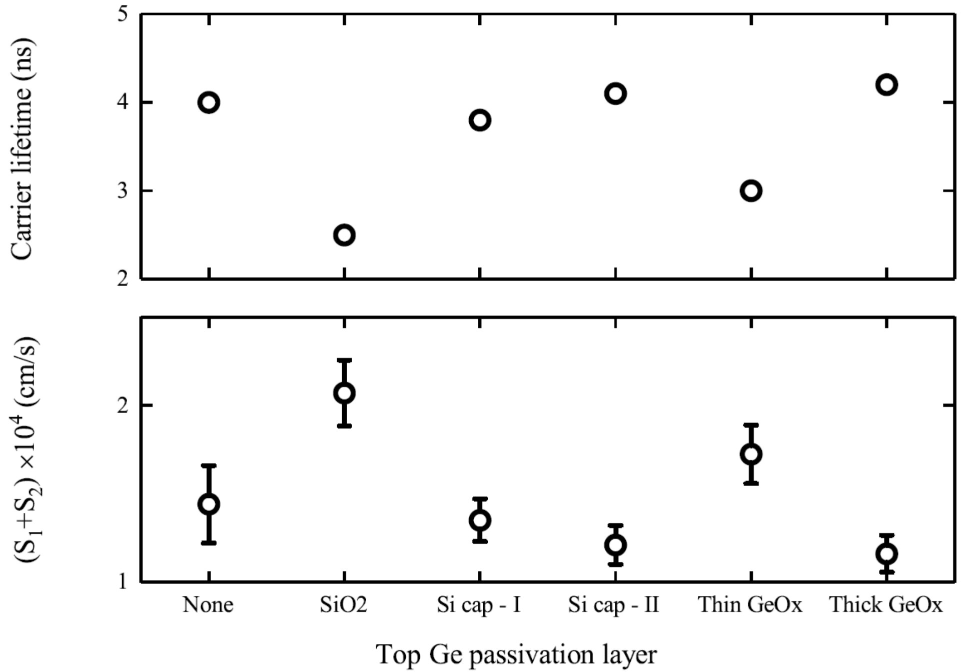
CARRIER LIFETIME IN UNDOPED GE





$$\frac{1}{\tau_{carrier}} = \frac{1}{\tau_{Bulk}} + \frac{S_{Ge,unpass} + SGe_{/Si}}{d}$$

- SiO_2 passivation layer → lowest lifetime
- Si cap or Thick GeOx → longest carrier lifetime of 4.3 ns.
- Measured lifetime < targeted 10 ns.

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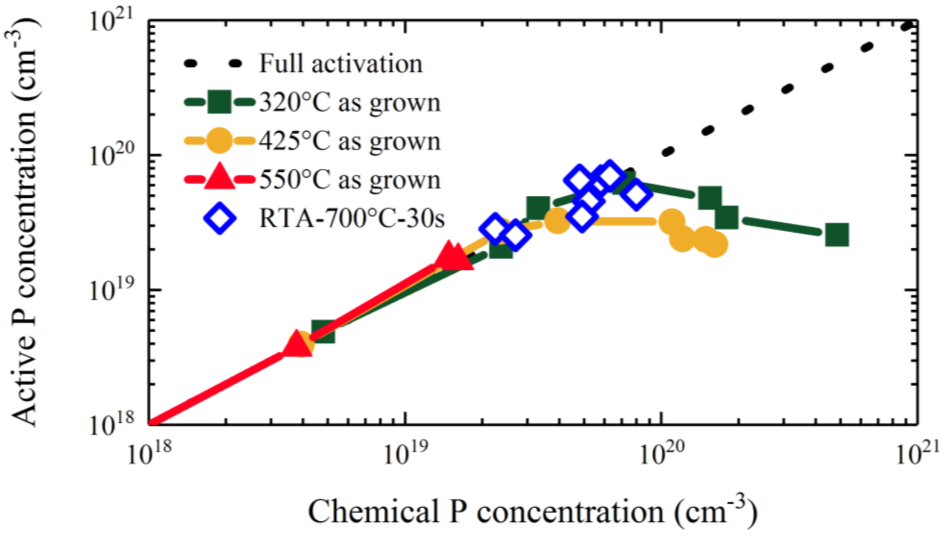
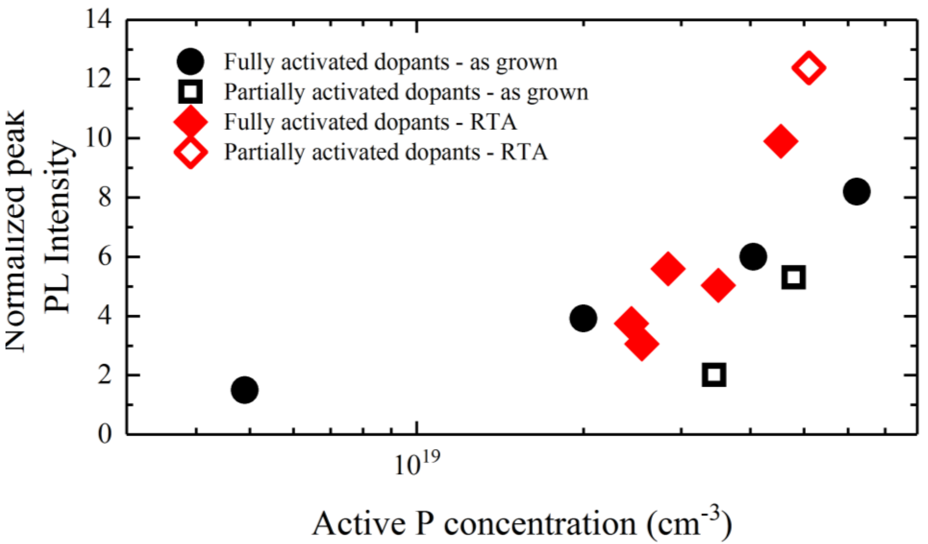
P-doped Ge on 1 μm Ge Virtual Substrate





Highest active P concentration:

- As grown → 6.2×10^{19} cm^{-3}
- Rapid thermal annealed → 5.9×10^{19} cm^{-3}

Less than targeted 1×10^{20} cm^{-3}

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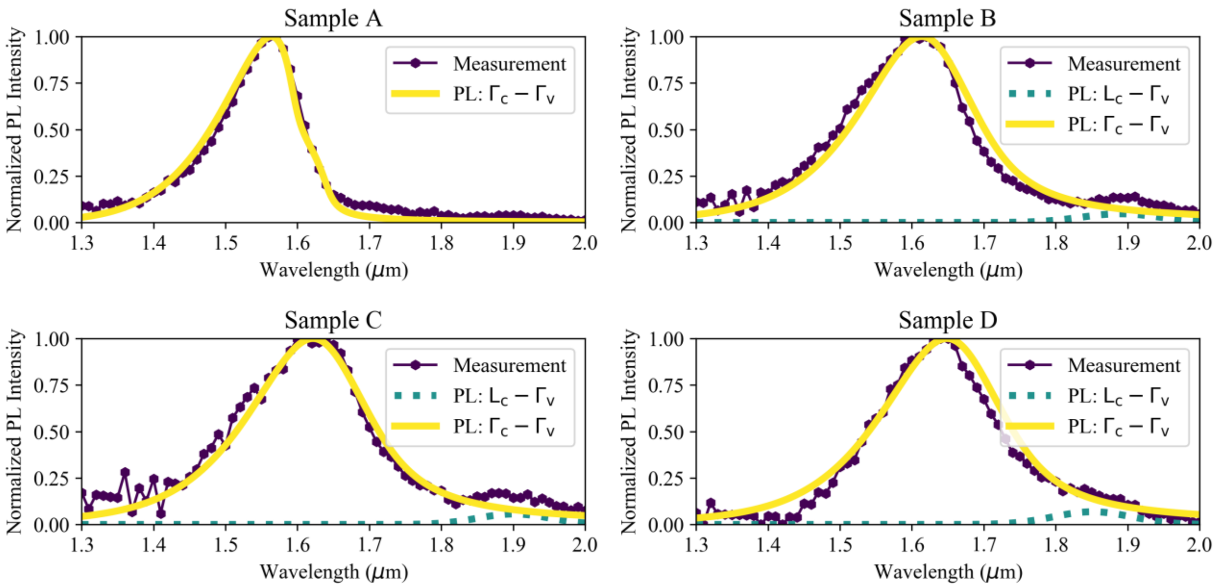
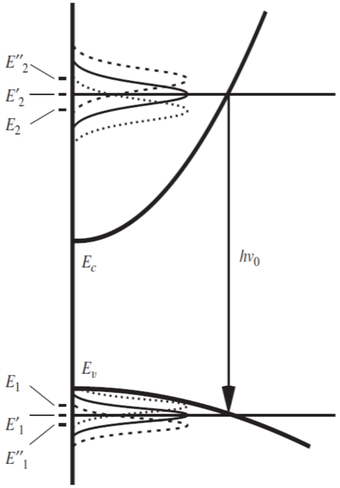
Shimura, Y., Srinivasan, S. A., Van Thourhout, D., Van Deun, R., Pantouvaki, M., Van Campenhout, J., & Loo, R. (2016). Enhanced active P doping by using high order Ge precursors leading to intense photoluminescence. *Thin Solid Films*, *602*, 56-59.

CARRIER SCATTERING STUDY: PL SPECTROSCOPY



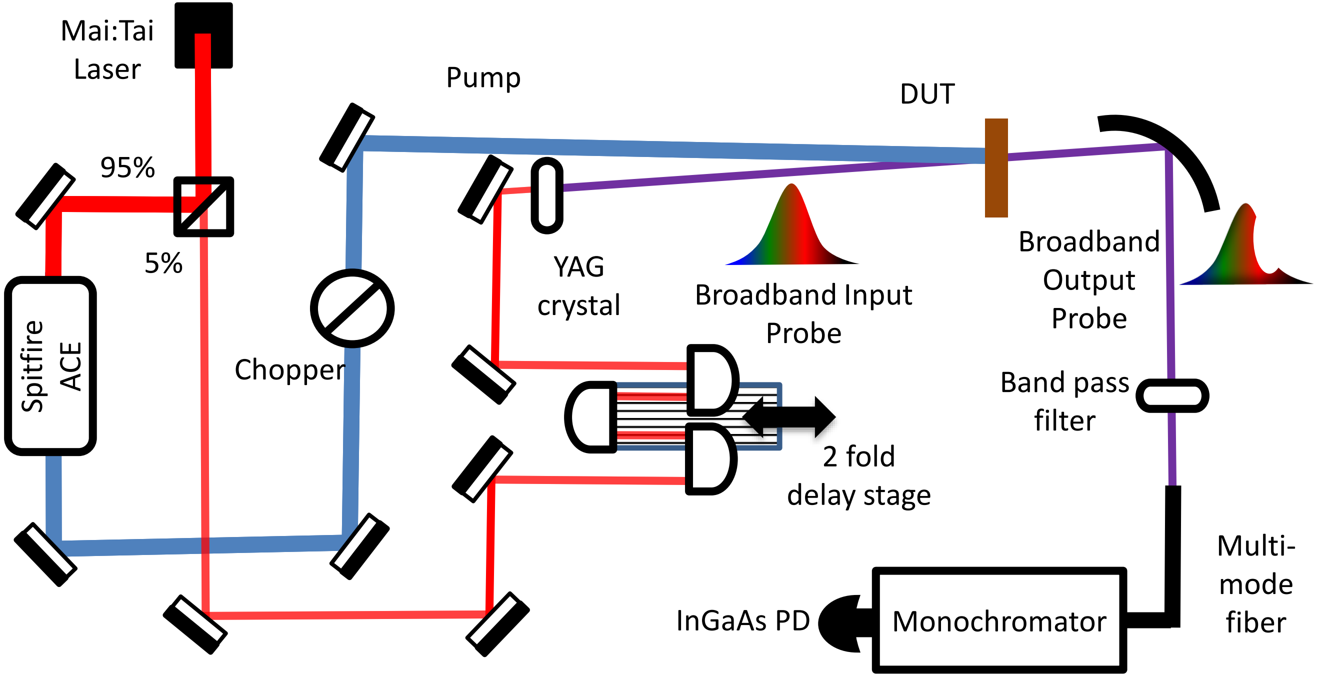


Name	Active P (cm^{-3})	Γ_{opt}
Sample A	0.0×10^{19}	8 meV
Sample B	2.65×10^{19}	47.5 meV
Sample C	4.5×10^{19}	50 meV
Sample D	5.35×10^{19}	45 meV

Carrier scattering induced broadening → broadened PL spectrum → caused by dopants

Srinivasan, S. A., Porret, C., Pantouvaki, M., Shimura, Y., Geiregat, P., Loo, R., ... & Van Thourhout, D. (2017). Analysis of homogeneous broadening in n-type doped Ge layers on Si for laser application. In *30th Annual Conference of the IEEE Photonics Society (IPC)* (pp. 311-312).

Transient absorption spectroscopy (TAS)

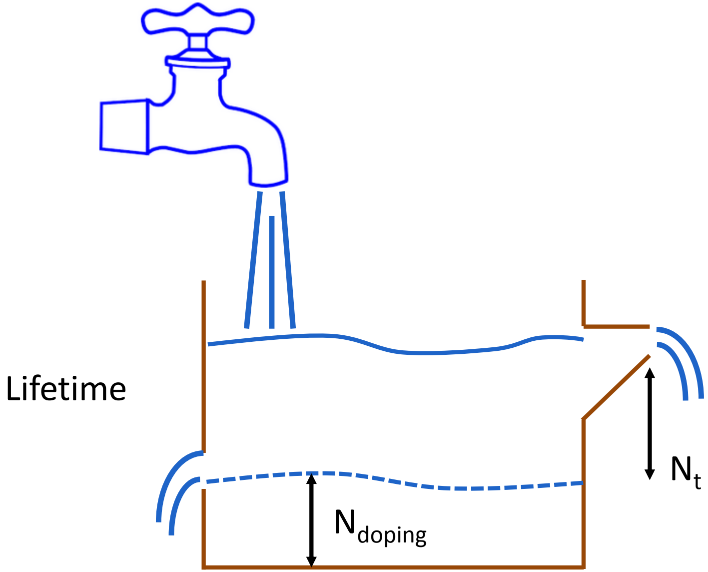


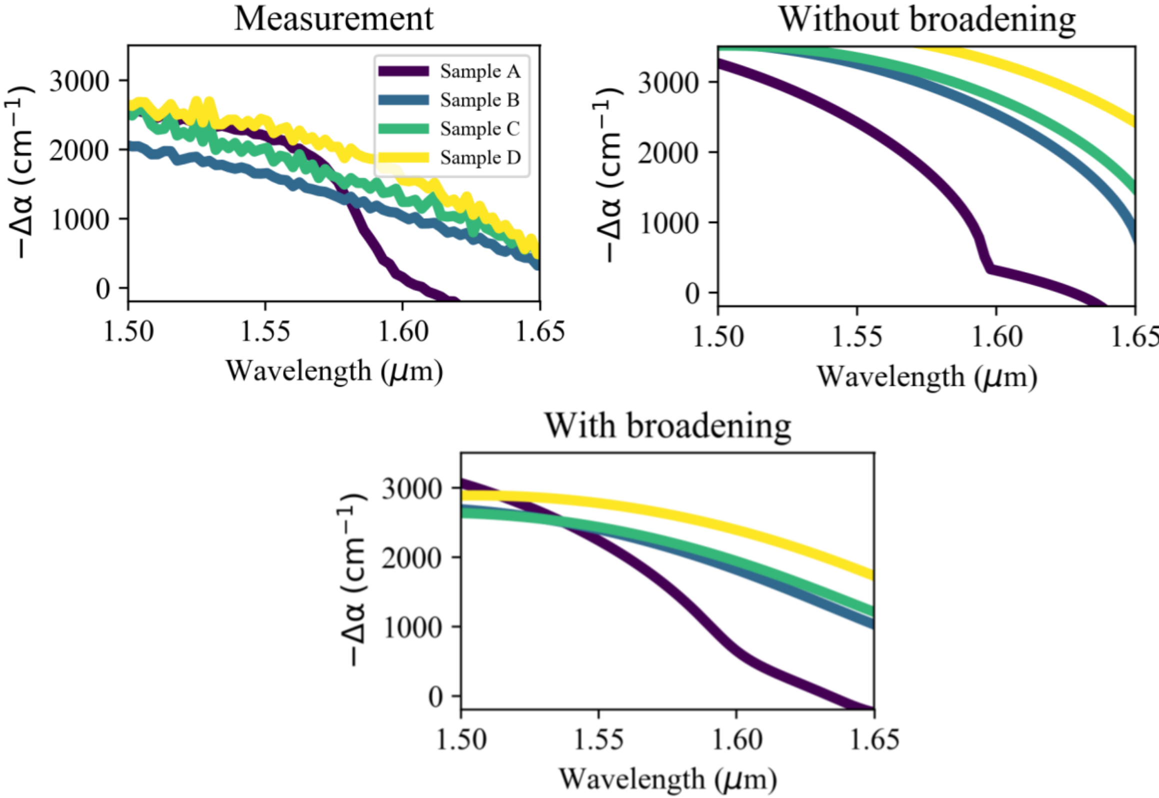
Experiment Condition	Value
Pump wavelength	≈ 1.3 µm
Ave Pump Intensity	28-140 mW/cm^2
Probe Wavelength	1.5-1.7 µm
$N_{ex,Pump}$	(1.5-8)×10^{18} cm^{-3}

- The measurement is performed in transmission mode.
- Change in absorption coefficient of the probe beam as a function of time is tracked.

S. A. Srinivasan, et al., IEEE GFP, (2017).

Carrier scattering study: Transient Absorption Spectroscopy

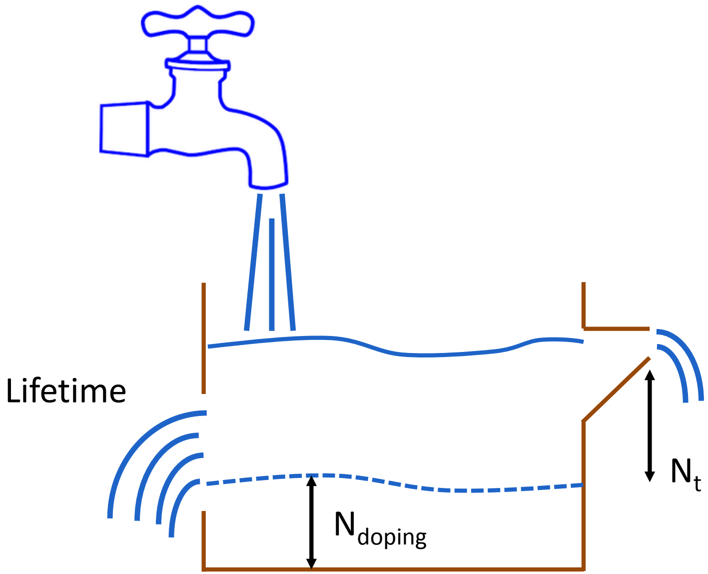


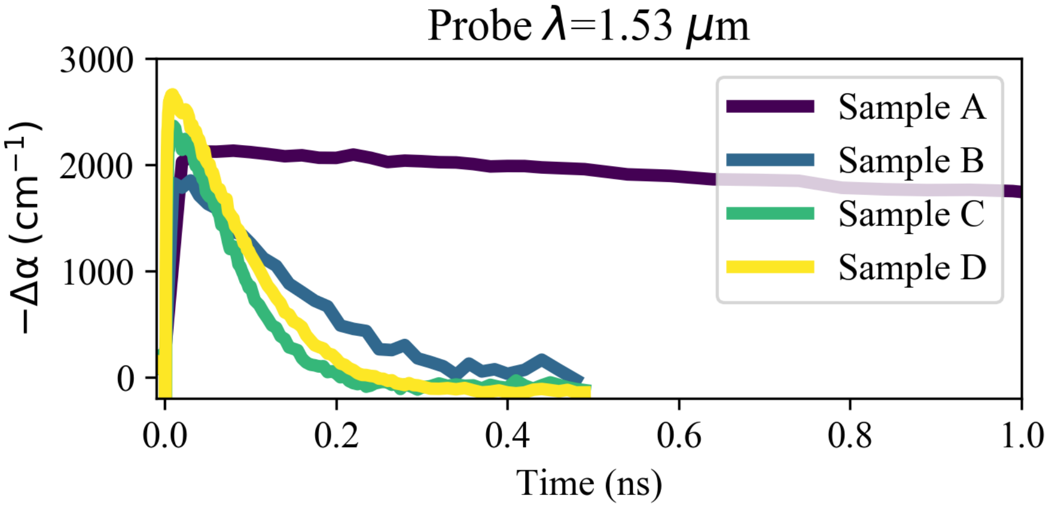


Carrier scattering induced broadening → suppressed and broadened OBE spectrum → caused by dopants.

S. A. Srinivasan, et al., IEEE GFP, (2017).

Carrier scattering study: Transient Absorption Spectroscopy





Lifetime in undoped Ge → 3-4 ns
Lifetime in doped Ge → < 0.3 ns

Reduced lifetime due to dopants.

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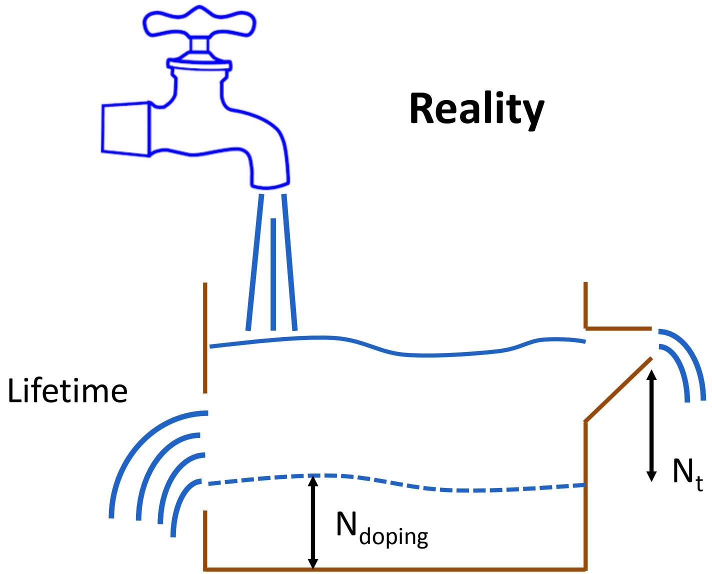
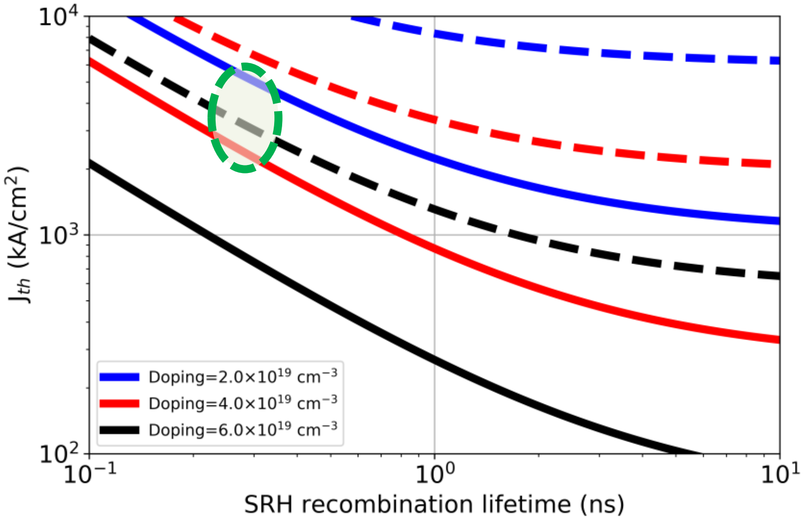
S. A. Srinivasan, et al., IEEE Photonics Conference, (2017).

GE LASER: CONCLUSION



Possible operating regime



Solid line → with no linewidth broadening.
Dotted line → with linewidth broadening Γ_{opt} = 45 meV.

Difficult to demonstrate an energy efficient P-doped Ge laser for optical interconnect applications.

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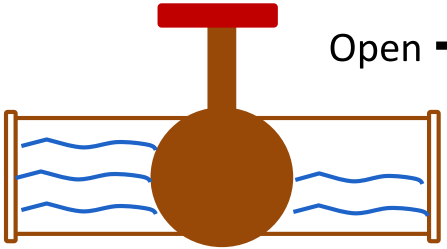
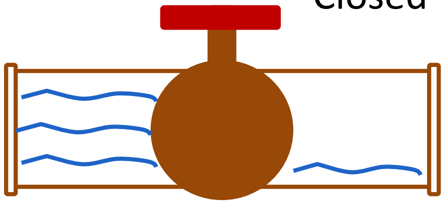
Electro-Absorption Modulator (EAM)

Pipe and valve analogy





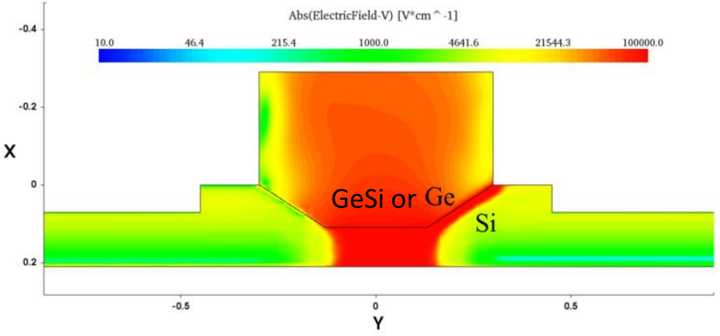
Ideal scenario:
Open → no loss
Closed → ∞ loss

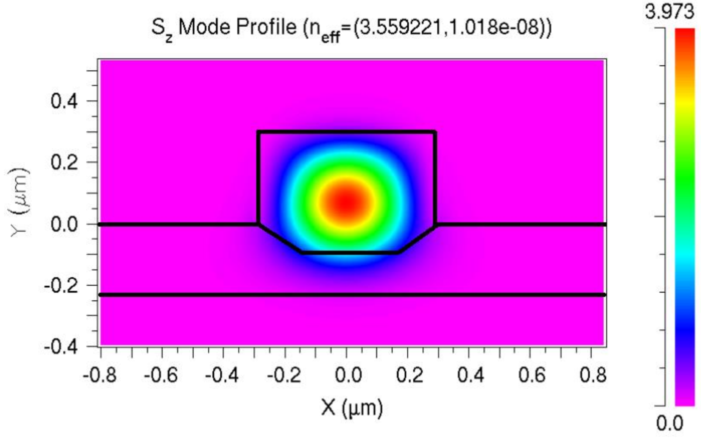
Reality:
Open → Insertion loss (IL)
Closed → Extinction Ratio (ER)

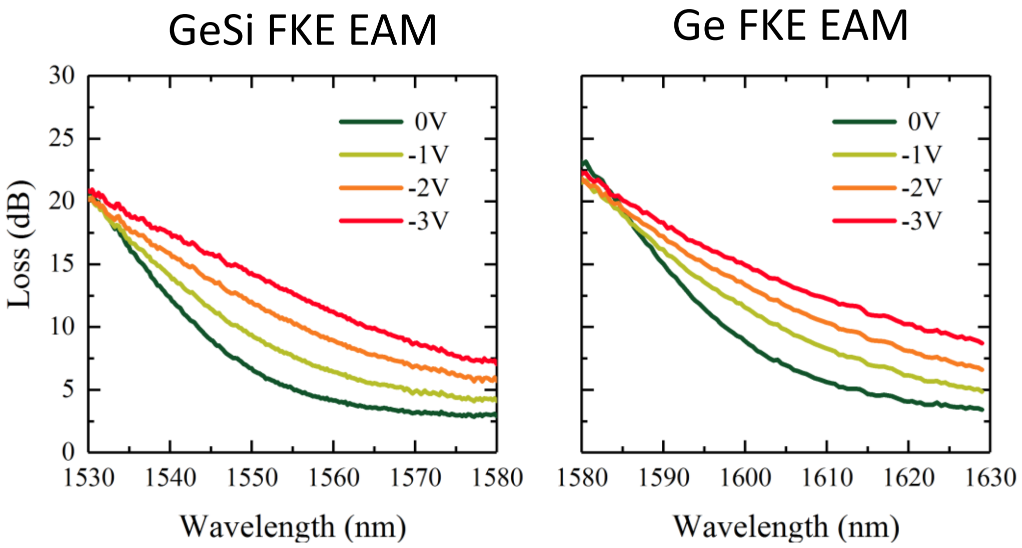
Factors determining the performance of a modulator:

FOM = ER/IL	Switching speed	Power Consumption	Operating wavelength
∞	> 40 GHz	< 60 fJ/bit	1530-1570 nm

GeSi Franz-Keldysh effect EAM: Static Performance - I







Electrical voltage modulates the intensity of light at the output of the waveguide.

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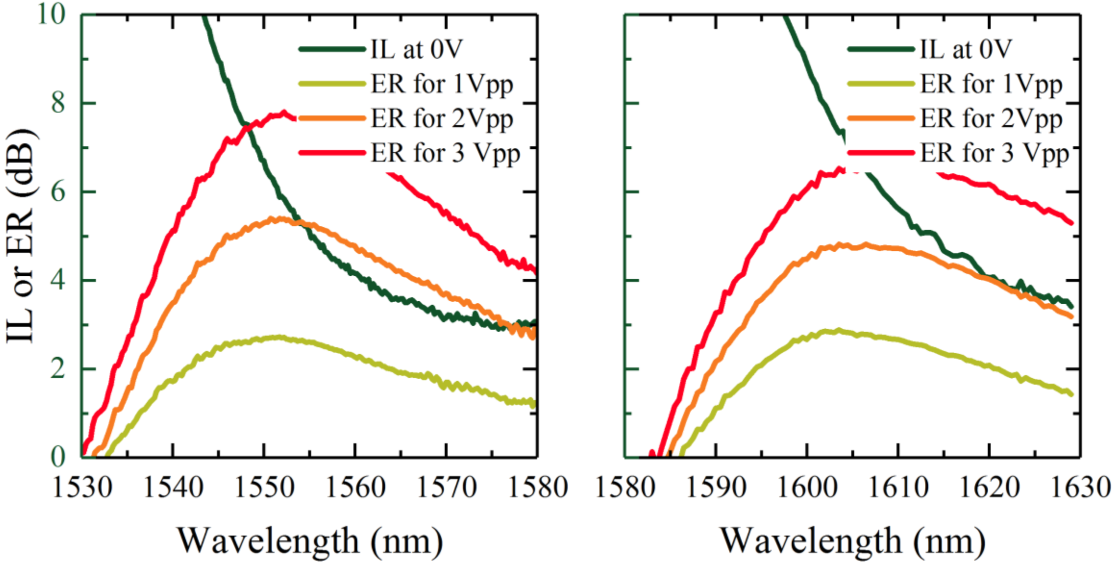
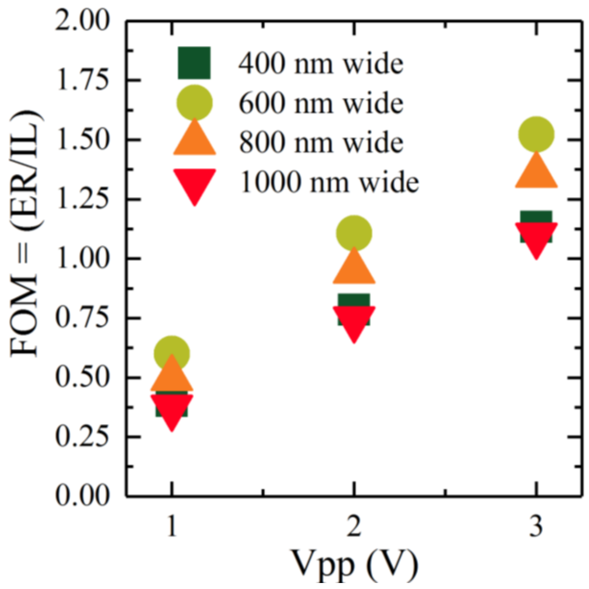
GeSi Franz-Keldysh effect EAM: Static Performance - II

GeSi FKE EAM

Ge FKE EAM





Low FOM due to indirect bandgap material.

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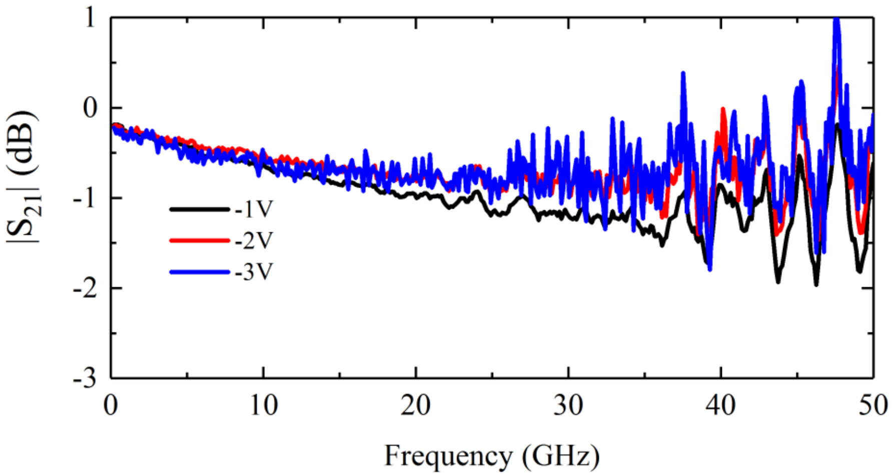
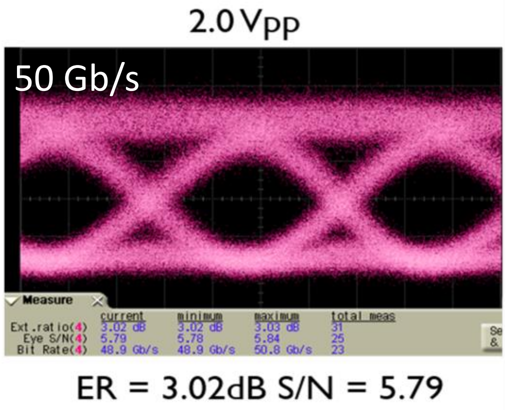
Srinivasan, S. A., Pantouvaki, M., Gupta, S., Chen, H. T., Verheyen, P., Lepage, G., ... & Van Campenhout, J. (2016). *Journal of Lightwave Technology*, *34*(2), 419-424.

Srinivasan, S. A., Verheyen, P., Loo, R., De Wolf, I., Pantouvaki, M., Lepage, G., ... & Van Campenhout, J. (2016, March). In *Optical Fiber Communications Conference and Exhibition (OFC), 2016* (pp. 1-3). IEEE.

GeSi Franz-Keldysh effect EAM: Dynamic performance

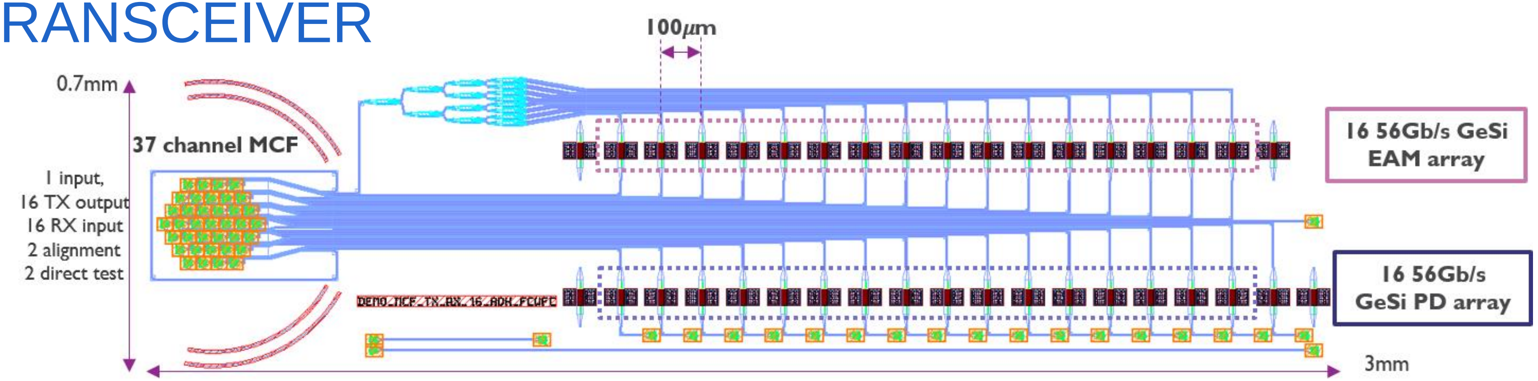




Enables 50 Gb/s NRZ-OOK modulation due to compact geometry and low junction capacitance. Power consumption 29 fJ/bit.

Srinivasan, S. A., Pantouvaki, M., Gupta, S., Chen, H. T., Verheyen, P., Lepage, G., ... & Van Campenhout, J. (2016). *Journal of Lightwave Technology*, *34*(2), 419-424.

Demonstrators using GeSi EAM: 896 Gb/s Transceiver



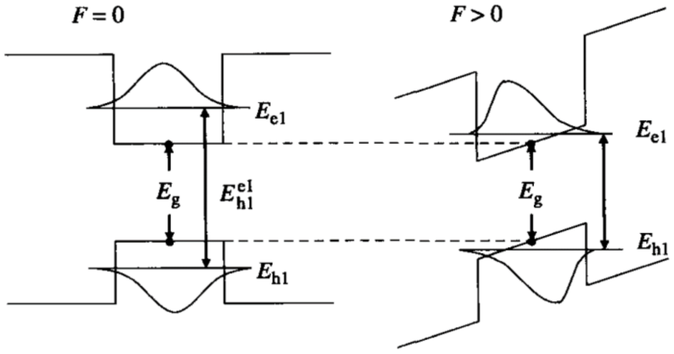
GeSi EAM array

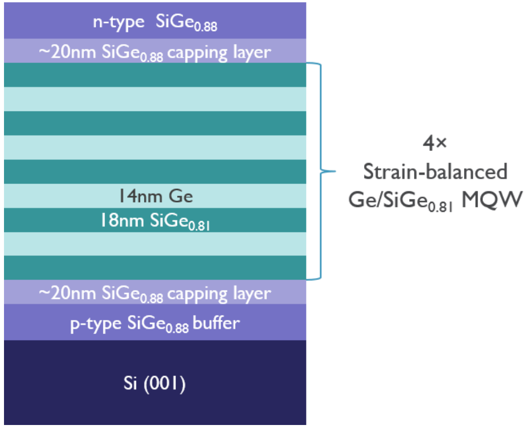
GeSi PD array

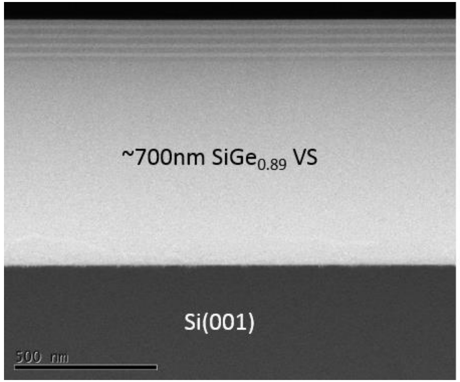
De Heyn, P., Kopp, V. I., Srinivasan, S. A., Verheyen, P., Park, J., Wlodawski, M. S., ... & Lepage, G. (2017, March). Ultra-dense 16× 56Gb/s NRZ GeSi EAM-PD arrays coupled to multicore fiber for short-reach 896Gb/s optical links. In *Optical Fiber Communications Conference and Exhibition (OFC), 2017* (pp. 1-3). IEEE.

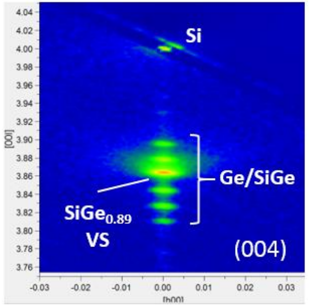
GeSi Quantum Confined Stark Effect EAM

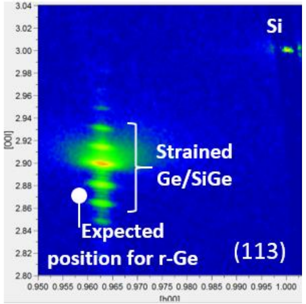
To boost the FOM of GeSi FKE EAM → GeSi QCSE EAM.



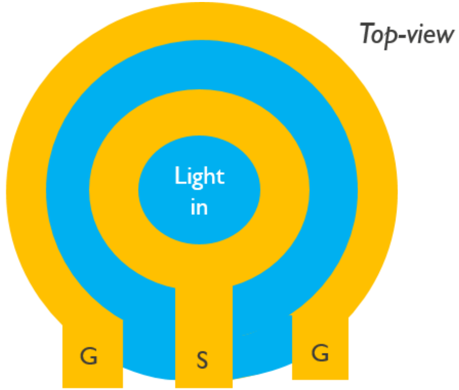


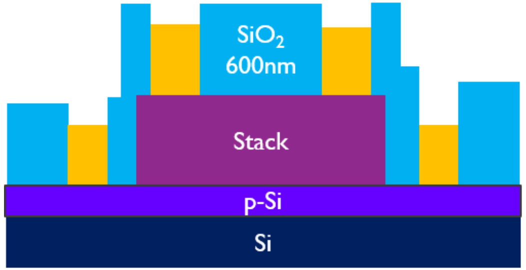




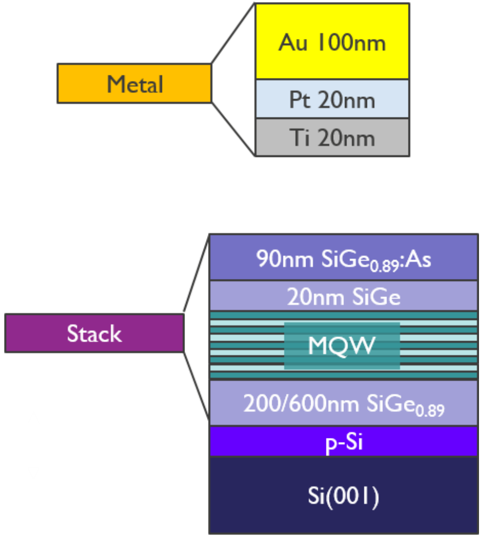


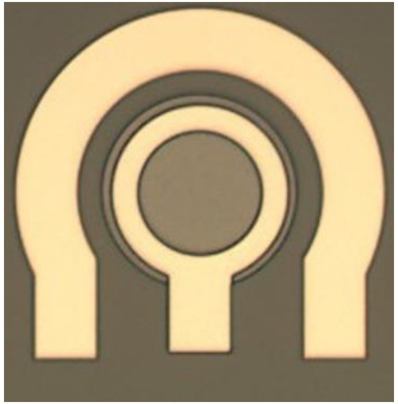
GeSi Quantum Confined Stark Effect EAM

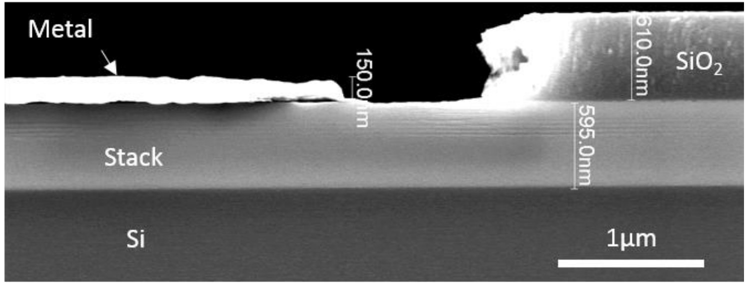




Device cross-section







S. A. Srinivasan, C. Porret, E. Vissers, P. Geiregat, D. Van Thourhout, R. Loo, M. Pantouvaki, J. Van Campenhout, ``High-contrast quantum-confined Stark effect in Ge/SiGe quantum well stacks on Si with ultra-thin buffer layers,” submitted to *CLEO Racific Rim*, Hong Kong, 2018.

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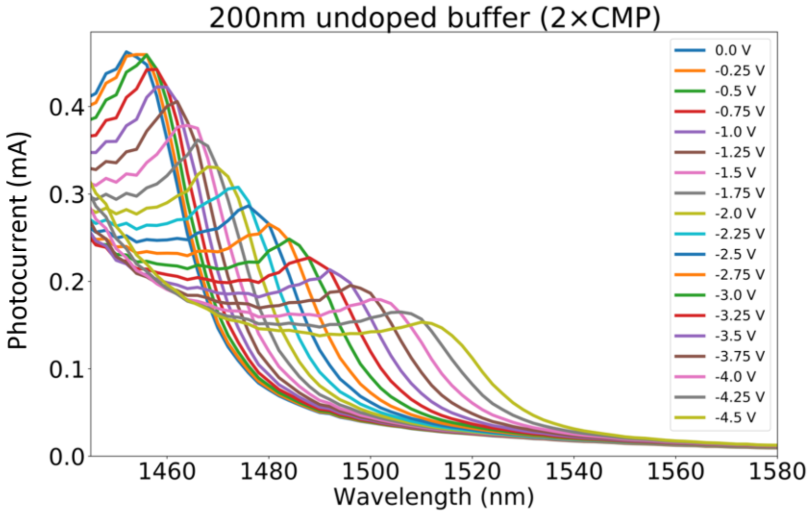
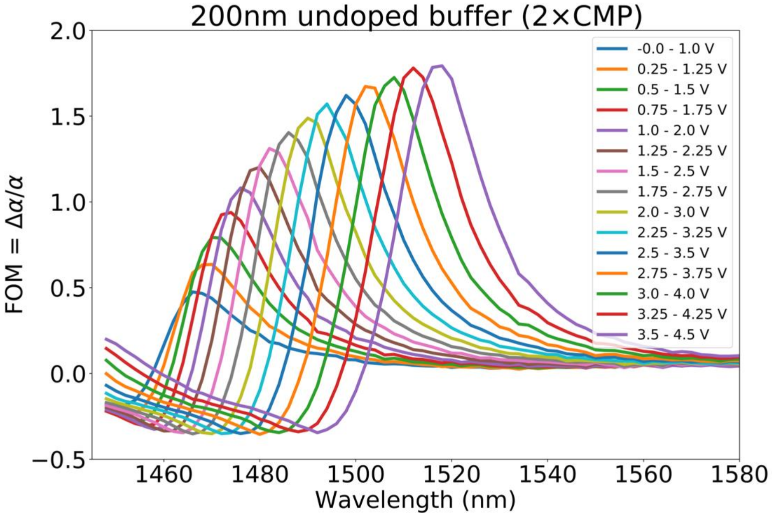
GeSi Quantum Confined Stark Effect EAM





FOM ($\Delta\alpha/\alpha$) ≈ 1.75 for 1 V swing → > 2× better than Ge FKE EAM.

Future perspectives:

1. Demonstrate waveguide integrated device → reevaluate FOM.
2. Demonstrate demonstrating at speeds >50 GHz.

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S. A. Srinivasan, C. Porret, E. Vissers, P. Geiregat, D. Van Thourhout, R. Loo, M. Pantouvaki, J. Van Campenhout, ``High-contrast quantum-confined Stark effect in Ge/SiGe quantum well stacks on Si with ultra-thin buffer layers," submitted to *CLEO Racific Rim*, Hong Kong, 2018.

Conclusion: Advanced Ge Devices for Optical Interconnects

- *P-doped Ge laser on Si* → Difficult to achieve energy efficient laser due to:

	Carrier Lifetime	Doping Level	Linewidth Broadening	J_{th} (kA/cm^2)
Target	> 10 ns	1×10^{20} cm^{-3}	< 10 meV	< 10
Reality	< 0.3 ns	5.35×10^{19} cm^{-3}	≥ 45 meV	> 1000

- *Ge based electro absorption modulator:*

Modulators	FOM ($\Delta\alpha/\alpha$)	Opt. BW	Speed	Power
Si MZM	0.47 for 2.5 Vpp	>80 nm	22 GHz	750 fJ/bit
Si MRR	0.72 for 1.5 Vpp	<0.2 nm	47 GHz	12.8 fJ/bit
Ge FKE EAM	1.2 for 3 Vpp	~ 30 nm	40 GHz	60 fJ/bit
Ge QCSE EAM	1.46 for 5 Vpp	~ 30nm	23 GHz	16 fJ/bit
GeSi FKE EAM (This work)	0.93 for 2 Vpp	~ 30 nm	>50 GHz	29 fJ/bit
Ge QCSE EAM (This work)	1.75 for 1 Vpp	~ 20nm	??	??

Pantouvaki, M., Srinivasan, ... & Absil, P. (2017). *Journal of Lightwave Technology*, *35*(4), 631-638.

O. Chaisakul, (2013). *Science and Technology of advanced materials*, 15(1):014601.

Feng, D.,... & Asghari, M. (2013). *IEEE Journal of Selected Topics in Quantum Electronics*, *19*(6), 64-73.

Acknowledgements

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C. Porret, Y. Shimura, G. Lepage, P. Verheyen, Y. Ban, P. De Heyn, E. Vissers, P. Absil, D. Cott, R. Loo, A. Prabhulinga, R. Paul, S. Anand, B. Snyder, N. Mangal, C. Alessandri, I. Kulkova, S. Balakrishnan, S. Lardenois, J. De Coster, S. Jansen, I. De Wolf.....

J. Verbist, B. Kuyken, U. Dave, R. Van Laer, A. Malik, Y. Zhu, Y. Shi, B. Tian, Z. Wang, P. Geiregat.......


Q&A

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