From Nanolasers to Photonic Integrated Circuits

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Why integration?
Why integration?

Moore’s Law of Electronic IC

Source: Intel
Why integration?

Density

Moore’s Law of Electronic IC

10B

1B

100M

10M

1M

100K

10K

1970

1980

1990

2000

2010

2020

Source: Intel

Source: Infinera
Why integration?

Moore’s Law of Electronic IC

The solution: Photonic IC

Source: Intel
## Electronic IC vs. Photonic IC

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<tr>
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### Promise of Photonic IC:
- Increase optical speed
- Increase optical bandwidth
- Decrease cost per bit
- Decrease power per bit

Source: Infinera
## Electronic IC vs. Photonic IC

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**Promise of Photonic IC:**
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<td><strong>Material</strong></td>
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<td>Silicon, compound semiconductor</td>
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## Promise of Photonic IC:

- Increase optical speed
- Increase optical bandwidth
- Decrease cost per bit
- Decrease power per bit

Source: Infinera
Electronic IC vs. Photonic IC

Moore’s Law of Electronic IC

Passive PIC debut

Silicon Photonics

Source: Intel & Light Reading
Photonic IC

Waveguides


Lasers

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Couplers

Ikeda et al. APL 92.20 (2008)

Modulators

Sorger et al. Nanophotonics 1.1 (2012)

Detectors

III-V material platform

Silicon Photonics

Waveguides


Photonic IC

©Photonic Integration Group, Eindhoven University of Technology

Lasers

©Photonic Integration Group, Eindhoven University of Technology

Couplers

Ikeda et al. APL 92.20 (2008)

Port 3

Port 4

Modulators

Sorger et al. Nanophotonics 1.1 (2012)

Detectors

Reducing the laser size: Challenges

- **Material gain requirement: threshold gain**

\[ g_{th} \propto \frac{1}{\Gamma \cdot Q} \]

\( \Gamma : \) mode confinement; \( Q : \) quality factor

\[ g_{th} \propto \text{non-radiative loss} \propto \frac{\text{surface area}}{\text{volume}} \] (below threshold)

- **Size requirement: diffraction limit**

\[ L_{\text{min}} \sim \frac{\lambda}{2n} \]
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Mirror  Gain medium  Mirror

Output
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\[ g_{th} \propto \text{non-radiative loss} \propto \frac{\text{surface area}}{\text{volume}} \]

(above threshold)
Nanolasers: State of the art

Desired nanolaser properties for dense chip-scale integration:

- electromagnetically isolated
- sub-wavelength in 3D
- room temperature operation
- continuous wave electrically pumped
- low lasing threshold
Nanolasers: State of the art

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• Dielectric disk lasers
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• Photonic crystal lasers

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- Photonic crystal lasers

- Nano-membrane lasers

Yang et al. Nat. Photon. 6, 615 (2012)

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- Dielectric disk lasers

- Photonic crystal lasers

- Nano-membrane lasers

- Nano-wire/rod lasers


Yang et al. Nat. Photon. 6, 615 (2012)

Lu et al. Science 337, 450 (2012)
Cavity design: metallic cavity

Desired nanolaser properties for dense chip-scale integration:

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- low lasing threshold
Cavity design: metallic cavity

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Metallic-cavity nanolaser

Cavity design: metallic cavity

Desired nanolaser properties for dense chip-scale integration:

- **electromagnetically isolated**
- sub-wavelength in 3D
- room temperature operation
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Metallic-cavity nanolaser

@ 77K

\[ Q = 140 \]
\[ g_{th} \approx 7 \times 10^5 \text{ cm}^{-1} \]
Cavity design: metallic cavity

Desired nanolaser properties for dense chip-scale integration:

- electromagnetically isolated
- sub-wavelength in 3D
- room temperature operation
- electrically pumped
- low lasing threshold

Metallic-cavity nanolaser

@ 300K
Q = 48
\( g_{th} \approx 3 \times 10^6 \text{ cm}^{-1} \)

material gain
\( g = 3000 \text{ cm}^{-1} \)
Lasers in Photonic ICs

Design: Optical cavity mode
Lasers in Photonic ICs

Design:
Optical cavity mode

Proof of concept:
Optically pumped laser
Lasers in Photonic ICs

Design:
Optical cavity mode

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Multi-physics design
for electrical pumping:
Optical, electrical, thermal
Lasers in Photonic ICs

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Demonstration: Electrically pumped laser
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Analysis:
• Modulation speed
• Energy efficiency

Demonstration:
Electrically pumped laser
Lasers in Photonic ICs

Design: Optical cavity mode

Insertion into Photonic ICs

Proof of concept: Optically pumped laser

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Demonstration: Electrically pumped laser

Analysis:
• Modulation speed
• Energy efficiency

Insertion into Photonic ICs
Cavity design: metallo-dielectric cavity

M. P. Nezhad et al, Nature Photonics, 4, 6, 395-399, 2010
Cavity design: metallo-dielectric cavity

Metallic cavity

Metallo-dielectric cavity

Gain

Dielectric “shield”

Cavity design: metallo-dielectric cavity

Metallic cavity

Metallo-dielectric cavity

Dielectric “shield”

Cavity design: metallo-dielectric cavity

Cavity design: metallo-dielectric cavity

A. Mizrahi et al, Optics Letters, 33, 1261-1263, 2008
Cavity design: metallo-dielectric cavity

A. Mizrahi et al, Optics Letters, 33, 1261-1263, 2008
Cavity design: metallo-dielectric cavity


- "shield" thickness
  - $\Delta=0\text{nm}$
  - $\Delta=100\text{nm}$
  - $\Delta=200\text{nm}$
Cavity design: metallo-dielectric cavity

A. Mizrahi et al, Optics Letters, 33, 1261-1263, 2008
Optically pumped room temperature nanolaser

- electromagnetically isolated
- sub-wavelength in 3D
- room temperature operation
- electrically pumped
- low lasing threshold

Lasers in Photonic ICs

- **Design:** Optical cavity mode
- **Demonstration:** Electrically pumped laser
- **Proof of concept:** Optically pumped laser
- **Multi-physics design for electrical pumping:** Optical, electrical, thermal
- **Analysis:**
  - Modulation speed
  - Energy efficiency
- **Insertion into Photonic ICs**
- **Demonstration:** Electrically pumped laser
Multi-physics design for electrical pumping

Optical
Cavity design: $\lambda$, $Q$, $g_{\text{th}}$

Electrical
Power dissipation, band diagram, heterostructure design

Thermal
- Heat generation & dissipation
- Explore high thermal-conductivity dielectric “shield” material

T-dependent parameters
Electrically pumped nanolaser

Qing Gu et al, *IEEE JQE*, Vol. 50, Issue 7 (2014);
Electrically pumped nanolaser

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Vertical confinement via InP undercut

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Qing Gu et al, *IEEE JQE*, Vol. 50, Issue 7 (2014);
InP undercut: Two-step selective etching

Before
InP undercut
InP undercut: Two-step selective etching

Before InP undercut

HCl:CH₃COOH

HCl:H₃PO₄
InP undercut: Two-step selective etching

Before InP undercut

HCl:CH₃COOH

HCl:H₃PO₄

HCl:H₃PO₄ = 1:4

HCl:CH₃COOH:H₂O = 1:4:5

500nm

200nm
Vertical confinement via InP undercut

$g_{th}$ (cm$^{-1}$) vs. Undercut (%)
Optical: robust design via InP undercut

Effect of undercut sidewall angle

Optical: robust design via InP undercut

Effect of undercut sidewall angle

Multi-physics design with $\text{Al}_2\text{O}_3$ shield

<table>
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Multi-physics design with Al$_2$O$_3$ shield

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Multi-physics design with $\text{Al}_2\text{O}_3$ shield

Multi-physics design with Al$_2$O$_3$ shield

\[ g_{th} = \frac{\lambda}{R_{core}} \]

\[ R_{core} = 575 \text{ nm} \]

Optical

\[ \lambda = 1584 \text{ nm} \]

\[ g_{th} = 63 \text{ cm}^{-1} \]

Spectral window of EL

1300nm - 1650nm

Multi-physics design with Al$_2$O$_3$ shield

\[ g_{th} \text{ (cm}^{-1}\text{)} \]

- $R_{\text{core}} = 575 \text{ nm}$

\[ \lambda = 1376 \text{ nm} \quad g_{th} = 29 \text{ cm}^{-1} \]
\[ \lambda = 1431 \text{ nm} \quad g_{th} = 192 \text{ cm}^{-1} \]
\[ \lambda = 1584 \text{ nm} \quad g_{th} = 63 \text{ cm}^{-1} \]

Spectral window of EL

Multi-physics design with $\text{Al}_2\text{O}_3$ shield

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**Spectral window of EL**

- Wavelength: 1300 nm to 1650 nm

**Electrical & Thermal**

- $\text{Al}_2\text{O}_3$, $K = 10$ W/(m*K)
- $\text{SiO}_2$, $K = 1.1$ W/(m*K)

- $T_{\text{steady state}} = 327$ K
- $T_{\text{steady state}} = 353$ K
- $T_{\text{steady state}} = 300$ K

Multi-physics design with Al$_2$O$_3$ shield

**Optical**

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- SiO$_2$, $K = 1.1 \text{ W/(m*K)}$

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- $T_{\text{steady state}} = 353 \text{ K}$

**Material Gain**

- Graph showing gain vs. wavelength for different temperatures: 77K, 300K, 327K

- Gain equation: $N = 7.072 \times 10^{18} \text{ cm}^{-3}$

Fabrication

500 nm

E-beam patterning/RIE (CH$_4$:H$_2$:Ar)
Fabrication

500 nm

E-beam patterning/RIE (CH$_4$:H$_2$:Ar)
Two-step selective InP wet etching

- HSQ
- N++ InGaAs
- N-InP
- InGaAs Gain
- P-InP
- P++ InGaAsP
- InP
Fabrication

500 nm

N++ InGaAs
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E-beam patterning/RIE (CH₄:H₂:Ar)
Two-step selective InP wet etching
Fabrication

- E-beam patterning/RIE (CH$_4$ : H$_2$ : Ar)
- Two-step selective InP wet etching

500 nm

Diagram:
- N++ InGaAs
- InP
- InGaAs Gain
- InP
- P++ InGaAsP
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Fabrication

500 nm

- E-beam patterning/RIE (CH₄:H₂:Ar)
- Two-step selective InP wet etching
- Dielectric “shield” deposition

Diagram:
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500 nm
Fabrication

500 nm

E-beam patterning/RIE (CH$_4$:H$_2$:Ar)
Two-step selective InP wet etching
Dielectric “shield” deposition
Expose the pillar top (for top contact)
Fabrication

500 nm

E-beam patterning/RIE (CH$_4$:H$_2$:Ar)
Two-step selective InP wet etching
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E-beam patterning/RIE (\text{CH}_4:\text{H}_2:\text{Ar})

Two-step selective InP wet etching

Dielectric “shield” deposition

Expose the pillar top (for top contact)
Fabrication

- E-beam patterning/RIE (CH$_4$:H$_2$:Ar)
- Two-step selective InP wet etching
- Dielectric “shield” deposition
- Expose the pillar top (for top contact)

Diagram:

- N++ InGaAs
- InGaAs Gain
- P++ InGaAsP
- Dielectric
- PR
- InP

Scale: 500 nm
**Fabrication**

500 nm

E-beam patterning/RIE (CH$_4$:H$_2$:Ar)

Two-step selective InP wet etching

Dielectric “shield” deposition

Expose the pillar top (for top contact)

Top contact (Ti/Pd/Au) formation
Fabrication

500 nm

E-beam patterning/RIE (CH$_4$:H$_2$:Ar)
Two-step selective InP wet etching
Dielectric “shield” deposition
Expose the pillar top (for top contact)
Top contact (Ti/Pd/Au) formation

PRPR

InGaAs
Gain

N++ InGaAs

Ti+Pd+Au

InP

Dielectric

P++ InGaAsP

InP

InP
Fabrication

- E-beam patterning/RIE (CH₄:H₂:Ar)
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- Expose the pillar top (for top contact)
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Fabrication

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E-beam patterning/RIE (CH$_4$:H$_2$:Ar)
Two-step selective InP wet etching
Dielectric “shield” deposition
Exposé the pillar top (for top contact)
Top contact (Ti/Pd/Au) formation
Metal cavity (Ag/Au) formation
Fabrication

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E-beam patterning/RIE (CH$_4$:H$_2$:Ar)
Two-step selective InP wet etching
Dielectric “shield” deposition
Expose the pillar top (for top contact)
Top contact (Ti/Pd/Au) formation
Metal cavity (Ag/Au) formation
Bottom contact formation (Ti/Pd/Au)
Wire-bond to sample holder
Characterization micro-EL setup

Sample

Current source

NA=0.4 M.O.

flip mirror

chopper

monochromator

InGaAs detector

lock-in amplifier

CCD camera
Characterization micro-EL setup

- Sample
- NA=0.4 M.O.
- Current source
- Flip mirror
- Chopper
- Monochromator
- InGaAs detector
- Lock-in amplifier
- CCD camera
Characterization micro-EL setup

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Lasers in Photonic ICs

Insertion into Photonic ICs

Design: Optical cavity mode

Proof of concept: Optically pumped laser

Multi-physics design for electrical pumping: Optical, electrical, thermal

Analysis:
- Modulation speed
- Energy efficiency

Demonstration: Electrically pumped laser
Purcell factor $F_P$

$$F_P = \frac{\text{spontaneous emission in a cavity}}{\text{spontaneous emission in free space}}$$

$< 1$: inhibition

$> 1$: enhancement
Purcell factor $F_P$

$$F_P = \frac{\text{spontaneous emission in a cavity}}{\text{spontaneous emission in free space}}$$

< 1: inhibition

> 1: enhancement

**Literature** $^{[1,2]}$

$$F_P = \frac{3\lambda^3}{4\pi^2 n^3} \frac{Q}{V_{\text{eff}}} \propto \frac{Q}{V_{\text{eff}}}$$


Approach

- Emitter-field-reservoir model in the quantum theory of damping

If the reservoir (environment) is cavity boundary
- corresponds to the transparent medium condition

Qing Gu et al, Optics Express, Vol. 21, No. 13 (2013)
Purcell factor, $T = 300\text{K}$

$$F_P = \frac{\pi (c/n_r)^3}{\tau_{\text{coll}}} \frac{\omega_k}{\bar{\omega}_{21}^3} \frac{1}{V_a} \left\{ \Gamma_k \right\} \int \int D(\omega_{21}) R(\omega - \omega_{21}, \tau_{\text{coll}}) L_k(\omega - \omega_k) d\omega d\omega_{21}$$

\begin{align*}
\uparrow & \quad \text{Inhomogeneous broadening} \\
\uparrow & \quad \text{Homogeneous broadening} \\
\uparrow & \quad \text{Cavity lineshape}
\end{align*}

Literature

$$F_P = \frac{3\lambda^3}{4\pi^2 n^3} \frac{Q}{V_{\text{eff}}} \propto \frac{Q}{V_{\text{eff}}}$$
Purcell factor, $T = 300K$

\[ F_P = \frac{\pi (c / n_r)^3}{\tau_{\text{coll}}^3} \frac{\omega_k}{\omega_{21}^3} \frac{1}{V_a} \{ \Gamma_k \} \int \int D(\omega_{21}) R(\omega - \omega_{21}, \tau_{\text{coll}}) L_k(\omega - \omega_k) d\omega d\omega_{21} \]

- Inhomogeneous broadening
- Homogeneous broadening
- Cavity lineshape

$L_k(\omega - \omega_k)$ is the broadest of the three lineshapes

Literature

\[ F_P = \frac{3\lambda^3}{4\pi^2 n^3} \frac{Q}{V_{\text{eff}}} \propto \frac{Q}{V_{\text{eff}}} \]

Qing Gu et al, Optics Express, Vol. 21, No. 13 (2013)
Purcell factor, $T = 300\,\text{K}$
Spontaneous emission factor $\beta$

$\beta = \frac{\text{spontaneous emission into the lasing mode}}{\text{spontaneous emission into the lasing mode} + \text{into other cavity modes} + \text{into free space radiation modes}}$
Spontaneous emission factor $\beta$

\[
\beta = \frac{\text{spontaneous emission into the lasing mode}}{\text{spontaneous emission into the lasing mode} + \text{into other cavity modes} + \text{into free space radiation modes}}
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<th>Nanoscale laser</th>
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<td>Spontaneous emission factor $\beta$</td>
<td>0.00001</td>
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Spontaneous emission factor $\beta$

\[ \beta = \frac{\text{spontaneous emission into the lasing mode}}{\text{spontaneous emission into the lasing mode} + \text{into other cavity modes} + \text{into free space radiation modes}} \]

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</table>
β factor in nanolasers

\[ β = \frac{\text{spontaneous emission into the lasing mode}}{\text{spontaneous emission into lasing mode} \oplus \text{into other cavity modes} \oplus \text{into free space radiation modes}} \]

- \( β = 0.001 \) micro-laser
- \( β = 1 \) nano-laser

\[ \text{Photon density (}\text{cm}^{-3}\text{)} \]

\[ \text{Current (A)} \]

\( β = 1 \text{ nano-laser} \)

\( β = 0.001 \text{ micro-laser} \)
β factor in nanolasers

\[ \beta = \frac{\text{spontaneous emission into the lasing mode}}{\text{spontaneous emission into lasing mode} + \text{into other cavity modes} + \text{into free space radiation modes}} \]

- \( \beta = 1 \) nano-laser
- \( \beta = 0.001 \) micro-laser
\[ \beta = \frac{\text{spontaneous emission into the lasing mode}}{\text{spontaneous emission into lasing mode}} \]

\[ \beta = 0.001 \]

\[ \beta = 1 \]

\[ \beta_{\text{max}} = \frac{F_P^{(\text{lasing})}}{\sum_k F_P^{(k)}} \]
$\beta$ factor, $T = 300K$

\[ \beta_{\text{max}} = \frac{\text{spontaneous emission into the lasing mode}}{\text{spontaneous emission into lasing mode} + \text{into other cavity modes} + \text{into free space radiation modes}} \]

\[ \beta_{\text{factor}, \, T = 300K} \]

\[ \begin{align*}
1310\text{nm} & : & Q = 65 & : & F_p = 0.032 \\
1373\text{nm} & : & Q = 64 & : & F_p = 0.079 \\
1387\text{nm} & : & Q = 63 & : & F_p = 0.096 \\
1416\text{nm} & : & Q = 478 & : & F_p = 0.170 \\
1546\text{nm} & : & Q = 61 & : & F_p = 0.097 
\end{align*} \]

\[ \beta_{\text{max}} = 0.377 \]

\[ \beta_{\text{max}} = \frac{\text{spontaneous emission into the lasing mode}}{\text{spontaneous emission into lasing mode} + \text{into other cavity modes} + \text{into free space radiation modes}} \]

\[ \beta_{\text{max}} = \frac{F_{P}^{(\text{lasing})}}{\sum_{k} F_{P}^{(k)}} \]

\[ F_P(T) = \frac{\pi (c/n_r)^3}{\tau_{\text{coll}}} \frac{\omega_k(T)}{\omega^3} \frac{1}{V_a} \left\{ \Gamma_k \right\} \int \int D(\omega_{21}, T) R(\omega - \omega_{21}, \tau_{\text{coll}}, T) L_k(\omega - \omega_k, T) d\omega d\omega_{21} \]
**β factor: temperature dependence**

**Purcell factor**

\[
F_P(T) = \frac{\pi (c/n_r)^3}{\tau_{coll}} \frac{\omega_k(T)}{\bar{\omega}_2^3} \frac{1}{V_a} \left\{ \Gamma_k \right\} \int \int D(\omega_2, T) R(\omega - \omega_2, \tau_{coll}, T) L_k(\omega - \omega_k, T) d\omega d\omega_2
\]

![Graph showing β_max vs Temperature (K) with R=225nm](image.png)
β factor: temperature dependence

Purcell factor

\[ F_P(T) = \frac{\pi (c/n_r)^3}{\tau_{\text{coll}}} \frac{\omega_k(T)}{\tilde{\omega}_{21}^3} \frac{1}{V_a} \{ \Gamma_k \} \int \int D(\omega_{21}, T) R(\omega - \omega_{21}, \tau_{\text{coll}}, T) L_k(\omega - \omega_k, T) d\omega d\omega_{21} \]
Lasers in Photonic ICs

**Design:**
Optical cavity mode

**Proof of concept:**
Optically pumped laser

**Multi-physics design**
for electrical pumping:
Optical, electrical, thermal

**Demonstration:**
Electrically pumped laser

**Analysis:**
- Modulation speed
- Energy efficiency

**Insertion into Photonic ICs**
Integration of III-V and Silicon

III-V/Si integration options

  • monolithic
  • heterogeneous

Integration of III-V and Silicon

III-V/Si integration options • monolithic
  • heterogeneous

Integration of III-V and Silicon

III-V/Si integration options
- monolithic
- heterogeneous

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Integration of III-V and Silicon

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• heterogeneous

Integration of III-V and Silicon

III-V/Si integration options

• monolithic
• heterogeneous

Integration of III-V and Silicon

III-V/Si integration options

• monolithic
• heterogeneous

- Large scale (mm scale)
- Low temperature process (< 400 °C)
- Direct bond between III-V and Si
- No alignment required

III-V/Si nanolaser

III-V/Si nanolaser
III-V/Si nanolaser

III-V/Si nanolaser

III-V/Si micro-DFB laser

III-V/Si micro-DFB laser

Outlook: Coupling light emission to waveguide

Summary:

- Nanolaser multi-physics design
- Thermal management
- Performance analysis
- Heterogeneous integration of III-V/Si
THANK YOU!