Optoelectronics (광전자공학)

Lecture 9. Surface Emitting Lasers

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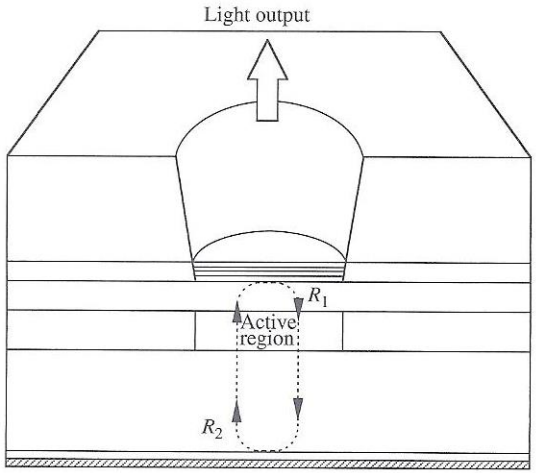
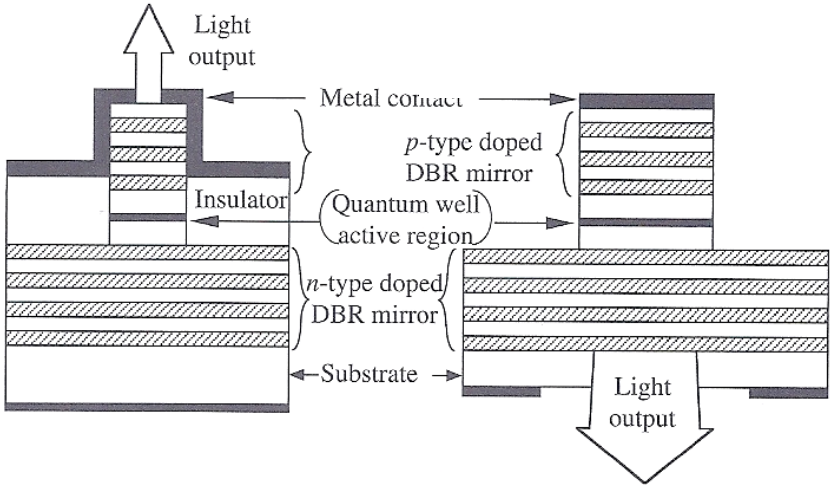
Surface Emitting Lasers

- **Vertical-cavity surface-emitting laser (VCSEL)**



Schematic diagram of a surface emitting laser



Front and back surface-emitting lasers

Advantages

✓Ease of coupling to optical fibers(∵ circular geometry)

✓Direct wafer scale probing, two-dimensional laser array(∵ vertical emission from the top or bottom of substrate)

✓Ultralow threshold operation, single-frequency operation(∵ small cavity volume)

✓Fabrication process without wafer lapping, device cleaving and dicing, facet coating, wire bonding

Surface Emitting Lasers

- **Brief VCSEL history**

Year	Event	Material	Wavelength
1977	First suggestion	AlGaAs/GaAs	0.85 μm
1979	First demonstration	InGaAsP/InP	1.3 μm
1984	Semiconductor DBR	InGaAsP/InP	1.3 μm
1986	Semiconductor DBR	AlGaAs/GaAs	0.85 μm
1986	6mA threshold at room temperature	AlGaAs/GaAs	0.85 μm
1988	First room temperature(RT) CW	AlGaAs/GaAs	0.85 μm
1989	2mA threshold quantum well device	InGaAs/GaAs	0.98 μm
1989	Sub-mA threshold device	AlGaAs/GaAs	0.98 μm
1991	First RT operation of deep red	InGaAsP/InP	0.78 μm
1993	First RT CW long wavelength	InGaAlP/GaAs	1.3 μm
1993	First RT operation of red color	InGaAs/GaAs	0.67 μm
1995	Oxidation of AlAs and sub-200μA threshold	AlGaAs/GaAs	0.98 μm
1996	10^7 hours of life time	AlGaAs/GaAs	0.85 μm
1996	> 200 mA CW output	InGaAs/GaAs	0.98 μm
1996	> 50% power conversion efficiency	InGaAs/GaAs	0.98 μm
1998	Optically pumped blue color	InGaN/GaN	0.4 μm

Surface Emitting Lasers

- **First suggestion**

Sketch of VCSEL conceived in 1977

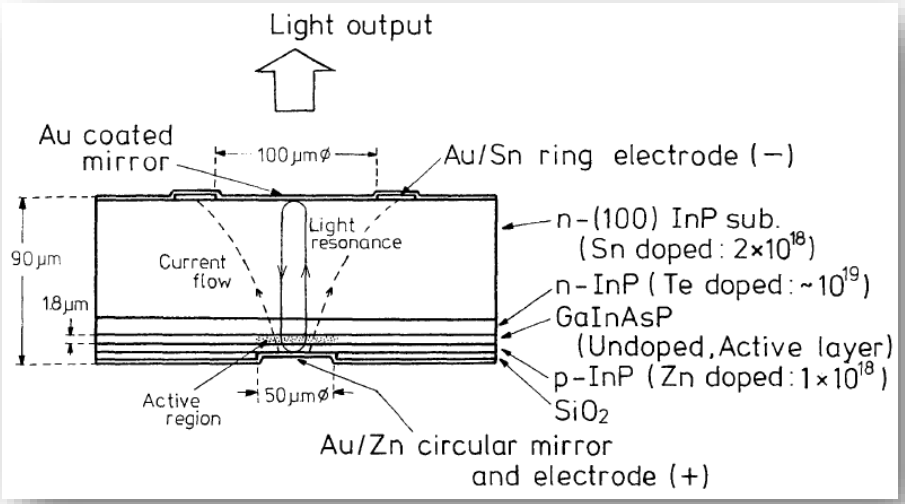
Prof. Kenichi Iga

✓This type of laser was first proposed by Prof. Kenichi Iga in 1977 at the Tokyo Institute of Technology as an alternative device design that could be packaged in a manner similar to that of a light-emitting diode (LED) and yet could be very simply and efficiently coupled to a fiber.

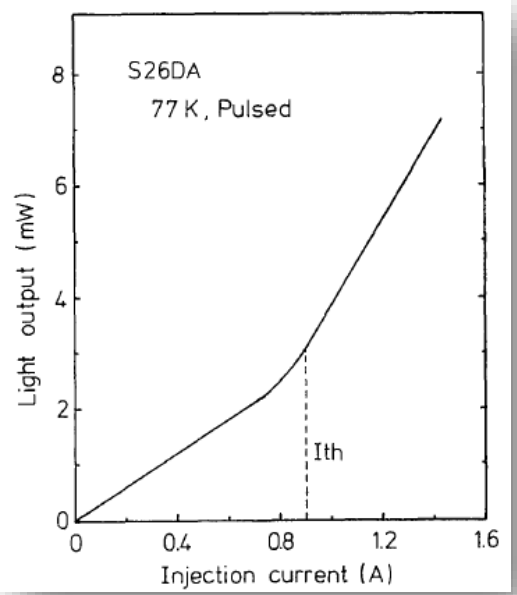
K. Iga, "Vertical-cavity surface-emitting laser: It's conception and evolution," *J. J. Appl. Phys*. 47, 1-10 (2008).

Surface Emitting Lasers

- **First demonstration**



Schematic structure of InGaAsP/InP surface emitting injection laser



Light output vs. injection current characteristic

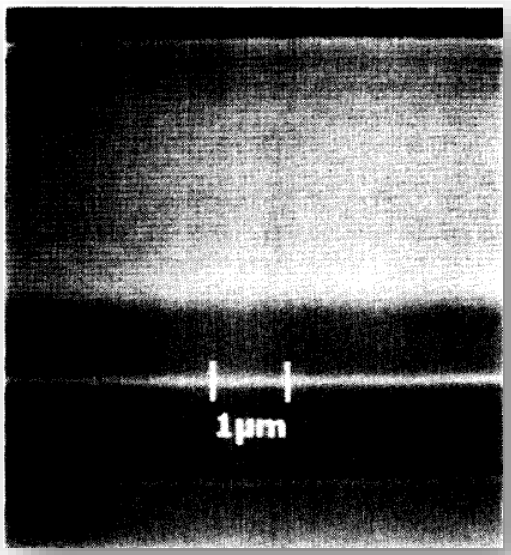
✓n-type InP layer, undoped InGaAsP active layer, p-type InP layer were grown sequentially on a (100) n-type InP substrate using *liquid phase epitaxy(LPE)*.

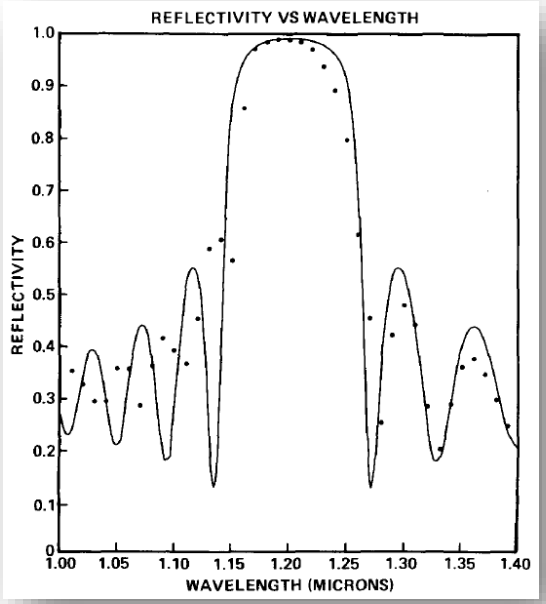
✓Threshold current was 900 mA at 77 K and light output of several mW was obtained.

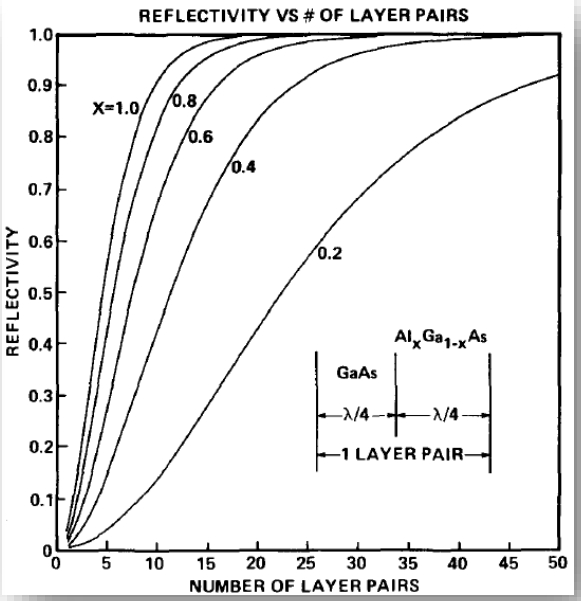
H. Soda, K. Iga, C. Kitahara, and Y. Suematsu, "GaInAsP/InP surface emitting injection lasers," *J. J. Appl. Phys.* 18, 2329-2330 (1979).

Surface Emitting Lasers

- **First GaAs/AlGaAs DBR mirror**







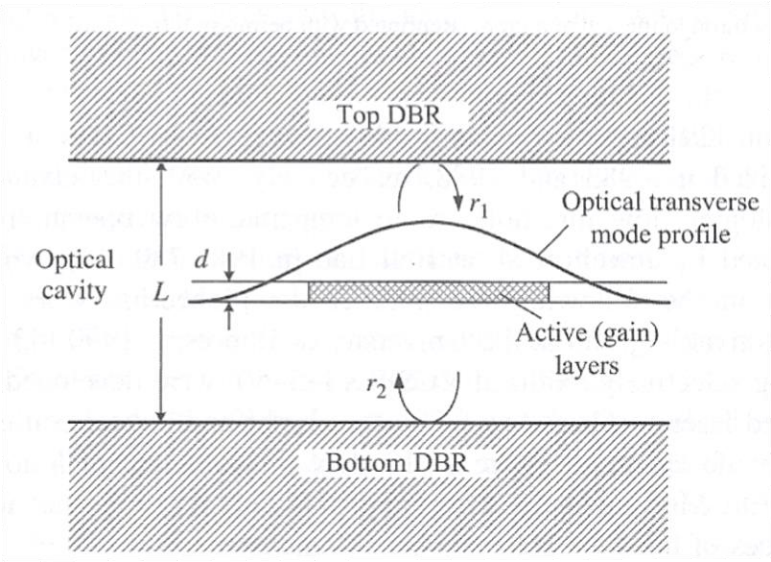
✓40 layers of alternating GaAs/$Al_{0.6}Ga_{0.4}As$ epitaxially grow on GaAs substrates using *metal organic chemical vapor deposition(MOCVD).*

R. L. Thornton, R. D. Burnham, and W. Streifer, "High reflectivity GaAs-AlGaAs mirrors fabricated by metalorganic chemical vapor deposition," *Appl. Phys. Lett.* 45, 1028-1030 (1984).

Surface Emitting Lasers

Lasing condition

The lasing condition of a VCSEL is round-trip resonance condition of a vertical Fabry-Perot cavity



Round-trip propagation condition for the lasing oscillation of a mode in a VCSEL cavity

$$r_1 r_2 e^{i2\beta L} = 1$$ ***Eq. (11.2.1a)***

Complex propagation constant

$$\beta = \beta_c + i\frac{(\alpha - \Gamma g)}{2}$$ ***Eq. (11.2.1b)***

Real part

$$\beta_c = \frac{2\pi}{\lambda} n = \frac{w}{c} n$$

Imaginary part

α : *absorption coefficient*

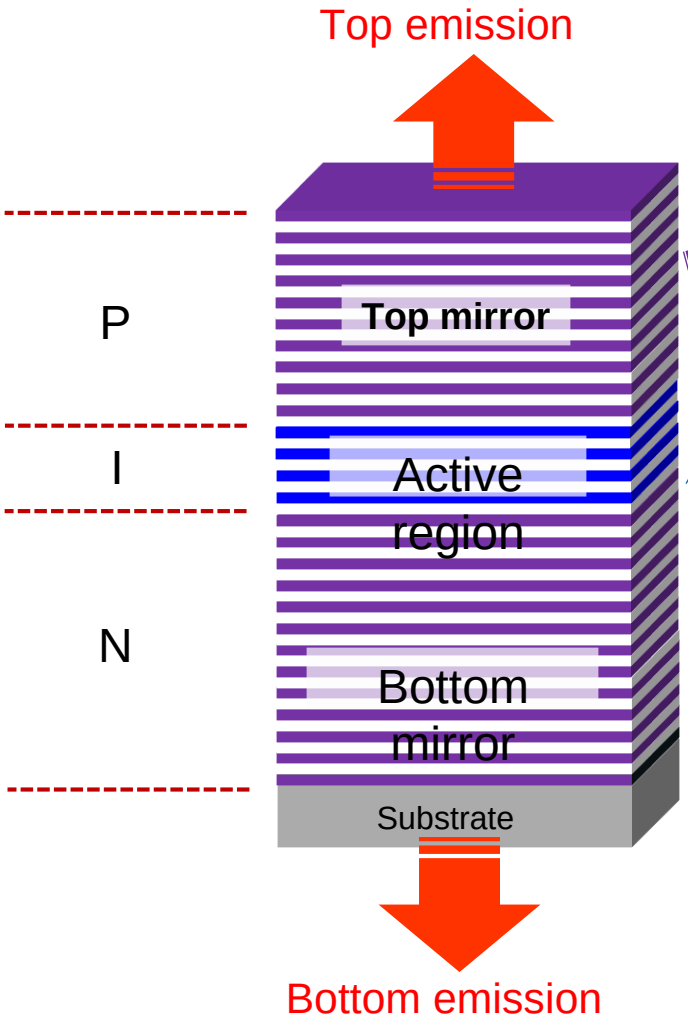
Γg : *threshold gain*

$$r_1 = |r_1| e^{i\varphi_1} \qquad r_2 = |r_2| e^{i\varphi_2}$$

Complex reflection coefficients for the DBR mirrors at the top & bottom

Surface Emitting Lasers

- **Basic VCSEL structure**



➢ ***Mirror design issue***

✓High mirror reflectivity

✓High reflective index contract

✓Compatible with the quantum layer

✓Low series resistance

✓Low optical absorption loss

✓DBR (distributed Bragg reflector) & metal

➢ ***Active region design issue***

✓High optical gain

✓Low threshold current

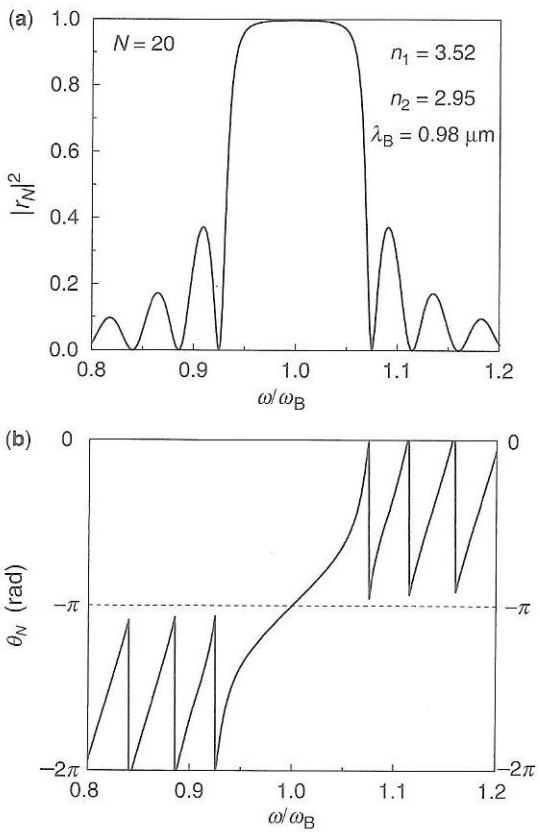
✓High coupling efficiency between gain and optical field

✓$n\lambda/2$ (optical thickness)

:spacer+gain layer(quantum wells)

Surface Emitting Lasers

- **Plane wave reflection from a distributed-Bragg reflector**



For (2N+1) layers, the power reflectivity becomes

$$|r_N|^2 = \frac{R_1}{R_1 + (1-R_1)\left(\frac{\sin\alpha}{\sin(N\alpha)}\right)^2}$$

Eq. (5.9.44)

N approaches a large number,

$$\left(\frac{\sin\alpha}{\sin(N\alpha)}\right)^2 \to e^{(-2(N-1)\alpha)} \to 0$$

$$|r_N|^2 \to 1$$

$$r_N = \frac{m_{21}}{m_{11}} e^{i2\varphi_1} = |r_N| e^{i\theta_N}$$

(a) The power reflectivity of a DBR structure is plotted as a function of wavelength near the stop band wavelength.

(b) The phase of the reflection coefficient.

Surface Emitting Lasers

- **Special case right at resonance $\lambda=\lambda_B$**

Reflection coefficient at resonance wavelength,

$$r_N = \frac{b^N\left(\frac{n_t}{n_1}\right) - a^N\left(\frac{n_1}{n_0}\right)}{b^N\left(\frac{n_t}{n_1}\right) + a^N\left(\frac{n_1}{n_0}\right)} = \frac{\left(\frac{n_2}{n_1}\right)^{2N} - \left(\frac{n_1^2}{n_0 n_t}\right)}{\left(\frac{n_2}{n_1}\right)^{2N} + \left(\frac{n_1^2}{n_0 n_t}\right)}$$

Eq. (5.9.49)

$$r_N \rightarrow \begin{cases} +1 & if \;\; n_2 > n_1 \\ -1 & if \;\; n_2 < n_1 \\ 0 & if \;\; \left(\frac{n_2}{n_1}\right)^{2N} = \frac{n_1^2}{n_0 n_t} \end{cases}$$

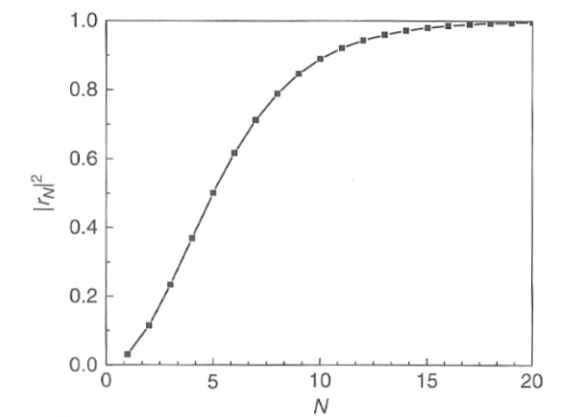
Eq. (5.9.50)

Eq. (5.9.51)

Assuming n_1(GaAs)=3.52 and n_2(AlAs)=2.95 at λ_B=0.98μm
$n_0=n_t=n_1$(GaAs)=3.52

$$|r_N|^2 = \left|\frac{\left(\frac{n_2}{n_1}\right)^{2N} - 1}{\left(\frac{n_2}{n_1}\right)^{2N} + 1}\right|^2$$

Eq. (5.9.52)



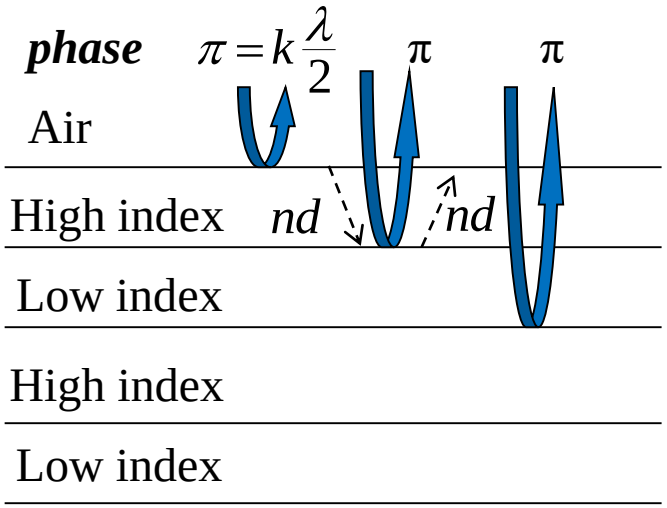
$|r_N|^2$ approaches unity quickly as N is above 10

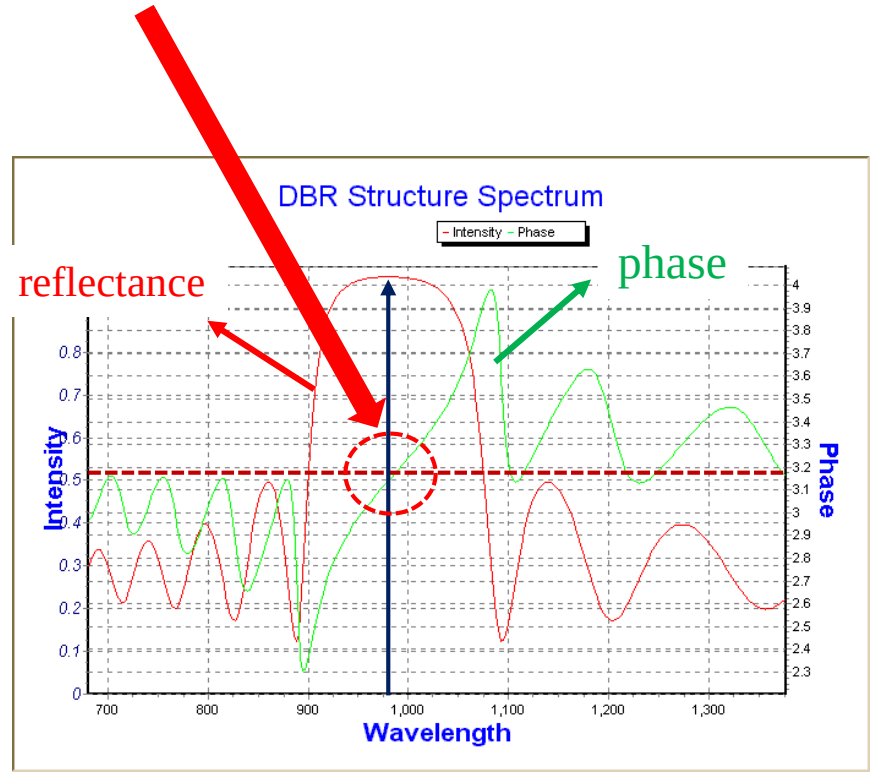
Surface Emitting Lasers

Design issues for distributed Bragg reflectors (DBRs)

- ✓ DBR is formed from multiple layers of alternating materials with varying refractive index to get the high reflection like mirror.

- ✓ from each individual interface added exactly ***in phase*** with the reflection from every other interface





In-phase condition

$$2nd = m\lambda + \frac{\lambda}{2}$$

$$\therefore d = \frac{\lambda}{4n}(2m+1)$$

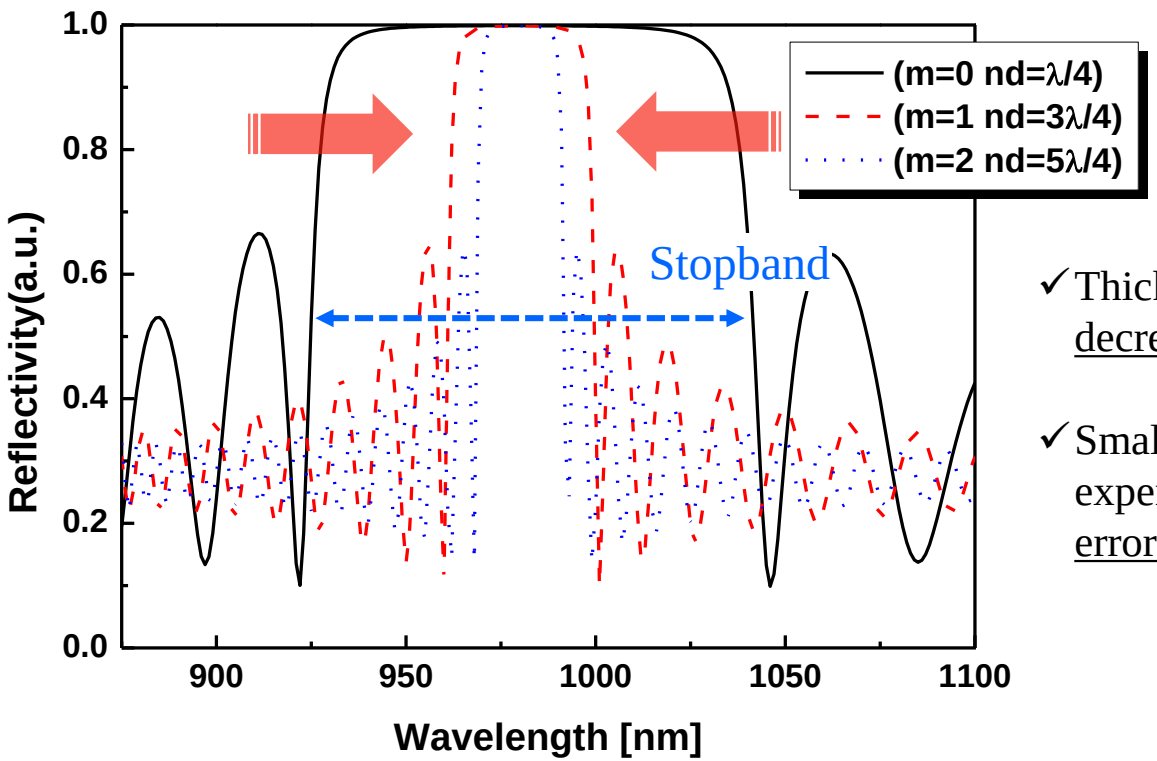
n : refractive index
d : thickness of each layer
m : integer
λ : wavelength in vacuum

- ✓ Thickness of DBR layers must satisfy ***Bragg condition*** at target wavelength !

F. L. Pedrotti., "Introduction to optics" *Chapter 7 Interference of light* (2007).

Surface Emitting Lasers

- **Design issues for distributed Bragg reflectors (DBRs)**



λ = 980nm
GaAs(mλ/4n) / AlAs(mλ/4n)-20pair

Bragg condition

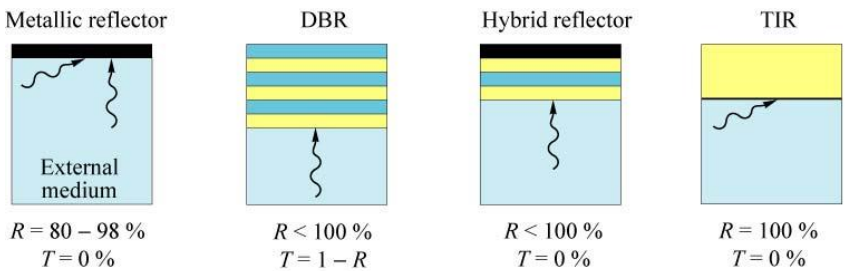
$$d = \frac{\lambda}{4n}(2m+1)$$

✓ Thicker thickness of DBR layers cause a decrease of ***stopband*** of reflectance.

✓ Small ***stopband*** design increase experimental difficulties and decrease error tolerance.

Surface Emitting Lasers

Different types of reflectors



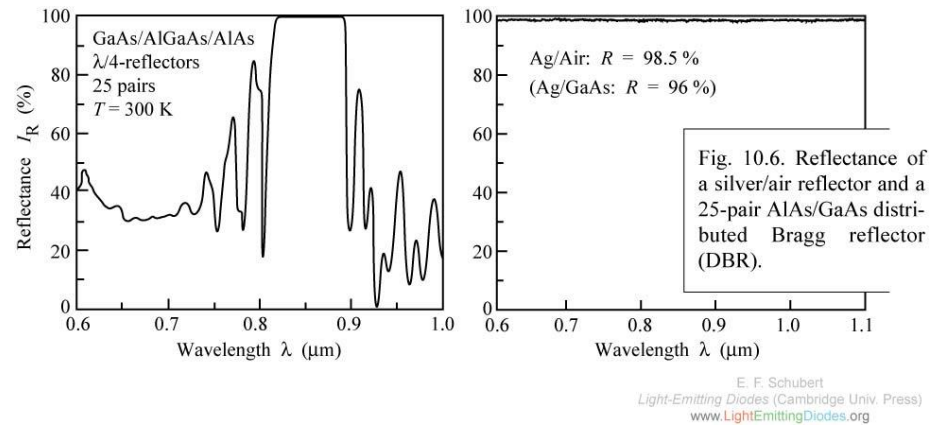


Fig. 10.6. Reflectance of a silver/air reflector and a 25-pair AlAs/GaAs distributed Bragg reflector (DBR).

✓ *Metallic reflector and hybrid reflectors* are absorbing and cannot be used as light-exit reflectors (T = 0%).

✓ *Total internal reflectors(TIR)* require that the angle of incidence be shallow in order to achieve high reflectivity.

✓ *Distributed Bragg reflector(DBR)* display narrow band of high reflectivity.

$$R_{DBR} = |r_N|^2 = \left| \frac{\left(\frac{n_2}{n_1}\right)^{2N} - 1}{\left(\frac{n_2}{n_1}\right)^{2N} + 1} \right|^2 \quad \textbf{\textit{Eq. (5.9.52)}}$$

$$\Delta\lambda_{stopband} = \frac{2\lambda_{Bragg}(n_2 - n_1)}{\pi n_{eff}} \qquad n_{eff} = 2\left(\frac{1}{n_1} + \frac{1}{n_2}\right)^{-1}$$

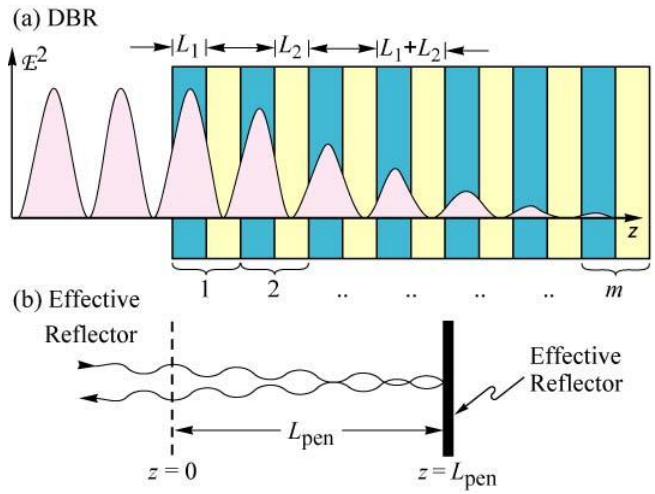
n_2: high refractive index
n_1: low refractive index

E. F. Schubert, “Light-Emitting diodes,” *Cambridge university press* (2006).

L. A. Coldren et al., “Vertical-cavity surface-emitting lasers: Design, fabrication, characterization, and applications,” *Cambridge university press* (1999).

Surface Emitting Lasers

Effective mirror model



< Illustration of the DBR penetration depth >

The incident and reflected wave amplitudes each experience a phase shift of βL_{pen} in traversing the distance to the effective mirror and back.

β: average propagation constant $\quad \frac{1}{\beta}=\frac{1}{2}\left(\frac{1}{\beta_1}+\frac{1}{\beta_2}\right)$

Expanding the simulated DBR reflection phase in a Taylor series about the Bragg wavelength

$$\varphi=\cancel{\varphi_0}+(\beta-\beta_0)\frac{\partial\varphi}{\partial\beta}+\cancel{\frac{(\beta-\beta_0)^2}{2}\frac{\partial^2\varphi}{\partial\beta^2}}+\dots\dots\dots\dots$$

$$=-2(\beta-\beta_0)L_{pen}$$

$$\boxed{L_{pen}=-\frac{1}{2}\frac{\partial\varphi}{\partial\beta}}$$ Penetration depth

Knowing that the reflection phase is zero at the Bragg wavelength(β_0), we can express reflection coefficient (r) as

$$r_{DBR}\big|_{z=0}=|r_{DBR}|e^{i\varphi}=|r_{DBR}|e^{2i(\frac{2\pi}{\lambda})L_{pen}}$$

$$r_{DBR}=|r_{DBR}|e^{i\varphi}=|r_{DBR}|e^{-2i(\beta-\beta_0)L_{pen}}$$

(within the linear region)

✓ Effective cavity length

$$L_{eff}=L_{cavity}+L_{pen,topDBR}+L_{pen,bot.DBR}$$

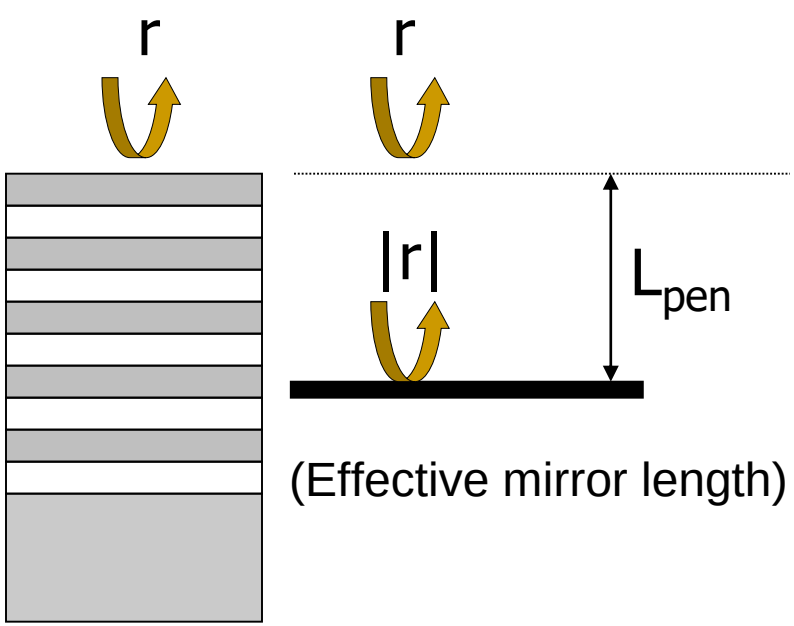
E. F. Schubert, “Light-Emitting diodes,” *Cambridge university press* (2006).

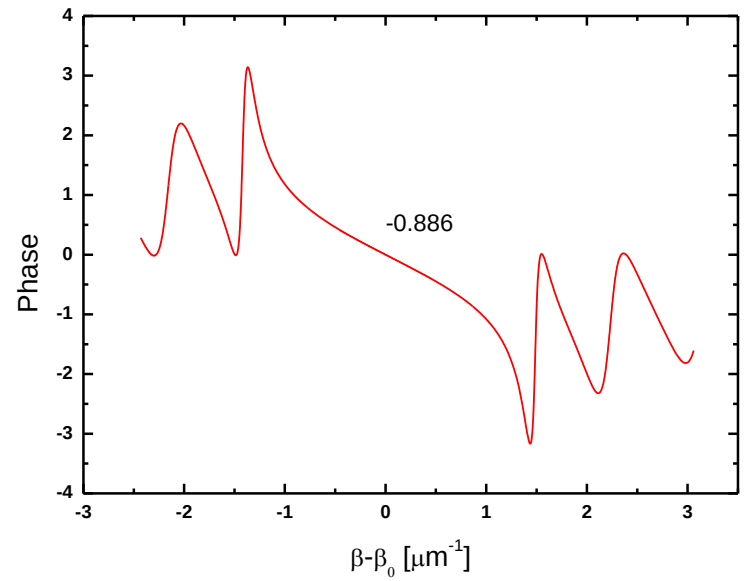
L. A. Coldren et al., “Diode lasers and photonic integrated circuits,” Chapter 3. Mirrors and resonators for diode lasers *John wiley & Sons, Inc.* (1995).

Surface Emitting Lasers

Effective mirror model

Phase varies relatively linearly near the reflection maximum. Such a reflection can be well approximated by a discrete mirror reflection equal to the magnitude of the reflection but placed a distance L_{eff} away.





$$L_{pen} = -\frac{1}{2}\frac{\partial\varphi}{\partial\beta} = 0.443\ \mu\text{m}$$

L. A. Coldren et al., "Diode lasers and photonic integrated circuits," Chapter 3. Mirrors and resonators for diode lasers *John wiley & Sons, Inc.* (1995).

Surface Emitting Lasers

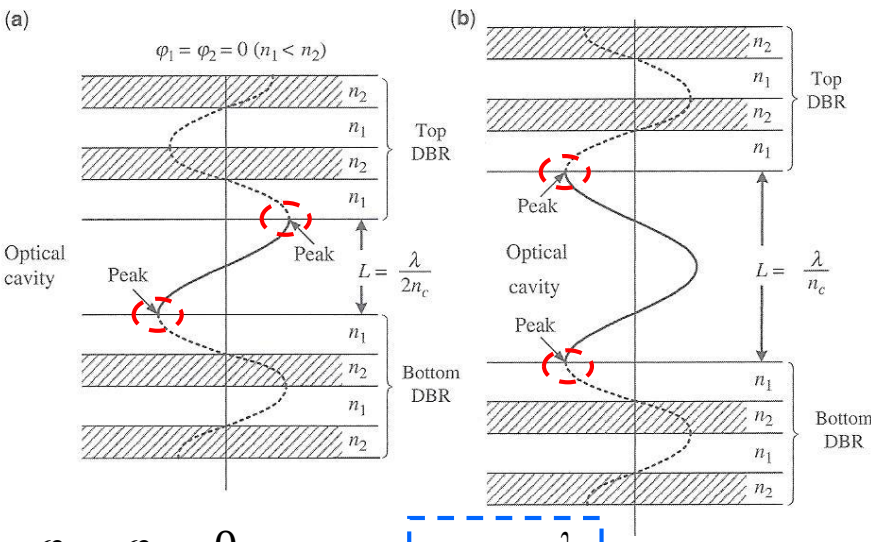
- **Design issues for active region I- Phase condition**

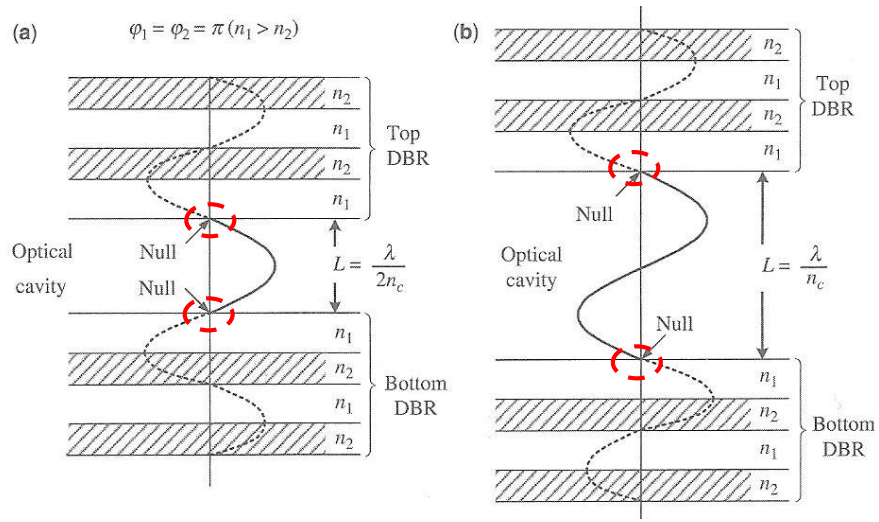
$$\beta_c = \frac{2\pi}{\lambda} n$$

The phase condition of a VCSEL is $\boxed{\varphi_1 + \varphi_2 + 2\beta_c L = 2m\pi}$ ***Eq. (11.2.3)***

lasing condition

$$|r_1||r_2|e^{i(\varphi_1+\varphi_2+2\beta L)} = 1$$





$\varphi_1 = \varphi_2 = 0$ $(n_1 < n_2)$ → $\boxed{L = m\frac{\lambda}{2n}}$

$\varphi_1 = \varphi_2 = \pi$ $(n_1 > n_2)$ → $\boxed{L = (m-1)\frac{\lambda}{2n}}$

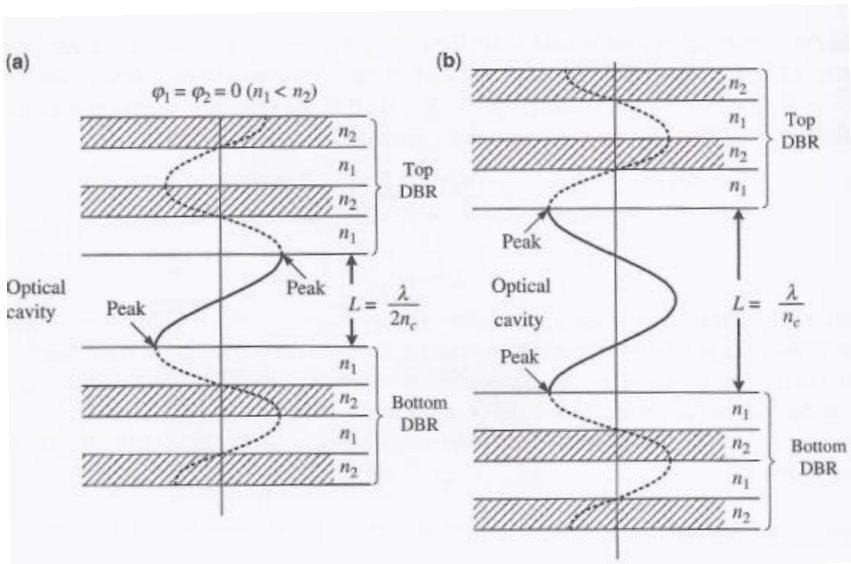
- ✓ ***Constructive interference*** between the incident and reflected waves
- ✓ Standing wave pattern will have a **peak** at the first interface of the top and bottom DBR

- ✓ ***Destructive interference*** between the incident and reflected waves
- ✓ Standing wave pattern will have a **null** at the first interface of the top and bottom DBR

Surface Emitting Lasers

Design issues for active region II

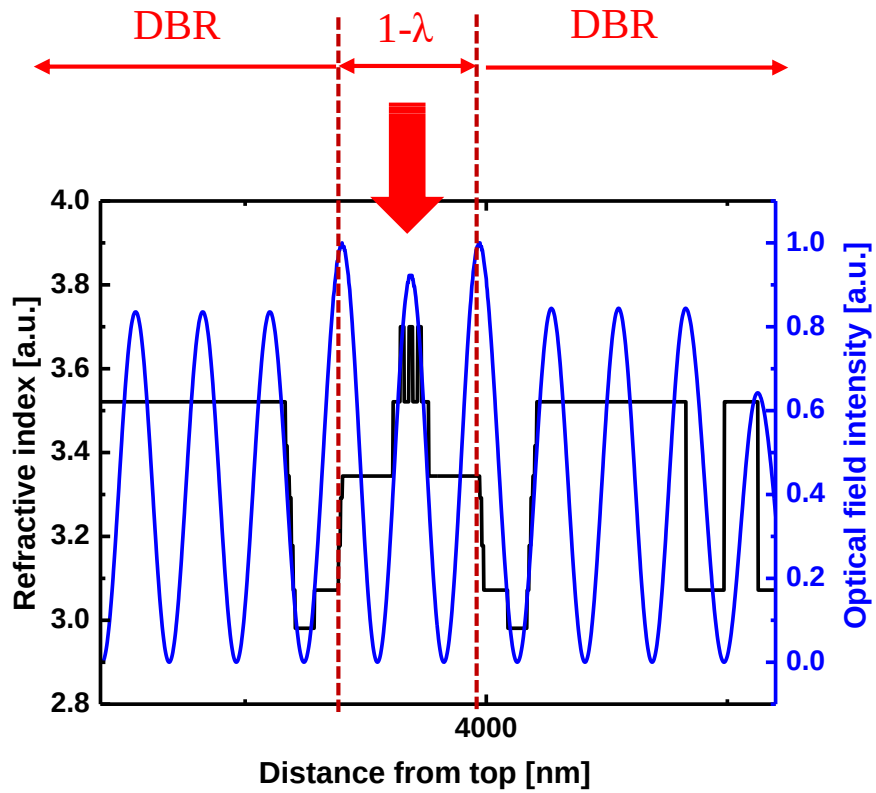
- ✓ ***Fabry-Perot (FP) MQW cavity*** must satisfy resonance condition which occur when $\beta L = m\pi$ (m=1,2,3...) equivalently when the cavity length is an integral number of half wavelengths.



$$\beta L = m\pi$$

$$\therefore L = m \times \frac{\lambda}{2n} \quad m: even\ number$$

Resonance condition



- ✓ For high efficiency laser , optical field is placed at quantum well region which occur when the cavity length is an integral ***even number of half wavelengths***.

Surface Emitting Lasers

Threshold condition

The threshold gain of a VCSEL is

$$\Gamma g = \alpha + \frac{1}{2L}\ln\left(\frac{1}{R_1 R_2}\right)$$

α : the optical absorptions inside and outside the active region, plus any diffraction loss
Γ : the longitudinal and transverse optical confinement factor

Eq. (11.2.4)

where $R_1 = |r_1|^2$ $\quad R_2 = |r_2|^2$

$$\Gamma = \left(\gamma \frac{d}{L}\Gamma_t\right)$$

d : the active layer thickness ,
L : the cavity length
γ : (1: thick active layer, 2:thin active layer) is placed at the maximum of the standing wave
d/L : account for the longitudinal optical confinement
$\boldsymbol{\Gamma_t}$: the transverse optical confinement factor

Eq. (11.2.5)

Loss parameter

$$\alpha L = 2\alpha_i L_{eff} + 2\alpha_d L_{cavity}$$

α_i : absorption in DBR
α_d : diffraction loss due to the mode mismatche

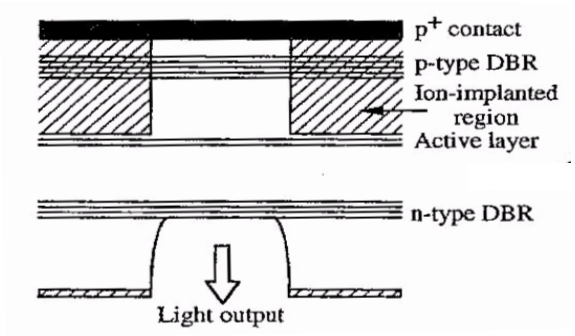
Eq. (11.2.6)

Depends on the size of the diameter of the active region and the locations of the mirrors.

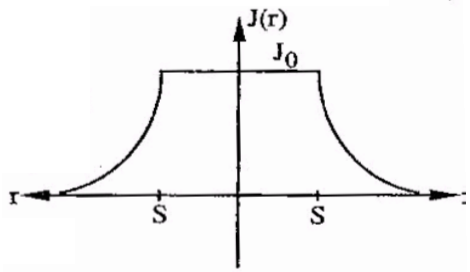
Surface Emitting Lasers

- **Carrier injection and optical profile**

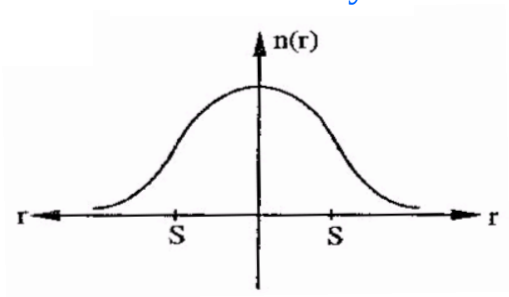
Gain-guided VCSEL with ion-plantation region



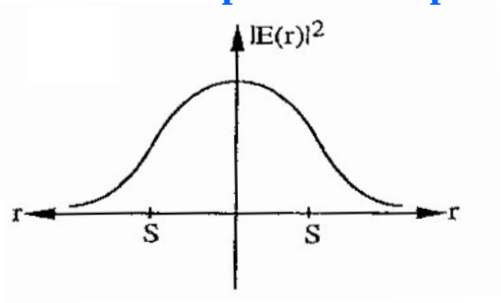
Current density



Carrier density



Fundamental optical mode profile

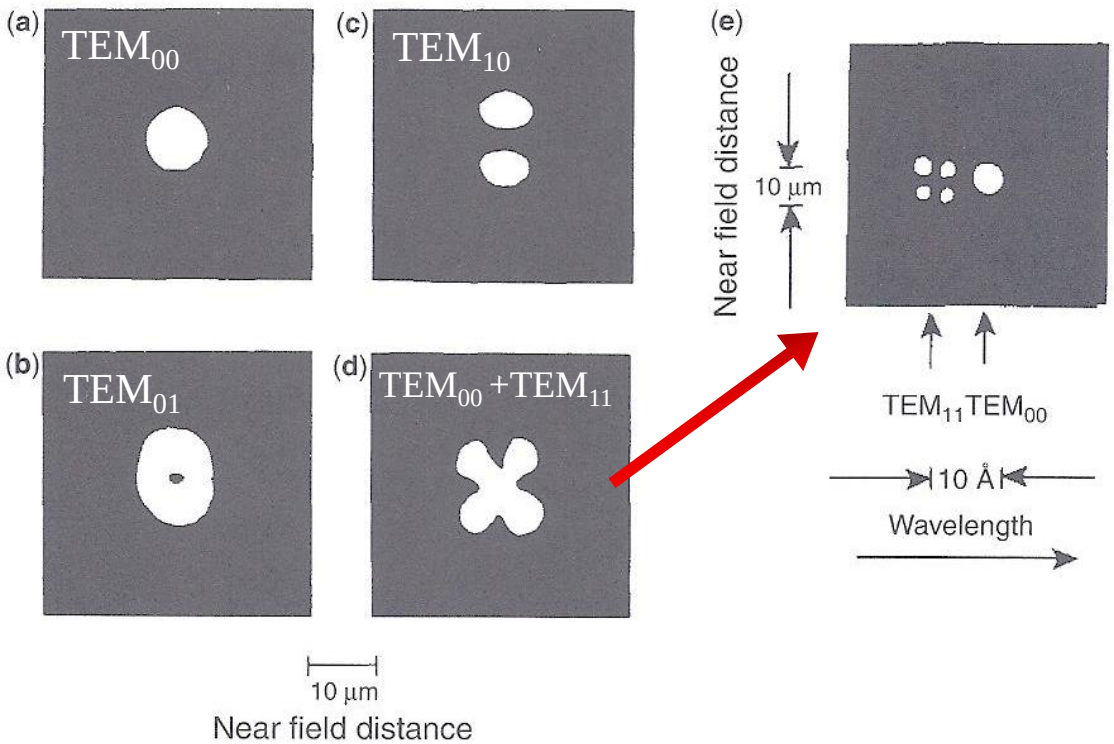


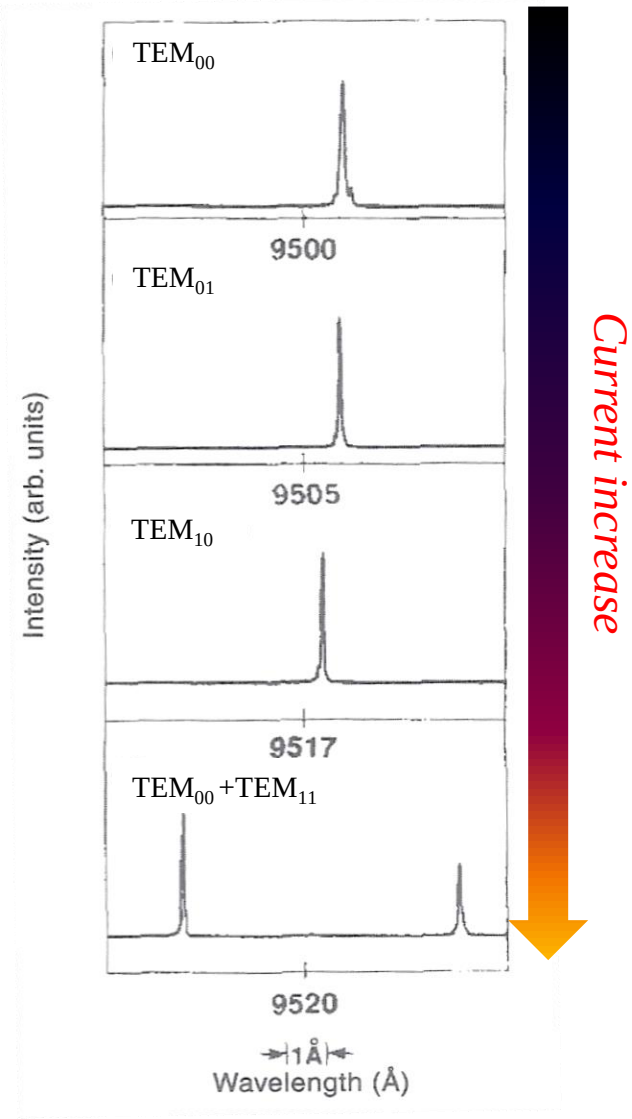
✓ **Depending on the fabrication processes** and the structures of the surface-emitting lasers, the ***current distribution***, the ***carrier density profile***, and the ***optical mode pattern*** vary.

Surface Emitting Lasers

- **Intensity distribution of transverse modes**

Near field patterns of a 15μm square VCSEL emitting



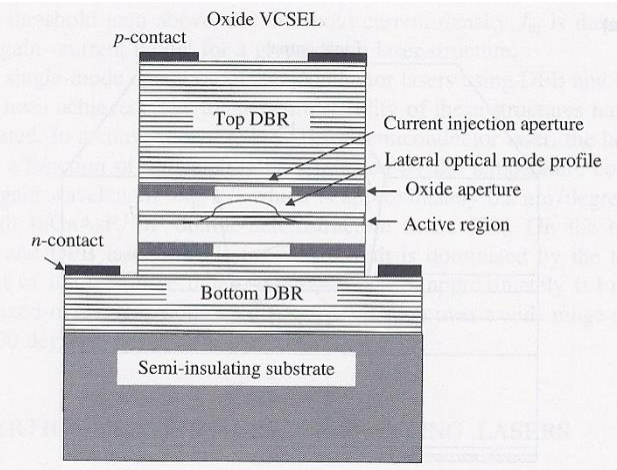


- ✓ TEM_{00}, TEM_{11} modes are clearly separated due to their wavelength differences.
- ✓ The ***red shift*** of the lasing wavelength is caused by the **junction heating** as the **injection current increases**.

Surface Emitting Lasers

Oxide-VCSELs: Index Confinement

Lateral confinement by oxide-apertures forms apertures for current flow into the active region of the optical cavity. The lower refractive index of the oxide regions provides lateral index confinement of the optical mode.



< Double-aperture oxide confined VCSEL>

- Advantage of oxide-VCSEL
  - ✓ High power conversion
  - ✓ Low threshold current density
  - ✓ Low resistance design using parabolic hetero-interface grading
  - ✓ Minimize lateral current spreading
  - ✓ Lower refractive index provides index guidance and current flow

Surface Emitting Lasers

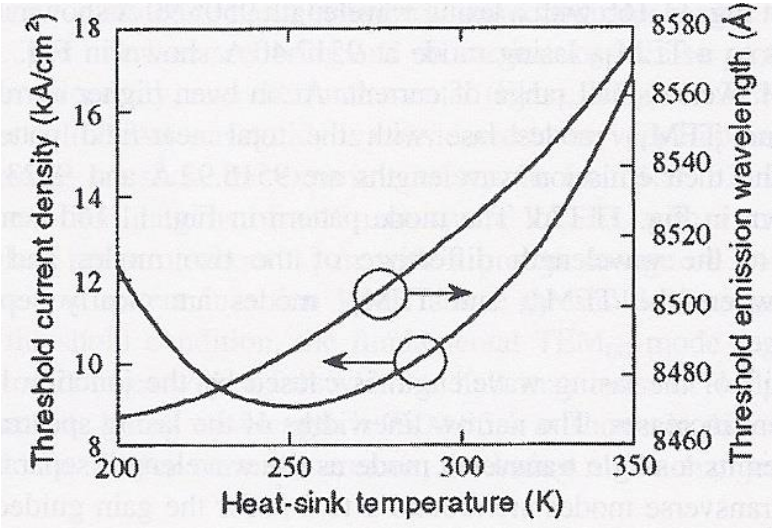
Temperature Dependence and Junction Heating I

The junction heating is important in surface-emitting lasers.

A simplified mode for the temperature rise due to the injection current from a circular disk is

$$\Delta T_{jct} = \frac{P_{IV} - P_{opt}}{4\sigma S} \qquad \textbf{Eq. (11.2.9)}$$

P_{IV} : the total input electric power
P_{opt} : the optical output power
σ : the thermal conductivity
S : the disk radius

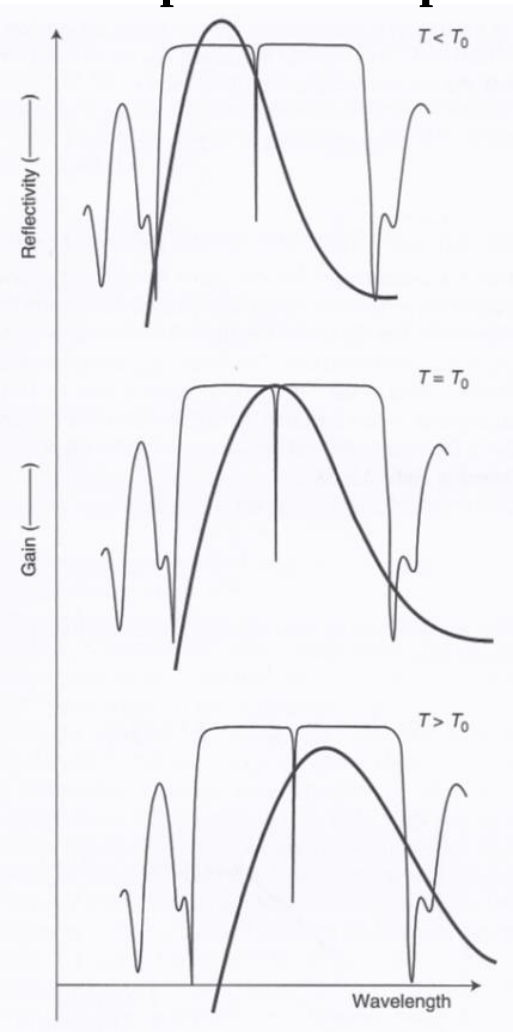


The dependence of the threshold current density and the emission wavelength as a function of the heat-sink temperature, based on a theoretical model.

For GaAs, the gain peak wavelength increase linearly at about 2.7 Å/K.

Surface Emitting Lasers

Temperature Dependence and Junction Heating II



Temperature increase

✓ **Resonance λ / gain alignment**

Temperature ↑ → Bandgap and Index ↑, Optical length ↑

- **Long wavelength shift of resonance λ mode(0.8Å/°C)**
- **Long wavelength shift of gain peak(3.3Å/°C)**

✓ **Since Resonance λ shift toward long-wavelength faster than gain peak, gain peak must be placed lower than Resonance λ.**

✓ **The minimum threshold current (I_{th}) occur when gain peak overlap Resonance λ.**

✓ **Threshold current (I_{th}) increase as temperature goes up, resulting in degradation of performance of VCSEL.**

Surface Emitting Lasers

Optical Output and Differential Quantum Efficiency I

The optical output power is

$$P_{out} = \frac{\hbar\omega}{q}\eta[I - I_{th}(I, T_{jct})]$$ ***Eq. (11.2.10)***

$$\eta = \eta_i \eta_{opt}$$ ***Eq. (11.2.11)***

where η depends on two factors:

(1) The **injection efficiency(η_i)** accounting for the fraction of injected carriers contributing to the emission process.

(2) The **optical efficiency(η_{opt})** accounting for the fraction of generated photons that are transmitted out of the cavity.

The optical efficiency is

$$\eta_{opt} = \frac{T_r}{A + T_r}$$ ***Eq. (11.2.13)***

$$A = 2\alpha_i L_{eff} + \alpha_d L \qquad T_r = \ln\left(\frac{1}{R_1 R_2}\right)$$ ***Eq. (11.2.12)***

A : the absorbance in top and bottom DBR

L_{eff} : an effective penetration length

L : the cavity length of the active

T_r : mirror transmission loss

Surface Emitting Lasers

Optical Output and Differential Quantum Efficiency II

The power conversion efficiency is given by

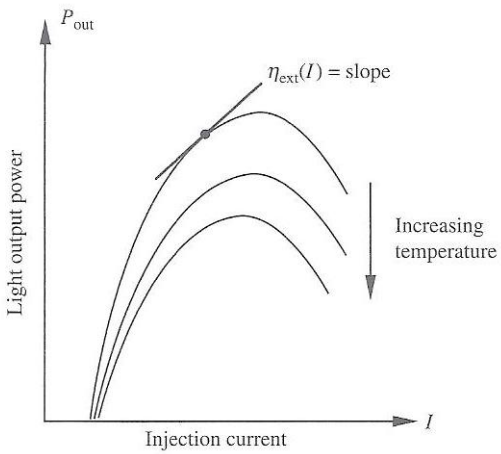
$$\eta_p = \frac{P_{out}}{VI} \qquad \textbf{Eq. (11.2.14)}$$

V : bias voltage
I : bias current
P_{out}: optical out power

The differential quantum efficiency is current-dependent

$$\eta_{ext}(I) = \frac{q}{\hbar\omega}\frac{dP_{out}}{dI} = \eta\left(1 - \frac{dI_{th}}{dI}\right) \qquad \textbf{Eq. (11.2.15)}$$

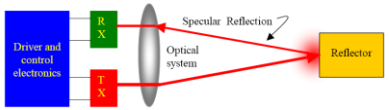
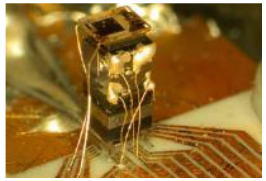
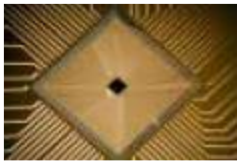
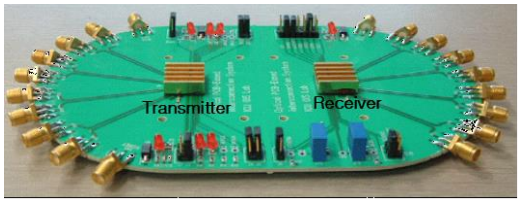
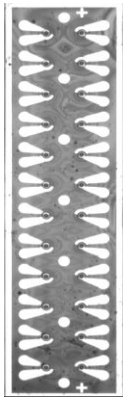
If $dI_{th} / dI > 1$, then the η_{ext}(I) can be negative as shown in figure.



A plot of the light output of a surface-emitting laser vs. the injection current for different temperatures. The slope at a particular current level I is the differential quantum efficiency, which can be negative at a high current level or a high temperature.

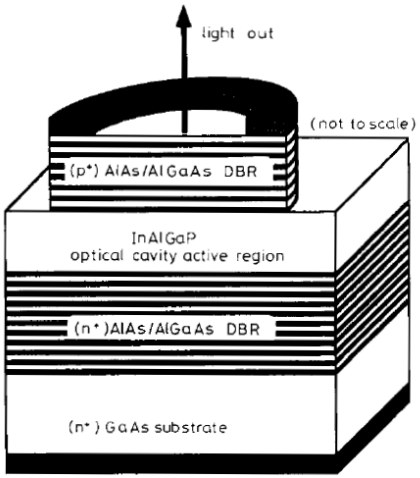
Surface Emitting Lasers

- **Current and emerging VCSEL applications**

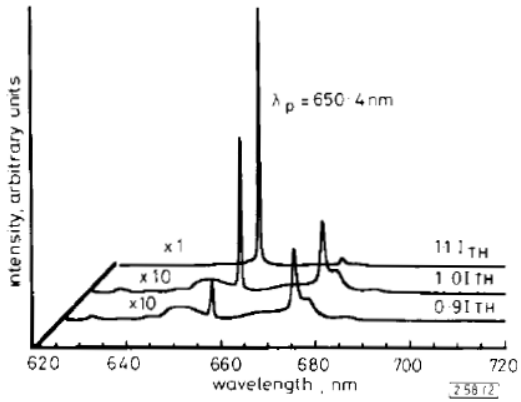
	Multi-mode operation	Single-mode operation
Single VCSEL	• Local area networks • Storage area networks • Bio-sensors • Proximity sensors  	• Laser absorption spectroscopy • Chip-scale atomic clocks • Laser based optical mouse sensors  
Array VCSEL	• Very short reach (VSR) links • Optical tweezers • Optical pumping source  	• Intra-system links • Optical memory • Laser printing   

Surface Emitting Lasers

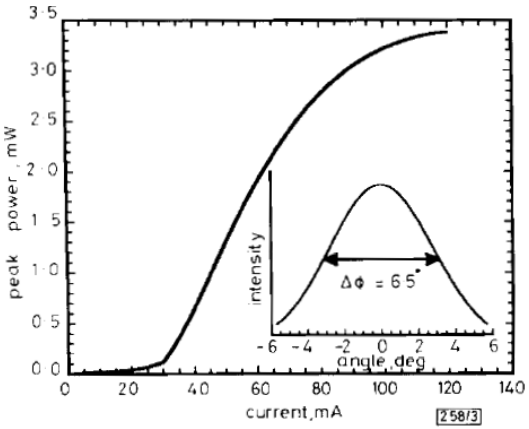
Red VCSELs



Visible VCSEL structure



Visible VCSEL lasing spectra



Light-current(LI) characteristic at room temperature

- Active layer: InGaAlP/InGaAlP
- In 1993, first demonstration of electrically injected visible VCSELs with an InAlGaP optical cavity active region*.
- 630-670nm is considered as the laser for the first-generation digital video disc system.
- Sub-milliampere thresholds, 11% power conversion efficiency and 8mW output power have been achieved**.
- Red VCSEL has been commercialized for application to printers and plastic fiber communications

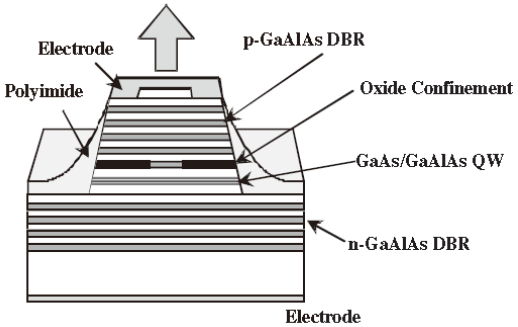
*Lott, J.A. et al., “Electrically-injected visible (639-661nm) vertical cavity surface emitting lasers,” *Electron. Lett.* 29, 830-832 (1993).

**M. H. Crawford et al., *OSA Trends in Optics and Photonics Series*, *Optical Society of America, Washington*, D.C. 15, 104 (1998).

K. Iga, “Vertical-cavity surface-emitting laser: It’s conception and evolution,” *J. J. Appl. Phys*. 47, 1-10 (2008).

Surface Emitting Lasers

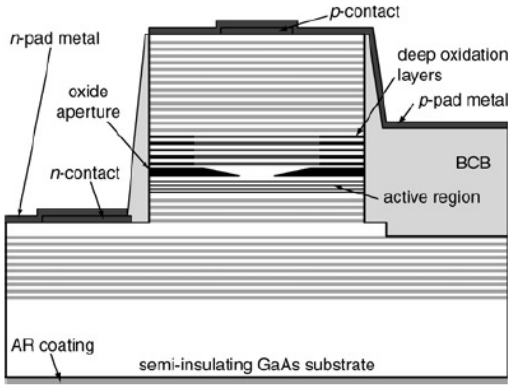
850nm wavelength VCSELs



Typical structure of a 850nm GaAs-based VCSEL

- Active layer: GaAs/AlGaAs
- The first room-temperature CW operation was achieved in 1988.
- In production levels, sub-mA thresholds and 10mW output have been achieved.
- Wide temperature characteristics of 850 nm VCSEL is a candidate of a light source of the media orientated system transport application*.

980nm wavelength VCSELs



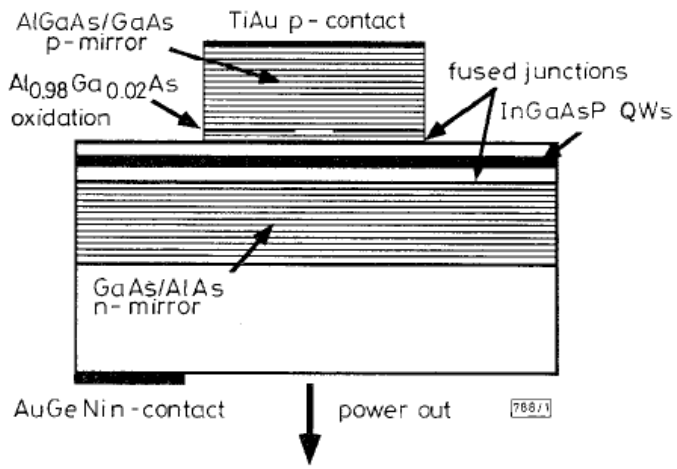
High speed 980nm VCSEL

- Active layer: InGaAs/GaAs/AlGaAs
- In 1995, a novel laser structure employing a selective oxidizing process applied to AlAs.
- A relatively high power of more than 50mW may be possible.
- High-efficiency, high-speed, tapered-oxide-apertured 980 nm VCSELs with high data-rate/power-dissipation ratio of 3.5 Gps/mW, making these devices suitable for interconnect applications**.

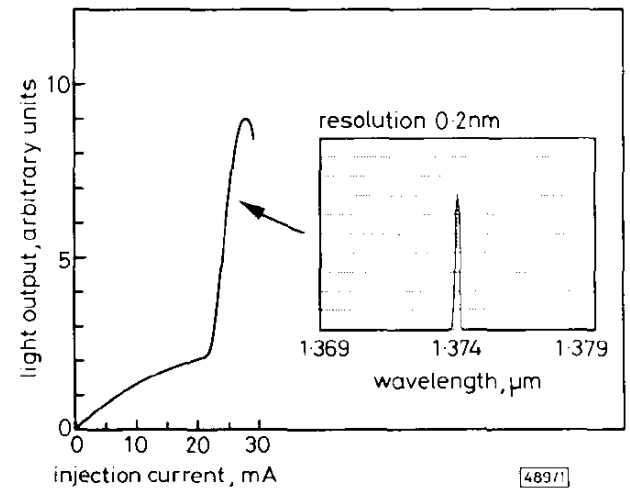
*K. Nishikata. et al., "Wide temperature operation of 850nm VCSEL and isolator-free operation of 1300nm VCSEL for a variety of application," *Proc. of SPIE* 5737, 8-19 (2005).
**Y. –C. Chang. et al., "High-efficiency, high-speed VCSELs with 35Gbit/s error-free operation," *Electron. Lett.* 43, 1022-1023 (2007).
K. Iga, "Vertical-cavity surface-emitting laser: It's conception and evolution," *J. J. Appl. Phys*. 47, 1-10 (2008).

Surface Emitting Lasers

- **Long wavelength VCSELs on InP substrate**



Epitaxial bonding of the InGaAsP/InP active region and GaAs/AlAs mirrors



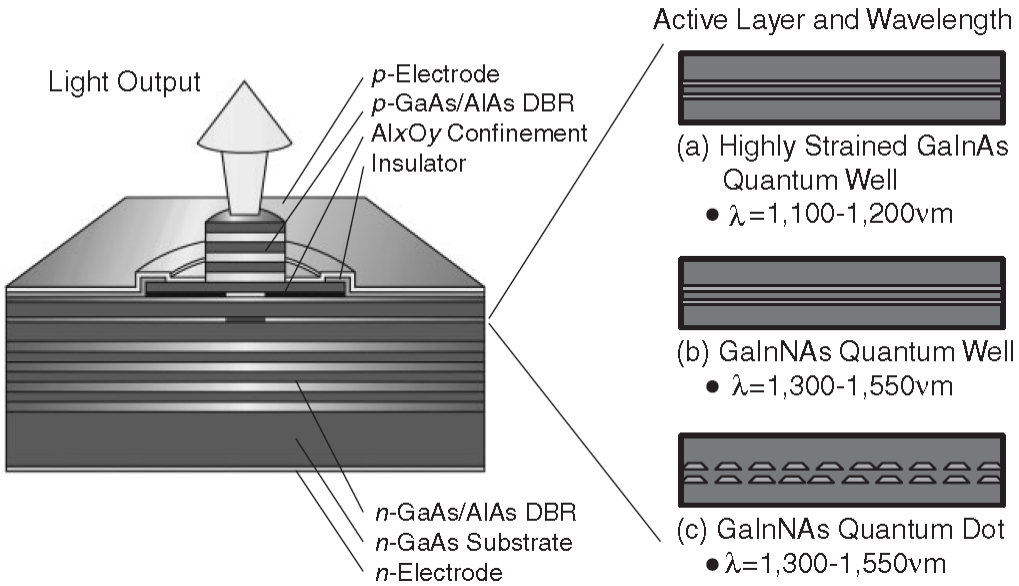
CW operation for 1,300nm was demonstrated using MgO/Si mirror

- Active : InGaAsP/InP
- Hybrid mirror technologies are being developed since the index difference between InGaAsP and InP is too small.
- A MgO/Si mirror with good thermal conductivity was demonstrated to enable room-temperature CW operation for 1,300nm surface-emitting lasers for the first time*.
- The CW threshold of 0.8mA and the maximum operating temperature of up to 71°C was reported for 1,550nm VCSELs with double bonded mirrors**.
- Parallel light wave systems are necessary to satisfy the rapid increase in information transmission capacity in LANs.

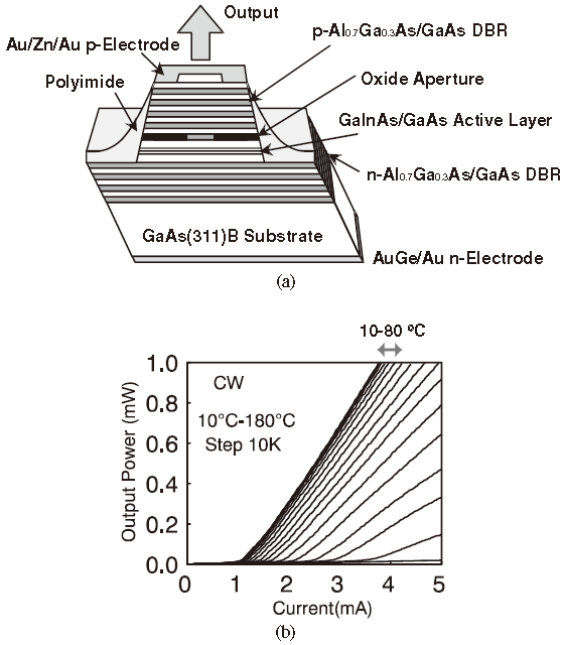
* T. Bada, "Near room temperature continuous wave lasing characteristics of GaInAsP/InP surface emitting laser," *Electron. lett.* 29 913-914 (1993).
**N.M. Margalit et al., "Submilliamp long wavelength vertical cavity lasers," *Electron. lett.* 32 1675-1677 (1996).
K. Iga, "Vertical-cavity surface-emitting laser: It's conception and evolution," *J. J. Appl. Phys*. 47, 1-10 (2008).

Surface Emitting Lasers

Long wavelength VCSELs on GaAs substrate



Long wavelength VCSELs formable on GaAs substrate



Higly strained 1,200-wavelength GaInAs/GaAs VCSEL grown on (311)B substrate.

- Active layer: InGaAsN/InGaAsN, InGaNAsSb/GaAsN and highly strained InGaAs/GaAs/AlGaAs
- GaAs/AlAs Bragg reflectors can be incorporated on same substrate.
- In content(=40%) can provide an excellent temperature characteristic.
- Viable for λ=1,200nm VCSELs for silica-fiber-based high speed LANs*.

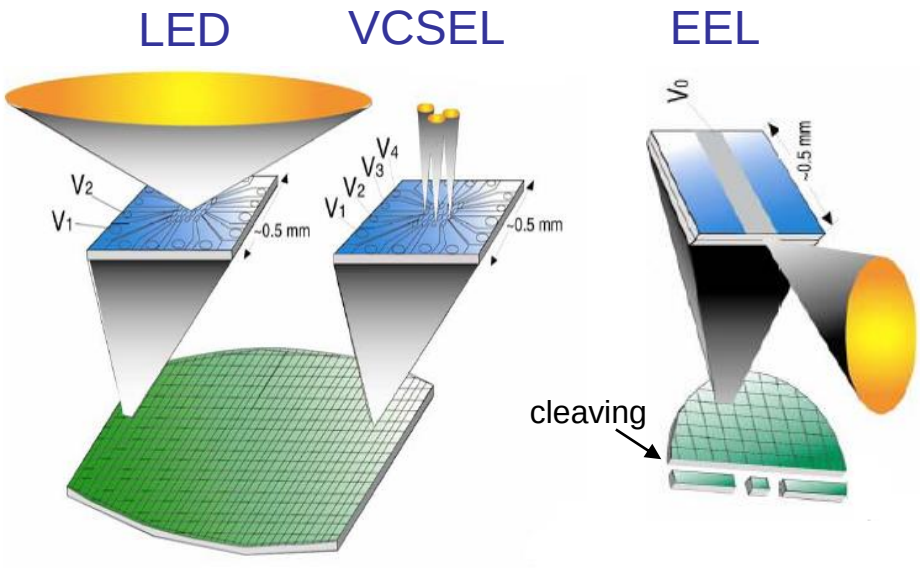
*F. Koyama et al., "1.2um highly strained InGaAs/GaAs quantum well lasers for singlemode fiber datalink," *Electron. lett.* 35 1079-1081 (1999).

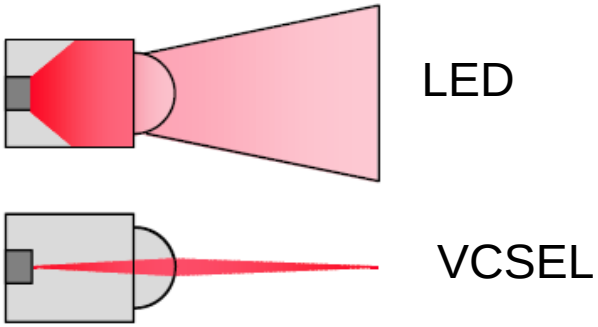
K. Iga, "Vertical-cavity surface-emitting laser: It's conception and evolution," *J. J. Appl. Phys*. 47, 1-10 (2008).

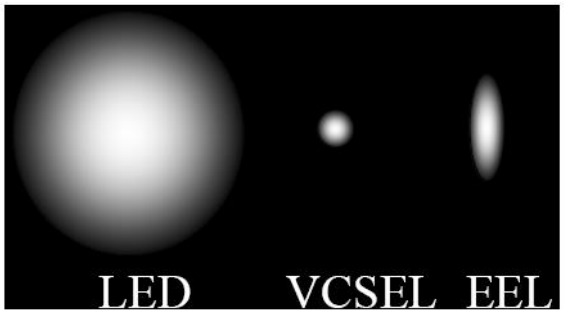
Surface Emitting Lasers

- **VCSEL output beam properties**

  - Symmetrical beam
  - Low divergence
  - Simple, low cost optics







Surface Emitting Lasers

- **Main parameters in VCSELs**

Parameter	Symbol	Stripe Laser	Surface Emitting Laser
Active layer Thickness	d	100Å-0.1μm	80Å-0.5μm
Active Layer Area	S	$3\times300\mu m^2$	$5\times5\ \mu m^2$
Active Volume	V	$60\mu m^3$	$0.07\ \mu m^3$
Cavity Length	L	300μm	≈1μm
Reflectivity	R_m	0.3	0.99-0.999
Optical Confinement	ξ	≈3%	≈4%
Optical Confinement (Transverse)	ξ_t	3-5%	50-80%
Optical Confinement (Longitudinal)	ξ_l	50%	2×1%×3 (3QW's)
Photon Lifetime	τ_p	≈1 ps	≈1 ps
Relaxation Frequency (Low Current Levels)	f_r	<5GHz	>10GHz

Surface Emitting Lasers

High speed VCSELs

- 3dB bandwidth in semiconductor lasers

$$f_{3dB} \cong \frac{\sqrt{1+\sqrt{2}}}{2\pi}\sqrt{\frac{v_g a}{qV_p}\eta_i (I - I_{th})}$$

v_g : group velocity

a : differential gain

V_p : optical cavity volume

η_i : internal quantum efficiency

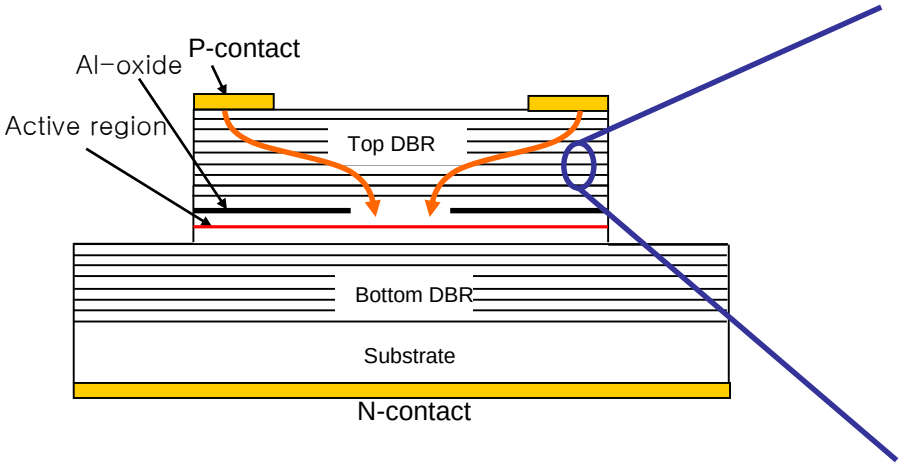
I_{th} : threshold current

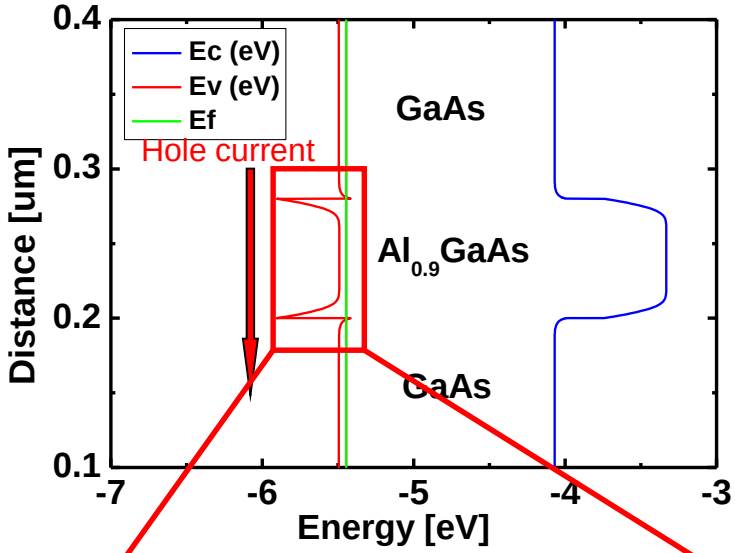
To increase the modulation bandwidth

- ✓ Increase differential gain
  → Optimization the thickness and number of QW
- ✓ Decrease threshold current
  → Uniform carrier injection, Optimization of interface grading
- ✓ Decrease RC time constant
  → Coplanar contact, interface grading

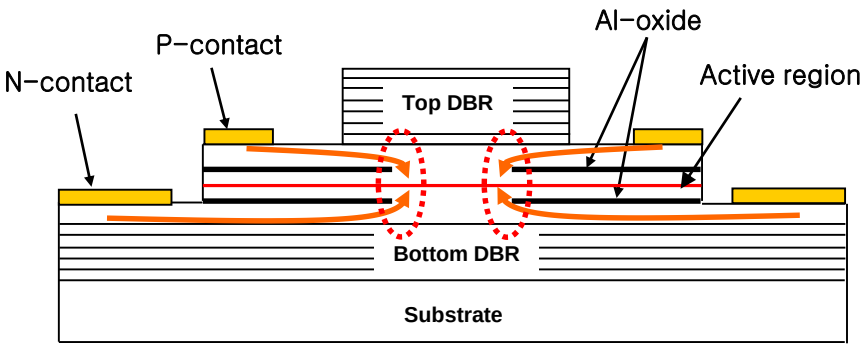
Surface Emitting Lasers

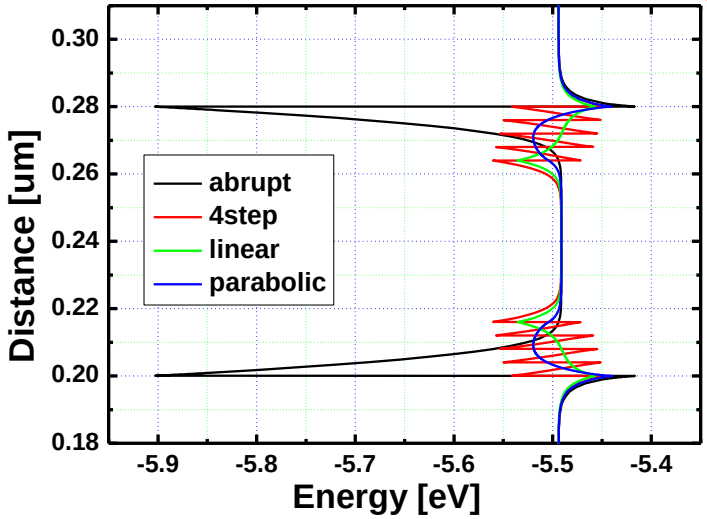
- **Extracavity contact**





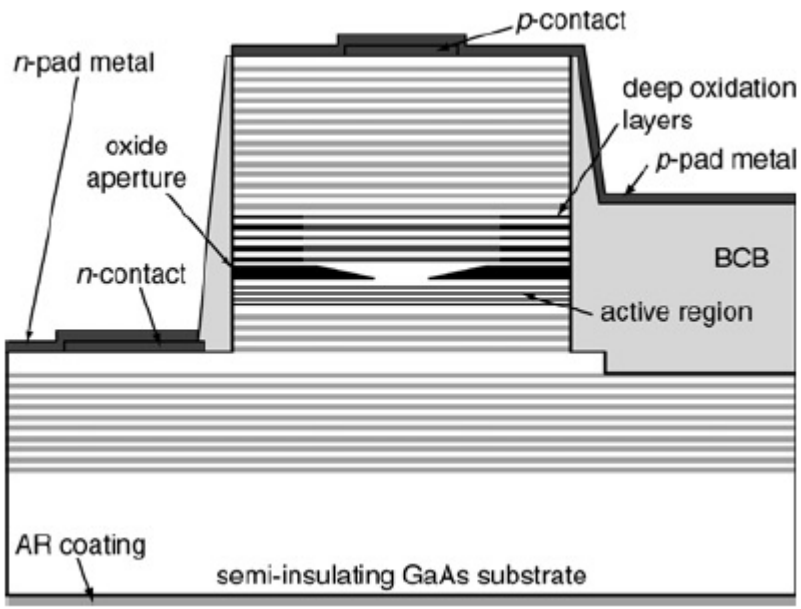
- **Intracavity contact**

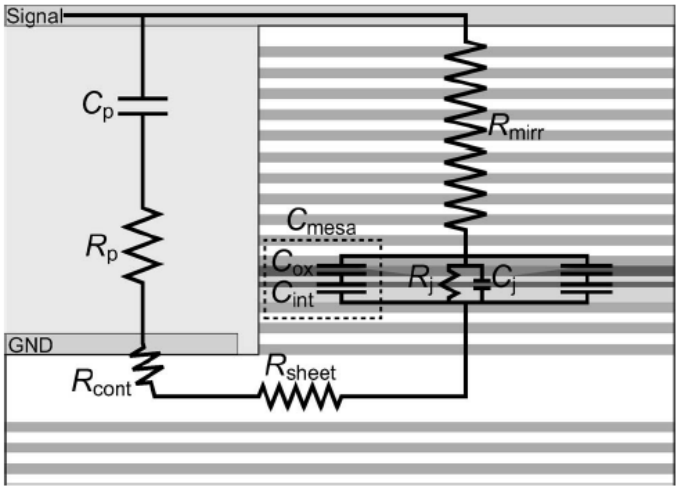


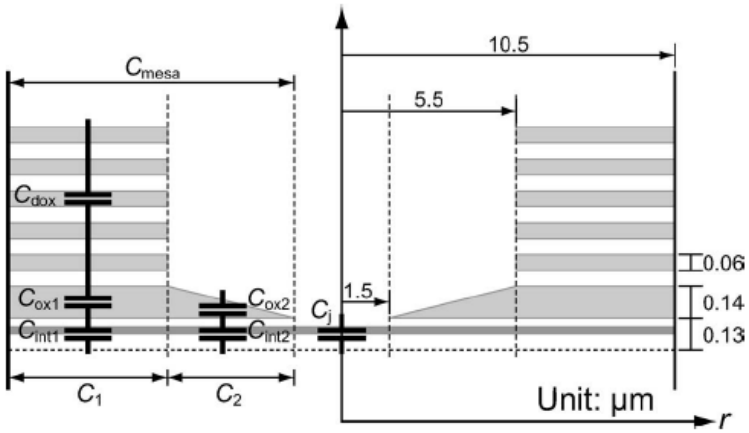


Surface Emitting Lasers

- **High speed VCSELs**







- Modified intra-cavity contact
- Tapered oxide aperture
- Deep oxidation layers

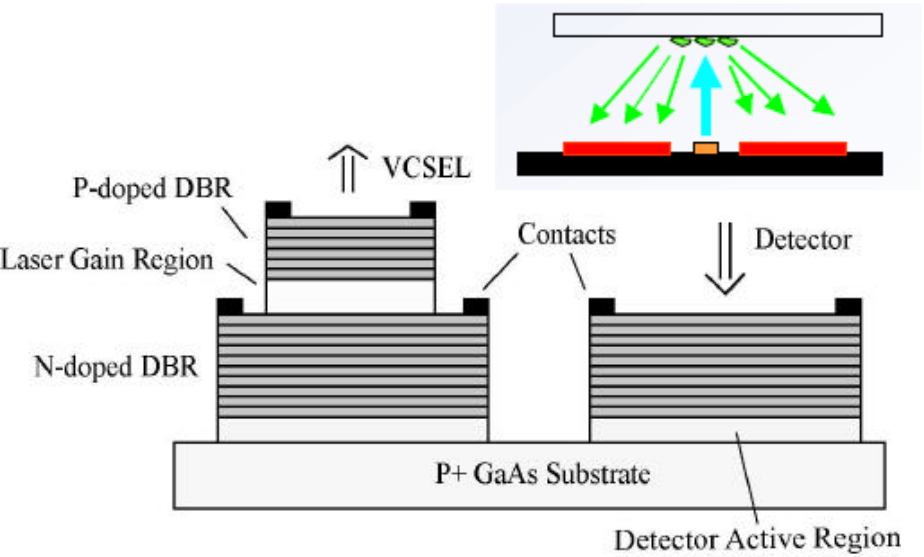
Y.-C. Chang et al., “Efficient, High-data-rate, tapered oxide-aperture vertical-cavity surface-emitting lasers,” IEEE J. Sel. Top. Quantum. Electron. 15, 704 (2009)

Surface Emitting Lasers

- **VCSEL/PD integration**

VCSEL/pin-PD integration

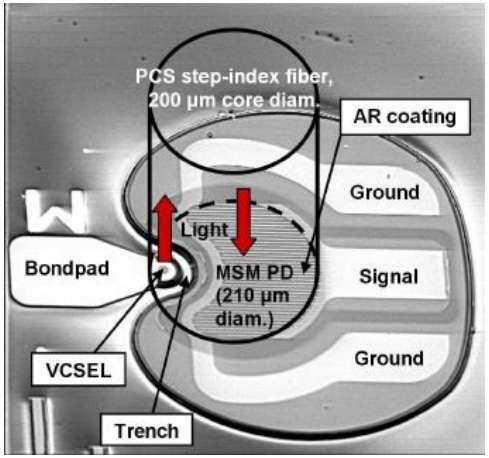
(Stanford Univ., 2004)

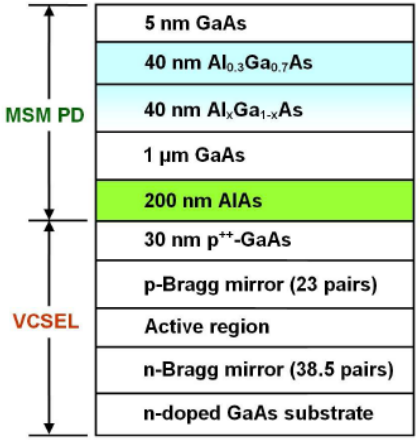


✓ VCSEL/pin-PD integration for bio sensor application
✓ Not applicable to high-speed operation

VCSEL/MSM-PD integration

(Univ. of Ulm, 2003)





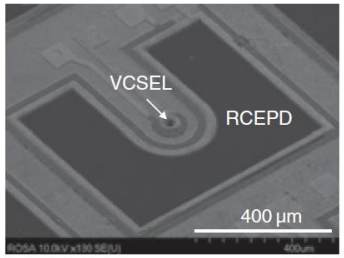
✓ VCSEL/MSM-PD integration for transceiver application
✓ Bi-directional optical interconnects

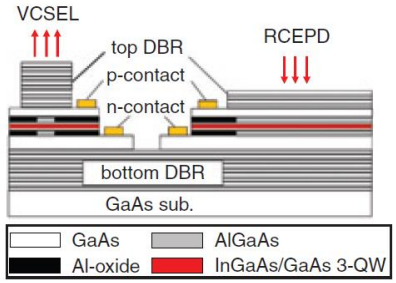
Surface Emitting Lasers

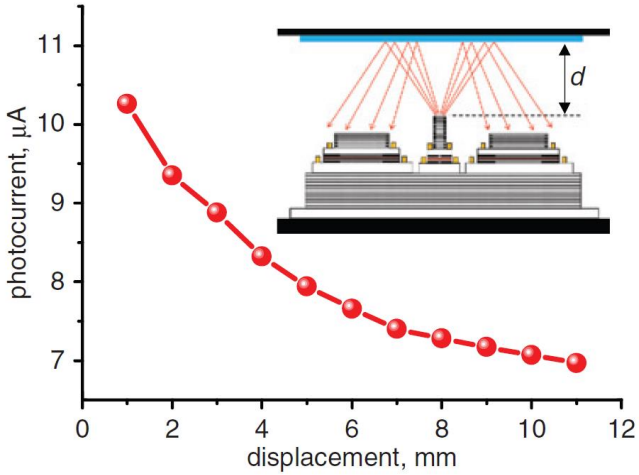
- **VCSEL/PD integration**

VCSEL/RCEPD integration

(GIST, 2016)



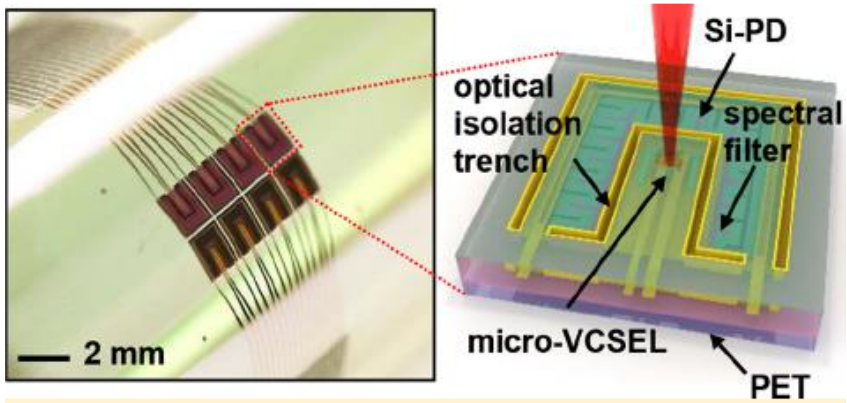


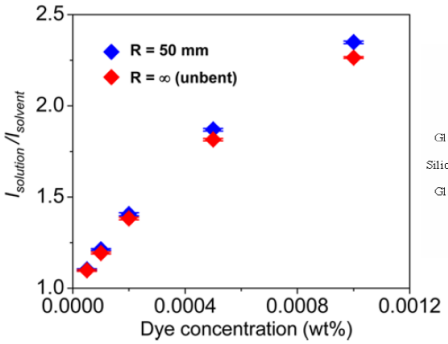


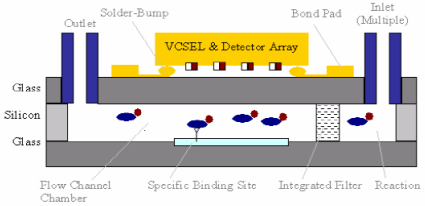
✓ **Monolithic integration**
✓ **Displacement sensor applications**

VCSEL/ Si-PD integration

(USC, 2016)



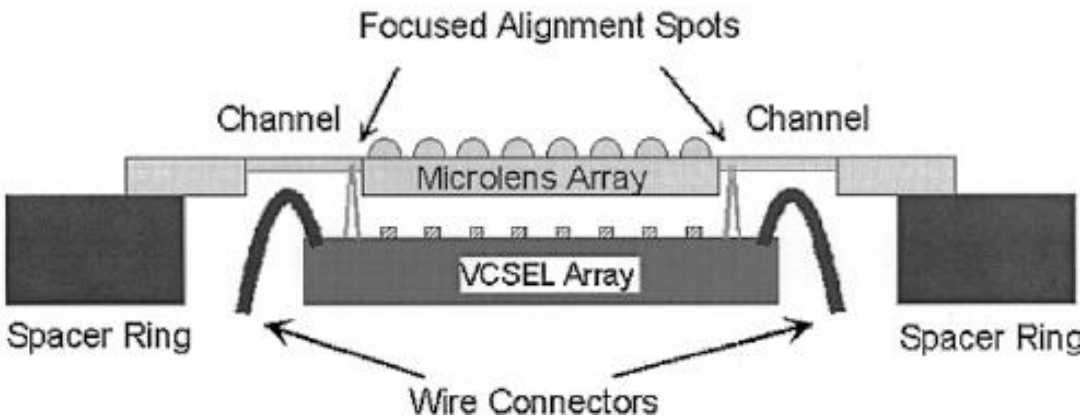




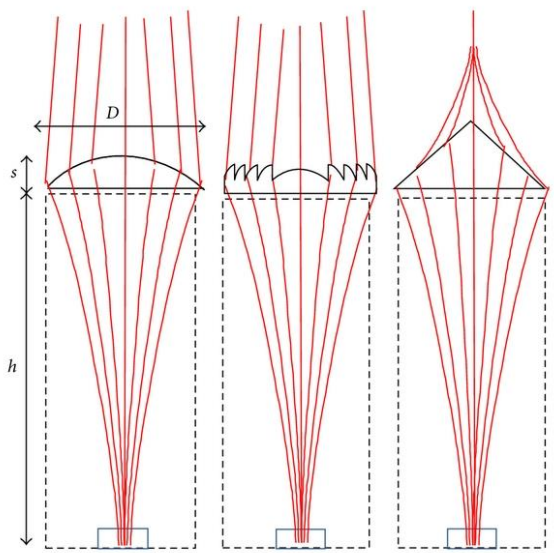
✓ **Hybrid integration**
✓ **Flexible forms, optofluidic applications**

Surface Emitting Lasers

- **VCSEL – microlens integration**

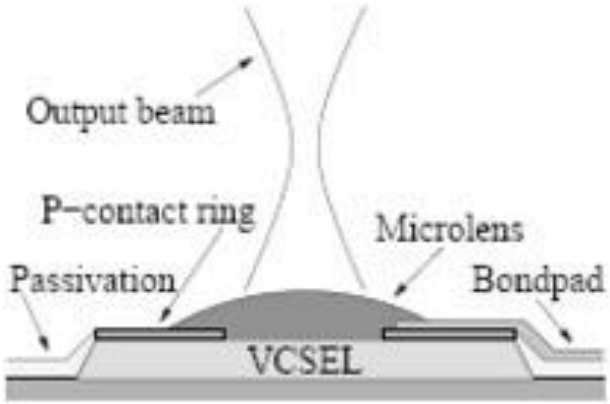


✓2D VCSEL arrays for optical interconnects



Top- or bottom-emitting VCSEL arrays

(a) (b) (c)

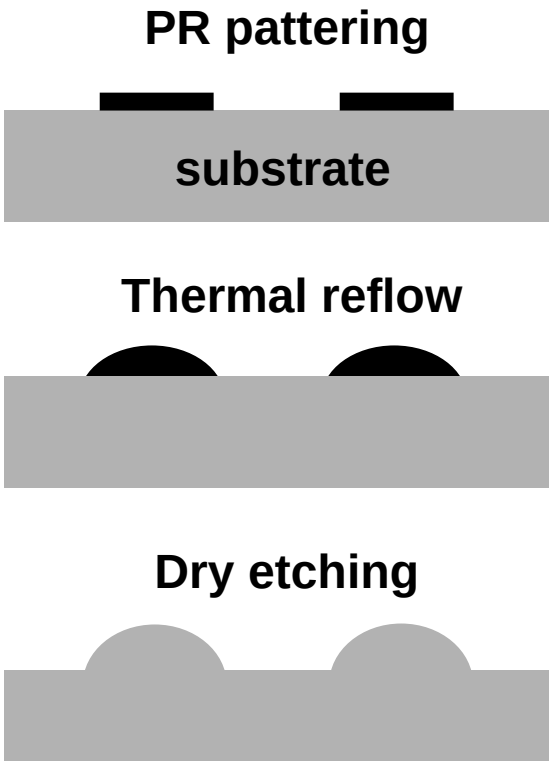


✓ Volume reduction
✓ Beam shaping

Surface Emitting Lasers

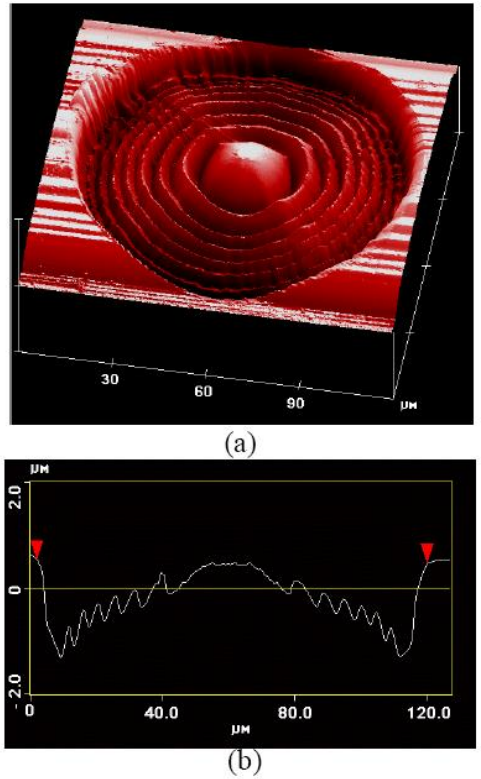
- **VCSEL – microlens integration**

PR reflow + dry etching



E. M. Stzelecka et al., Microlectron. Eng. 35, 385 (1997)

Focused ion beam milling



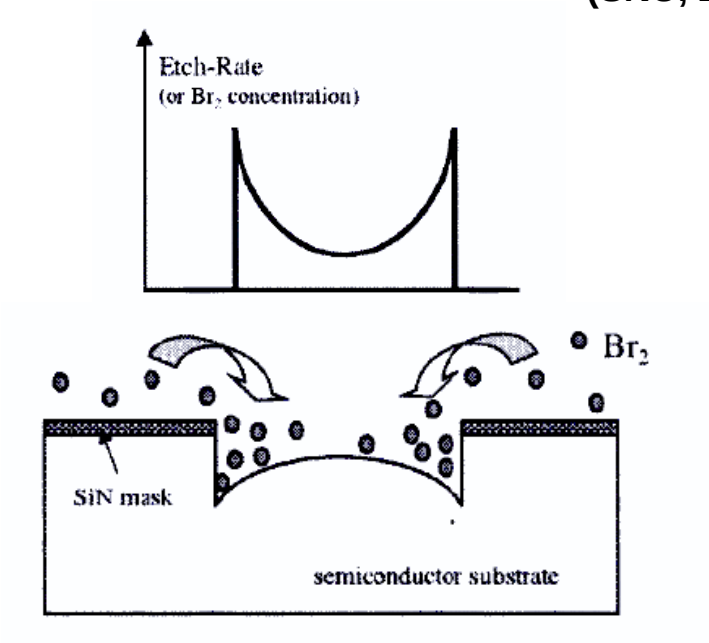
F. Qi et al., Opt. Express 10, 413 (2002)

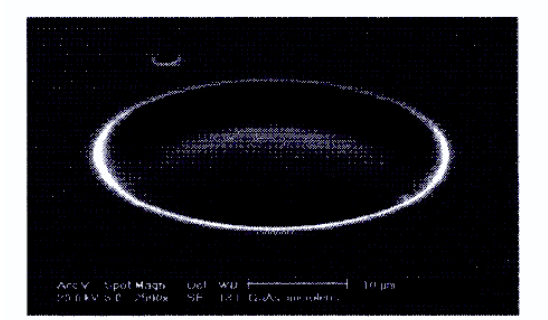
Surface Emitting Lasers

- **VCSEL – microlens integration**

Diffusion-limited wet-etching

(SNU, 2000)

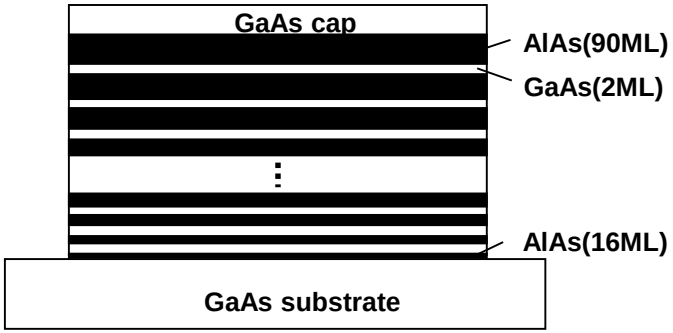




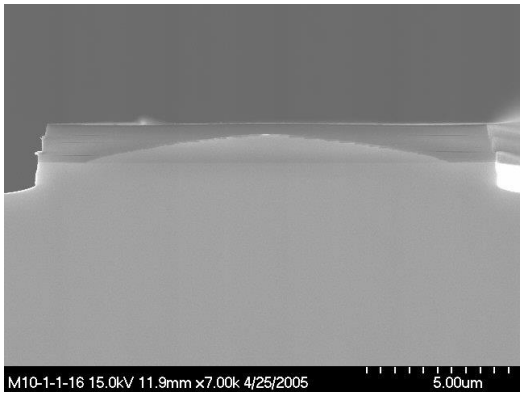
Selective oxidation

(GIST, 2006)

Epitaxial layer structure



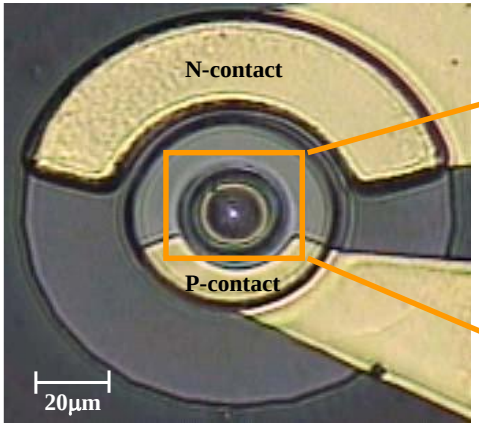
Linear composition grading of AlxGa1-xAs (x=0.89~0.98) using digital alloy method



Surface Emitting Lasers

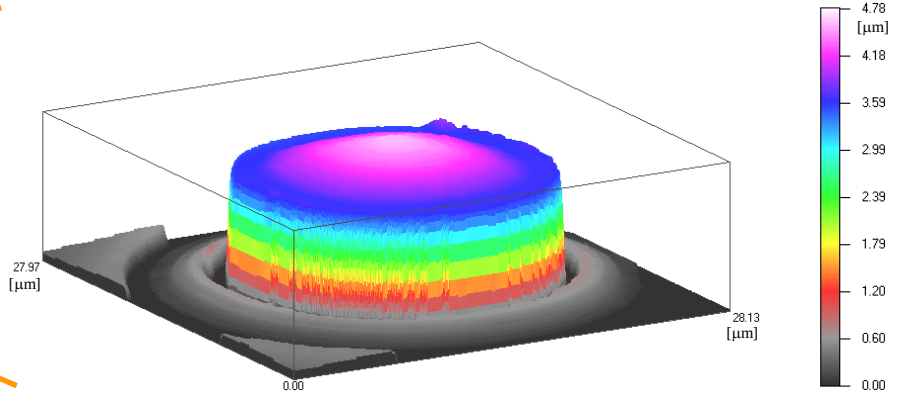
- **VCSEL – microlens integration**

Optical microscope image

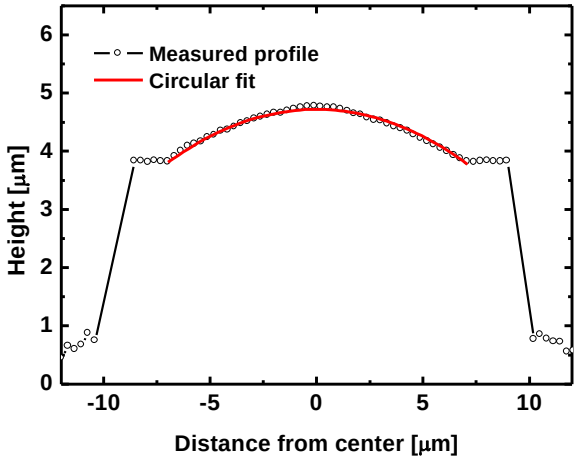


3-D confocal microscope image

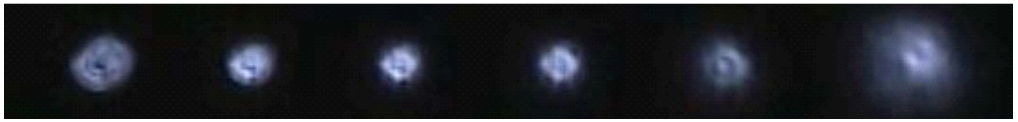
(GIST, 2007)

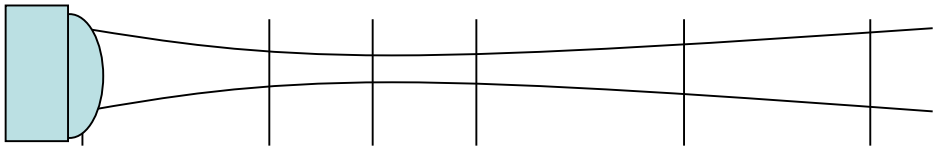


Microlens profile



Output beam from oxide-removed microlens-integrated VCSEL





Question or Comment?