IGA Kenichi "Invention of a Surface Emitting Laser and Its Realization"
伊賀健一(1940-) 「面発光レーザーの発明と実現」

1. Bio of IGA Kenichi

IGA Kenichi

Born in Hiroshima Prefecture in 1940. Graduated from Hiroshima University High School in 1959. Graduated from Tokyo Institute of Technology in 1963 and completed the doctoral course at the same graduate school in 1968 (Doctor of Engineering). From the same year, he worked as a research associate at Tokyo Institute of Technology and became an associate professor in 1974 and a professor in 1984. Engaged in research on surface emitting lasers and microoptics. 1979-1980 Visiting Staff of Bell Labs. 2001 Professor Emeritus of Tokyo Institute of Technology. 2001-2007 Director of Japan Society for the Promotion of Science and 2007-2012 President of Tokyo Institute of Technology. Honorary Professor of National Chiao Tung University.

Fellow of the Japan Society of Applied Physics (JSAP) / Representative of the Microoptics Group. Honorary member, Fellow, and 2002-president of the Institute of Electronics, Information and Communication Engineers (IEICE), and Fellow of Laser Society. Life Fellow of IEEE, Fellow of Optica, Foreign Member of NAE of USA.

Received IEICE Achievement Award, JSAP Achievement Award, Medal with Purple Ribbon, Toray Science Award, Ichimura Prize in Science for Outstanding Achievement, Asahi Prize, Fujiwara Award, C & C Prize, 2013 Franklin Award (Gold Medal and Bower Award and Prize in Science), 2018 The Order of Sacred Treasure, Gold and Silver Star, JSAP Optical Engineering Award (Takano Award), 2021 IEEE Edison Medal, 2021 Honorary citizen of Machida City.

２． Abstract

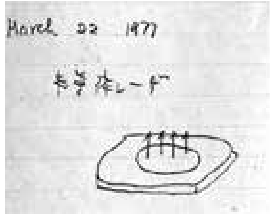

Fig. 1 A sketch of a VCSEL idea in 1977.

Kenichi Iga’s achievement can be summarized as the invention of a **vertical cavity surface emitting laser (VCSEL)** and its pioneering research toward engineering to open up new photonics field. His effort is not only limited to technical issues, but also extended to the contribution to the world-wide promotion of VCSELs by writing a lot of books and by organizing international conferences.

Iga suggested the idea of surface emitting laser in 1977. Since his first demonstration of a VCSEL in 1979 at Tokyo Institute of Technology, he has established the fundamental technical and theoretical bases for the lasers and inspired much research in the field and has significantly impacted to opto-electronics area including high-speed data communications. Today it is said that, approximately 75% of all data-communication laser pieces sold are by VCSELs mostly for Gigabit Ethermet, fiber channels, and high-speed optical interconnects. In addition, various applications of VCSELs are going on, that include digital data transfer, high-resolution full color laser printers, optical free space communications, optical mouse, 3D face recognition in smart phone, LiDARs, and so on. It is reported that the world market of > 9 B$ at the year of 2020.

3. Research Achievement on Surface Emitting Lasers

3.1 Invention of a surface emitting laser

Iga conceived of a surface-emitting laser on March 22, 1977. His sketch of the idea is shown in Fig. 1. In contrast to the conventional Fabry-Perot edge-emitting semiconductor lasers, this invention consists of a laser cavity vertical to the wafer surface on which many layers are monolithically grown, including an active layer. Soon later, it began to be called the vertical-cavity surface-emitting laser (VCSEL).

The essential contents include the features of the VCSEL concept, the motivation behind the invention, a breakthrough for the realization, and several technologies that became essential for later devices such as quantum wells, semiconductor Bragg reflectors, and AlAs oxidation technique. He initiated the first successful continuous tuning of lasing wavelength by a mechanical method, which became the scheme of MEMS-tuned VCSEL in later years.

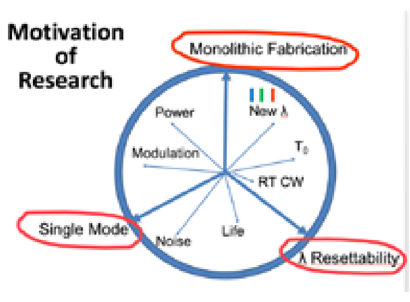

Fig. 2 The motivation of research leading to VCSEL invention

3.2 Motivation of invention

3.2.1 Conception

The motivations are illustrated in Fig. 2. During the research on semiconductor lasers by his group starting in 1970 at Tokyo Institute of Technology, he was dissatisfied with the conventional semiconductor lasers from the viewpoint of their fabrication and device characterization. The cavity of the conventional semiconductor lasers was fabricated by cleaving wafers, i.e., by cutting an epitaxially grown wafer along a specific crystal plane (100) with the cavity length of approximately a few hundred microns. In the initial stage of production, the cleaving process was carried out using a kind of surgical knife. It was far from mass production, for example, on the order of 10^9 pieces. As another disadvantage originating from the edge-emitting laser structure, device characterization was possible only after the cleaving process was completed, which made device characterization difficult, including the initial quality test on a wafer scale. This feature had also led to the difficulty in realizing two-dimensional semiconductor laser arrays.

Another consideration was how to realize a single-mode laser, that is, the lateral mode and longitudinal mode. Around 1976, he was interested in a short-cavity semiconductor laser and the possibility of maintaining in dynamic single-mode capability by making a short cavity to widen the free spectrum range (FSR). One of the conclusions made on the basis of computer simulation was that we must make the cavity length smaller than 50 µm.

The third problem was how to control the lasing frequency, namely, how to guarantee the reproducibility of lasing frequency. It is almost impossible to precisely control the oscillation frequency of Fabry-Perot edge-emitting lasers lasing under the multimode condition. Also, the cutting position that determines the cavity length may have an error much larger than wavelength. Some grating filters are used to control oscillation frequency, as in distributed feedback (DFB) and distributed Bragg reflector (DBR) lasers. Since resonant frequency is determined by the grating period, the precise frequency should be dependent on waveguide structures that affect the equivalent index.

After critical consideration to solve the aforementioned issues associated with conventional edge-emitting lasers, he reached the conclusion that the laser cavity should be made vertical, not transverse to the semiconductor wafer surface. He thought that the cavity can be made of semiconductor layers and/or dielectric layers, which can be fabricated by semiconductor processes, not by manual cleaving processes.

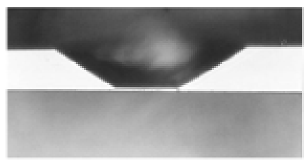

Fig. 3 Cross section of a 10 µm cavity

3.2.2 Stripe lasers and VCSELs

The difference between stripe lasers and VCSEL for obtaining single-mode operation is shown below. In the case of a small stripe width on the order of microns, the lateral mode can be single as indicated in the figure by an ellipse. On the other hand, resonance occurs at multiple frequencies. To realize single-frequency operation, some filtering structure is required, such as distributed Bragg reflectors.

Iga considered the case of VCSEL shown in Fig.1. For small-diameter VCSELs, the lateral mode is single and the longitudinal mode can also be single, since the free spectral range (FSR) is large owing to small cavity length.

3.3 Early stage of research

3.3.1 Initial device

On the basis of the initial idea of the surface-emitting semiconductor laser, he pursued analytical and experimental research on this new structure. The concept and the first experimental results on spontaneous vertical light emission from a GaInAsP/InP device were presented at the 25th Spring Meeting of Applied Physics Societies, Japan, in March 1978. The second report was presented at the 26th Fall Meeting of Applied Physics Societies, Japan, in November 1978. The paper consisted of results from the analysis of mirror reflectivity for vertical cavity laser and experiments on vertical cavity formation with a convex mirror surface [9)].

In 1979, his group demonstrated the lasing operation of a GaInAsP/InP VCSEL under the pulsed injection current condition at 77 K. This is the first demonstration of current injected VCSEL lasing oscillation and showed the possibility of VCSEL as a practical-semiconductor laser. Subsequently, he and his group have been continuously conducting elaborate research and development of VCSELs and have achieved many basic results. Many papers that have contributed to the growth of VCSEL devices and related applications have been published.

3.3.2 Achievement for device realization

The primary breakthrough was the fabrication of a 10 µm cavity VCSEL that demonstrated a clear VCSEL mode even at 77 K, in 1982; i.e., single-mode, circular beam, and linear polarization. In Fig. 3, we show an image of a cleaved cross section. The central portion corresponds to a laser cavity as narrow as 10 µm.

A pulsed threshold current as small as 6 mA was reported at room-temperature in a AlGaAs/GaAs VCSEL with a cavity length of 7 µm. The first room-temperature continuous wave (CW) operation was achieved in 1988 by Koyama and I using a GaAs system as shown in Fig. 4. This experiment demonstrated the possibility of VCSEL as an engineered semiconductor laser. We employed MOCVD crystal growth and multilayer mirror formation techniques to lower the threshold current density. We also achieved a near-room-temperature CW in a 1,300 nm VCSEL in 1993.

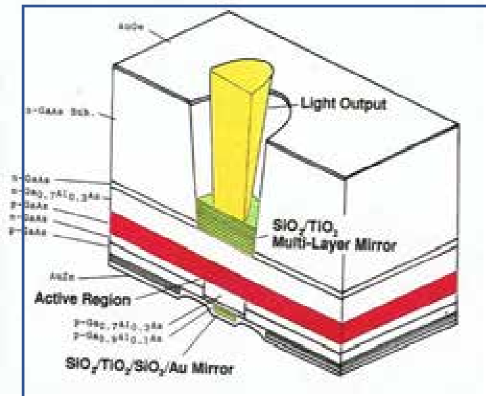

Fig. 4 VCSEL that achieved the first room-temperature CW operation

3.3.3 Reduction in threshold current of early VCSELs

A short cavity easily leads to a small laser cavity volume, which drastically lowers the VCSEL threshold current if sufficient photon confinement in the cavity is achieved. Low threshold currents are preferable for many applications in ecosystems. A strong research and development competition ensued in a worldwide scale from the end of the 1980s to the 1990s, where he and his group were almost always of the forefront. Aa described before, a pulsed threshold current as small as 6 mA was reported at room-temperature in a AlGaAs/GaAs VCSEL with a cavity length of 7 μm [12]. This was the first time that a threshold current lower than 10 mA was realized in VCSELs at that time. The injection current was confined in the active region of 6 μm diameter. Single-longitudinal mode oscillation was achieved up to 6.7 times the threshold current.

3.3.4 Demonstration of VCSELs of various materials

Iga's group tried to find the possibility of fabricating VCSELs using various materials. Since 1977, basic studies have been carried out by us on semiconductor crystal growth, crystal evaluation, and applications in various emission wavelengths. The principal results are summarized as follows.

*AlGaAs/GaAs: Its first CW operation at 77 K was in 1986 and reported in 1987 The emission wavelength was 884 nm. The first CW operation at room-temperature was in 1988[12),13)]. Its emission wavelength was 894 nm.

* GaInAsP/InP: His group successfully demonstrated the first lasing operation of VCSELs using GaInAsP/InP material in 1979[10)]. The emission wavelength was 1,180 nm at 77 K under pulsed current injection. The first CW operation at room-temperature in 1993 [14)]. The emission wavelength was 1,374 nm.

*GaInAsN/GaAs: Long-wavelength lasers were realized on the GaAs substrates using the GaInAsN system lattice-matched to GaAs [16),17)].

*InGaAs/AlGaAs: The record low CW threshold current of 70 μA at room-temperature was realized in 1995. The emission wavelength was 989 nm [18)].

*GaInN/GaN: A design was considered for blue-emitting VCSELs. Also, crystal growth by MOCVD was performed. As described in the list above, we have been contributing to the expansion of the emission wavelength region of VCSELs from long to near-infrared wavelengths, which has been effective for finding new VCSEL applications. Later on, red emitting and blue-emitting VCSELs were investigated by many organizations to develop applications in visible regions.

3.4 Technologies introduced into VCSELs

As a forerunner of VCSEL research and development, Iga's group introduced new technologies into VCSELs for the first time in the world. Those included quantum well structures as the active region and semiconductor multilayered distributed Bragg reflectors as laser cavity mirrors. An external movable mirror was introduced for wavelength tuning.

3.4.1 Quantum well structure

The threshold current of surface-emitting lasers with a multi-quantum well (MQW) active region was theoretically estimated by Uenohara et al. On the basis of the results, we introduced the MQW structure into the active region of surface-emitting lasers. A GaAlAs/GaAs MQW surface-emitting laser was grown by MOCVD and its first lasing operation was demonstrated by current injection at 77 K the under pulsed condition. After these pioneering trials, many researchers have actively utilized the MQW structure as the active gain material to reduce the threshold current of VCSELs.

3.4.2 Semiconductor multilayered Bragg reflector

We first introduced a semiconductor multi-layered Bragg reflector as one of the mirrors for VCSEL[25)]. This VCSEL cavity consisted of a pair of on n-$Al_{0.1}Ga_{0.9}As$/AlAs multilayer Bragg reflector and a Au/SiO_2 mirror. With this structure, besides the satisfactory high reflectivity achieved, manual processes are not necessary for fabricating a laser cavity. Soon after this achievement, a VCSEL was realized, whose principal components fully consisted of semiconductors. Both upper and lower mirrors of the VCSEL were formed with semiconductor multilayered Bragg reflectors. A drastic improvement in VCSEL fabrication productivity was accomplished. The semiconductor DBR is one important feature that Iga wanted to improve by eliminating the cleaving process in the formation of the cavity in conventional edge-emitting lasers. The semiconductor multilayered distributed Bragg reflector is utilized in almost all VCSELs at the time of 2021.

3.4.3 Movable mirror for frequency tuning

The VCSEL can emit light withpure single wavelength characteristics owing to its short cavity length. Since the exact emission wavelength is defined by the effective cavity length, continuous wavelength tuning is possible by changing the cavity length.
To achieve a wide range of tunability, a mechanical tuning method was experimentally demonstrated by us with an InGaAsP/InP VCSEL. One of the mirrors was replaced with a movable external mirror. It was driven mechanically by pushing a tuning rod, as shown in Fig. 6.

The wavelength was changed continuously over 40-86Å at 77 K without any mode hopping. This indicated clearly the possibility of continuous wavelength tuning in VCSELs, which later attracted interest for various applications. Frequency tunable VCSELs are now becoming important light sources for spectroscopic sensing and Datacom with wavelength division multiplexing. Since around 2019, tunable VCSELs have been used for a ranging sensor in combination with a light beam deflector where the emitting beam angle depends on the wavelength.

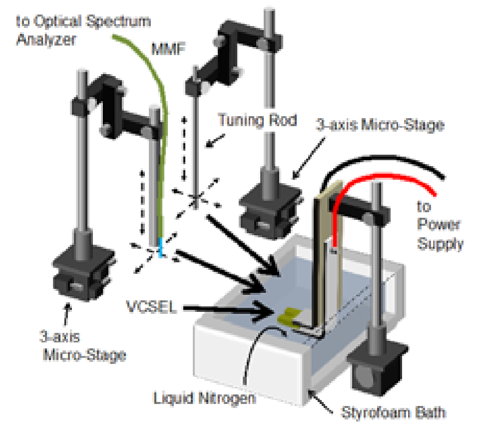

Fig. 5 External-mirror-driven frequency tuning of VCSEL.
(Drawn by N. Yokouchi)

3.4.3 Polarization control

A surface-emitting laser normally oscillates with linearly polarized waves, but it may become unstable at high output and must be stabilized. It would be good if there was a difference in the optical loss and optical gain due to polarization. Iga's group tried to control with an inclined substrate. In the VCSEL using the (311) substrate by Nobuhiko Nishiyama et al., extremely stable polarization was achieved.

3.5 VCSEL applications in applied systems

3.5.1 Advantages of VCSELs and possible applications

With the progress of the device performance, the features of VCSELs, such as hiA surface-emitting laser normally oscillates with linearly polarized waves, but it may become unstable at high output and must be stabilized. It would be good if there was a difference in the optical loss and optical gain due to polarization, but in the laboratory, we tried control with an inclined substrate. In the VCSEL production using the (311) substrate by Nobuhiko Nishiyama et al., Extremely stable polarization was achieved.gh productivity, high efficiency, low power consumption, a circular beam, a single frequency, and a two-dimensional array, are becoming well recognized by the society and their application areas have been expanding explosively since the mid 1990s. The application areas started from data communications followed by those of sensors, printers, and computer mouse pointers until the mid-2010s. After that, although the market size of data communication and sensing has grown steadily and is expected to grow further and occupy the main body of VCSEL and related markets, VCSELs are finding applications in new areas such as infrared illumination, pumping, and industrial heating.

In Fig. 7, we show the oscillation frequency vs diameter of VCSEL. We distinguish the single-mode and multimode version of VCSELs, and their application areas. In the case of single-mode devices, we can achieve single transverse mode operation by reducing the diameter of the device to a few microns. A circular beam and single oscillation frequency can be obtained. On the other hand, in the case of multimode devices that have larger diameters, such as several microns or larger, we can attain high optical output and high-speed modulation capability. From 1999, the VCSEL was applied to high-speed LANs, such as Gigabit Ethernet and its mass production started. To date, VCSELs have been applied to various IoT fields. The market size of production is forecast to reach 40 B$ in 2025 (After 17 forecast reports by 17 companies including Yole/CIEO Report).

3.5.2 Related Microoptics

Iga is also an active proponent of **microoptics**, utilizing gradient-index planar microlens array, and has been working toward the dream of realizing 2-D arrayed optical devices in combination with surface emitting lasers. He first proposed and realized planar microlens array in 1979. His much effort and collaboration with Nippon Sheet Glass Co. in successful developments of commercial planar microlens arrays including 1000×1000 microlens pieces for LCD projectors. He also proposed and demonstrated novel self-aligning optics based on a planar microlens array. This proposed concept that Iga named "3D Stacked Integrated Optics" will be helpful for realizing simple optical couplers used in large-scale parallel optical fiber communications. He organized Microoptic Group and has served as the representative from 1988 to present.

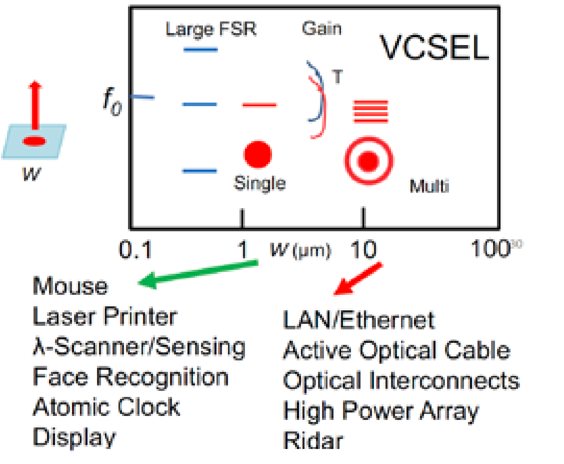

Fig. 6 Modes of VCSEL

4. Notices

The VCSEL and its arrays have opened a parallel microoptics world and contributed to the industrialization of new optoelectronics systems. The applications introduced here will provide a huge potential for VCSEL markets. VCSELs are the most suitable light sources for a large area of applications owing to their advantageous features such as low cost attributable to their high productivity, high reliability, low power consumption, and small size. As described here, the VCSEL is becoming an indispensable key component that supports the present and future information society from datacom to smart sensing [45)]. It is not easy now to imagine a society without VCSELs.

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