Semiconductor Laser in the 21st Century

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Abstract

The semiconductor laser has been taking an important role in optoeletronics and IT backbones and will be keeping its position for the coming at least 10 years. There would still be a lot of chances to meet really novel subjects in research and development, e. g. the coverage of full spectral ranges, temperature insensitive operation, ultra-high power capability, frequency control, large scale integration, and so on. In this paper, we like to discuss on the semiconductor laser for tomorrow based upon the experience of founding research of vertical cavity surface emittng laser(VCSEL).

Keywords: laser, semiconductor laser, surface emitting laser, vertical cavity surface emitting laser , VCSEL, optoelectronics

1. INTROCUCTION

Can semiconductor laser survive in the 21st Century? More than 100 years passed after Thomas Edison invented the white lamp and it is still used in many occasions although the fluorescent lamp and other sophisticated illuminations were developed. By learning from this , the semiconductor laser may be existing until 2060, since it appeared in 1962.

The semiconductor laser was realized in 1962 [1]-[4] and only pulsed operation was possible until the end of 1960's until Hayashi and Panish [5] and Alferov and coworkers [6] reported room temperature continuous wave (RT-CW) operation of GaAs/AlGaAs double heterosturecture[7] lasers. Together with the discovery of low loss optical fiber behavior, this gave a big impact to optical fiber communication and accelerate the development. The long wavelength laser was initiated around in 1976 by the introduction of GaInAsP/InP system be J. J. Hsieh et al. [8] and A. P. Bogatov et

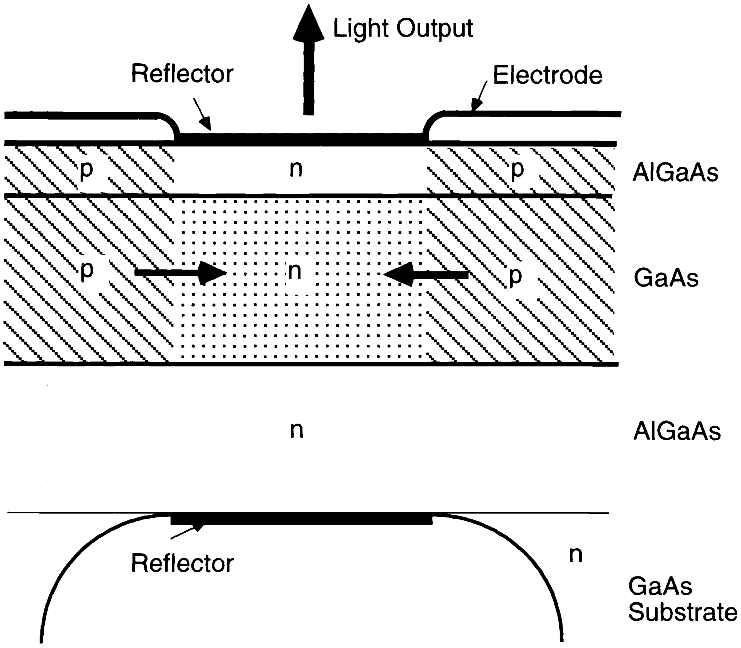

Fig. 1 Initial model of vertical cavity surface emitting laser (1977)

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al.[9], independently. As for laser cavity structure, Kogelnik and Shank [10] proposed distributed feedback (DFB) configuration which can form a resonator in a monolithic way. Nakamura experimentally demonstrated a DFB laser by means of GaAs with optical pumping[11]. Suematsu presented a concept of dynamically-single mode laser for high speed optical fiber communication[12] and demonstrated this idea using integrated lasers[13]. The present author suggested the so-called surface emitting laser in 1977 [14][15] as shown in Fig. 1 and the initial device was demonstrated[16] in 1979. Now it is known as vertical cavity surface emitting laser (VCSEL) has been applied in high speed networks as in Gigabit ether net. Visible semiconductor lasers have been widely introduced in optical disk system such as CD players, DVD systems, and higher density optical storages by employing blue GaInN/GaN lasers initially demonstrated by Nakamura[17].

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[18][19] 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[20]. This scheme may be useful for future surface emitting lasers technology. One of the challenges is to increase dot density. We have achieved 9×10^{10} cm^{-2} in long wavelength GaInNAs/GaAs system[22]. 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[23]. 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[24]. 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 [25]. 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.[26]. Also, the use of Nitrogen in GaInNAs system may provide long wavelength semiconductor lasers on GaAs substrates[27] [28] which give us good temperature characteristics. A Tl-included semiconductor GaTlAs and its family may have a bandgap energy which is independent of temperature[29].

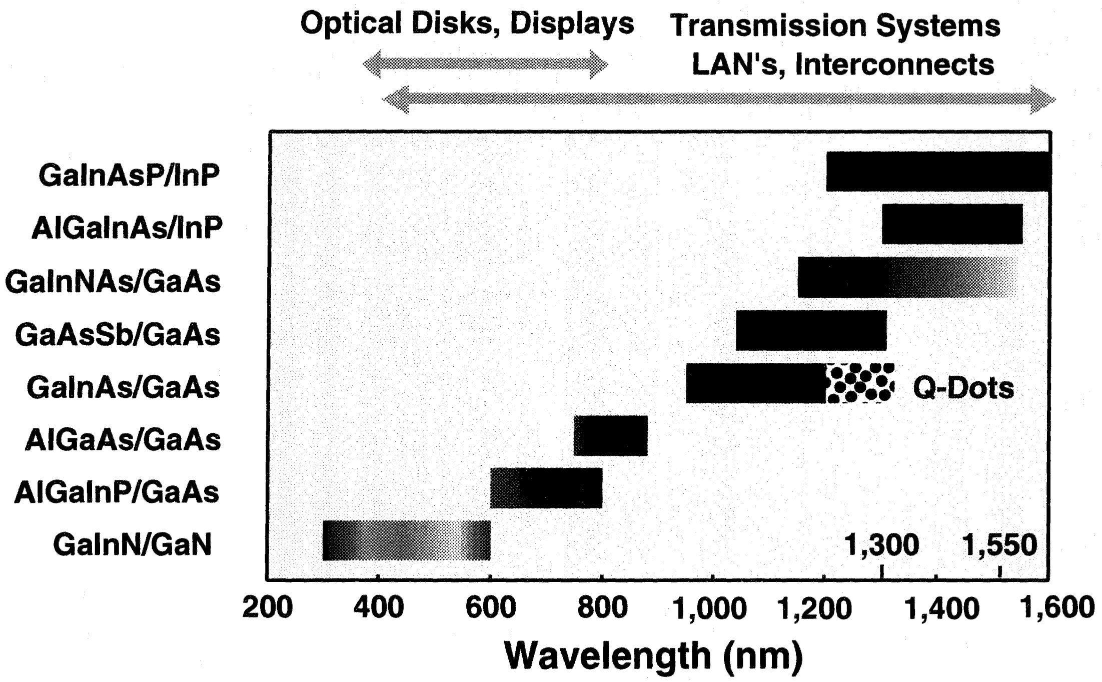


Fig. 2 Materials for semiconductor lasers

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[30] and LED's by using pn-junction was reported[31]. 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[32]. 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[33]. 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 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[34][35]. 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.

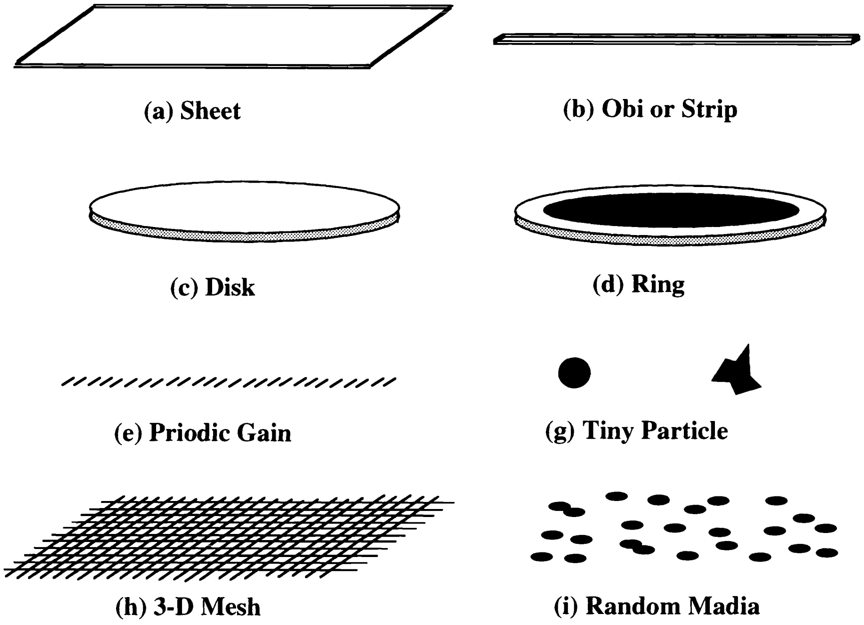

(a) Sheet
(b) Obi or Strip
(c) Disk
(d) Ring
(e) Priodic Gain
(g) Tiny Particle
(h) 3-D Mesh
(i) Random Madia

Fig. 3 Active engines for semiconductor lasers

As for the resonant cavity for semiconductor lasers the following issues 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[37] and tunneling injecton[38] 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?

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 VCSEL structure may provide a number of advantages shown below;

a) Ultra-low threshold operation is expected from its small cavity volume, reaching 1 microampere level.
b) $(I-I_{th})/I_{th}>100$ is possible. (I =Driving current, I_{th}=Threshold current)
c) Wavelength and thresholds are relatively insensitive against temperature variation.
d) Dynamic single mode operation is possible.
e) Large relaxation frequency providing high speed modulation capability.
f) Long device lifetime due to completely embedded active region and passivated surfaces
g) High power-conversion efficiency, i.e. >50%.
h) Vertical emission from substrate
i) Easy coupling to optical fibers due to good mode matching, from single mode through thick multimode fibers.
j) A number of laser devices can be fabricated by fully monolithic processes yielding very low cost chip production.
k) The initial probe test can be performed before separating devices into discrete chips.
l) Easy bonding and mounting
m) Cheep modules and packages cost
n) Densely packed and precisely arranged two-dimensional laser arrays can be formed.
o) Vertical stack integration of multi-thin-film functional optical devices can be made intact to VCSEL resonator, taking the advantage of micro-machine technology, as well.
p) Compatible integration together with LSI's

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.

It is recognized that the present author suggested the device of VCSEL in 1977[14]. The first article which was published in public is in 1978[15] which was in the Annual Meeting of Applied Physics Society. The article is reproduced in Fig. 4 with its English translation. The first device came out in 1979[16], where we used 1300 nm wavelength GaInAsP/InP material for active region. In 1986, we made a 6 mA threshold GaAs device[39][40], and after that, we employed the metal organic chemical vapor deposition (MOCVD) and the first room temperature continuous wave (CW) device using GaAs material was demonstrated in 1987[41]. And after that in 1989, Jack Jewell of AT&T demonstrated an GaInAs VCSEL exhibiting few mA of threshold current[42]. These two experiments encouraged people to be getting into the research of vertical cavity surface emitting lasers.

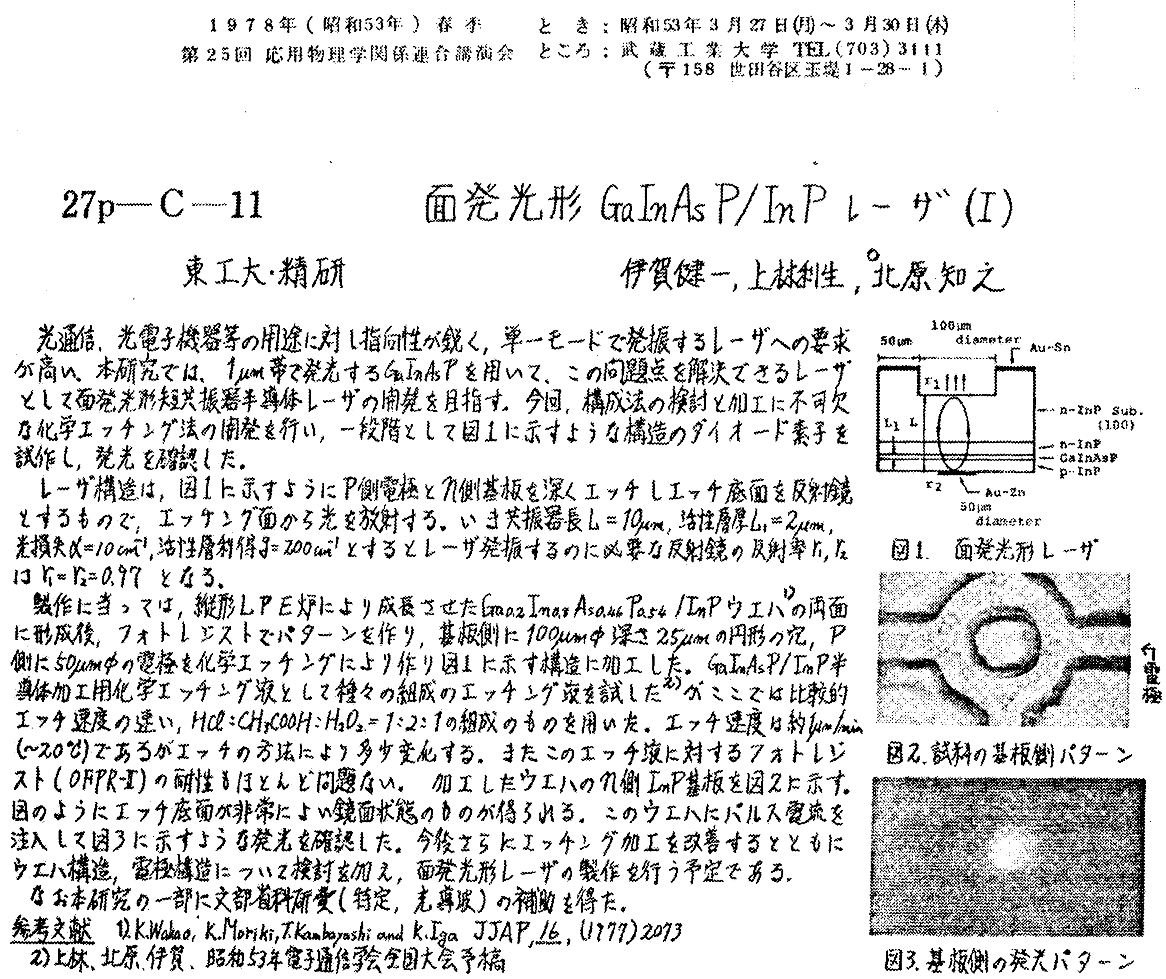
The First Presentation, March 1978

K. Iga, T. Kambayashi, and C. Kitahara:
The 25th Spring Meeting of Applied Physics Societies 27p-C-11(1978) 63.

The demand for semiconductor lasers operating in single-mode and emitting a sharp beam is strongly recognized. For the purpose of solving this problem, we aim at the development of a surface emitting laser. As a initial stage, this study suggests a device idea as shown in Fig. 1 and presents a necessary etching technology. Also we confirmed the LED structure as a preliminary experiment for realization.

The surface emitting laser structure is consists of p-electrode and etched surface of substrate as has been shown in Fig. 1 and the light is taken from the etched well. From theoretical estimation, it is led that the reflectivities r_1 and r_2 for two mirrors should be >0.97 assumed that cavity length L=10μm, active layer thickness L_1=2μm, optical loss $a=10cm^{-1}$, and optical gain $g=200cm^{-1}$, respectively.

We grew the $Ga_{0.2}In_{0.8}As_{0.46}P_{0.54}$/InP wafer by a vertical LPE system. We formed a p-electrode of 50μm on the epi-side and etched a hole of 100μm in diam and 25μm in depth. We have used a so-called KKI etch consisting of $HCl:CH_3COOH:H_2O_2=1:2:1$ having a relatively large etching rate after a lot of trials. The etching rate is 1μm/min and there was no problem in the damage of photoresist OFPR. The photograph of etched surface is shown in Fig. 2 which shows a mirror surface. We observed a near field pattern under pulsed condition as shown in Fig. 3. We are going to improve the epitaxy and etched condition to realize a surface emitting laser together with the innovation of reflectors/electrode.



１９７８年（昭和53年）春季　　とき：昭和53年３月27日(月)～３月30日(木)
第２５回 応用物理学関係連合講演会　ところ：武蔵工業大学 TEL（703）3111
（〒158 世田谷区玉堤１－28－１）

27p—C—11　　面発光形GaInAsP/InPレーザ(I)

東工大・精研　　伊賀健一，上林利生，°北原知之

光通信，光電子機器等の用途に対し指向性が鋭く，単一モードで発振するレーザへの要求が高い。本研究では，1μm帯で発光するGaInAsPを用いて，この問題点を解決できるレーザとして面発光形短共振器半導体レーザの開発を目指す。今回，構成法の検討と加工に不可欠な化学エッチング法の開発を行い，一段階として図1に示すような構造のダイオード素子を試作し，発光を確認した。

レーザ構造は，図1に示すようにP側電極とn側基板を深くエッチしエッチ底面を反射鏡とするもので，エッチング面から光を放射する。いま共振器長L=10μm，活性層厚L_1=2μm，光損失$\alpha=10cm^{-1}$，活性層利得$g=200cm^{-1}$とするとレーザ発振するのに必要な反射鏡の反射率r_1, r_2は$r_1=r_2=0.97$となる。

製作に当っては，縦形LPE炉により成長させた$Ga_{0.2}In_{0.8}As_{0.46}P_{0.54}$/InPウエハ[1]の両面に形成後，フォトレジストでパターンを作り，基板側に100μmφ深さ25μmの円形の穴，P側に50μmφの電極を化学エッチングにより作り図1に示す構造に加工した。GaInAsP/InP半導体加工用化学エッチング液として種々の組成のエッチング液を試した[2]がここでは比較的エッチ速度の速い，$HCl:CH_3COOH:H_2O_2=1:2:1$の組成のものを用いた。エッチ速度は約1μm/min(~20℃)であるがエッチの方法により多少変化する。またこのエッチ液に対するフォトレジスト(OFPR-II)の耐性もほとんど問題ない。加工したウエハのn側InP基板を図2に示す。図のようにエッチ底面が非常によい鏡面状態のものが得られる。このウエハにパルス電流を注入して図3に示すような発光を確認した。今後さらにエッチング加工を改善するとともにウエハ構造，電極構造について検討を加え，面発光形レーザの製作を行う予定である。

なお本研究の一部に文部省科研費（特定，光導波）の補助を得た。

参考文献　1) K.Wakao, K.Moriki, T.Kambayashi and K.Iga JJAP, 16, (1977) 2073
2) 上林、北原、伊賀、昭和53年電子通信学会全国大会予稿

図1. 面発光形レーザ

図2. 試料の基板側パターン

図3. 基板側の発光パターン

Fig. 4 The first presentation of surface emitting laser by K. Iga with English translation(March, 1978)

6. CURRENT TECHNOLOGY OF VCSELS

Since 1992, VCSELs based on GaAs have been extensively studied and some of 980nm[43], 850nm[44] and 780[45] nm devices are now commercialized into optical systems. Those VCSEL's can employ almost the same technology which is used in GaAs-based integrated circuits as for cellular phones. In practical 850 nm devices, sub-mA thresholds and 10 mW outputs have been achieved. The power conversion efficiency of 57% has been demonstrated[46]. The Gigabit ethernet has already been in markets by the use of multimode-fiber-based optical links. As for the reliability of VCSELs, 10^7 hours of room temperature operation is estimated based upon the acceleration test at high temperature using proton-defined devices[47]. In 1998, some preliminary test results began to be reported on oxide-defined devices exhibiting no substantial negative failures[48]. It has been made clear that the oxide aperture can function as a focusing lens, since the central window has a higher index and the oxide region exhibits a lower index. This provide us of some phase shift to focus the light toward the center axis to reduce the diffraction loss. The Al-oxide is effective both for current and optical confinements and solve the problems on surface recombination of carriers and optical scattering.

The GaInAs/GaAs strained pseudomorphic system grown on a GaAs substrate can emit 980 nm which is transparent in silicon substrate. It exhibits a very high laser gain and has been introduced into surface emitting lasers together with using GaAs/AlAs multi-layer reflectors[49] . In 1995, we have developed a novel laser structure employing selective oxidation process applied to AlAs which is one of the members of multi-layer Bragg reflector[50]. The typical size was 20 μm core starting from 30 μm mesa diameter. We have achieved about 1 mW of power output and submicro-ampere threshold. We have made a 5μm diameter device and achieved a threshold of 70 μA at room temperature CW operation [51] . A relatively high power higher than 50 mW is becoming possible [52]. The power conversion efficiency 50 % is reported [53]. This is due to the availability of low resistive DBR's in corporation with Al-oxide aperture. Actually, in devices of about 1 μm in diameter, higher than 20% of power conversion efficiencies were reported[54], [55]. Regarding the power capability, near 200 mW has been demonstrated by a large size device in Univ. Ulm [56]. In two-dimensional array involving 1000 VCSEL's with active cooling, more than 2W of CW output was achieved[57].

The importance of 1,300 or 1,550 nm devices[58][59][60] [61]is currently increasing, because parallel lightwave systems are really needed to meet rapid increase of information transmission capacity in local area networks (LAN,s). In 1993, the author's group demonstrated a 1300 nm room temperature CW device[58]. A wafer fusion technique enabled us to operate 1,550 nm VCSELs at higher temperatures[61]. The epitaxial bonding of GaInAsP/InP active region and GaAs/AlAs mirrors was introduced, where 144 °C pulsed operation was achieved by optical pumping. The CW threshold of 0.8 mA and the maximum operating temperature up to 69 °C have been reported for 1,550 nm VCSEL's with double bonded mirrors [62]. More recently, the maximum operation was achieved at 71 °C [63]. In 1998, a tandem structure of 1,300 nm VCSEL optically pumped by 850 nm VCSEL has been demonstrated to achieve 1.5mW of output power[64]. However, the cost of wafer consumption in wafer fusion devices may become the final bottle neck of low-cost commercialization

The AlGaInAs lattice matched to InP is also considered. This system may exhibit a larger conduction band offset than the conventional GaInAsP system. Moreover, we can grow a thin AlAs layer to make the native oxide for current confining aperture like the GaAs/AlAs system. The preliminary study has been made to demonstrate a stripe laser in the author's group, where a large T_0 was demonstrated[65]. By using this system the first monolithic VCSEL was fabricated demonstrating room-temperature CW operation[66].

The another viable material is long wavelength emitters which can be formed on GaAs substrate as shown in Fig. 5. One of those systems is GaInNAs lattice-matched to GaAs. This system has been pioneered by Kondow et al. [67] by a gas source molecular beam epitaxy (GSMBE) and λ=1,190 nm stripe lasers were fabricated, where the Nitrogen content is 0.4%. Room

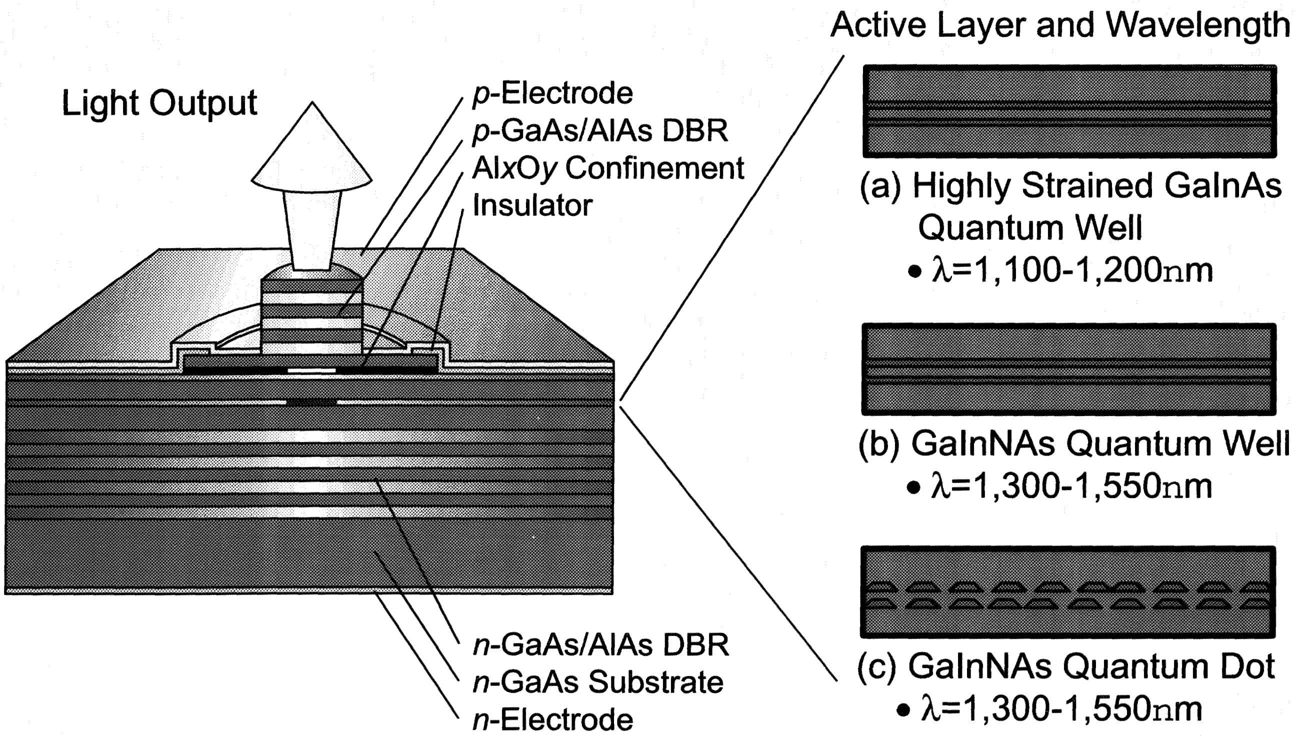


Fig. 5 Long wavelength VCSEL possibility on GaAs substrate

temperature CW operation of horizontal cavity lasers has recently been obtained exhibiting the threshold current density of 1.5 kA/cm2. Also stripe geometry lasers were demonstrated having the threshold of 24 mA at room temperature[68]. It is reported that the characteristic temperature T_0>270K around at room temperature [69]. If we can increase the nitrogen content up to 5%, the wavelength band of 1,300-1,550 nm may be covered. In particular, GaAs/AlAs Bragg reflectors can be incorporated on the same substrate, and AlAs oxidation is utilized [70]. Some consideration of device design was presented[71]. In any case, this system will substantially change the surface emitting laser performances in the long wavelength range. Larson et al. realized a first VCSEL using this system [72]. Recently, we reported a GaInNAs VCSEL grown by MOCVD[73].

During the research of GaInNAs lasers we found that a highly strained GaInAs/GaAs system containing large In-content (=40%) can provide an excellent temperature characteristic[74], i. e., operating with T_0>200K[75]. This system should be viable for λ>1,200 nm VCSELs for silica-fiber-based high speed LANs[76].

A quantum dot structure is considered as a long-wavelength active layer on GaAs substrate. A 1150 nm GaInAs-dot VCSEL was reported with a threshold current of 0.5 mA[77]. Recently, a GaAsSb QW on GaAs substrate has been demonstrated for the purpose of 1,300 nm VCSELs [78]. An AlGaAsSb/GaAs system has been found to form a good DBR[79]. A tunnel junction and AlAs oxide confinement structures may be very helpful for long wavelength VCSEL innovation[80].

The VCSEL in 780 nm wavelength range was demonstrated in 1987 by optical pumping, and the first current injection device was developed by Y. H. Lee of AT&T Bell [81]. If we choose the Al content x to be 0.14 for $Ga_{1-x}Al_xAs$, the wavelength can be as short as 780 nm. This is common for compact disc lasers. When the quantum well is used for active layer, blue shift should be taken into account. The threshold of 0.2 mA and the output of 1.1mW were demonstrated.

The AlGaInP/GaAs system emitting red color ranging 630-670 nm is considered as a laser for the first generation digital video disc system. In 1993, a room temperature high performance CW red color GaInAlAs device was demonstrated[82]. GaInAlP/GaAs VCSEL's are developed and room temperature operation exhibiting sub-milliampere threshold and 8mW out-

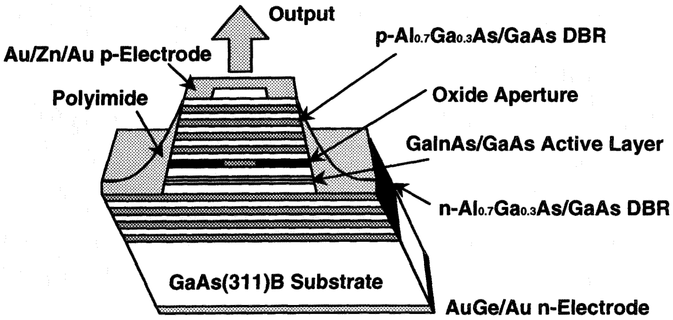


Fig. 6(a) VCSEL on GaAs(311)B substrate

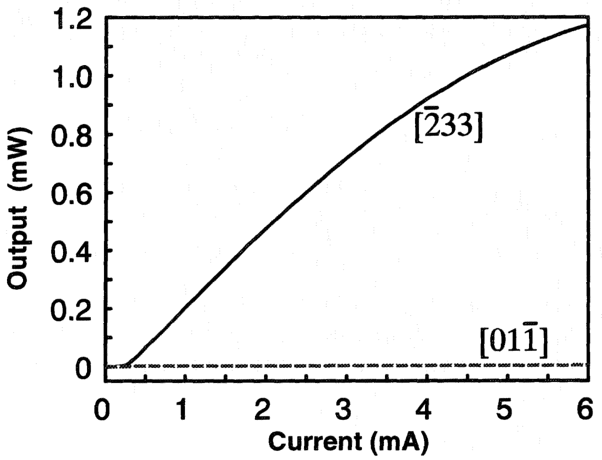


Fig. 6(b) I-L characteristic of VCSEL on GaAs(311)B substrate

put and 11% of conversion efficiency have been obtained. In 1998, sub-milliampere thresholds, 11% of power conversion efficiency, 8mW of output power have been achieved.

Visible surface emitting lasers are important for disk, printers, and display applications, in particular, red, green and blue surface emitters may provide much wider technical applications, if realized. Since 1996, the research of green-blue-ultraviolet devices has been started[83]. The GaN and related materials can cover wide spectral ranges green to UV. The reported reliability of GaN based LED's and LD's looks to indicate a good material potentiality for surface emitting lasers as well. The introduction of quantum wells for wide-bandgap lasers is really effective. The trial for realizing blue to UV VCSEL's has just started. Some of optical pumping experiments have been reported[84], [85]. It is necessary to establish some process technologies for device fabrication such as etching, surface passivation, substrate preparation, metallization, current confinement formation, and so on. AlN/GaN DBR and ZrO/SiO_2 DBR are formed for VCSELs [84], and some selective growth techniques are attempted. A photo-pumped GaInN VCSEL was reported[85][86]. Also we are trying to grow GaInN/GaN on silica glass for large area light emitters.

Most of VCSELs grown on GaAs (100) substrates shows unstable polarization states due to isotropic material gain and symmetric cavity structures. VCSELs grown by MBE on GaAs (311)A substrates, however, show a very stable polarization state [87]. Also, trials of growth on (GaAs)B substrates by using MOCVD has been performed[88], [89]. Single transverse mode and polarization mode controlled VCSELs have not been realized at the same time.

The schematic structure of a fabricated top emitting VCSEL grown on GaAs (311)B is shown in Fig. 6(a), which has been grown by low pressure MOCVD[90]. The bottom n-type distributed Bragg reflector (DBR) consists of 36 pairs of $Al_{0.7}Ga_{0.3}As$/GaAs doped with Se. The top p-type DBR consists of 21 pairs of Zn-doped $Al_{0.7}Ga_{0.3}As$ / GaAs and a 70 Å thick AlAs carbon high-doping layer inserted at the upper AlGaAs interface by the carbon auto-doping technique

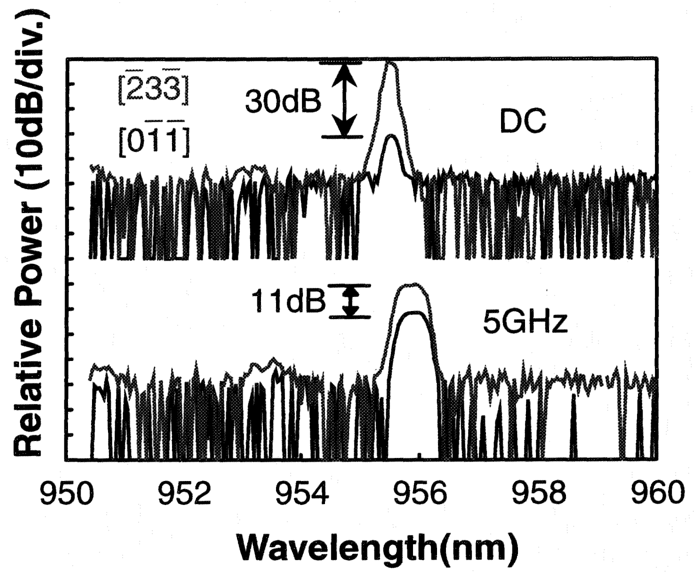


Fig.7 Modulation characteristic of VCSEL on GaAs(311)B substrate

proposed by us. The active layer consists of three 8 nm thick $In_{0.2}Ga_{0.8}As$ quantum wells and 10nm GaAs barriers surrounded by $Al_{0.2}Ga_{0.8}As$ to form a cavity. An 80 nm thick AlAs was introduced on the upper cavity spacer layer to form an oxide confinement. We oxidized the AlAs layer of etched 50-µm-square mesa at 480°C for 5 minutes in an N_2/H_2O atmosphere by bubbling in 80 °C water and formed an oxide aperture of 2.5µmx3.0µm.

Figure 6(b) shows a typical current-light (I-L) and current-voltage (I-V) characteristic under room temperature CW operation. The threshold current is 0.26 mA, which is comparable to the lowest value reported for non-(100) substrate VCSELs. The threshold voltage is 1.5 V and the maximum output power is 0.7 mW at 4 mA.

In the entire tested driving range ($I < 16I_{th}$), a large side mode suppression ratio (SMSR) of over 35 dB and an orthogonal polarization suppression ratio (OPSR) of over 25 dB were achieved at the same time. The single polarization operation was maintained at 5GHz modulation condition[91], [92] as shown in Fig. 7.

The selective oxidation of AlAs is becoming a standard current and optical confinement scheme for mA threshold devices. Technology of mode-stable lasers using (311)B substrate is demonstrated for polarization control[93]. We have obtained completely single mode VCSEL by employing most of available advanced techniques.

7. INTEGRATION AND APPLICATIONS

A wide variety of functions, such as frequency tuning, amplification, and filtering should be integrated. Another possible way of moduling is to use the micro-optical bench(MOB) concept [94] to ease the assembling of components without precise alignment as shown in Fig. 8. Moreover, a 2-D parallel optical logic system can deal with a large amount of image information with high speed. To this demand, a surface emitting (SE) laser will be a key device. Optical neural chips have been investigated for the purpose of making optical neuro-computers and VSTEP integrated device [95].

High power capabilities from VCSEL's is very interesting by featuring largely extending 2-D arrays. For the purpose of realizing coherent arrays, coherent coupling of these arrayed lasers has been tried by using a Talbot cavity and phase compensation is considered. It is pointed out that 2-D arrays are more suitable to make a coherent array than a linear configuration, since we can take the advantage of 2-D symmetry. The research activity is now forwarded to monolithic integration of VCSEL's

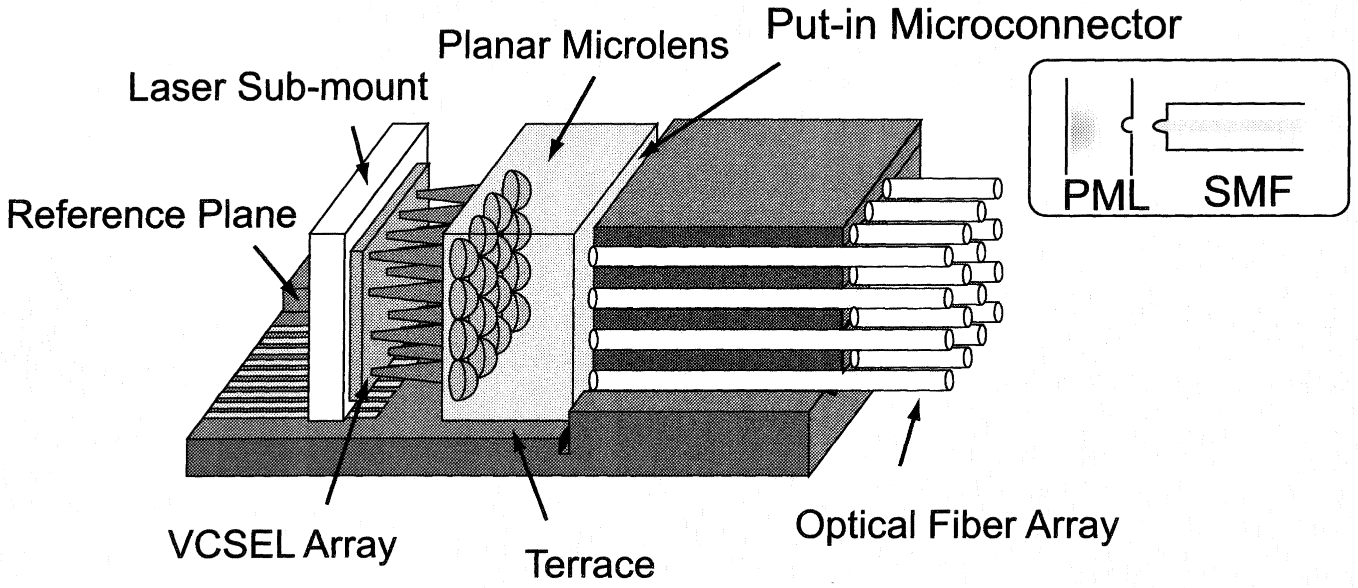


Fig. 8 Micro optical bench (MOB) concept for VCSEL moduling

taking the advantage of small cavity dimensions. A densely packed array has also been demonstrated for the purpose of making high power lasers and coherent arrays. Into VCSEL's, surface operating photonic elements using quantum wells such as an optical switch, frequency tuner, optical filter, and super-lattice functional devices are now tried to be integrated. Monolithic lenses can be formed on VCSEL's by an etching process to narrower the beam divergence [96].

Lastly we like to discuss on the possible applications of VCSEL's. In low power consumption and high speed modulation is inevitable low power interconnect applications enabling >10Gbits/s transmission or 1Gb/s zero-bias operation[97]. Actually, transmission experiments over 10Gbits/s and zero-bias transmission have been reported. We measured an eye diagram for 10 Gbits/s transmission experiment through a 100m multimode fiber[97]. Finally, VCSEL's in long wavelength may find the market in 10 Gigabit LAN's together with high speed detectors and silica fibers. In any way, GaInAs and GaInNAs VCSEL's show the best performance and the research to challenge the extreme characteristics will be continued. The development of 1,200-1,550 nm VCSELs may be one of the most important issues in surface emitting laser research [98].

The red color VCSEL emitting 650 nm can match to the low loss band of plastic fibers. Short distance data links are considered by using 1 mm diameter plastic fibers having graded-index have been developed. This system provides us of very easy optical coupling. VCSEL's can very nicely match to this application.

By taking the advantage of wide band and small volume transmission capability, the optical interconnect is considered to be inevitable in the computer technology. Some parallel interconnect scheme is wanted and new concepts is being researched. Vertical optical interconnect of LSI chips and circuit boards may be another interesting issue. A new architecture for 64 channel interconnect has been proposed and a modeling experiment was performed using GaInAs VCSEL arrays [99].

Several schemes for optical computing have been considered, but one of the bottle necks may be a lack of suitable optical devices, in particular, 2-D VCSEL's and surface operating switches. Fortunately, very low threshold VCSEL's have been developed, and stack integration together with 2-D photonic devices are now actually considered.

Green to UV VCSEL's will be useful in the optoelectronics field as in ultra-high density optical memories. The present author proposed a model of optical pickup[76] using VCSEL as shown in Fig. 16. This kind of simple pickup is now being commercialized. Near field optics scheme is considered to realized high density optical memories [77]. A possible device was demonstrated [78]. Full color flat displays and large area projectors, illuminations and light-signals, light decorations, UV-lithography, laser processes, medical treatment, and so on.

8. SUMMARY

We have discussed on future prospects 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, if realized.

Vertical optical interconnects of LSI chips and circuit boards and multiple fiber systems may be the most interesting field. From this point of view, the device should be as small as possible. The future process technology for it including epitaxy and etching will drastically change the situation of microlasers. Some optical technologies are already introduced in various subsystems, and, in addition, the arrayed microoptic technology would be very helpful for advanced systems.

The most promising application of semiconductor lasers will be Giga-bit LANs. GaAs VCSELs emitting 850nm of standardized wavelength are mass-produced for >1Gbits/s LAN and simple optical links. For 10 Giga-bit LAN systems, 1,300-

1,550nm devices are requested.

To establish an appropriate module technology utilizing VCSELs, a micro optical bench (MOB) has been investigated together with planar microlens array. Related to planar microlens array application and ultra-parallel information processing, an image recognition system is investigated using SDF filtering. Micro-machining technology(MEMS) will be very helpful.

In summary, the ultra-parallel and ultra-high speed optoelectronics based upon sophisticated semiconductor lasers will open up a new era of 2000 millennium.

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