ADVANCED GERMANIUM DEVICES FOR OPTICAL INTERCONNECTS

Srinivasan Ashwyn Srinivasan
INTERNET PROTOCOL TRAFFIC

2017 This Is What Happens In An Internet Minute

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


INTERNET PROTOCOL TRAFFIC

Data Center to user 14%
Data Center to Data Center 9%
Within Data Center 77%

Source: Cisco Global Cloud Index, 2015-2020.

A Within Data Center (77%)
Storage, production and development data, authentication

B Data Center to Data Center (9%)
Replication, CDN, intercloud links

C Data Center to User (14%)
Web, email internal VoD, WebEx...
DATA CENTER: GOOGLE, MAYES COUNTY, OKLAHOMA, US

150×240 m² = 5× Anfield (Liverpool FC)
CHALLENGES IN THE DESIGN OF THE DATA CENTERS

1. Computation speed
2. Interconnection speed

CHALLENGES IN THE DESIGN OF THE DATA CENTERS

1. Computation speed
2. Interconnection speed

1. Equipment costs
2. Administering the data centers

0.5s delay
Google 20% ↓

0.1s delay
amazon 1% ↓


## Challenges in the Design of the Data Centers

<table>
<thead>
<tr>
<th>Speed/Latency</th>
<th>Cost</th>
<th>Power Consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>2. Interconnection speed</td>
<td>2. Administering the data centers</td>
<td>2. Data storage node</td>
</tr>
</tbody>
</table>

### Equipment Costs

1. Heating, ventilation and air conditioning (HVAC)

### Administering the Data Centers

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

### Speed/Latency

- **Google**:
  - 0.5s delay
  - 20% ↓

- **Amazon**:
  - 0.1s delay
  - 1% ↓

---


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

1) Skin effect losses
2) Dielectric losses


Requirements for optical interconnects:

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

Optical Interconnect

Light, instead of electricity, is used to carry information

**Light source**
- Electrical Input
- Optical output

**Modulator**
- Electrical Input
- Optical output

**Transport medium**
- Manipulate light by routing/filtering. Medium for light propagation

**Photodetector**
- Optical Input
- Electrical output

Let there be light!!!
Convert electrical signal to optical signal.
Convert optical signal to electrical signal.
## Optical Interconnects in Data Centers

<table>
<thead>
<tr>
<th></th>
<th>Server to TOR (&lt;3 m)</th>
<th>TOR to Leaf (3-20 m)</th>
<th>Leaf to Spine (400-2000 m)</th>
<th>Spine to Core (500-2000 m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deployed today</td>
<td>10G Cu</td>
<td>40G MMF</td>
<td>40G MMF</td>
<td>40G SMF</td>
</tr>
<tr>
<td>Being upgraded</td>
<td>25G Cu</td>
<td>100G SMF</td>
<td>100G SMF</td>
<td>100G SMF</td>
</tr>
<tr>
<td>For future</td>
<td>50/100G Cu</td>
<td>400G SMF</td>
<td>400G SMF</td>
<td>400G SMF</td>
</tr>
</tbody>
</table>

MMF - Multi mode fiber

SMF - Single mode fiber
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

Cross-section

Optical Module

- Light source
- Modulator
- Photodetector
- Transport medium

Cartoon

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>DFB LD Array</td>
<td>Laser array</td>
</tr>
<tr>
<td>LC</td>
<td>Light coupler</td>
</tr>
<tr>
<td>MOD</td>
<td>Modulator</td>
</tr>
<tr>
<td>PD</td>
<td>Photodetector</td>
</tr>
<tr>
<td>(de)MUX</td>
<td>(de)Multiplexer</td>
</tr>
<tr>
<td>FC</td>
<td>Fiber coupler</td>
</tr>
<tr>
<td>TSV</td>
<td>Through Silicon Vias</td>
</tr>
<tr>
<td>DRV</td>
<td>Electrical driver</td>
</tr>
<tr>
<td>TIA</td>
<td>Transimpedance Amplifier</td>
</tr>
<tr>
<td>CTRL</td>
<td>Controller circuit</td>
</tr>
</tbody>
</table>

**Silicon Photonics**

Material platform based on Si to realize optical transceivers

<table>
<thead>
<tr>
<th>Devices</th>
<th>Material</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photodetector</td>
<td>Ge</td>
<td>Yes</td>
</tr>
<tr>
<td>Micro Ring modulator (MRR)</td>
<td>Si</td>
<td>Yes</td>
</tr>
<tr>
<td>Mach Zehnder Modulator (MZM)</td>
<td>Si</td>
<td>Yes</td>
</tr>
<tr>
<td>Grating couplers/ Light coupler/ Fiber couplers</td>
<td>Si</td>
<td>Yes</td>
</tr>
<tr>
<td>(de)MUX filters</td>
<td>Si</td>
<td>Yes</td>
</tr>
<tr>
<td>Light source (Laser diode)</td>
<td>??</td>
<td>None</td>
</tr>
</tbody>
</table>


Imec’s 200mm Silicon photonics platform

Need for monolithically integrated light source!!
**GERMANIUM DEVICES FOR OPTICAL INTERCONNECTS**

<table>
<thead>
<tr>
<th>Active medium</th>
<th>Temp (K)</th>
<th>$J_{th}$ ($P_{th}$) – current density</th>
<th>$\lambda$(nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>III-V Quantum dot</td>
<td>300</td>
<td>&lt; 1 kA/cm$^2$</td>
<td>1310</td>
</tr>
<tr>
<td>P-doped Ge</td>
<td>300</td>
<td>280-510 kA/cm$^2$</td>
<td>1576-1650</td>
</tr>
</tbody>
</table>

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

---

Light emission from Direct Bandgap Material

Longer lifetime $\Rightarrow$ Increased light emission

Electrical Input

Spontaneous + Nonradiative recombination rate $\Rightarrow$ Lifetime

Optical Output

Water bucket analogy

Ideal direct bandgap material

- Dopants
- Injected electrons
- Injected holes

Gamma

<111>

Gamma
Light emission efficiency from undoped Ge

Lifetime $N_t$

Undoped and unstrained Ge

Dopants

Injected electrons

Injected holes

$k <111>$

Γ

E
LIGHT EMISSION EFFICIENCY FROM DOPED Ge

High doping, longer lifetime $\rightarrow$ Increased light emission

Lifetime

$N_{doping}$ $N_t$

0.2 % biaxially strained and n-type doped Ge

Dopants
- Injected electrons
- Injected holes
**GE LASER: REQUIREMENTS**

High doping, longer lifetime $\rightarrow$ Increased light emission

Design target for $J_{th} < 10 \text{kA/cm}^2$:
1. Lifetime $> 10 \text{ ns}$.
2. Doping level as high as $1\times10^{20} \text{ cm}^{-3}$.
Carrier lifetime in undoped Ge

\[ \frac{1}{\tau_{\text{carrier}}} = \frac{1}{\tau_{\text{Bulk}}} + \frac{S_{\text{Ge,unpass}} + S_{\text{Ge/Si}}}{d} \]

- SiO₂ passivation layer \(\rightarrow\) lowest lifetime
- Si cap or Thick GeOₓ \(\rightarrow\) longest carrier lifetime of 4.3 ns.
- Measured lifetime < targeted 10 ns.
**P-DOPED GE ON 1 μM GE VIRTUAL SUBSTRATE**

Highest active P concentration:
- As grown → $6.2 \times 10^{19}$ cm$^{-3}$
- Rapid thermal annealed → $5.9 \times 10^{19}$ cm$^{-3}$
Less than targeted $1 \times 10^{20}$ cm$^{-3}$

Carrier scattering induced broadening $\rightarrow$ broadened PL spectrum $\rightarrow$ caused by dopants

<table>
<thead>
<tr>
<th>Name</th>
<th>Active P (cm$^{-3}$)</th>
<th>$\Gamma_{\text{opt}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample A</td>
<td>0.0$\times10^{19}$</td>
<td>8 meV</td>
</tr>
<tr>
<td>Sample B</td>
<td>2.65$\times10^{19}$</td>
<td>47.5 meV</td>
</tr>
<tr>
<td>Sample C</td>
<td>4.5$\times10^{19}$</td>
<td>50 meV</td>
</tr>
<tr>
<td>Sample D</td>
<td>5.35$\times10^{19}$</td>
<td>45 meV</td>
</tr>
</tbody>
</table>
TRANSIENT ABSORPTION SPECTROSCOPY (TAS)

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

<table>
<thead>
<tr>
<th>Experiment Condition</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pump wavelength</td>
<td>≈ 1.3 µm</td>
</tr>
<tr>
<td>Ave Pump Intensity</td>
<td>28-140 mW/cm²</td>
</tr>
<tr>
<td>Probe Wavelength</td>
<td>1.5-1.7 µm</td>
</tr>
<tr>
<td>$N_{\text{ex,Pump}}$</td>
<td>(1.5-8)×10^{18} cm^{-3}</td>
</tr>
</tbody>
</table>

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

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

Possible operating regime

Solid line $\rightarrow$ with no linewidth broadening.
Dotted line $\rightarrow$ with linewidth broadening $\Gamma_{\text{opt}} = 45$ meV.

Difficult to demonstrate an energy efficient P-doped Ge laser for optical interconnect applications.
**Electro-Absorption Modulator (EAM)**

**Ideal scenario:**
Open $\Rightarrow$ no loss  
Closed $\Rightarrow$ $\infty$ loss

**Reality:**
Open $\Rightarrow$ Insertion loss (IL)  
Closed $\Rightarrow$ Extinction Ratio (ER)

Factors determining the performance of a modulator:

- **FOM** = ER/IL
- Switching speed
  - $\infty$
- Power Consumption
  - $< 60$ fJ/bit
- Operating wavelength
  - 1530-1570 nm
**GeSi Franz-Keldysh Effect EAM: Static Performance - I**

Electrical voltage modulates the intensity of light at the output of the waveguide.
Low FOM due to indirect bandgap material.


Enables 50 Gb/s NRZ-OOK modulation due to compact geometry and low junction capacitance. Power consumption 29 fJ/bit.
DEMONSTRATORS USING GE Si EAM: 896 GB/s TRANSCEIVER

To boost the FOM of GeSi FKE EAM \( \rightarrow \) GeSi QCSE EAM.
FOM ($\Delta \alpha / \alpha$) $\approx 1.75$ for 1 V swing $\rightarrow > 2 \times$ better than Ge FKE EAM.

Future perspectives:
1. Demonstrate waveguide integrated device $\rightarrow$ reevaluate FOM.
2. Demonstrate demonstrating at speeds $>50$ GHz.

CONCLUSION: ADVANCED GE DEVICES FOR OPTICAL INTERCONNECTS

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

<table>
<thead>
<tr>
<th>Carrier Lifetime</th>
<th>Doping Level</th>
<th>Linewidth Broadening</th>
<th>$J_{th}$ (kA/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target</td>
<td>$&gt; 10$ ns</td>
<td>$1\times10^{20}$ cm⁻³</td>
<td>$&lt; 10$ meV</td>
</tr>
<tr>
<td>Reality</td>
<td>$&lt; 0.3$ ns</td>
<td>$5.35\times10^{19}$ cm⁻³</td>
<td>$\geq 45$ meV</td>
</tr>
</tbody>
</table>

- **Ge based electro absorption modulator:**

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


ACKNOWLEDGEMENTS

Dries Van Thourhout, Joris Van Campenhout, Marianna Pantouvaki

