Development of Semiconductor Laser for Optical Communication

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The performance of the semiconductor laser has been dramatically improved by applying quantum well structure including strained layer superlattice and innovation of crystal growth techniques such as organometallic vapor phase epitaxy. The semiconductor laser used for optical communication came to be indispensable for our life as an optical component connecting not only long-distance large-capacity trunk networks but also access networks. This paper describes the development of the semiconductor laser for optical communication focusing mainly on Sumitomo Electric's R&D activities. With the progress of optical transmission technology, various kinds of semiconductor lasers have been developed for the application to wavelength division multiplexing, high speed, low power consumption, and photonic integration.

Keywords: semiconductor laser, optical communication, quantum well

1. Introduction

The performance, functionality and productivity of the semiconductor laser have been dramatically improved since its invention in 1962. Today it came to be indispensable for our life as optical components connecting home and the Internet as well as long-distance large-capacity trunk networks.

It may be said that the information revolution pulled by the explosive spread of the Internet is originated from three innovations from 1969 to 1970, the room temperature continuous wave operation of the semiconductor laser, the invention of the low loss optical fiber and the beginning of ARPAnet (Advanced Research Projects Agency Network) experiment. In those days, we already started research and development of optical fiber and compound semiconductor materials such as GaAs which was widely used as a substrate material of compound semiconductor devices. We started the research and development of compound semiconductor devices for optical communication from the middle of the 1980's in order to establish optical communication business vertically integrating technology from materials, devices to systems.

This paper describes the development of the semiconductor laser for optical communication focusing mainly on Sumitomo Electric's R&D activities with the progress of transmission technology. By the beginning of 1990's 1.3 μm Fabry-Perot (FP) lasers were developed for the application to metro-access networks. In the 1990's practical use of wavelength division multiplexing (WDM) started and pumping lasers for fiber amplifiers and distributed feedback (DFB) lasers were developed for WDM application. In the 2000's with the recovery from the IT bubble burst, further improvements of modulation speed, power consumption and functionality were progressed by the development of new material, vertical cavity surface emitting laser (VCSEL) and photonic integration.

2. Development of high performance FP laser

2-1 Materials and crystal growth techniques

Wavelengths used for optical communication are mainly 1.55 μm for long-distance transmission and 1.3 μm for short- and mid distance transmission due to the minimum loss and minimum dispersion in optical fiber, respectively as shown in **Fig. 1**. However, recently over 400 nm band ranging from 1260 nm to 1675 nm came to be used by the introduction of the WDM technology mentioned later. It is required that the band gap of the material composing semiconductor laser correspond to the oscillation wavelength of the laser and its lattice constant match to the lattice constant of the substrate to maintain high crystal quality. Typical compound semiconductors that meet these conditions are GaInAsP, AlGaInAs grown on the InP substrate and GaInNAs, (Ga)InAs dots structure grown on the GaAs substrate. Today, GaInAsP is widely used from view points of reliability of device and handling in its process.

Liquid Phase Epitaxy (LPE) has been used for the growth of high quality compound semiconductors. However, molecular beam epitaxy (MBE) and Organometallic

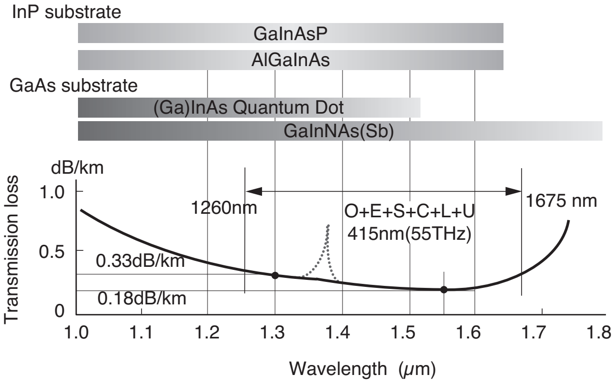


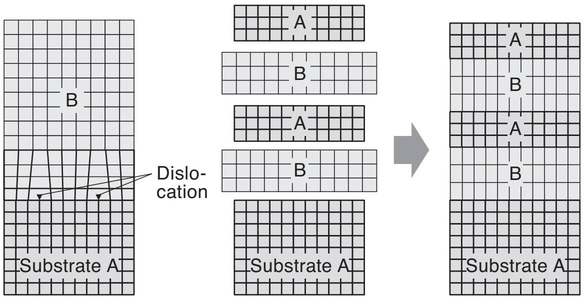
Fig. 1. Fiber transmission loss and related compound semiconductors

Vapor Phase Epitaxy (OMVPE) have been developed rapidly from the beginning of the 1980's. These crystal growth technologies are suitable for mass production and enable to grow a very thin layer which is essential for realizing high performance devices. Especially, OMVPE which is suitable for the synthesis of phosphorus compounds and selective area growth has been used for the growth of semiconductor lasers. We established OMVPE crystal growth techniques as a core technology for the fabrication of semiconductor devices in the late 1980's. We designed the reactor and the gas supply system of OMVPE for realizing ultrafine structure with good uniformity. Excellent uniformity over a 2-inch wafer with monolayer hetero-interface abruptness was obtained(1)-(3).

2-2 Development of quantum well structure

The lattice constant and the band gap of a compound semiconductor can be controlled by changing the composition of the compound. In the structure that two compound semiconductors with different band gaps pile up alternatively, electrons and holes are confined in the lower band gap layers. The thickness of the lower band gap layer approaches to electron mean free pass (several 10 nm), energy levels of electron and hole are quantized. This structure is called quantum well (QW) or multiple quantum well (MQW) when the structure consists of multiple layers. In the MQW structure, novel phenomenon which cannot be obtained in the bulk material appears. By applying MQW structure to the active region of the laser, the performances of the laser such as threshold current, temperature characteristics and modulation frequency were significantly improved(4), (5) and MQW became an essential technology for realizing high performance lasers.

Further improvement of laser performance was expected by introducing a strain in the active region of the laser in addition to MQW technology. In general, the lattice constant must be matched to that of the substrate to maintain high crystal quality. However, in the MQW structure, the strain caused by lattice mismatch can be accumulated in the crystal by deforming the lattice without generating misfit dislocation since the layer is very thin as shown in **Fig. 2**. Therefore, the flexibility of MQW design will be improved by relaxing the restriction of lattice matching condition(6). The effect of stain on the performance of devices has been intensively studied and demonstrated such as the reduction of threshold current(7), (8), higher frequency characteristics and improved reliability(9)-(11).



Dislocations are generated when B layer is thicker than the critical thickness

No dislocation is generated when B layer is thinner than the critical thickness
(B layer is under biaxial compressive strain)

Fig. 2. Strained quantum well structure

We have applied strained quantum well structure to visible laser(12)-(15) and pumping laser for optical fiber amplifier(12), (16) for the first time and confirmed significant improvement of device performance. The strained quantum well technology provided the tool to control effective mass in addition to quantum size effect and came to be a core technology for creating high performance compound semiconductor devices by expanding the flexibility of the band engineering.

2-3 Development of all OMVPE grown MQW FP laser

We first developed 1.31 µm MQW FP laser for metro-access network application. **Figure 3** shows a schematic diagram of the laser. The active region of the laser consists of GaInAsP MQW. After the first growth, the wafer was wet etched to form mesa stripe waveguide and p-InP and n-InP current blocking layers were selectively grown. Then the upper cladding layer and contact layer were grown to form planar buried heterostructure (PBH). Finally, the trench was formed to reduce parasitic capacitances and electrodes were made after thinning the substrate. It should be mentioned that OMVPE was employed for all crystal growth process to improve the uniformity over a 2-inch wafer. The device showed excellent high temperature characteristics with a maximum operating temperature of 130 °C and good uniformity over the 2-inch wafer with standard deviation of threshold current of 0.76 mA(17).

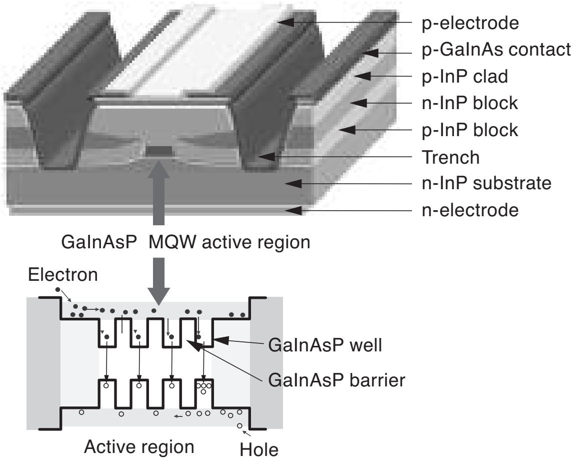


Fig. 3. FP laser structure

This MQW laser manufacturing process innovation promoted the laser which had been treated like an art craft to the mass production stage and contributed to the reduction of production costs and the improvement of productivity. This wafer process has formed the backbone of our manufacturing technology of semiconductor lasers.

3. Development of lasers for WDM application

3-1 Progress of WDM transmission technology

WDM transmission is a method to transmit different wavelength optical signals in a single fiber. Therefore, by applying WDM transmission technology, significant increase of the transmission capacity can be realized relatively easily without installing new optical fibers. WDM transmission with a narrow wavelength spacing called DWDM (Dense WDM) was introduced to long-haul trunk networks from the mid-90's. Then, a wide wavelength spacing called CWDM (Coarse WDM) was introduced to metro-access networks as a cost effective solution to increase the transmission capacity.

The innovation of optical amplifier greatly contributed to realize WDM transmission system (18). Optical fiber amplification technology, as shown in **Fig.4**, enables to amplify an optical signal in a relatively wide wavelength range without converting an optical signal into an electrical signal regardless of transmission speed and format. Erbium doped fiber amplifier (EDFA) is commonly used for the amplification of 1.5 µm band optical signal by the excitation of 0.98 µm, and/or 1.48 µm high power laser. We started to develop high power pumping laser for fiber amplifier from the early 90's based on the technology developed for 1.3 µm FP laser.

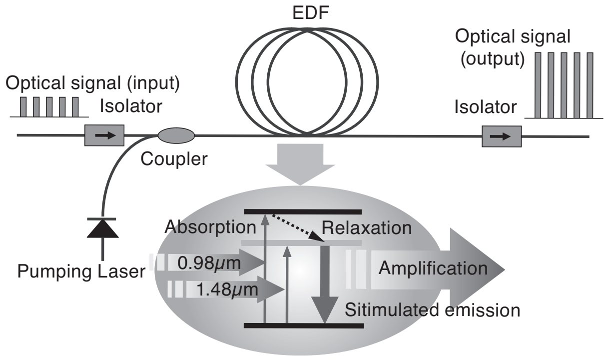


Fig. 4. Principle of erbium-doped fiber amplifier (EDFA)

3-2 Fiber amplifier pumping lasers

Two types of pumping lasers, 1.48 µm laser composed on InP and 0.98 µm laser composed on GaAs are used for EDFA. These devices are requested to increase optical output power with keeping high reliability.

In the development of 1.48 µm laser, we introduced compressively strained quantum well structure to the active region of the laser to improve output power for the first time. As shown in **Fig. 5** the optical output power increased more than 30% by introducing 1% strain in the quantum well. High reliability has also been confirmed by several acceleration tests including more than 5,000 hour's aging with output power of 160 mW (16), (19). These results clearly indicated that stained quantum well technology was very effective to improve device performance. The high power laser module using this device shown in **photo 1** was highly evaluated in the market.

For improving optical output power of the laser module, the polarization and the wavelength multiplexing were also used. We fabricated fiber-grating laser modules using 1.48 µm semiconductor optical amplifiers (SOAs) and fiber gratings with oscillation wavelength ranging from 1.46 µm to 1.49 µm. Optical output power of 520 mW was achieved by combining 4 fiber-grating laser modules using fiber interference coupler (20).

In the development of 0.98 µm pumping laser elimination of sudden failure of the device by catastrophic optical damage (COD) due to high optical density at the facet was a major issue to be solved.

COD occurs at the vicinity of the facet by positive feedback cycle of temperature increase by optical absorption, band gap reduction by temperature increase and the enhancement of optical absorption by band gap reduction. This results in a sudden increase of temperature at the facet and the destruction of the facet region. Therefore, we developed window structure device which has higher band gap at the facet to suppress optical absorption near the facet. The window structure was formed by selective nitrogen ion implantation near the facet region and subsequent annealing which enhances atomic interdiffusion in the quantum well (21)-(23). As a result, COD tolerance was significantly improved. We also developed a

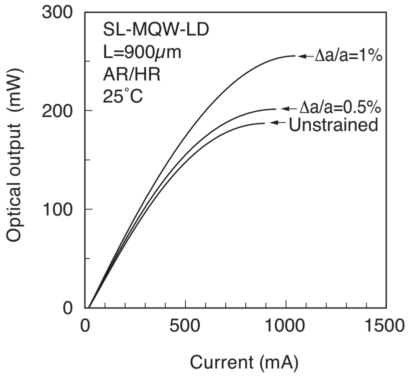


Fig. 5. I-L Characteristic of strained and unstrained MQW 1.48 µm pumping laser

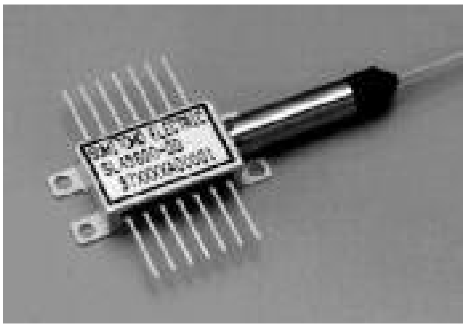


Photo 1. Fiber amplifier pumping laser module

method to purge the device which might cause COD failure by quantifying the decrease of COD level in the screening process (24), (25). These findings were also applied to the subsequent development of high speed devices to improve their reliability.

3-3 Distributed feedback (DFB) laser

WDM technology has also been widely used in metro-access networks with increasing traffic in photonic network. In the metro-access networks, CWDM is mainly used with wide wavelength spacing of 20 nm. The light source used for CWDM system is required to operate in the wide temperature range with high side-mode suppression ratio (SMSR) without temperature control.

In general, DFB laser in which the grating is formed in the vicinity of the active region is used as shown in **Fig. 6**. The oscillation wavelength of DFB laser is determined mainly by the equivalent refractive index of the grating region and the grating pitch.

Temperature dependence of the oscillation wavelength of DFB laser is determined by the temperature dependence of refractive index of the material (~0.1nm/°C) composed DFB laser active region. On the other hand, temperature dependence of gain peak of DFB laser is determined by the temperature dependence of material gain (~ 0.4nm/°C). Consequently, the gain peak of DFB laser shifts toward longer wavelength from the oscillation wavelength at high temperature, and it shifts toward shorter wavelength from the oscillation wavelength at low temperature. Then, this results in the reduction of output power at high temperature due to the reduction of the gain and multimode operation at low temperature. Therefore, for uncooled operation in the wide temperature range with high SMSR, it is important to control the detuning which is the wavelength difference between the laser gain peak and oscillation wavelength.

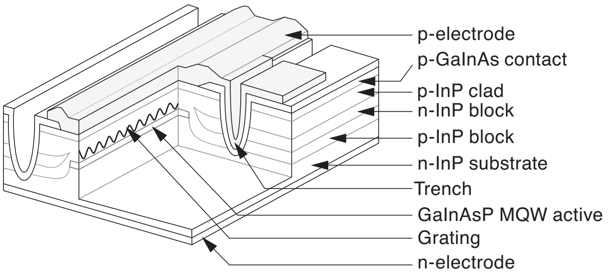


Fig. 6. DFB laser structure

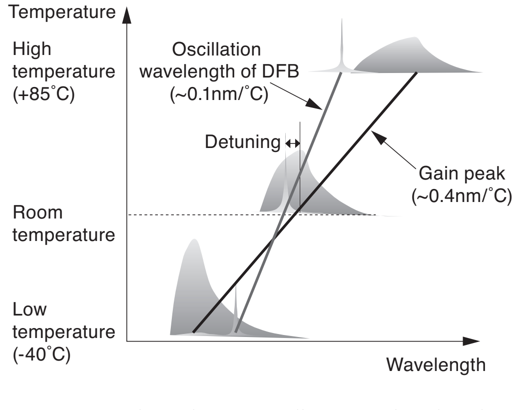


Fig. 7. Temperature dependence of oscillation wavelength and gain peak

The grating applied to DFB laser is formed by electron beam lithography or laser interference lithography, etching and subsequent planar buried growth. We established the process which enabled to form highly uniform grating over a 2-inch wafer and applied it to FP laser process described previously to fabricate DFB laser. The detuning and doping concentrations in p-InP and n-InP current blocking layers were optimized to operate in the wide temperature ranging from -40 to 85 °C (26). We fabricated the grating on the active region so that high quality MQW structure can be maintained and this selection made the detuning control easier. Therefore, we could have DFB lasers operating wavelength ranging from 1270 nm to 1610 nm with good temperature characteristics in the early stage of the spread of CWDM system. Transmitter optical sub-assemblies (TOSAs) using these devices shown in **photo 2** became one of our main products.

As the CWDM systems were widely used, it was desired that device performances were uniform in a wide wavelength ranging typically from 1470 nm to 1610 nm (S to L-band) which was the most commonly used.

However, in general, device characteristics will degrade as the oscillation wavelength becomes longer due to the increase of losses such as Auger recombination and inter-valence band absorption. We improved the performance of devices operating in the longer wavelength region and reduced the oscillation wavelength dependence of device performance by optimizing the distribution of doping concentration and quantum well structure for the reduction of internal losses (27).

Figure 8 shows the I-L characteristics of S, C, L-band DFB lasers at 85°C. Considerable improvement in the reduction of the threshold current and the increase of the slop efficiency in the L-band device were obtained. As a result, very good uniformity in I-L characteristics of DFB lasers over S to L-band was achieved. The modulation characteristic which was sufficient for 2.5 Gbps operation at 85 °C over S to L-band was also obtained and the power penalty after 100 km transmission at 85 °C was less than 1 dB.

These DFB lasers operating in the temperature rang-

Photo 2. S, C, L-band DFB laser TOSAs (S: 1470,1490,1510 nm C: 1530,1550,1570 nm L: 1590, 1610 nm)

ing from -40 to 85 °C without cooling were used not only digital application mentioned above but also analogue application such as analogue CATV (28).

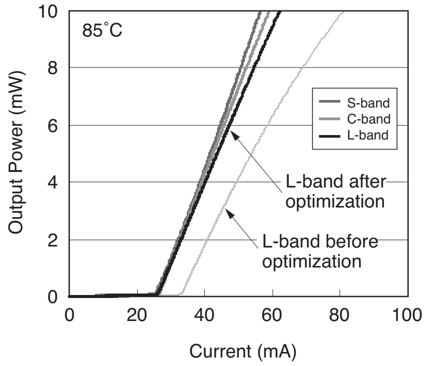


Fig. 8. I-L characteristics of S, C, L-band DFB lasers before and after optimization

4. Development of high speed and low power consumption devices

4-1 Approach for high speed operation

The modulation speed has also been increased rapidly while the use of the wavelength has been progressed by the spread of WDM system. The history of standardization showed that the modulation speed increased 4 times in 5 years in Synchronous Digital Hierarchy (SDH) and 10 times in 3 years in Ethernet. And the standardization of 100 Gbps Ethernet is scheduled to be finished in May 2010.

The modulation speed of semiconductor laser is limited by mainly two factors, relaxation frequency and parasitic impedance. For 10 Gbps application, we first reduced parasitic impedance to improve electric bandwidth. The trench shown in **Fig. 3** was buried by BCB (Benzocyclobutene) to reduce parasitic capacitances of the device. The modulation bandwidth was increased up to 15 GHz and the device satisfied the specification of 10 Gbps Ethernet application. However, it became clear that this device could not be used for SDH application and higher bit rate application due to the limitation of the relaxation frequency, which was originated from material properties. Therefore, we developed new material AlGaInAs to improve the relaxation frequency especially at high temperature. **Figure 9** shows the schematic of band gap for three different material systems, GaInAsP/InP, AlGaInAs/InP, and GaInNAs/GaAs. AlGaInAs and GaInNAs material systems have larger conduction band offset comparing with that of GaInAsP material system. Therefore, AlGaInAs material system can provide better carrier confinement which enhances the relaxation frequency.

AlGaInAs can be lattice-matched to the InP substrate and consists of only one group V element. Therefore, the uniformity of composition over a wafer can be improved due to an easy control of the composition and large part of the conventional InP based device process can be employed for the fabrication of the device. On the other hand, since Al is easily oxidized in its nature, this could trigger problems such as the reduction of resistance under high optical density and the generation of crystal defects in the process. Therefore, much effort has been made to ensure the reliability of the device.

We fabricated PBH laser shown in **Fig. 3** with AlGaInAs MQW active region while paying much attention to the specific nature of the material. As a result, we obtained a median lifetime of 240,000 hours estimated from more than 10,000 hours accelerated aging at 85 °C which was sufficient for practical use and also realized 10 Gbps DFB laser operation at 85 °C (29).

The configuration of 100 GbE will be 25GbpsX4 WDM system. To realize 25 Gbps direct modulation further improvement of electronic bandwidth of the device was required. Therefore, we developed planar buried BCB ridge-waveguide DFB laser shown in **Fig. 10** to reduce parasitic capacitances of the device. We succeeded in the reduction of the capacitance and the device showed excellent high speed performances with the modulation efficiency 3 GHz/mA$^{1/2}$ at room temperature which was the highest value obtained in our edge emitting lasers. Electronic bandwidth over 20 GHz and clear eye-opening with extinction ratio of 6 dB at 26 Gbps as shown in **Fig. 10** were also

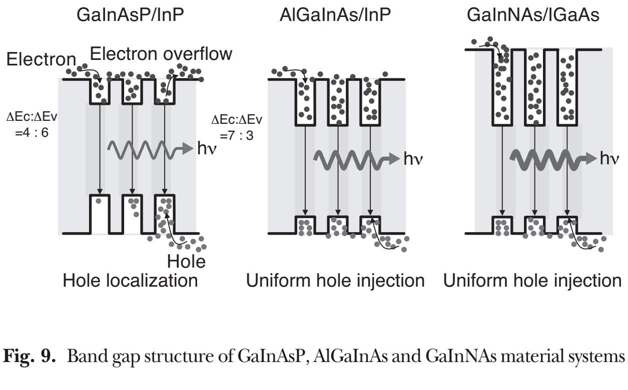


Fig. 9. Band gap structure of GaInAsP, AlGaInAs and GaInNAs material systems

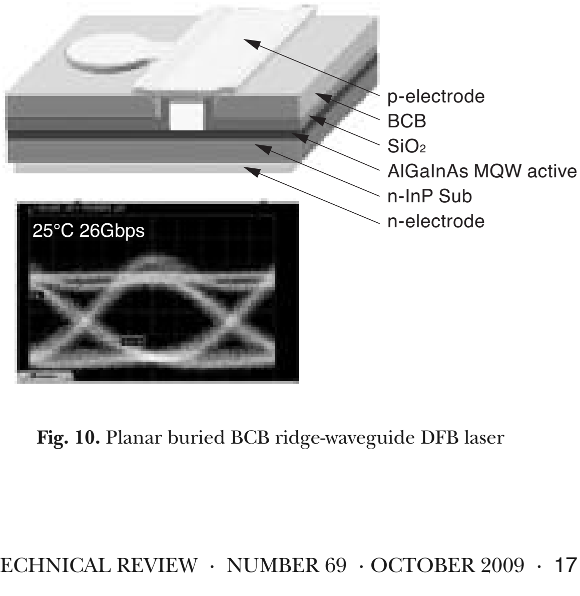


Fig. 10. Planar buried BCB ridge-waveguide DFB laser

obtained (30), (31). This laser is a very promising device for over 10 Gbps applications.

4-2 Development of low power consumption devices

The reduction of power consumption of the device is very important for realizing not only high density assembling and downsizing of TOAS but also the reduction of the power consumption of total system that uses the device. Power consumption per bit as well as the cost per bit will be important factor to choose the device.

GaInNAs material system can be grown on the GaAs substrate and can form larger conduction band offset than that of AlGaInAs material system. Therefore, by applying GaInNAs to the active region of devices, the improvement of temperature characteristics of devices and the realization of cost-effective highly productive devices are expected (32). In addition to these advantages, low thermal resistance AlGaAs/GaAs semiconductor distributed Bragg deflector (DBR) can be employed for long wavelength VCSEL. These material features have been demonstrated by performances of several devices including FP lasers (33)-(35), DFB lasers (36), SOAs (37), and long wavelength VCSELs (38), (39).

The major issue for practical use of long wavelength VCSEL is to meet the specifications that have been determined for edge emitting lasers. Especially optical output power and high frequency performance at high temperature were difficult requirement to overcome. To improve these characteristics of the VCSEL, we have developed new structure device shown in **Fig. 11**, in which the tunnel junction for current confinement and the dielectric DBR for upper mirror were introduced to reduce series resistance and effective cavity length, respectively (40)-(42).

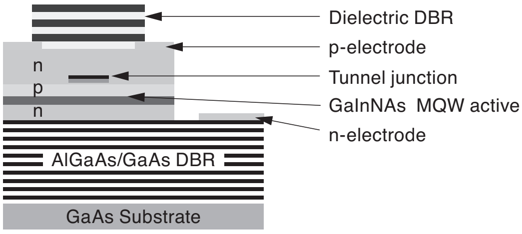


Fig. 11. Long wavelength VCSEL structure

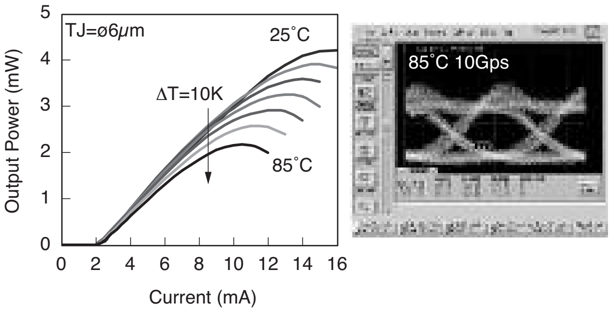


Fig. 12. Temperature dependence of I-L characteristics of VCSEL and 10 Gbps eye pattern at 85 °C

Figure 12 shows typical temperature dependence of I-L characteristics of the device with the tunnel junction diameter of 6 µm and 10 Gbps eye pattern at 85 °C. Maximum optical output power at 25 °C and 85 °C were 4.2 mW and 2.2 mW, respectively. 10 Gbps operation at 85 °C was also achieved with only 7 mA bias current. These results clearly indicate this device has high potential for the application of short- and mid distance transmission with very low power consumption.

5. Development of Photonic Integrated Devices

Photonic integrated device proposed in 1969 (43) is one of promising approaches for realizing multi-functional high performance devices with compact in size and low cost. This technology is called photonic integrated circuit (PIC) and has been practical used as planar silica waveguide optical passive components such as optical splitters and arrayed waveguide gratings (AWGs). However the progress of semiconductor PIC is gradual. Since the degree of completion of each active element is not sufficient to omit the screening, monolithic integration will increase the complexity of inspections and reduce the yield. Therefore, the formation of photonic integration has remained simple.

One of the simplest photonic integrated devices is the electroabsorption modulator (EAM) monolithically integrated with DFB laser. EA-DFB laser modulates a signal by absorbing light from DFB laser by changing the absorption edge of the modulator with electric field. Since EA-DFB laser operates without carrier injection, high speed modulation with low chirp due to small refractive index change by the modulation can be realized. Therefore, this device is suitable for high speed mid- and long distance transmission application such as 100 GbE and 40 Gbps transmission.

We integrated 1.3µm-DFB laser and EMA consisting of GaInAsP MQW structure by the butt joint using selective growth technique. EA-DFB laser shown in **Fig. 13** is fabricated by high mesa etching and Fe-InP regrowth which works as a current blocking layer with low capacitance. The device operates up to at least 40 Gbps at 25 °C with clear eye-opening as shown in **Fig. 14**. This demonstrates that this EA-DFB laser can be applied for 320 Gbps (40GbpsX8 wavelengths) system in near future (44).

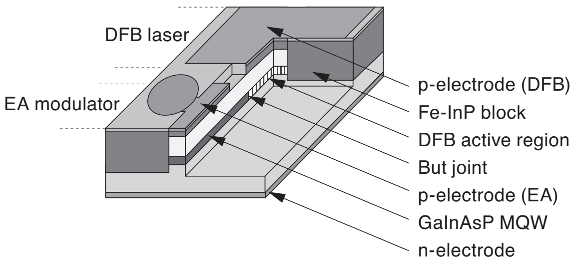


Fig. 13. EA-DFB laser

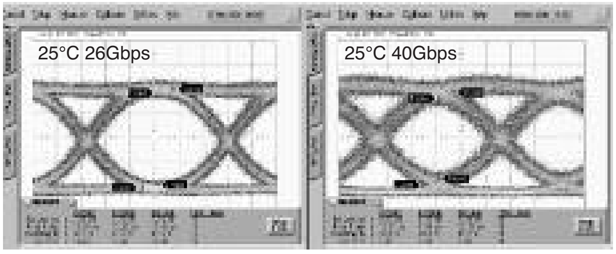


Fig. 14. 26 Gbps and 40 Gbps eye patterns of EA-DFB laser at 25°C.

Great efforts have been made not only for improving the performance of existing devices mentioned above but also for realizing new functional devices such as wavelength tunable laser (45)-(48), wavelength converter (49), (50) monolithic integrated ONU (Optical Network Unit) (51), optical network node device (52) in many research organizations.

As a degree of completion of individual devices becomes higher, the benefit of monolithic integration increases, and it is expected that PIC technology provides a valid solution for the reduction of cost per the product of bit rate and transmission distance as well as power consumption per the product of bit rate and transmission distance.

6. Conclusion

We have described the development of the semiconductor laser for optical communication focusing mainly on Sumitomo Electric's R&D activities. Through such development, cumulative shipments of long wavelength semiconductor lasers reached 10 million devices in January 2007. In the early stage of commercialization, the laser was said like an art craft so that it was difficult to use without paying careful attention. Now it is commonly used even at home as a key device that supports the infrastructure of information society. This change mainly originated from the device technology innovations based on quantum well structure and breakthrough of crystal growth technology that enable to grow it and remarkable improvement of electronics technology.

In 2012, the semiconductor laser reaches 50 years old. However, with the increase of traffic in future photonic networks, further improvement of the performance such as high speed modulation toward theoretical limit, advanced application of wavelength and polarization and utilization of photonic integration is expected. Exciting challenge will be continued for the next breakthrough in photonic device technology.

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