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Vertical-cavity surface-emitting diode lasers

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New kind of injection lasers, namely vertical-cavity surface-emitting diode lasers, is presented. Since their best constructions seem to be already mature for various applications, they are described in detail. At present, their most severe disadvantage to overcome is connected with relatively high electrical resistance of p-type distributed Bragg reflectors which causes intense heating of the area close to the active region. Various solutions to this problem are described in detail. Numerous up-dated bibligraphy on this subject is also given.

1. Introduction

A general structure of diode lasers [1] has not been changed for years. Typically, laser beam is propagated inside a semiconductor crystal within the active layer (Fig. 1**a**) in a direction perpendicular to a current flow. So, light is gained continuously during its entire round trip between resonator mirrors. The laser emission takes place from an edge of the chip through resonator mirrors formed usually by cleaving. Conventional lasers of this kind are called edge-emitting diode lasers (EE lasers).

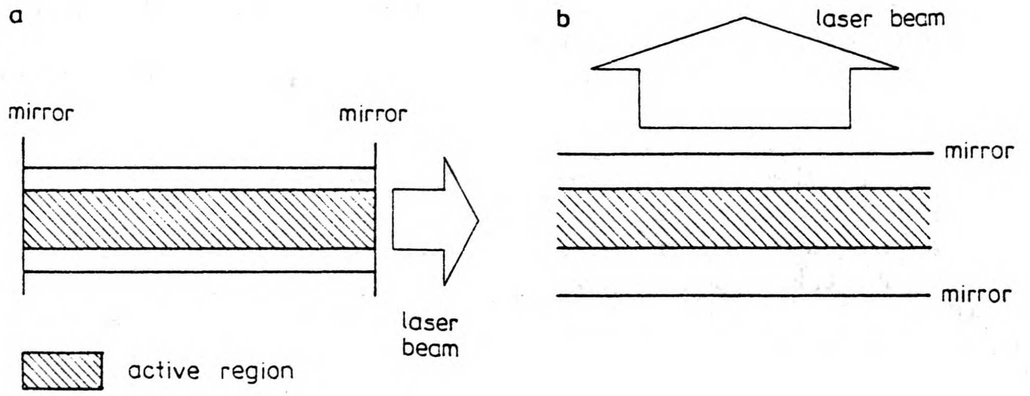

Fig. 1. Schematic diagram of an edge-emitting laser (**a**) and a vertical-cavity surface-emitting laser (**b**)

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A new class of diode lasers, called vertical-cavity surface-emitting lasers (VCSE lasers), have optical resonators situated orthogonally to those in EE lasers (Fig. 1**b**), i.e., in this case, the laser beam is propagated in the direction perpendicular to a waver plane. This simple alteration is the resonator orientation changes radically the following laser properties:

– laser beams are no longer both astigmatic and strongly divergent as it is in the case of an EE laser, but they are typically circularly symmetric Gaussian beams,

– because of their ultra-short cavity lengths, VCSE lasers can lase inherently in a single longitudinal mode even under transient-state conditions,

– high two-dimensional packing density for addressable arrays of VCSE lasers is available,

– an initial waver test is possible before its separation into chips,

– VCSE lasers appear to have the smallest active region volumes to date, i.e., even less than 0.05 μm^3 [2], an order of magnitude less than the smallest EE lasers (optically pumped VCSE lasers have still less active volumes, even as small as 0.002 μm^3 [2].

In comparison to the EE lasers, VCSE lasers are characterized by much shorter gain lengths. Therefore, to reduce their end losses, much higher mirror reflectivities (~ 1) are used.

VCSE lasers were pioneered by Professor KENICHI IGA et al. [3] at the Tokyo Institute of Technology, where the first working VCSE diode lasers were invented in 1979 [4], their first pulsed room-temperature operation was demonstrated in 1984 [5], and their first continuous wave operation was reported in 1988 [6]. Since then an increasing interest in VCSE lasers is widely observed as a result of their unique properties and advantages over EE lasers. Their potential applications include optical interconnections in highly parallel architectures, image processing, optical pattern recognition, medicine, local area communications, long distance optical communications, optical neural networks, etc.

Now, the VCSE diode lasers are usually produced in one of the following structures:

– an etched-well structure,
– a post back-emitting structure,
– a post top-emitting structure,
– a gain-guided back-emitting structure, and
– a gain-guided top-emitting structure.

All the above structures together with their modifications will be described in detail in the present paper.

2. Etched-well VCSE diode lasers

2.1. Structures

Although the etched-well structure was the first of VCSE lasers for which a laser operation was reported, now it is only of historical importance. Its main disadvantage is connected with necessity of etching a deep well through the substrate to let its laser beam out. This, however, means additional technological steps to perform and make the structure less resistible mechanically.

There are four principal versions of the etched-well VCSE diode lasers:

- a structure with both dielectric distributed Bragg reflector (DBR) mirrors [7]–[13],
- a structure with the front semiconductor DBR mirror and the rear dielectric DBR mirror [14],
- a structure with the front dielectric DBR mirror and the rear semiconductor DBR mirror [15], [16], and
- a structure with both of semiconductor DBR type mirrors [17], [18].

All structures are shown in Fig. 2.

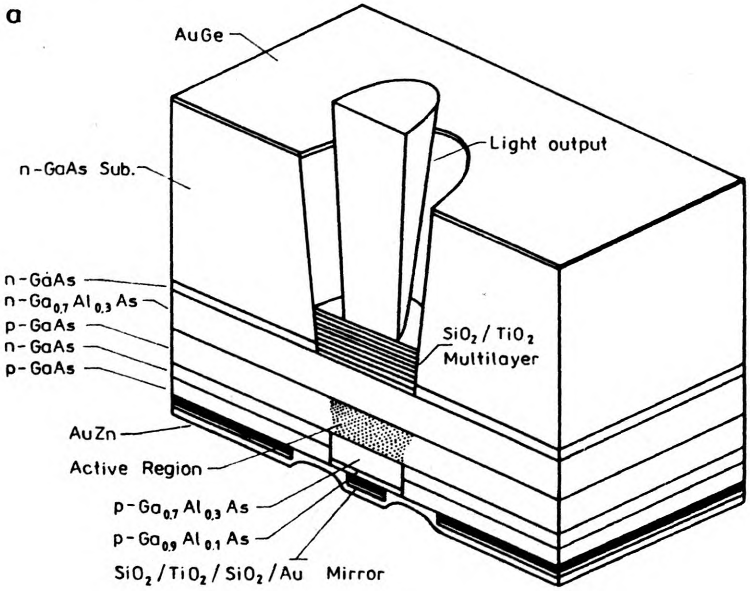

Fig. 2a

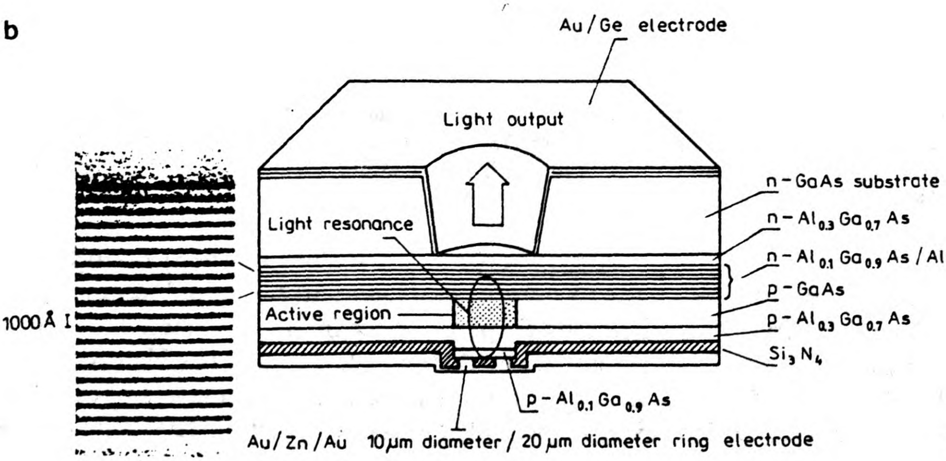

Fig. 2b

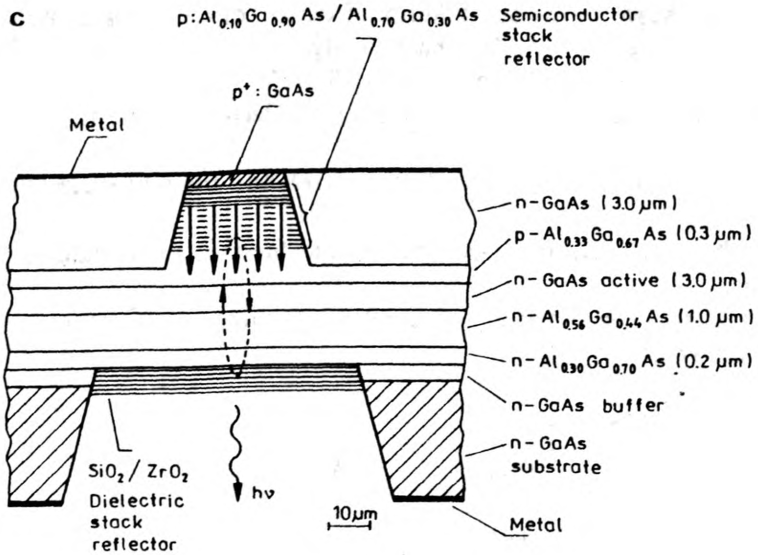

Fig. 2c

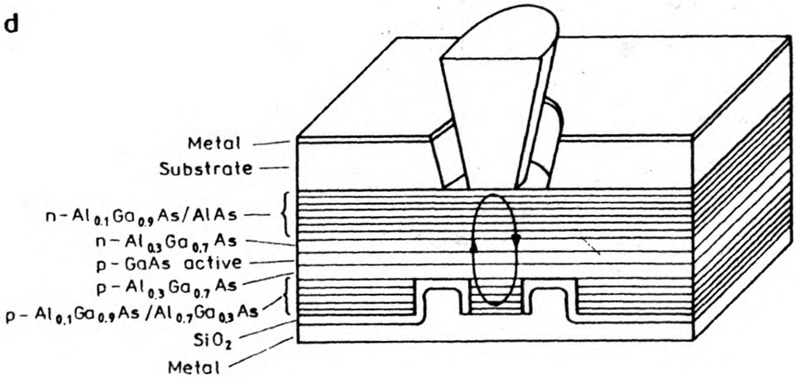

Fig. 2d

Fig. 2. Structures of etched-well VCSE diode lasers: **a** – with both mirrors of dielectric semiconductor DBR type [13], **b** – with the front semiconductor DBR mirror and the rear dielectric DBR mirror [14], **c** – with the front dielectric DBR mirror and the rear semiconductor DBR mirror [16], and **d** – with both semiconductor DBR mirrors [17]

The last structure is seemingly the simplest one. It does not need double-stage crystal growth (to produce a buried heterostructure) and an additional technological step to form dielectric DBR mirrors by evaporation technique. It is manufactured in a single growth process. But it employs semiconductor DBR mirrors which need very careful high advanced technology to fabricate numerous very thin layers of excellent uniformity and quality. However, at present, the semiconductor DBR mirrors are used in practically all modern structures of VCSE diode lasers. They are described in more detail in [19].

Since its first lasing operation reported in 1979 [4], the etched-well VCSE diode laser was for nine years the best VCSE configuration. An enormous effort has been made to optimize its structure [20] – [40]. One of the most important key structure parameters brought into question was the thickness *d* of the active layer. One group [3], [6], [15], [16], [32] of scientists claimed they had found the thickness *d* equal to about 2 – 3 μm to be the most profitable for low-threshold laser operation, whereas the others [17], [38], [39] used successfully much thinner (~0.5 μm) active layers. A detailed theoretical model [41] of VCSE laser operation enables us to clear up this misunderstanding. From a minimal-threshold-current-density point of view, the optimal thickness of the active layer appeared to be a strong function of mirror reflectivities. The higher product of mirror reflectivities is achieved, thinner is optimal active layer.

2.2. Operation characteristics

For years the etched-well VCSE structure seemed to be the only one suitable for practical purposes. Anyway, it is characterized by very narrow spectral linewidth (50 MHz at an output power of 1.4 mW under room-temperature continuous-wave (cw) operation [42]; this value may be reduced to even less than 1 MHz [43]), low intensity noise (– 145 dB/Hz for an output power of 2.2 mW [13]), and the highest output power (120 mW for room-temperature pulsed operation [16]) ever reported for the VCSE laser structures. For the room ambient temperature, the lowest cw threshold current (5.2 mA) and the highest external differential quantum efficiency (16%) were reported by IBARAKI et al. [15] for the 5-μm-diameter etched-well laser with both semiconductor DBR mirrors. On the other hand, the lowest cw threshold current (4.5 mA) for the 1.3-μm InGaAsP/InP etched-well lasers at 77 K was achieved by OSHIKIRI et al. [35].

The etched-well VCSE lasers are p-side-down devices, i.e., their active regions are situated relatively close to their heat sinks. Therefore, in spite of an intense heat generation within their volume, they have quite good thermal properties [44] – [46], compared with the other VCSE lasers.

3. Post microresonator VCSE diode lasers

3.1. Structures

Arrays of laser logic gates constitute efficient devices for photonic switching in communication networks and for digital or neural computing. In such information processing applications, the minimizing of the threshold current is essential. In EE lasers, the lowest threshold currents ~0.55 mA [47] – [49] were achieved in single-quantum-well devices. VCSE lasers offer a unique possibility of minimizing drastically the volume of active material to fabricate ultra-small microlasers, and hence they are potentially ultra-low-threshold devices.

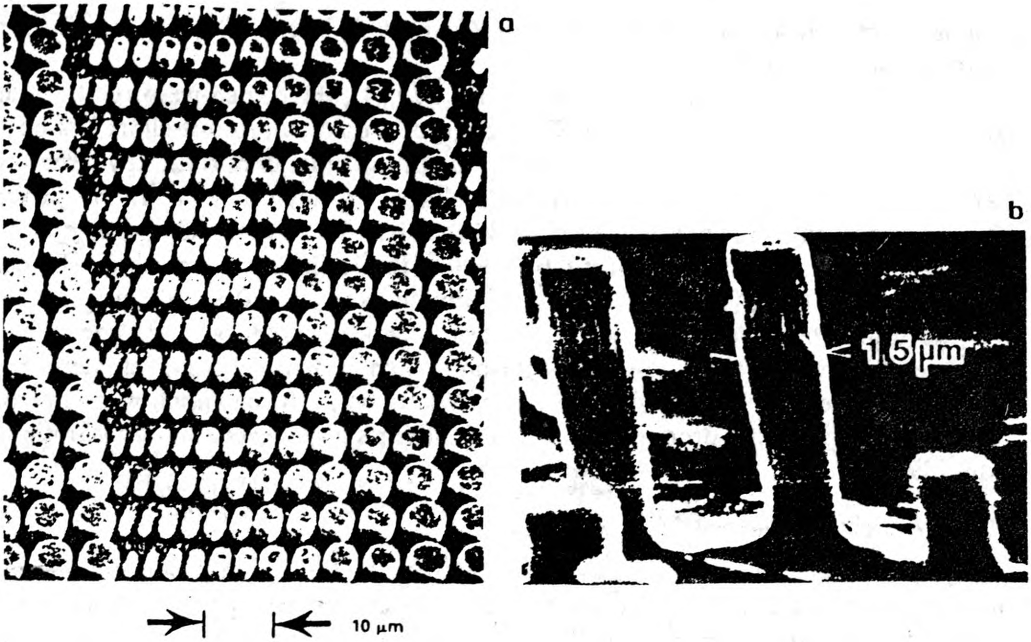

Fig. 3. Small portion of the array of microlasers: **a** — general view [2], and **b** — enlarged side view [52]

The simplest method of defining a microlaser from a grown waver relies on physical removal of the material everywhere except for the cavity itself. This is usually accomplished by masking the shape of the laser and etching away the unwanted semiconductor material by using either a suitable chemical solution or chemically assisted ion beam etching [50], [51]. With this method, it was posible to manufacture more than one million electrically pumped microlasers (Fig. 3) with diameters of a few micrometers on a single GaAs chip [53]. The achieved density was as high as about 2 million resonators per cm^2 [54]. The smallest microlaser has a diameter of less than 0.25 µm [55].

Three principal structures of post microlasers are shown in Fig. 4. The first one enables us to produce the smallest microresonators. Next two structures demonstrate better heat sinking of the laser cavity which leads to improved cw laser performance. But in this case, the decreasing of the active area diameter much below 5µm is followed by undesirable increase in diffraction losses [56].

In back-emitting lasers, the laser beam is propagated through a thick GaAs substrate. To minimize absorption in this material, emitted radiation should have considerably longer wavelength than GaAs lasers. This is accomplished by manufacturing those lasers with the $In_xGa_{1-x}As/GaAs$ strained multiple-quantum-well (MQW) active regions. For $x = 0.18-0.20$, the observed wavelengths ranged from about 940 to 1020 nm, while the GaAs substartes remain still transparent [57], [58]. For the InGaAs single-quantum-well (SQW) to be elastically strained, its

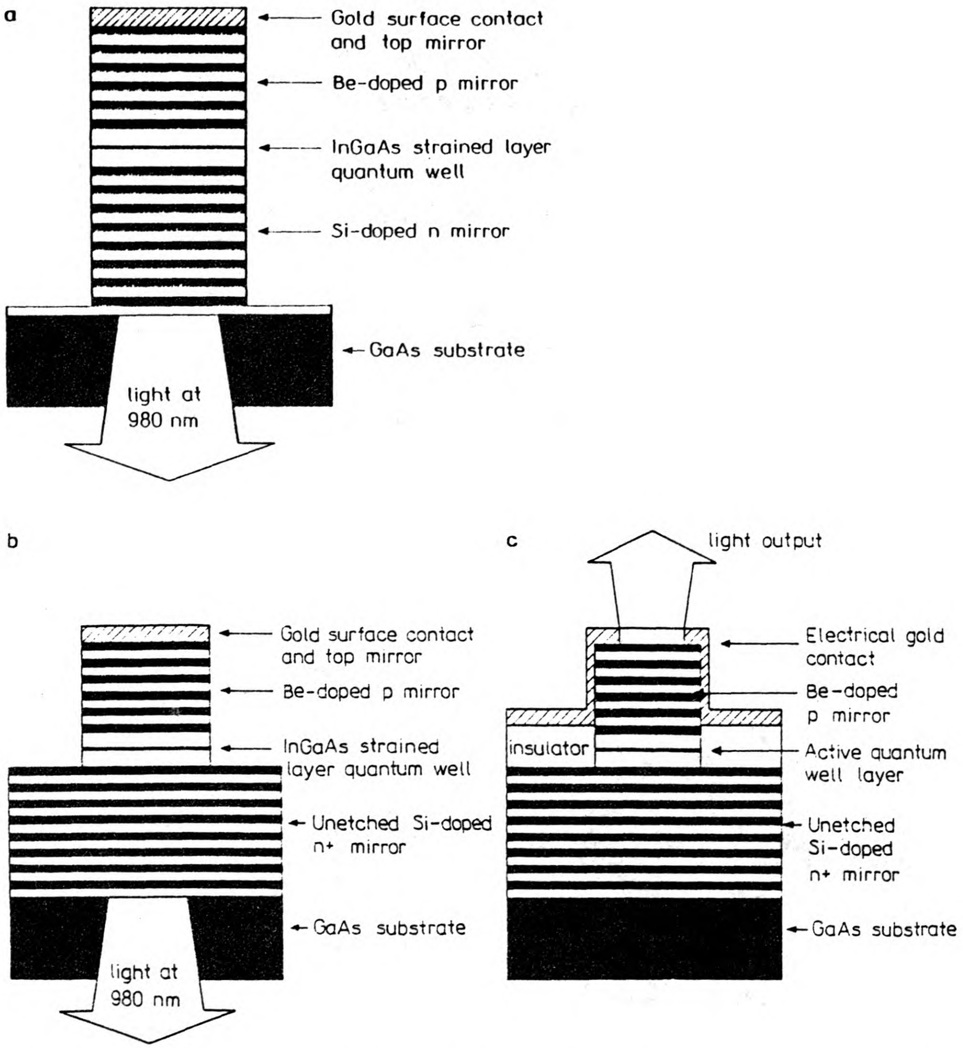

Fig. 4. Structures of post microresonator VCSE diode lasers [55]: a, b – back-emitting microlasers, c – top-emitting microlaser

thickness should be well below the critical thickness [59] of about 20 nm. If laser emission is required from the surface of the waver (Fig. 4c), a window for the laser beam propagation must be opened through the p-side contact layers.

3.2. Operation characteristics

The post microlasers are distinctly index-guided devices. Their air-post versions lase in a number of transverse modes due to the large index difference between the resonator material and its surroundings [60]. To some extent, it may be improved by covering the pillar resonator with an insulating material (Fig. 5), e.g., with polyimide [61].

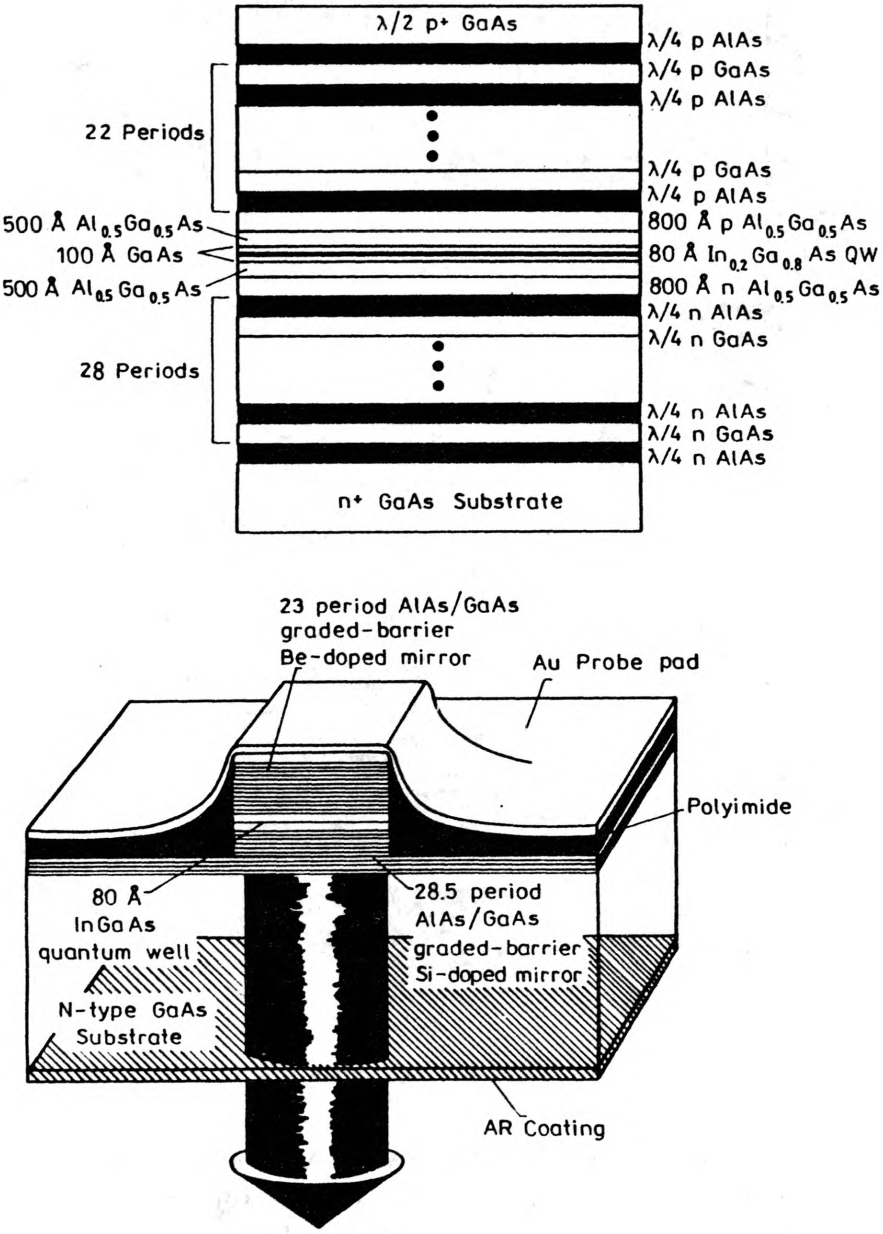

Fig. 5. Back-emitting microlaser with polyimide layer surrounding a pillar resonator [61]

Another serious disadvantage of small-diameter microlasers is connected with surface nonradiative recombination on a resonator perimeter [63], [64]. It constitutes an additional intense heat source in the neighbourhood of the active region worsening their thermal properties. Another intense heat source due to the periodic potential well/barrier structure of semiconductor DBR mirrors is described in detail in [19].

The threshold current density of post microlasers is as low as 1 kA/cm^2 [65]. The lowest room-temperature cw threshold current up to date (0.7 mA) was reported for a back-emitting 7-μm-diameter laser [61]. A wet chemical treatment of the surface of a 5-μm-diameter laser (after ion etching was used) reduces its threshold current from 1.5 mA to 0.8 mA [64]. The highest available external differential quantum efficiency is about 30% [65].

Post microlasers are very suitable devices for optical switching and interconnections. Their modulation speeds as high as 1 Gb/s were reported with less than 10^{-10} bit error rate [2]. These lasers were also used in compact and ultrafast holographic memory systems. They are capable of retrieving a high-resolution page (100 kbits) in less than 1 ns [52].

The first continuously wavelength-tunable air-post VCSE microlaser was reported by Chang–Hasnain et al. [66]. The laser junction is cooled due to the Peltier effect [67], [68] or heated by the Joule heat generation within the DBR mirrors. The total tuning range is 1.8 nm (540 GHz).

4. Gain-guided VCSE diode lasers

4.1. Structures

At present, the gain-guided constructions of VCSE diode lasers seem to be the most advanced ones. Their two principal versions, i.e., back-emitting and top-emitting

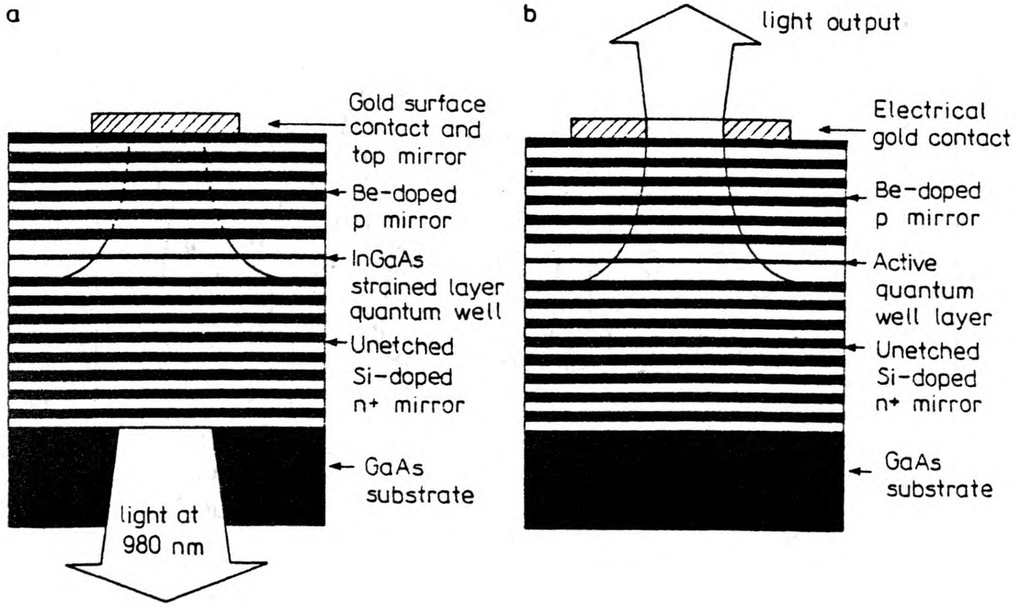

Fig. 6. Schematic configuration of: **a** – back-emitting gain-guided laser and **b** – top-emitting gain-guided laser, defined by ion implantation [55]

structures are presented schematically in Fig. 6. In the top-emitting structure, the output beam propagation takes place through an open window in the top contact, and through the substrate in the back-emitting ones. So, in the latter construction, as in the case of back-emitting post microresonator VCSE lasers, active regions must be manufactured as $In_{0.2}Ga_{0.8}As$ strained quantum wells.

In the above devices, the current confinement is provided by proton implantation [69]–[75] of areas surrounding the active region. The procedure is essentially the same as that commonly used for gain-guided stripe-geometry EE lasers. The implantation creates high resistive material, but from thermal point of view it does not affect essentially its thermal conductivity at room temperatures [76].

At the moment, the most modern configuration of VCSE lasers is the multiquantum well (MQW) graded-index-separate-confinement-heterostructure (GRINSCH) equipped with semiconductor distributed Bragg reflectors (DBRs) with graded, superlattice or stair-case interfaces [78], (see [19]). A plot of the refractive index

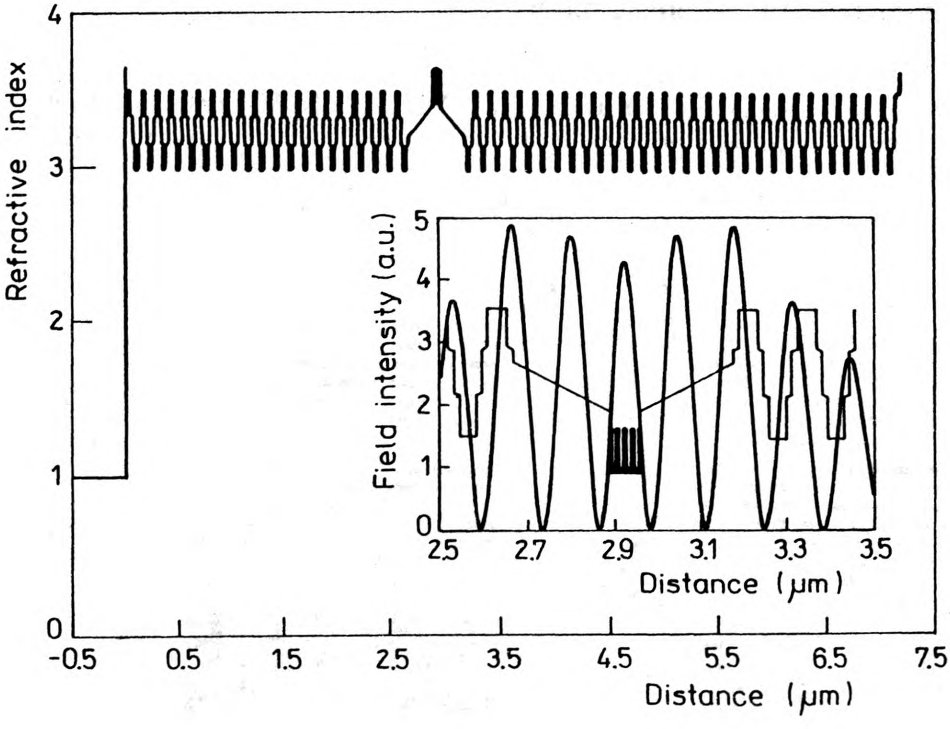

Fig. 7. Refractive index profile of the entire MQW GRINSCH VCSE laser structure with stair-case interfaces in DBR mirrors. Insert shows the standing wave intensity radiation [77]

profile within the entire structure of such a laser (with stair-case interfaces) is shown in Fig. 7. The thicknesses of the AlGaAs spacer graded layers on both sides of MQW active region are such that the central antinode of the electric field standing waves (shown in the insert) overlaps the quantum wells to maximize the longitudinal confinement factor [79].

4.2. Mode and polarization characteristics

Superiority of the mode characteristics of gain-guided VCSE lasers as compared to those of post-resonator ones was confirmed by CHANG–HASNAIN et al. [60]. The air-post index-guided VCSE lasers emit multiple transverse modes due to the large index difference between the resonator volume and the cladding air. On the other hand, the broad-area gain-guided VCSE lasers lase in the fundamental TEM_{00} mode near their thresholds. At higher currents, higher-order modes (TEM_{10} and TME_{11} modes) are successively excited. A 5 μm square gain-guided laser emits only a single transverse mode.

Polarization characteristics [80], [81] of quantum well gain-guided VCSE lasers appear to be significantly different from their edge-emitting counterparts. Near threshold, the VCSE lasers emit a highly linearly polarized TEM_{00} mode, but the polarization direction varies randomly from one laser to another. With increasing current, linearly polarized higher-order transverse modes begin to lase with a polarization direction orthogonal to that of the fundamental mode. The above observation indicates that there is no fundamental polarization selection mechanism in quantum-well VCSE lasers.

4.3. Back-emitting gain-guided VCSE diode lasers

The best operation characteristics of back-emitting gain-guided VCSE diode lasers were achieved by WALKER et al. [82]. Their lasers were equipped with DBR mirrors with continuously graded interfaces and with lower doping levels near the active region. For the 45 μm square devices at room temperature, cw threshold current density was as low as 800 A/cm^2, maximum power as high as 9 mW, whereas threshold voltage and series resistance at threshold as low as 1.6 V and 18 Ω, respectively. The above achievements render these devices compatible with 5-V silicon driver integrated circuits.

Dynamical behaviour of back-emitting gain-guided VCSE lasers was investigated by CHANG–HASNAIN et al. [83]. A large wavelength chirp in lasing spectrum was observed for lasers with high threshold voltage due to resistive heating close to the active region. After having optimized the laser design, the gain-guided VCSE lasers with relatively low threshold voltage (2.6 V) were achieved, which enabled von LEHMEN et al. [84] to design the first hybrid integration of the above silicon driver with VCSE laser arrays. Bit rates up to 622 Mbit/s were reported.

A discrete tuning over 6.1 nm (1830 GHz) was reported in a multiple wavelength tunable VCSE laser arrays consisting of 140 unique, uniformly separated, single-mode wavelength emission emitters [85], [86]. The wavelength tuning is obtained by using a three-mirror coupled-cavity configuration. The arrays may be used as optical memory or logic devices.

The first vertical-to-surface transmission electrophotonic device with a vertical cavity was demonstrated by NUMAI et al. [87]. The device exhibits thyristor-like current-voltage characteristics which are required for optical and electrical switching.

4.4. Top-emitting gain-guided VCSE diode lasers

The best operation characteristics of top-emitting gain-guided VCSE diode lasers were reported by ZHOU et al. [88]. They used a continuously graded mirror composition grown by MOCVD. Their lasers with 35 μm active region diameter demonstrated at room temperature cw threshold current density as low as 1200 A/cm^2, cw output power and differential external quantum efficiency as high as 2 mW and 80%, respectively, as well as threshold voltage and series electrical resistance as low as 2.1 V and 22 Ω, respectively. Even higher cw output power, 3 mW, was reported by TELL et al. [73]. Short-wavelength, deep-red (770 nm) cw operation of a top-emitting gain-guided VCSE diode laser was demonstrated by LEE et al. [89]. High-speed (5 Gbit/s) pseudorandom direct intensity modulation was achieved with this laser by CHOA et al. [90].

Careful optimization of the configurations of lasers enables their cw operation at ambient temperatures up to 90 °C [91] with a relatively high temperature sensitivity factor of threshold current $T = 330$ °C [92]. But their still poor thermal properties need some essential improvements because an intense heat generation within DBR mirrors [19] deteriorates the laser performance. This, however, may to some extent be profitable, because considerable temperature increase near the laser axis creates thermal waveguide in which cases the threshold current density for cw operation being sometimes lower than that for pulse operation [77], [93].

5. Other constructions of VCSE lasers

Gain-guided VCSE lasers are devices without any current confinement mechanisms. This disadvantage was overcome in burried-heterostructure (BH) VCSE diode lasers [94] – [96], whose construction is analogous to that of stripe-geometry BH lasers. BH VCSE lasers are equipped with dielectric output mirrors to reduce heating problems because of high resistivity of p-type semiconductor DBR mirrors [19]. The laser operation characteristics did not reward for much more complex technology: they hardly achieved room-temperature cw operation with the lowest reported threshold current density over 20 kA/cm^2.

The main disadvantage of the present modern constructions of VCSA lasers is, however, connected with high electrical resistivity of their p-type semiconductor DBR mirrors. This drawback may be overcome by introducing lateral current injection. Then the current does not flow through high resistivity p-type DBR layers and heat generation within a laser diode is drastically reduced. Such a solution was proposed by LEI et al. [97] in their modified top-emitting VCSE lasers, whose room-temperature cw threshold currents were as low as 2.3 mA (threshold current density 2900 A/cm^2). A similar but more sophisticated construction was proposed by by Yoo et al. [98], [99]. Technology used to fabricate this laser is based on a double ion implantation technique. Both the p-electrode and the n-electrode are placed on the top surface (Fig. 8) and the total step height of the device is less than 1 μm. So, the current path does not lead through the p-type DBR mirrors. The operation characteristics exhibited by this laser, however, are not good enough, as could be expected. Its lowest pulsed threshold current was equal to 15 mA (threshold current density 3100 A/cm^2), and the cw operation was not reported.

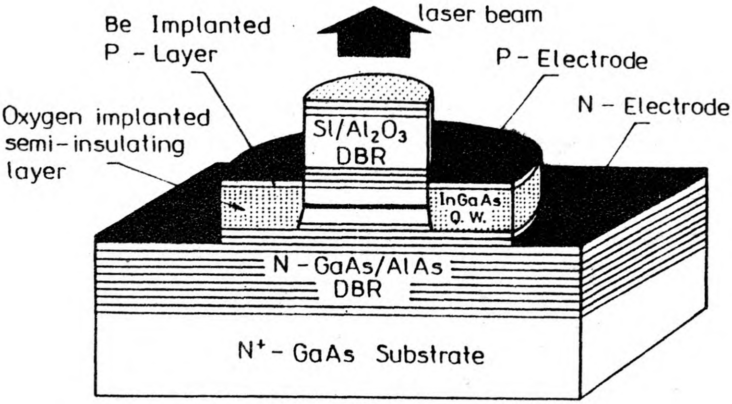

Fig. 8. Schematic diagram of the VCSE laser construction proposed by Yoo et al. [99]

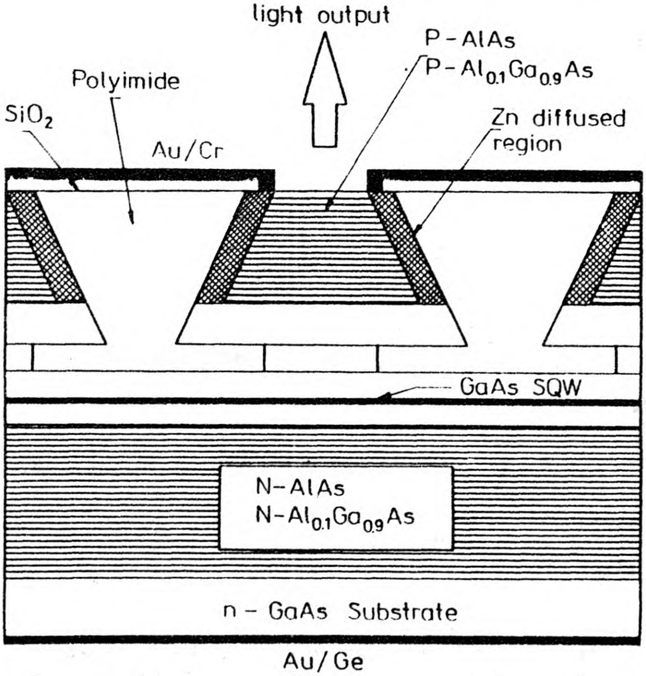

Fig. 9. Schematic diagram of a mushroom structure VCSE laser [100]

Much more efficient structure was proposed by YANG et al. [100]. In their modified top-emitting VCSE laser (Fig. 9), called a mushroom laser, zinc diffusion was performed to selectively disorder the multilayer in the periphery of the mesa, forming a lateral conducting path with lower resistance while leaving the multilayer above the active region intact. The mushroom VCSE laser with an 8 μm × 8μm active region demonstrates at room temperature relatively low series electrical resistance of 250 Ω, a low cw threshold current of 3 mA (threshold current density 4700 A/cm^2) and a cw light output power exceeding 1 mW. Although the best operation parameters of gain-guided VCSE lasers are somewhat better, it should be remembered that the mushroom structure is relatively new and may be essentially improved in the future.

A similar structure, the VCSE laser with air bridges (Fig. 10), was reported by HSIN et al. [101]. The air between the p$^-$-multilayer bridge and the n$^+$-multilayer

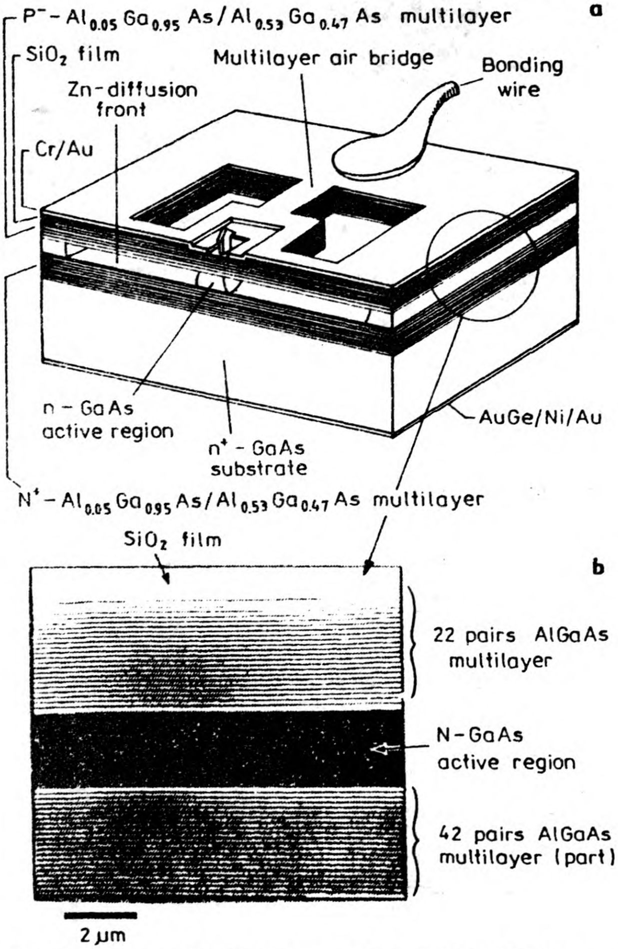

Fig. 10. Structure of a VCSE laser with air bridges [101]: **a** – schematic diagram and **b** – cross-sectional SEM picture of the DBR structure circled in figure **a**. The white parts of the stripes are $Al_{0.53}Ga_{0.47}Al$ layers

reflector forms a low index insulator for both optical field confinement and electrical current confinement inside the microcavity active region. A very low threshold current of 1.5 mA (threshold current density 7600 A/cm^2) was achieved. Modfification [102] of this structure consisted in performing selective zinc diffusion into the side of the square columns to provide a low resistance current path from the contact to active region. As a result, room-temperature cw output power greater than 3 mW was reported.

6. Conclusions

Vertical-cavity surface-emitting diode lasers constitute the most rapidly developing kind of injection lasers. The progress observed is so speedy that often constructions one-two years old seem to be archaic. But the lasers of this new category are steadily becoming mature devices, ready for various applications, while their numerous advantages appear to be very important. Anyway, the future in various branches of contemporary science and technology inevitably belongs to them.

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