Lasers

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Advanced topics in silicon photonics 377-2-5906

Lecture 4

Outline

Light sources

It is highly desirable to have a silicon-compatible material that can provide optical emission and optical gain, for light sources (lasers, LEDs) and for on-chip optical amplifiers.

One of the main challenges of the silicon photonics platform is the lack of an on chip light source.

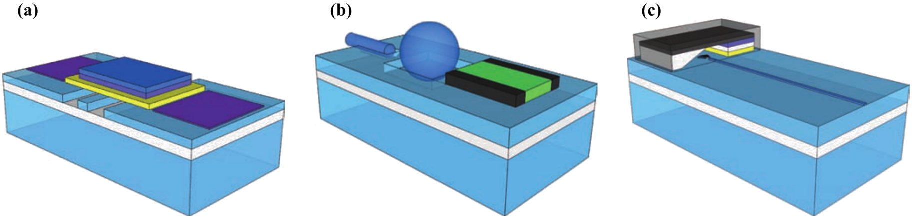
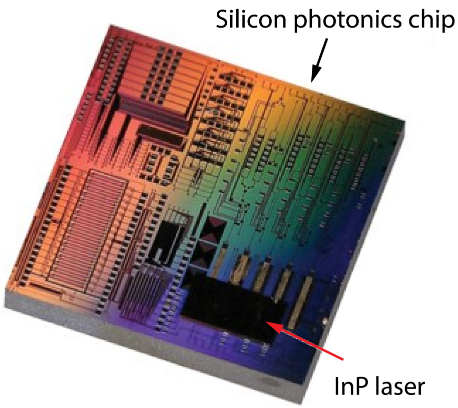
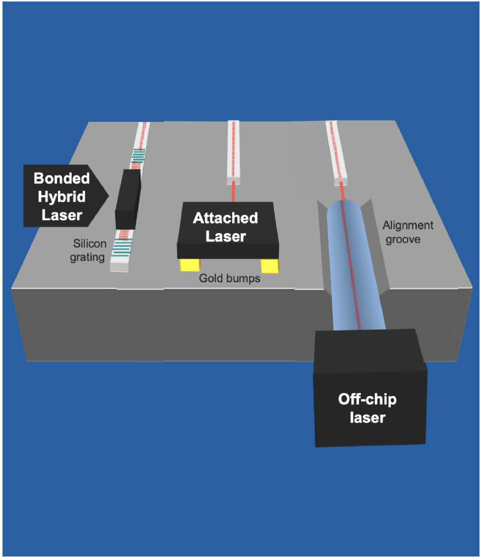


Figure 1: Laser integration techniques: (a) Bonded III-V laser with evanescent mode coupling. (b) Optical fiber to spherical lens coupling. (c) Surface-mounted laser package with vertical reflector aligned to on-chip grating coupler.



Silicon photonics chip with 3-D hybrid integrated InP laser array.



Song, Bowen, et al. "3D integrated hybrid silicon laser." Optics Express 24.10 (2016): 10435-10444.
https://www.photonics.com/Articles/A_Hybrid_Silicon_Laser/a27801

Hybrid Silicon Laser

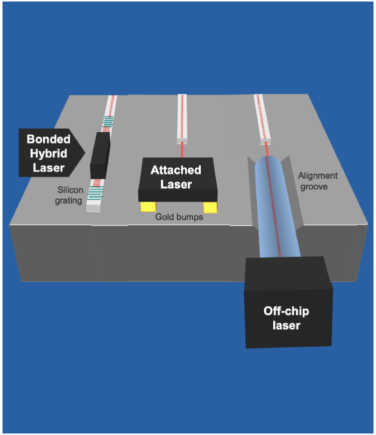
- Bond InP based material to silicon
- No alignment
- Many lasers with one bonding step
- Amenable to high integration
- Potentially lowest cost

Direct Attached Laser

- Tight alignment tolerances
- Requires gold metal bonding
- Passive alignment challenges
- Less Expensive

Off-chip Laser

- High power laser required
- Requires fiber attach
- Non-integrated solution
- Expensive



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Light Source Integration

Classification of light sources for high-density inter-chip interconnects

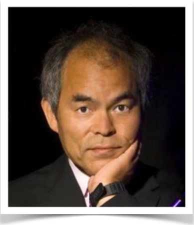
- Off-chip sources
- On-chip sources
  - Hybridly integrated compound semiconductor lasers
  - Monolithically integrated Ge lasers
    - Vertical cavity surface emitting lasers (VCSELs)
    - Edge emitting lasers
      - Evanescent-coupled lasers
      - Grating-coupled lasers
      - Butt-coupled lasers

- **1917** - A. Einstein publishes ”On the quantum mechanics of radiation”, explaining spontaneous and stimulated emission
- **1954** - Ch.H. Townes et al.: First maser (= Microwave Amplifier by Stimulated Emission of Radiation) based on ammonia molecules.
- **1959** - G.Gould submits construction sketches for an optical maser for a US patent and introduces the term ”laser” (= Light Amplifier by Stimulated Emission of Radiation)
- **1959** - N.G. Basoc et al.: Proposition for a semiconductor laser
- **1960** - T.H. Maiman: First laser, consisting of a ruby bar ($Cr^{3+}:Al_2O_3$) Charles H. Townes with two parallel faces as resonator and a pulsed flashbulb as optical pumping source, emission wavelength 0.6943 μm
- **1962** - F.H. Dill; W.E.Howard et al.: Continuous stimulated 0.84 μm emission of GaAs diodes at temperatures of 2 K to 77 K

Charles H. Townes

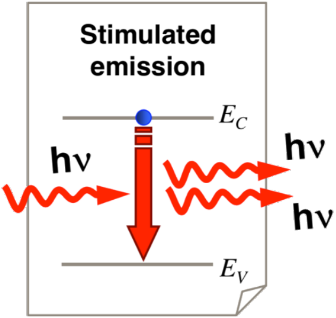
- **1963** - H. Kroemer; Zh.I. Alferov and R.F. Kazarinov: Proposition of a double- heterostructure laser diode
- **1968** - Zh.I. Alferov *et al.*: Pulsed-mode operation of a double-hetero structure laser diode
- **1970** - Zh.I. Alferov *et al.*: First continuously emitting double-heterostructure laser diode at room temperature
- **1970** - L. Esaki and R.Tsu: First quantum well structures
- **1976** - J. Hsieh: Continuously emitting InGaAsP laser diode with an emission wavelength of 1.25 μm
- **1991** - M. Haase et al.: First short-term operation of a blue-green emitting laser diode on the basis of the II-VI semiconductor ZnSe
- **1996** - S. Nakamura: First efficient blue emitting laser diode at room temperature based on GaN

Zhores I. Alferov

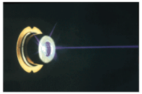


Shuji Nakamura

Stimulated emission



Generates optical gain



Useful in lasers

- The external photon stimulates radiation with the same frequency it has. → **narrow spectral width**.
- All photons propagate in the same direction and contribute to output light → high current-to-light conversion efficiency and **high output power**.
- The stimulated light will be well **directed**.
- External and stimulated photons are in phase → **coherent radiation**.

Direct and indirect semiconductors

Almost all the III-V semiconductors can be used to fabricate semiconductor lasers.

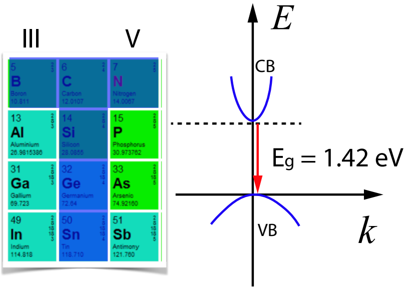


Figure 2: Direct optical transitions (GaAs): efficient photon sources

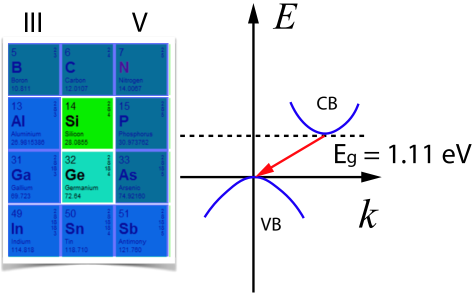


Figure 3: Indirect optical transitions (Si, Ge): inefficient photon sources (but efficient photo-detectors)

Indirect semiconductors

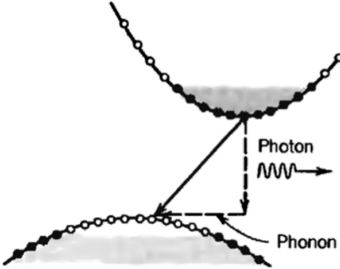


Figure 4: The energy can be carried off by one photon, but one or more phonons (lattice vibrations) are required to conserve momentum. Simultaneous multi-particle interactions are unlikely.

[1]

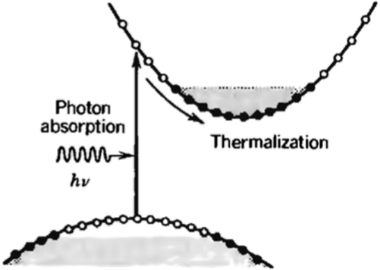
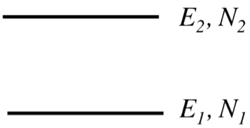


Figure 5: Photon absorption is a sequential, two-step process (first absorb photon energy, then momentum transferred to phonons). Thus, is not unlikely.

Einstein relations



Population of two levels:

$$\frac{N_1}{N_2} = \frac{g_{D1}\exp(-E_1/kT)}{g_{D2}\exp(-E_2/kT)} = \frac{g_{D1}}{g_{D2}}\exp\left(\frac{E_2-E_1}{kT}\right)$$

$\mathrm{g}_{\mathrm{D}1,2}$ = degeneracies of the levels

Upward and downward transition rate:

$$r_{12} = N_1\varphi(\nu)B_{12}$$

$$r_{21} = \underbrace{N_2A_{21}}_{\text{Spontaneous emission rate}} + \underbrace{N_2\varphi(v)B_{21}}_{\text{Stimulated emission rate}}$$

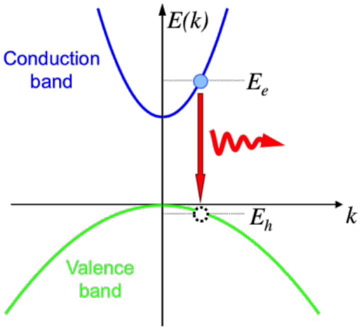
where B_{12} is Einstein coefficient for absorption, B_{21} is Einstein coefficient for stimulated emission and $A_{21} = 1/\tau_{21}$, Einstein coefficient for spontaneous emission.
Equilibrium $(\mathrm{r}_{12} = \mathrm{r}_{21}) \Rightarrow$

Population inversion and optical gain

Typically $E_2 > E_1, N_1 > N_2$, and absorption $\alpha > 0$ $\rightarrow$ a medium with **loss**
Wanted: population inversion so that $N_2 > N_1$ and $\alpha < 0 \rightarrow$ a medium with **gain**!
A semiconductor is not a two level system:

$$E_e = E_c + \frac{m_r^*}{m_e^*}(\hbar\omega - E_g)$$

$$E_h = E_v - \frac{m_r^*}{m_h^*}(\hbar\omega - E_g)$$



Population inversion and optical gain

Emission probability that a CB state of energy E_2 is occupied by an electron and a VB state of energy E_1 is empty (occupied by a hole).

$$f_e(\nu) = f_c\left(E_2\right)\left[1 - f_v\left(E_1\right)\right] \tag{1}$$

Absorption probability that a CB state of energy E_2 is empty (occupied by a hole) and a VB state of energy E_1 is occupied by an electron.

$$f_a(\nu) = \left[1 - f_c\left(E_2\right)\right] f_v\left(E_1\right) \tag{2}$$

Gain = emission − absorption

$$g(\hbar\omega) = \frac{\pi q^2 \hbar}{m_0^2 c n_r \varepsilon_0} \frac{1}{\hbar\omega} \left|a \cdot p_{cv}\right|^2 N_{cv}(\hbar\omega) \left[f^e\left(E_e\right) + f^h\left(E_h\right) - 1\right]$$

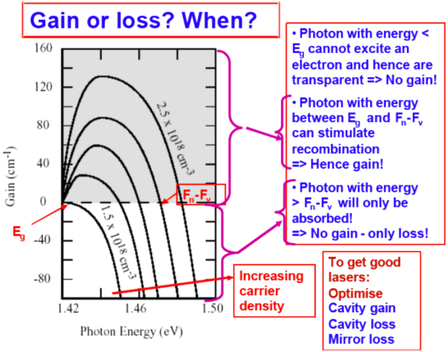
Gain requires inversion: $f^e\left(E_e\right) + f^h\left(E_h\right) > 1$

The quasi-Fermi levels must penetrate their respective bands!

Gain vs. photon energy

Net gain coefficient = (rates of stimulated emission – absorption) / incident photon flux

$$\gamma_0(\nu) = \left[r_{\mathrm{st}}(\nu) - r_{\mathrm{ab}}(\nu) \right] / \phi_\nu$$



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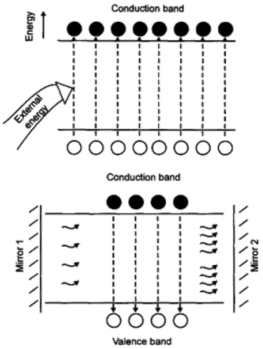
Positive feedback and light amplification



[1]

We also need **positive feedback** that adds the output (stimulated photons) to the input (external photons). This can be achieved by using mirrors at the end of the active region → a **resonator** is formed and **light amplification** takes place.

For lasing it is essential that the gain in the resonator overcomes the losses due to absorption and transmission at the mirrors.

In semiconductor lasers lasing is achieved **by current injection across a forward-biased junction**. For efficient operation the injected carriers need to be confined in the vicinity of the junction. This is achieved with the use of **heterojunctions**.

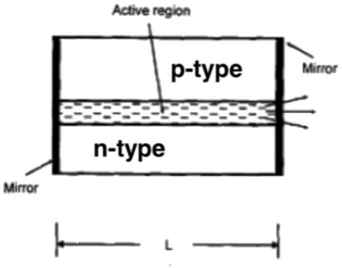
Fabry-Perot laser

- The simplest way to create a resonant cavity is to cleave the end faces of the semiconductor heterojunction. Optical feedback is achieved by multiple reflection at the sample facets
- The device is called a **Fabry-Pérot laser diode** (FP-LD)
- Semiconductor-air interface produces a reflection coefficient at normal incidence of

$$R = \left(\frac{n_{FP} - n_{air}}{n_{FP} + n_{air}} \right)^2$$

- For GaAs this reflection coefficient is

$$R = \left(\frac{3.6 - 1}{3.6 + 1} \right)^2 = 0.32$$



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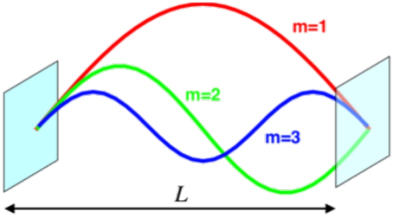
Fabry-Perot laser



Refractive index in cavity

Cavity length

$$\lambda_m = \frac{2n_r L}{m}$$

Longitudinal mode order

- Fabry-Pérot cavities sustains longitudinal modes. Each mode has a different wavelength.
- In general, the laser cavity length L is equal to a few 100 μm $\Rightarrow m \gg 1$.

Longitudinal (axial) modes

The laser output consists of a large number of discrete frequency components. To calculate mode spacing, first solve for m : $m = \frac{2n_r L}{\lambda_m}$
Then differentiate and solve for $d\lambda$(n depends on λ) :
$\Rightarrow \quad \frac{dm}{d\lambda} = -\frac{2Ln_r}{\lambda^2} + \frac{2L}{\lambda}\frac{dn_r}{d\lambda}$

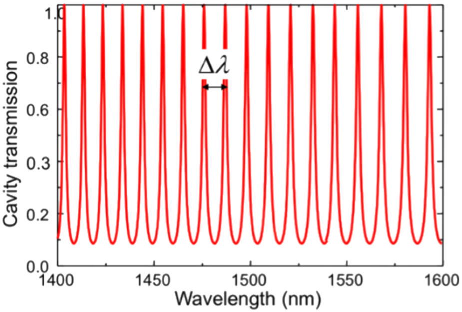


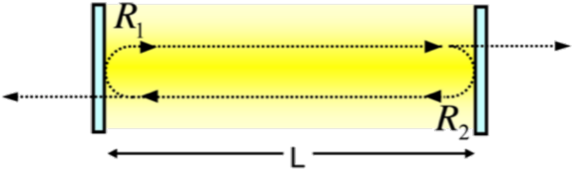
Figure 6: [2]

Frequency/Wavelength separation of adjacent modes:

$$\Delta\lambda = \frac{\lambda^2}{2Ln_r}\left(1 - \frac{\lambda}{n_r}\frac{dn_r}{d\lambda}\right)^{-1} \quad \text{or} \quad \Delta f = \frac{c}{2Ln_r}\left(1 + \frac{f}{n_r}\frac{dn_r}{df}\right)$$

Lasing condition

Loss γ **in the cavity**
Gain g **in active region**



Loss coefficient γ: takes into account all the losses (scattering, absorption, diffraction) except the transmission at the ends.
Gain inside the cavity after one round trip: $e^{2\Gamma g L - 2\gamma L}$
Mirror loss after one round trip: $R_1 R_2$
Optical intensity after one round trip: $I = I_0 R_1 R_2 e^{2(\Gamma g - \gamma)L}$
In order to be sustained, the light wave intensity should be the same after one round trip in the cavity

Lasing condition

Modal gain is a measure of the power transferred from the active region into the propagating mode.

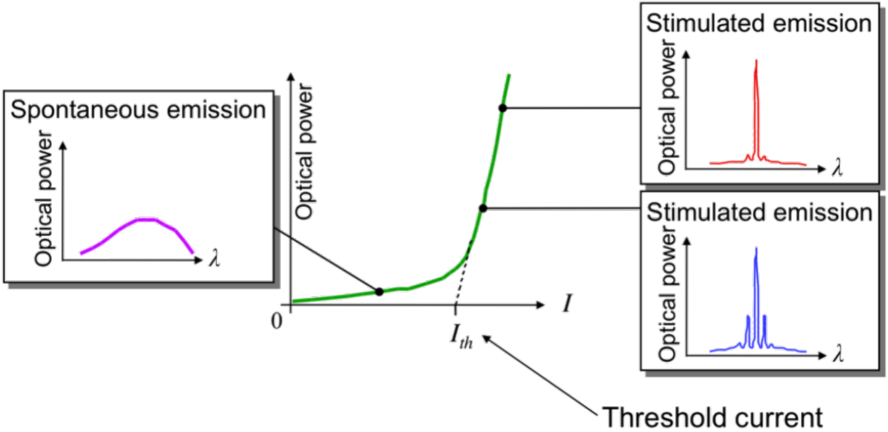
$$I = I_0 R_1 R_2 e^{2(\Gamma g - \gamma)L} \tag{3}$$

At threshold:

$I = I_0 \Rightarrow \Gamma g_{\mathrm{th}} = \gamma + \frac{1}{2L} \ln\left(\frac{1}{R_1 R_2}\right)$

Γ Is a measure of modal confinement (the fraction of optical intensity in the active region), and is a strong function of the active region thickness d. For example if $d > 0.1\ \mu$m $\rightarrow \Gamma \sim 1$, if $d \sim 5 - 10$ nm $\rightarrow \Gamma < 0.05$

Lasing condition



Level Systems

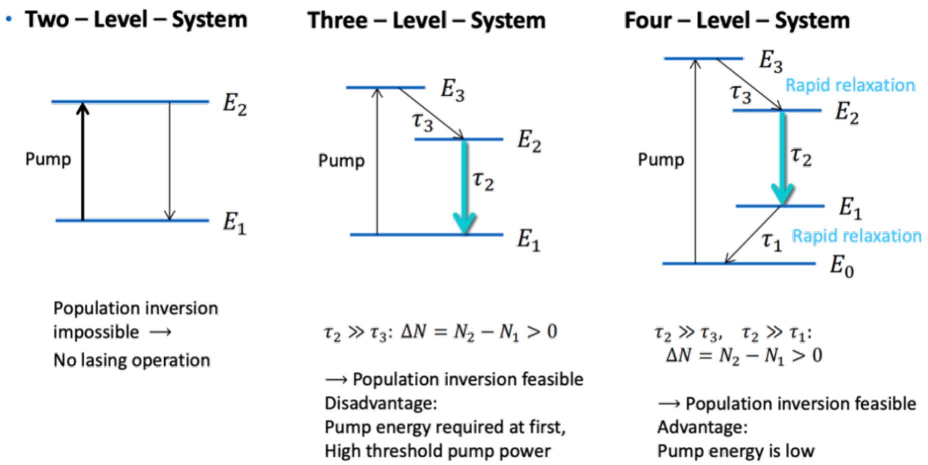


Figure 7: [3]

Laser on silicon is it possible?

Several approaches to build emitters on Si:

1. Nanostructures.
   (Emission at wrong wavelength for Si waveguides)
2. Erbium doping.
   (Some electroluminescence achieved, problems with efficiency, no gain demonstrated yet)
3. Germanium.
4. III/V on silicon.
   (Best lasers, challenges in integration)

Semiconductor materials and its lattice constant

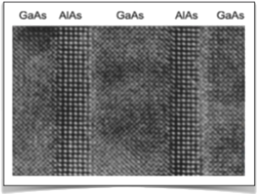
Direct semiconductor

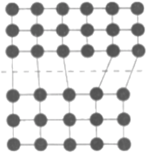
	GaAs	GaSb	InSb
Energy gap (eV)	1,435	0,72	0,18
B (cm³/s)	7,2 x 10^{-10}	2,4 x 10^{-10}	4,6 x 10^{-11}
τ_R(s)	1,3 x 10^{-9}	4,2 x 10^{-9}	2,2 x 10^{-8}

Indirect semiconductor

	Si	Ge
Energy gap (eV)	1,12	0,66
B (cm³/s)	1,8 x 10^{-15}	5,3 x 10^{-14}
τ_R(s)	5,6 x 10^{-4}	1,9 x 10^{-9}

- By adjusting the composition of the compound material, its lattice constant can be adjusted to match that of the substrate.
- A good lattice match allows to grow high-quality crystal layers.
- Lattice mismatch results in crystalline imperfections which can lead to non-radiative recombination.
- Lattice mismatch reduce the laser lifetime.





Hybrid and heterogeneous silicon lasers

The hybrid laser is a heterogeneous integration approach of bonding III-V materials such as **InP** onto the silicon photonic platform.

The combination of the two materials brings to the silicon platform the advantage of the high optical gain and efficient light emission available in III-V materials.

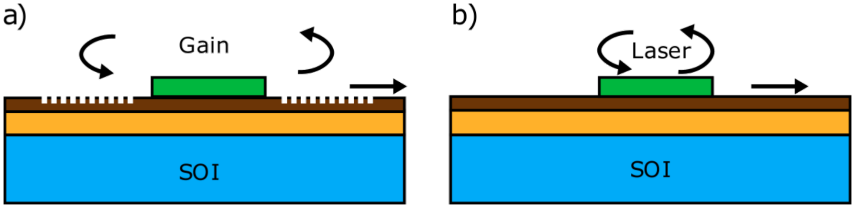
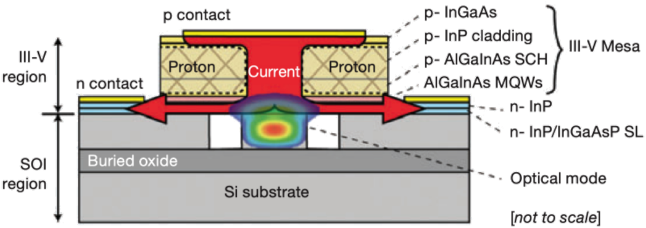


Figure 8: (a) Hybrid laser. A hybrid optical waveguide is formed in the silicon/III-V layers. (b) Bonded laser. The laser cavity is implemented in the III-V material. The light is coupled to the silicon evanescently. [4]

Hybrid and heterogeneous silicon lasers



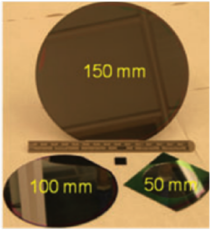


Figure 9: (Left) Schematic of hybrid silicon laser. (Right) Silicon wafers containing 2-mm-thick InGaAlAs layers bonded to SOI wafers. [5]

Hybrid and heterogeneous silicon lasers

The laser diode is butt-coupled to a polymer waveguide after which the optical mode is gradually transformed into the SOI waveguide mode.

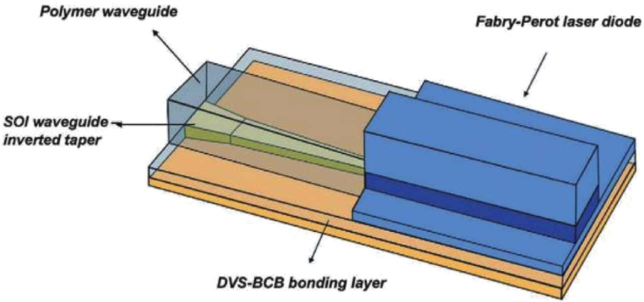


Figure 10: Schematic of the layout of the optical coupling using an inverted adiabatic taper approach. [6]

Hybrid micro-ring laser with a Si bus waveguide

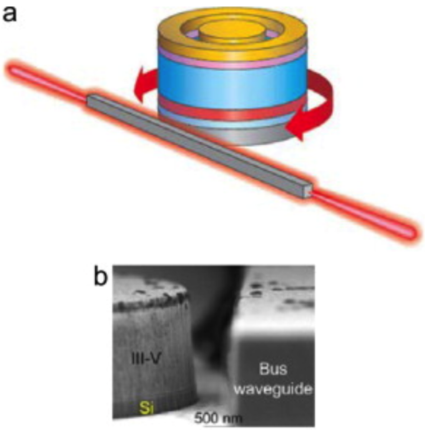


Figure 11: (a) Scheme of a hybrid micro-ring laser with a Si bus waveguide. (b) SEM image of resonator sidewall and bus waveguide. [7]

Distributed feedback (DFB) laser

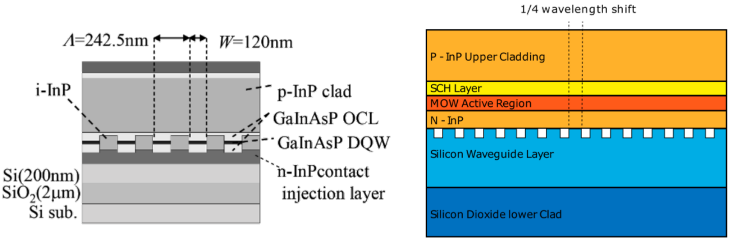


Figure 12: III-V DFB laser bonded on silicon. Left : the DFB grating is located in the active layer. Right: the DFB grating is located in the silicon waveguide layer. [6]

Racetrack resonator lasers

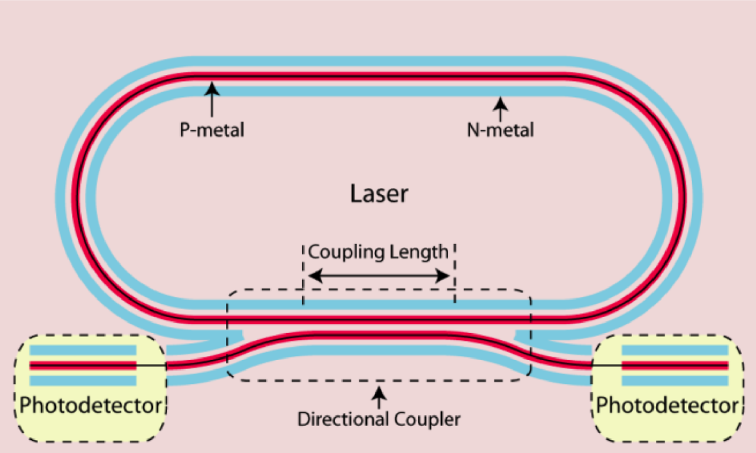


Figure 13: The racetrack resonator and the photodetectors layout (top view). [8]

Distributed Bragg reflector (DBR) laser

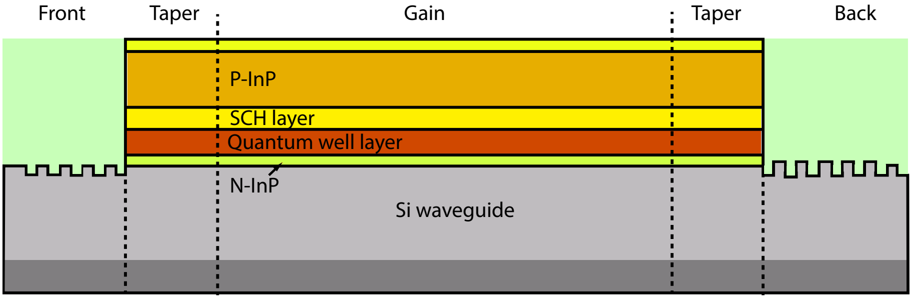
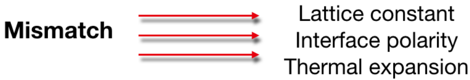


Figure 14: DBR silicon evanescent laser layout. [9]

III-V Monolithic growth

Challenges for monolithic approach:



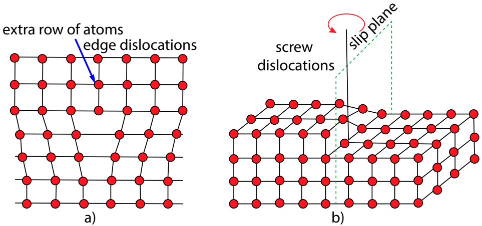


Figure 15: Schematic diagrams of **a)** an edge and **b)** screw dislocation in an atomic lattice.

III-V Monolithic growth

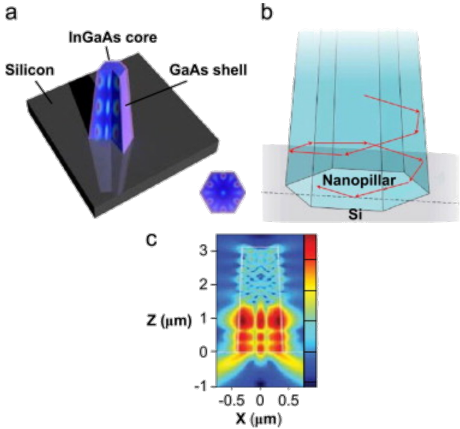


Figure 16: (a) Scheme of a nanopillar laser monolithically integrated onto Si. hexagon: top-view scheme. (b) The path of light in the helical mode resonating in the pillar. (c) Simulation of the electric field intensity of the optical mode trapped in the nanopillar. [10]

Germanium source on Si

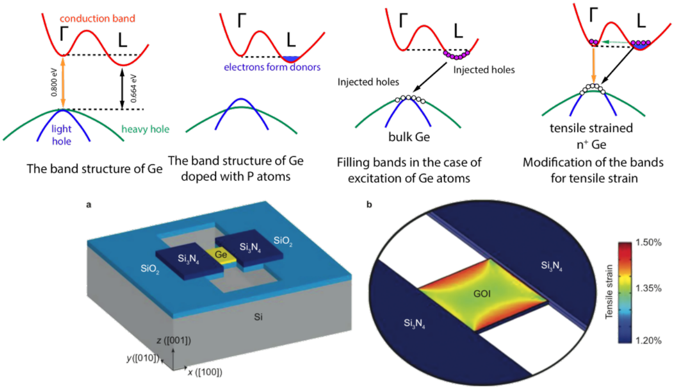


Figure 17: (a) Schematic illustration of an idealized structure for inducing uniaxial tensile strain. (b) Uniaxial simulation of a 25 μm x 25 μm Ge-on-insulator (GOI) device layer with 100 μm x 200 μm Si_3N_4 stressors with 100-μm-long released lengths. Color bar shows the [100] strain tensor component (ϵ_x). [11]

- **Molecular bonding** is based on the Van-Der-Waals interactions between two oxidized and hydrophilic surfaces. The bonding layer thickness can be reduced to less than ten nm. Therefore a very intimate contact between the surfaces is needed and the bonding quality is very sensitive to the surface roughness and particles. The bonding layer thickness can vary between few nm and several hundred nm.
- **Adhesive bonding** uses the thermosetting polymer as a bonding agent. They can compensate for the surface roughness, therefore the bonding tolerances are relaxed compared to molecular bonding. However, the bonding layer thickness cannot be easily reduced below fifty nm and the thermal conductance is lower in the polymer than in silica.
- Metal bonding is characterized by low bonding temperature, high thermal conductivity, no critical cleanliness requirements and a potentially conductive interface between silicon and bonded layers. However, due to its strong light absorption, the bonding metals have to be kept far from the light propagation area.

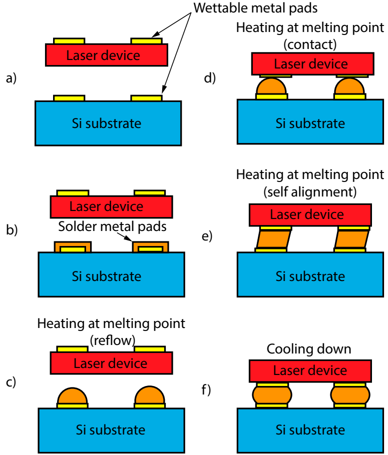


Figure 18: Fabrication sequence for the flip-chip solder bonding technique. [9]

Silicon Raman lasers (Raman Scattering)

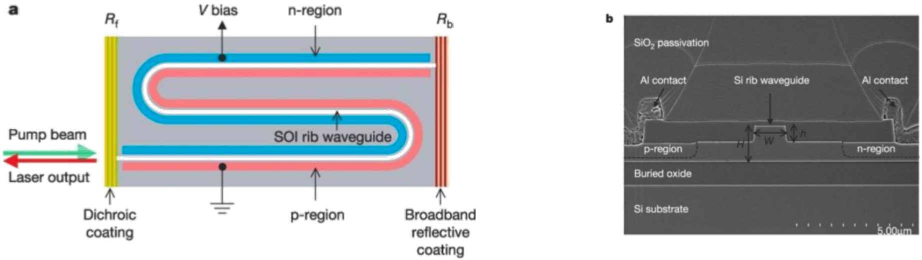


Figure 19: (a) Schematic layout of the silicon waveguide laser cavity with optical coatings applied to the facets and a p-i-n structure along the waveguide. (b) Scanning electron microscope cross-section image of a silicon rib waveguide with a p-i-n diode structure. [12]

Silicon Raman lasers (Raman Scattering)

Two-photon absorption (TPA)

- A nonlinear loss mechanism in which two photons combine their energies to boost an electron in the valence band to the conduction band
- TPA increases with the number of photons in a waveguide
- A limiting factor when using high optical pump powers
- TPA-induced FCA nonlinear optical loss can also be reduced by optimizing the **p-i-n** reverse-biased diode.

Erbium-doped light source

Working mechanism: Using Er as an atomic emitting center
Gain material: SiOx:Er; SiNx:Er; Er silicates
Advantages:

- CMOS compatible fabrication;
- Wavelength output is 1.55μm;
- Lies in eye-safe region of the spectrum;
- Preferred wavelength for high-power;
- Long-distance fiber communications

Challenge: Low EL efficiency; Obtain net gain

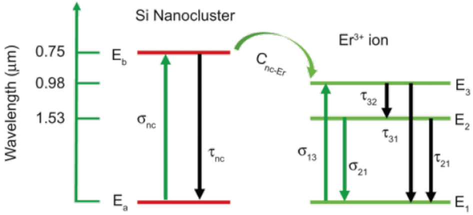


Figure 20: Energy levels of Er and silicon Si-nc in Er-doped Si-rich materials. Si-ncs and Er^{3+} are modeled as a two and three level system, respectively. C_{nc-Er} is the transfer coefficient between Si-ncs and Er^{3+}. [13]

laser on a Si_3N_4 waveguide

For broadband sources, silicon cannot be used, as its small band-gap limits infrared emission. Silicon nitride can be used for broadband generation using super continuum generation from visible to mid-infrared using super continuum generation.

In addition, silicon nitride waveguides are CMOS-compatible platforms.

laser on a Si_3N_4 waveguide

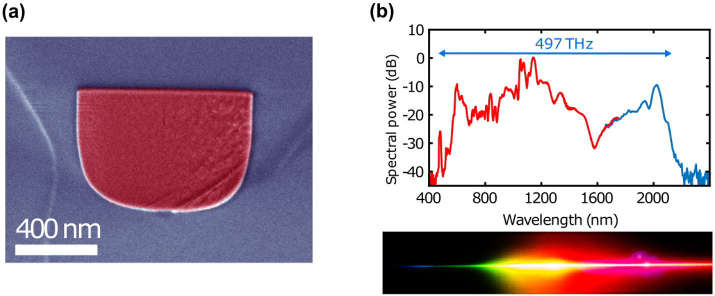
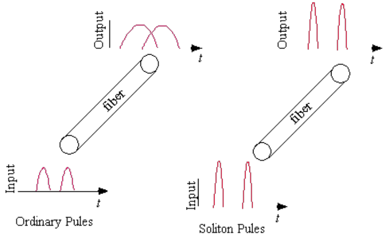


Figure 21: (a) SEM picture (false color) of a waveguide facet. (b) Supercontinuum spectrum generated in a 5.5 mm long Si_3N_4 waveguide with $h = 1$ μm, $w = 0.8$ μm, and $E_p = 590$ pJ with photograph of the spectrum after being dispersed by a diffraction grating.

Soliton in lasers

First observation of Solitary Waves in 1838 John Scott Russell (1808-1882) - Scottish engineer at Edinburgh

- A solitary wave is a wave that retains its shape, despite dispersion and nonlinearities.
- A soliton is a pulse that can collide with another similar pulse and still retain its shape after the collision, again in the presence of both dispersion and nonlinearities.



Nonlinear-optical effects can compensate for dispersion, yielding a soliton, which can be very short and remain very short, despite dispersion and nonlinear-optical effects.

Supplementary materials

Bonding type	Coupling scheme	Characterisation	Remarks	Year	Ref.
Die-to-wafer adhesive DVS-BCB bonding (thickness=300 nm)	adiabatic taper butt joined to the active waveguide	Pumping regime: CW λ ~ 1555 nm P_{max} = 1,9 mW (5°C)	Integrated photodetectors. Dry-etch facets.	2006	[10]
Wafer-to-wafer Molecular bonding (thickness < 5 nm)	Evanescent on SOI channel waveguide	Pumping regime: CW λ = 1577 nm (at 70 mA) I_{th} = 65 mA T_{max} = 40°C P_{max} = 1,8 mW	H^+ implantation on both sides of the mesa	2006	[11]
Wafer-to-wafer Molecular bonding (thickness < 5 nm)	Evanescent on SOI rib waveguide	Pumping regime: CW λ = 1326 nm (at 100 mA) I_{th} = 30 mA T_{max} = 105°C P_{max} = 5,5 mW	The second order transverse mode is lasing	2007	[12]
Wafer-to-wafer Molecular bonding (thickness < 5 nm)	Evanescent on SOI rib waveguide	Pumping regime: CW Mode locking with 4 ps pulses at 10 and 40 GHz	Integrated absorber for mode locking	2007	[13]
Wafer-to-wafer Molecular bonding (thickness < 5 nm)	Evanescent on SOI channel waveguide	Pumping regime: CW λ = 1490 nm I_{th} = 60 mA T_{max} = 45°C P_{max} = 12.5 mW	Hybrid mode on the output	2009	[14]
Die-to-wafer Molecular bonding (thickness: 400 nm)	none	Pumping regime: CW λ = 1565 nm I_{th} = 200 mA P_{max} = 1.5 mW	Contacts free of gold	2009	[15]
Die-to-wafer Molecular bonding (thickness: 100 nm)	Taper on silicon waveguide	Pumping regime: quasi-CW λ = 1570 nm I_{th} = 100 mA P_{max} = 7.5 mW	Wide band DBR mirror reflector	2010	[16]
Die-to-wafer adhesive DVS-BCB (thickness: 45nm)	Evanescent on SOI rib waveguide	Pumping regime: CW λ = 1310 nm I_{th} = 65 mA P_{max} = 3 mW	Hybrid mode on the output	2011	[17]

Figure 22: State of the art of Fabry-Perot hybrid laser on silicon.

Bibliography I

[1] Junji Ohtsubo. *Semiconductor lasers: stability, instability and chaos*, volume 111. Springer, 2012.

[2] Rosa Ana Perez-Herrera, Manuel Lopez-Amo, SW Harun, and H Arof. Multi-wavelength fiber lasers. In *Current Developments in Optical Fiber Technology*. In-Tech, 2013.

[3] Karl F Renk. *Basics of laser physics*. Springer, 2012.

[4] Lukas Chrostowski and Michael Hochberg. *Silicon photonics design: from devices to systems*. Cambridge University Press, 2015.

[5] Alexander W Fang, Hyundai Park, Oded Cohen, Richard Jones, Mario J Paniccia, and John E Bowers. Electrically pumped hybrid algainas-silicon evanescent laser. *Optics express*, 14(20):9203–9210, 2006.

[6] Gnther Roelkens, Dries Van Thourhout, Roel Baets, R Nötzel, and Meint Smit. Laser emission and photodetection in an inp/ingaasp layer integrated on and coupled to a silicon-on-insulator waveguide circuit. *Optics express*, 14(18):8154–8159, 2006.

[7] Di Liang and John E Bowers. Recent progress in lasers on silicon. *Nature photonics*, 4(8):511, 2010.

Bibliography II

[8] Alexander W Fang, Richard Jones, Hyundai Park, Oded Cohen, Omri Raday, Mario J Paniccia, and John E Bowers. Integrated algainas-silicon evanescent racetrack laser and photodetector. *Optics express*, 15(5):2315–2322, 2007.

[9] Charles Cornet, Yoan Léger, and Cédric Robert. *Integrated lasers on silicon*. Elsevier, 2016.

[10] Roger Chen, Thai-Truong D Tran, Kar Wei Ng, Wai Son Ko, Linus C Chuang, Forrest G Sedgwick, and Connie Chang-Hasnain. Nanolasers grown on silicon. *Nature Photonics*, 5(3):170–175, 2011.

[11] Jinendra Raja Jain, Aaron Hryciw, Thomas M Baer, David AB Miller, Mark L Brongersma, and Roger T Howe. A micromachining-based technology for enhancing germanium light emission via tensile strain. *Nature Photonics*, 6(6):398, 2012.

[12] Haisheng Rong, Richard Jones, Ansheng Liu, Oded Cohen, Dani Hak, Alexander Fang, and Mario Paniccia. A continuous-wave raman silicon laser. *Nature*, 433(7027):725–728, 2005.

[13] Gerald M Miller, Ryan M Briggs, and Harry A Atwater. Achieving optical gain in waveguide-confined nanocluster-sensitized erbium by pulsed excitation. *Journal of Applied Physics*, 108(6):063109, 2010.