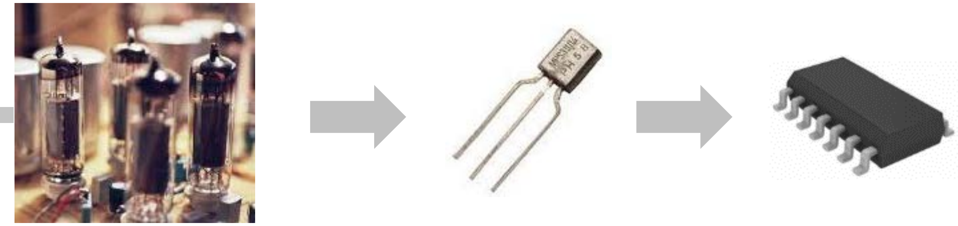
From Nanolasers to Photonic Integrated Circuits

Qing Gu

Nanophotonics Lab

Electrical & Computer Engineering, UT Dallas

Why integration?



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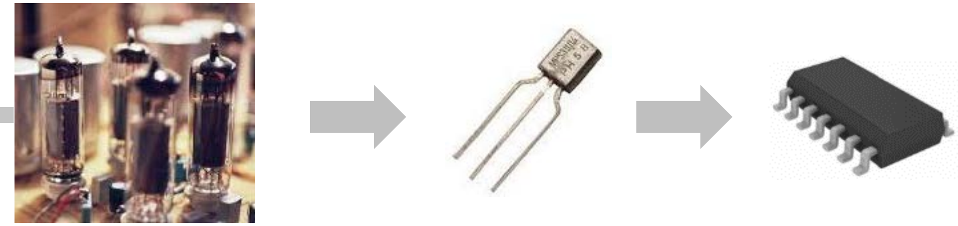
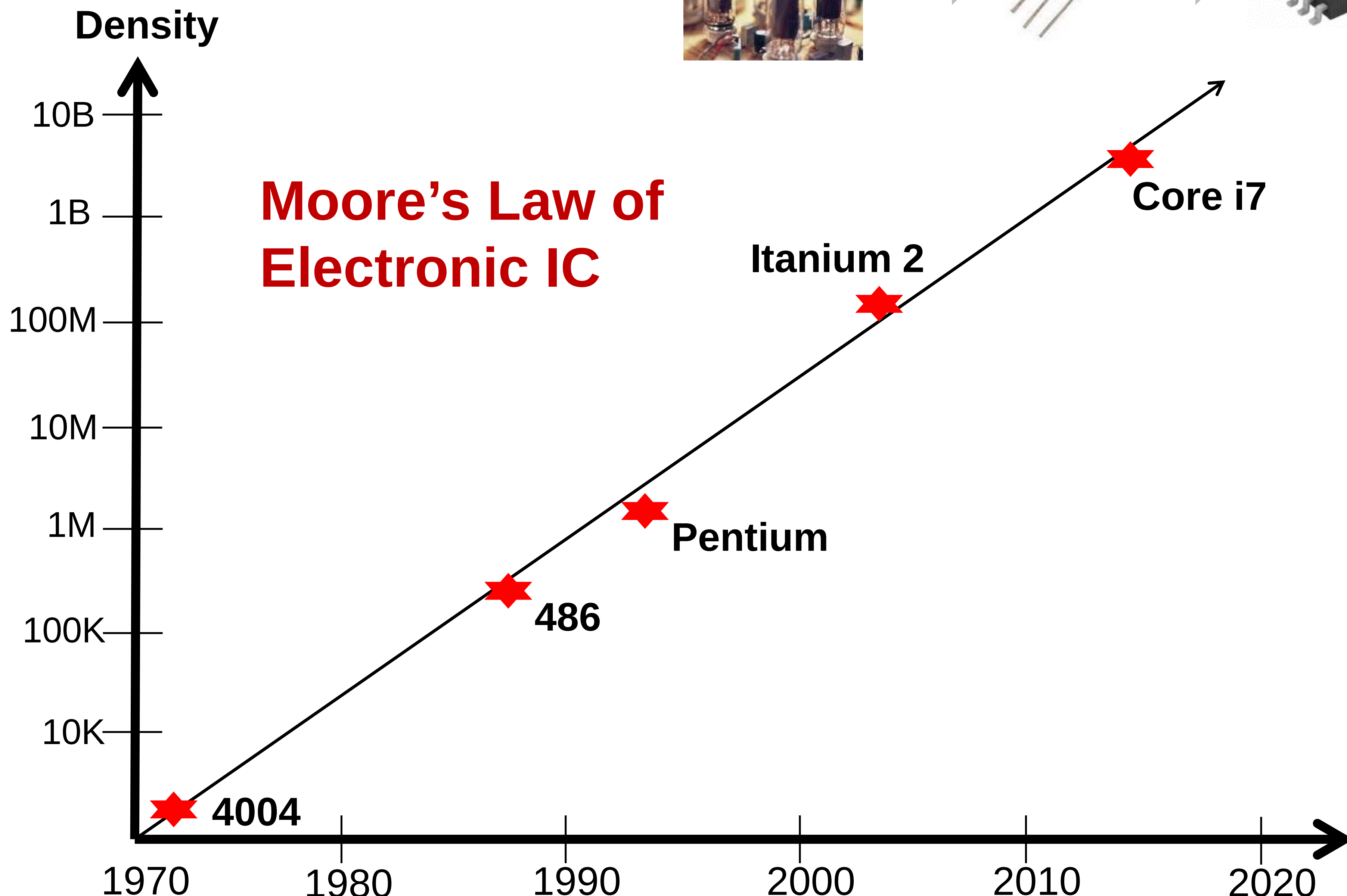
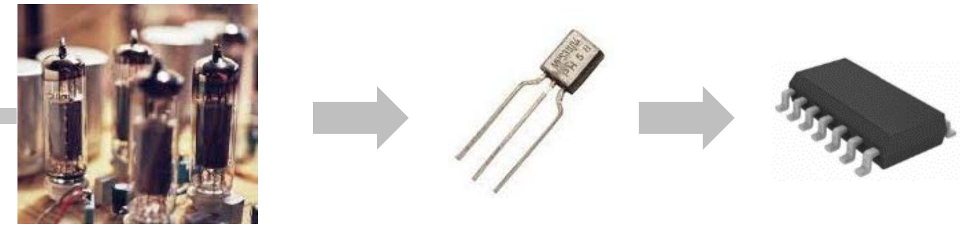
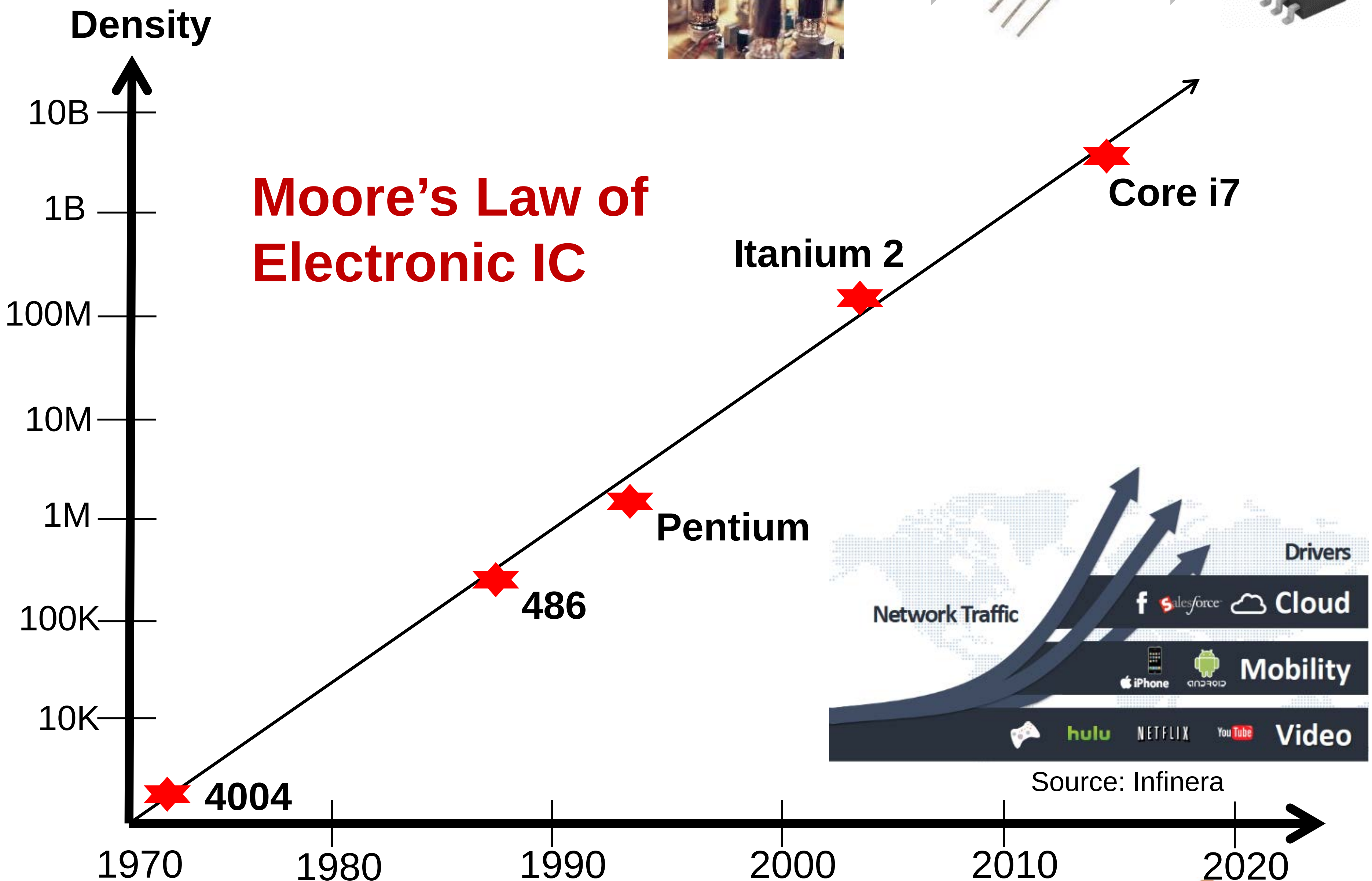




Source: Intel

Why integration?





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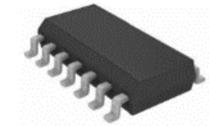

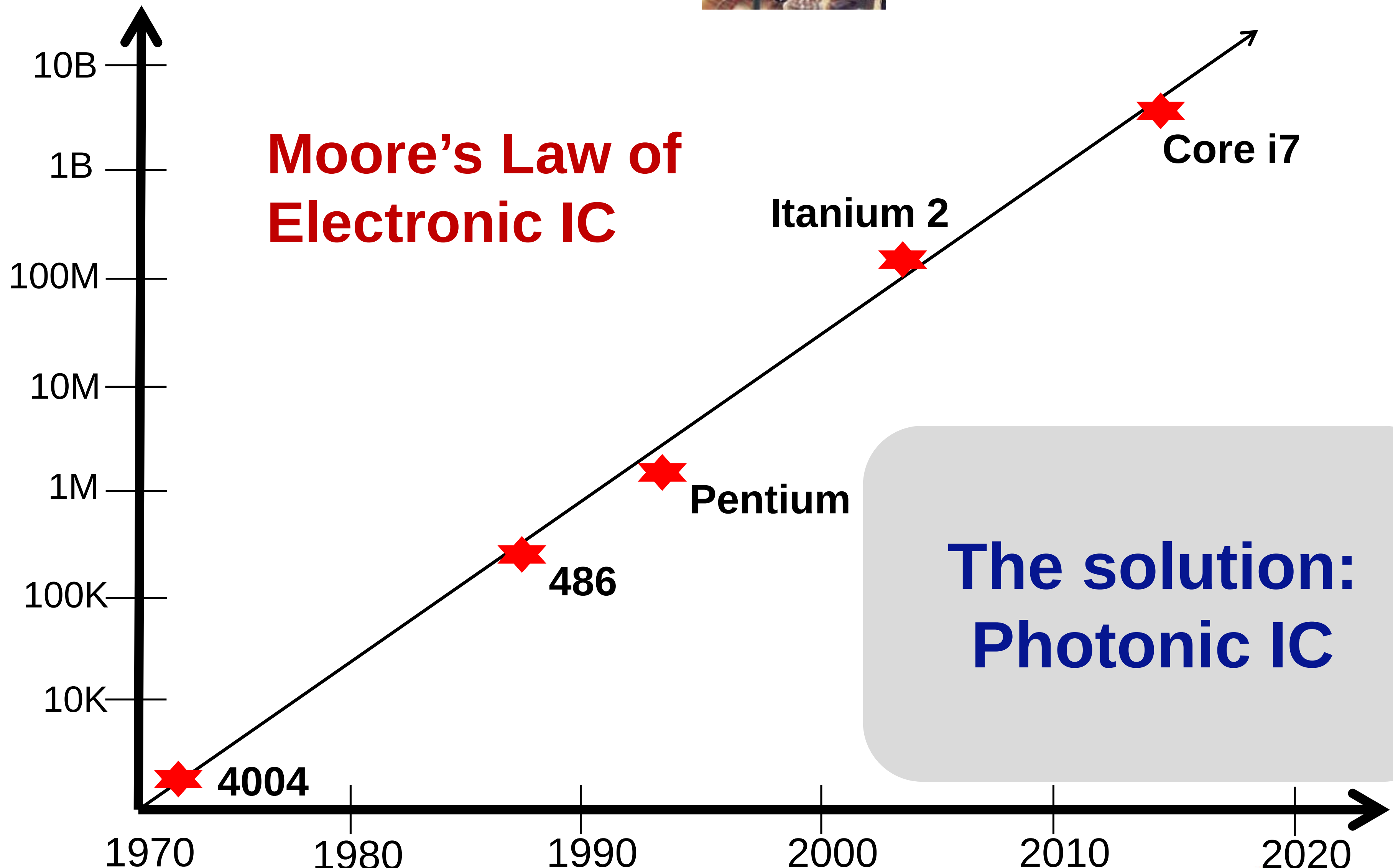

Source: Intel

Moore's Law of Electronic IC

The solution: Photonic IC

Electronic IC vs. Photonic IC

	Electronic IC	Photonic IC
Signal	Electrical	Optical

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

	Electronic IC	Photonic IC
Signal	**Electrical**	**Optical**
Components	**Transistors, capacitors, resistors**	**Waveguides, lasers, detectors, modulators, filters**

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Material	Silicon	Silicon, compound semiconductor

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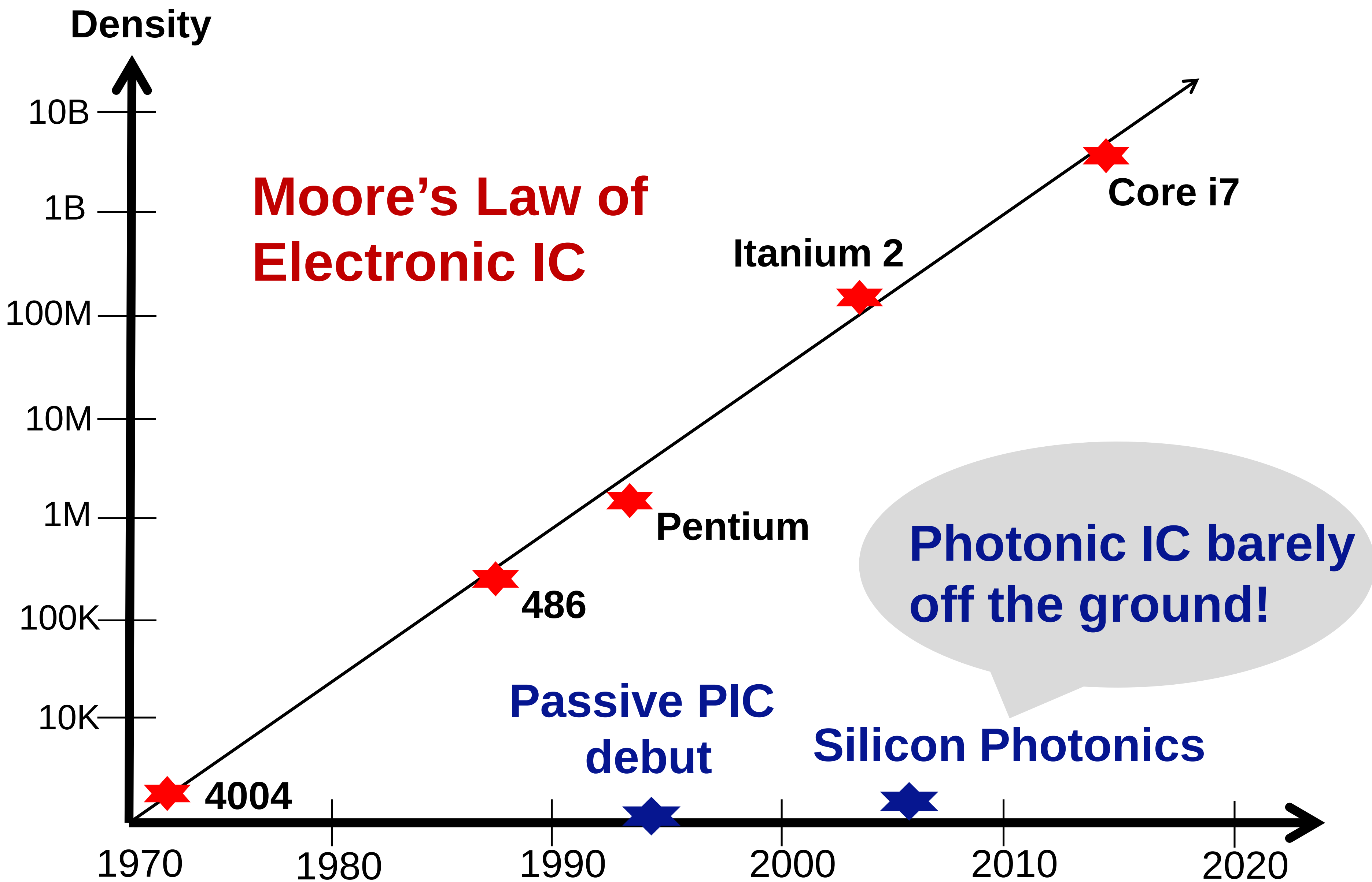
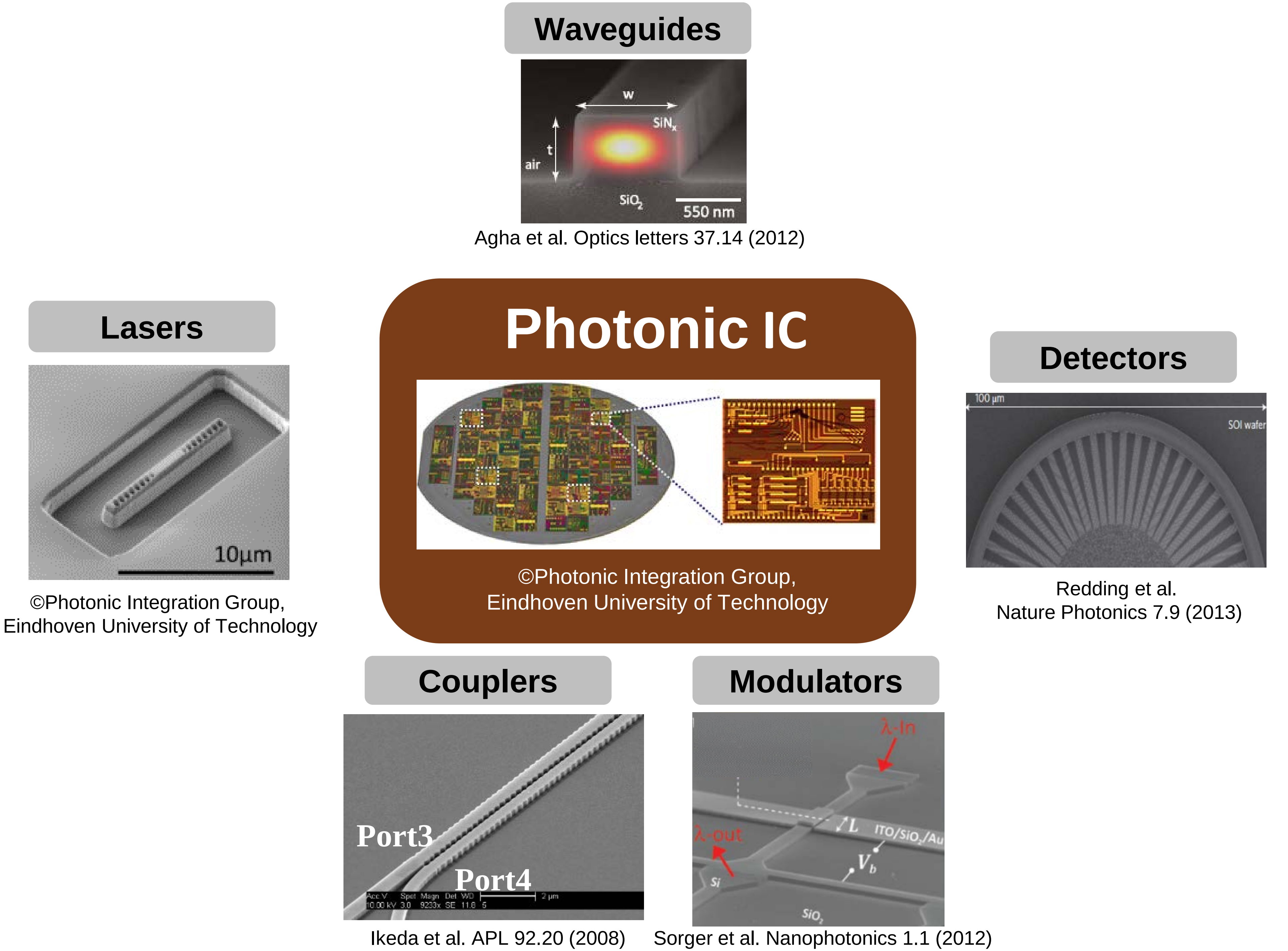


Source: Intel & Light Reading


Waveguides
w
SiNx
t
air
SiO2
550 nm
Agha et al. Optics letters 37.14 (2012)
Lasers
10μm
©Photonic Integration Group,
Eindhoven University of Technology
Photonic IC
©Photonic Integration Group,
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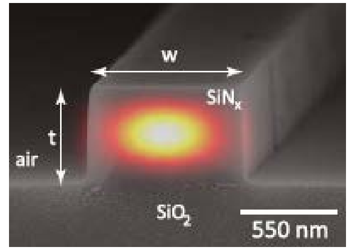
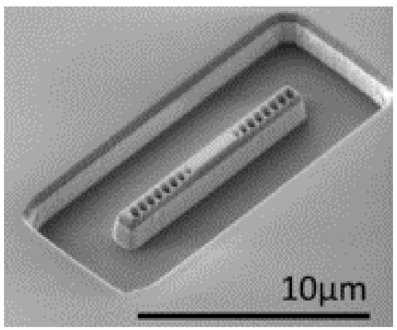
Detectors
100 μm
SOI wafer
Redding et al.
Nature Photonics 7.9 (2013)
Couplers
Port3
Port4
Modulators
λ-In
λ-out
L
ITO/SiO2/Au
Vb
Si
SiO2
Ikeda et al. APL 92.20 (2008)
Sorger et al. Nanophotonics 1.1 (2012)

Waveguides



Agha et al. Optics letters 37.14 (2012)

Lasers



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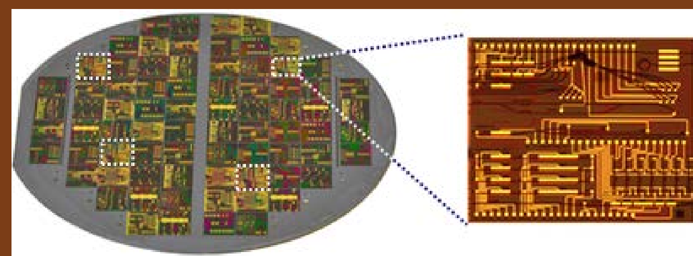
Photonic IC



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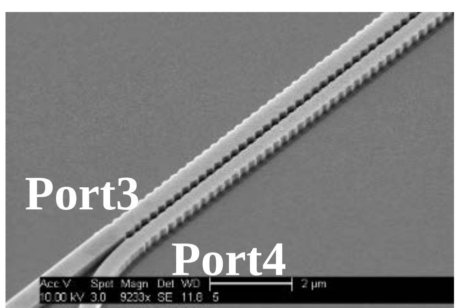
Detectors

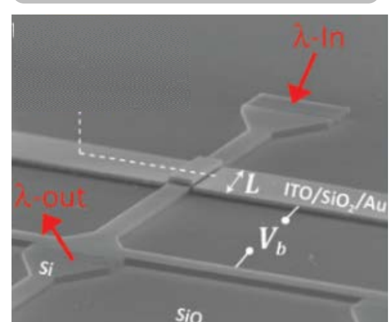
Redding et al.
Nature Photonics 7.9 (2013)

Couplers



Ikeda et al. APL 92.20 (2008)

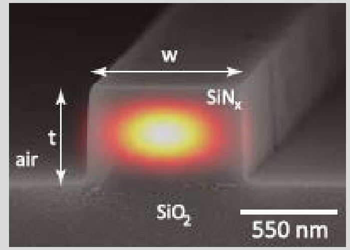
Modulators



Sorger et al. Nanophotonics 1.1 (2012)

Silicon Photonics

Waveguides



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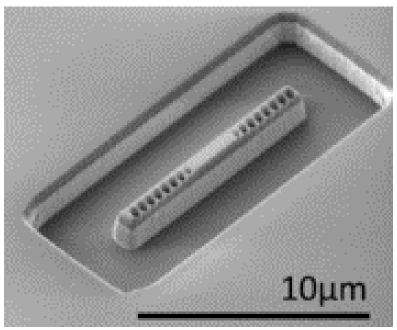

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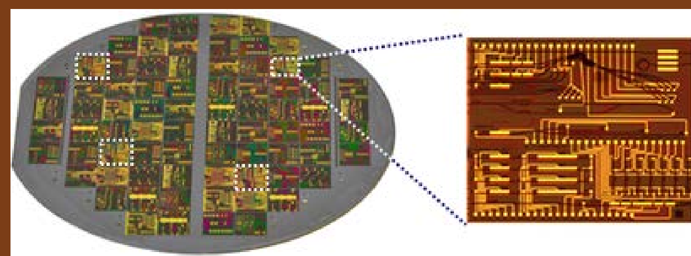
Photonic IC



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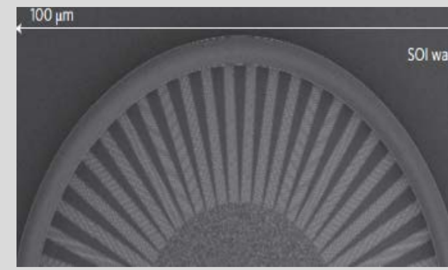

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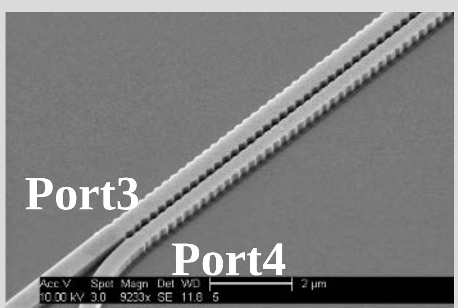

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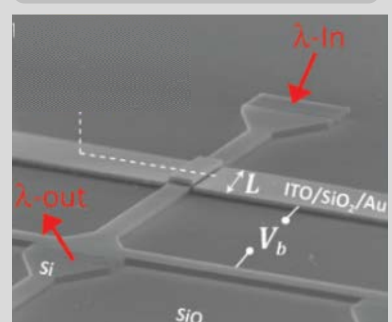
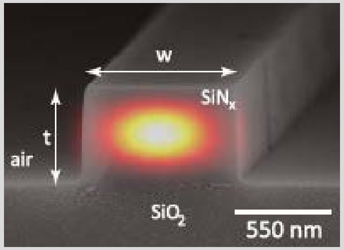


Sorger et al. Nanophotonics 1.1 (2012)

Silicon Photonics

III-V material platform

Waveguides



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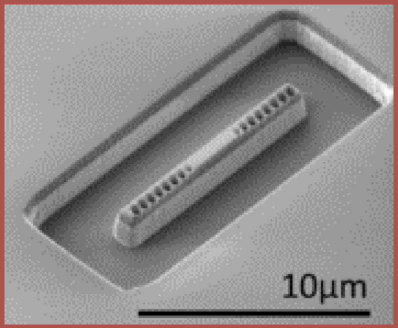

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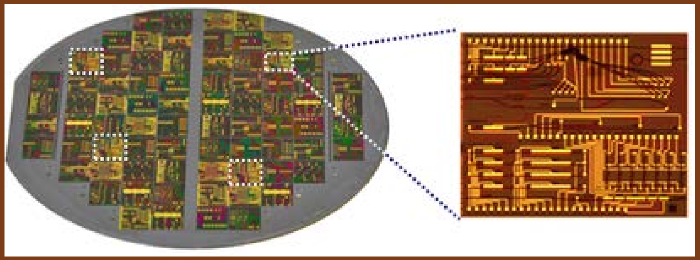

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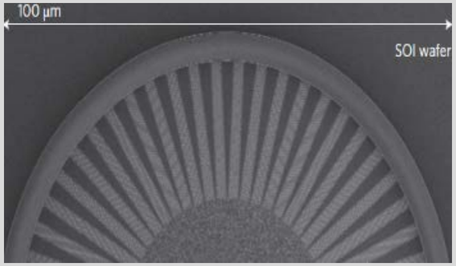

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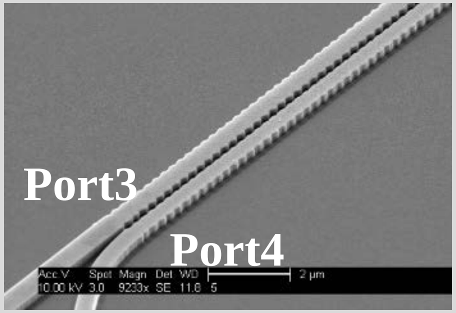

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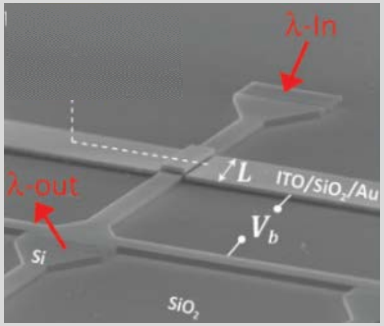

Sorger et al. Nanophotonics 1.1 (2012)

Reducing the laser size: Challenges

- Material gain requirement: threshold gain

$$g_{th} \propto \frac{1}{\Gamma \cdot Q}$$ $\mathbf{\Gamma}$: mode confinement; $\mathbf{Q}$: quality factor

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

- Size requirement: diffraction limit $L_{\min} \sim \lambda / 2n$

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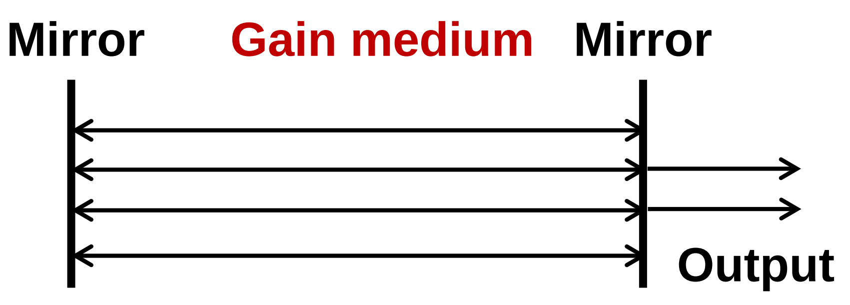

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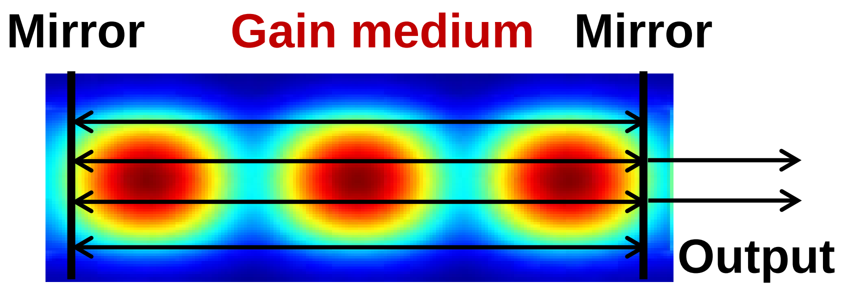

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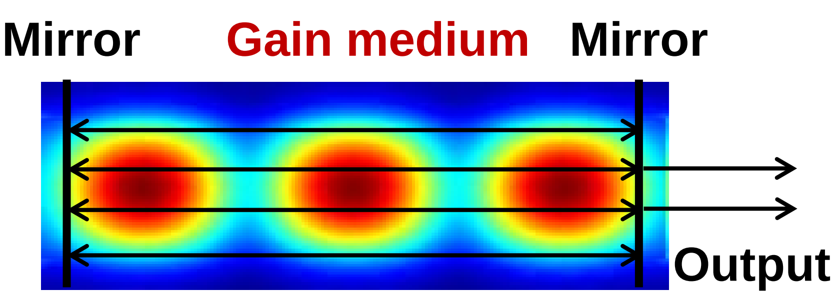

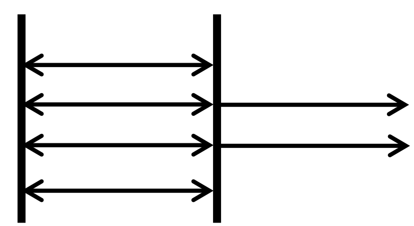

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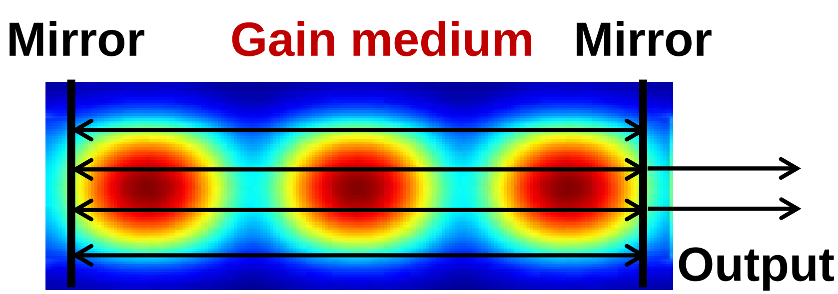

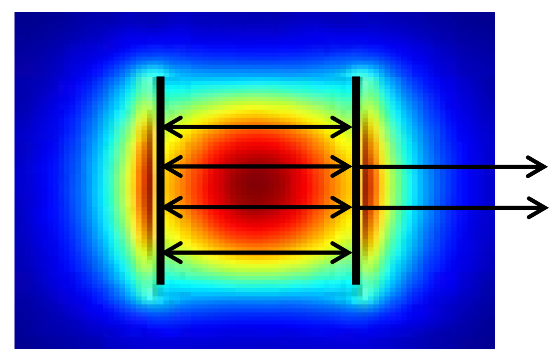

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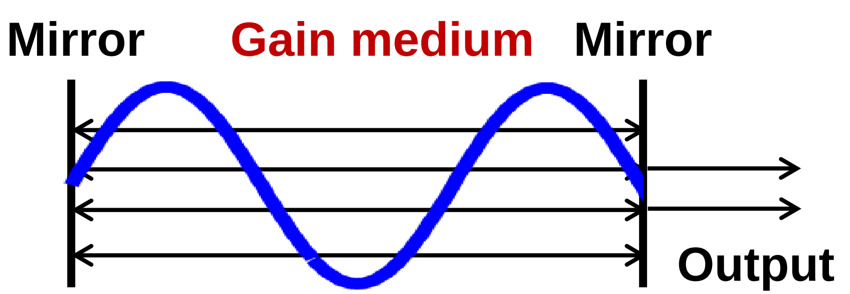

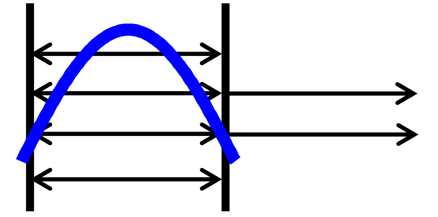

Nanolasers: State of the art

Desired nanolaser properties for dense chip-scale integration:

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

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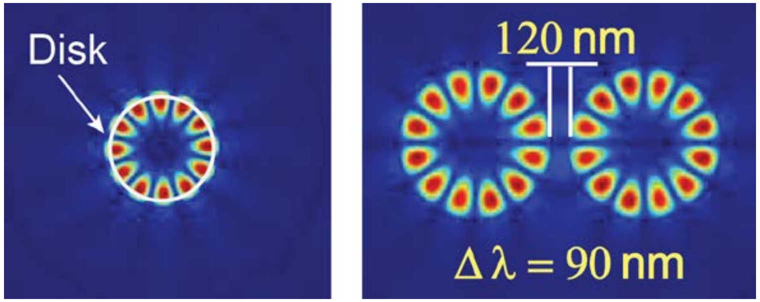
- **Dielectric disk lasers**



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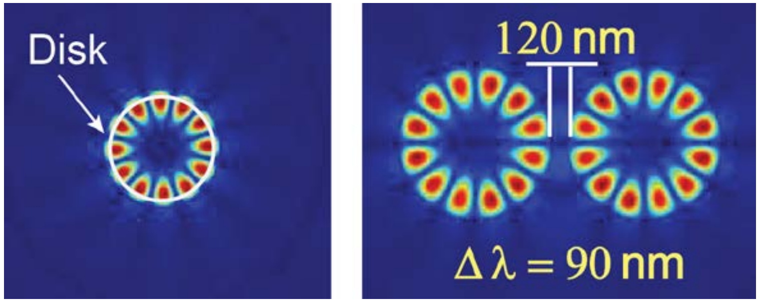
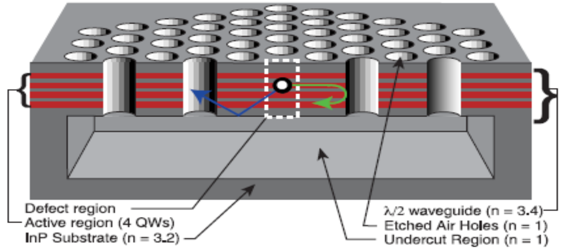


- **Photonic crystal lasers**



Painter *et al.* Science 284, 1819 (1999)

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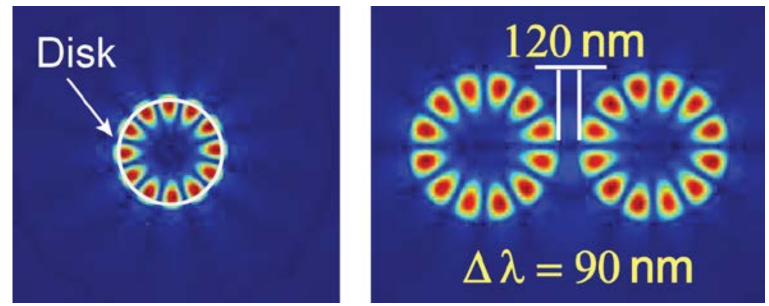

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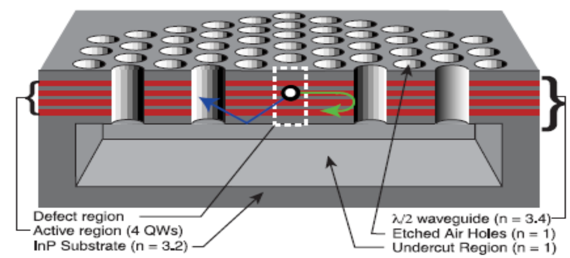

Painter *et al.* Science 284, 1819 (1999)

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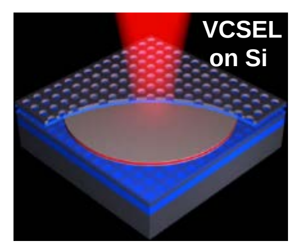

Yang *et al.* Nat. Photon. 6, 615 (2012)

- **Nano-membrane lasers**

Nanolasers: State of the art

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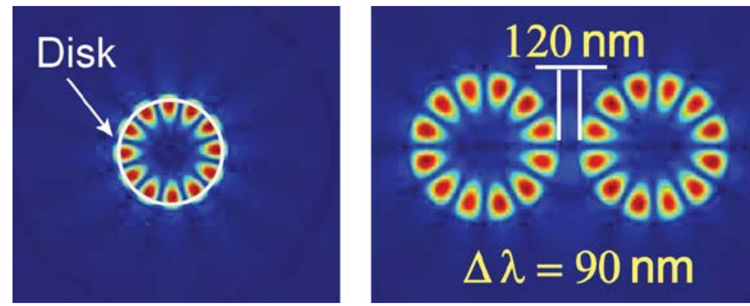

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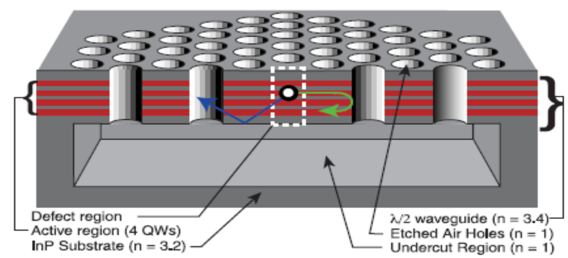

Painter *et al.* Science 284, 1819 (1999)

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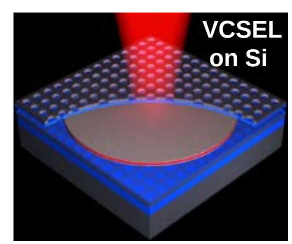
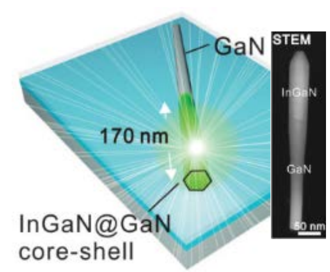


Yang *et al.* Nat. Photon. 6, 615 (2012)

- **Nano-wire/rod lasers**



Lu *et al.* Science 337, 450 (2012)

Cavity design: metallic cavity

Desired nanolaser properties for dense chip-scale integration:

✓ **electromagnetically isolated**

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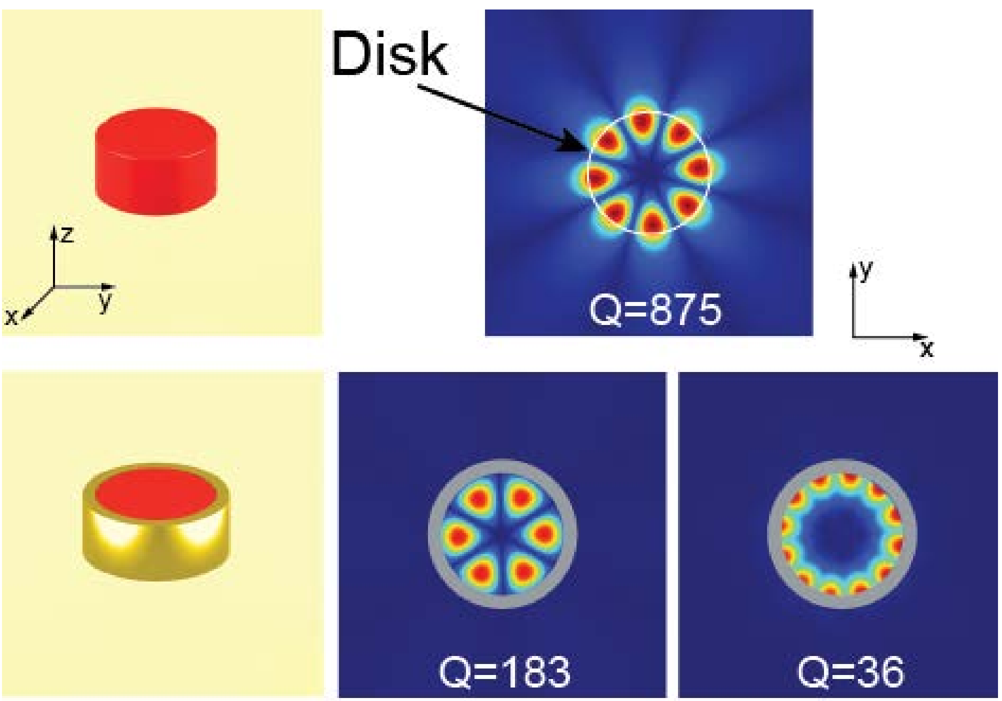

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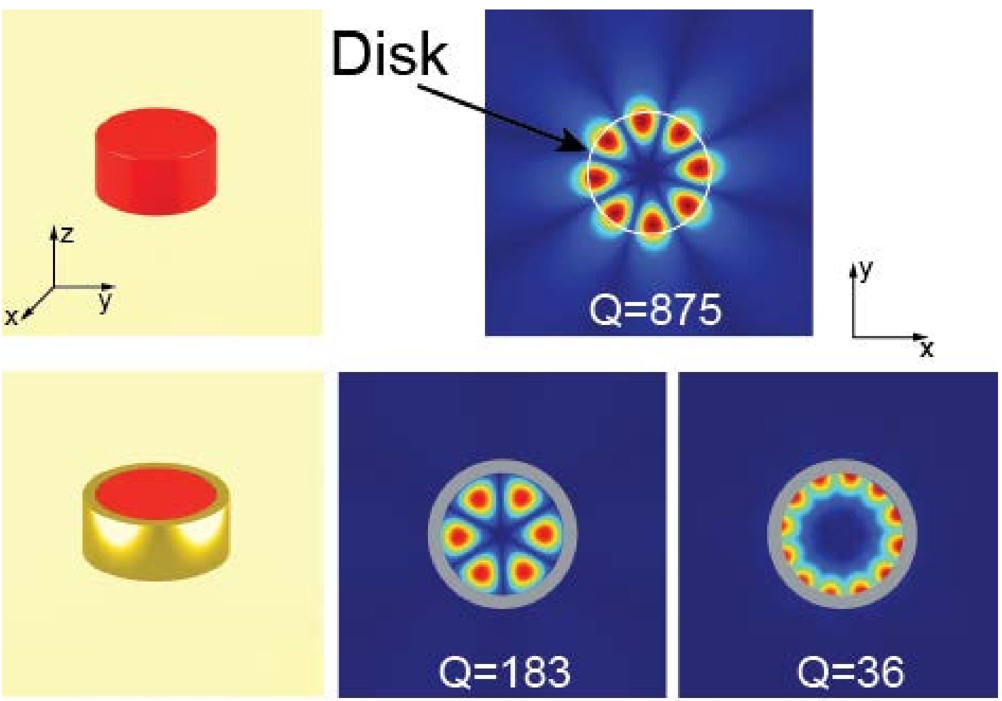
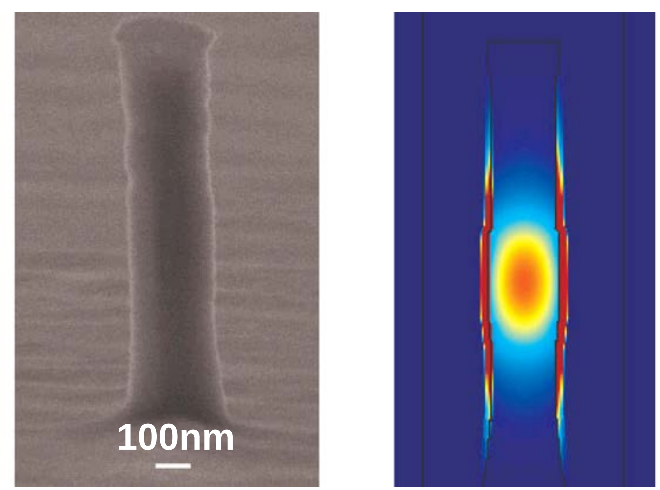


Metallic-cavity nanolaser



Hill, *et al.* Nat. Photon., 1, 589 (2007)

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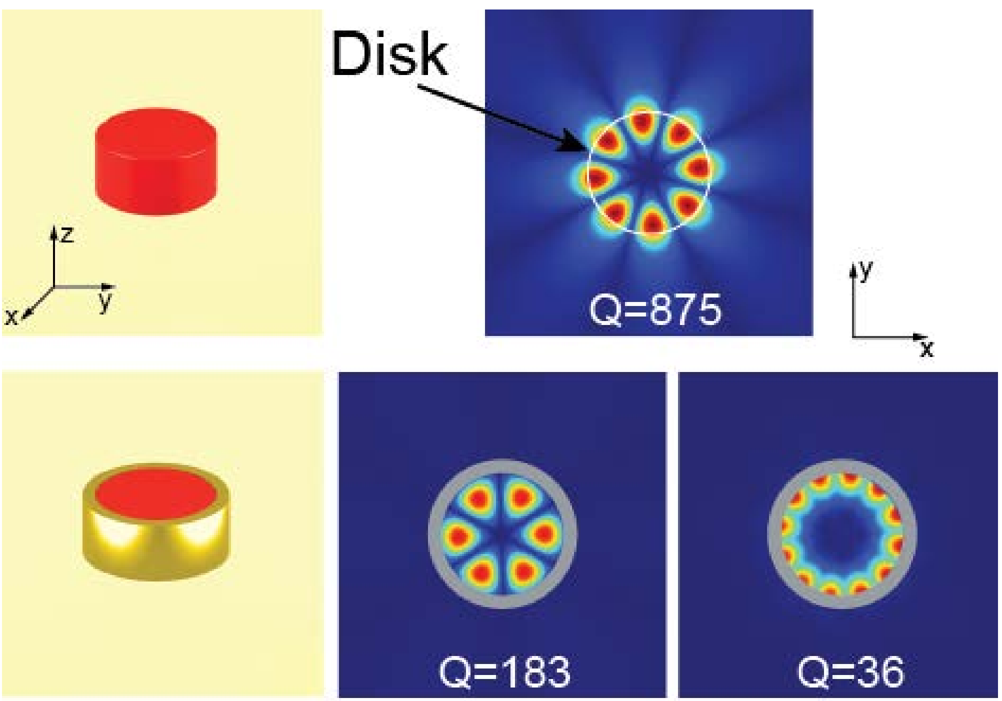

Metallic-cavity nanolaser

@ 77K

Q = 140

$g_{th} \approx 7x10^{5}$ cm^{-1}

Cavity design: metallic cavity

Desired nanolaser properties for dense chip-scale integration:

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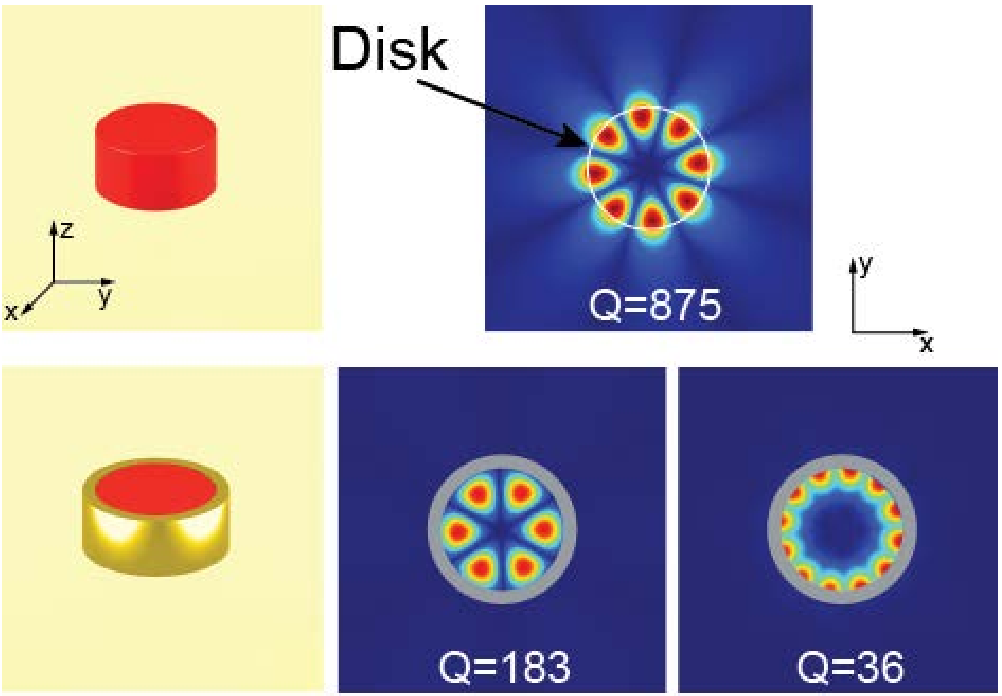
- ✓ sub-wavelength in 3D
- x room temperature operation
- ✓ electrically pumped
- x low lasing threshold



Metallic-cavity nanolaser

@ 300K

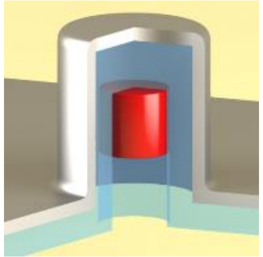
Q = 48

$$g_{th} \approx 3x10^{6}\ cm^{-1}$$

material gain

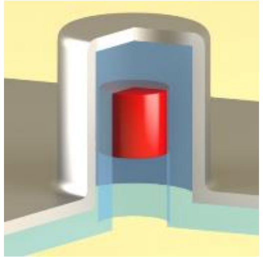
$$g = 3000\ cm^{-1}$$

Lasers in Photonic ICs



Design:
Optical cavity mode

Lasers in Photonic ICs



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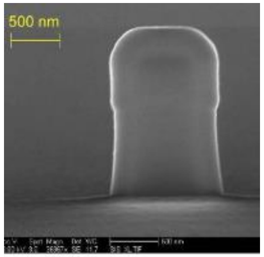
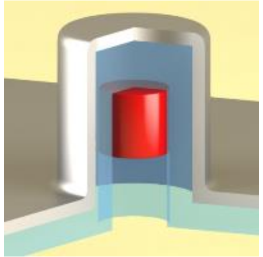
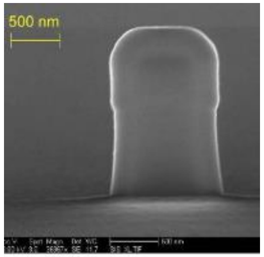


Proof of concept:
Optically pumped laser

Lasers in Photonic ICs

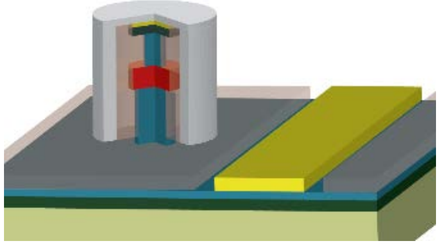


Design:
Optical cavity mode

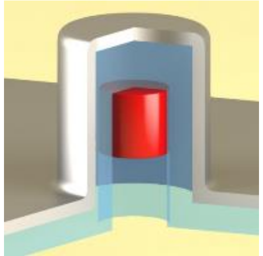


Proof of concept:
Optically pumped laser

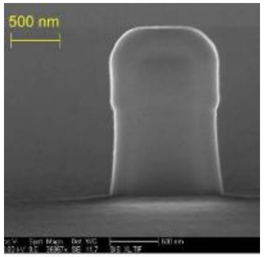
Multi-physics design
for electrical pumping:
Optical, electrical, thermal



Lasers in Photonic ICs



Design:
Optical cavity mode



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Optically pumped laser

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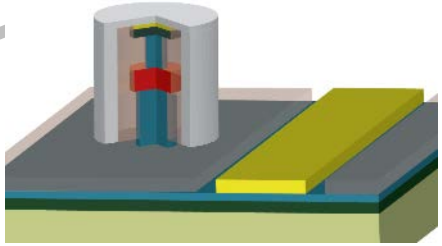
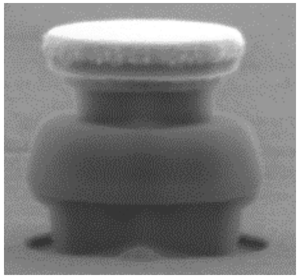
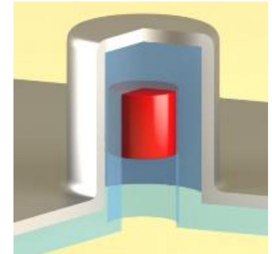
Optical, electrical, thermal



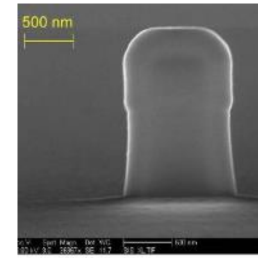
Demonstration:
Electrically pumped laser



Lasers in Photonic ICs



Design:
Optical cavity mode



Proof of concept:
Optically pumped laser

Multi-physics design
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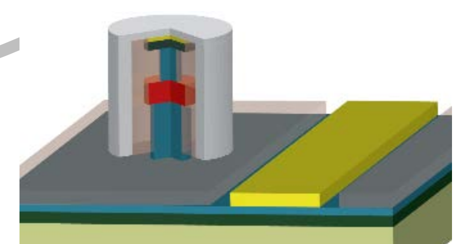
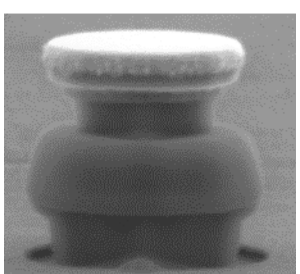
Optical, electrical, thermal

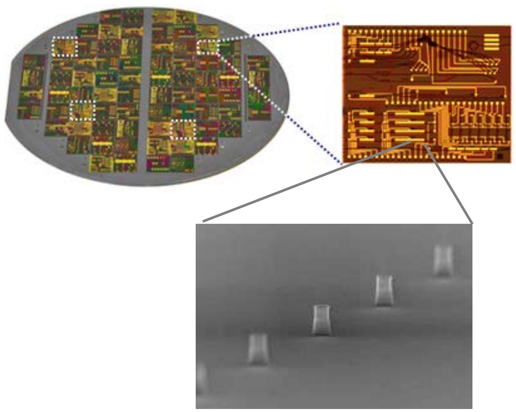


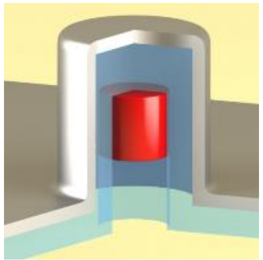
Demonstration:
Electrically pumped laser



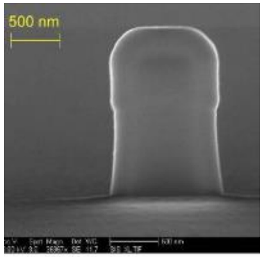
Analysis:
- **Modulation speed**
- **Energy efficiency**

Lasers in Photonic ICs



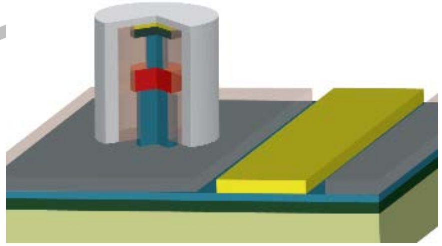


Design:
Optical cavity mode

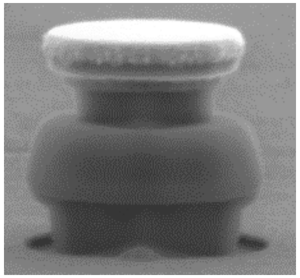


Proof of concept:
Optically pumped laser

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



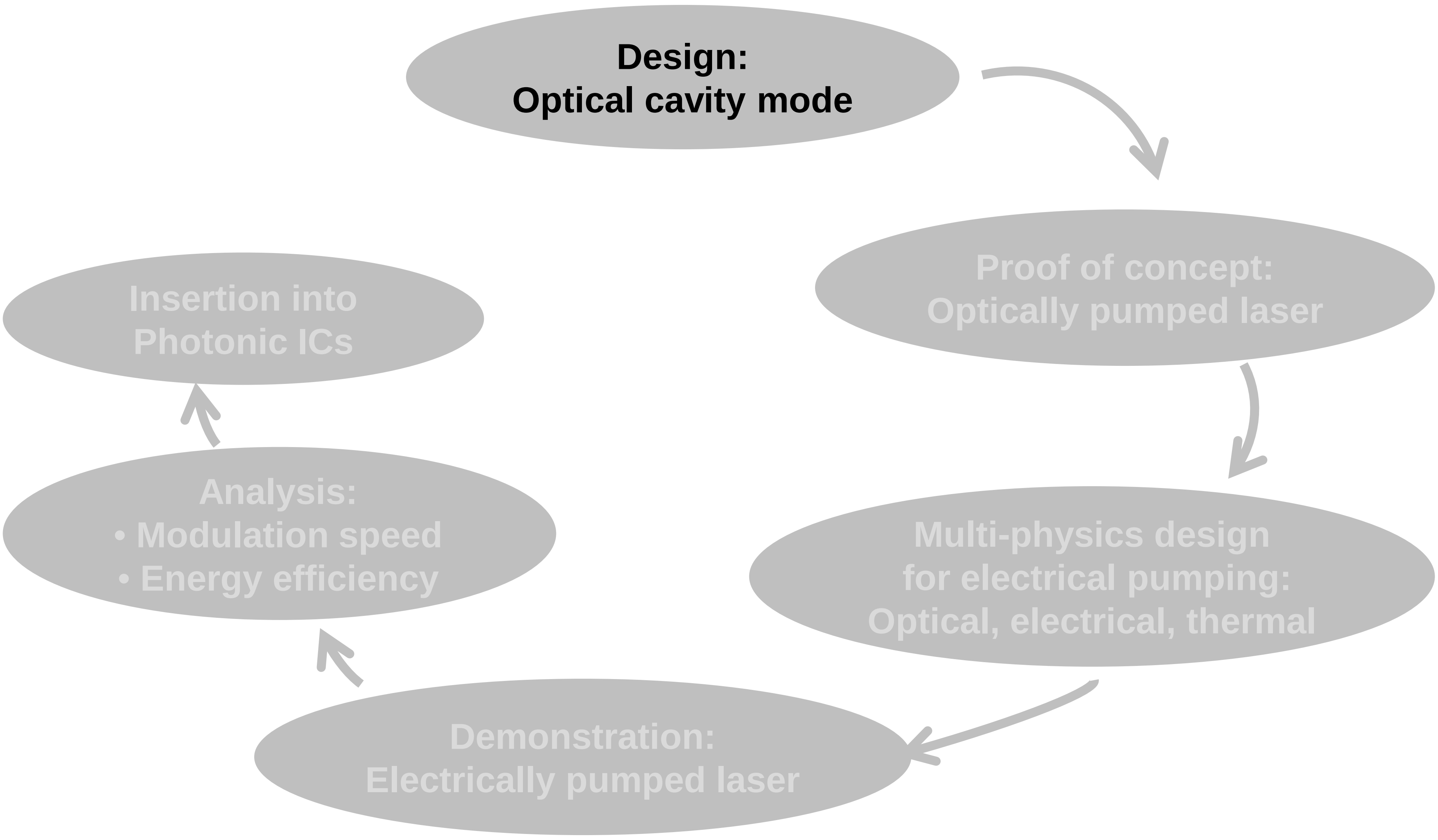
Demonstration:
Electrically pumped laser



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

Insertion into
Photonic ICs

Lasers in Photonic ICs



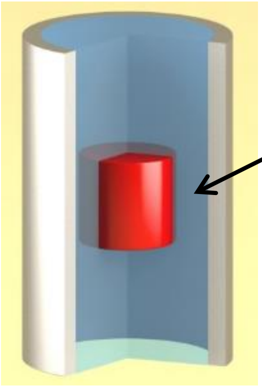
Cavity design: metallo-dielectic cavity

Metallic cavity

Cavity design: metallo-dielectic cavity

Metallic cavity

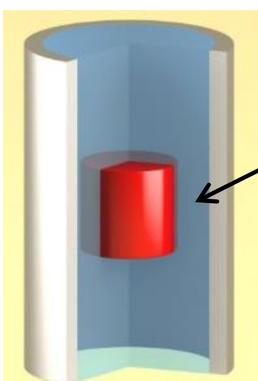
Metallo-dielectric cavity



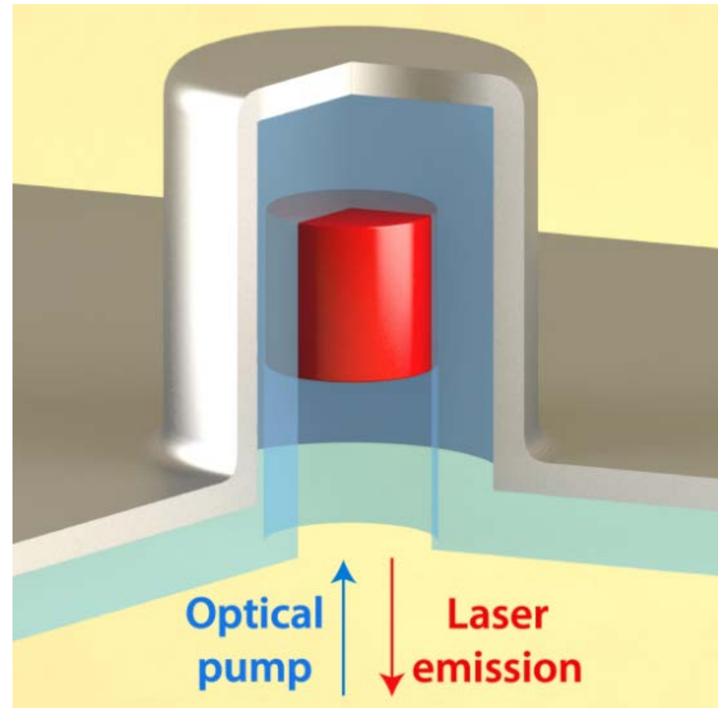
Cavity design: metallo-dielectic cavity

Metallic cavity

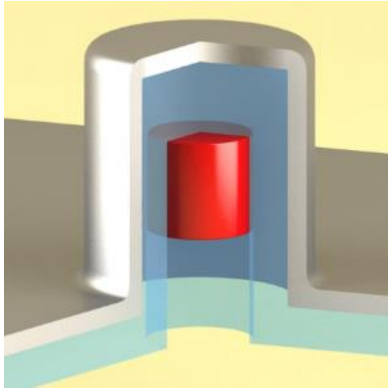
Metallo-dielectric cavity

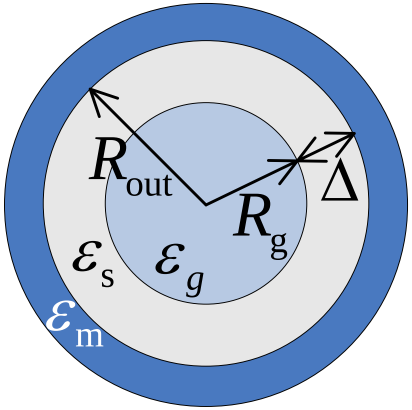


Dielectric
“shield”



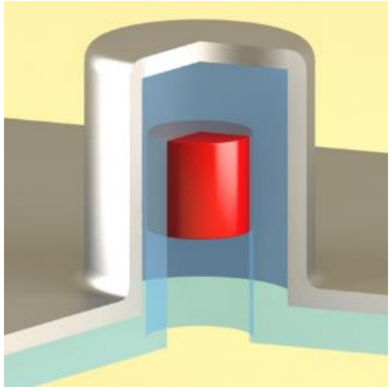
Cavity design: metallo-dielectric cavity

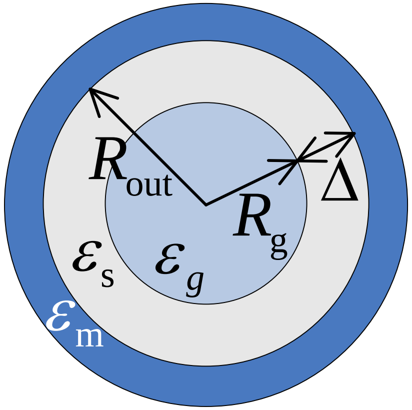


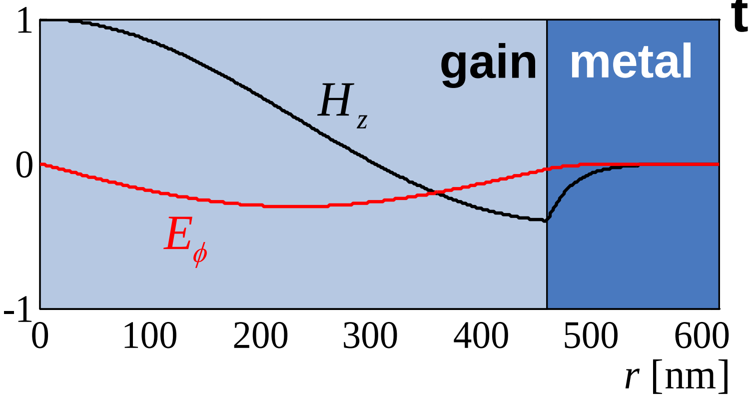


A. Mizrahi et al, *Optics Letters*, 33, 1261-1263, 2008

Cavity design: metallo-dielectric cavity





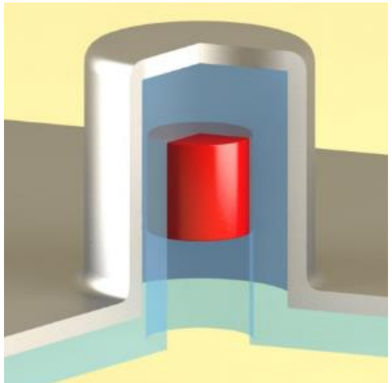


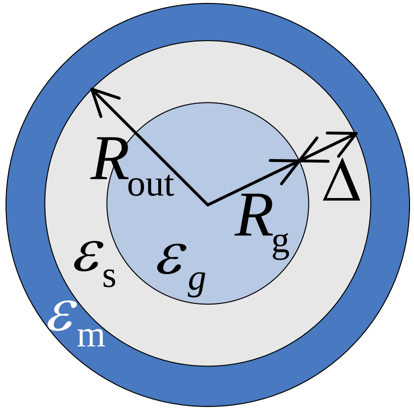
“shield” thickness

Δ=0nm

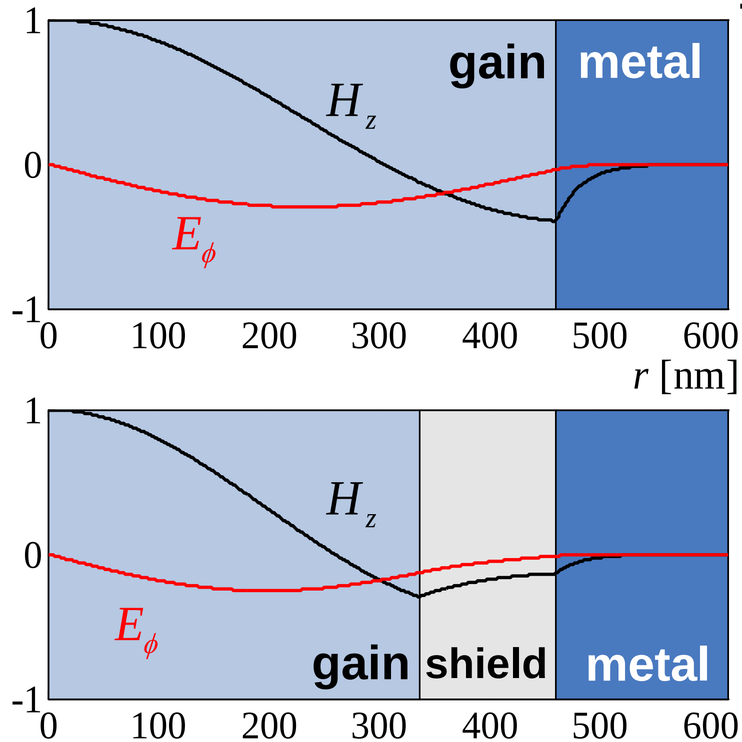
A. Mizrahi et al, *Optics Letters*, 33, 1261-1263, 2008

Cavity design: metallo-dielectric cavity





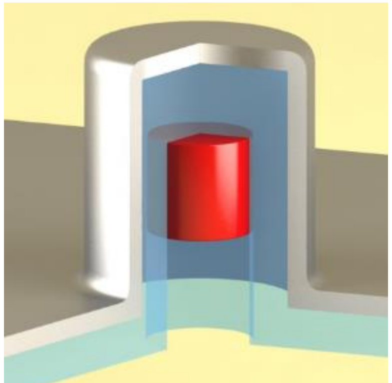
“shield” thickness

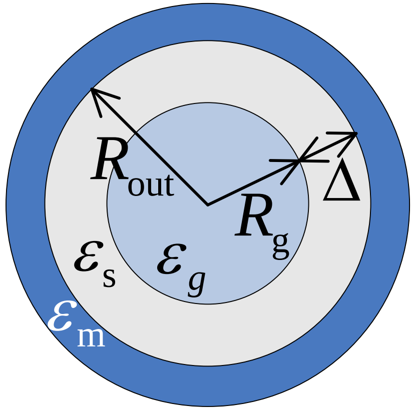


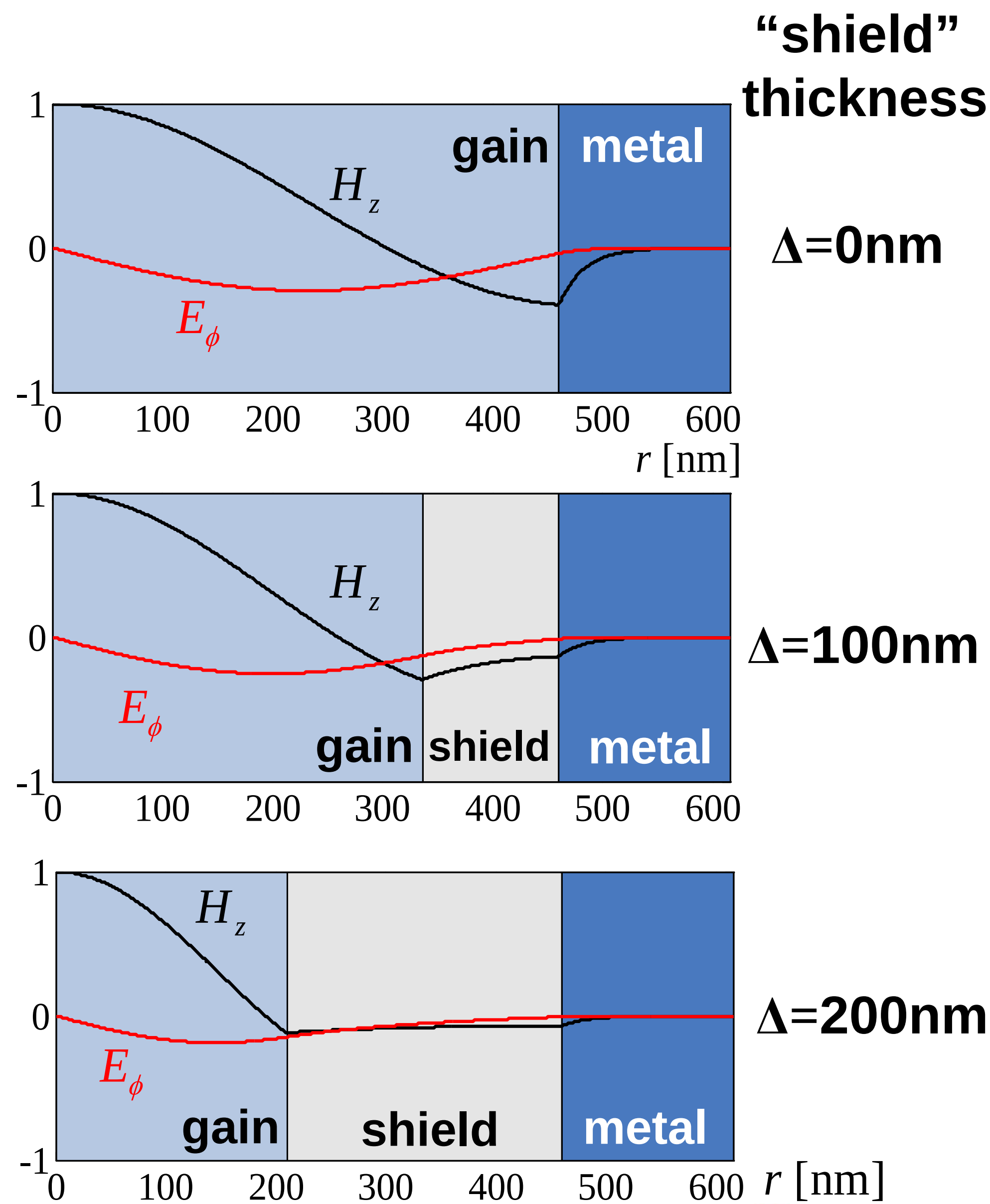
Δ=0nm

Δ=100nm

Cavity design: metallo-dielectric cavity

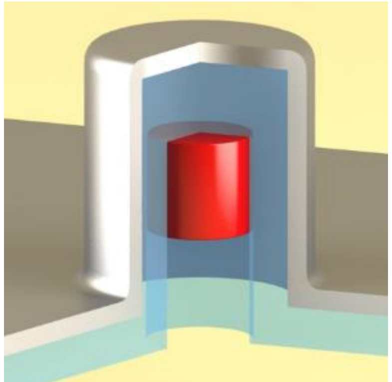


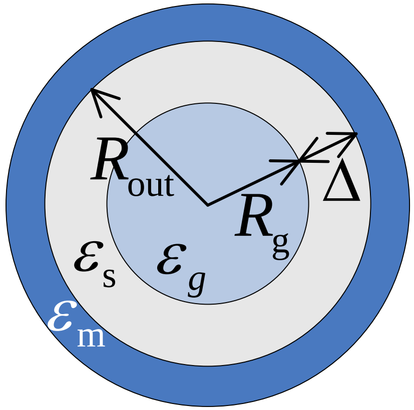


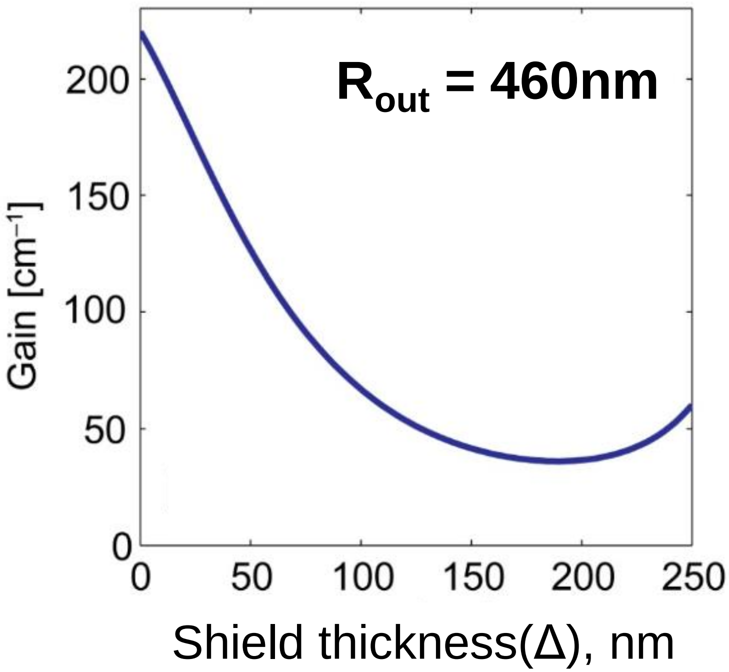


A. Mizrahi et al, *Optics Letters*, 33, 1261-1263, 2008

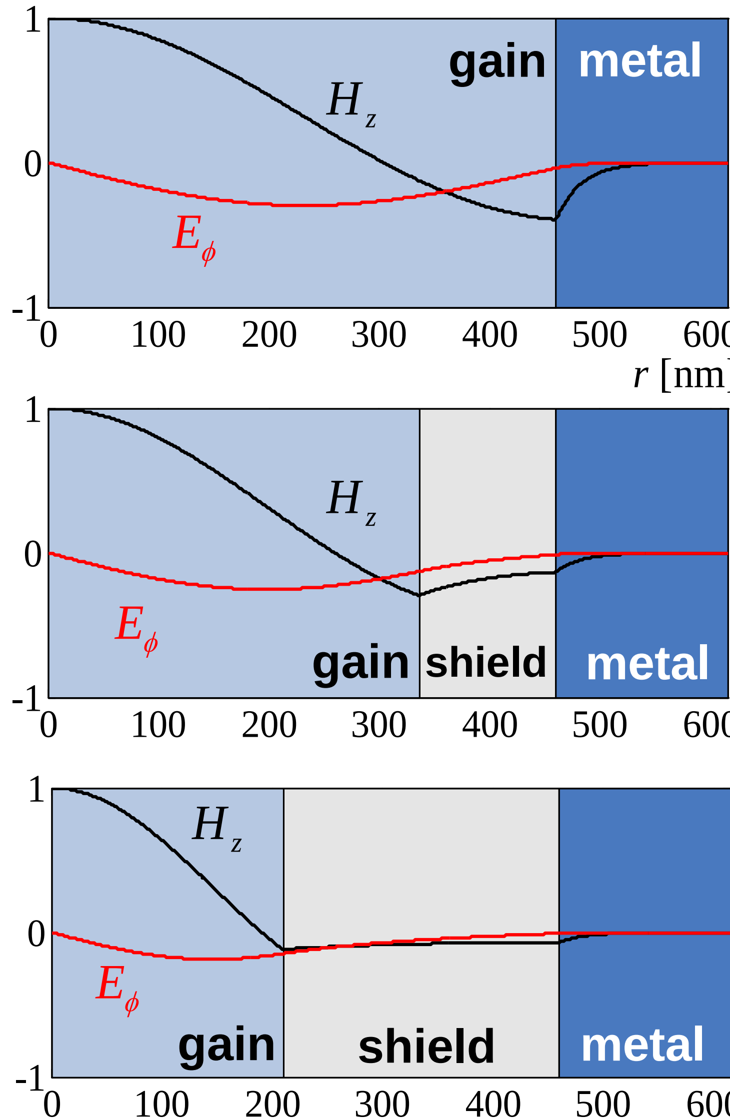
Cavity design: metallo-dielectric cavity







"shield" thickness



Δ=0nm

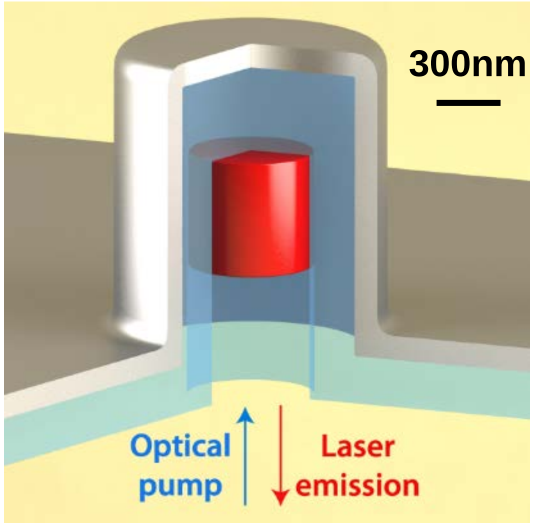
Δ=100nm

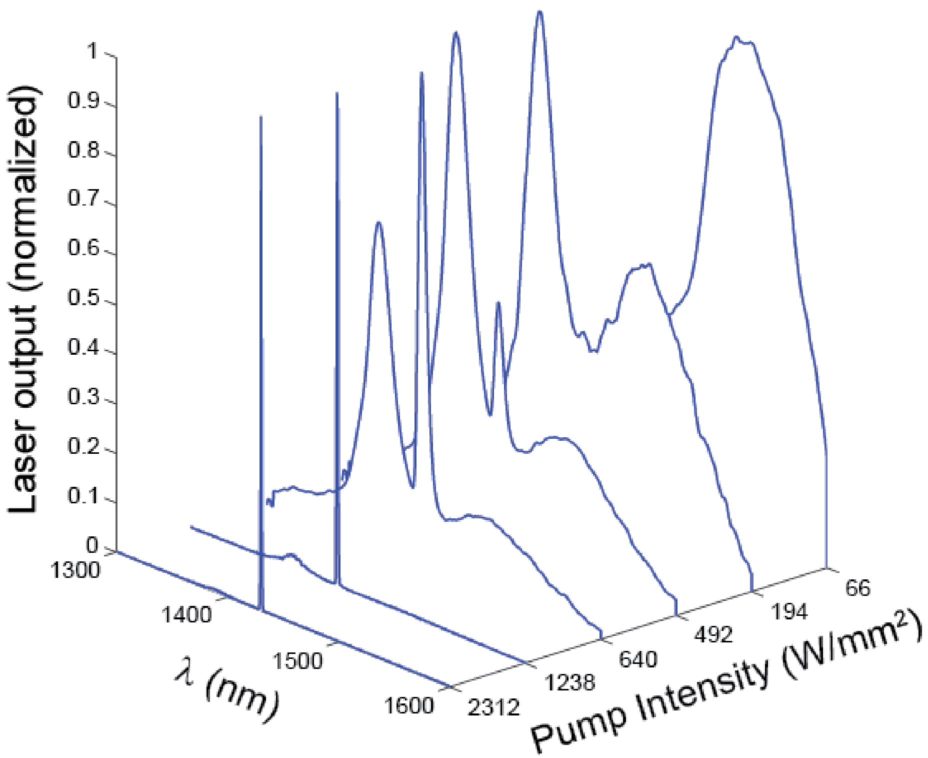
Δ=200nm

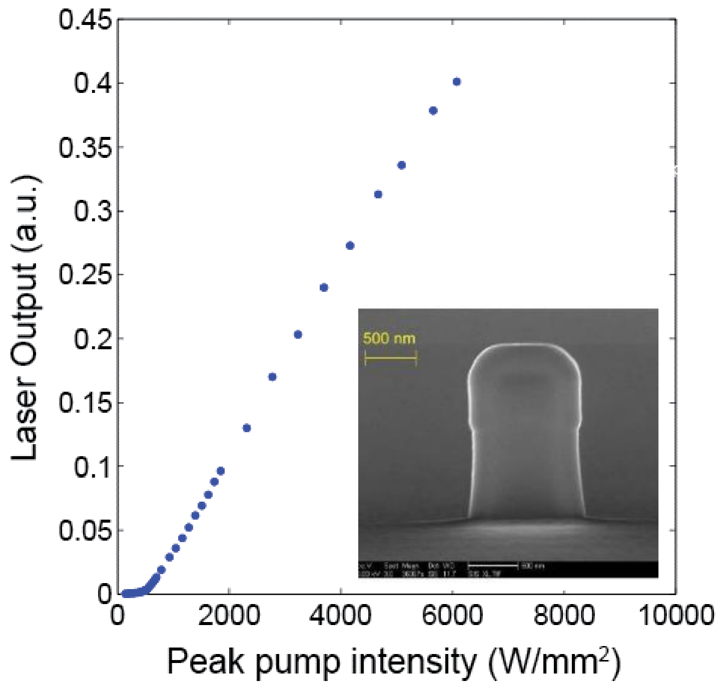
A. Mizrahi et al, *Optics Letters*, 33, 1261-1263, 2008

Optically pumped room temperature nanolaser

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







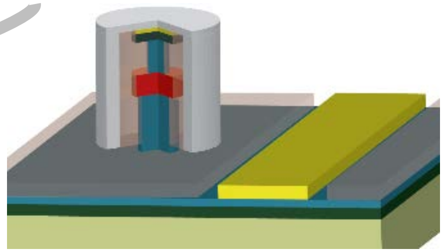
M. P. Nezhad et al, *Nature Photonics*, 4, 6, 395-399, 2010

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

Multi-physics design for electrical pumping

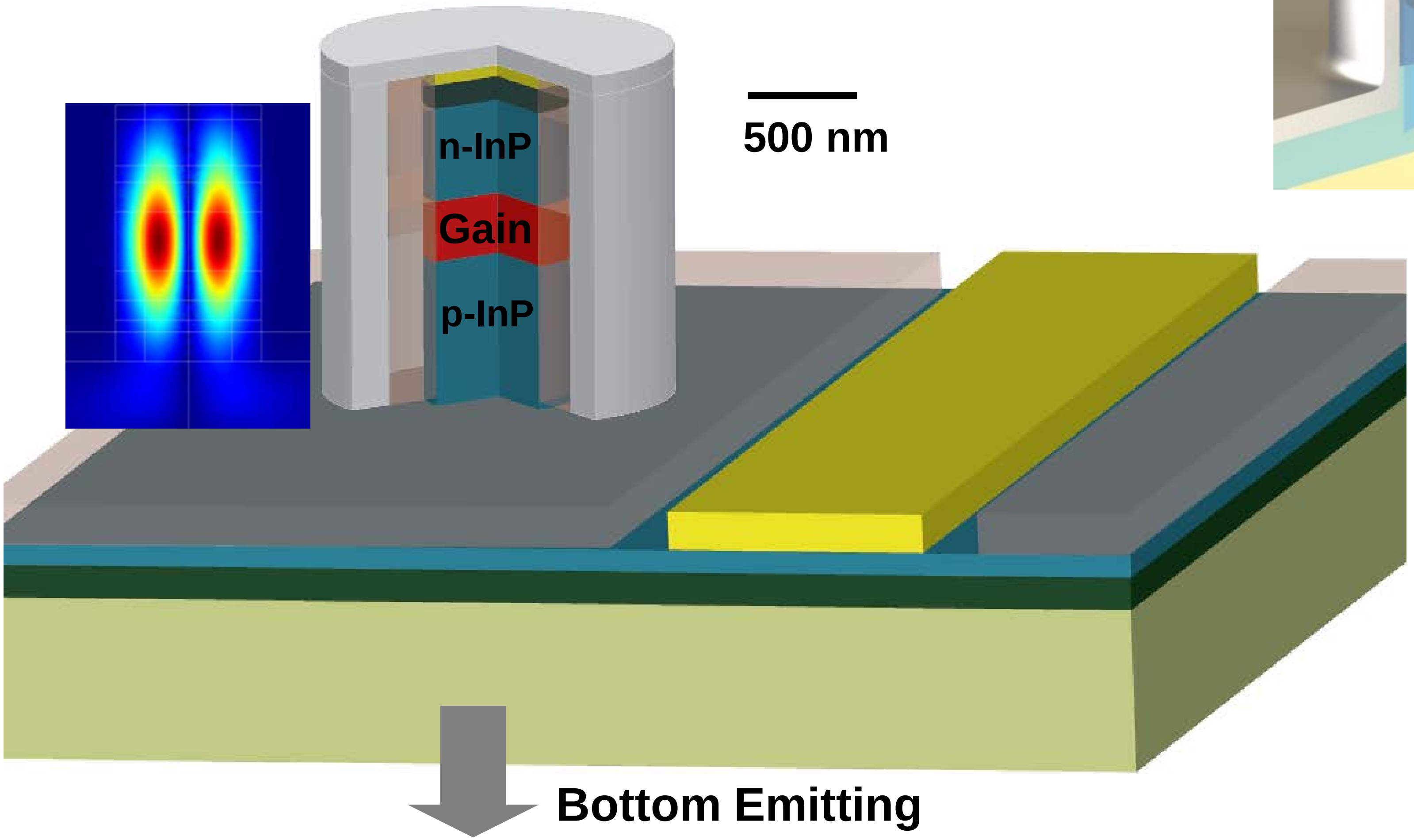
Optical
Cavity design: λ, Q, g_{th}

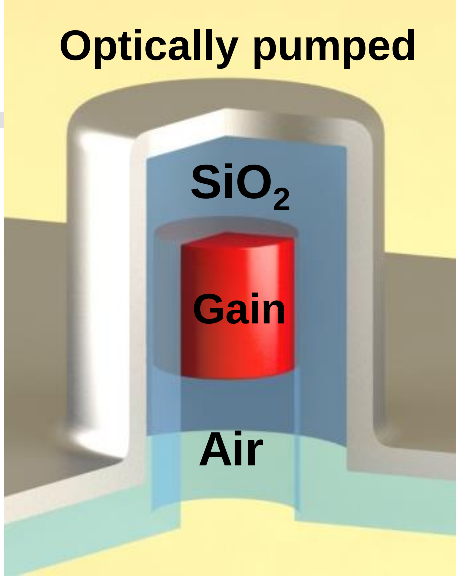
Electrical
Power dissipation, band diagram, heterostructure design

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

T-dependent parameters

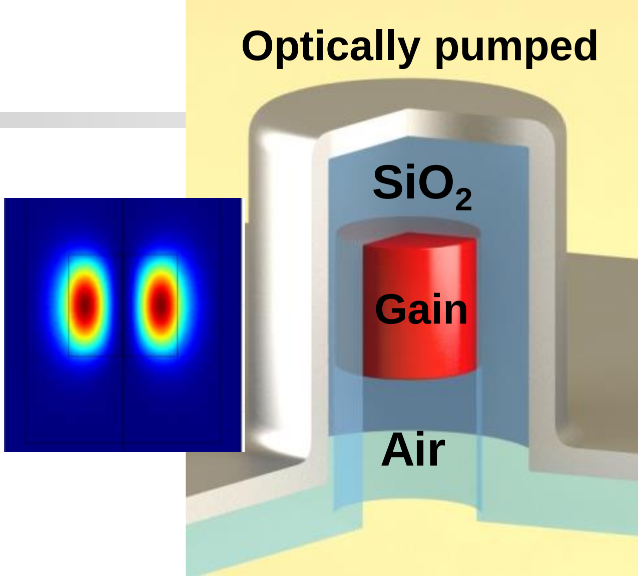
Electrically pumped nanolaser

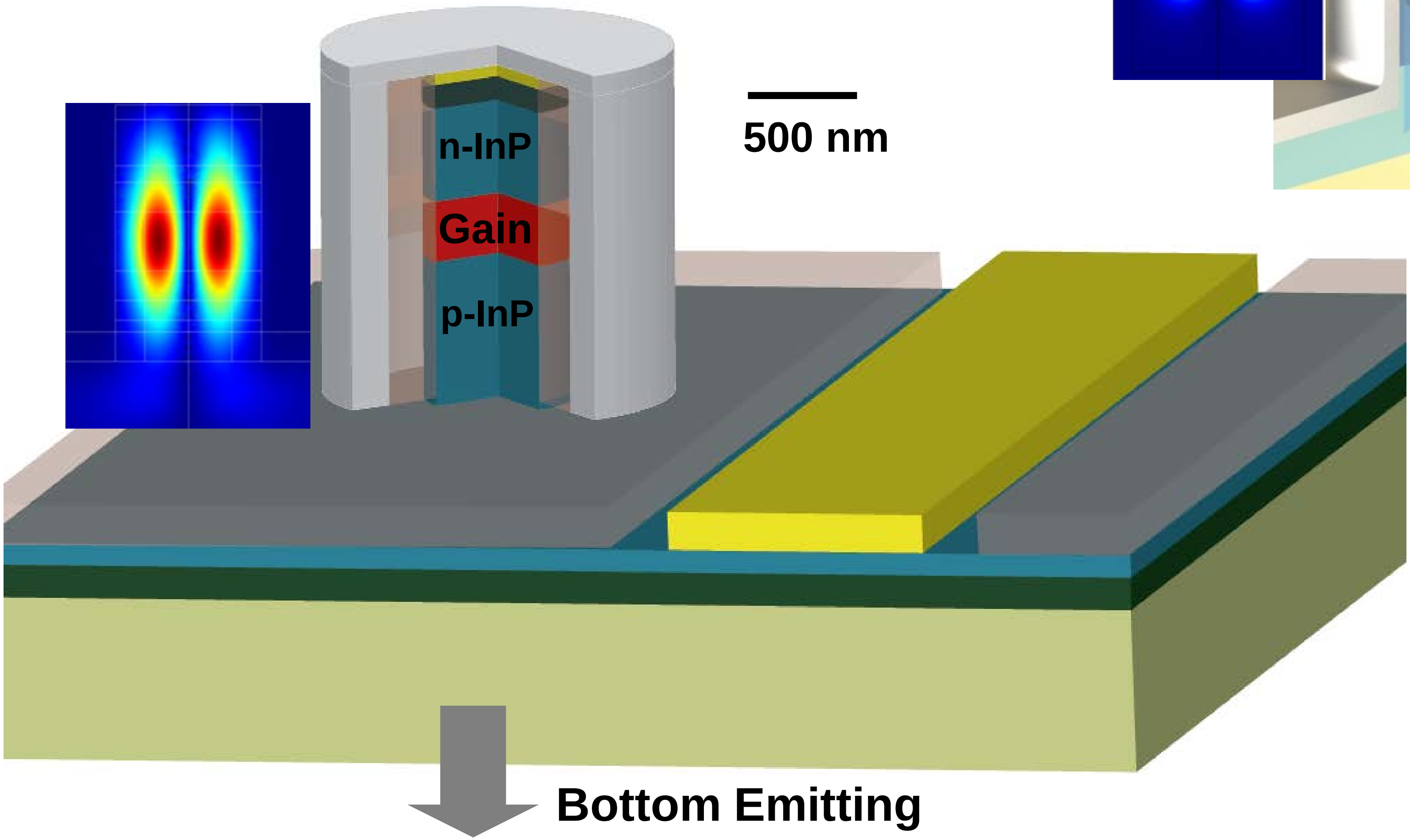




Qing Gu et al, *IEEE JQE*, Vol. 50, Issue 7 (2014);

Electrically pumped nanolaser

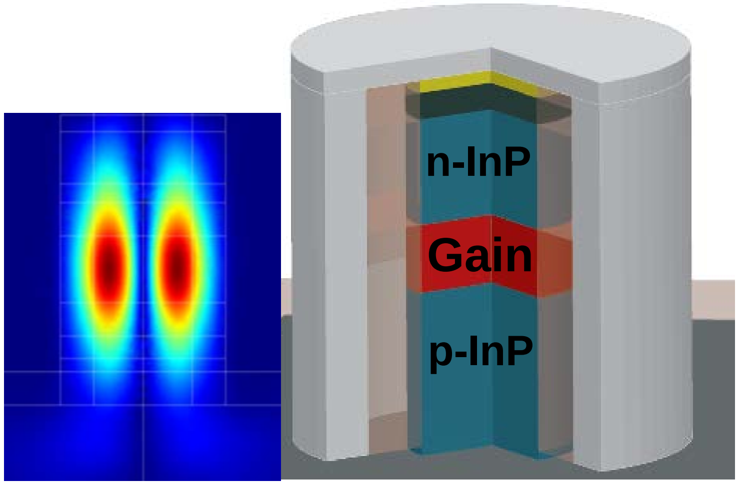




Qing Gu et al, *IEEE JQE*, Vol. 50, Issue 7 (2014);

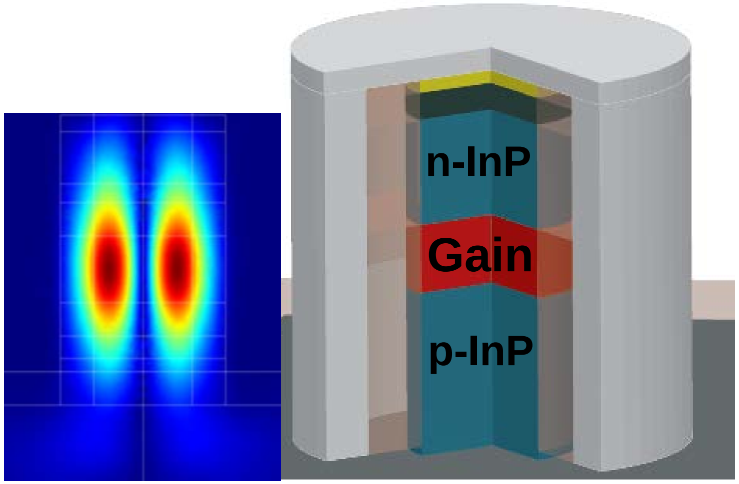
Electrically pumped nanolaser

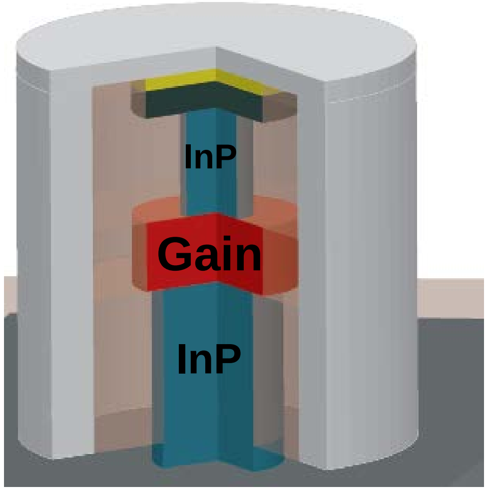
Vertical confinement via InP undercut



Electrically pumped nanolaser

Vertical confinement via InP undercut

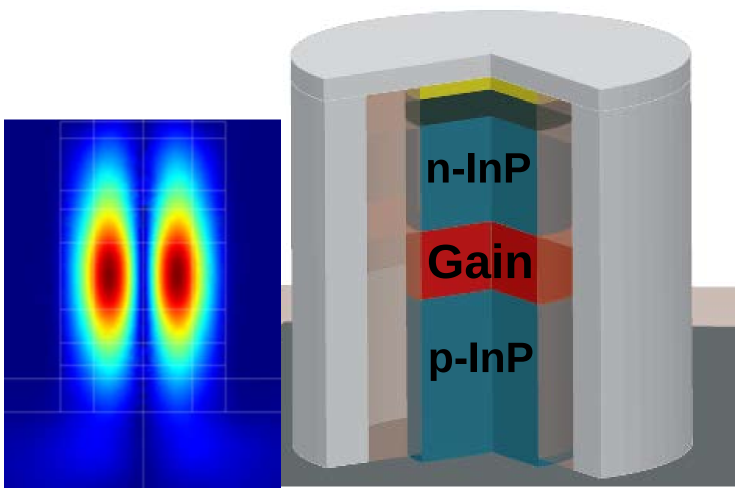


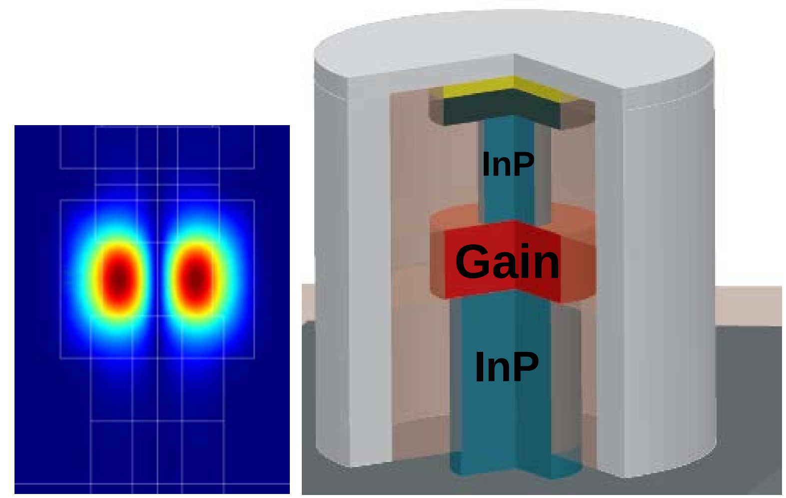


Qing Gu et al, *IEEE JQE*, Vol. 50, Issue 7 (2014);

Electrically pumped nanolaser

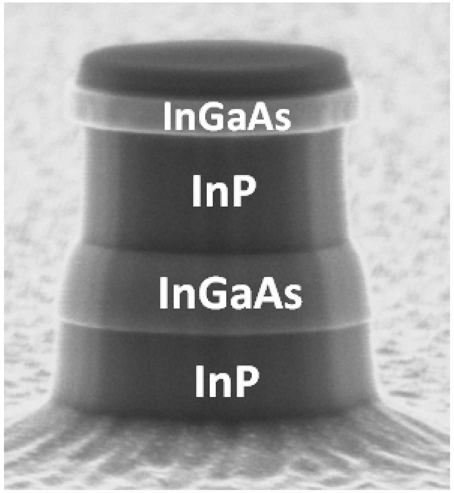
Vertical confinement via InP undercut





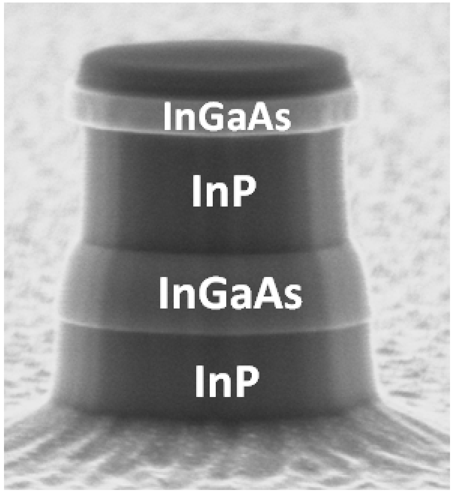
Qing Gu et al, *IEEE JQE*, Vol. 50, Issue 7 (2014);

InP undercut: Two-step selective etching

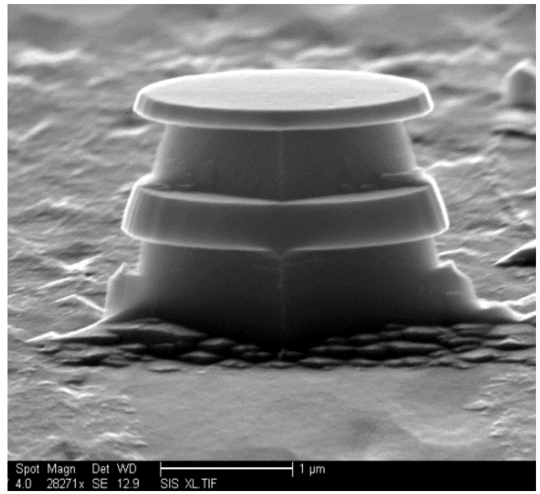


Before
InP undercut

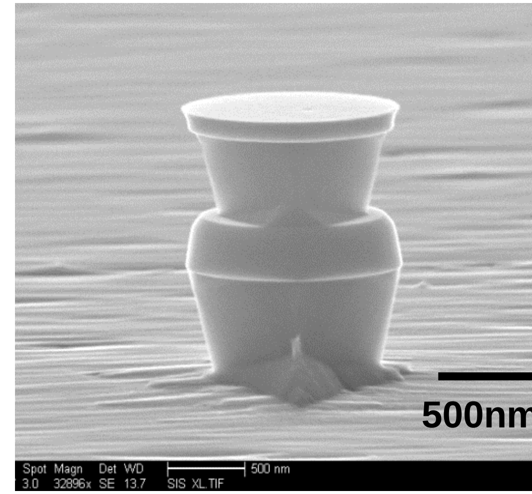
InP undercut: Two-step selective etching



Before
InP undercut

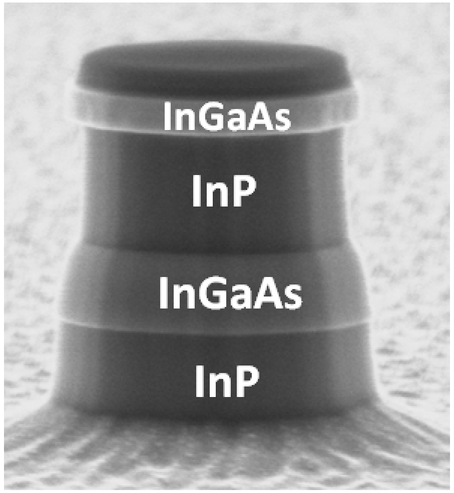


$HCl:CH_3COOH$

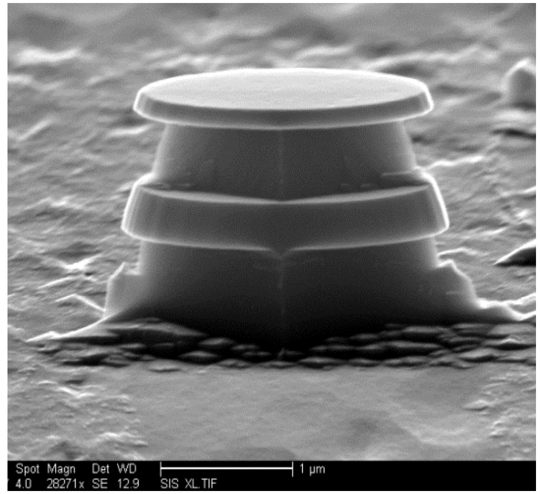


$HCl:H_3PO_4$

InP undercut: Two-step selective etching



Before
InP undercut



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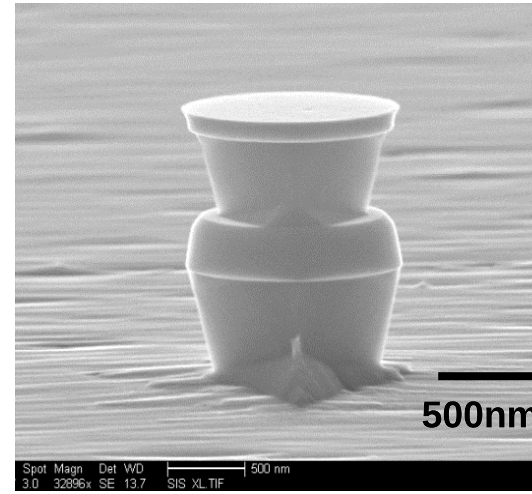
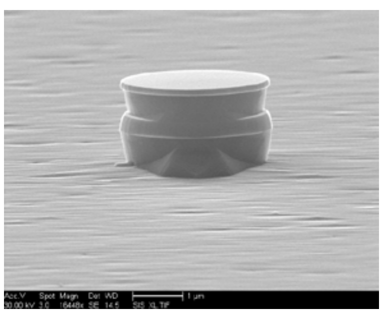
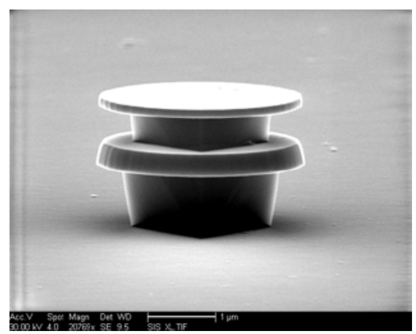


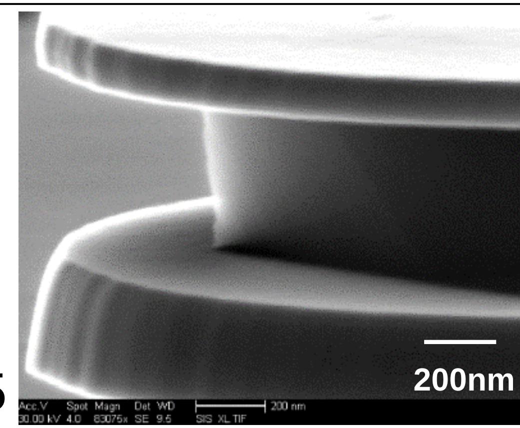
$HCl:H_3PO_4$



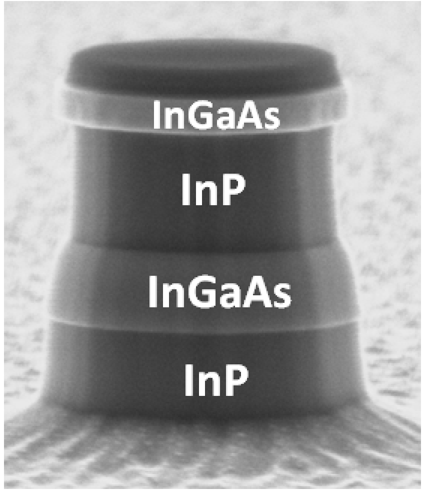
$HCl:H_3PO_4 = 1:4$

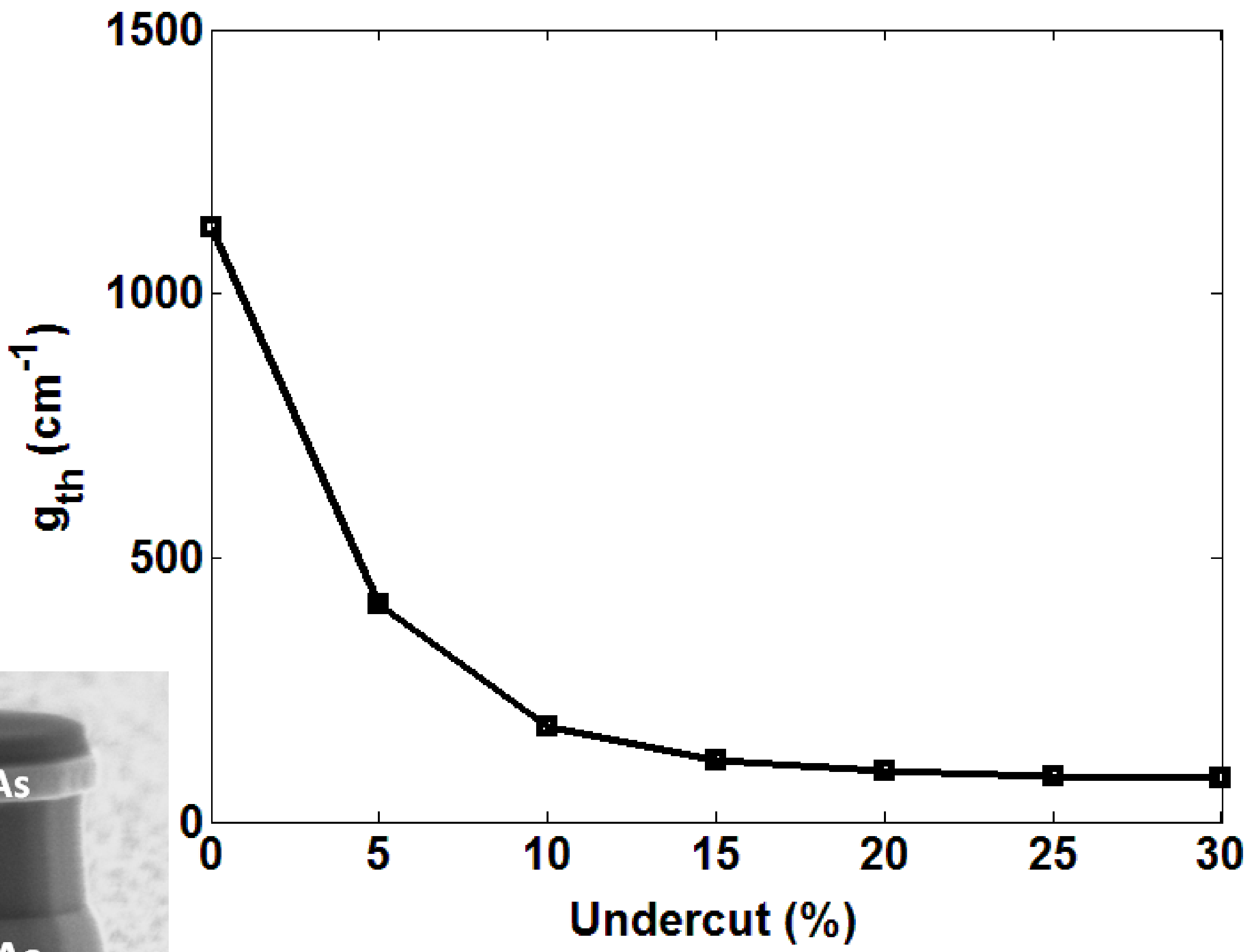


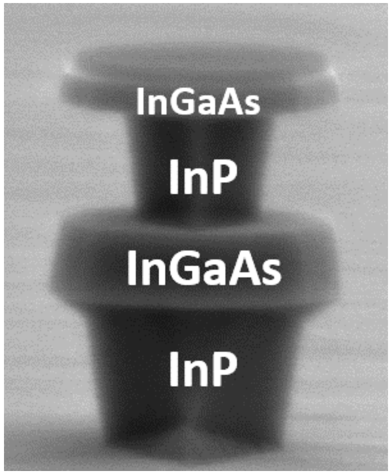
$HCl:CH_3COOH:H_2O = 1:4:5$



Vertical confinement via InP undercut

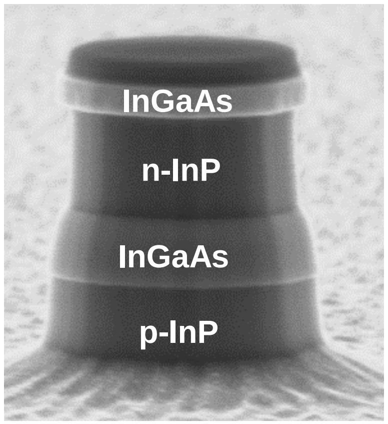


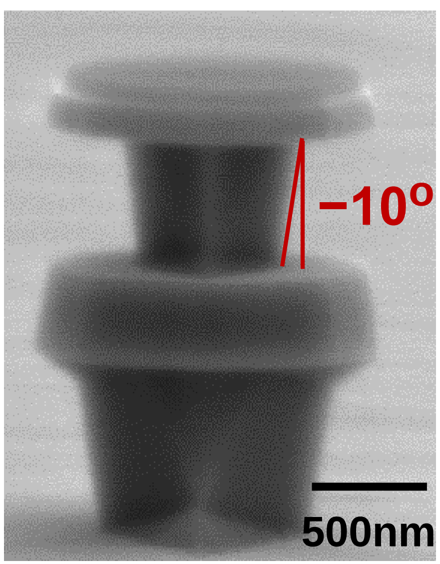


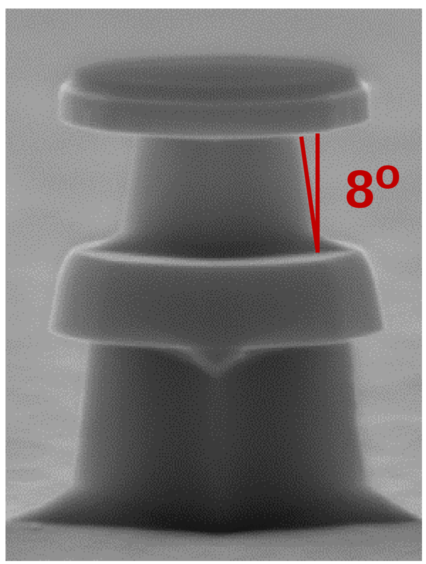


Optical: robust design via InP undercut

Effect of undercut sidewall angle

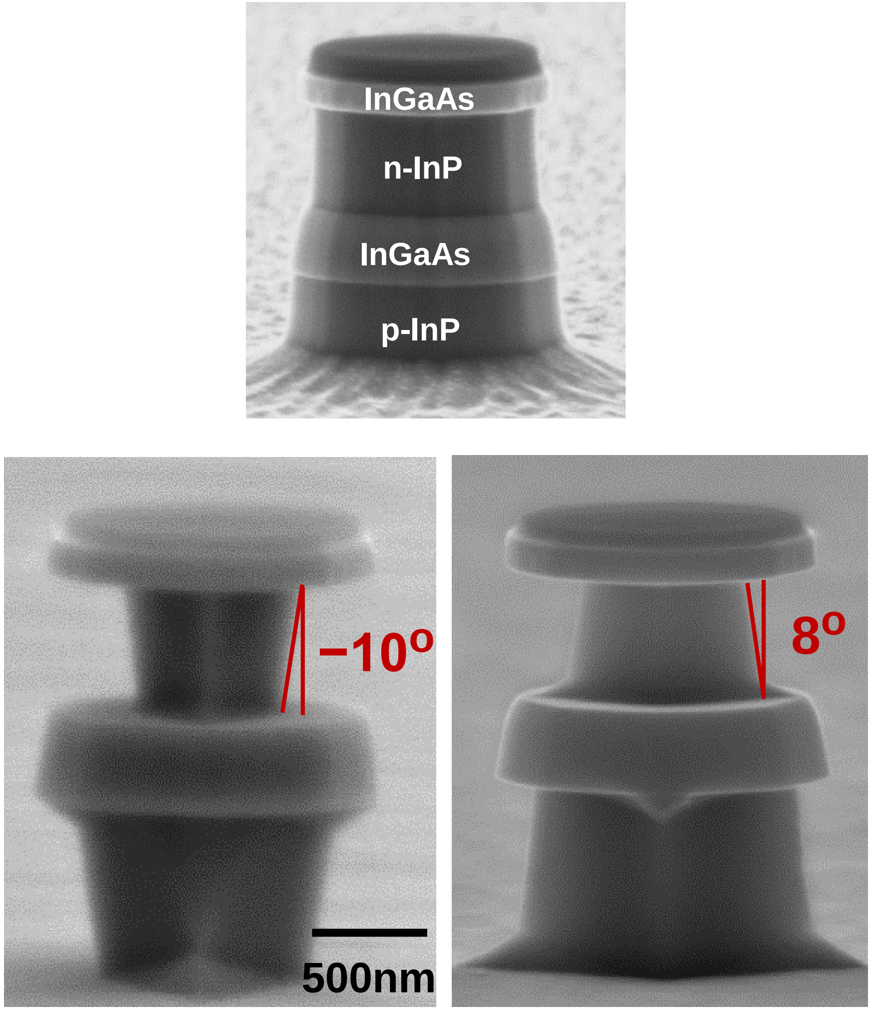


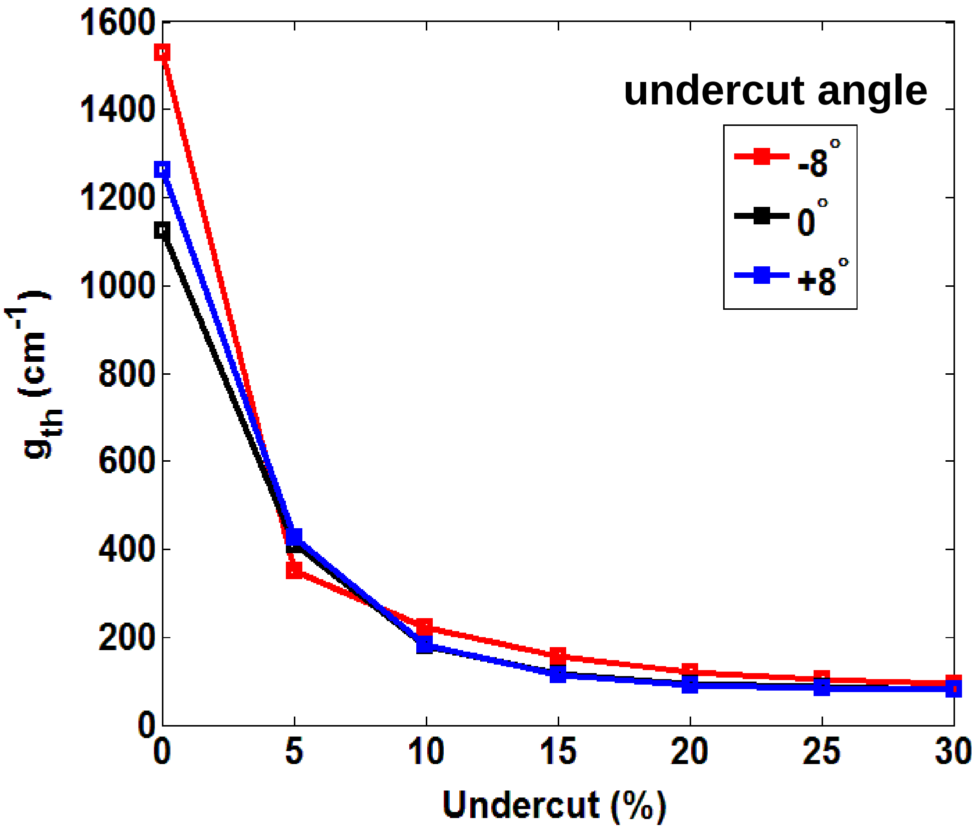




Optical: robust design via InP undercut

Effect of undercut sidewall angle

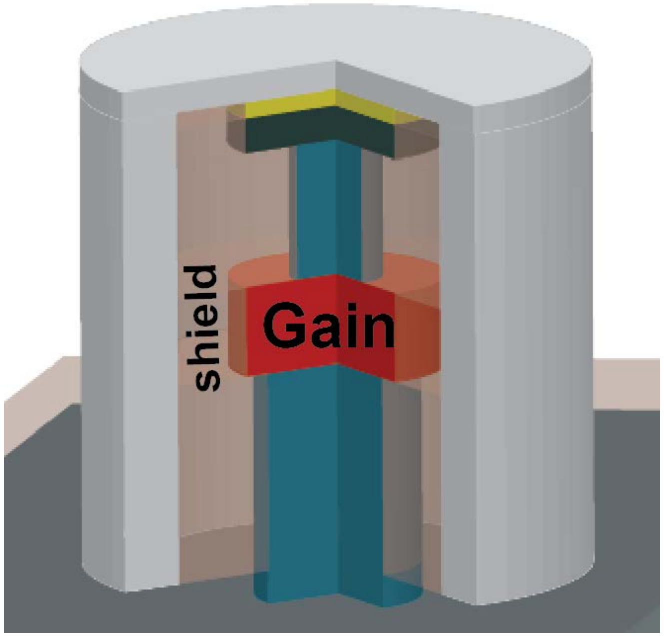




Qing Gu et al, *IEEE JQE*, Vol. 50, Issue 7 (2014); Janelle Shane et al, *IEEE JQE*, Vol. 51, Issue 1 (2015)

Multi-physics design with Al_2O_3 shield

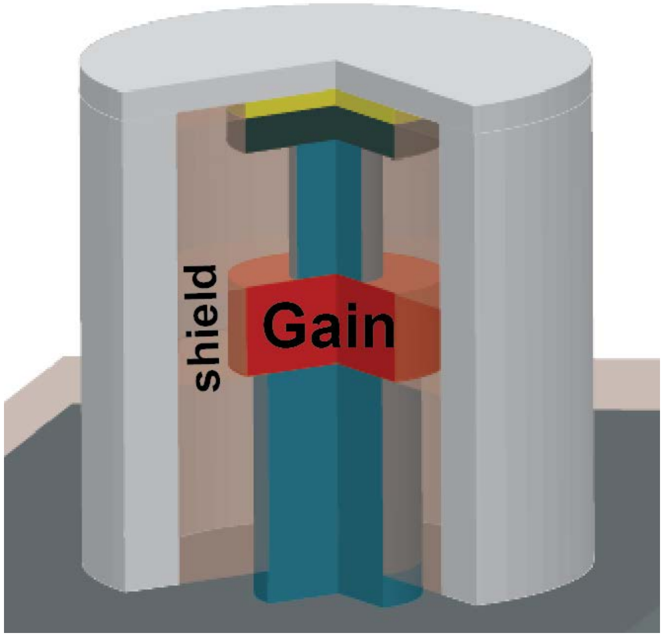
	SiO_2
Thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)	1.1
Refractive index	1.46



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

Multi-physics design with Al_2O_3 shield

	SiO_2	Al_2O_3
Thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)	1.1	2 - 20
Refractive index	1.46	1.64



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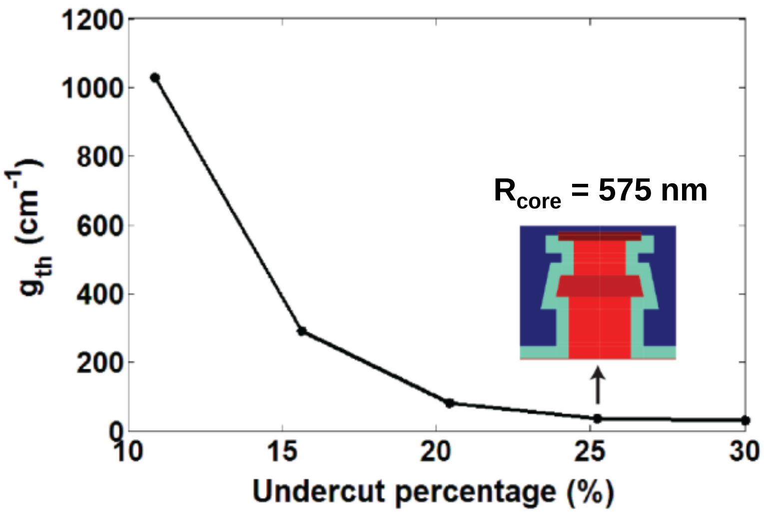
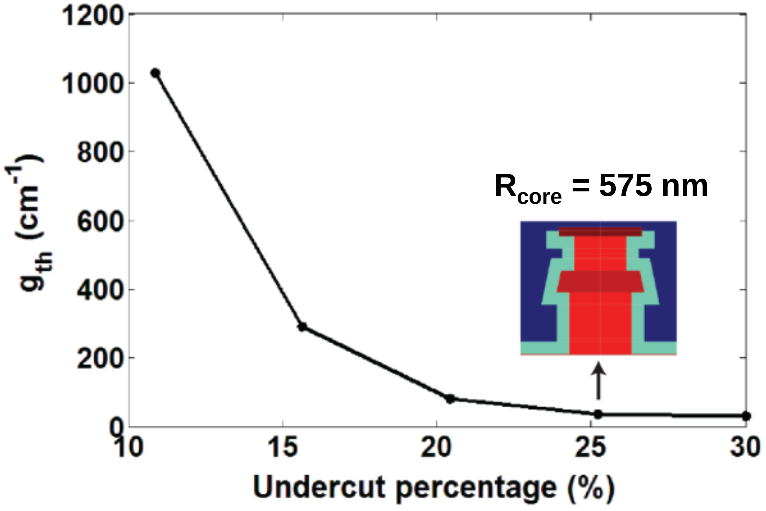
Multi-physics design with Al_2O_3 shield

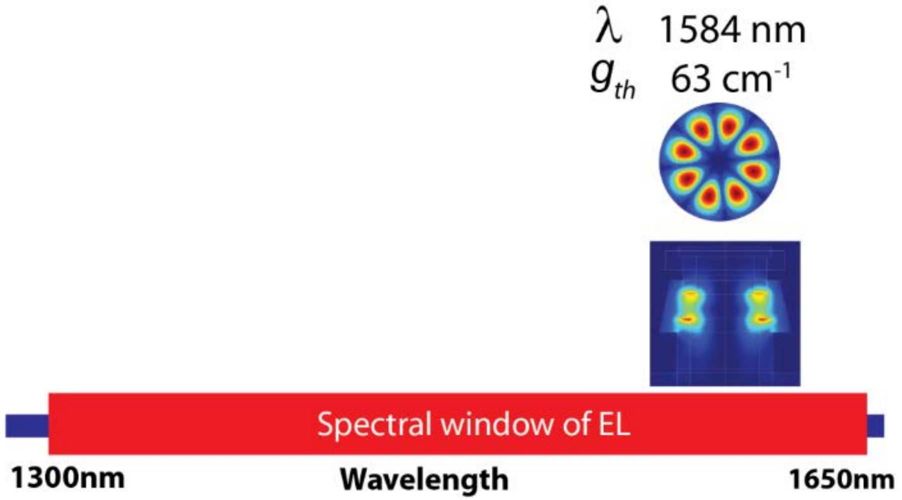
Optical



Multi-physics design with Al_2O_3 shield

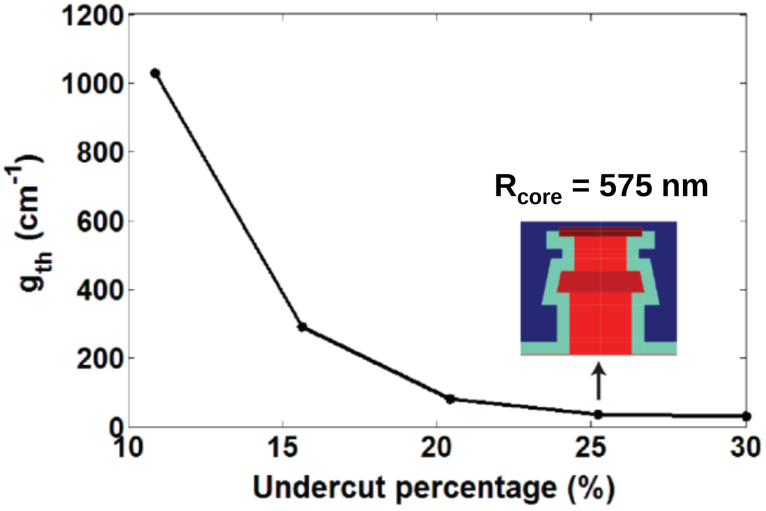
Optical

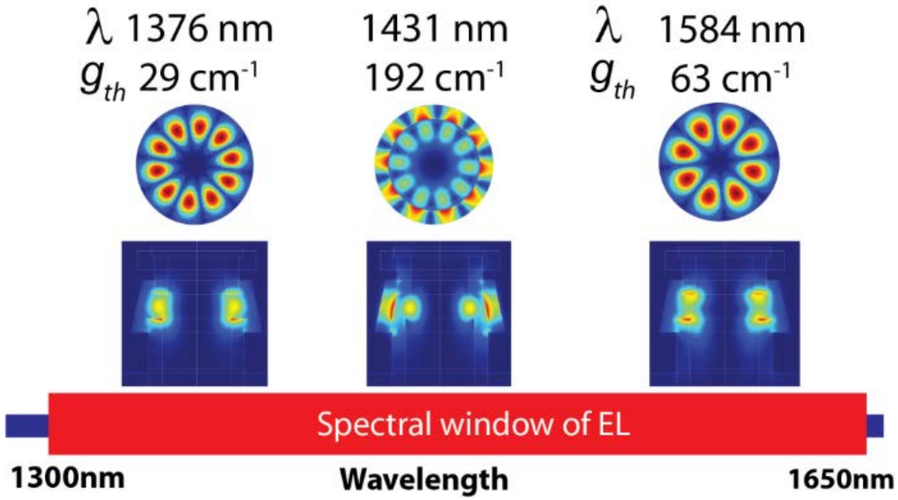




Multi-physics design with Al_2O_3 shield

Optical

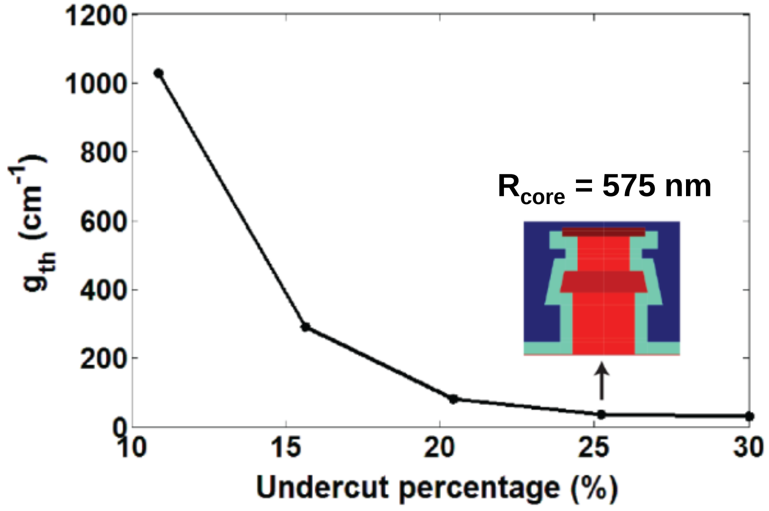


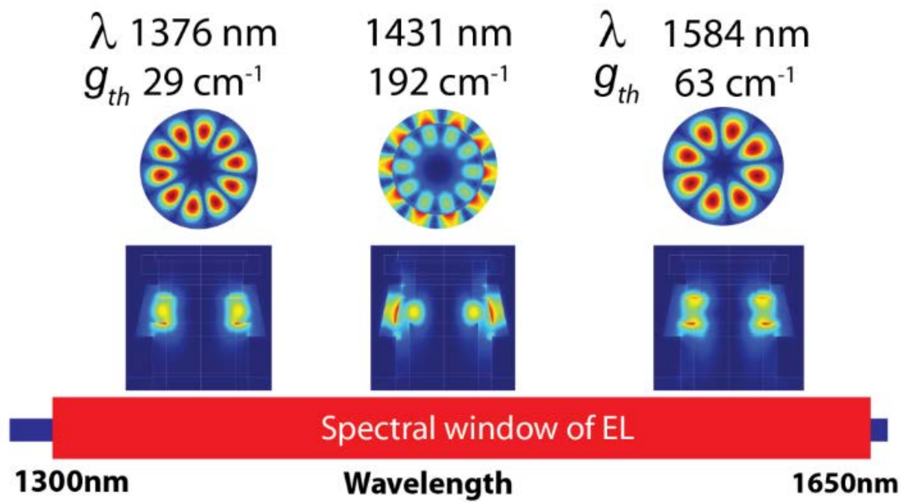


Qing Gu et al, *Nanophotonics*, Vol. 4, Issue 1 (2015)

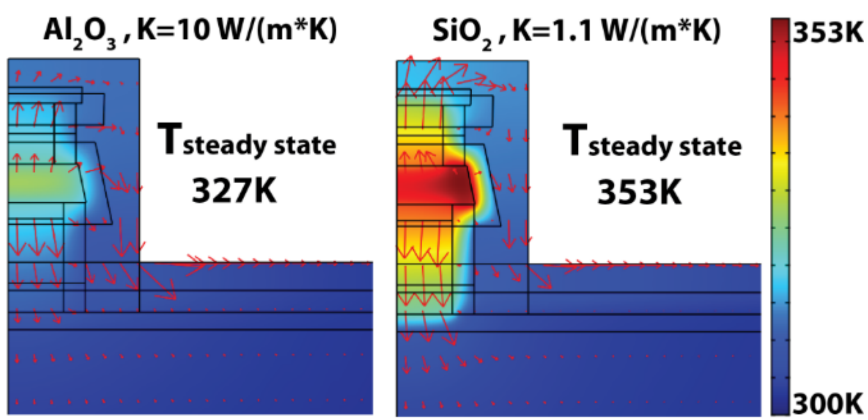
Multi-physics design with Al_2O_3 shield

Optical





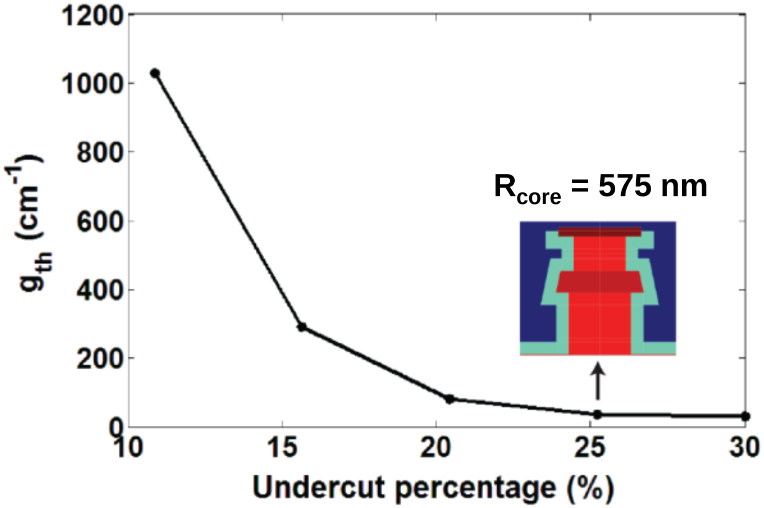
Electrical & Thermal

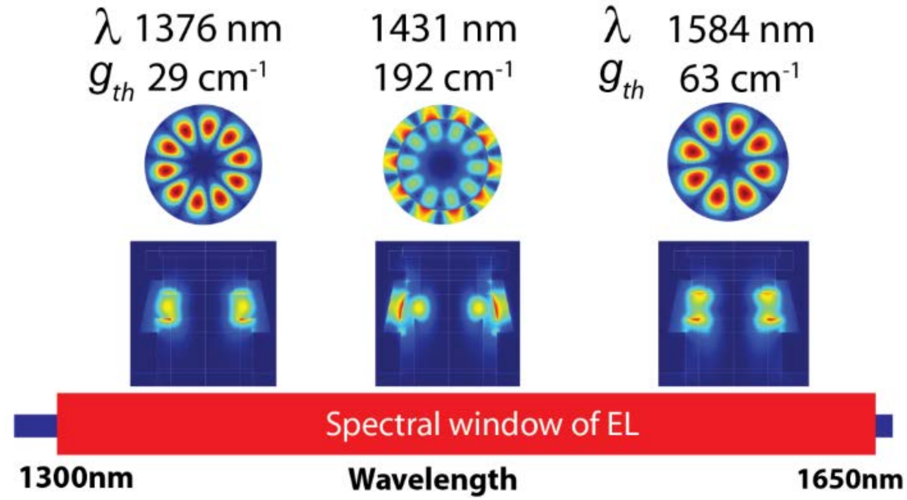


Qing Gu et al, *Nanophotonics*, Vol. 4, Issue 1 (2015)

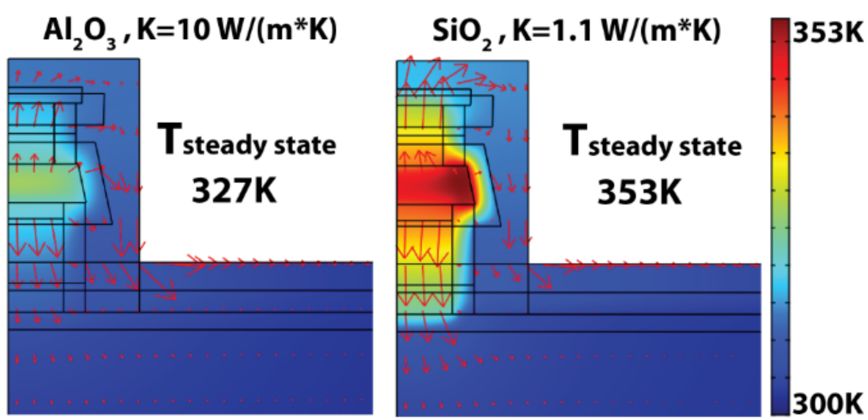
Multi-physics design with Al_2O_3 shield

Optical

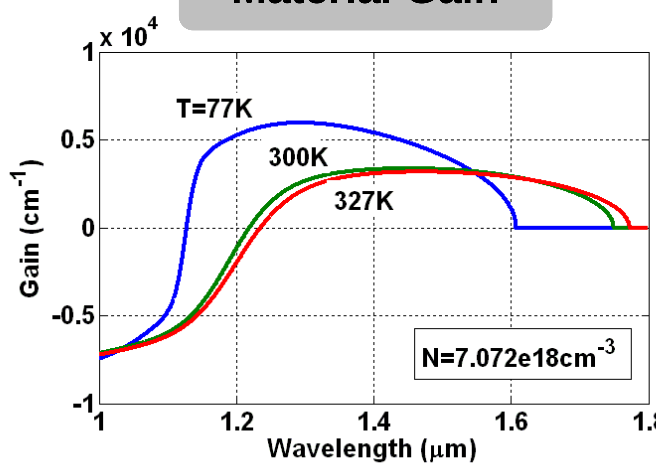




Electrical & Thermal



Material Gain

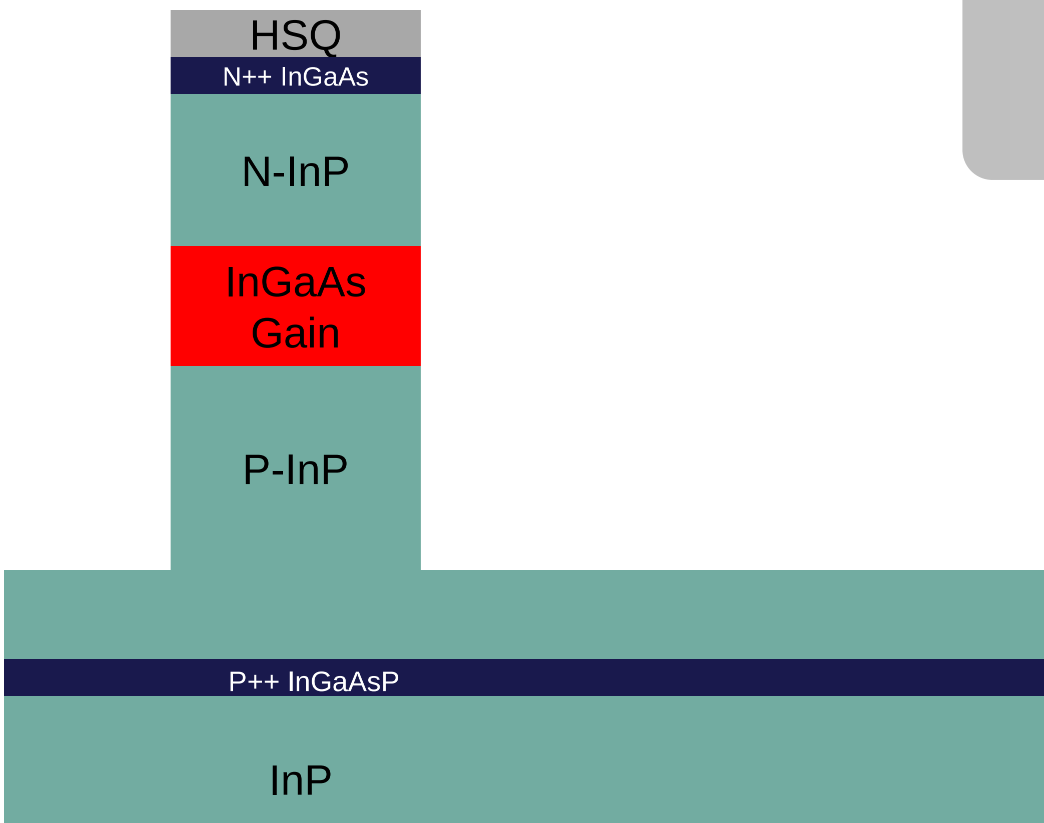


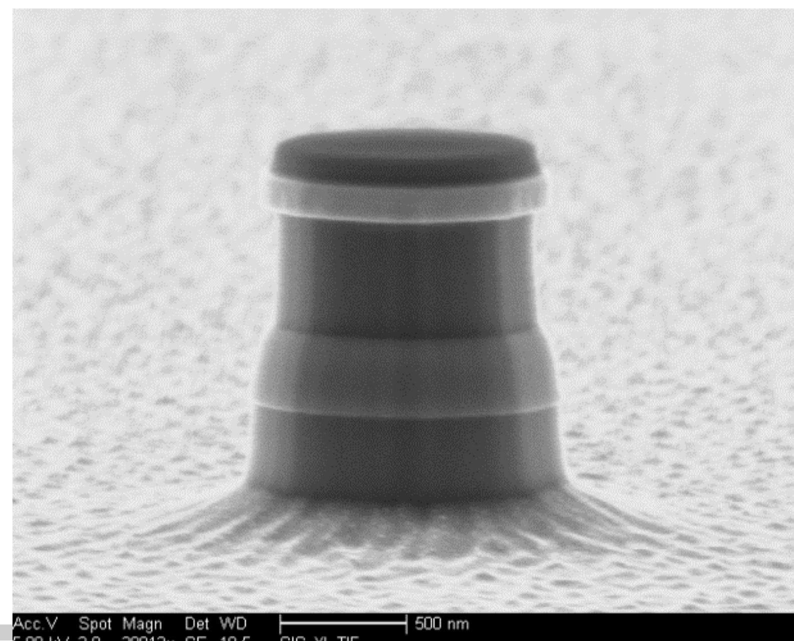
Qing Gu et al, *Nanophotonics*, Vol. 4, Issue 1 (2015)

Fabrication

E-beam patterning/RIE (CH_4:H_2:Ar)

500 nm



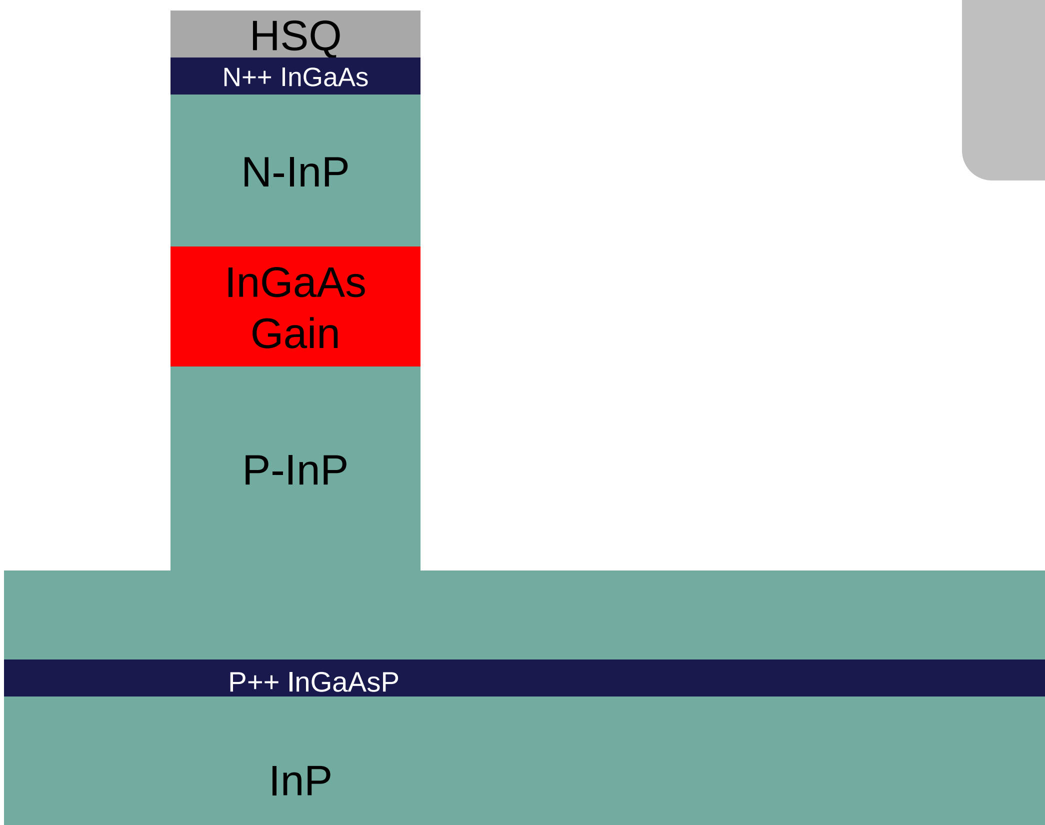


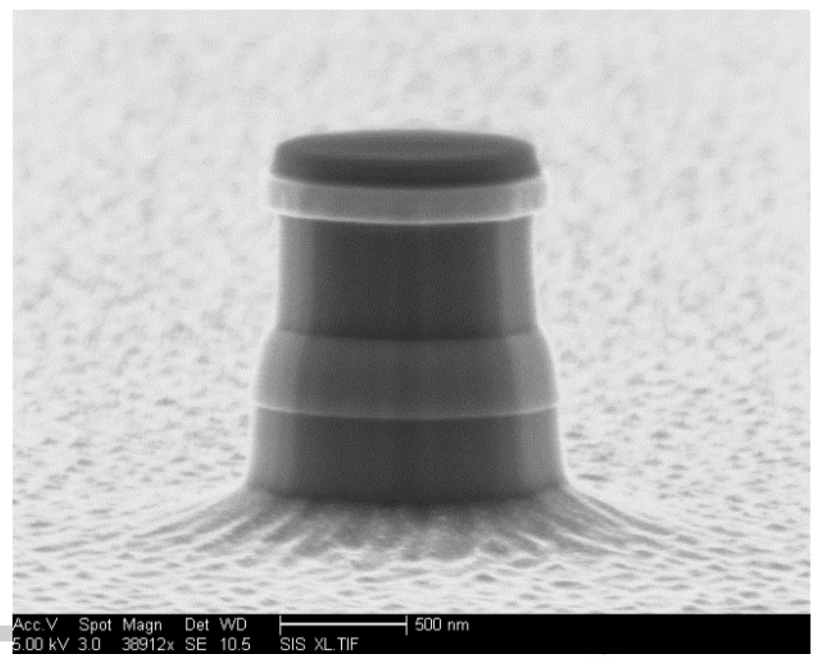
Fabrication

E-beam patterning/RIE (CH_4:H_2:Ar)

Two-step selective InP wet etching

500 nm



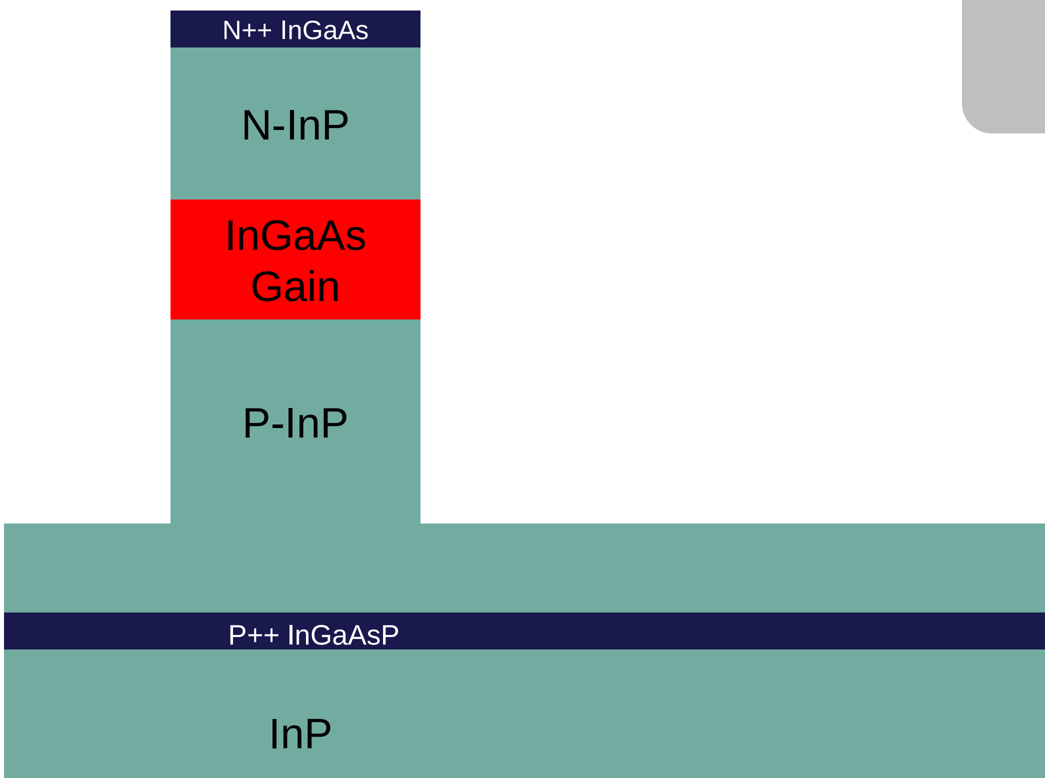


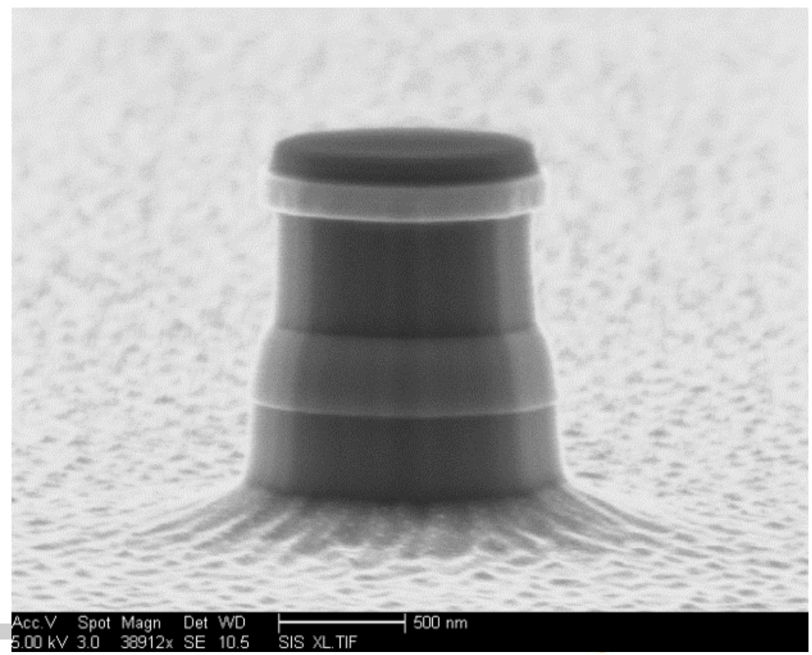
Fabrication

E-beam patterning/RIE (CH_4:H_2:Ar)

Two-step selective InP wet etching

500 nm



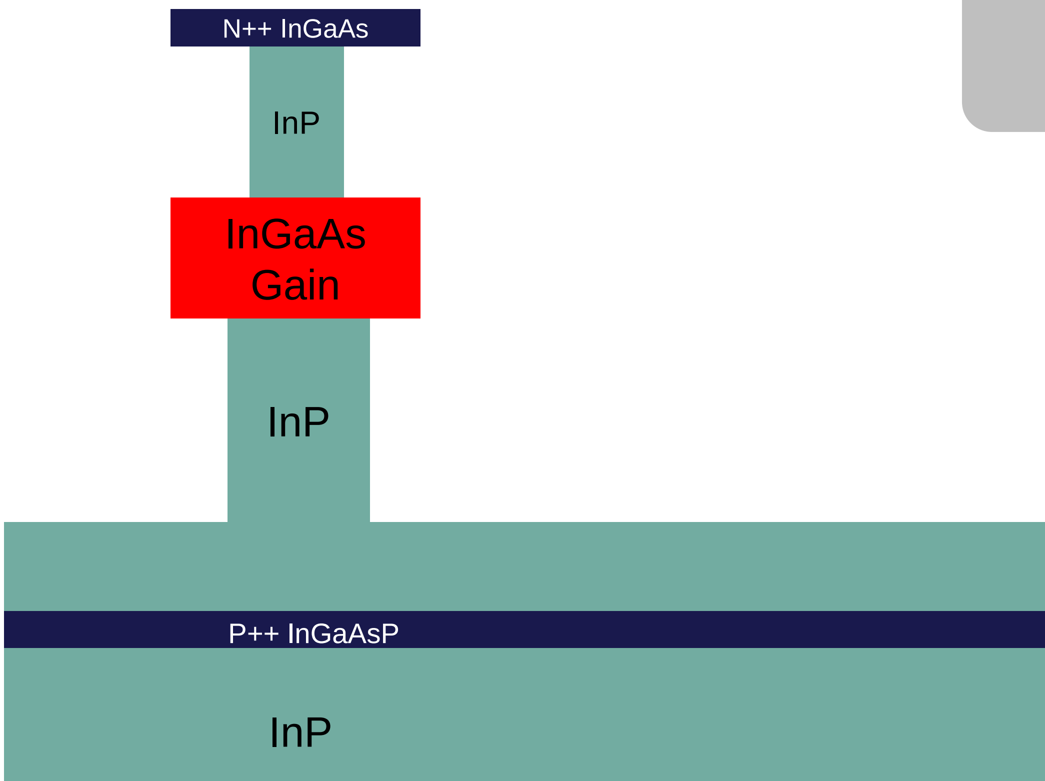


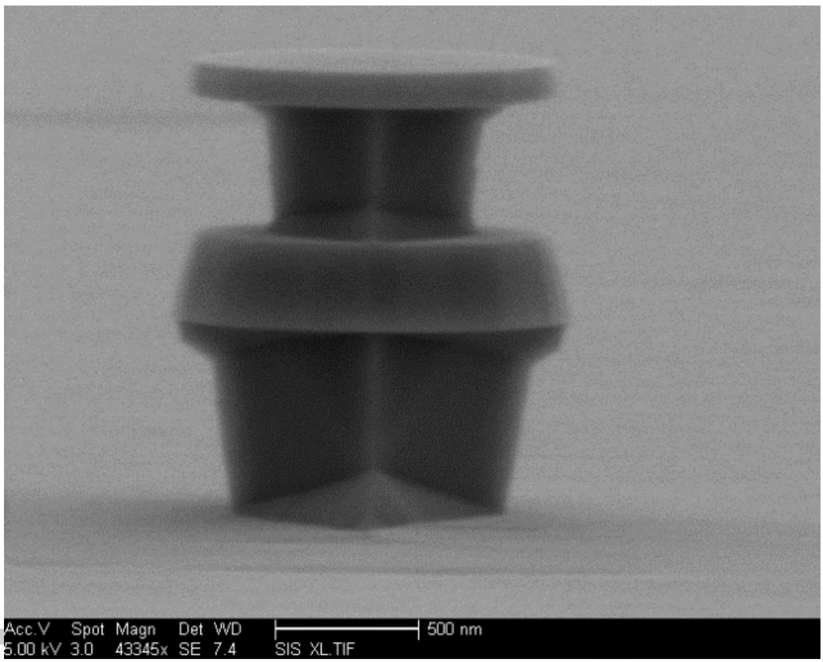
Fabrication

E-beam patterning/RIE (CH_4:H_2:Ar)

Two-step selective InP wet etching

500 nm

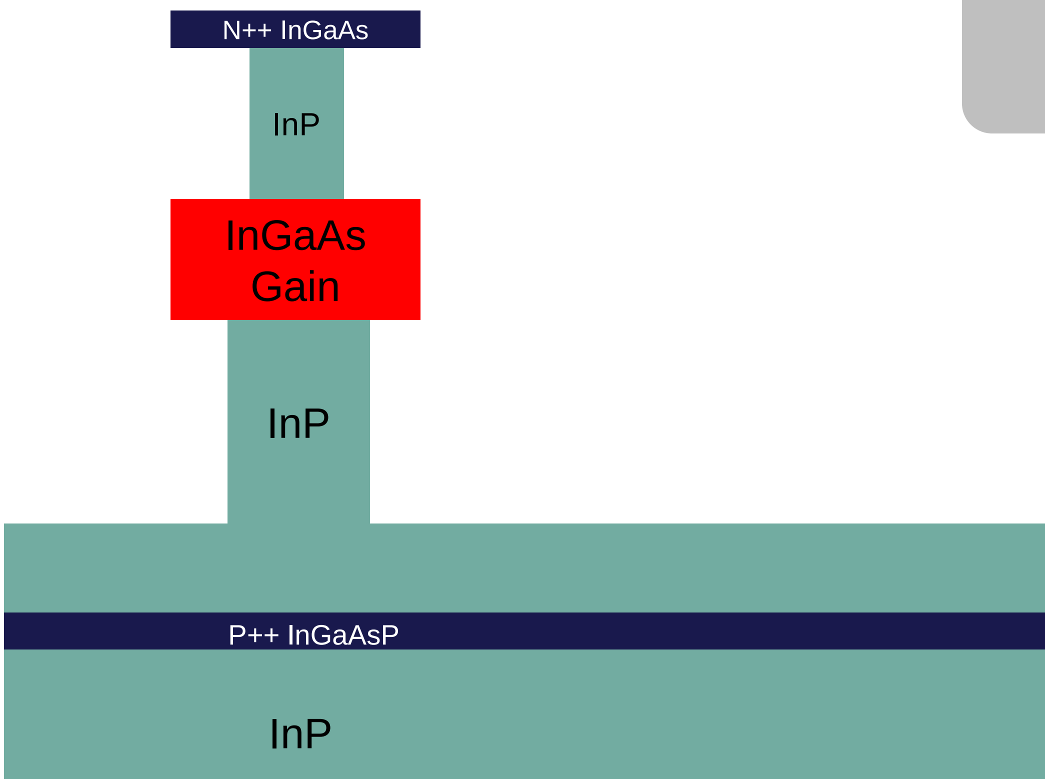


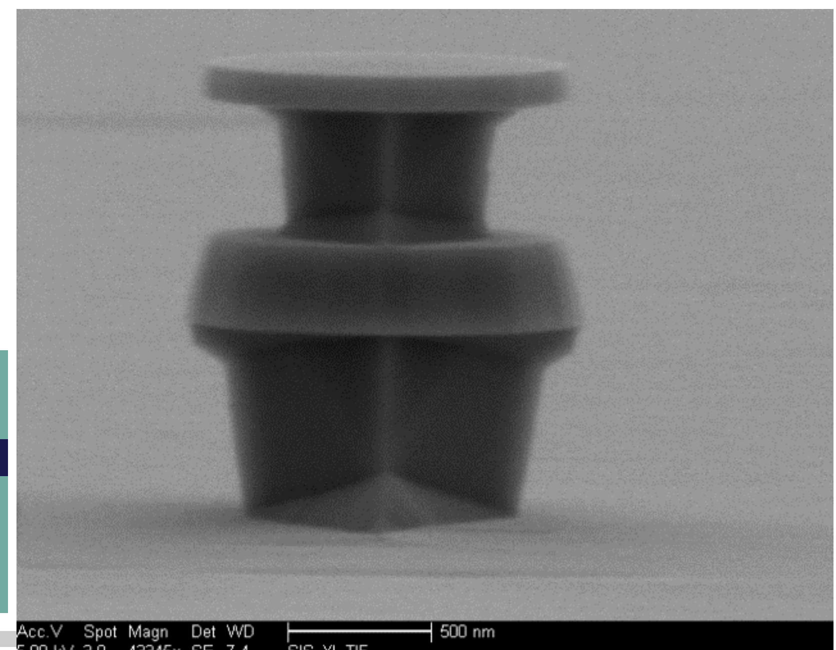


Fabrication

500 nm

- E-beam patterning/RIE (CH_4:H_2:Ar)
- Two-step selective InP wet etching
- Dielectric “shield” deposition





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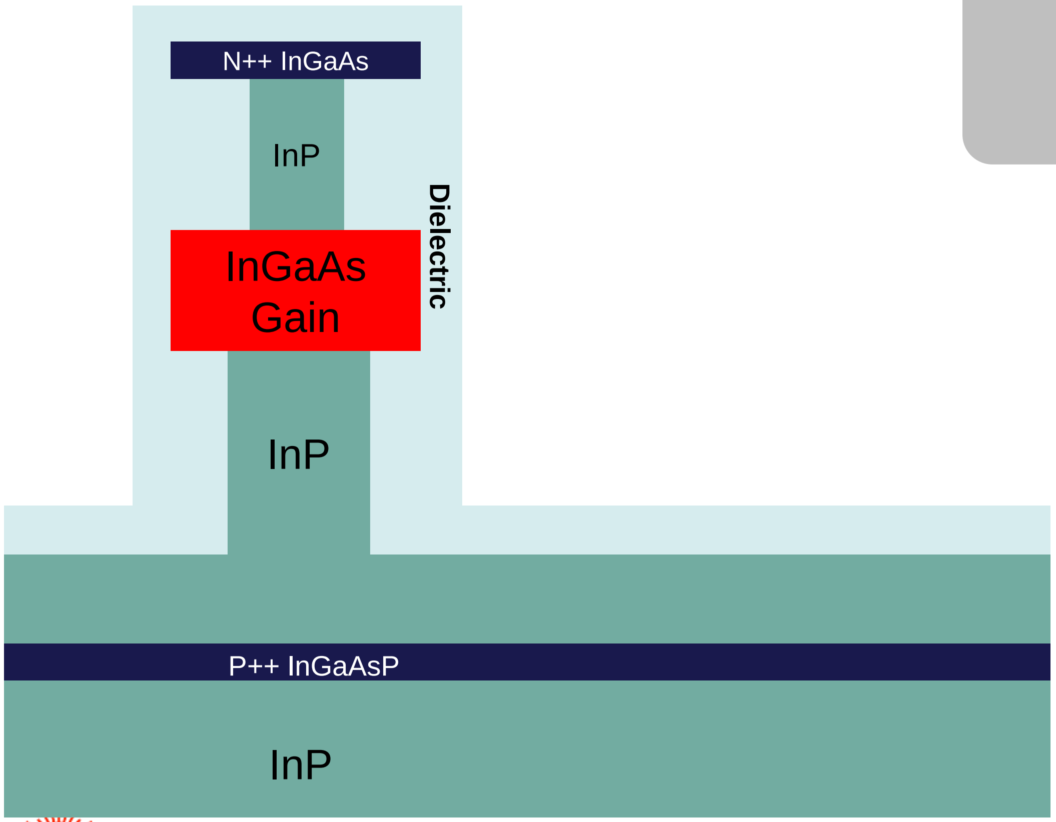
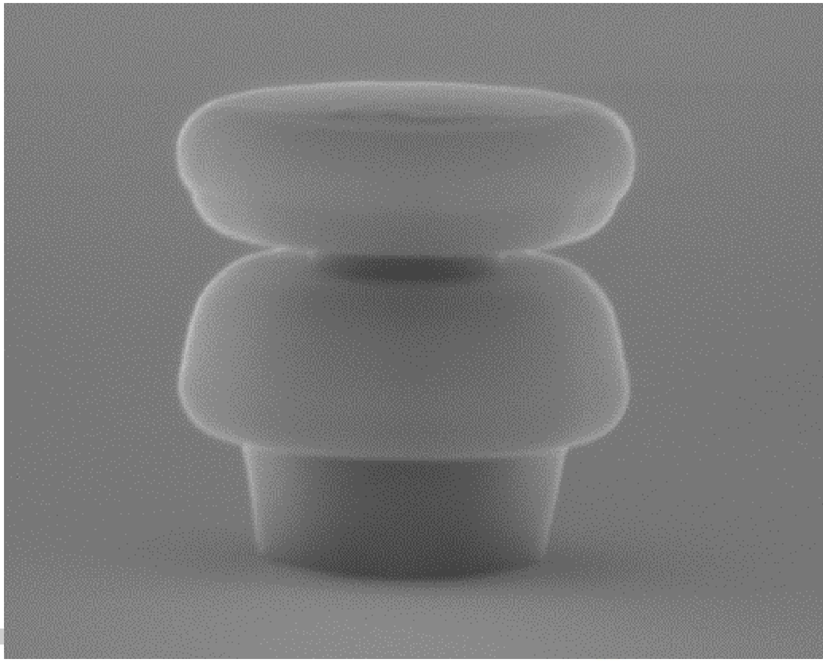
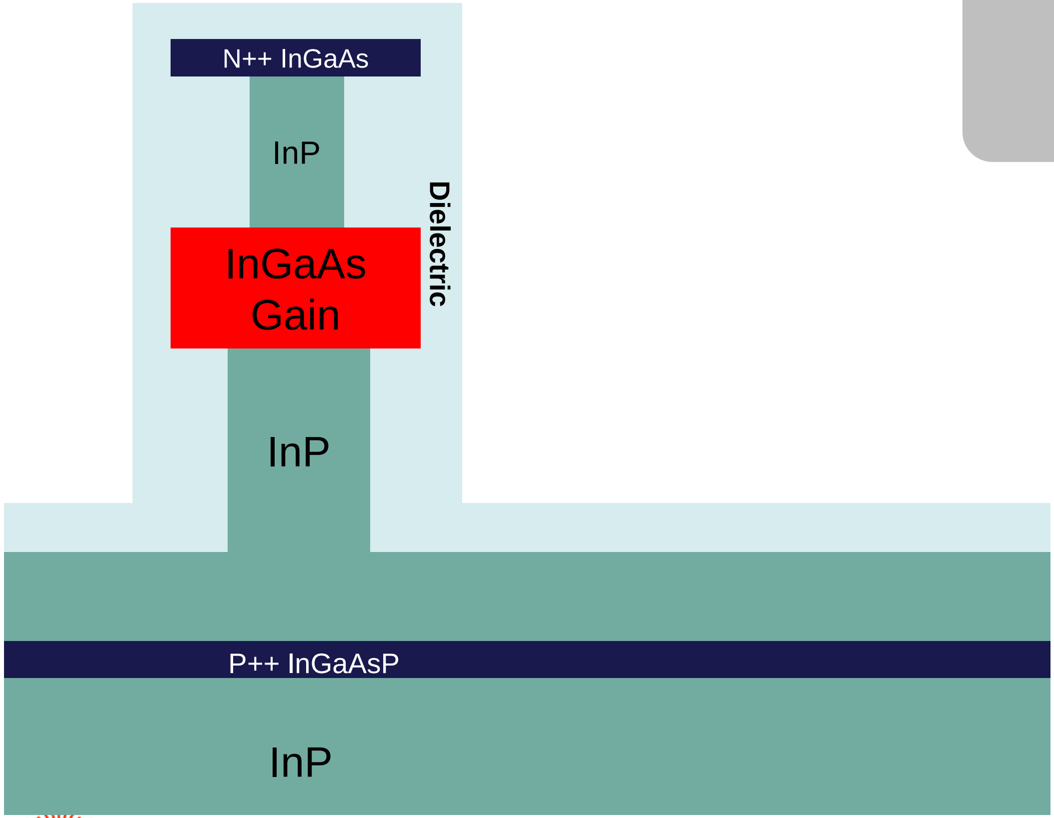


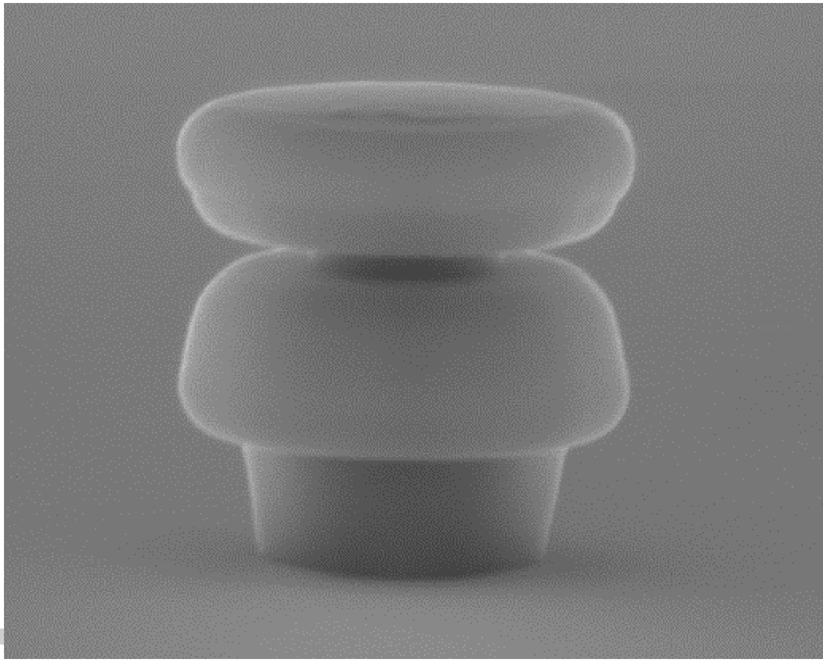


Fabrication

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)





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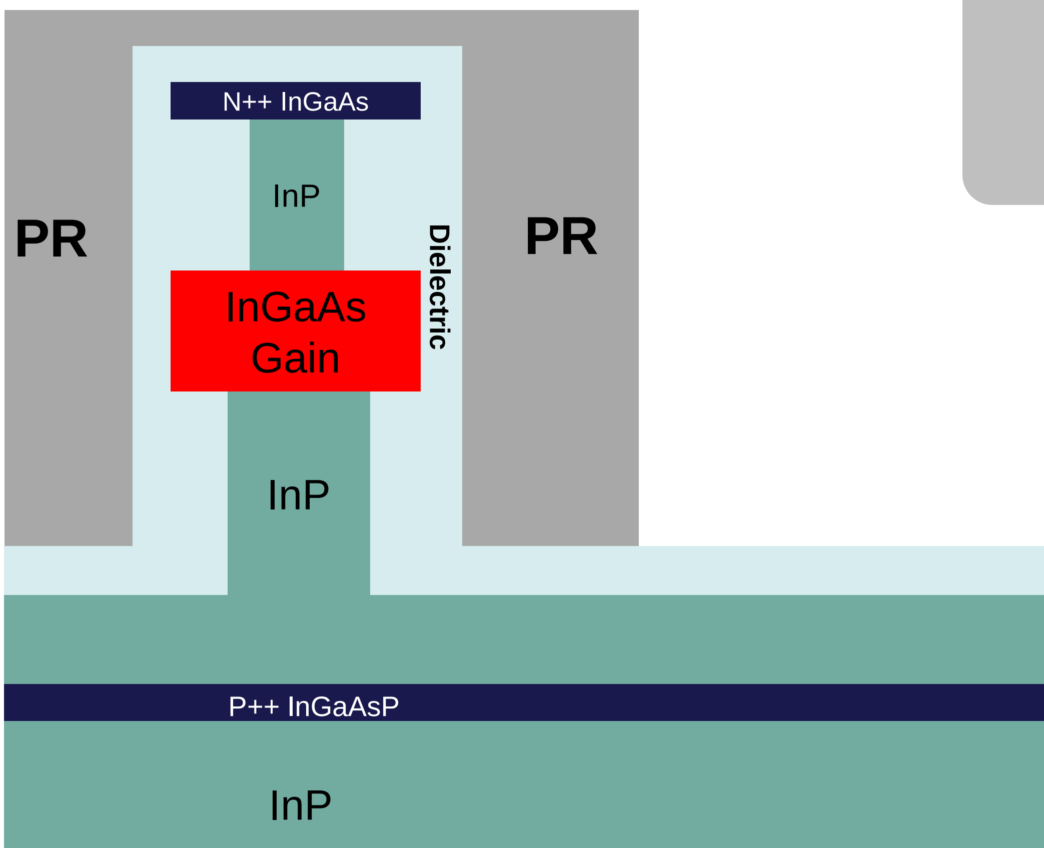

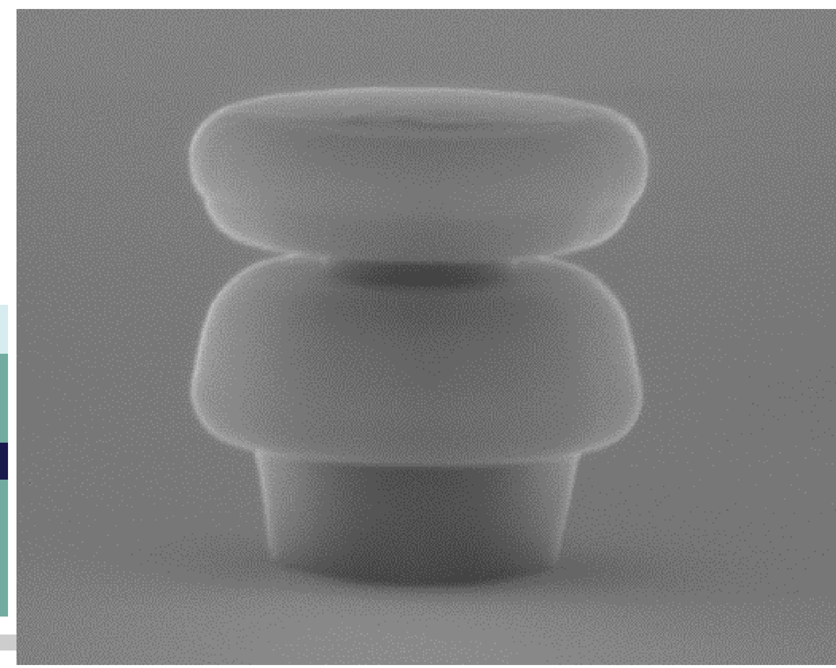

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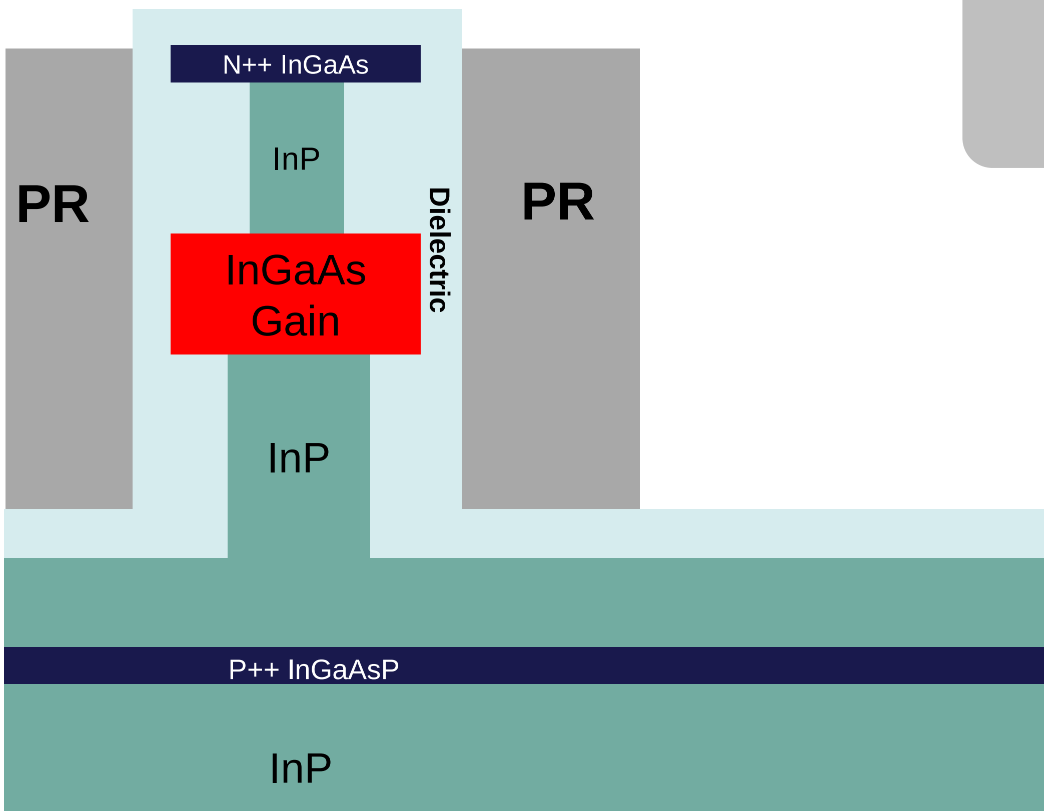

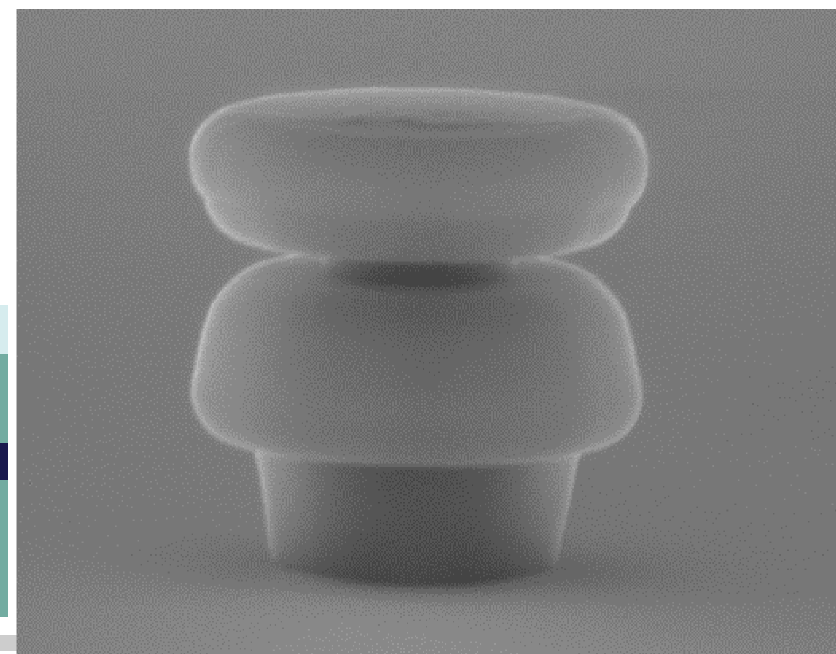

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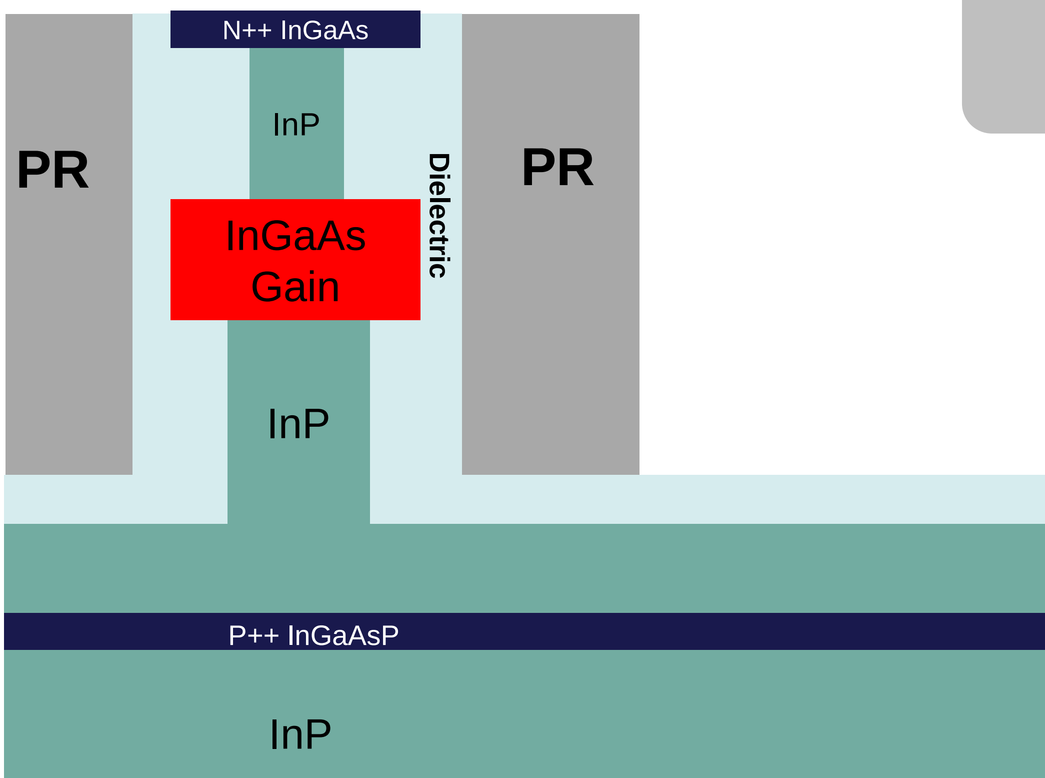
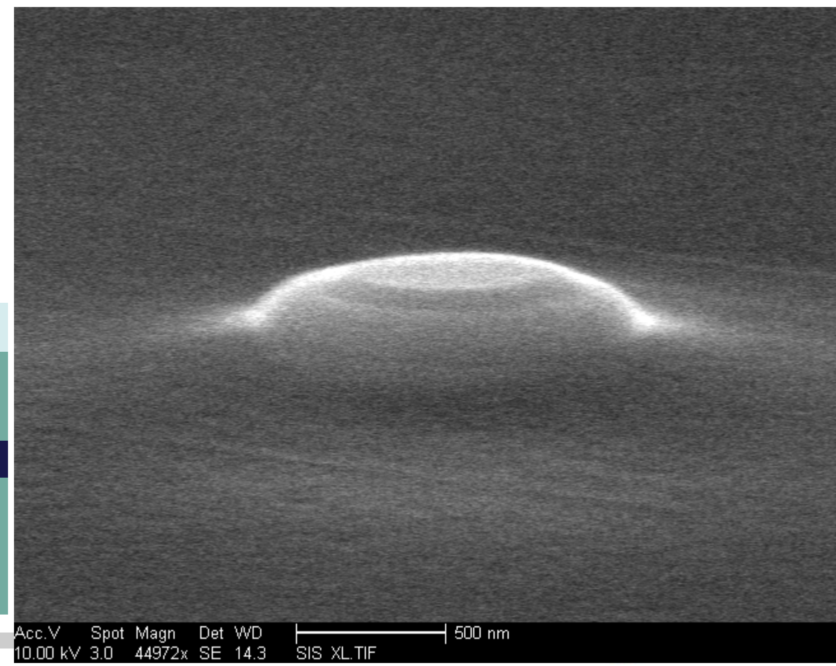




Fabrication

500 nm

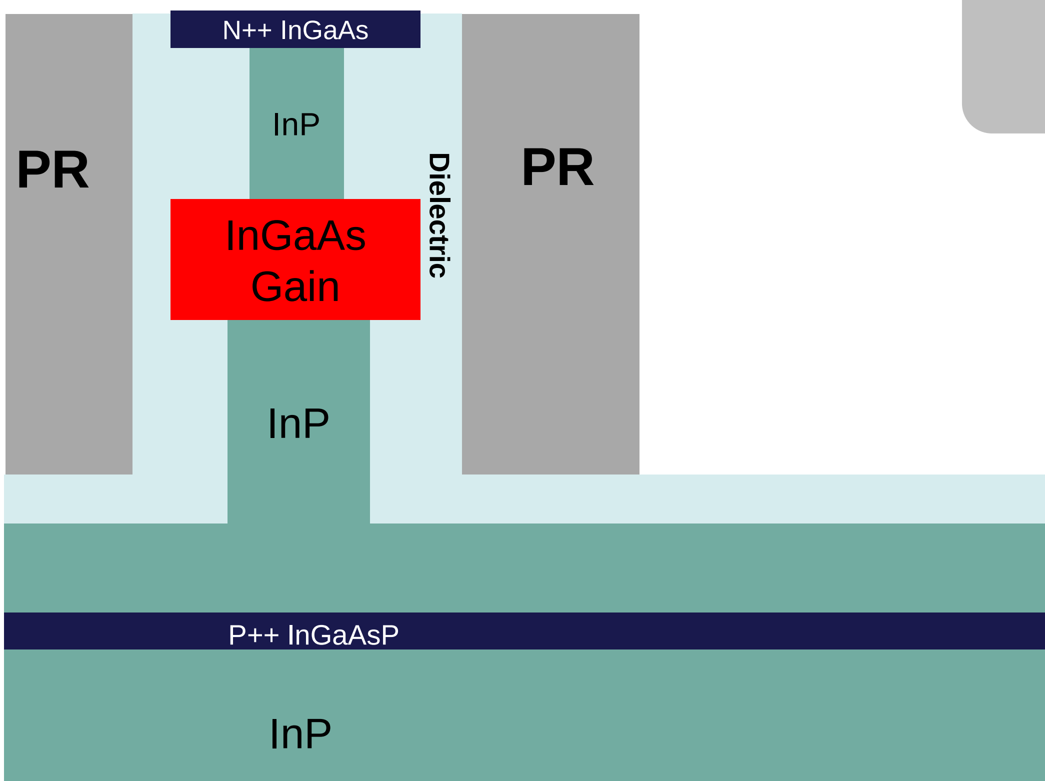
E-beam patterning/RIE (CH_4:H_2:Ar)

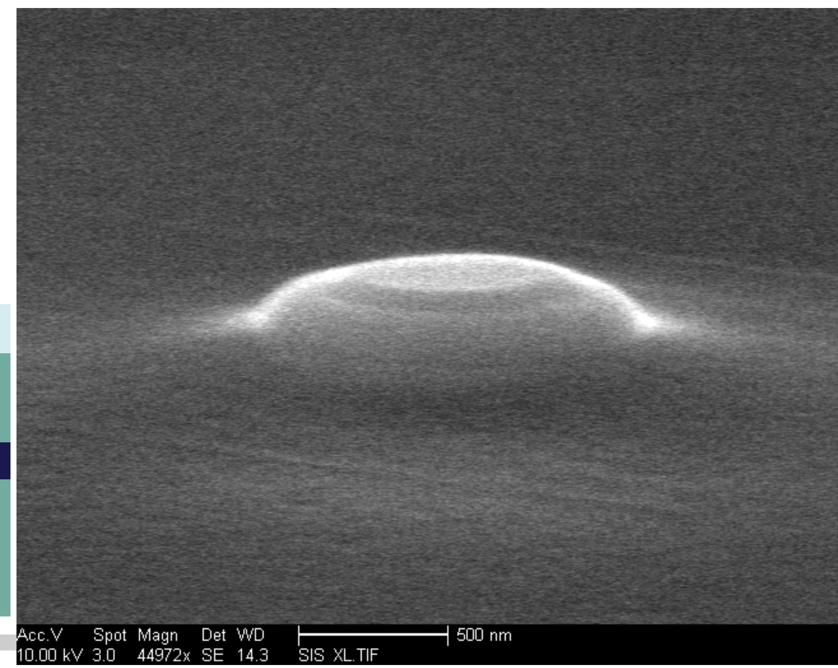
Two-step selective InP wet etching

Dielectric “shield” deposition

Expose the pillar top (for top contact)

Top contact (Ti/Pd/Au) formation





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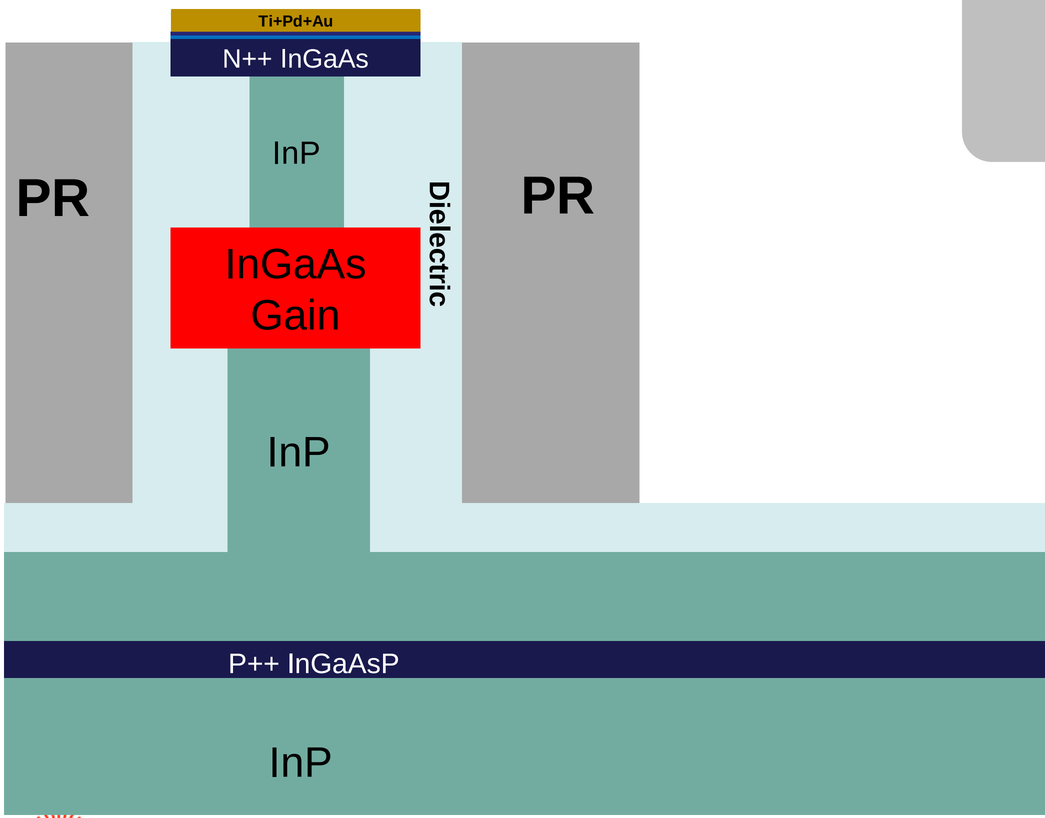

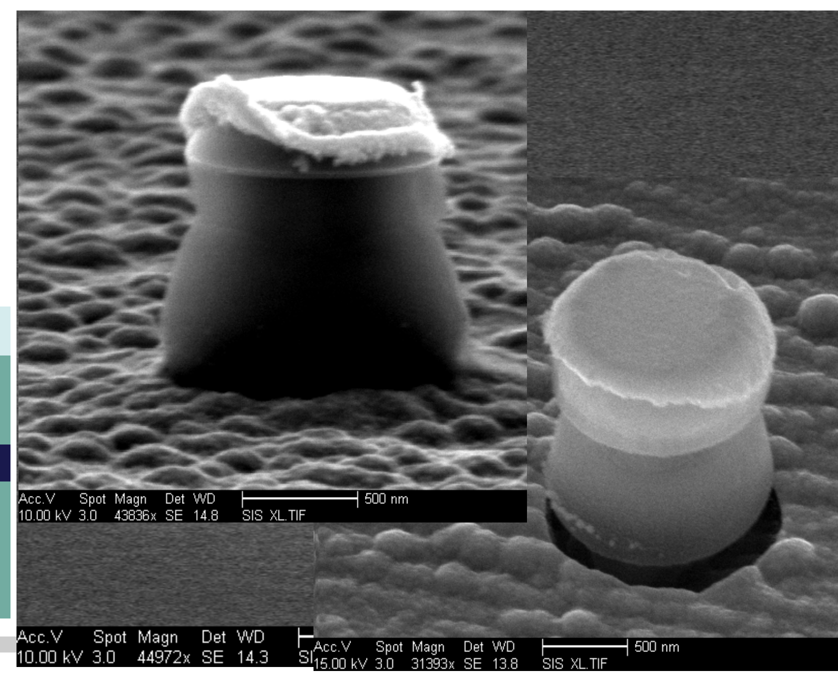

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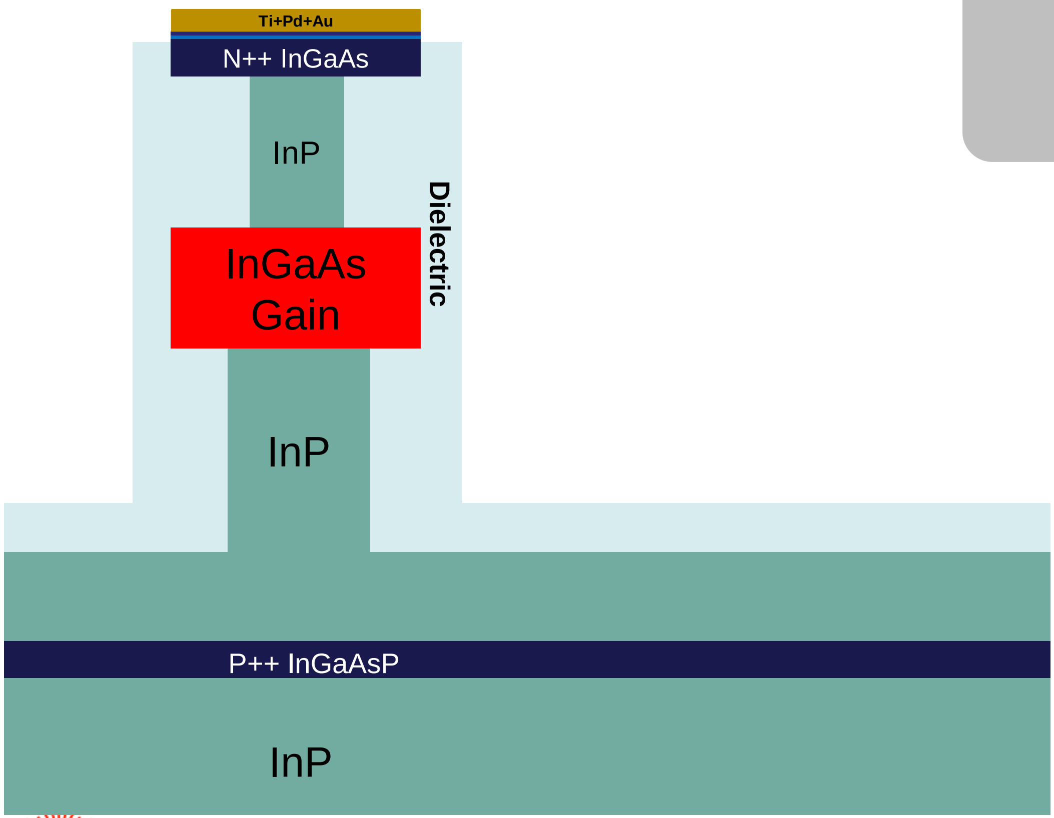

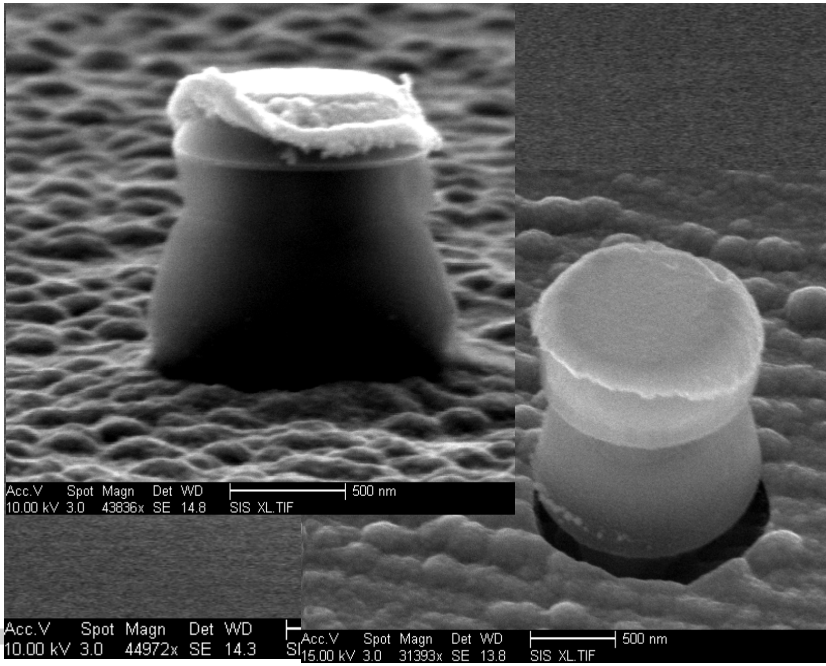

Fabrication

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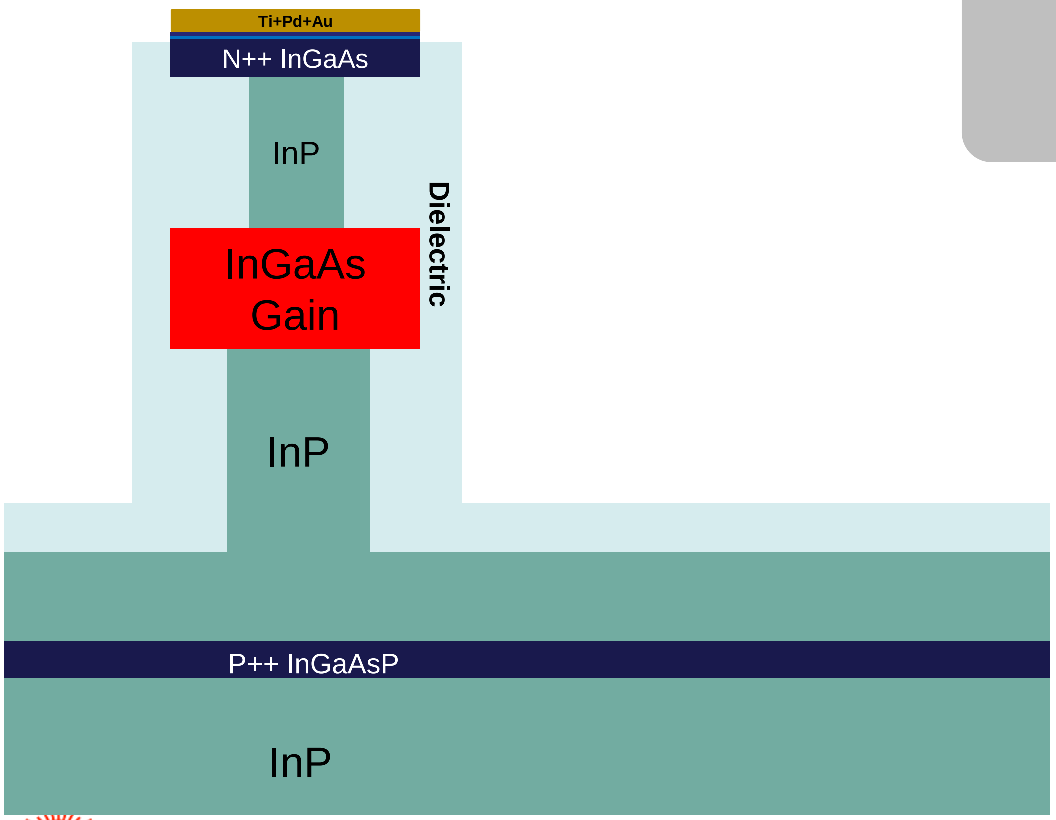
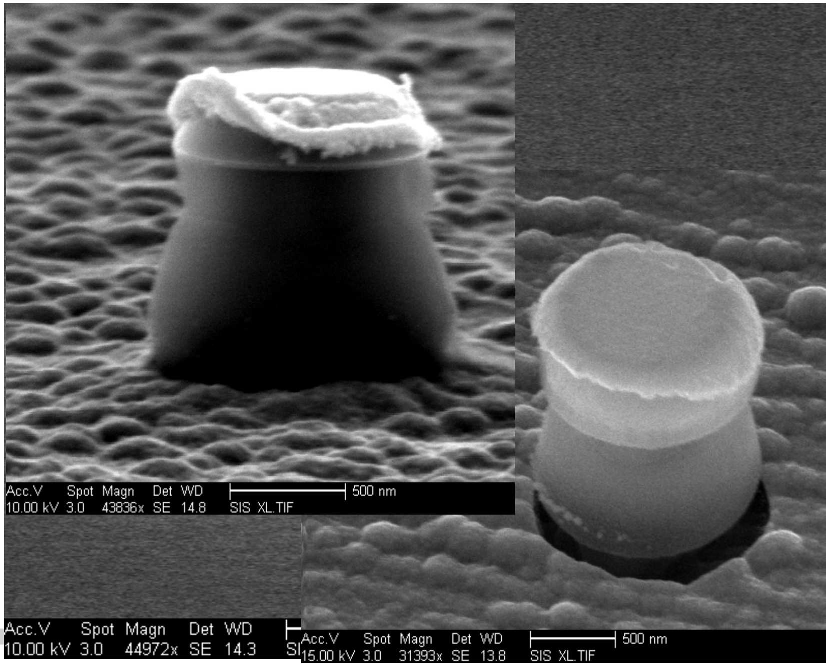
- Two-step selective InP wet etching
- Dielectric “shield” deposition
- Expose the pillar top (for top contact)
- Top contact (Ti/Pd/Au) formation
- Metal cavity (Ag/Au) formation





Fabrication

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- Two-step selective InP wet etching
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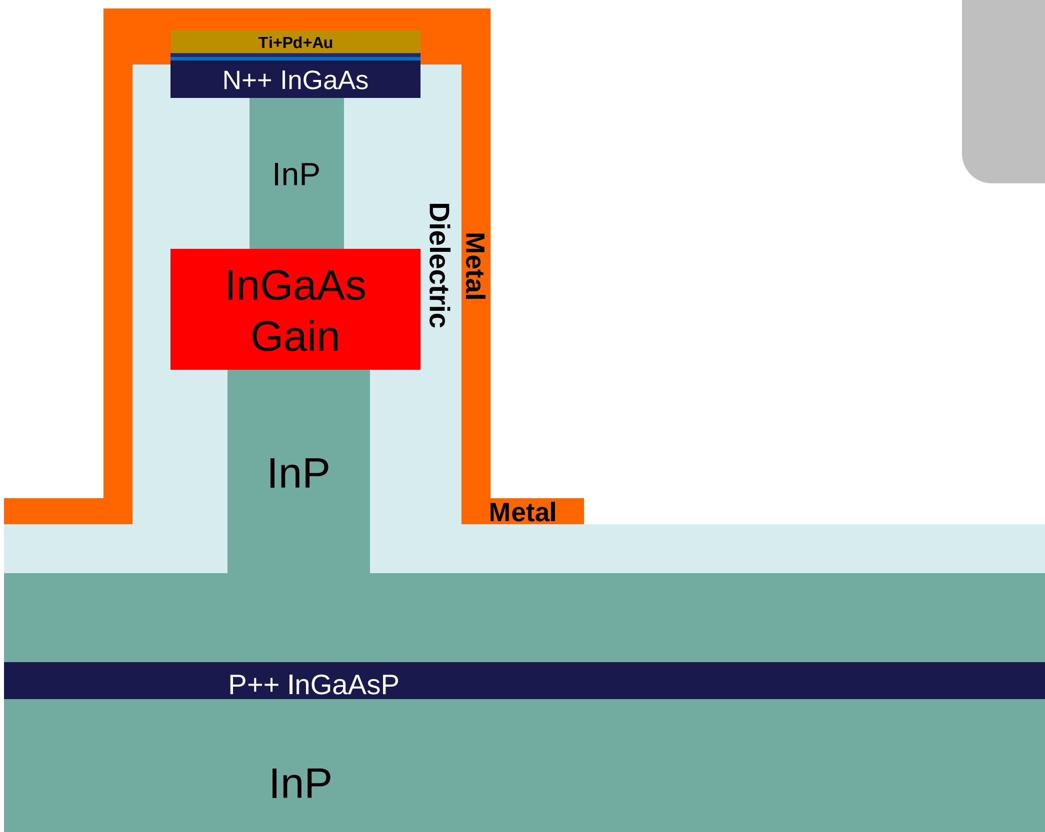
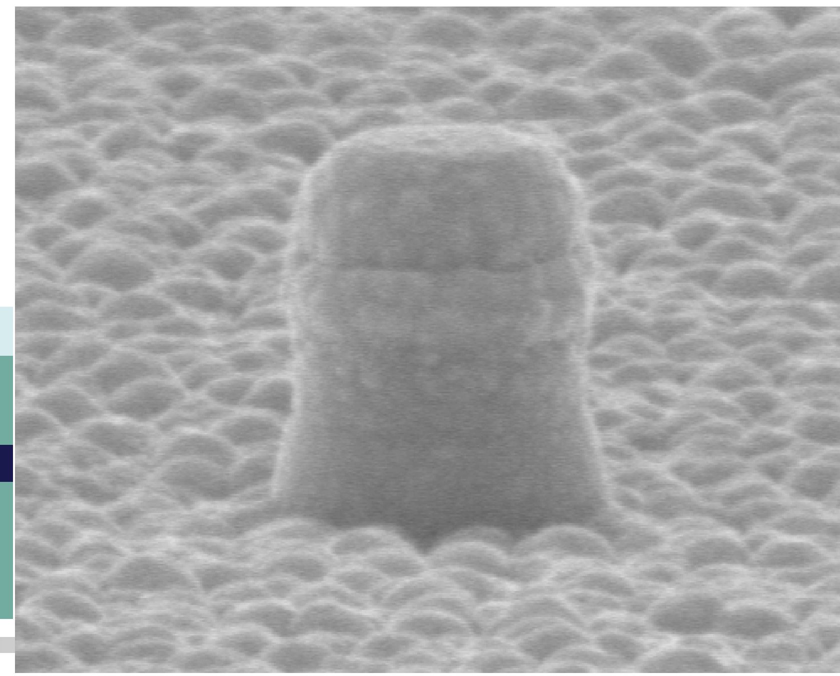
500 nm





Fabrication

500 nm

E-beam patterning/RIE (CH_4:H_2:Ar)

Two-step selective InP wet etching

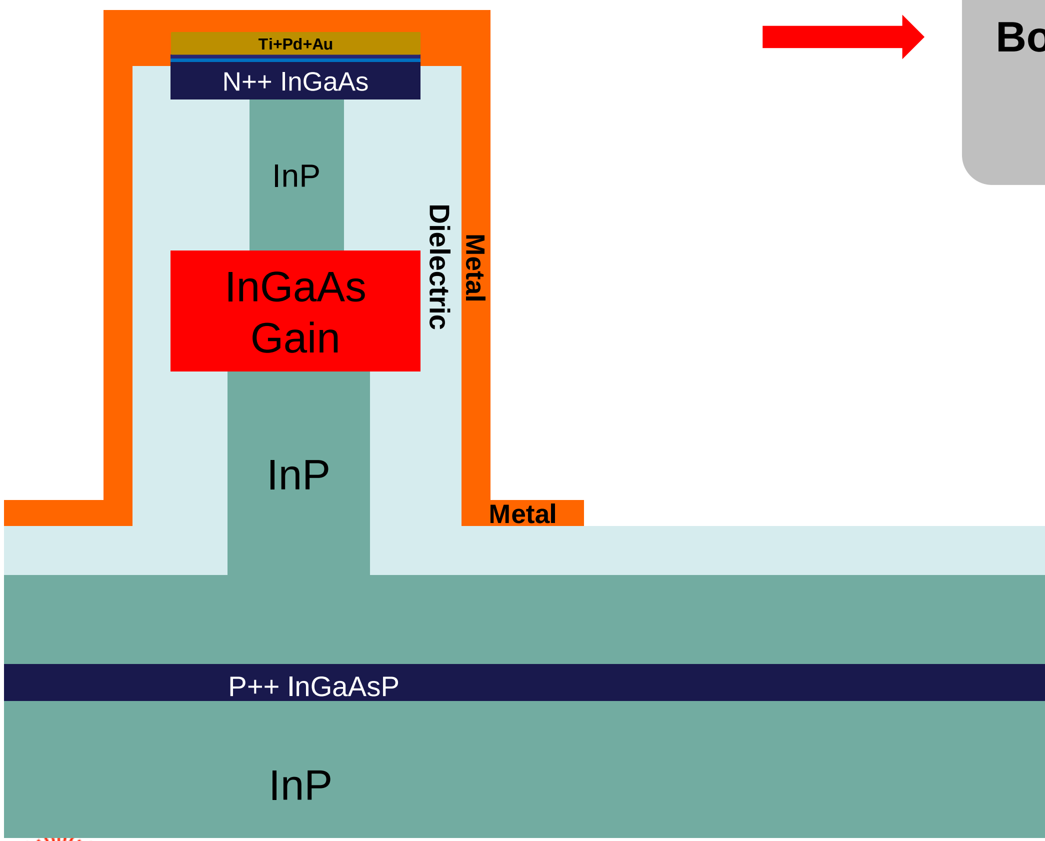
Dielectric “shield” deposition

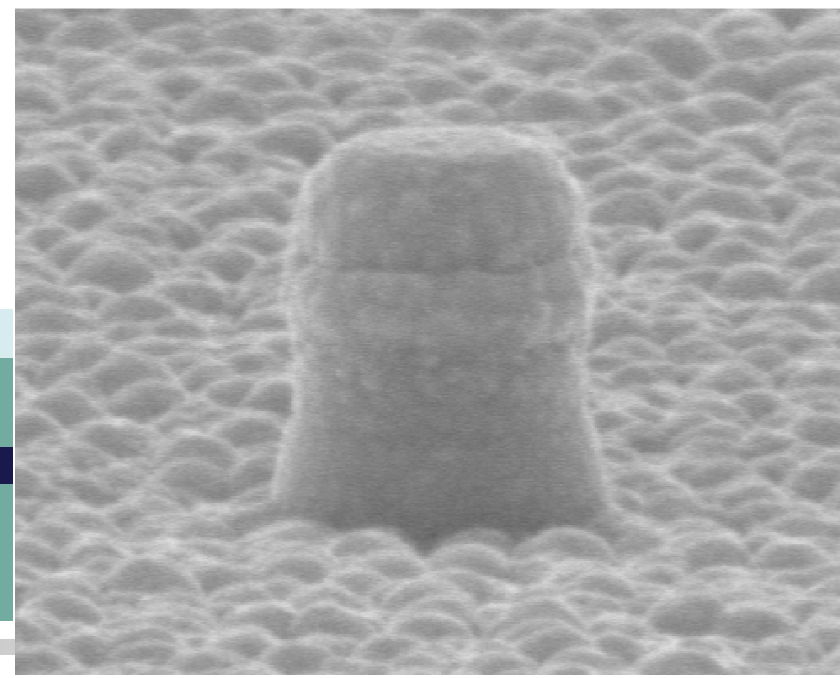
Expose the pillar top (for top contact)

Top contact (Ti/Pd/Au) formation

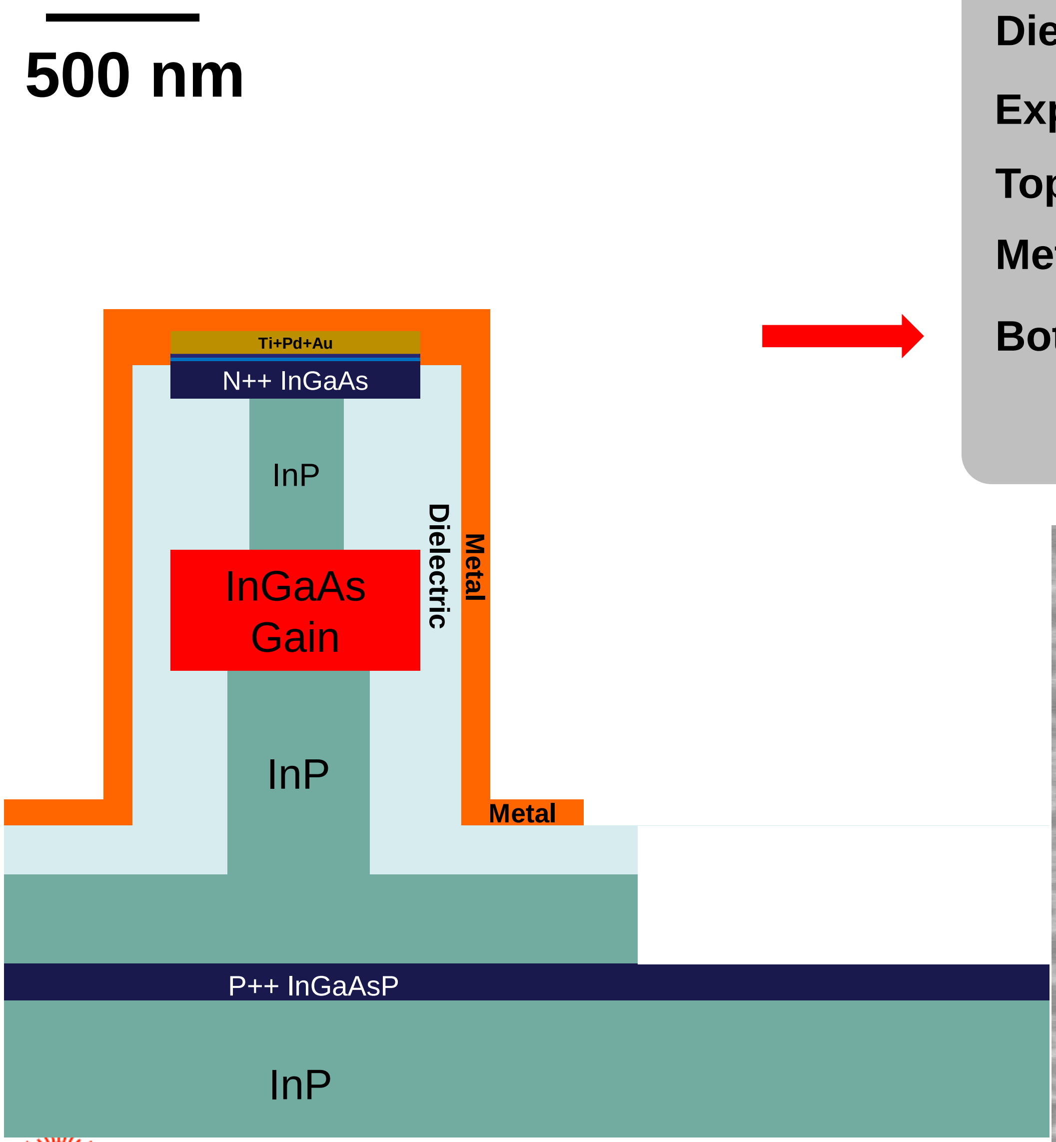
Metal cavity (Ag/Au) formation

Bottom contact formation (Ti/Pd/Au)

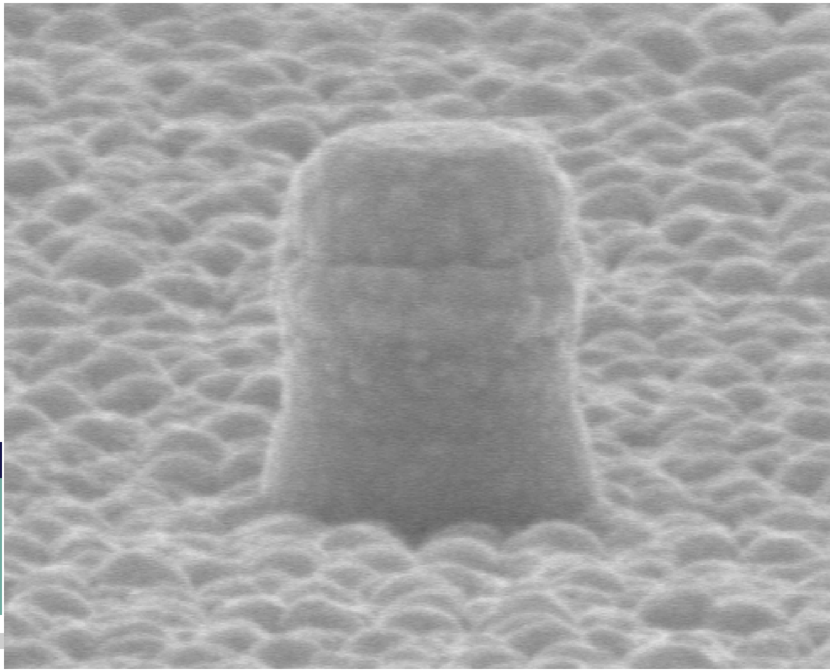




Fabrication



- 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)
- Top contact (Ti/Pd/Au) formation
- Metal cavity (Ag/Au) formation
- Bottom contact formation (Ti/Pd/Au)



Fabrication

500 nm

E-beam patterning/RIE (CH_4:H_2:Ar)

Two-step selective InP wet etching

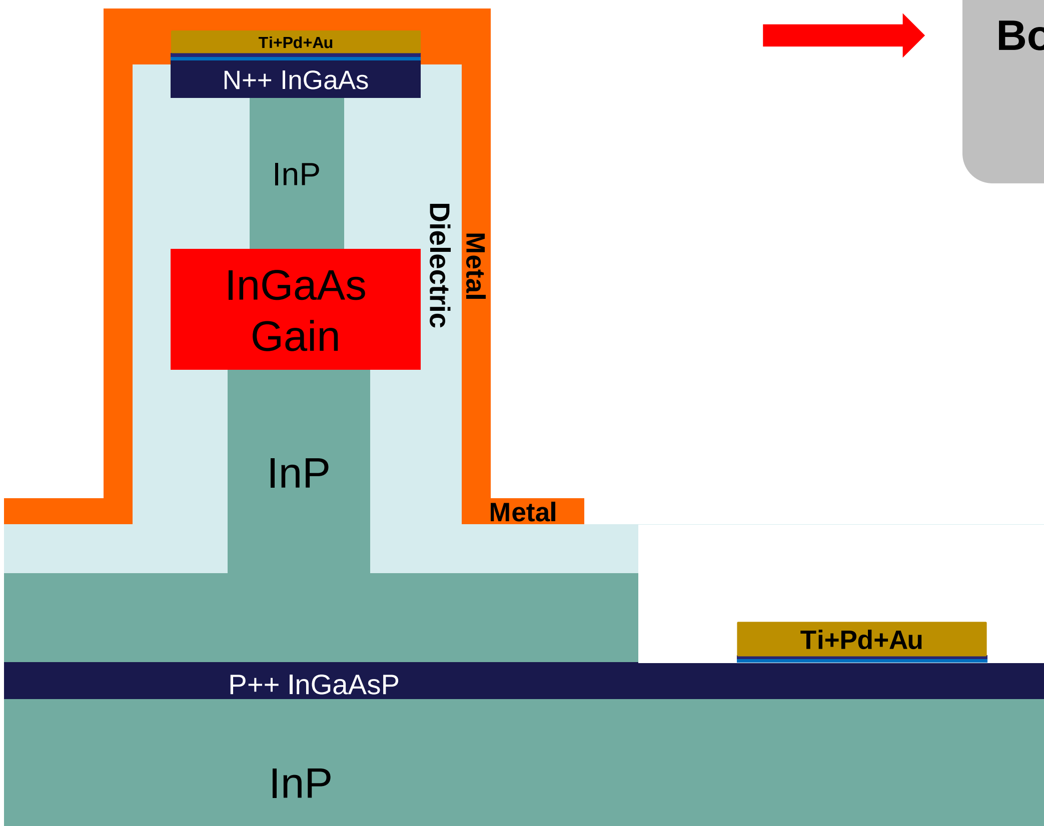
Dielectric “shield” deposition

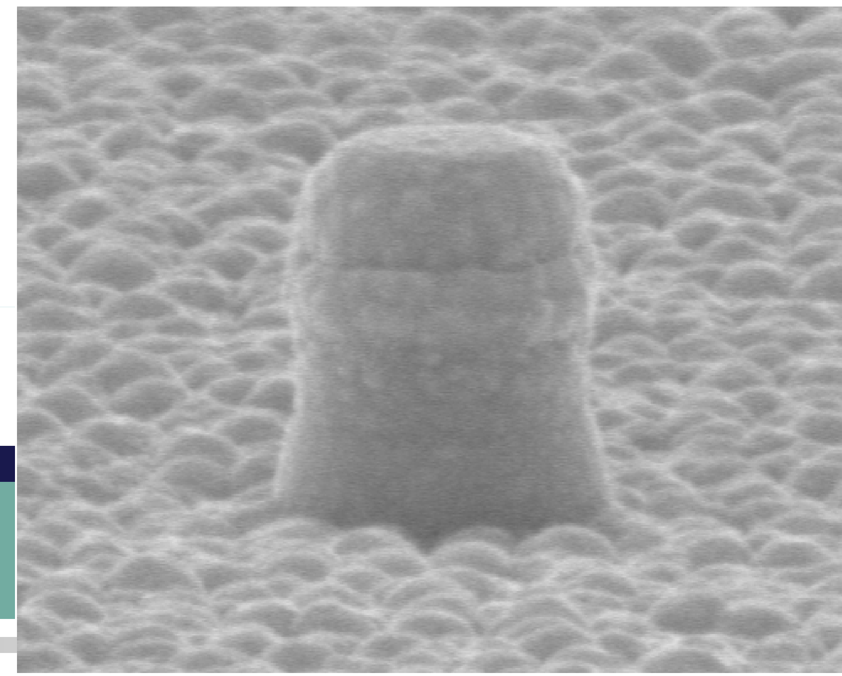
Expose the pillar top (for top contact)

Top contact (Ti/Pd/Au) formation

Metal cavity (Ag/Au) formation

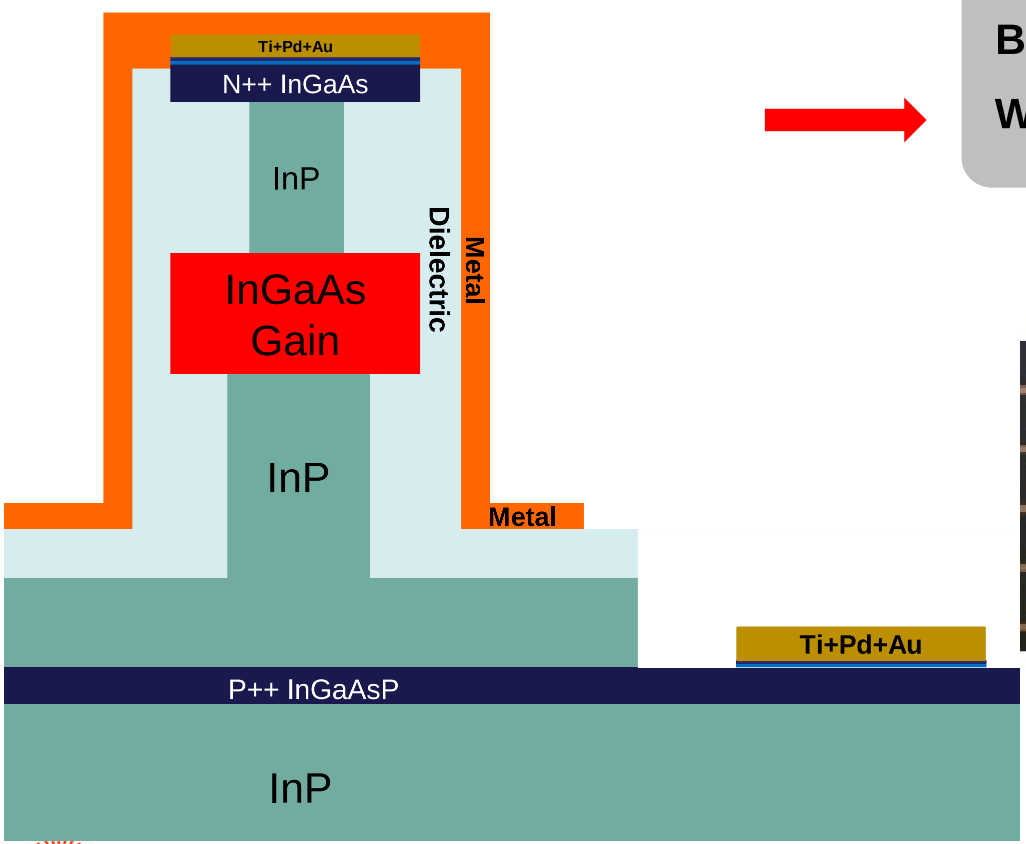
Bottom contact formation (Ti/Pd/Au)



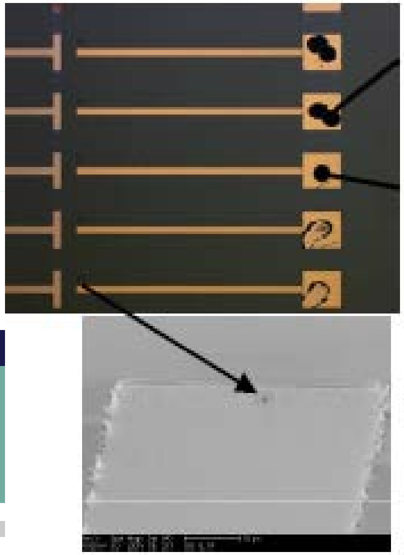


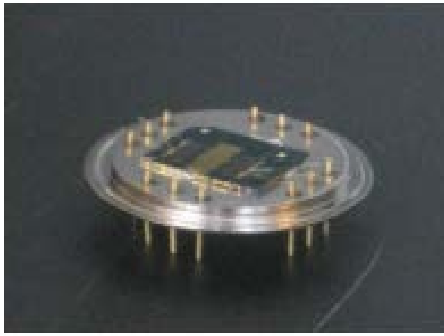
Fabrication

500 nm



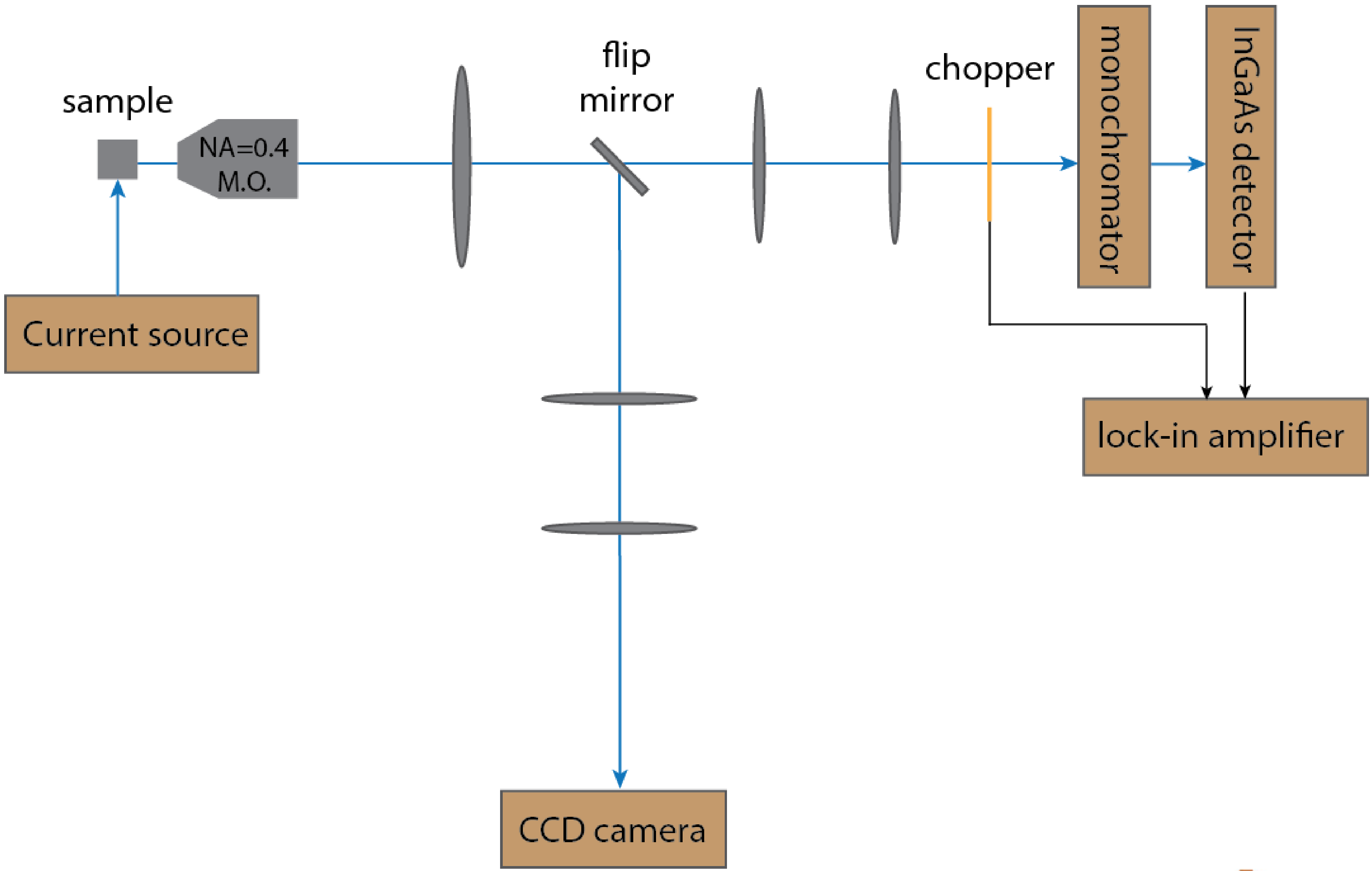
- E-beam patterning/RIE ($CH_4:H_2:Ar$)
- Two-step selective InP wet etching
- Dielectric “shield” deposition
- Expose the pillar top (for top contact)
- Top contact (Ti/Pd/Au) formation
- Metal cavity (Ag/Au) formation
- Bottom contact formation (Ti/Pd/Au)
- Wire-bond to sample holder



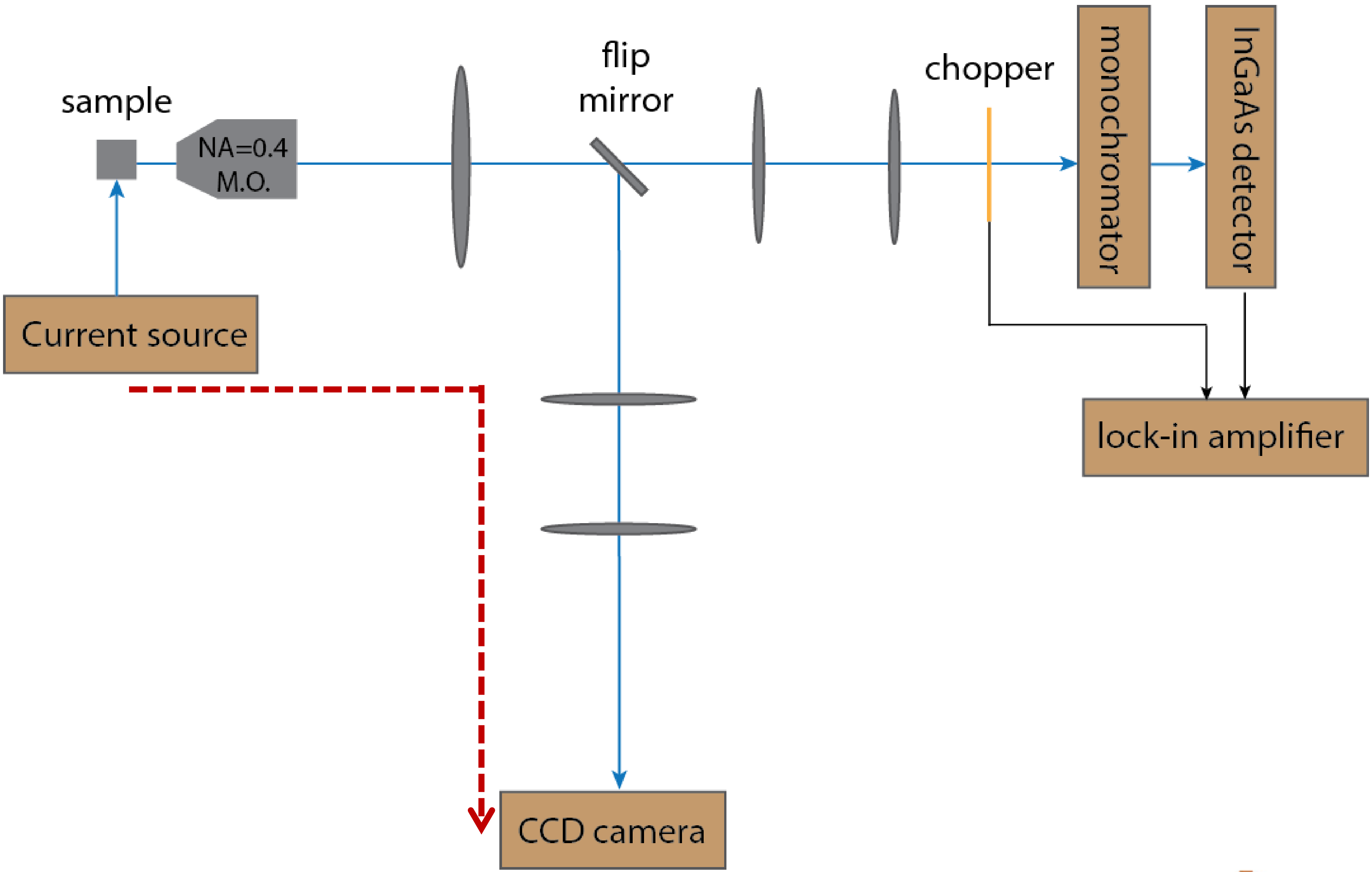


Laser device in low magnification

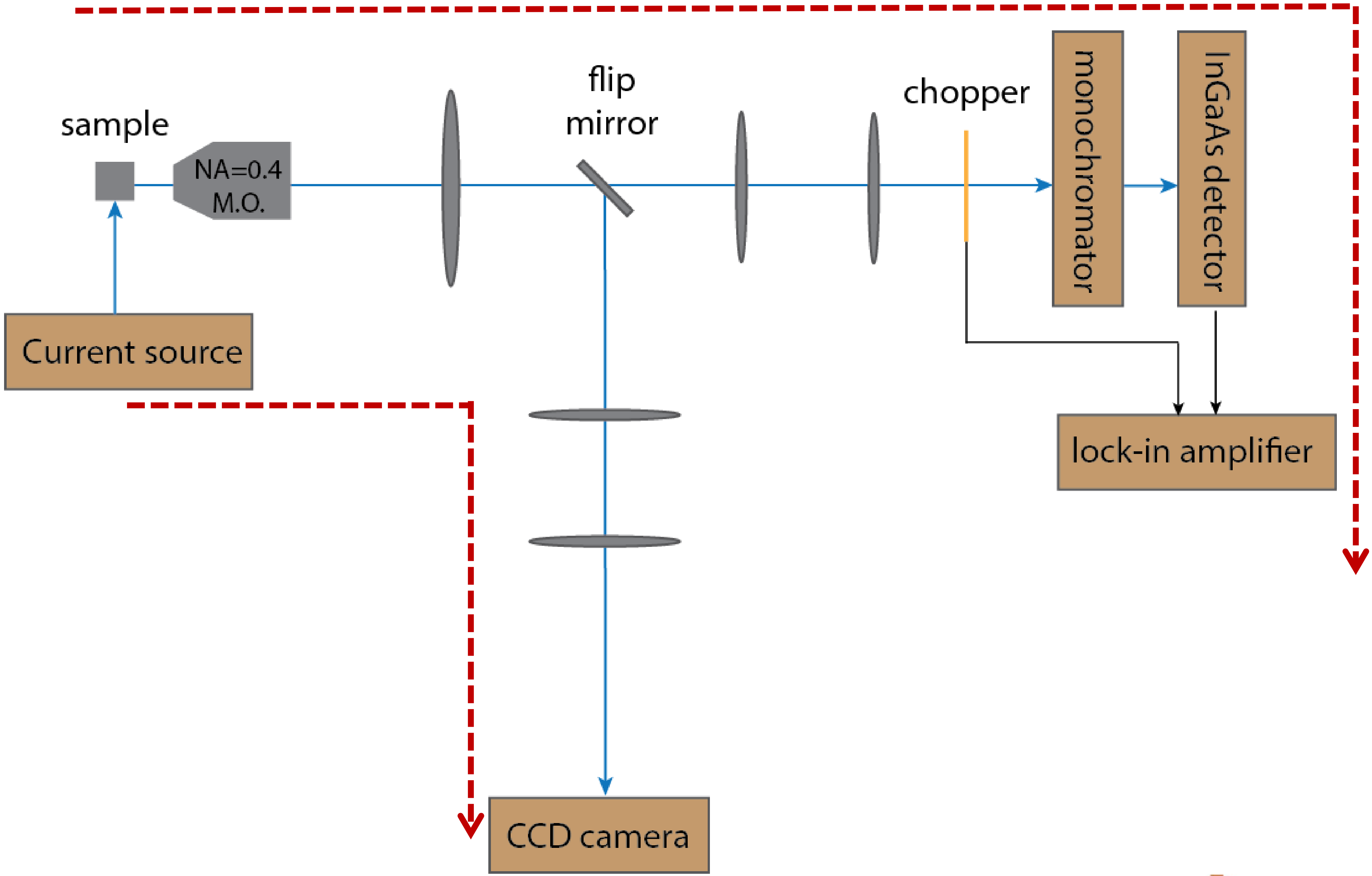
Characterization micro-EL setup



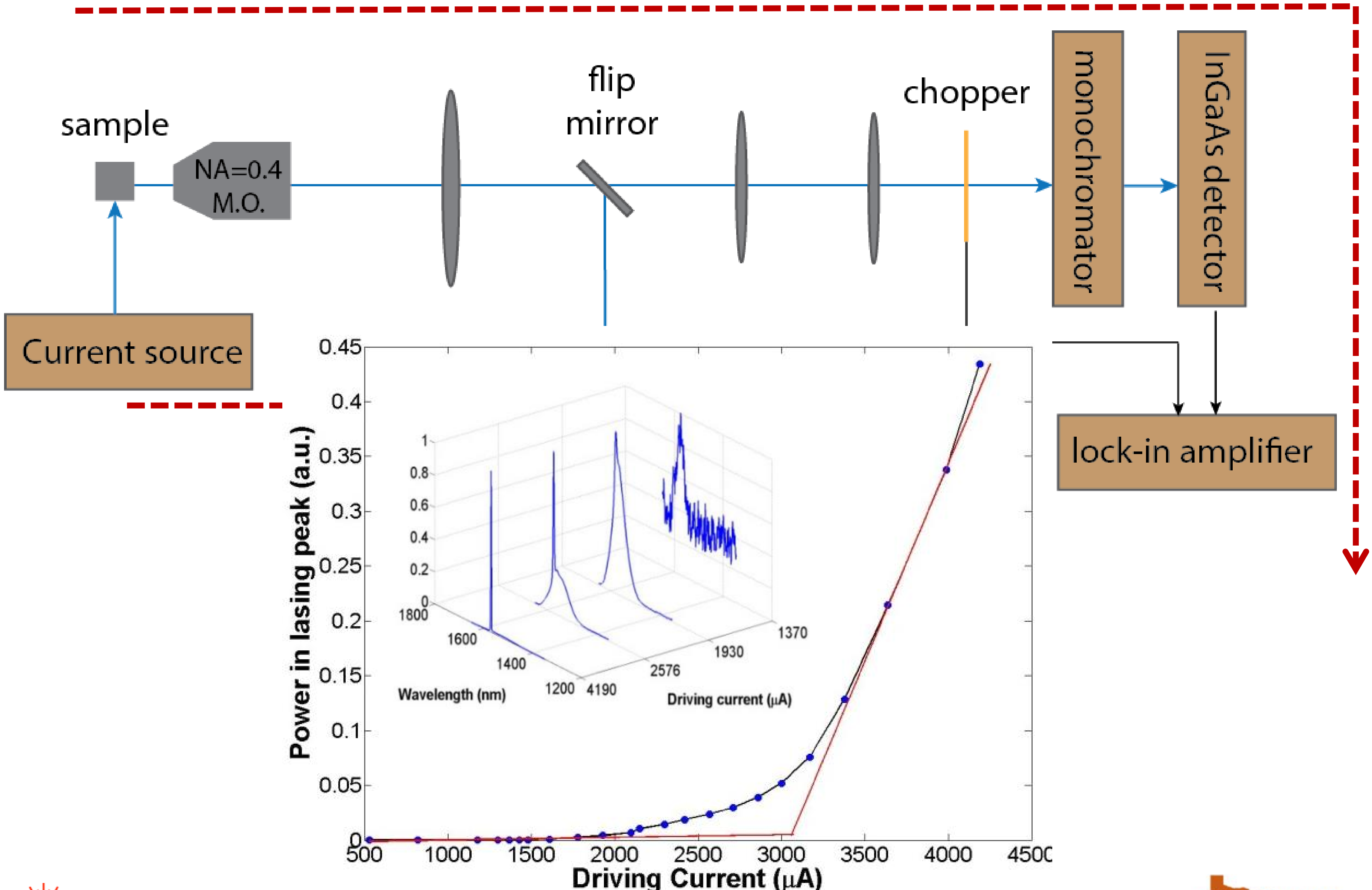
Characterization micro-EL setup



Characterization micro-EL setup



Characterization micro-EL setup



Lasers in Photonic ICs

Design:
Optical cavity mode

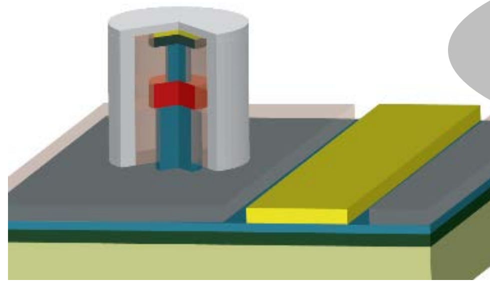
Proof of concept:
Optically pumped laser

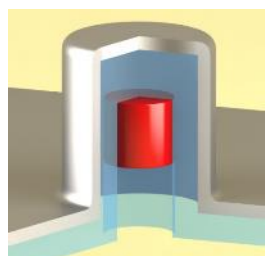
Multi-physics design
for electrical pumping:
Optical, electrical, thermal

Demonstration:
Electrically pumped laser

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

Insertion into
Photonic ICs





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]

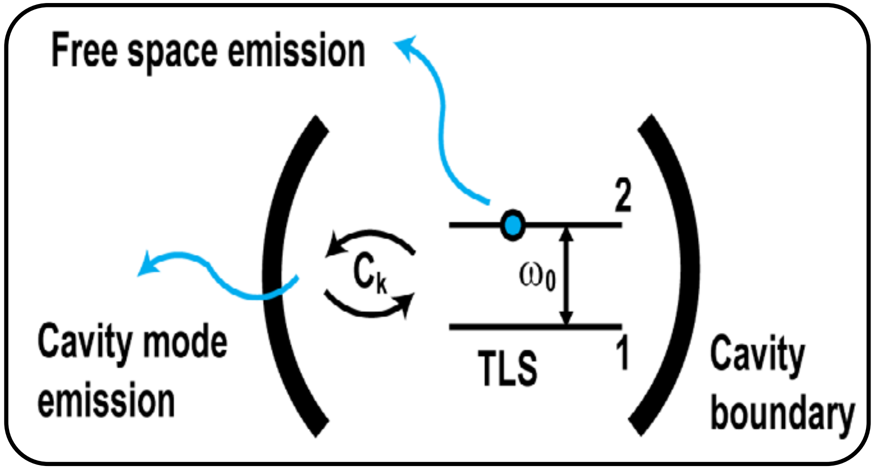
$$F_P = \frac{3\lambda^3}{4\pi^2 n^3}\frac{Q}{V_{eff}} \propto \frac{Q}{V_{eff}}$$

[1] Purcell et al,"Spontaneous emission probabilities at radio frequencies.“ *Physical Review* (1946)

[2] Gérard et al, "Enhanced spontaneous emission by quantum boxes in a monolithic optical microcavity." *Physical Review Letters* (1998)

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 = 300K

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

Inhomogeneous broadening (for $D(\omega_{21})$)

Homogeneous broadening (for $R(\omega - \omega_{21}, \tau_{coll})$)

Cavity lineshape (for $L_k(\omega - \omega_k)$)

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

Qing Gu et al, *Optics Express*, Vol. 21, No. 13 (2013)

Purcell factor, T = 300K

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

Inhomogeneous broadening (↑ $D(\omega_{21})$)

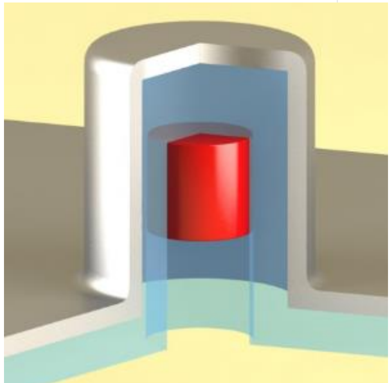
Homogeneous broadening (↑ $R(\omega-\omega_{21}, \tau_{coll})$)

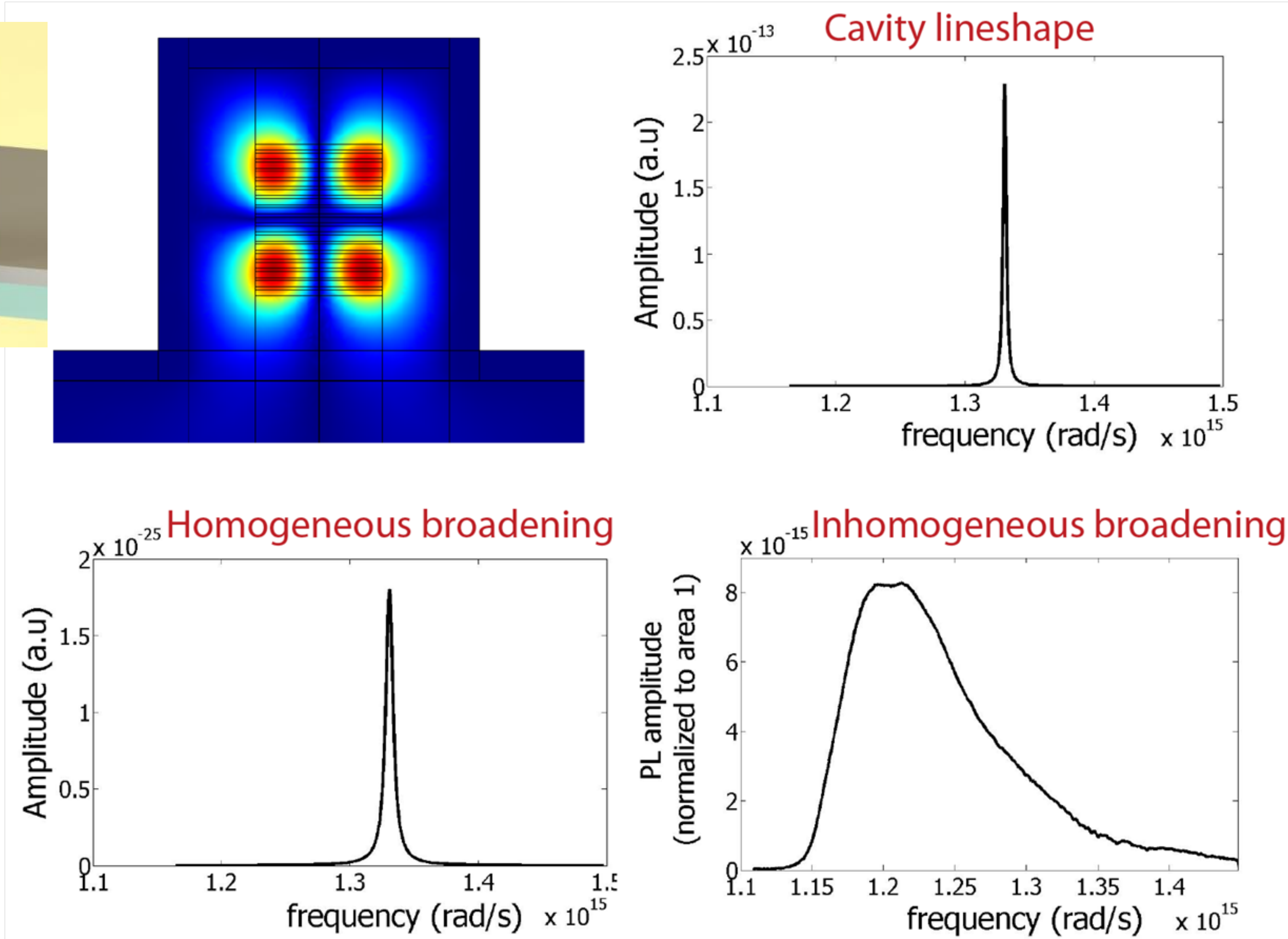
Cavity lineshape (↑ $L_k(\omega-\omega_k)$)

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

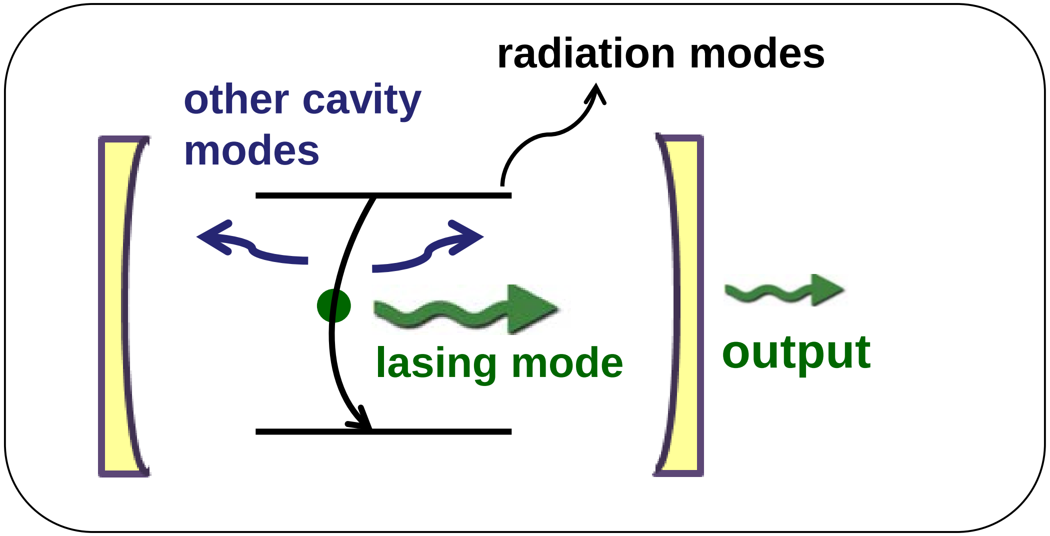
Literature $$F_P = \frac{3\lambda^3}{4\pi^2 n^3} \frac{Q}{V_{eff}} \propto \frac{Q}{V_{eff}}$$

Purcell factor, T = 300K



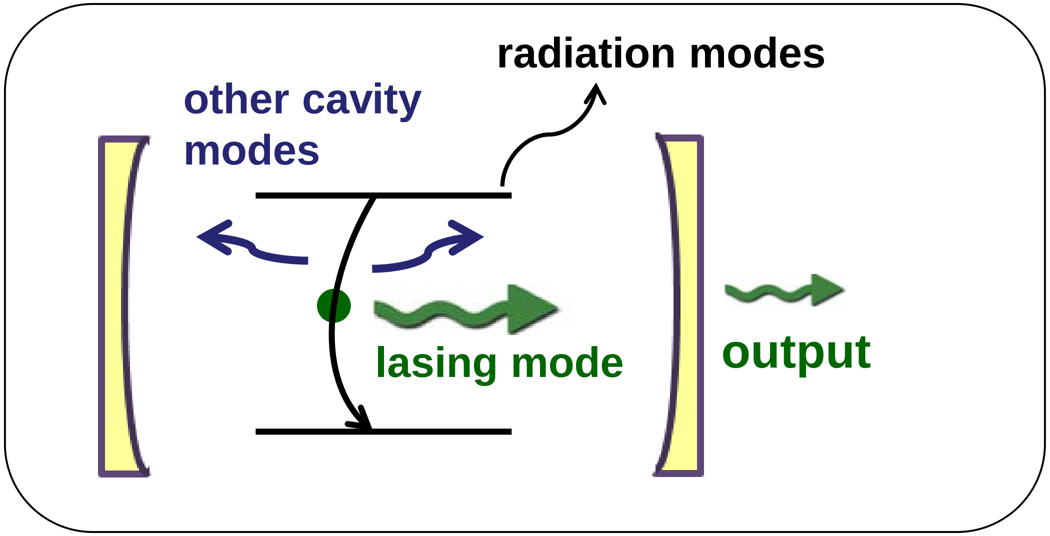


Spontaneous emission factor β



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

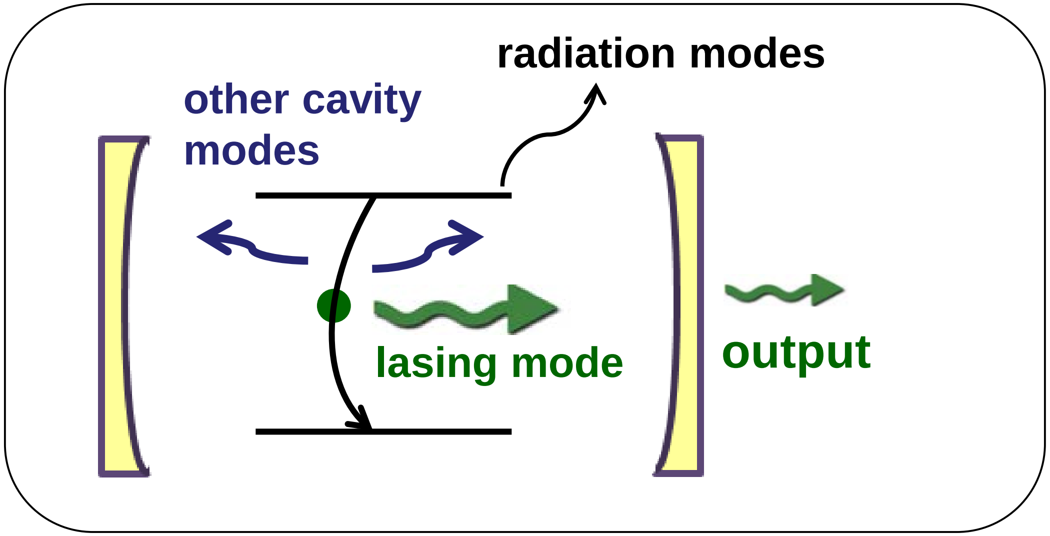
Spontaneous emission factor β



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

	Conventional laser	Nanoscale laser
Spontaneous emission factor β	0.00001	0.1 - 1

Spontaneous emission factor β



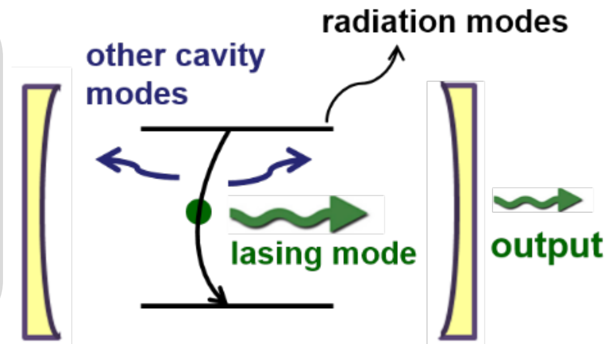
β ⟷ **energy efficiency**

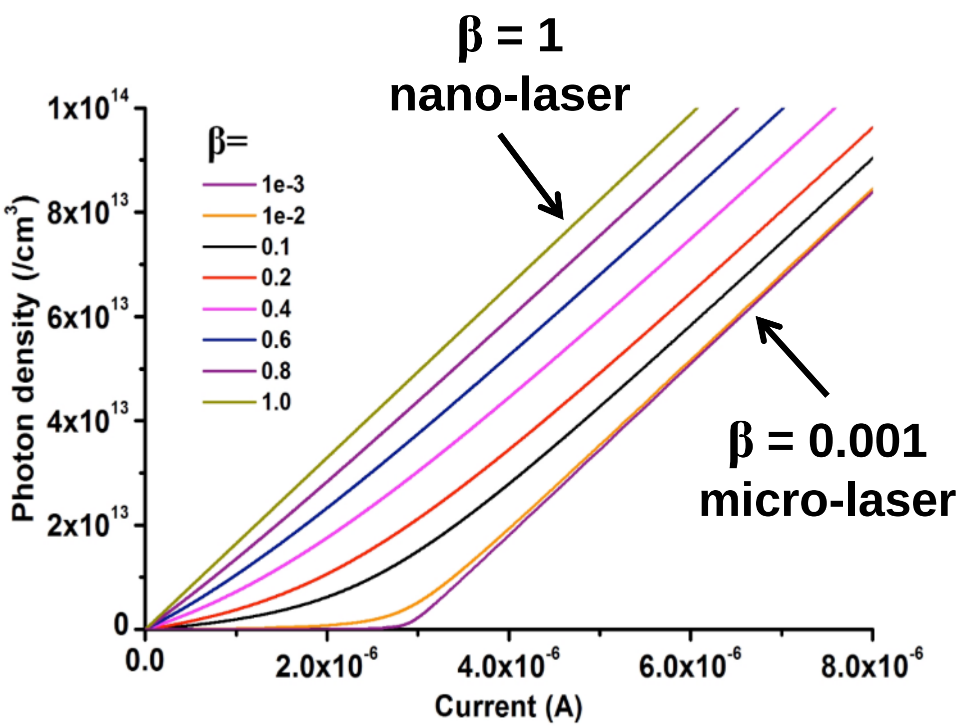
$$\beta = \frac{\text{spontaneous emission into the lasing mode}}{\text{spontaneous emission into the lasing mode} + \text{into other cavity modes} + \text{into free space radiation modes}}$$

	Conventional laser	Nanoscale laser
Spontaneous emission factor β	0.00001	0.1 - 1

β factor in nanolasers

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





β factor in nanolasers

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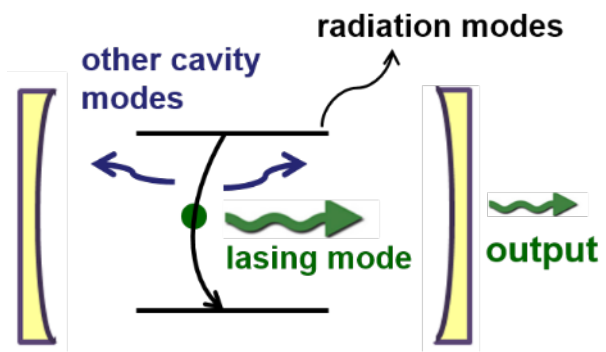

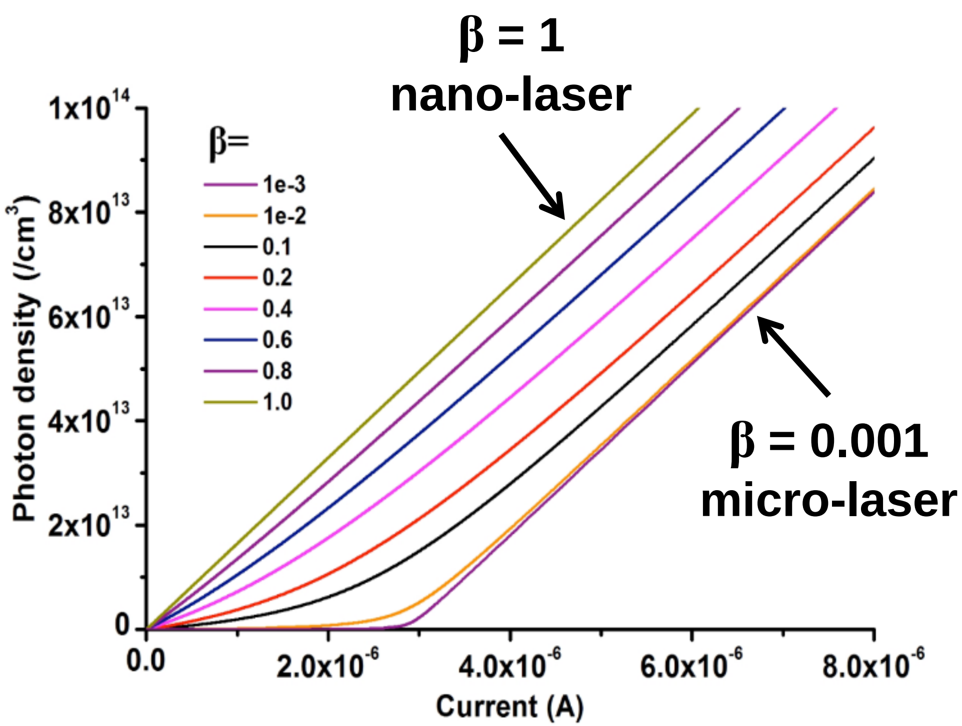

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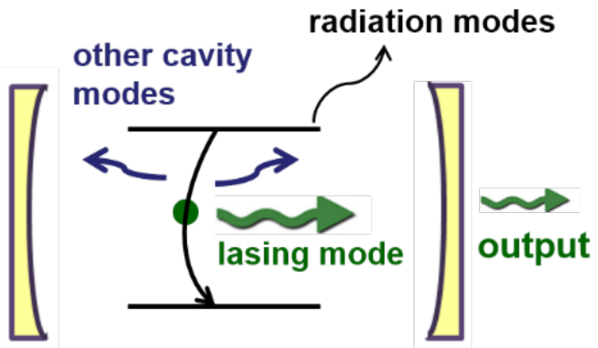
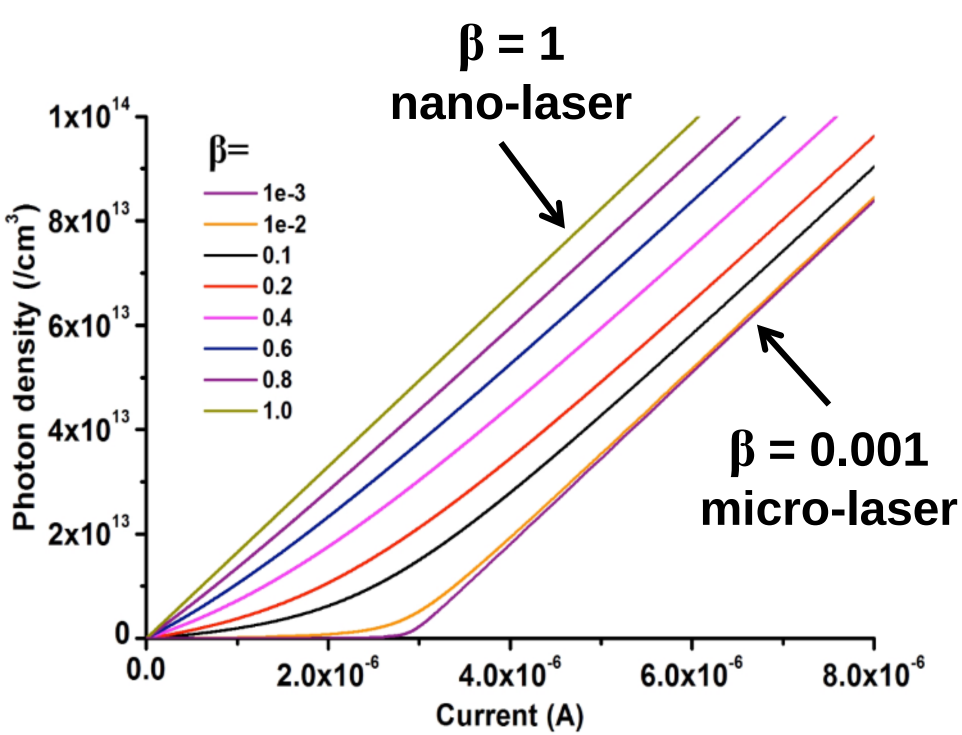
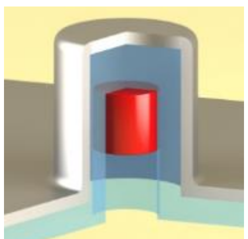




$$\beta_{max} = \frac{F_P^{(1asing)}}{\sum_k F_P^{(k)}}$$

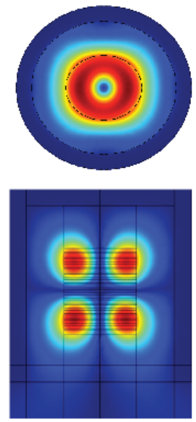
β factor, T = 300K



1416nm

Q = 478

Fp=0.170



Wavelength — Spectral window of PL

1300nm — 1670nm

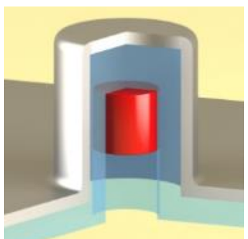
$$\beta_{\mathbf{max}} = \frac{\textbf{spontaneous emission into the lasing mode}}{\textbf{spontaneous emission into lasing mode} + \textbf{into other cavity modes} + \textbf{into free space radiation modes}}$$

$$\beta_{\max} = \frac{F_P^{(\mathrm{1asing})}}{\sum_k F_P^{(k)}}$$

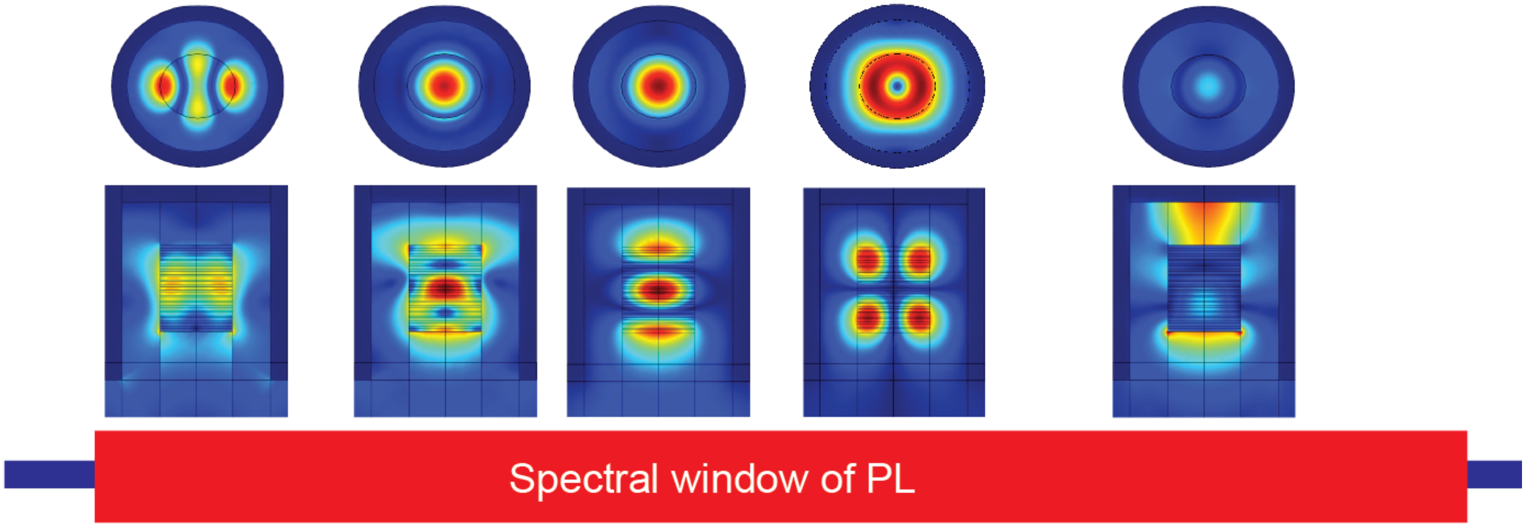
Qing Gu et al, *Optics Express*, Vol. 21, No. 13 (2013)

β factor, T = 300K

1310nm	1373nm	1387nm	1416nm	1546nm
Q = 65	Q = 64	Q = 63	Q = 478	Q = 61
Fp=0.032	Fp=0.079	Fp=0.096	Fp=0.170	Fp=0.097



Wavelength



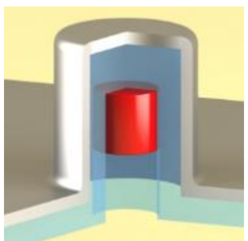
1300nm 1670nm

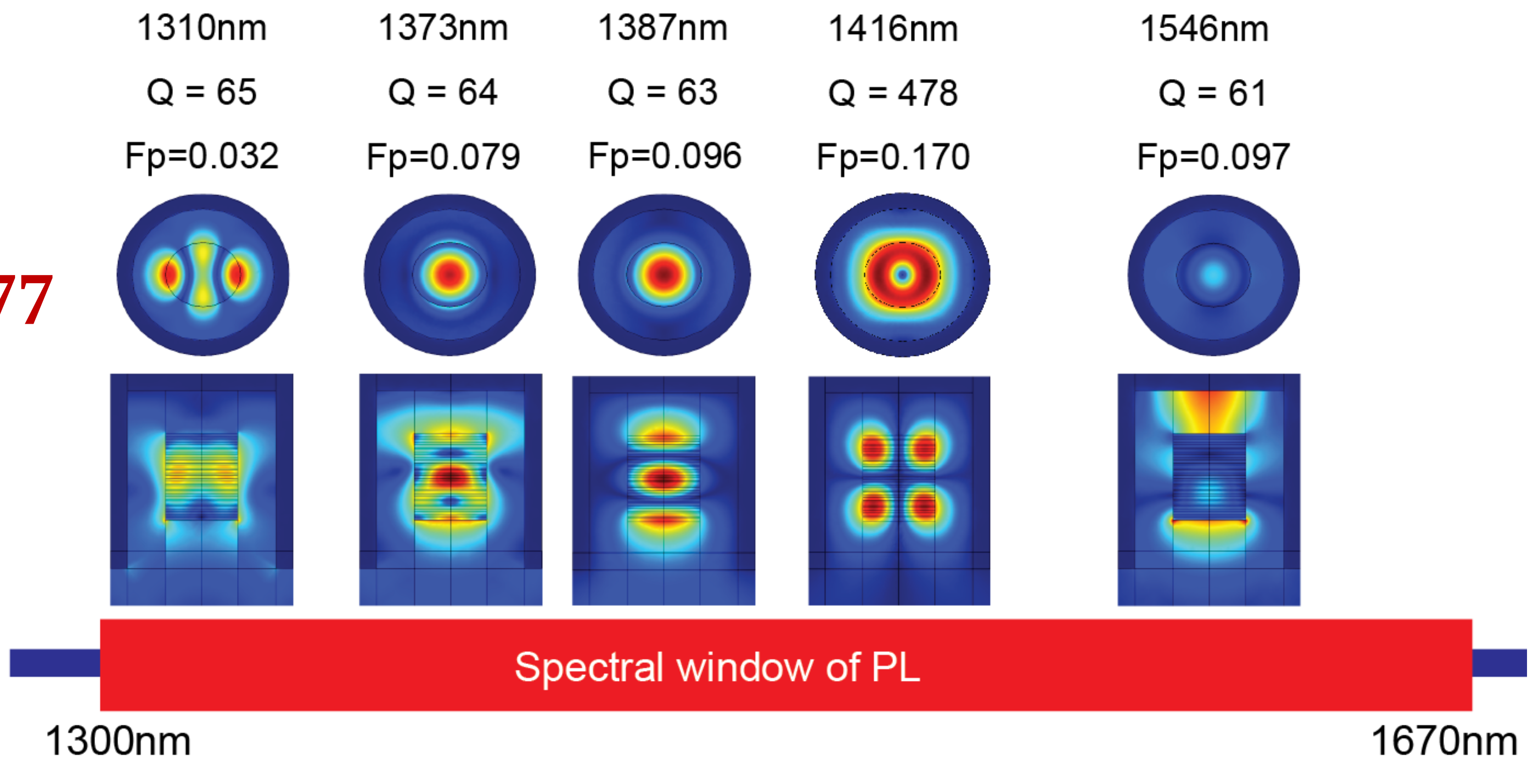
$$\beta_{max} = \frac{\text{spontaneous emission into the lasing mode}}{\text{spontaneous emission into lasing mode} + \text{into other cavity modes} + \text{~~into free space radiation modes~~}}$$

$$\beta_{max} = \frac{F_P^{(lasing)}}{\sum_k F_P^{(k)}}$$

β factor, T = 300K

$\beta_{max} = 0.377$





Wavelength

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

(The term "into free space radiation modes" is struck through with a red arrow.)

$$\beta_{max} = \frac{F_P^{(lasing)}}{\sum_k F_P^{(k)}}$$

β factor: temperature dependence

Purcell factor

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

Joseph Smalley et al, *IEEE JQE*, Vol. 50 (2014)

β factor: temperature dependence

Purcell factor

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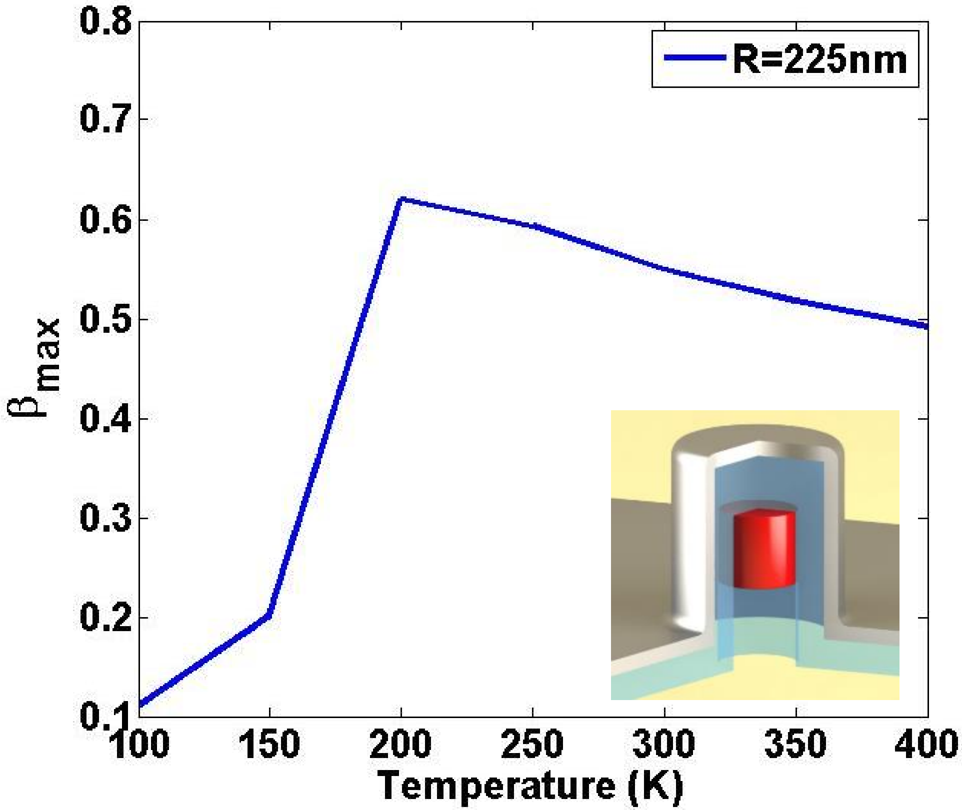

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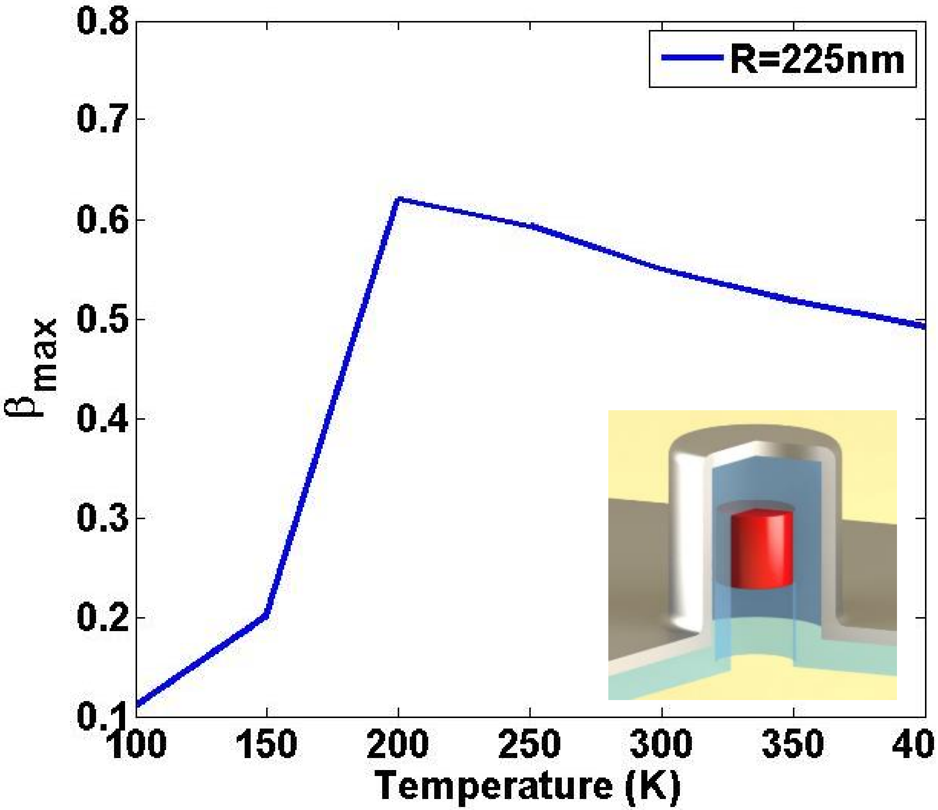
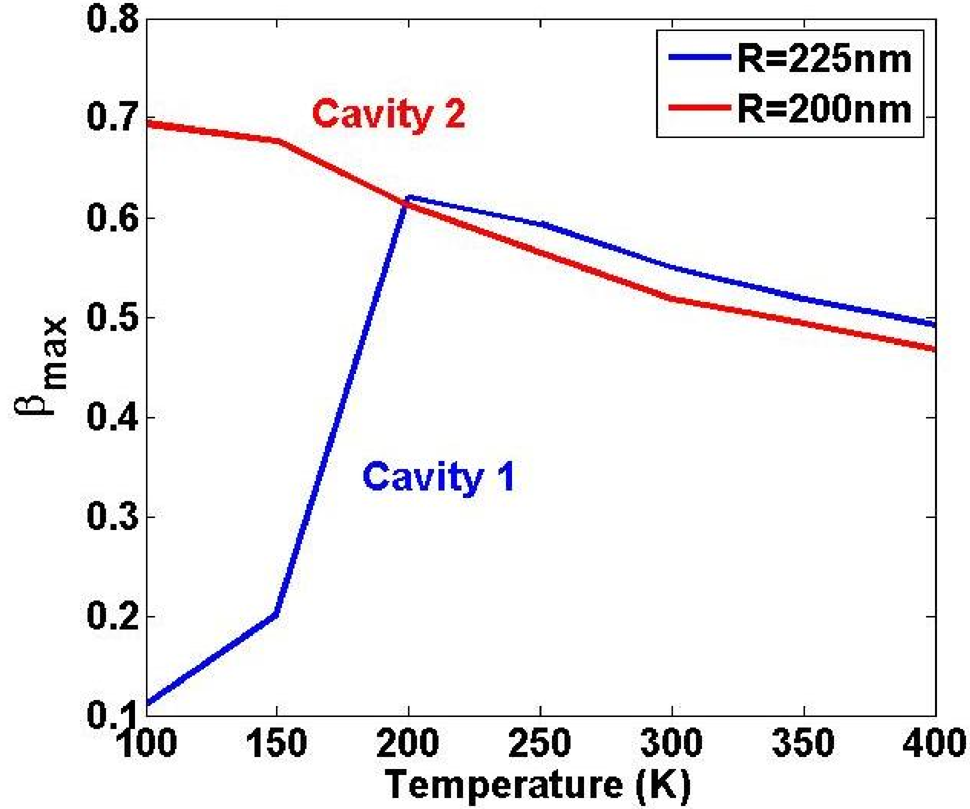
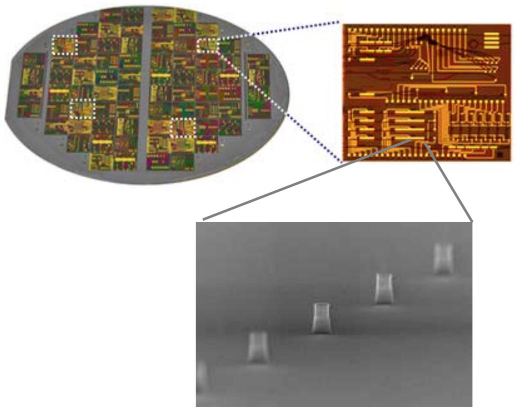




Joseph Smalley et al, *IEEE JQE*, Vol. 50 (2014)

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

Olesya Bondarenko et al, *Applied Physics Letters*, Vol. 103, 043105 (2013)

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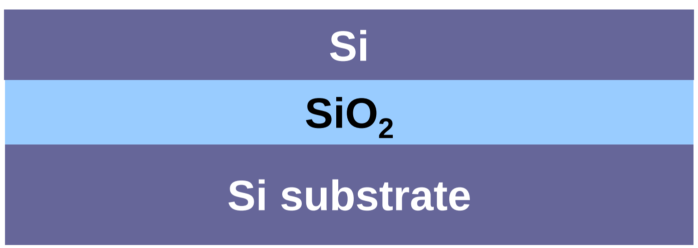

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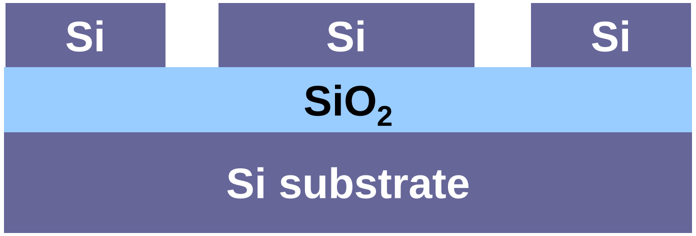

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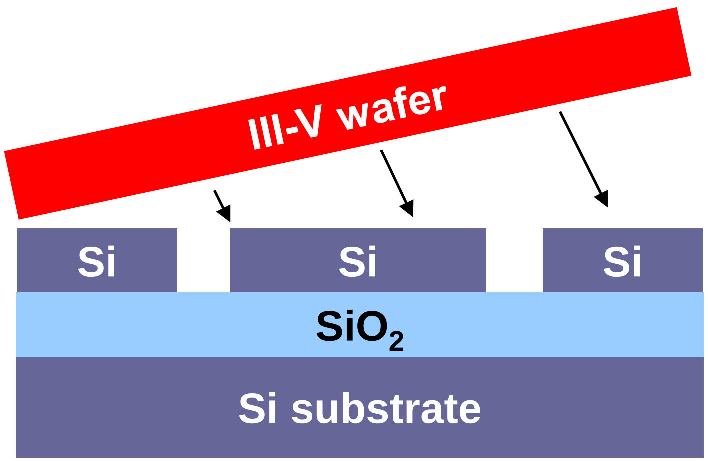

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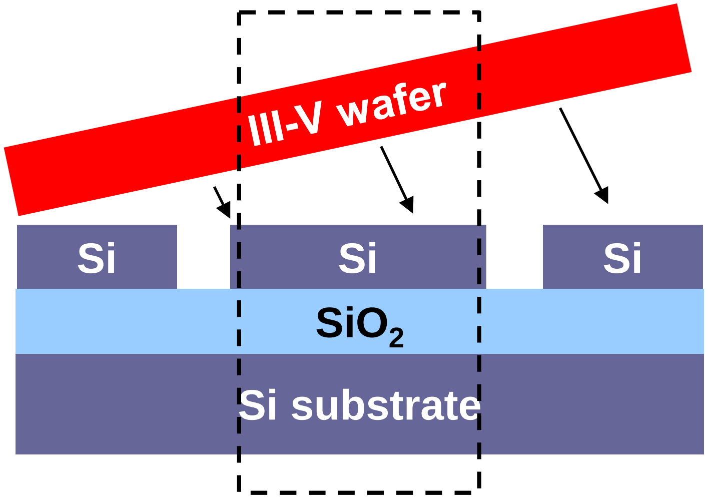

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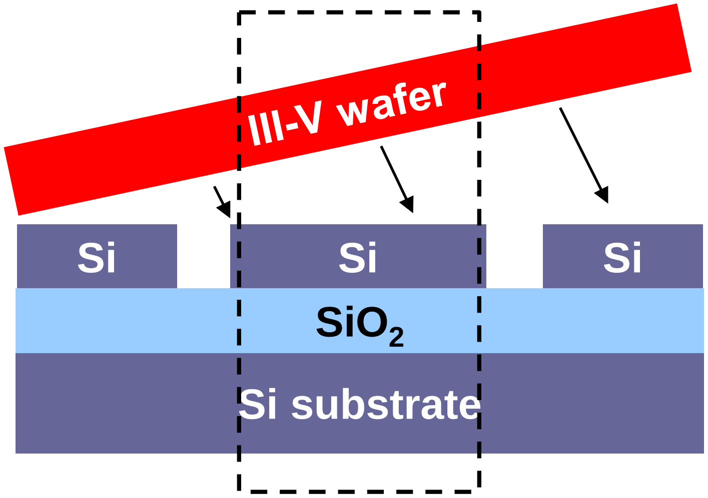

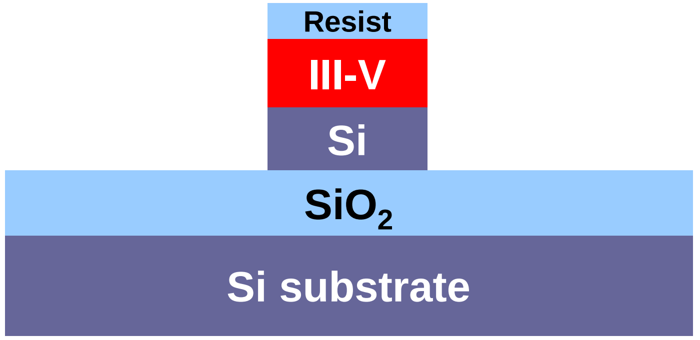

Olesya Bondarenko et al, *Applied Physics Letters*, Vol. 103, 043105 (2013)

Integration of III-V and Silicon

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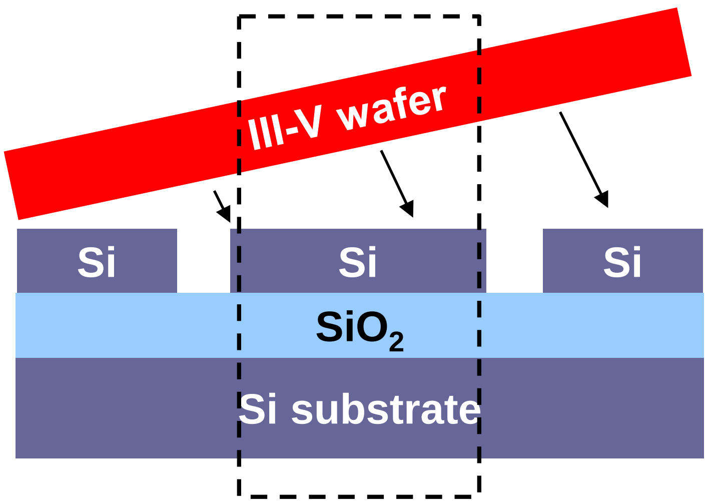
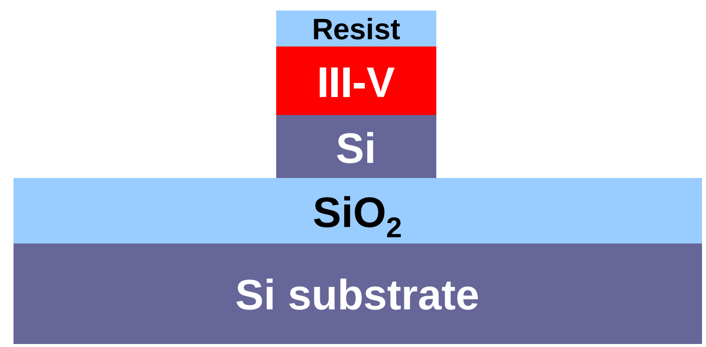
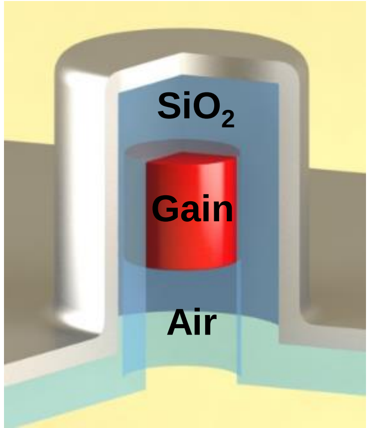




- Large scale (mm scale)
- Low temperature process (< 400 ^{o}C)
- Direct bond between III-V and Si
- No alignment required

Olesya Bondarenko et al, *Applied Physics Letters*, Vol. 103, 043105 (2013)

III-V/Si nanolaser



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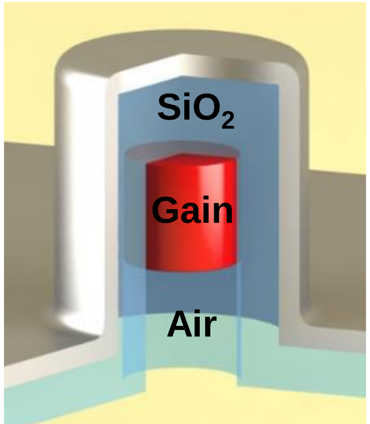

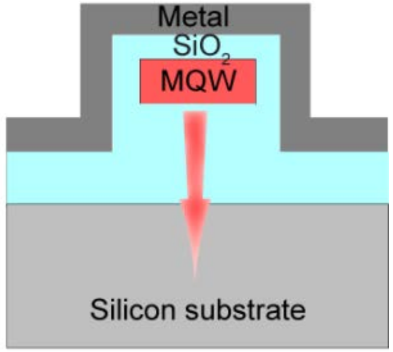

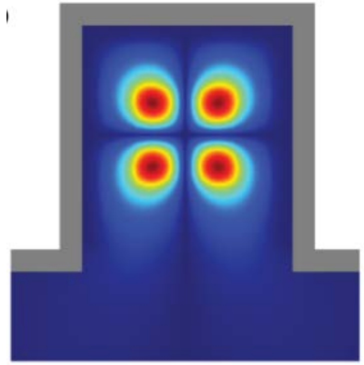

Olesya Bondarenko et al, *IEEE Photonics Journal*, Vol. 3 (2011)

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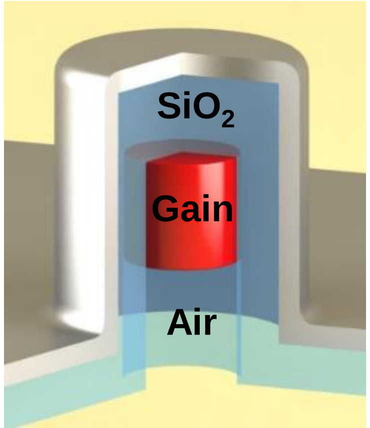

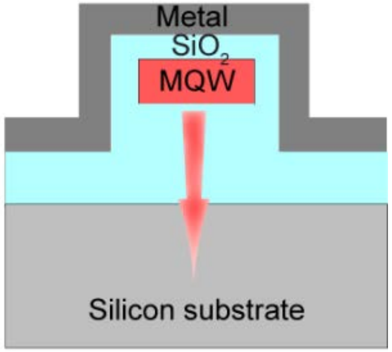

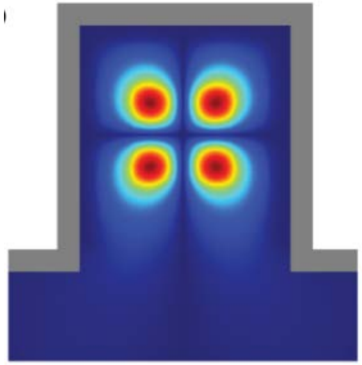

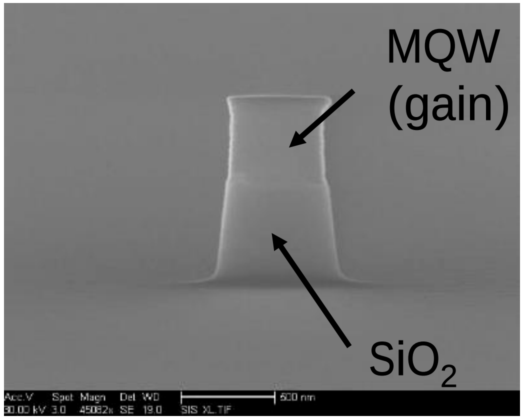

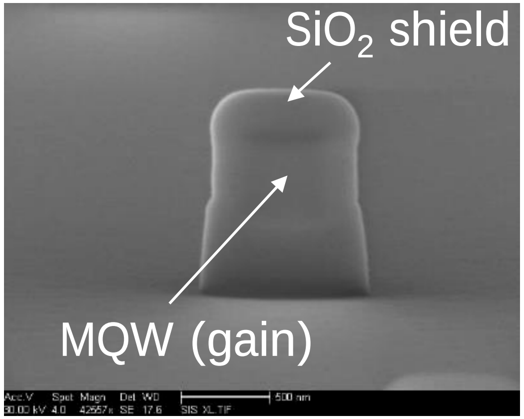

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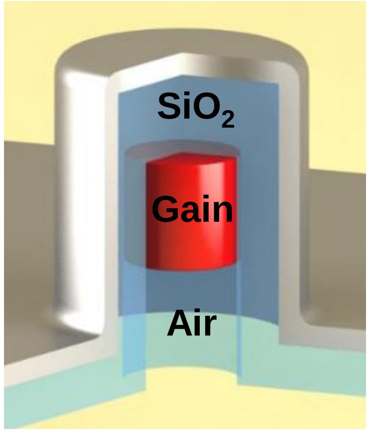
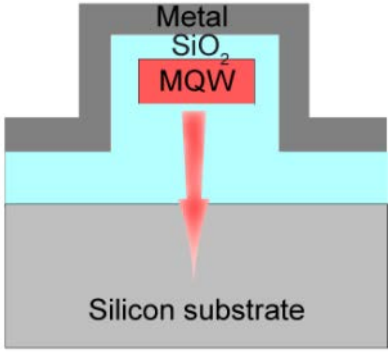
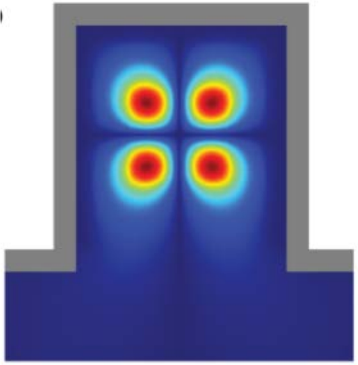
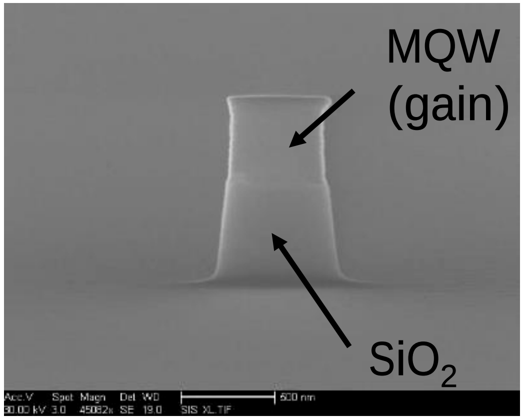
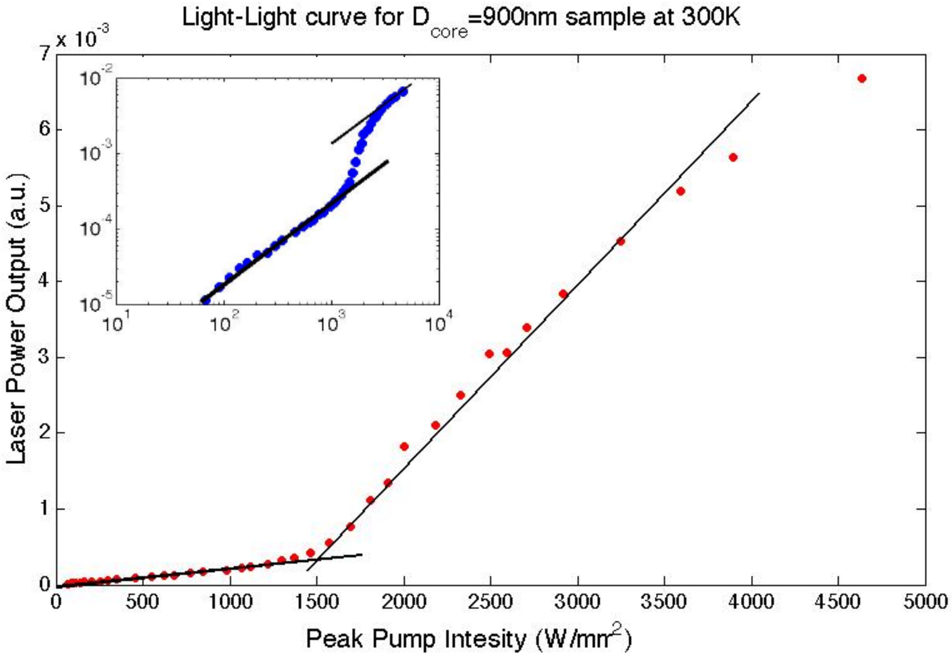
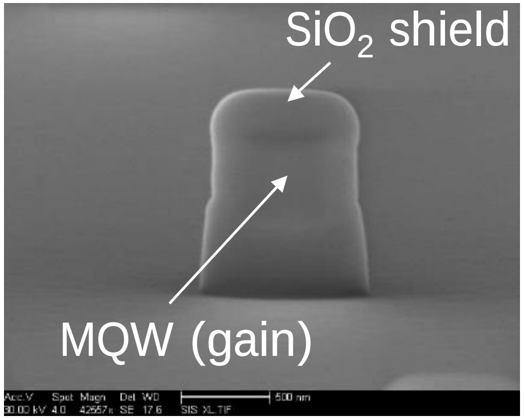






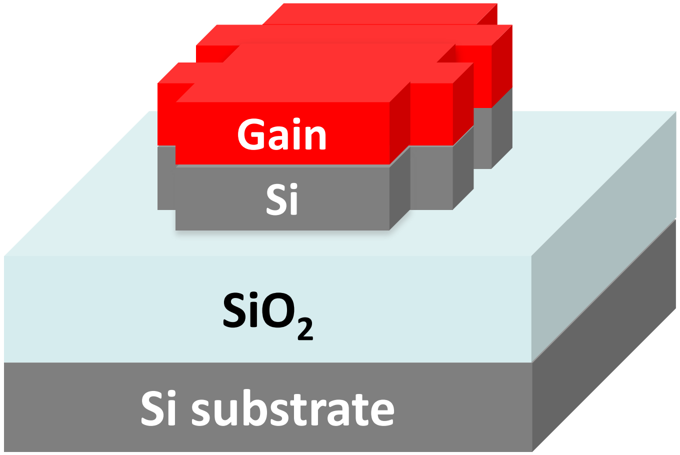


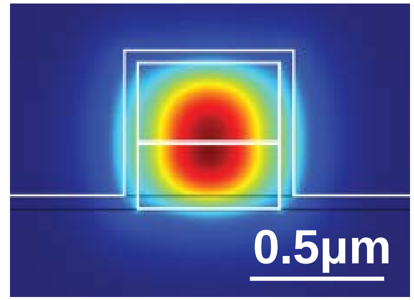




Olesya Bondarenko et al, *IEEE Photonics Journal*, Vol. 3 (2011)

III-V/Si micro-DFB laser





Olesya Bondarenko et al, *Applied Physics Letters*, Vol. 103, 043105 (2013)

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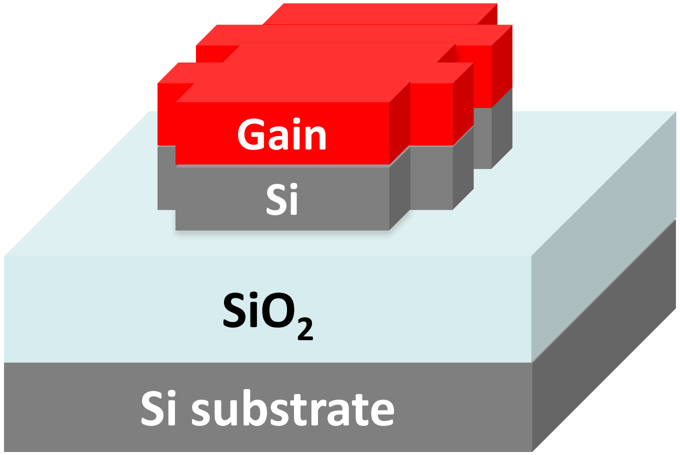
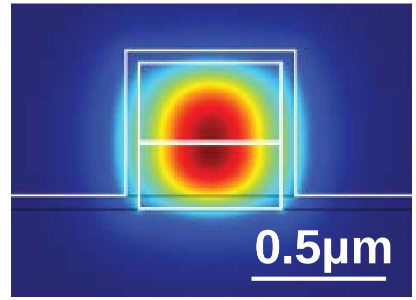
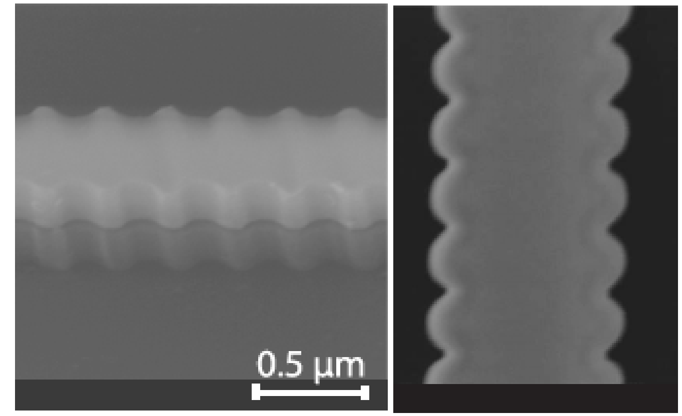
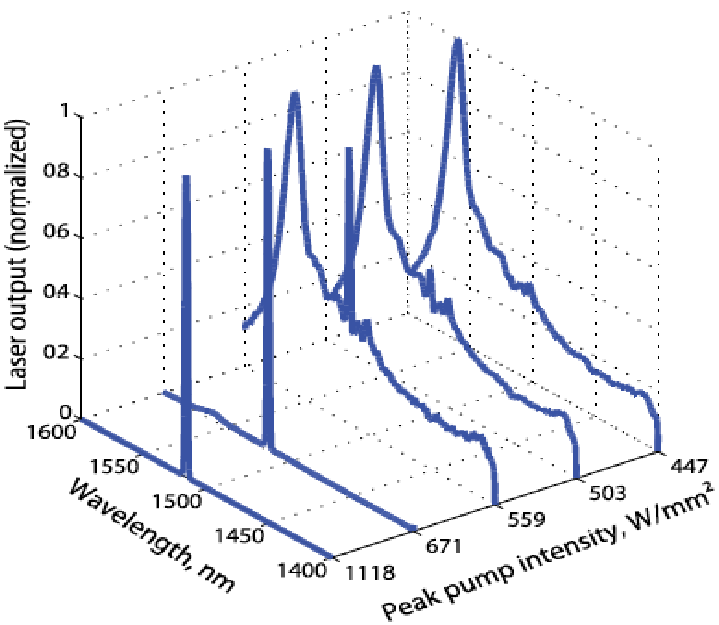
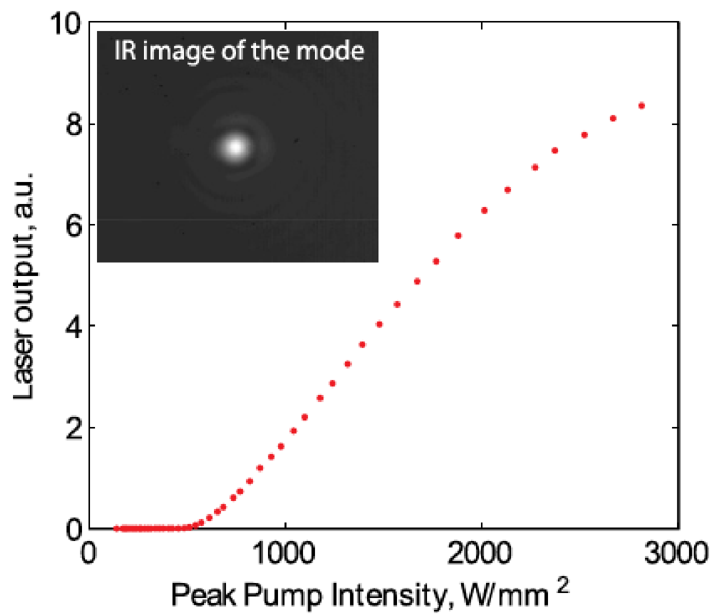




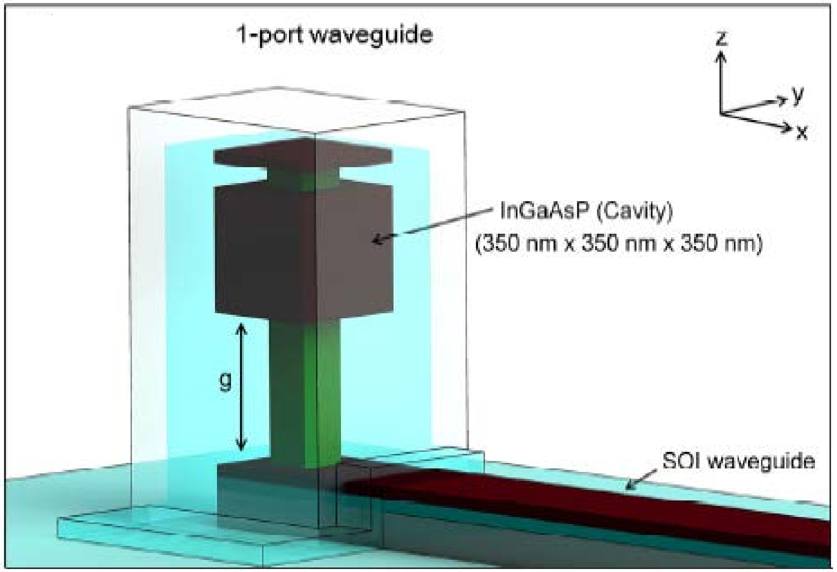


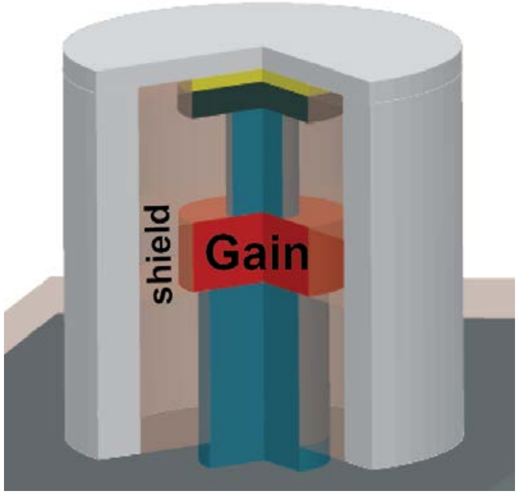


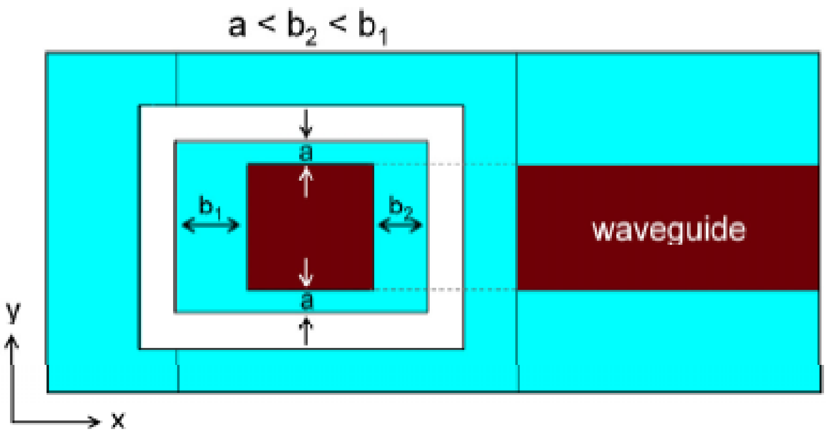


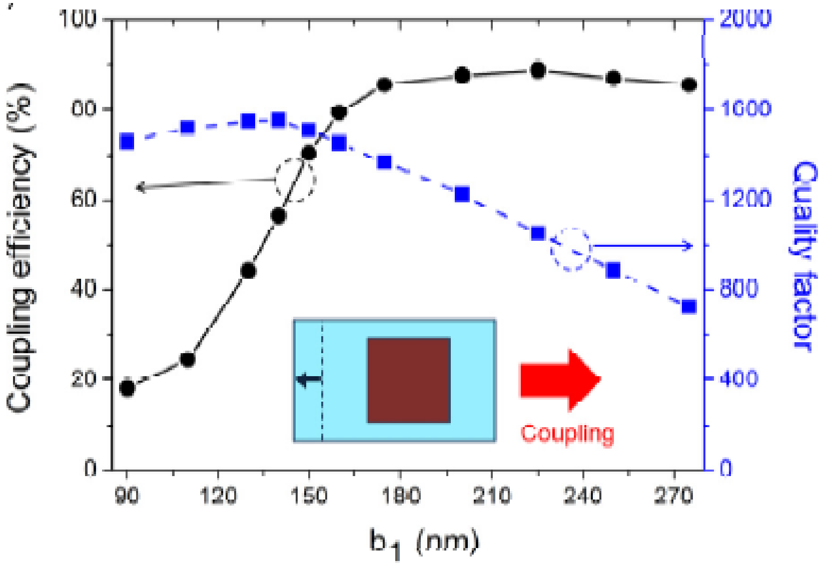
Olesya Bondarenko et al, *Applied Physics Letters*, Vol. 103, 043105 (2013)

Outlook: Coupling light emission to waveguide





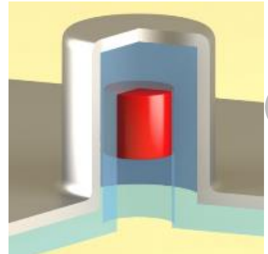




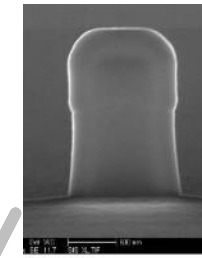
Myung-Ki Kim et al, *Optics Express,* Vol. 21, (2013)

Summary:

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

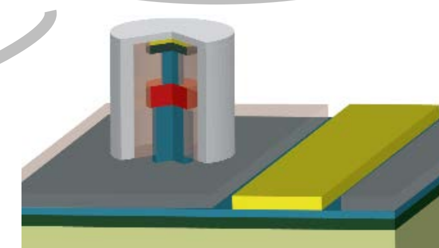


Design:
Optical cavity mode

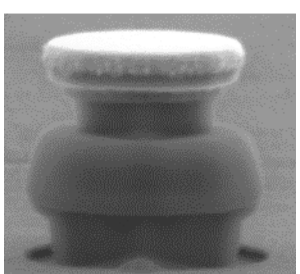


Optically pumped laser

Multi-physics design

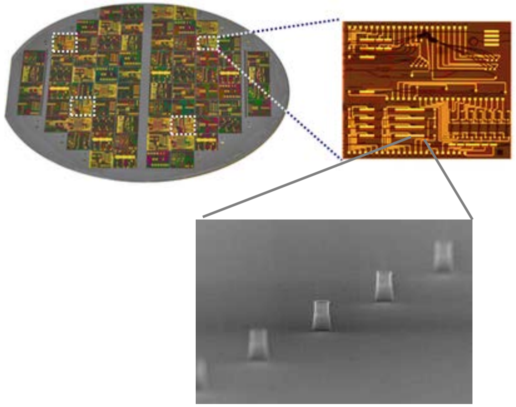


Electrically pumped laser



Performance analysis

Insertion into Photonic ICs



THANK YOU!