Nanophotonic Devices for Energy-Efficient Optical Interconnect

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• **Nano-hv team**
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• **Collaborators**
  – Nano-LED: Prof. Eli Yablonovitch
  – Nanolaser: Prof. Connie Chang-Hasnain
  – Nano-PD: Prof. Elad Alon

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  – Samsung GRO
Outline

• Introduction
• Energy-sensitivity trade-off in optical interconnect
• Energy-efficient nano-emitters
• Energy-efficient nano-photoreceivers
• Summary
Interconnect Energy Limits Chip Performance

- > 50% of microprocessor power was in interconnects
  - Expected to rise to >80%

- Current electrical interconnect
  - Off-chip ~ 1 pJ/bit
  - On-chip ~ 100 fJ/bit

- Optical interconnect
  - Increase bandwidth
  - Lower energy

Microprocessor Power Consumption (ITRS 2007)

- Clock (28%)
- Logic (23%)
- Memory (22%)
- Signaling Wires (27%)

Energy-Sensitivity Trade-off

- **Quantum limit**
  - 17 photon/bit to achieve BER=10^{-15}

- **State of the art**
  - Interconnect: $10^5$ ph/bit, @ 1 pJ/bit
  - Long haul: $10^4$ ph/bit, @10 pJ/bit

- **Questions we try to answer:**
  - Can we achieve quantum-limited detection (20 ph/bit) at fundamental energy limit (~ 10 aJ/bit)?
Scaling to Nanodevices

Power Consumption Due to Laser Bias

(e.g., bias at 5µA)

Nanoscale Detector

Nanoscale Emitter

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Nanolasers
**Pure Dielectric (Semiconductor) Cavity**

$(500\text{nm} \times 400\text{nm} \times 200\text{nm})$

**Metal Optic Cavity**

$Q = 8$

$V_m = 0.35 \ (\lambda/n)^3$

$Q = 75$

$V_m = 0.29 \ (\lambda/n)^3$

$Q = 3100$

$V_m = 0.25 \ (\lambda/n)^3$

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p.8
Nanopatch Laser

Nanolaser

Berkeley’s Nanopatch Laser
(Yu, et al. Optics Express 2010)

MOS Transistors

4 MOS transistors fabricated with Intel’s 45-nm technology

Electric Dipole (TM_{111})

Magnetic Dipole (TE_{011})

World’s Smallest Semiconductor Laser
(400nm diameter, 0.3λ)

InGaAsP

Au

Normalized Intensity

Normalized Intensity

Wavelength (nm)

Wavelength (nm)
Gold air bridge has minimum impact on nanopatch cavity:

- Nanopatch cavity: $Q_{\text{total}} = 65$, $Q_{\text{rad}} = 1600$
- Nanopatch with air-bridge: $Q_{\text{total}} = 60$, $Q_{\text{rad}} = 430$
Optical Antenna-Based Nano-LEDs
Enhance Spontaneous Emission by Optical Antenna

Bulk Spontaneous Emission

- Spontaneous emission is slow
  - Dipole length $x_0 \ll \lambda$ (wavelength)

Spontaneous Hyper Emission (SHE)

- Stronger and faster than stimulated emission
- Bandwidth approaches 100’s GHz, or even THz
- No energy wasted in current bias
  - First photon is fast!
- Spatially coherent
  - Sub-diffraction-limit emitter
  - Light can be focused to nano detectors
SHE Enhancement

**Bulk Spontaneous Emission**

\[ \frac{1}{\tau_0} = \frac{2\pi^2 (qx_0)^2}{3\varepsilon \hbar \cdot \lambda^3} \propto \frac{x_0^2}{\lambda^3} \]

**SHE Radiation Rate:**

\[ \frac{1}{\tau} = \frac{(qx_0)^2}{\hbar d^2} \cdot \frac{Q}{\varepsilon l_{eff}} \propto \frac{x_0^2}{\lambda d^2} Q \]

**Enhancement Factor:**

\[ F \propto \frac{d^2}{\lambda^2} Q \]

Attach antenna at nanoscale (<< 50nm) is important
SHE Quantum Efficiency

- SHE competes with Ohmic loss in metals

- SHE efficiency

\[ \eta = \frac{1/Q_{\text{Rad}}}{1/Q_{\text{Rad}} + 1/Q_{\text{Ohmic}}} = \frac{Q}{Q_{\text{Rad}}} \]

- Need efficient antenna (low \( Q_{\text{rad}} \)) for high SHE efficiency
  - 50% efficiency possible
Antenna Designs

Metal Coated Quantum Well

Antenna on Quantum Well

Semiconductor in Antenna Gap

Arch-Antenna over Semiconductor

Enhancement: (with dye molecule) x28

Enhancement: x10

Enhancement: x8

Enhancement: x50

Kinkhabwala et. al.

Fattal et. al.

Arbel et. al.
SHE-LED Fabrication

(Side View)

- Flip-chip bond to glass and substrate removal
- E-beam lithography and wet etching to define semiconductor ridges
- E-beam lithography and metal lift-off to define antenna

Ridge Height: 35nm
Ridge Width: 24nm
Metal Thickness: 40 nm
Photoluminescence Measurement

Emission polarized perpendicular to antennas

Emission polarized parallel to antennas

With Antennas  Without Antennas

Counts (arb.)
Wavelength (nm)
Optical Antenna-based Nano-Photodetectors
Motivation for Nanophotodiodes

<table>
<thead>
<tr>
<th></th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth</td>
<td>$BW \propto 1/C$</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>$P_{\text{min}} \mu \sqrt{C}$</td>
</tr>
<tr>
<td>Photovoltage</td>
<td>$V_{\text{photo}} \propto 1/\sqrt{C}$</td>
</tr>
</tbody>
</table>

- Receiver performance improve with shrinking capacitance
  - Capacitance $\propto$ Size

- Optical antennas enable nanoscale photodetector
  - Overcome diffraction limit
  - Enhance absorption
Recently Reported Antenna Coupled Nanophotodiodes

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<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>C-shaped aperture(^1)</td>
<td>200 x 150 x Thickness(?)</td>
<td>1310</td>
<td>0.084%</td>
</tr>
<tr>
<td>Dipole Antenna(^2)</td>
<td>150 x 60 x 80</td>
<td>1310</td>
<td>0.0079%</td>
</tr>
<tr>
<td>Bull’s Eye(^3)</td>
<td>1000 x 1000 x 200</td>
<td>1310</td>
<td>0.00038%</td>
</tr>
<tr>
<td>Ge NW Antenna(^4)</td>
<td>280 x 280 x 2000</td>
<td>1500</td>
<td>2.4%</td>
</tr>
</tbody>
</table>

Fundamental Efficiency of Antenna-Coupled Nanophotodetectors

Incident Light

Re-Radiation Loss $Q_{rad}$

Ohmic Loss (metal absorption)

Absorption By PD $Q_{metal}$

$Q_{semi}$

Coupling Efficiency

$\eta_{coupling} = \frac{A_{eff}}{A_{inc}} = \frac{\lambda^2 D}{4\pi A_{inc}}$

Internal Efficiency

$\eta_{internal} \leq \frac{1}{\frac{Q_{semi}}{Q_{metal}}} + 1$
Example 1: Dipole Antenna

- Ge size: 60x60x60 nm³
- 2μm diameter Gaussian beam
- Q calculated by ringdown using FDTD simulation

<table>
<thead>
<tr>
<th>Q_{Au}</th>
<th>Q_{Ge}</th>
<th>Q_{Rad}</th>
<th>Q_{Abs}</th>
</tr>
</thead>
<tbody>
<tr>
<td>36</td>
<td>136</td>
<td>4</td>
<td>29</td>
</tr>
</tbody>
</table>

internal = 9% coupling = 0.5%

total = 0.06%
Example 2: Nanopatch Antenna

- Ge size: 150h x 190d nm³
- Less relative energy in metal
- Calculated by FDTD

<table>
<thead>
<tr>
<th>$Q_{\text{Au}}$</th>
<th>$Q_{\text{Ge}}$</th>
<th>$Q_{\text{Rad}}$</th>
<th>$Q_{\text{Abs}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>39</td>
<td>47</td>
<td>28</td>
<td>21</td>
</tr>
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</table>

- Internal = 45%
- Coupling = 23%
- Total = 10%

- Coupling can be improved by using PD arrays.
- Fundamental limit is “internal efficiency”
- 45% possible (>70% with Ag and InGaAs)
Conclusion

• Nanophotonic devices enable energy-efficient interconnect
  – It is possible to achieve quantum-limit detection (~ 20 photons/bit) with low energy (10 aJ/bit)
  – Both are orders of magnitude lower than state of the art

• Current progress
  – 400nm dia. nanopatch laser (smallest semiconductor laser)
  – 20nm wide SHE-LED (60x stronger emission from antenna)
  – Theoretical investigation of nano-PD efficiency (>50% possible)

• Future work
  – Integration with Si photonics