Integrated High Speed VCSELs for Bi-Directional Optical Interconnects

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Outline

- Introduction
- Model description
- Structure optimization of VCSEL
- Conclusions
Computers: past, present and future

- Cray1 1980s
- Cray X1 2000s
- Pocket PC 2000s
- PC 2020s

Goal by 2010: first petaflop (Cray X1 successor)
1998: first teraflop (Cray T3E)
1989: first gigaflop (Cray Y-MP)

Billions of calculations/second

Moore’s Law rate (2x every 18 mos.)
We need the optoelectronic devices with

- **good performance** (high-modulation bandwidth, low power consumption, high efficiency)
- **manufacturing advantages** (amenable to high-volume production, wafer-level testing, and ease of integration).

Beyond 10 GHz, copper interconnects, become bandwidth limited due to frequency-dependent losses such as the skin effect in the conductors and the dielectric loss from the substrate material.

VCSELs over Edge Emitter lasers

VCSELs are characterized by:
- Low threshold Current.
- High power conversion efficiency.
- Less heating.
- Convenient operating wavelength.
- High speed of operation > 10 GHz.
- Surface normal light output.
- Circularly shaped, low NA output beams.
- Small size compared to other kinds of laser diodes.
- Very good potential for 2D arrays.
- Low cost wafer scale fabrication.

Important space applications:
- High speed fiber optic networks.
- Free space optical communication.
- Optical interconnects.
- Optical storage systems.
Intracavity contacted VCSEL array

- Bypass the current flow through mirrors ⇒ lowers the series resistance
- Use of undoped DBR mirror ⇒ reduce free carrier absorption ⇒ better reflectivity
- Co-planar contact ⇒ suitable for flip-chip bonding
- Current crowding effect
Interactions between physical processes in LD

PICS3D Crosslight program
Total current magnitude for different pumping currents

- \( I_c = I_{th} \) 0 mA [0-265] A/c
- \( I_c = 7.5 \) mA [0-21000] A/c
- \( I_c = 15 \) mA [0-44000] A/c
- \( I_c = 22.5 \) mA [0-66000] A/c
- \( I_c = 30 \) mA [0-87000] A/c
Thermal phenomena

Basic thermal equation

\[ C_p \rho \frac{\partial T}{\partial t} = \nabla \cdot \kappa \nabla T + H \]

Heat coefficient

Material density

Thermal conductivity

Heat sources

~17 %

~ 1 %

80 %

0.001 %

~ 2 %

\[ H = H_{\text{Joule-\text{dc}}} + H_{\text{Joule-op}} + H_{\text{rec}} + H_T + H_P \]

Steady-state

Electrical field

Optical wave absorption on loss semiconductors

Recombination heat

Thomson heat

Peltier heat
Heat sources in ICOC VCSEL

- Joule heat: [0-3.1] mW/μm³
- Recomb heat: [0-13.3] mW/μm³

Grid: x, μm and y, μm

Graph showing the distribution of heat sources with contours indicating the intensity of joule heat.
Structure optimization

\[ R_{ot} = \frac{d_{top\, mirror}}{d_{oxide\, window}} \]

- Graded layer thickness
- Oxide window diameter
- Contact layer thickness
Graded layer thickness I

I-L and I-V characteristics and energy band diagram in the center of structure for different values of graded layer thickness (GLT)

GLT↓→Energy “notches”  ↑→R_{tot}↑

V. V. Lysak, et. al, Appl. Phys. Lett. 87 (2005), 231118 1-3
Graded layer thickness II

Radial distribution of electron concentration

f3dB bandwidth

GLT $\uparrow$ $\rightarrow$ current crowding effect $\uparrow$

GLT $\downarrow$ $\rightarrow$ $\text{R}_{\text{tot}}$ $\uparrow$ $\rightarrow$ f3dB $\downarrow$

GLT $\uparrow$ $\rightarrow$ V_{eff} $\uparrow$ $+$ nonuniform current distribution $\rightarrow$ f3dB $\downarrow$
Contact layer thickness

Contact layer is a part of DBR mirror → $d=(2k+1)\lambda/4n$

a) V-I and b) L-I characteristics for different values of n - and p - contact layer thickness of $\lambda/4n$ (solid lines), $3\lambda/4n$ (dashed lines), $5\lambda/4n$ (dash-dotted lines) and $7\lambda/4n$ (dotted lines)
Contact layer thickness II

Radial distribution of the lattice temperature in active layer

Radial distribution of the electron concentration

CLT↑ → $R_{\text{layer}}$ ↓ → $R_{\text{tot}}$ ↓ → $T_{\text{active}}$ ↓ → Gain↑
Contact layer thickness III

Decreasing the CLT increases the differential resistance (see V-I characteristics). On the other hand, increasing the CLT changes the parameters as follows:

- increases the effective volume of resonator and decreases the gain enhancement factor due to increasing the penetration depths of DBR mirrors;
- reduces differential gain from the current crowding effect

\[ f_R = \frac{1}{2\pi} \sqrt{\frac{\Gamma \xi v_g}{q V_{eff}} \frac{\partial g}{\partial N} (I - I_{th})} \]
Capacitance management

\[ C_{ox} \downarrow \text{Counter-flowing paths for electrons and holes} \rightarrow \text{asymmetrical contacts and suppress the conductivity} \]
Experimental part

L-I-V characteristics

- Oxide aperture dia.: 5 µm
- Threshold current: 0.7±0.05 mA
- Threshold voltage: 1.7 V
- Slope efficiency: 0.36±0.01 W/A @ I=2mA
- Differential quantum efficiency: 28.4±0.7 %@ I=2mA
- Differential resistance: 150 Ω @ I=6mA

3dB bandwidth 10 GHz at 10 mA
Conclusion

- we have analyzed the thermal, electrical, optical, and modulation properties of the 980 nm InGaAs ICOC VCSELs with different geometrical values
- devices with the optimal GLT of 40-60 Å have the highest output power and the widest modulation bandwidth due to compromise between the low resistance and more uniform radial carrier distribution in the active layer
- devices with the optimal CLT of $5\lambda/4n$ have the widest modulation bandwidth and the modulation conversion efficiency factor is approximately $5.92 \text{ GHz/(mA)}^{0.5}$ due to compromise between the effective volume of resonator, current crowding suppression and total resistance
- The VCSEL with 5 mm diameter oxide aperture has a threshold current of 0.7 mA, a threshold voltage of 1.7V and a maximum output power of 7mW. 0.36W/A slope efficiency at 6mA and 29% differential quantum efficiency were achieved at room temperature. A maximum 3dB modulation frequency at a bias current of 10mA reached 10 GHz.

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