Quantum and Photonics Devices
- How Small Is Small enough?-

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Abstract Nano-and ITtechnologies will be keeping its position in research and development for the coming at least 10 years. There would still be a lot of opportunities to meet really novel devices covering full spectral operating ranges, temperature insensitive operation, ultra-low power consumption, frequency control, large scale integration, and so on. In this talk, we like to discuss mostly on the scaling laws of semiconductor lasers based on the vertical cavity surface emittng laser (VCSEL).

1. INTRODUCTION

The semiconductor laser was realized in 1962 [1]-[4] , where polished or cleaved mirrors were employed to form Fabry-Perot cavity. Kogelnik and Shank [5] proposed distributed feedback (DFB) configuration which can form a resonator in a monolithic way. The present author suggested the so-called surface emitting laser in 1977 [6][7] as shown in Fig. 1 and the initial device was demonstrated[8] in 1979. With VCSEL configuration, the laser cavity can be as small as a few microns and quantum and nanotechnologies are employed in its side. Now it is known as vertical cavity surface emitting laser (VCSEL) has been applied in high speed networks as in Gigabit ether net. This device appearance is one of the motivation of promoting nano-technology[9].

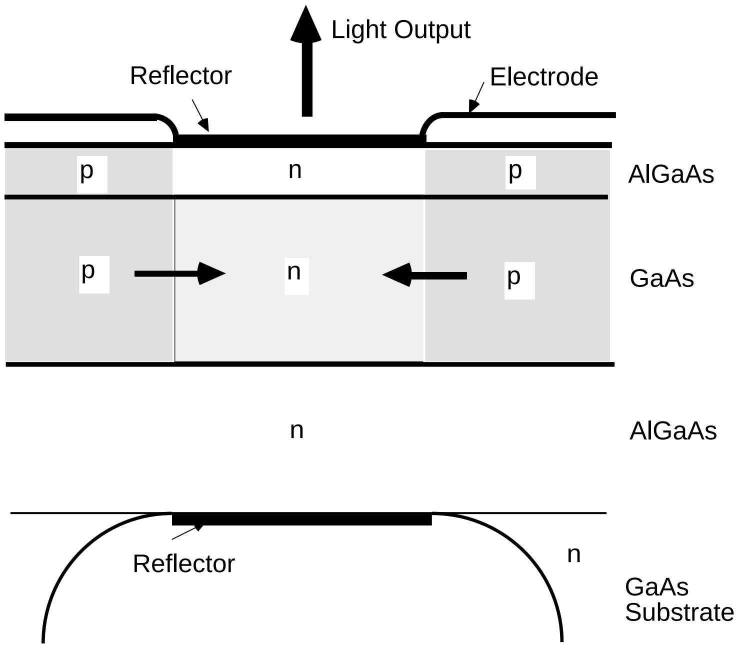

Fig. 1 Initial model of vertical cavity surface emitting laser (1977)

2. NEW LASER PRINCIPLE

The dipole transition of electrons and holes is the basis of light emission and amplification in semiconductor lasers. The transition from or to impurity levels was investigated in the early stage of semiconductor laser research, but any superior characteristics was not recognized. However, advanced crystal growth and doping technology may revive impurity involvement for laser transition, i. e., by the formation of artificial molecules, Anderson localization dot, band-edge modification, and so on.

Currently, the quantum well is considered to be the fundamental active engine of semiconductor lasers. The question whether the quantum wires and dots could make its full use of abilities for quantum effect has been carried over to this century. Self-organized formation has been attempted for making quantum dots in various material systems. GaInN quantum dots are applied to a semiconductor laser. This scheme may be useful for future surface emitting lasers technology. One of the challenges

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is to increase dot density. We have achieved $9x10^{10}$ cm^{-2} in long wavelength GaInNAs/GaAs system. In a separate sample, we obtained laser operation of GaInNAs dot laser in low temperature.

As for another stimulated emission, a quantum cascade laser operation has been demonstrated[20]. This is based upon the transition from one of the sublevels in conduction band of semiconductor to the other lower state in the same band. Only electrons in conduction band are associated with this phenomenon, i. e. this is a monopolar device. High energy electrons injected from an injector to a higher sub-level in quantum well can couple to the lower level in the same well. If the transition occurs to the lower sub-level of the different well, this is said to be Type II transition. The typical material is AlInAs/GaIns on InP substrate which can emit 3-17 micron of wavelength. The best performance is demonstrated in 8 microns and vicinity and room temperature pulsed or low temperature continuous wave operation have been possible. In infrared regions, more than several hundred mW of power output was achieved. Other material such as GaAs-based superlattice and CaF system have been attempted. High precision control of thickness is crucial for tuning the multiple well structure for enhancing the laser gain.

When an electron and hole are localized in a small region relative to de Broglie wave packet, an exciton is formed with a certain period of life time. This coupling is week and generally it can be existing in a short time. But in the case of GaInN system, it is observed that the exciton can be alive in room temperature. The excitonic transition is also contribute to the emission and amplification of light which corresponding to a longer wavelength than band edge emission.

The strain intentionally introduced into semiconductor heterostructure has been applied to modify the band structure and to obtain high performance semiconductor lasers. We have achieved the crystal growth of a highly strained GaInAs on GaAs with Indium content of about 40% which is associated with the emission wavelength of beyond 1200 nm. It has been found that a long wavelength semiconductor laser can be realized on GaAs substrate providing a good temperature characteristic, i. e., the characteristic temperature T_0 of near or beyond 100K . The VCSEL device in this material will be mentioned later. The innovation of crystal growth technology will enable us to explore new materials which have been difficult to realize.

3. NEW MATERIALS FOR SEMICONDUCTOR LASER

We summarize the materials used in semiconductor lasers as shown in Fig. 2. Most of III-V compound semiconductors have begun to be considered to realize semiconductor lasers. In particular, Boron doped GaInN system is considered to widen the possibility of ultraviolet lasers in shortest wavelength obtainable from III-V systems. Also, the use of Nitrogen in GaInNAs system may provide long wavelength semiconductor lasers on GaAs substrates which give us good temperature characteristics. A Tl-included semiconductor GaTlAs and its family may have a bandgap energy which is independent of temperature.

The II-VI semiconductors were considered to provide green light from semiconductors and developed for optical disk systems. However, the research activity shrunk down except ones using InP-based CdZnSe and families after the GaN system was found to be a viable candidate for even shorter emitters. Oxide II-VI's such as ZnO has been studied for short wavelength semiconductors and optical pumped lasers have been demonstrated and LED's by using pn-junction was reported. Diamond could be a laser as a IV element and nano-structure Si has been has been extensively studied to sue as an emitter from Si-based devices. However, there has not been discovered a possible technology for realizing a semiconductor injection laser at this moment.

How about organic semiconductor lasers? Recently in 2000, green emitting tetracen laser was demonstrated by current injection scheme. Two field-effect-transistors were placed intact to supply electrons and holes independently to inject them into the active region. Ahead of this experiment, Electro-chemiluminescence (ECL) was applied to operate dye laser by current injection fashion and blue light laser was reported. This may be the first organic injection laser. In 2000, Dr. Hideki Shirakawa who is a graduate of Tokyo Institute of Technology obtained 2000 Nobel Prize in chemistry with two coreceipients for their first development of conducting organics. Organic semiconductor laser may be a very viable candidate for visible solid state semiconductor lasers which may provide green light for displays and illuminations. Against this, can AlGaInP, GaInN and other III-V systems be existing in future?

4. LASER STRUCTURE AND DESIRABLE PERFORMANCE

The items of active region for semiconductor lasers reported in the past are summarized in Fig. 3. The wide plate (a) is used for high power laser emittable of more than 1 W from one chip. The stripe geometry (b) is employed in most of semiconductor

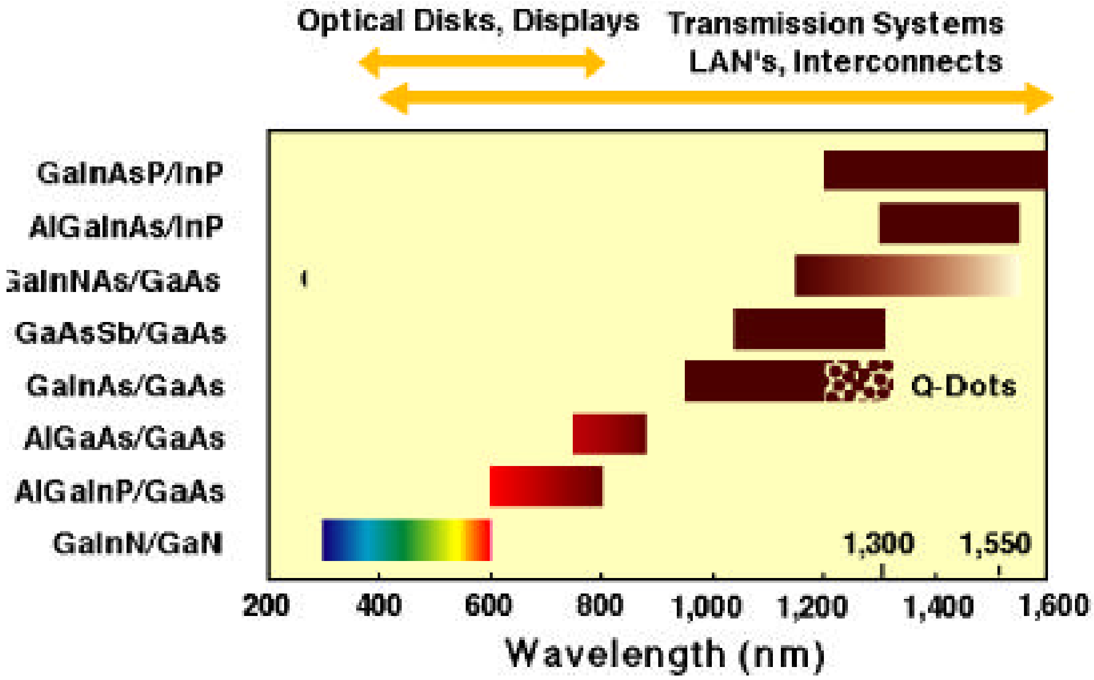

Fig. 2 Materials for semiconductor lasers

lasers for the operation in single transverse mode. The circular or square plate (c) is applied in surface emitting lasers. The ring shape (d) is for the purpose of realizing microdisk cavity laser or ring laser. The three dimensional periodic structure is relatively new one which is considered as so-called photonic crystal laser. This is associated with a kind of distributed feedback laser with three dimensional fashion to inhibit the spontaneous emission in all the directions centered at a small active region.the micro- or nano-particle (e) could be a laser. Random medium is a complex of small particles which provides a feedback loop in some unknown route[36]. The last two may be only by optical pumping, since the electron injection scheme seems to be hard to realize. But it may be interesting, if it can be applied into markers for biotic sensors.

As for the resonant cavity for semiconductor lasers the following issues listed in **Table I** have been considered related to the active region schemes, i. e., Fabry-Perot (FP), distributed feedback (DFB), distributed Bragg reflector (DBR), vertical cavity as in surface emitting lasers, whispering gallery, microdisk, nano-sphere, and so on.

There are several methods for laser excitation including current injection through pn-junction, optical pumping, electron beam pumping in vacuum, electrochemiluminescence, and so on. Most of engineered lasers are based on current injection scheme, but recently surface emitting lasers with optical excitation by monolithically integrated pumping laser was begun to be commercialized. We must not ignore to consider other pumping schemes considering the innovation of technology. In order to reduce the threshold to have an efficient laser, the current and photon confinement in a small volume has been a technical target to achieve. The aluminum oxide from selective oxidation of AlAs and tunneling injecton have been introduced mostly in surface emitting lasers. Some transparent electrode and the use of room temperature super conductors may be a dream for future semiconductor lasers.

Now let us discuss how the laser performance could have a progress by looking at the following challenges;

a) Can spontaneous emission completely controlled?
b) Can photonic crystal be applied in usable semiconductor lasers?
c) What is the ultimate threshold current level?
d) What is the limitation of modulation frequency, beyond 40 Giga bits/s in directly modulation fiber networks? This is an old and still a new issue.
e) Can the CW output be beyond 10 kW in small spot?
f) Can the presently existing temperature dependence of semiconductor lasers be vanished in threshold, wavelength, efficiency, and so on?
g) Absolute resettability and controllability of lasing wavelength in a simple way?
h) Multiple wavelength lasers?

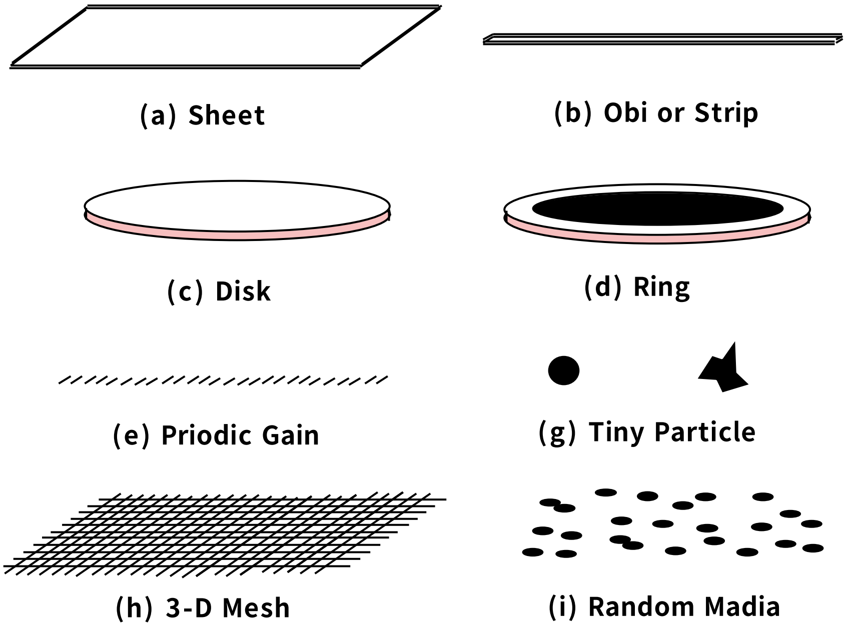

Fig. 3 Active engines for semiconductor lasers

Table I Laser Cavity

1) Fabry-Perot (FP)
2) Distributed Feedback (DFB)
3) Distributed Bragg Reflector (DBR)
4) Vertical Cavity Surface Emitting Laser
5) Whispering Gallery
6) Microdisk
7) Photonic Crystal
8) Nano-Sphere
9) Random Media

i) Wavelength tuning and control?
j) Integration, its method and scale?
k) Large scale arrays and coherent arrays?
l) Possibility of beam steering?

5. PROSPECT OF SURFACE EMITTING LASERS

Large scale networks and computing are now introducing optical technology as in optical computing, optical interconnects, and parallel lightwave systems. The progress of surface emitting (SE) laser or vertical cavity surface emitting laser (VCSEL) in the late 1990's was very fast and various applications into ultra-parallel optoelectronics have been considered. What is the surface emitting (SE) laser or VCSEL? The structure is substantially different from conventional stripe lasers; i.e., the vertical cavity is formed by the surfaces of epitaxial layers, and light output is taken from one of the mirror surfaces as has been shown in Fig. 1.

The structure common to most of VCSELs consists of two parallel reflectors which sandwich a thin active layer. The reflectivity necessary to reach the lasing threshold should normally higher than 99.9 %. Together with the optical cavity formation, the scheme for injecting electrons and holes effectively into small volume of active region is necessary for current injection device. An AlAs oxidation is considered to be the most effective process to perform it.

The VCSEL structure may provide a number of advantages including ultra-low threshold operation due to its small cavity volume V_a .We may have some scaling laws describing the VCSEL performances. The threshold current Ith is given by the equation;

$$I_{th} \quad \frac{eB_{eff}}{\eta_i \eta_{spon}} N_{th}^{2} V_a \tag{1}$$

The relaxstion frequency f_r is given when the driving current is much larger than threshold current by the equation;

$$f_r = \frac{1}{2\pi\tau_s}\sqrt{\frac{\tau_s}{\tau_p}\frac{\eta_i\eta_{spon}}{eB_{eff}N_{th}^{2}}\frac{I}{V_a}} \tag{2}$$

High speed modulation is possible due to small active volume V_a .

On the other hqand, the free spectral range of surface emitting laser is expressed in terms of cavity length L_c by;

$$\Delta\lambda = \frac{\lambda_0^2}{2n_{eff}} \frac{1}{L_c} \qquad (3)$$

Dynamic single mode operation is maintained due to this single mode condition. Wide frequency tuning range is based on the same physics.

Due to these physics the VCSEL may provide a number of advantages shown below;

a) Ultra-low threshold operation is expected from its small cavity volume.

b) Dynamic single mode operation.

c) Wide and continuoous wavelength tuning.

d) Large relaxation frequency.

e) Easy coupling to optical fibers.

r) Monolithic fabrication and easy device separation without perfect cleaving requirement.

g) Vertical stack integration by MEMS technology.

As one of semiconductor lasers in this century, we like to review the progress of VCSELs in wide range of optical spectra based on GaInAsP, AlGaInAs, GaInNAs, GaInAs, GaAlAs, AlGaInP, ZnSe, and GaN in the following part of this paper.

We show some of semiconductor materials for surface emitting lasers in Fig. 2. In practical 850 nm devices, sub-mA thresholds and 10 mW outputs have been achieved. The power conversion efficiency of >50% has been demonstrated. As for the reliability of VCSELs, 10^7 hours of room temperature operation is estimated. Life test results on oxide-defined devices exhibited higher reliability. The Gigabit Ethernet has already been in markets by the use of multimode-fiber-based optical links. This system is being extended to 10 Gigabits/s Ethernet.

The importance of 1,300 or 1,550 nm devices is currently increasing for metropolitan area networks (MAN). A 1,550 nm VCSEL with MEMS tunable functions began to be introduced into a high end MAN system. One of viable materials for long wavelength emitters is a GaInNAs system which can be formed on GaAs substrateas shown in Fig. 3[10].

In order to control the polarization of VCSEL output, (311)B substrate has been introduced and >30dB of orthogonal polarization suppression ratio (OPSR) was obtained even in high speed modulation condition. Recent results of (311)B VCSEL are shown in Fig. 5[10].

The application into optical disks looks to be another disruptive technology to simply replace currently existing lasers

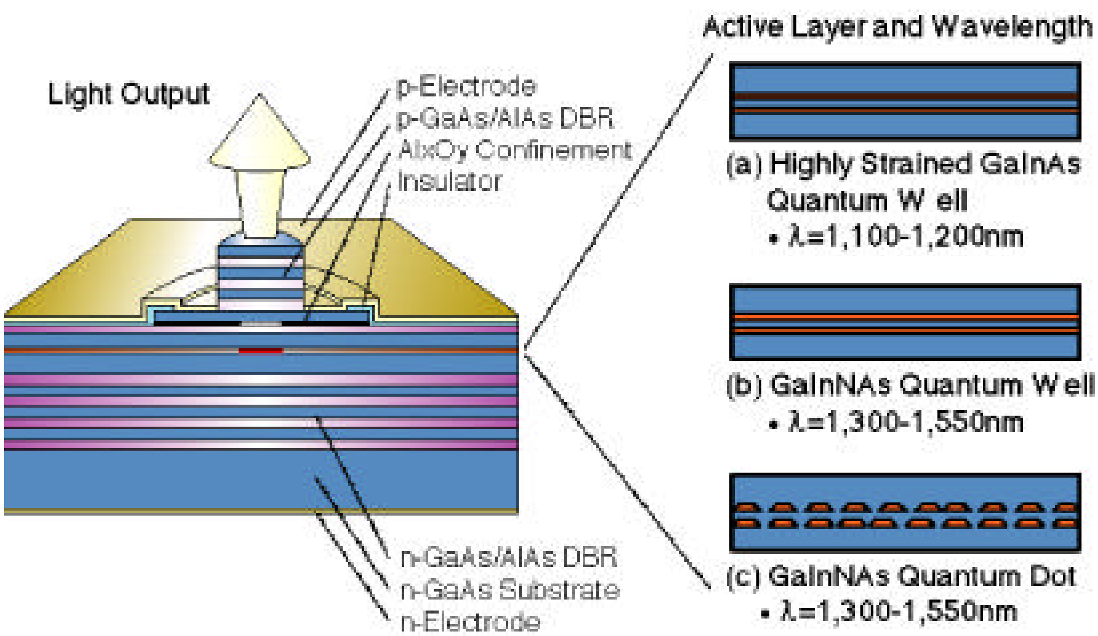

Fig. 4 Long wavelength VCSEL possibility on GaAs substrate

and pickups by taking the advantage of easy moduling scheme. GaN VCSEL may open up new field, if realized.

6. SUMMARY

We have discussed on future prospects mostly of semiconductor lasers in terms of materials, structures, and performances. The technology for surface emitting lasers has still been expected for high performance devices. The threshold current below 0.01-0.1 mA was demonstrated and extremely low thresholds lower than 1 microampere are the target of research. Reasonably high power >200mW and power conversion efficiency >50% are also demonstrated, that are equivalent or better than conventional stripe lasers. Long wavelength devices are facing some difficulties of high temperature and large output, but there are several innovating technologies to open up the bottlenecks. Very short wavelength lasers may cultivate wider applications. Micro-machining technology(MEMS) will be very helpful. In summary, the nano-devicess based upon sophisticated semiconductor lasers will open up a new era of the 21st century.

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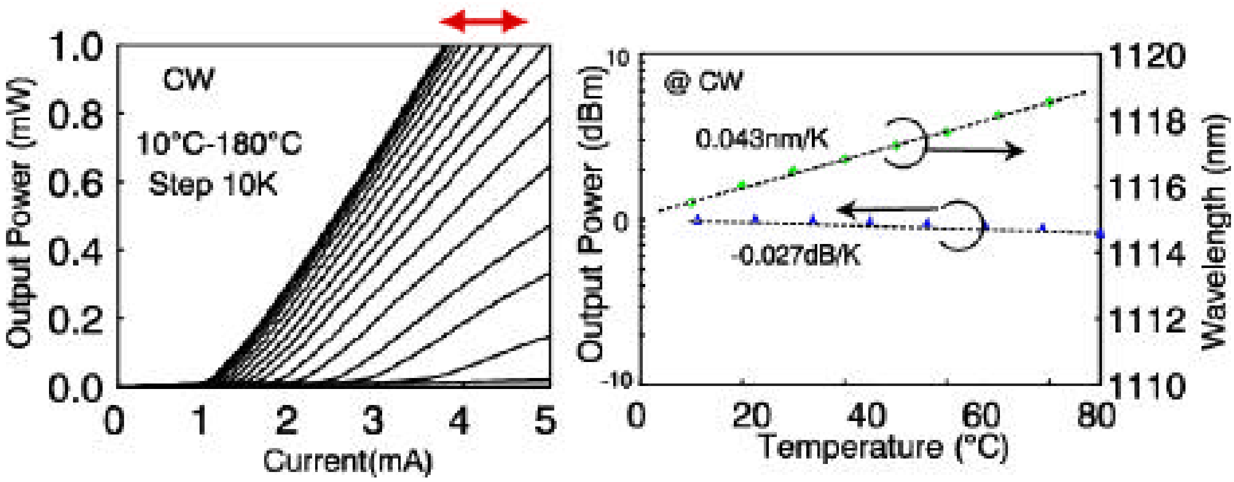

FIG. 5 Lasing characteristics of GaInAs/GaAs VCSEL grown on (311)B substrate