

# VCSEL Industry Communication & Sensing

Babu Dayal Padullaparthi  
Jim Tatum  
Kenichi Iga

# Table of Contents

[Cover](#)

[Series Page](#)

[Title Page](#)

[Copyright Page](#)

[Dedication Page](#)

[About the Book and Authors Biographies](#)

[Foreword](#)

[References](#)

[Preface](#)

[Introduction](#)

[Acknowledgments](#)

[List of Image Contributions](#)

[1 Semiconductor Lasers and VCSEL History](#)

[1.1 History and Basics of Semiconductor Lasers](#)

[1.2 Semiconductor Lasers and Manufacturing](#)

[1.3 VCSEL History and Development](#)

[1.4 Timeline and Milestones](#)

[1.5 State of VCSEL Development](#)

[References](#)

[2 VCSEL Fundamentals](#)

[2.1 Introduction to Lasers](#)

[2.2 Basic VCSEL Structure](#)

[2.3 Quantum Well Gain Region \(Active Region\)](#)

[2.4 Distributed Bragg Reflector Mirrors](#)

[2.5 Light Output Characteristic](#)

[2.6 Forward Voltage Characteristic](#)

[2.7 Optical Modes](#)

[2.8 Beam Divergence](#)

[2.9 Modulation Characteristics](#)

[2.10 Temperature Characteristics](#)

[2.11 Thermal Transient Behavior and Short-Pulse Operation](#)

[2.12 Other VCSEL Structures](#)

[2.13 VCSEL Materials](#)

[2.14 Summary](#)

[References](#)

### [3 VCSEL Industry](#)

[3.1 Industry Background](#)

[3.2 VCSEL Industry Landscape](#)

[3.3 VCSEL Commercial Products](#)

[3.4 Summary](#)

[References](#)

[Bibliography](#)

### [4 Data Communications Applications](#)

[4.1 Introduction](#)

[4.2 Growing Data](#)

[4.3 Data Centers and High-Performance Computing](#)

[4.4 Optical Interconnects](#)

[4.5 Data Encoding and Multiplexing](#)

[4.6 High-Speed VCSELs](#)

[4.7 Optical Link Impairments](#)

[4.8 Energy Efficient VCSELs](#)

[4.9 Datacom Market](#)

#### [4.10 Summary](#)

#### [References](#)

### [5 VCSELs for 3D Sensing and Computer Vision](#)

#### [5.1 Optical Sensors in Consumer Electronics](#)

#### [5.2 Why VCSELs for Smart Optical Sensors?](#)

#### [5.3 3D Sensing \(Mobile\) Products](#)

#### [5.4 Computer Vision and Virtual Reality](#)

#### [5.5 3D Sensing Mobile and Camera Industry Prospects \(until 2025\)](#)

#### [5.6 Summary](#)

#### [References](#)

### [6 Automotive LiDARs](#)

#### [6.1 Introduction to LiDARs](#)

#### [6.2 Operating Principle of LiDARs](#)

#### [6.3 VCSELs in LiDAR Industry: Landscape and Direction](#)

#### [6.4 Key Aspects of LiDARs](#)

#### [6.5 Examples of VCSEL- and EEL-Based LiDARs](#)

#### [6.6 Automotive Communication: IVE \(Infotainment\) and C-V2X](#)

#### [6.7 Market Summary](#)

#### [References](#)

### [7 Illumination, Night Vision, and Industrial Heating](#)

#### [7.1 Introduction](#)

#### [7.2 Optical Properties of Illumination Sources](#)

#### [7.3 Commercial Examples of VCSEL Illuminators](#)

#### [7.4 VCSEL-Based Industrial Heating](#)

#### [7.5 Summary](#)

### [8 Single-Mode VCSELs for Sensing Applications](#)

[8.1 Introduction](#)

[8.2 Single-Mode VCSELs](#)

[8.3 Single-Mode VCSEL Application Examples](#)

[8.4 Summary](#)

[References](#)

## [9 Single-Mode VCSELs for Communications Applications](#)

[9.1 Introduction](#)

[9.2 LW-VCSEL Design and Manufacturing](#)

[9.3 Quantum Communications](#)

[9.4 Summary](#)

[References](#)

## [10 Future Prospects](#)

[10.1 VCSEL Industry](#)

[10.2 Datacom VCSELs](#)

[10.3 VCSEL Arrays for 3D Sensing \(Short Distance\)](#)

[10.4 VCSEL Arrays for 3D Sensing and Imaging \(Long Distance\)](#)

[10.5 kW-Level VCSEL Arrays for Industrial and Night Vision](#)

[10.6 Single-Mode VCSELs for Communication and Sensing](#)

[10.7 Quantum Technologies](#)

[10.8 Neuromorphic/Neurophotonic Technologies](#)

[10.9 Biomedical/Bio-Photonic Applications](#)

[10.10 New Directions of VCSEL Technologies \(as of March 2021\)](#)

[10.11 Concluding Remarks](#)

[References](#)

## [Appendix A: VCSELs Design Engineering](#)

### [A.1 Background](#)

#### [References](#)

## [Appendix B: Epitaxial Growth Engineering](#)

### [B.1 Technologies and Materials for VCSELs](#)

### [B.2 Epitaxial Growth](#)

### [B.3 Reactor Readiness and Calibrations](#)

### [B.4 Post-Growth Characterizations and Acceptance](#)

### [B.5 Epitaxial Growth on Large-Sized Wafers](#)

#### [References](#)

#### [Bibliography](#)

## [Appendix C: Wafer Process Engineering](#)

### [C.1 Background of Wafer Processing](#)

### [C.2 Wafer Processing Methods: DOE and Lot](#)

### [C.3 Wafer Probe Measurements](#)

#### [References](#)

#### [Bibliography](#)

## [Appendix D: Wafer Level Testing](#)

### [D.1 Introduction](#)

### [D.2 Post-Epitaxial Characterization](#)

### [D.3 Wafer Fabrication Data](#)

### [D.4 Wafer Level Performance Test](#)

### [D.5 Package Level Validation](#)

### [D.6 Summary](#)

#### [References](#)

## [Appendix E: Reliability and Product Qualification](#)

### [E.1 Introduction](#)

### [E.2 Reliability Model Development](#)

[E.3 Failure Modes in VCSELs](#)

[E.4 Array Reliability and Sparing](#)

[E.5 Considerations for High-Power 2D VCSEL Arrays](#)

[E.6 Qualification Standards](#)

[E.7 Ongoing Quality Verification](#)

[E.8 Summary](#)

[References](#)

[Appendix F: Eye Safety Considerations](#)

[References](#)

[Appendix G: Laser Displays and TV](#)

[G.1 What is a Laser Display?](#)

[G.2 Displays and Color Gamut](#)

[G.3 Laser Light Sources for Display](#)

[G.4 Laser Backlight Method](#)

[G.5 Summary of Laser Displays](#)

[References](#)

[Appendix H: Red VCSELs](#)

[H.1 Introduction](#)

[H.2 Data Communications](#)

[H.3 Blood Oximetry](#)

[H.4 Hair Regrowth](#)

[References](#)

[Appendix I: GaN-Based VCSELs](#)

[I.1 AlGaInN Laser Materials](#)

[I.2 AlGaInN Laser Development](#)

[I.3 AlGaInN Blue VCSELs](#)

[I.4 AlGaInN Green VCSELs](#)

[I.5 White Light Generation by VCSELs](#)

[References](#)

[Appendix J: Photodetectors](#)

[J.1 Introduction](#)

[J.2 Noise in Photodetectors](#)

[J.3 Photodetectors for Communication and Sensing](#)

[References](#)

[Image Gallery](#)

[Index](#)

[The Comsoc Guides to Communications Technologies](#)

[End User License Agreement](#)

## List of Tables

### Chapter 1

[Table 1.1 Categorization of semiconductor lasers.](#)

[Table 1.2 Milestones of surface emitting laser research and development.](#)

[Table 1.3 Differences between VCSEL and edge-emitting lasers \(EEL\).](#)

[Table 1.4 Attributes of VCSEL in datacom, sensing, and manufacturing.](#)

[Table 1.5 Mode dependent VCSEL applications.](#)

### Chapter 2

[Table 2.1 Design choices for VCSEL sections.](#)

[Table 2.2 Semiconductor material choices for VCSEL active regions and mirro...](#)

### Chapter 3



[Table 3.1 Die quantity and cost estimates for different product \(die\) sizes...](#)

[Table 3.2 Key specifications for VCSEL epi-wafer growth.](#)

[Table 3.3 Key specifications for wafer-fab \(processing\).](#)

[Table 3.4 Appearance of VCSEL players post Apple's i-phone X announcement\\*...](#)

[Table 3.5 Typical scenario of net yield estimation.](#)

## Chapter 4

[Table 4.1 Classification of data centers by size.](#)

[Table 4.2 Classification of datacenters by reliability.](#)

[Table 4.3 Classification of data centers by reliability.](#)

[Table 4.4 Transmitter-related specifications for IEEE 802.3 for 1Gbps \(clau...](#)

[Table 4.5 Classification of multi-mode optical fiber.](#)

## Chapter 5

[Table 5.1 Difference between d-TOF and i-TOF.](#)

[Table 5.2 Differences among 3D cameras used in latest consumer electronic p...](#)

[Table 5.3 Power scaling of VCSEL arrays for product applications.](#)

[Table 5.4 Difference among XR technologies.](#)

## Chapter 6

[Table 6.1 Differences among 3D sensing technologies used in latest consumer...](#)

[Table 6.2 Benchmarking of scanning and non-scanning LiDARs for applications...](#)

[Table 6.3 Laser transmitters and detectors for various LiDAR applications.](#)

[Table 6.4 Latest situation of LiDARs in the industry.](#)

## Appendix B

[Table B.1 Comparisons between MBE and MOCVD processes.](#)

[Table B.2 Substrate parameters to be considered for VCSEL layer growth.](#)

## Appendix C

[Table C.1 Process summary for various products.](#)

[Table C.2 Critical points for various products.](#)

## Appendix E

[Table E.1 Summary of published reliability models.](#)

[Table E.2 Impact on wear-out reliability as spare channels are added to VCSE...](#)

[Table E.3 Superset of tests from Telcordia, JEDEC, and AECQ qualification te...](#)

## Appendix F

[Table F.1 IEC classification of lasers.](#)

[Table F.2 MPE formulas for lasers between 700 and 1050 nm.](#)

## Appendix G

[Table G.1 Laser display development history and events.](#)

[Table G.2 Categorization of displays \[6\].](#)

[Table G.3 Laser display and semiconductor laser.](#)

## Appendix H

[Table H.1 Summary of current POF-based fiber networking standards.](#)

## Appendix J

[Table J.4.1 Summary of key performance parameters/characteristics of PDs \[Ba...](#)

# List of Illustrations

## Chapter 1

[Figure 1.1 Schematic of a vertical-cavity surface-emitting laser \(VCSEL\)....](#)

[Figure 1.2 Schematic of semiconductor lasers \(a\) Edge-emitting laser \(EEL\). ...](#)

[Figure 1.3 Voltage-current \(V-I\) characteristic of a p-n junction with no in...](#)

[Figure 1.4 Double heterostructure laser. \(a\) The carrier densities of electr...](#)

[Figure 1.5 Quantum well structure with separate optical confinement. \(a\) The...](#)

[Figure 1.6 Population distribution of electrons and holes in semiconductor w...](#)

[Figure 1.7 Optical gain of semiconductor vs. energy.](#)

[Figure 1.8 Schematic of edge-emitting Fabry-Pérot lasers and VCSELs. The cou...](#)

[Figure 1.9 Fabry-Pérot cavity and resonant spectra. \(a\) Fabry-Pérot cavity. ...](#)

[Figure 1.10 The manufacturing processes of edge-emitting lasers.](#)

[Figure 1.11 The manufacturing and testing processes of VCSELs.](#)

[Figure 1.12 A fully processed VCSEL layer structure on 6" \(150 mm\) GaAs subs...](#)

[Figure 1.13 Stages of VCSEL development. The inset figure shows the sketch o...](#)

[Figure 1.14 The first demonstration of a surface-emitting laser.](#)

[Figure 1.15 Initial VCSELs achieving room-temperature continuous operation.](#)

[Figure 1.16 Origin of single-mode and multi-mode behavior in VCSELs.](#)

[Figure 1.17 VCSEL-based optical communication and sensing systems.](#)

[Figure 1.18 Published papers on VCSEL.](#)

[Figure 1.19 Application fields of VCSEL market as of 2021; data taken from v...](#)

[Figure 1.20 The modified hype cycle of VCSEL industrialization.](#)

[Figure 1.21 Total addressable market of VCSELs at module levels till 2025....](#)

## Chapter 2

[Figure 2.1 Cross section of an oxide-confined VCSEL showing the basic compon...](#)

[Figure 2.2 Energy band diagram of a 60 Å GaAs QW showing the quantum wells \(...\)](#)

[Figure 2.3 \(a\) Optical gain \( \$\text{cm}^{-1}\$ \) for a 60 Å GaAs quantum well with N...](#)

[Figure 2.4 Simplified schematic of a DBR mirror showing the reflections from...](#)

[Figure 2.5 \(a\) Power reflectivity for 10, 20, 30, and 40 periods of a DBR mi...](#)

[Figure 2.6 Light output as a function of current with the threshold current,...](#)

[Figure 2.7 Forward voltage as a function of current with the series resistan...](#)

[Figure 2.8 Plot of the electric field and index of refraction of a typical V...](#)

[Figure 2.9 Optical emission spectra from a single-mode VCSEL showing SMSR = ...](#)

[Figure 2.10 \(a\) Optical emission spectrum of a multimode oxide isolated VCSE...](#)

[Figure 2.11 Measured L-I characteristic of a polarization-controlled VCSEL w...](#)

[Figure 2.12 Measured far-field beam profile of a 25 Gbps VCSEL at  \$I = 1, 3, \dots\$](#)

[Figure 2.13 Measured modulation transfer function \(triangles\), the intrinsic...](#)

[Figure 2.14 Measured modulation transfer function of a typical VCSEL capable...](#)

[Figure 2.15 Light output and forward voltage as a function of current at tem...](#)

[Figure 2.16 Extracted performance metrics from Figure 2.15 as a function of ...](#)

[Figure 2.17 Thermal response of a VCSEL active region \(dashed lines\) to elec...](#)

[Figure 2.18 \(a\) Light output as a function of current for pulsewidths rangin...](#)

[Figure 2.19 \(a\) Common top-emitting VCSEL structure. \(b\) Bottom-emitting VCS...](#)

## Chapter 3

[Figure 3.1 Core fields module-level VCSELs market projection for the next fi...](#)

[Figure 3.2 Chip demands of VCSELs for the next five years.](#)

[Figure 3.3 Spine-leaf DC architecture considerations in Cisco Systems.](#)

[Figure 3.4 Typical \(a\) front- and \(b\) back-facing smartphone layouts.](#)

[Figure 3.5 Sources of VCSEL business attractiveness \(“highway”\).](#)

[Figure 3.6 Fully processed 6” \(150 mm\) GaAs VCSEL wafer.](#)

[Figure 3.7 VCSEL demand and cost trends as a function of wafer size.](#)

[Schematic 3.1 Multiple technological abilities of VCSELs.](#)

[Figure 3.8 \(a\) PL map of GaN QWs grown on Si 8” \(200 mm\) substrate. \(Reprint...](#)

[Figure 3.9 A schematic \(a\) cross section of generic, and \(b\) top-views of so...](#)

[Figure 3.10 \(a\) Etch depth sampling points and \(b\) its depth variation across...](#)

[Figure 3.11 Oxidation rate dependence of \(a\) time, \(b\) thickness, and \(c\) Al...](#)

[Figure 3.12 Schematic of \(a\) oxidation depth as a function of Al\(x\) mole fra...](#)

[Figure 3.13 Bathtub curve failure distribution trends of an optical componen...](#)

[Schematic 3.1 Business models for III-V opto foundries.](#)

[Figure 3.14 VCSEL supply chain \(with business models overlapped\).](#)

[Figure 3.15 Schematic of VCSEL product development or manufacturing stages f...](#)

[Figure 3.16 Essential stages of cycle time during VCSEL product development....](#)

[Figure 3.17 Examples of few MM and SM products.](#)

## Chapter 4

[Figure 4.1 Fixed and mobile Internet traffic in petabytes per month.](#)

[Figure 4.2 Total Internet traffic \(black line\), Moore's law at 1.5 years \(bl...](#)

[Figure 4.3 Total computing capacity \(circles\), the fastest \(triangles\), and ...](#)

[Figure 4.4 \(a\) Fat tree or spine and leaf architecture preferred by data cen...](#)

[Figure 4.5 Architecture of a modern Facebook data center \[10\].](#)

[Figure 4.6 Typical cable carrier racks in a large data center. \(a\) This part...](#)

[Figure 4.7 Evolution of communications standards speeds \(a\) Ethernet speeds ...](#)

[Figure 4.8 Comparison of bandwidth density and energy per bit for some commo...](#)

[Figure 4.9 Schematic of common optical interfaces used in networking equipment...](#)

[Figure 4.10 Some common VCSEL-based optical transceivers, active optical cab...](#)

[Figure 4.11 \(a, b\) Converter for HDMI electrical to optical link extension c...](#)

[Figure 4.12 Comparison of components for a VCSEL transmitter and an EEL-base...](#)

[Figure 4.13 Schematic of single, SDM, and WDM optical channels.](#)

[Figure 4.14 Schematic of PAM-2 and PAM-4 signaling with representative optic...](#)

[Figure 4.15 Schematic of a 5G network \[17\].](#)

[Figure 4.16 Examples of some commercially available VCSELs capable of 25 Gbp...](#)

[Figure 4.17 Differential gain as a function of In content in an 850 nm quant...](#)

[Figure 4.18 \(a\) Modal gain and \(b\) differential gain as a function of carrie...](#)

[Figure 4.19 \(a\) Photon lifetime as a function of etch depth into the DBR. \(b...](#)

[Figure 4.20 Schematic of the parasitic electrical components of a VCSEL.](#)

[Figure 4.21 \(a\) Schematic of a photonic resonance oxide-confined VCSEL. \(b\)...](#)

[Figure 4.22 \(a\) Schematic of a photonic resonance VCSEL defined by a photoni...](#)

[Figure 4.23 Simulated S21 response and resulting eye diagrams for two differ...](#)



[Figure 4.24 \(a\) Demonstration of equalization of the small signal response o...](#)

[Figure 4.25 \(a\) Frequency response of a rectangular pulse \(dashed line\) and ...](#)

[Figure 4.26 Summary of achieved data rates using PAM-2 and PAM-4 VCSELs \[30\]...](#)

[Figure 4.27 Reference electrical drive signal \(solid lines\) and the resultin...](#)

[Figure 4.28 Schematic of light transmission through graded in optical fiber ...](#)

[Figure 4.29 Schematic of power launch profile in a MMF and the resulting enc...](#)

[Figure 4.30 Chromatic dispersion bandwidth for OM4 MMF at 850 nm. The CD is ...](#)

[Figure 4.31 \(a\) Junction are capacitance of a GaAs photodiode as a function ...](#)

[Figure 4.32 Breakdown of power usage in a data center and the breakdown of p...](#)

[Figure 4.33 Breakdown of power usage in a data center and the breakdown of p...](#)

## Chapter 5

[Figure 5.1 Three types of 3D sensing and imaging technologies object detecti...](#)

[Figure 5.2 Various 3D sensing technologies, namely stereo vision, time-of-fl...](#)

[Figure 5.3 Schematic of d-TOF and i-TOF.](#)

[Figure 5.4 Principle of triangulation or structured light in 3D sensing/imag...](#)

[Figure 5.5 Random patterns projected by commercial 3D sensors. \(a\) Microsoft...](#)

[Figure 5.6 \(a\) A 3 W hexagonal VCSEL array chip for 3D sensing.\(b\) L-I c...](#)

[Figure 5.7 \(a\) Different contributions of losses in a VCSEL for reaching max...](#)

[Figure 5.8 \(a and b\) Diffractive optical elements \(DOE\) diffusers and encode...](#)

[Figure 5.9 VCSEL illumination module integrated with diffuser.](#)

[Figure 5.10 \(a\) Schematic of radial transverse mode patterns overlapped with...](#)

[Figure 5.11 A block diagram of 3D IR sensor module with its essential elemen...](#)

[Figure 5.12 A four-emitter VCSEL transmitter used as proximity sensor in iPh...](#)

[Figure 5.13 A flip-chip bonded 940 nm VCSEL array chip made for TOF flood il...](#)

[Figure 5.14 \(a\) Concept of generation of distributed light or dot matrix....](#)

[Figure 5.15 A 0.3 W VCSEL packaged chip from OSRAM for TOF and structured-li...](#)

[Figure 5.16 A vacuum sweeper robot from iRobot Braava m6 using structured-li...](#)

[Figure 5.17 Limited human vision perceptions and FOV.](#)

[Figure 5.18 Schematic of reality-virtuality continuum.](#)

[Figure 5.19 Examples of AR-based products: \(a\) smartphone and \(b\) smart glas...](#)

[Figure 5.20 A 2.0 W VCSEL chip packaged with microlens arrays for facial rec...](#)

[Figure 5.21 Market forecast for smartphones.](#)

## Chapter 6

[Figure 6.1 Classification of LiDARs for ranging applications.](#)

[Figure 6.2 Concept of sensor fusion for advanced driver assistance systems \(...\)](#)

[Figure 6.3 Levels of ADAS with key functions.](#)

[Figure 6.4 Automotive LiDAR detection in the city center, where both light s...](#)

[Figure 6.5 Working principles of TOF, phase shift, and FMCW measurement tech...](#)

[Figure 6.6 World first automotive standards qualified and individually addre...](#)

[Figure 6.7 \(a\) Block diagram of LiDAR SOC.\(b\) A solid-state LiDAR module...](#)

[Figure 6.8 Display of scanned image from flash LiDAR system with VCSEL trans...](#)

[Figure 6.9 A flash LiDAR module integrated on rear side of autonomous shuttl...](#)

[Figure 6.10 Function of three kinds of LiDARs.](#)

[Figure 6.11 Solar irradiance seen at the ground.](#)

[Figure 6.12 MPE as energy density versus wavelength for various exposure tim...](#)

[Figure 6.13 Structured light points from 2D-VCSEL arrays with \(a\) high and \(...\)](#)

[Figure 6.14 TOF detection with AND gate and probability of capturing backgro...](#)

[Figure 6.15 Majestic display of LiDAR transmitter made from 940 nm VCSEL arr...](#)

[Figure 6.16 Individual \(a\) row-, \(b\) column-, and \(c\) zone-wise addressable ...](#)

[Figure 6.17 A car loaded with MEMS-based LiDARs for MMS project.](#)

[Figure 6.18 \(a\) Lumentum FWCM LOSA using 1550 nm DBR laser.\(b\) Far-field...](#)

[Figure 6.19 An example of highly reliable 940 nm VCSEL \(a\) bare and \(b\) pack...](#)

[Figure 6.20 An infotainment system in the cockpit of an AV.](#)

[Figure 6.21 Historical evolution of serial bus technologies.](#)

## Chapter 7

[Figure 7.1 Output beam characteristics of VCSEL, LED, and EELs.](#)

[Figure 7.2 Coherence length of an illuminator as a function of the spectral ...](#)

[Figure 7.3 Relative optical emission spectrum of LEDs, EELs, and VCSELs at –...](#)

[Figure 7.4 Components of a VCSEL-based optical mouse \[12\].](#)

[Figure 7.5 VCSEL-based infrared flashlight available on \[www.alibaba.com\]\(http://www.alibaba.com\)](#)

[Figure 7.6 Infrared night vision camera with a VCSEL illuminator available o...](#)

[Figure 7.7 Illuminator with 30 W of peak power and capable of direction illu...](#)

[Figure 7.8 Thermal transit time as a function of distance between the emitte...](#)

[Figure 7.9 Illuminator modules produced by Princeton Optronics \(now AMS\) cap...](#)

[Figure 7.10 Night vision images collected with VCSEL illuminators \[6\]. Note ...](#)

[Figure 7.11 Scaling of VCSEL power from a single emitter at 10 mW to systems...](#)

[Figure 7.12 \(a\) A 10 kW heating system with over 3M VCSEL emitters, and \(b\) ...](#)

[Figure 7.13 Map of heating applications and the required BPP and total optic...](#)

[Figure 7.14 Map of heating applications and the required pulsewidth and powe...](#)

[Figure 7.15 \(a\) Difference between flash lamp or carbon filament heaters and...](#)

[Figure 7.16 Map of heating applications and the required pulsewidth and powe...](#)

## Chapter 8

[Figure 8.1 Schematic of InP-, GaSb-, and GaAs-based VCSEL technologies used ...](#)

[Figure 8.2 \(a\) Analogy of a VCSEL to an optical fiber showing multiple trans...](#)

[Figure 8.3 A single-mode VCSEL with a small metal aperture used in laser pri...](#)

[Figure 8.4 \(a\) Cross section of a VCSEL with surface relief etch. \(b\) SEM im...](#)

[Figure 8.5 \(a\) Cross-section schematic of a photonic crystal VCSEL. \(b\) Top-...](#)

[Figure 8.6 \(a\) Orientation of \[100\] GaAs substrate and \(b\) \[111\] GaAs substr...](#)

[Figure 8.7 \(a\) A VCSEL structure grown on a \[311\]B substrate and \(b\) the opt...](#)

[Figure 8.8 \(a\) Top-view image of a VCSEL with a surface grating. \(b\) AFM ima...](#)

[Figure 8.9 Polarization-controlled VCSEL using an HCG.](#)

[Figure 8.10 \(a\) Simplified schematic of a VCSEL with a widely tunable wavele...](#)

[Figure 8.11 \(a\) Simplified schematic of a tunable VCSEL with a cantilever DB...](#)

[Figure 8.12 Evolution of the tuning ratio as a function of time \[22\].](#)

[Figure 8.13 \(a\) Schematic of an LED- and-VCSEL based mouse \[26\]. \(b\) 3D sche...](#)

[Figure 8.14 \(a\) Schematic of self-mixing \[28\]. \(b\) Philips Twin-Eye<sup>™</sup> sensor ...](#)

[Figure 8.15 Optical Encoder. \(a\) Schematic of an optical encoder. \(b\) Chip s...](#)

[Figure 8.16 Schematic of a VCSEL-based laser printing engine.](#)

[Figure 8.17 \(a\) 40 element VCSEL array used in an industrial laser printer, ...](#)

[Figure 8.18 Absorption spectrum and detectivity level of some important gase...](#)

[Figure 8.19 VCSEL wavelengths available for gas sensing form Vertilas \(www.v...](#)

[Figure 8.20 GaSb VCSEL designed to operate in the mid-infrared region.](#)

[Figure 8.21 \(a\) Portion of the atomic spectrum of Cs showing the relevant VC...](#)

[Figure 8.22 \(a\) Schematic of a physics package for a VCSEL-based atomic cloc...](#)

[Figure 8.23 The oscillator module for an atomic clock.](#)

[Figure 8.24 The principle of SS-OCT.](#)

[Figure 8.25 Images of OCT: \(a\) Vasculature and capillaries \(red and yellow\) ...](#)

[Figure 8.26 Cross-sectional image of the eyeball by OCT using VCSEL: \(a\) OCT...](#)

## Chapter 9

[Figure 9.1 VCSEL structures for LW-VCSEL.](#)

[Figure 9.2 \(a\) LW-VCSEL die. \(b\) LW-VCSEL in an LC fiber TOSA. \(c\) Tunable V...](#)

[Figure 9.3 Light field and single-photon emission \[30\].](#)

[Figure 9.4 Concept of quantum encryption \(K. Iga\).](#)

## Chapter 10

[Figure 10.1 Estimated future VCSEL chip markets.](#)

[Figure 10.2 Schematic of past, present, and future VCSEL markets and applica...](#)

## Appendix A

[Figure A.1 Key stages of VCSEL development for mass production.](#)

[Figure A.2 \(a\) A generic top-emitting, oxide-confined VCSEL structure for ma...](#)

[Figure A.3 \(a\) Basic elements in MQW-based active region. \(b\) Example of pho...](#)

[Figure A.4 Structure of \(a\) oxide window \(OW\) and tilted OW at \(b\) node and ...](#)

[Figure A.5 The concepts of thermal conductivity of  \$\text{Al}\_x\text{Ga}\_{1-x}\text{As}\$  systems ...](#)

[Figure A.6 Discretization of device into \(a\) finite difference \(FDM/FDTD\) an...](#)

[Figure A.7 Flowchart of VCSEL device in numerical modeling.](#)

[Figure A.8 Interplay of material properties with strength of simulations for...](#)

[Figure A.9 Schematics of active regions with \(a\)  \$1.0\lambda\$  and \(b\)  \$0.5\lambda\$](#)

[Figure A.10 \(a\) A schematic of surface relief integrated VCSEL. \(b\) A sch...](#)

[Figure A.11 Schematics of \(b\) electrical equivalent, \(a\) dual and shallow ox...](#)

[Figure A.12 \(a\) Concept of  \$n\_{\text{eff}}\$ . \(b\) Phase conditions and experimental varia...](#)

[Figure A.13 \(a\) LIV characteristics of VCSELs with different top heat sink s...](#)

[Figure A.14 Design \(dotted line\) and operation \(continuous line\) PCE charact...](#)

## Appendix B

[Figure B.1 Technologies and materials used for VCSEL growth at various wavel...](#)

[Figure B.2 Materials lattice constant vs bandgap at various wavelengths. App...](#)



[Figure B.3 GaAs epi-wafer share in photonics.](#)

[Figure B.4 Schematics of epitaxial growth in \(a\) MBE and \(b\) MOCVD.](#)

[Figure B.5 Key growth parameters as black-box items.](#)

[Figure B.6 \(a\) Multiple sections and growth temperature relationship in a VC...](#)

[Figure B.7 Flowchart of MOCVD calibrations for a VCSEL structure.](#)

[Figure B.8 Quasi layer structures for \(a\) Al\(x\) composition and \(b\) p- and n...](#)

[Figure B.9 Quasi layer structures for \(a\) p-DBR and \(b\) n-DBR reflectivities...](#)

[Figure B.10 \(a\) PL wavelength map of 6" \(150 mm\) wafer for 940 nm VCSSEL....](#)

[Figure B.11 \(a\) Mini and \(b\) full VCSEL structures to grow in a MOCVD system...](#)

[Figure B.12 SIMS doping profile of p-DBR, AR and n-DBR in a VCSEL structure....](#)

[Figure B.13 PL map of GaN QWs grown on Si 8" \(200 mm\) substrate.](#)

## Appendix C

[Figure C.1 \(a\) Cross-sectional image of HEMT.\(b\) Cross-sectional image o...](#)

[Figure C.2 \(a\) Top anode-bottom cathode \(TB\), and \(b\) top anode-top cathode ...](#)

[Figure C.3 \(a\) DOE and lot steps and \(b\) process and product oriented steps ...](#)

[Figure C.4 Schematic of visual inspection patterns/contours for \(a\) datacom ...](#)

[Figure C.5 Schematic generic process flow of high-speed \(datacom\) top-emitti...](#)

[Figure C.6 Sequence of process flow for \(a\) top anode-bottom cathode \(TB\), a...](#)

[Figure C.7 Schematic generic process flow of high-power \(3D sensing and imag...](#)

[Figure C.8 Key process conditions for VCSEL manufacturing.](#)

[Figure C.9 Example of Six Sigma methodology used in parameter analysis.](#)

[Figure C.10 Wafer probe \(a\) power and \(b\) wavelength maps for a fully proces...](#)

## Appendix D

[Figure D.1 Schematic of a VCSEL manufacturing process showing test aggregati...](#)

[Figure D.2 Schematic of VCSEL testing stages.](#)

[Figure D.3 \(a\) Measured VCSEL reflectance spectrum on wafer immediately afte...](#)

[Figure D.4 VCSEL oxide aperture imaged with different center wavelengths sho...](#)

[Figure D.5 VCSEL oxide aperture measurement interpolated onto a 150 mm diame...](#)

[Figure D.6 \(a\) Variation of VCSEL threshold current and \(b\) slope efficiency...](#)

[Figure D.7 Wafer maps showing the variation in DC-measured parameters on a 1...](#)

- wafer-bonding [191](#)
- wafer-fab (processing) specifications [57](#), [58](#)
- wafer fabrication [191](#)
  - data [247](#)–248
- wafer level test [248](#)–252
- wafer level probing (WLP) [237](#)
- wafer level testing [245](#)
  - package level validation [252](#)
  - performance test [248](#)–252
  - post-epitaxial characterization [245](#)–246
- wafer probe measurements [243](#)–244
- wafer process engineering [235](#)
  - back-end processing [239](#)–240
  - design of experiment (DOE) [237](#)–243
  - front-end processing [237](#)–239
  - generic process flows [240](#)–241
  - photomask design [236](#)–237
  - process configurations [236](#)
  - quality gates [243](#)
  - summary and conditions [242](#)–243
  - wafer probe measurement [243](#)–244
- wafer process traveler (WPT) [240](#)
- wafer-to-wafer (WTW) [231](#)
- wafer tracking systems (WTS) [240](#)
- wall plug efficiency [113](#)–114, [250](#)

wavelength division multiplexing (WDM) [43](#), [84](#), [174](#)  
wavelength tuning [174](#)–175  
wavelength uniformity [65](#), [115](#)  
wear-out failures [255](#)  
wear-out reliability [267](#)  
wet oxidation process [112](#)  
wet thermal oxidation [60](#), [238](#)–239  
wide area network (WAN) [75](#)  
within-wafer (WIW) [231](#)

## **y**

yield improvement [65](#)  
yield optimization [65](#)

# THE COMSOC GUIDES TO COMMUNICATIONS TECHNOLOGIES

---

Nim K. Cheung, Senior Editor  
Richard Lau, Associate Editor

---

*The ComSoc Guide to Next Generation Optical Transport:  
SDH/SONET/OTN*  
Huub van Helvoort

*The ComSoc Guide to Managing Telecommunications  
Projects*  
Celia Desmond

*WiMAX Technology and Network Evolution*  
Kamran Etemad and Ming-Yee Lai

*An Introduction to Network Modeling and Simulation for  
the Practicing Engineer*  
Jack Burbank, William Kasch, and Jon Ward

*The ComSoc Guide to Passive Optical Networks: Enhancing  
the Last Mile Access*  
Stephen Weinstein, Yuanqiu Luo, and Ting Wang

*Digital Terrestrial Television Broadcasting: Technology and  
System*  
Jian Song, Zhixing Yang, and Jun Wang

*TV White Space: The First Step Towards Better Utilization  
of Frequency Spectrum*  
Ser Wah Oh, Yugang Ma, Edward Peh, and Ming-Hung Tao

*Digital Services in the 21st Century: A Strategic and  
Business Perspective*  
Antonio Sanchez and Belen Carro

*Toward 6G: A New Era of Convergence*

Amin Ebrahimzadeh and Martin Maier

*VCSEL Industry: Communication and Sensing*

Babu Dayal Padullaparthi, Jim A. Tatum and Kenichi Iga