

Chapter 1

VCSELs: A Research Review

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Abstract This chapter attempts to briefly review the research history of vertical-cavity surface-emitting lasers (VCSELs). Based on the contents of previous monographs on VCSELs written in English, we motivate the selection of topics in the present book and give an introduction to the individual chapters. Moreover, we mention some other research that is not covered in a dedicated chapter in order to provide the readers with even deeper insights into VCSEL research. Future directions and opportunities are also indicated.

1.1 Research History Reflected in VCSEL Books

VCSEL research started with the suggestion of this novel type of semiconductor laser by Prof. Kenichi Iga in the year 1977 and in particular with the first publication in Dec. 1979 [1]. Even before that, in 1965 Ivars Melngailis published a remarkable paper [2] reporting longitudinal lasing operation at about $5.2\text{ }\mu\text{m}$ wavelength in a $220\text{ }\mu\text{m}$ long cavity made from n^+pp^+ -doped InSb. The surfaces were polished and a Ag–Au contact was evaporated on the p^+ -side. At a temperature of about 10 K, current pulses with a duration of 50 ns and an amplitude of at least 20 A (corresponding to a current density of 60 kA/cm^2) were injected parallel to the direction of emission. An external longitudinal magnetic field was needed for focusing. Interestingly, the author already lists a number of advantages inherent to such a structure: Array formation, coherent emission over large areas with associated small beam divergence, and large output powers, all of which we know from VCSELs today.

The importance of VCSELs is reflected in the fact that they have the second largest production volume among all types of semiconductor lasers today—only exceeded by

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Fabry–Pérot-type edge-emitting lasers for use in optical disk drives for data storage. They are the most versatile laser diode, have enormous market growth potential, and will most probably soon become number one. Thus by now we are faced with a huge number of publications on VCSELs. In addition to research papers and review articles there are several books with an exclusive focus on VCSELs [3–8], where two of them were written by single authors and four are edited multi-author volumes. About nine years have passed since the last book was produced. The contribution of the present book to the field can be best appreciated by browsing the contents of its predecessors.¹

A book by G.A. Evans and J.M. Hammer from the year 1993 [9] already contains a chapter on VCSELs and arrays, whereas its main purpose was to present the progress with horizontal-cavity lasers and two-dimensional arrays in which surface emission is achieved with grating couplers or integrated beam deflectors. In their chapter, K. Iga and F. Koyama describe the many advantages of VCSELs and the early research progress. Expected performances are analyzed theoretically and experimental results are summarized both in the InGaAsP–InP and AlGaAs–GaAs material systems. At that time, continuous-wave room-temperature lasing and sub-mA threshold currents had already been achieved with GaAs-based devices.

In 1995, T.E. Sale presented a comprehensive book [3] as an extended version of his own Ph.D. Thesis on VCSELs [10]. Distributed Bragg reflectors (DBRs) are described in some detail, including the challenge to achieve low ohmic resistances. An entire chapter deals with gain calculations for compressively strained InGaAs–GaAs quantum wells (QWs) which became very popular as active region since J. Jewell demonstrated first full-monolithic VCSELs with epitaxial DBRs and those QWs in 1989 [11]. Such devices typically have emission wavelengths in the range of 950–1,000 nm. Sale discusses and analyzes own experimental results on devices grown by molecular beam epitaxy (MBE) as well as metal-organic chemical vapor deposition (MOCVD). These lasers had a resonant period gain (RPG) structure with three InGaAs QWs separated by GaAs barriers with half a material wavelength thickness and showed moderate performance. The RPG concept was demonstrated for VCSELs in 1989 [12, 13] but turned out to be inferior to a regular multiple-QW (MQW; mostly three QWs are used) concept with thin barriers. It is interesting to note that somewhat more elaborate RPG structures with a larger number of periods are nowadays applied in optically pumped semiconductor disk lasers, also known as vertical-external-cavity surface-emitting lasers (VECSELs) [14]. VCSEL types considered by Sale use etched mesas and proton implantation for current confinement. The selective oxidation of AlGaAs with close to 100% Al content to produce current apertures of just a few ten nanometers thickness and quasi arbitrary diameter was not yet considered because pioneering demonstrations [15] were done just before publication of the book. Polarization effects in VCSELs find no mention and little attention is given to the dynamic VCSEL properties.

¹ Readers who are not very familiar with VCSELs yet will find it helpful to study also [Chap. 2](#) of this book, where we discuss many of the terms that are mentioned here in much greater detail.

In the same year, T.P. Lee edited a book containing seven chapters [4] which was a reprint of a special issue of the International Journal of High Speed Electronics and Systems. It starts with an overview of InGaAsP–InP VCSELs for 1.3 and 1.55 μm operation. At that time, continuous-wave room-temperature lasing of such devices had not yet been achieved. The preparation of dielectric mirrors for VCSELs is presented next, addressing the difficulties with epitaxial DBR formation especially for long-wavelength devices. The third chapter presents a buried-heterostructure-type antiguided VCSEL targeted for single-mode emission as well as two-dimensional multiple-wavelength VCSEL arrays for wavelength division multiplexing (WDM) applications, which were obtained by tailoring the spatial growth temperature pattern in MBE. The performance of optimized MOCVD-grown proton-implanted 850 nm VCSELs suitable for mass production is reported next. Record performance data were obtained. The devices were applied in a first 32-channel parallel-optical link with 500 Mbit/s individual data rate. The first (and extensive) chapter on red emitting InAlGaP–GaAs VCSELs is also part of this book. The devices already showed continuous-wave room-temperature lasing with remarkable output power and conversion efficiency. Thermal effects in VCSELs are then discussed in great detail and various thermal models are presented. Chapter 7 deals with the reliability of proton-implanted 850 and 980 nm VCSELs. The mean-time-to-failure was then still in the range of 10^5 h. Improvements by about two orders of magnitude were seen in the years after these initial observations.

The book edited by C. Wilmsen, H. Temkin, and L.A. Coldren in 1999 [5] very well reflects in 12 chapters the rapid progress in VCSEL research at that time. It contains comprehensive introduction and design chapters with much emphasis on oxide-confined VCSELs, which had already outperformed the other device types with all key performance parameters. Microcavity effects which are very important for understanding spontaneous emission in resonant-cavity light-emitting diodes (RCLEDs) are treated in detail in another chapter. For the first time, full attention is given to the epitaxy of VCSELs, recognizing the fact that the high crystal quality of epitaxial layers is the indispensable prerequisite of every high-performance semiconductor laser. Likewise, VCSEL fabrication issues are excellently covered in the book. VCSEL polarization effects are also mentioned, however, with a main focus on free-space optical data links with polarization-selective losses. The need for polarization stability is stressed. The authors come to the conclusion ([16], p. 265): “Therefore, we believe that the most promising way of achieving complete polarization stability is to use VCSEL structures with anisotropic gain or integrated polarization-selective reflectors”. We will get back to this statement later. Chapter 7 deals with visible light emitting VCSELs, in particular in the red spectral regime. First optically pumped lasing had been observed from GaN-based VCSEL structures but no electrically pumped devices were then feasible. A chapter on 1.3 and 1.55 μm emission long-wavelength VCSELs showed that these devices were still relatively immature when compared with already commercially available 850 nm devices. Wafer fusion combining AlGaAs-based DBRs with an InGaAsP-based cavity region seemed to be a promising approach. In the book, VCSEL applications are introduced in Chap. 9, followed by three chapters on aspects of optical interconnection. Extended temperature

operation, polarization control through anisotropically etched mesas, WDM arrays, two-dimensional fiber-optic and free-space interconnects, as well as smart pixels through hybrid or monolithic integration of optoelectronic and electronic components are among the topics. A detailed overview of VCSEL-based fiber-optic transceivers is given. Data rates of such modules were mainly in the range of 0.5–1.25 Gbit/s.

Shortly after this, in the year 2000 J. Cheng and N.K. Dutta presented an edited book with a short overview and six chapters [6]. Chapter 1 gives much insight into oxide aperture formation in AlGaAs–GaAs VCSELs, which allows to produce microcavities with very small active areas and associated threshold currents below 100 μ A. It is followed by a review of the technology and performance of such oxide-confined lasers. Chapter 3 investigates proton-implanted 850 nm VCSELs for optical data links in terms of small-signal, noise, and large-signal properties including turn-on delays. The latter topic received some attention at that time because the low threshold currents of VCSELs even seemed to allow bias-free data transmission (see also Sect. 2.5 of this book). A commercial fiber-optic transceiver for 1 Gbit/s data rate is introduced. The concept of a 32-channel, 1 Gbit/s-range parallel-optical interconnect module including receiver and driver electronics as well as packaging is presented next. Chapter 5 treats VCSEL modulation aspects, parallel-optical links, WDM VCSEL and photodetector arrays, optical switching, and reconfigurable and multi-access network scenarios in some detail. Again, data rates range from a few 100 Mbit/s–1 Gbit/s. Finally an overview of 950 nm range micromechanical tunable VCSELs using a movable cantilever is given in the last chapter.

In 2003, S.F. Yu authored a remarkable VCSEL book focusing on modeling aspects [7]. It briefly outlines recent VCSEL developments and the commercial status. Then it covers in much detail the one-dimensional design of VCSEL resonators, the transverse mode characteristics, the polarization properties, the thermal and electrical behavior, the dynamic characteristics, spontaneous emission, as well as nonlinear effects in VCSELs.

Finally, also in 2003 the (to the author's knowledge) last, 12-chapter-long monograph on VCSELs was published [8]. The project was initiated by H. Li who passed away a little later. Kenichi Iga then became the co-editor. The text starts with a historical account and an overview of VCSEL operation in different wavelength regimes. Details of optical gain calculations are presented, followed by the third chapter which explains the operation principles of oxide-confined VCSELs including state-of-the-art static, noise, and dynamic behavior. Digital data transmission over single-mode and multimode fibers is shown up to data rates of 12.5 Gbit/s. Chapter 4 deals with the theory of anisotropic optical gain of QWs grown on non-(001)-oriented substrates. The corresponding experimental VCSEL work is reviewed and polarization stability of lasers is demonstrated. Thus, here the above statement ([16], p. 265) on anisotropic gain in [5] is addressed. VCSEL modeling is represented in two chapters in terms of a static three-dimensional coupled electrical–optical–thermal model and comprehensive dynamic models with high complexity up to a quasi-three-dimensional case. Microcavity oxidized VCSELs and light-emitting diodes are discussed in Chap. 7. The use of quantum dots in the active region is emphasized for improved carrier confinement and for reaching longer wavelengths on GaAs

substrates. Various designs of DBRs for VCSELs and cavity effects including external optical feedback are presented in the next chapter. The problems associated with the realization of 1.3 and 1.55 μm long-wavelength VCSELs in various material systems including dilute nitride GaInNAs–GaAs are summarized in Chap. 9, whereas Chap. 12 focuses on a rather successful approach in InAlGaAs–InP material employing a buried tunnel junction for current confinement. Continuous-wave lasing at elevated temperatures is demonstrated at 1.5 and 1.8 μm wavelengths. Chapter 10 introduces the design of special radiation-tolerant 0.04 and 1.28 Gbit/s VCSEL-based multimode fiber data links in a particle collider environment. The progress in GaN-based blue and near-ultraviolet wavelength vertical-cavity emitters is presented in Chap. 11. A quasi-continuous-wave optically pumped VCSEL at 355 nm and electrically pumped RCLEDs with emission in the range of 410–440 nm wavelength are shown.

1.2 New Developments Motivating This Book

Enormous progress of VCSEL performance and applications has been achieved since the last two VCSEL books have been published in 2003. In what follows we introduce the contents of the present book with respect to the previous work discussed in the preceding section. In a certain sense, this book is related to [8], which was also published by Springer-Verlag. Owing to a largely different selection of subjects it can nevertheless not be considered simply a second edition.

The 18 chapters are arranged into four groups. Entirely new contributions are made to the fields of vectorial three-dimensional optical modeling, single-mode VCSELs, polarization control, polarization dynamics, very-high-speed design, high-power emission, use of high-contrast gratings, GaInNAsSb long-wavelength VCSELs, optical video links, VCSELs for optical mice and sensing, as well as VCSEL-based laser printing.

The first group on “Basic VCSEL Characteristics” contains:

1. This chapter, which shall give a general overview of the field.
2. A text about VCSEL fundamentals outlining laser design principles and (static, noise, and dynamic) operation characteristics of oxide-confined GaAs-based VCSELs in the 850 and 980 nm wavelength regions. It is meant to make the book accessible to a broad range of readers with different technical background.
3. A chapter on three-dimensional modeling of VCSELs, considering coupled optical, electrical, and thermal phenomena. Strong emphasis is put on a vectorial optical model with the ability to handle non-circular geometries which are vital to the performance of, e.g., polarization-stable surface grating VCSELs introduced in Chap. 5.
4. The first book chapter dealing specifically with single-mode VCSELs, reviewing different cavity designs that have been presented in the literature. Transverse single-mode emission has become important in recent years in particular for

optical sensing. Whereas until the year 2004, almost all commercial VCSELs were designed for multimode emission, nowadays single-mode devices have about half the market volume.

The second group is concerned with “Device Technology and Performance”:

5. A chapter on polarization control of VCSELs addresses the fact that the light output polarization is inherently unstable in most types of VCSELs. On the other hand, a stable polarization is required for most optical sensing applications. Different stabilization methods are reviewed. It is shown that monolithic semiconducting surface gratings provide a convenient solution to the polarization problem. Such VCSELs are commercial products today. The use of “integrated polarization-selective reflectors”, as stated above [5] ([16], p. 265) is indeed most promising, whereas anisotropic gain currently is too difficult to incorporate into high-performance VCSEL structures.
6. Another “first” of this book is a chapter devoted to the rich variety of polarization dynamics of VCSELs. The authors provide a very detailed overview of the literature, both from theoretical and experimental points of view and thus contribute to a deeper understanding of the nonlinearities inherent these semiconductor lasers.
7. In recent years, VCSELs have been optimized for high-speed operation at data rates of as much as 40 Gbit/s. This chapter analyzes the modulation bandwidth which is determined by the intrinsic laser response and extrinsic parasitic effects. The state of the art at wavelengths from 850 nm to 1.6 μm is reviewed. Alternative modulation schemes are also considered.
8. Another breakthrough over the past several years is the demonstration and commercialization of high-power, high-efficiency two-dimensional VCSEL arrays, mainly in the 808 and 980 nm spectral domains. This chapter is the first to summarize the progress in this field. The devices feature high reliability, wavelength stability, low-divergence circular output beams, and low-cost manufacturing. They thus enable a number of new applications and have become a strong contender to edge-emitting diode lasers which presently dominate the market.
9. More in the research stage is the fascinating work on high-contrast gratings that have the prospects to replace an entire DBR stack with a single nanostructured layer of semiconductor material. Lithographic control of polarization, transverse mode structure, and emission wavelength is provided. Also wavelength tuning can be much more efficient.

The third group of chapters is concerned with VCSELs showing “From Infrared to Violet Emission”:

10. The first chapter is essentially an update of Chap. 12 in [8]. Long-wavelength VCSELs with buried tunnel junctions show excellent characteristics meanwhile and are commercial products. The chapter discusses InP- and GaSb-based devices for applications in optical communications and gas sensing. Maximum emission wavelengths exceed 2.3 μm .
11. An alternative promising approach to long-wavelength VCSELs is the growth of GaInNAsSb compounds on GaAs substrates. Such research is described in this

chapter. Edge-emitting laser diodes and first monolithic 1500 nm VCSELs are demonstrated.

12. Since the last book chapter was written in [5], a lot of progress has been achieved with red emitting VCSELs. This chapter presents the crystal growth issues in AlGaAs and AlGaInP on GaAs, electrical, optical, thermal, and dynamic laser characteristics as well as optical data transmission over polymer optical fibers. The incorporation of InP quantum dots allows to reach record-low threshold current densities and reduced temperature sensitivity.
13. Compared to the status in [5, 8], the new developments on GaN-based blue and near-ultraviolet emitting VCSELs are even more dramatic. The chapter describes the challenge of DBR formation and different microcavity configurations. First electrically pumped VCSELs emitting continuously at room temperature have been fabricated. Future prospects and emerging applications are discussed.

The final group named “VCSEL Applications” covers single-fiber and parallel-optical data transmission, sensing in optical mice, as well as printing:

14. We start with a very valuable review of the 850 nm VCSEL-based transceiver market for data communications over multimode optical fibers, which has grown tremendously over the last decade.
15. A special application of VCSEL-based transceivers in optical video links is described next. History, current status, and technical issues for mass market rollout are discussed.
16. A comprehensive overview of the advancements in VCSEL-based parallel-optical links is given in this chapter. Commercial and research activities, deployment in large computing systems and test beds, fiber connectorization, reliability, and future applications are all covered extensively.
17. For the first time, VCSEL use in optical computer mice is described in the present book chapter. Comparisons to LEDs as illumination source are made and an advanced interference sensor based on laser self-mixing is introduced. Such sensors employ optoelectronic chips in which VCSELs are monolithically integrated with intra-cavity PIN-type photodiodes. Aspects of mass production are also addressed.
18. Finally, also for the first time a VCSEL book chapter specifically addresses laser printing. Two-dimensional 8×4 VCSEL arrays at 780 nm wavelength enable 2,400 dots per inch resolution, high printing speed, and reduced power consumption. Key technologies for achieving high image quality are pointed out.

1.3 Other Research Not Covered by the Chapters

In this section we briefly list some VCSEL research that is not explicitly mentioned in the individual chapters. Hereby the versatility of this type of laser becomes very apparent. In addition, a few recent references on selected topics of this book are provided.

- In-depth overviews of the *history* of VCSEL research have been compiled by K. Iga [17–19], see also Chap. 1 in [4], Chap. 1 in [8], and (together with F. Koyama) Chap. 3 in [9].
- Particularly rapid progress is currently seen in the field of *high-speed* VCSELs. Complementing Chap. 7 of this book, [20] presents the state of the art as of Dec. 2010. A focus on 980 nm high-speed VCSELs is put in [21].
- *Bidirectional* single-wavelength (no WDM) Gbit/s-rate data transmission over multimode fiber [22–24] (see also the end of Chap. 2 of this book) can lead to cost-effective transceiver solutions for some application areas and thus might be considered for commercialization. For this, VCSELs are monolithically integrated with metal–semiconductor–metal (MSM) or PIN-type photodetectors.
- The *nonlinear dynamics* of VCSELs induced by optical injection, optical feedback, current modulation, and mutual coupling are reviewed in a recent paper [25], supplementing the nonlinear polarization effects described in Chap. 6 of this book.
- A very good overview of advances in *long-wavelength* VCSELs is given in [26]. References are provided for various approaches based on highly strained InGaAs–GaAs QWs, InGaAs quantum dots, GaAsSb QWs, dilute nitride GaInNAs QWs on GaAs, and InAlGaAs–InP QWs. Besides the use of buried tunnel junctions (see Chap. 10 of this book), wafer fusion has led to devices with excellent performance [27]. High-speed modulation at 25 Gbit/s of a 1.1 μm VCSEL at 100°C [28] and at 35 Gbit/s (25°C) and 25 Gbit/s (55°C) of a 1.53 μm device [29] were achieved.
- Multiple-wavelength VCSEL arrays for *WDM applications* have been realized by epitaxial MOCVD growth on patterned substrates. A maximum lasing span of 192 nm [30] and a 110-channel VCSEL array centered at 1,226 nm with a thermally tuned wavelength spacing of 0.1 nm [31] have been reported. A novel hollow-waveguide multiplexer [32] might enable the coupling of such arrays to multimode fibers in a very compact way.
- Impressive results on micromechanically actuated 1.55 μm VCSELs with larger than 100 nm *tuning range* have recently been obtained [33] (see also Chaps. 9 and 10 of this book).
- *Athermal operation* with a tuning coefficient as small as 0.002 nm/K has been achieved with a cantilever-type 840 nm-range VCSEL [34, 35].
- Up-to-date insights into *red emitting* VCSELs from an industrial point of view are provided in [36].
- *Quantum dot* VCSELs have been developed and show very good operation characteristics [37, 38]. However, at present there is no compelling advantage of these devices that would lure an established VCSEL company to incorporate such active regions into their designs.
- *Photonic crystals* have been much explored for use in VCSELs [39], with an initial focus on increasing the single-mode output power (see also Chap. 4 of this book). Coherently coupled arrays with low beam divergence are among the more recent prospects [40].
- A self-consistent *VCSEL model* is presented in [41] and applied to various resonator configurations and wavelength regimes, with much attention paid to single-mode operation.

- As reviewed in [42], the integration with *micro-optical elements* provides many opportunities for the beam control of VCSELs.
- Beam control is also achieved particularly well with *VECSELs* [14]. For electrically pumped devices, up to now the laser community was not able to rival the amazing work done by Novalux a few years ago (reviewed in [43, 44]). More recent results on frequency doubling to the blue spectral region [45] are by far inferior to tens of milliwatts at 490 nm or hundreds of milliwatts continuous-wave Gaussian mode emission at 980 nm that were reported by the company. Anyhow, manufacturing the extended cavity mirror at the back side of the substrate has enabled to achieve fundamental mode powers of up to 15 mW [46]. VECSELs at 850 nm with a short external cavity length of only 25 μm were fabricated with the goal of obtaining higher output power and reduced emission linewidth [47]. Moreover, electrically pumped VECSELs are also considered for particle sensing in microfluidics [48].
- *All-optical signal processing*—if accomplished in a viable way—is of much interest for optical telecommunications. Contributions to this field have also been made with VCSEL-type devices. Among these are an *optical inverter* based on transverse mode switching (induced by mode locking) in a two-mode VCSEL [49], a *polarization converter* to a fixed polarization state based on similar principles [50], and an optical *nonlinear phase-shifter* [51] (enabling both positive and negative shifts to compensate laser chirp and fiber nonlinearities, respectively [52]) based on a VCSEL structure with a saturable absorber.
- An extensive review of *cavity soliton* effects in broad-area VCSELs is provided in [53]. Applications might be found in the fields of all-optical information processing and VCSEL characterization.
- *Slow-light* effects have been exploited in a Bragg waveguide as part of a 1.5 μm VCSEL structure to achieve efficient electro-absorption in an only 20 μm long device [54].
- The paper [55] reports a metal nano-apertured GaAs-based VCSEL in which a 100 nm diameter Au nanoparticle leads a *plasmon enhancement* of the optical field. Potential applications are in sub-wavelength optical near-field probing. Related research in [56] has even shown field enhancements in a 970 nm VCSEL suitable for *near-field optical recording*.
- Recent progress with metal-coated *nanocavity* pillar-type surface-emitting lasers is summarized in [57].
- Concepts of *spin-controlled* VCSELs are discussed in [58]. Those devices could enable much faster dynamics. Both optical excitation and electrical spin injection are considered.
- VCSELs are also being investigated as light sources in *optical tweezers* and traps used in biophotonics. In particular there are opportunities for the integration with *microfluidic chips* [59].

1.4 The Future

As is well known, predictions are difficult to make, especially when they concern the future.² It is much easier to check to which degree previous predictions have materialized.

Interestingly, from the beginning, optical data storage has been listed as a future VCSEL application. A miniaturized 780nm VCSEL-based compact disk (CD) pickup head had been developed in Korea [60]. However, the available single-mode powers even nowadays are too small for data writing which has been an essential feature of every optical disk drive for a long time. Thus in reality the VCSEL never entered the optical storage market. Near-field optical recording as mentioned in the previous section might be a new option but right now it seems to be more likely that optical disks will altogether be replaced by solid-state silicon-based memory technologies in future.

Also VCSEL-based displays have been prophesied again and again. Optical displays today are extremely advanced but visible (i.e., visible radiation emitting) VCSELs are not. Their brightness is simply insufficient for projection displays. Pico projectors for mobile devices are equipped with high-power LEDs [61]. For larger-scale, laser-based projection, VECSELs are better candidates [14].

As a third example, in the past there was much speculation about optical computing. For instance, two-dimensional image processing with VCSEL arrays was praised and some nice demonstrations were made. Many papers have also been published on all-optical logic. A striking underestimation of the creativity and capabilities of the silicon electronics industry was usually behind such optimism.

Optical computing is dead but optics in computing is alive. In particular this is true for supercomputers. As detailed in [Chap. 16](#) of this book, e.g., more than five million VCSELs transmit data in a fully configured modern IBM high-performance computing system, mostly in parallel-optical links using multimode fiber ribbon cable. This is where VCSELs are really good at. The penetration further down into the system, i.e., from the rack-to-rack level to the backplane and printed-circuit board levels and to the inter-chip level is much harder. Research in this direction is ongoing for at least two decades [62, 63]. Current projections say that optical interconnects are much needed at these levels [64]. A huge number of devices would be required, i.e., annual VCSEL production volumes would exceed 10^9 (one billion) units. On the other hand, the price pressure is enormous. The price of an 850nm VCSEL now approaches 0.10 US dollars for high-volumes, but it is an open question if a one-cent VCSEL can be made. VCSEL production currently moves from 3-inch toward 4-inch diameter GaAs substrates. Further improving the yield and decreasing the footprint of the chips are essential issues.

Concerning VCSEL use in mainstream computing, in the year 2010 there was much enthusiasm about *Light Peak*, a converged I/O (input/output) technology demonstrated by Intel in Sept. 2009 and at that time supported by the big

² In similar form, this quote can be attributed to Mark Twain, Winston Churchill, Karl Valentin, and perhaps others.

players Sony, Nokia, and Apple. It was designed to work with 850 nm VCSELs and multimode fiber with data rates of 10 Gbit/s initially and up to 100 Gbit/s later. Target devices were PCs (personal computers), handhelds, workstations, consumer electronics, and so on. Through the economies of scale, Light Peak was expected to change the cost structures for optical links. A multi-hundred-million annual VCSEL market was predicted. First devices were said to be available to the public even in late 2010. Just a few months later, searching for Light Peak resulted in finding *Thunderbolt*, an *electrical* solution at 20 Gbit/s, limited to 3 m cable length. As often before, optics could not meet the cost target. Moreover, the optical connectors were found not to be consumer-compliant. This is a very good example for the usual fight of “copper versus optical”. An optical physical layer for Thunderbolt is still planned, but predictions are difficult to make. . . A so-called active optical cable (AOC) would be the most viable implementation. Such a cable has electrical connectors and the electrical-to-optical-to-electrical conversions and the optical transmission over fiber are entirely hidden from the user. In general, a growing importance of AOCs for VCSEL-based optical links can be expected. More information on AOCs is provided in [Chap. 16](#) of this book.

With respect to optical technologies at the intra-chip level, there is enormous activity in the silicon photonics community for several years. Still the goal is to overcome the electrical interconnection bottleneck that is on the horizon. It is difficult to see where a regular VCSEL would find a place here. Most scenarios envisage external (i.e., outside of the chip) continuous-wave emitting WDM light sources. Wavelengths should be at least 1.2 μm to avoid absorption in Si, and high optical power would probably be needed to compensate the propagation and splitting losses in the optical circuits.

Having mentioned long wavelengths just before, we may ask why we are still waiting for the real breakthrough of long-wavelength VCSELs on the market. As written in [Chaps. 10](#) and [11](#) of this book, very good devices are commercially available. On the other hand, volumes are comparatively low. First of all, it is hard to beat the price of a Fabry–Pérot edge-emitting laser produced in a highly automated laser factory. Then, there has been a strong cost reduction for distributed feedback (DFB) laser diodes in recent years. At this point it needs to be mentioned that the most successful long-wavelength VCSEL structures to date, e.g., based on buried tunnel junctions or wafer fusion, are more difficult to fabricate than short-wavelength 850 or 980 nm devices. Yield is thus also an issue. Moreover, optical telecommunication specifications are very demanding. Finally, if all telecom specifications are met, lower power consumption might indeed become the winning argument for long-wavelength VCSELs. This is what VCSEL lovers are hoping for.

Gas sensing is a good market for long-wavelength VCSELs with much opportunity for growth. Here much higher prices are paid per device compared to optical interconnects. The wide adoption of VCSEL-based gas sensors will be strongly correlated with the cost of such units.

Talking about optical sensing, the VCSEL mouse is a great invention. [Chapter 17](#) explains that, compared to previous generations of computer mice, it has better resolution, higher speed and acceleration, enhanced surface compatibility (i.e., works

on almost all surfaces), and also lower power consumption, which is important for cordless mice to improve battery lifetime. However, unfortunately, for regular office applications (in contrast to, e.g., computer-aided design work or advanced gaming), LED mice do a fine job. When you buy a computer and it comes with a mouse, it is most probably an LED mouse. Of course, if you have to purchase a mouse yourself, the VCSEL community expects you to honor the achievements of the pioneers in the field by *not* buying an LED mouse (even if you would save a dollar)—and not a mechanical mouse.

With regard to other consumer products, it remains to be seen if, e.g., VCSELs become part of mobile phones, which would be a huge market. Data transmission between display and processing unit, optical finger navigation,³ or proximity sensing are among the opportunities.

In addition to position sensing in general, not only in computer mice (or, more general, computer input devices) but also in various kinds of encoders, VCSELs are likewise well suited for contactless distance and velocity measurements for a wide range of applications. This is described in [Chap. 17](#) of this book. Much growth can be expected in this field.

With the advent of high-efficiency, high-power VCSELs, as described in [Chap. 8](#) of this book, a whole new range of applications are now in within reach and should be exploited. Tailored illumination [\[65\]](#) is just one of them.

About 8 years ago there was much hope to bring 850 nm VCSELs into automotive systems. The use of these lasers (instead of red emitting LEDs) in combination with 200 μm core diameter polymer-clad silica (PCS) fibers in data buses was strongly promoted by the car manufacturer Daimler [\[66\]](#) (see also [\[22\]](#) for a bidirectional transmission solution using this medium). Suitable high-temperature-compatible VCSELs had been developed for that purpose. Nevertheless the next-generation data bus at 150 Mbit/s data rate was still LED-based [\[67\]](#). Data rates in cars will continue to increase and the VCSEL will thus remain on the agenda—another arena for “copper versus optical”. Apart from optical networks, potential high-volume opportunities for VCSELs in automotive systems are LIDAR (light detection and ranging) units as well as speed-over-ground and lane-keeping sensors. None of them, however, is close to market introduction.

Getting back to data storage from above, in fact the magnetic storage density has experienced tremendous growth over the last decades. However, the current approach is soon reaching its superparamagnetic limit where the magnetic state becomes thermally unstable. Heat-assisted magnetic recording (HAMR) is a future technique for hard disk drives proposed by Seagate with which the recording density can potentially be increased by two orders of magnitude [\[68, 69\]](#). It relies on the effect that local heating above the Curie point lowers the resistance to magnetic polarization. In practice this requires a temperature increase by more than 300 K in about 1 ns for a spot size of, e.g., 25 nm. A possible approach is to use near-field

³ Based on similar physical principles as the laser mouse, optical finger navigation in mobile phones is gaining acceptance and might find widespread use in electronic equipment like music players, digital cameras, or keyboards.

optics with surface plasmon resonance. Initial experiments have been carried out with 830 nm edge-emitting lasers at power levels of 80 mW and 35 μm incident spot size. If we would find a VCSEL-based solution, we had a new, gigantic market. Just imagine a VCSEL in every future magnetic writing head!

Other remarks about future opportunities for VCSELs in addition to “it’s all about cost” are made by the authors of the individual chapters of this book. I would like to close this section by reminding the readers of the observation that the wisest prophets make sure of the event first.⁴

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⁴ This quote is attributed to Horace Walpole.

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