Invited Paper

Characteristics and reliability of high-power GaAs/AlGaAs laser diodes with decoupled confinement heterostructure

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ABSTRACT

High Power GaAs/AlGaAs laser diodes with a decoupled confinement heterostructure (DCH) have been developed. This novel structure features broadened waveguide layers and thin carrier block layers sandwiching an active layer. Catastrophic optical damage (COD) level was twice as high as the corresponding separated confinement heterostructure (SCH) laser diode due to the improvement of mode profile.

Al-content of cladding layers is greatly reduced in DCH laser diode without degrading temperature characteristics. The decrease of electrical and thermal resistivities allows high-power and high-efficiency operation. CW output, 4.6W was obtained with a 50μm-aperture 809nm DCH laser diode. The maximum efficiency was 49% at 2.8W. Life test was carried out over 2,000 hours under the conditions of 1.0W-50°C. The median life was estimated to be more than ten thousand hours at this condition.

Decoupled confinement heterostructure is advantageous for the fabrication of the index guided structure, since the reduction of chemically active Al-composition relieves the process difficulties related to the chemical etching and the selective re-growth. Index guided laser diode with a buried ridge structure presented 400mW single mode operation at 860nm. The life test was carried out under the conditions of 300mW-50°C. All the 25 devices showed no failure up to 7,000 hours.

Keywords: High power laser diode, AlGaAs laser diode, Decoupled confinement heterostructure, Index guided structure

1. INTRODUCTION

High power laser diodes are going to acquire a variety of new applications, e.g., solid state laser pumping, fiber amplifier pumping, printing, soldering, and other material heat treatments.

Laser diodes are ideal light sources for many applications, since they are very efficient and mass-productive. However, they seem to have essential problem at the points of high-brightness and high-power. Available fundamental mode output power of a narrow stripe laser diode is limited to two hundred milli-watts at most.[4,8] Broad-area structure[7], linear diode laser array, and laser diode bar-stack were developed to increase the total power, but the brightness of these light sources decreased with increasing the available power.

Brightness of a light source is essential for many applications, especially, for direct thermal applications and the pumping of a variety of fiber lasers and Yb-doped solid state lasers. So, a lot of works were devoted to realize high brightness operation of laser diodes.[5,6,9,17,18,19,20]

In this paper we report the development of high power GaAs/AlGaAs laser diodes with a novel heterostructure, decoupled confinement heterostructure (DCH).[12,20]

2. DECOUPLED CONFINEMENT HETEROSTRUCTURE

Maximum power of GaAs/AlGaAs laser diode is generally limited by catastrophic optical damage (COD). The most prevailing structure for the high power GaAs/AlGaAs laser diodes is single quantum well separated confinement heterostructure (SQW-SCH) [4,5,7,9], where the optical facet degradation is minimized[14] and the resulting long cavity design helps to decrease the electrical and thermal resistance of the device. SQW-SCH structure has been thought to be most appropriate for the high power lasers.

Fig.1 shows the epitaxial and waveguide mode profiles of a typical DCH laser in comparison with a conventional SCH laser. DCH laser diode is characterized by thin carrier-block layers sandwiching active layer and broadened waveguide layers.

A nearly Gaussian beam profile is realized in the DCH laser, since the carrier and optical confinements are completely decoupled. Suppression of the beam intensity at the active layer is realized without increasing total epitaxial thickness. Improvement of the mode profile will be also possible by a simple broadened waveguide concept[17,19], however, it will bring the degradation of temperature characteristics or the increase of Al-content in the epitaxial structure[10,11] in the case of GaAs/AlGaAs laser diodes.

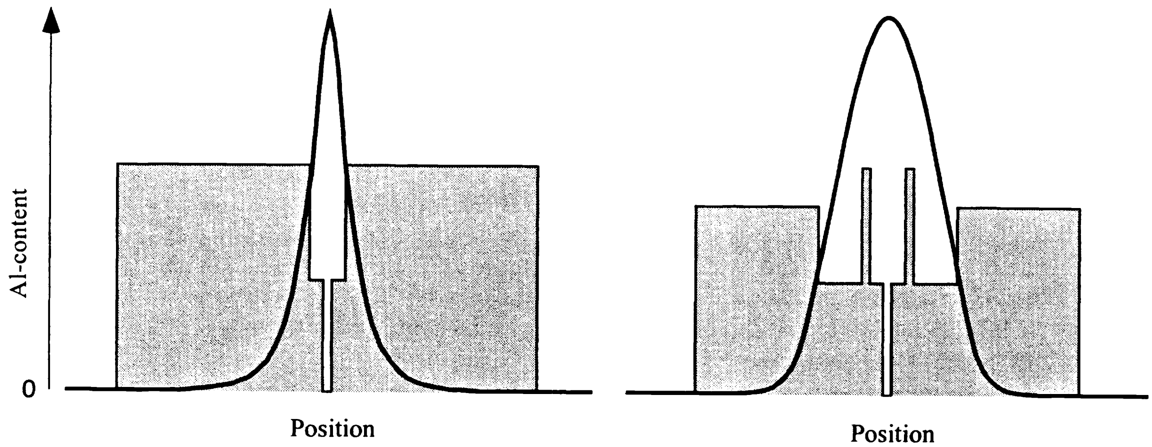

Fig.1 Epitaxial profiles and waveguide modes of typical SCH and DCH laser diodes.

Fig.2 and 3 show the thermal and electrical resistivities of AlGaAs alloy.[1] Lowering of Al content leads to the decrease of electrical and thermal resistances of the epitaxial layer, which is essential for the high-power and high-efficiency operation.

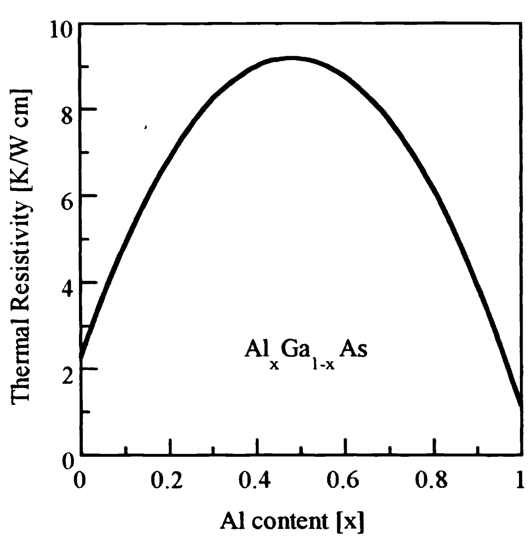

Fig.2 Thermal resistivity of AlGaAs alloy

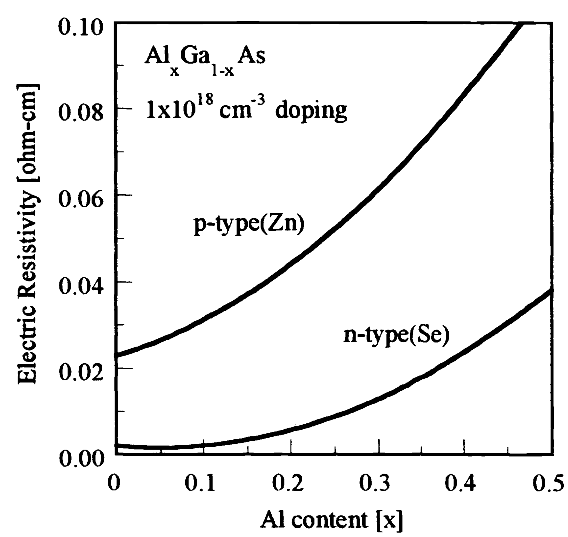

Fig.3 Electrical resistivity of AlGaAs alloy

All the devices were grown by a low pressure MOVPE, and were made by a rather conventional fabrication process. Both facets were passivated by Al2O3 sputtering and Si/SiO2 high reflection coating was done on the rear facet. The mirror reflectivities were 2% and 96%, respectively. The laser diode chips were mounted on a Cu-W submount upside down. For the comparison, DCH and SCH laser diodes were prepared with the same process.

The waveguide structures were designed to make the beam divergence angle to be 35 degrees in FWHM within the 3-layer slab waveguide approximation.[2] The influences of the quantum well and carrier block layers on the waveguide mode profile were trivial, since these layers were optically thin enough. Especially, in DCH structure, the influence of the quantum well layers and carrier block layers on the waveguide mode could be canceled out. The normalized frequencies of the slab waveguide, defined by $V = \pi\, d/\lambda\, (n_w^2 - n_c^2)^{0.5}$ were π for DCH laser and $\pi/6$ for SCH laser. Here, d is the thickness of waveguide between cladding layers, λ is the wavelength, and n_w and n_c are refractive index of waveguide and clad layers, respectively. The mode profiles are shown in Fig. 1. To adjust the gain coupling coefficient, double quantum well structure was adopted for DCH laser in contrast to single quantum well for SCH laser. The quantum wells were GaAs layer with 4nm thickness for both.

Fig.4 shows the measured vertical far field patterns for the DCH and SCH laser diodes. DCH laser has a nearly Gaussian far-field pattern, while far-field pattern of SCH laser has large high angle tails. These features reflect the Fourier transform of the near field patterns.[2] $M\perp^2$ factors [13] of the beams were measured by the Coherent Mode Master to be 1.1 and 1.5, respectively.

Fig.5 shows the output characteristics of 50μm-aperture DCH and SCH laser diodes measured in pulsed mode with 50μsec. pulse width. Maximum powers were limited by catastrophic optical damage (COD), 3W and 6W for SCH and DCH lasers, respectively. The COD level was strongly correlated with the modal intensity at the active layer.

On the other hand the threshold current of DCH laser diode was twice as high as that of SCH laser, since the quantum well number was doubled to keep the modal gain in DCH laser.

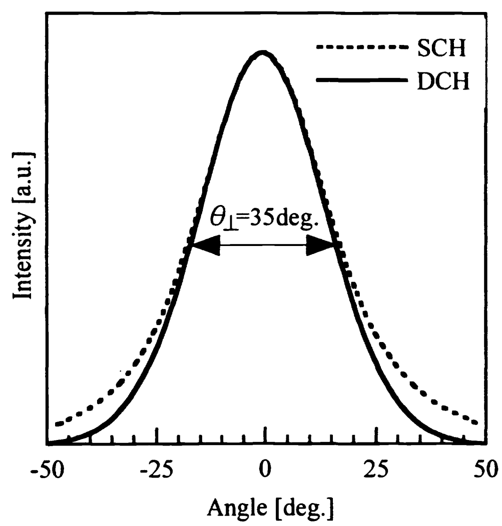

Fig.4 Far-field pattern of DCH and SCH lasers

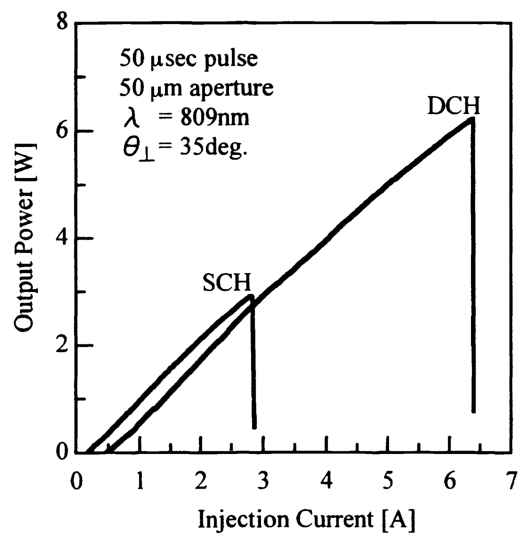

Fig.5 Pulse output of SCH and DCH lasers

3. 809nm BROAD AREA LASER DIODES

In DCH laser diode, better beam quality and higher COD level could be obtained at the expense of the increase of threshold current. The high threshold current would be a big problem, especially, for a broad-area laser diode where the thermal load is a critical issue. However, the electric and thermal resistance of DCH laser diode can be greatly reduced by the reduction of Al content, since electric and thermal properties of AlGaAs alloy depend on Al content strongly as shown in Fig.2 and 3. This allows high power CW operation of DCH laser diodes.

Fig. 6 shows a cross sectional figure of a 809nm broad-area laser diode. The N-type current blocking GaAs layer was formed in the p-type GaAs contact layer. This thick contact layer allowed stable junction down die-bonding.

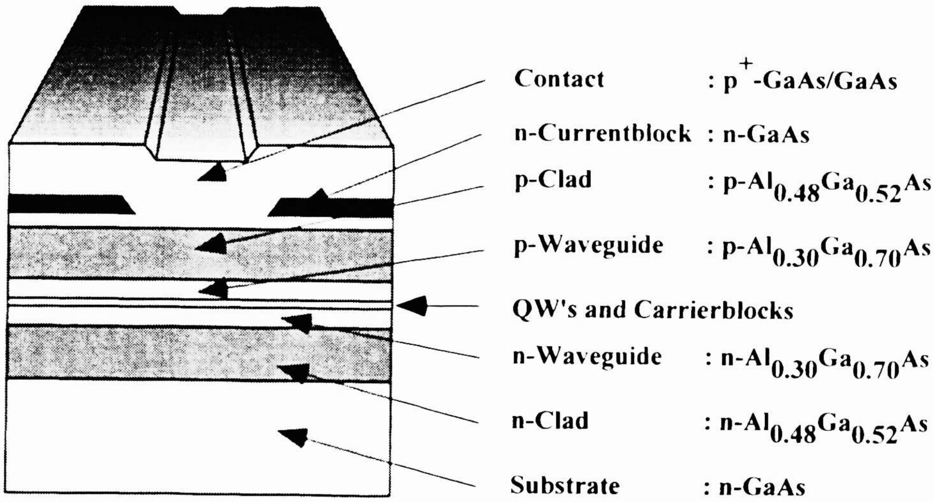

Fig.6 Cross sectional figure of a 809nm broad-area laser diode.

Fig. 7 shows CW output characteristics of 809nm 50μm-aperture DCH laser diode at 20°C. The cavity length was 1.8 mm and the characteristics temperatures was about 150K. The maximum output power was 4.6 W, which was limited by thermal saturation. The maximum energy conversion efficiency was 49% at the current, 2.8A. Such a highly efficient operation was realized by the low electrical resistance and high slope efficiency, compensating for the threshold current increase.

The FWHM of lateral beam divergence of 50μm broad-area DCH laser was typically 6~7 degrees at the output power of 1.0W. The corresponding $M_{\parallel}^2$ factor is around 8. Beam quality was improved even in the lateral direction. Better beam quality allows better focusing and better fiber coupling. In fact, 85% coupling ofthe output beam into 50μm core SI-fiber with NA=0.12 was realized by using a fiber lens.

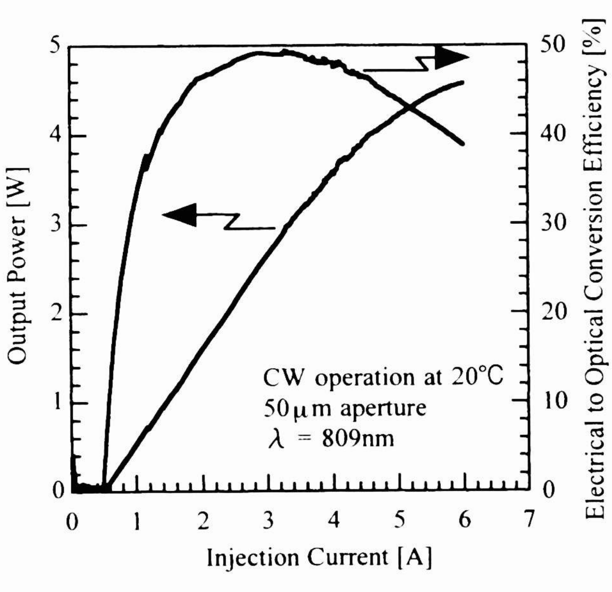

Fig.7 CW output of a 50μm-aperture DCH laser

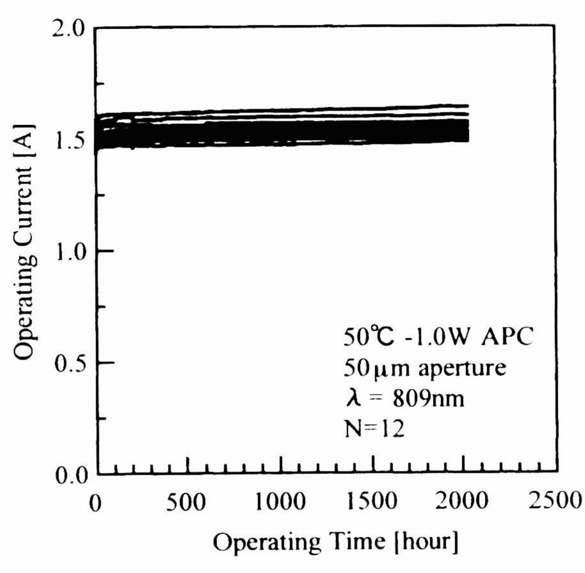

Fig.8 Life test at the conditions of 1.0W-50°C

Step-stress tests up to 1.6W with a step of 0.2W-24 hours revealed that DCH laser diodes were tough even for the gradual optical facet degradation.[14] Fig.8 shows the life test of 809nm 50μm-aperture DCH laser diodes at the conditions of 1.0W and 50°C. Stable operations were obtained over 2,000 hours. The median life was estimated to be about ten thousand hours at this condition.

4. 860nm INDEX GUIDED LASER DIODES

Single mode operation is desired for many applications. Index guided structure and current blocking structure have to be made by micro-photolithography technique. DCH laser diode is advantageous for the fabrication of the index guided structure, since the reduction of chemically active Al-composition relieves surface oxidation problem in chemical etching and makes the selective growth easy.

A 860nm single mode laser diode with four 7nm GaAs quantum wells was designed. Fig.9 shows a cross sectional figure of a real index guided laser diode. The fabrication process was as follows: The basic DCH structure and GaAs process cap layer were grown on the GaAs substrate by a first MOVPE growth. Next, the ridge structure was formed by wet etching with a SiO_2 process mask. By a second MOVPE selective growth, the ridge structure was buried with AlGaAs alloy whose Al-content was a little bit higher than the waveguide layer. After removing the SiO_2 mask, the upper GaAs buffer (contact) layer was formed by a third MOVPE growth.

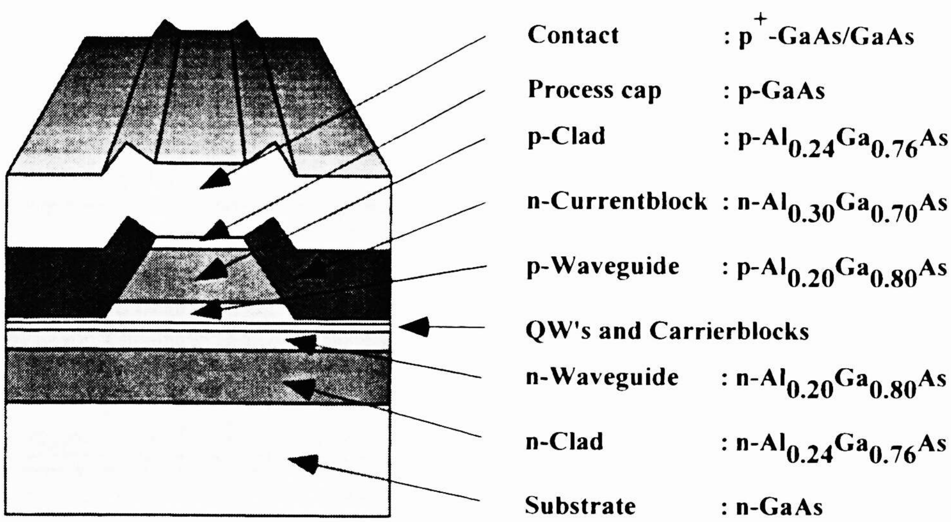

Fig.9 860nm single mode laser diode with buried ridge waveguide structure.

In the case of similar SCH laser diode, the ridge structure with high Al content (>0.4) must be buried with much higher AlGaAs alloy in order to make real index guided structure.[6] Therefore there are some difficulties which are related to increase of chemically active Al content, for example, interface degradation caused by oxidation and AlGaAs resorbence on the SiO_2 mask at the second step MOVPE selective growth.

In DCH laser diode Al content of AlGaAs alloy at the selective growth could be less than 0.3. Consequently real index guided structure could be produced stably by relatively standard technique. Furthermore, we can fabricate the waveguide layer directly because DCH does not allow the existence of minority carriers in the waveguide layer. This makes the process margin concerning etching depth wide, together with the Gaussian mode profile. So we can regulate the lateral index guided structure reproducibly.

This situation contrasts to the previous works in SCH laser diodes sharply.[5,6]

Fig.10 shows output characteristics of 860nm index guided DCH laser. This device had very high COD level, 800mW, which is unprecedented for a simple narrow stripe laser diode without special facet passivation.[4,5] The real index guided structure leads a high slope efficiency, 1.0W/A. The vertical beam divergence was 18 deg. in FWHM. The insertion in Fig.10 shows lateral FFP. Single mode operation was obtained up to 400mW. The M^2 factor of the beam was 1.1 for vertical and lateral directions. Single mode DCH laser diode was superior in beam quality.

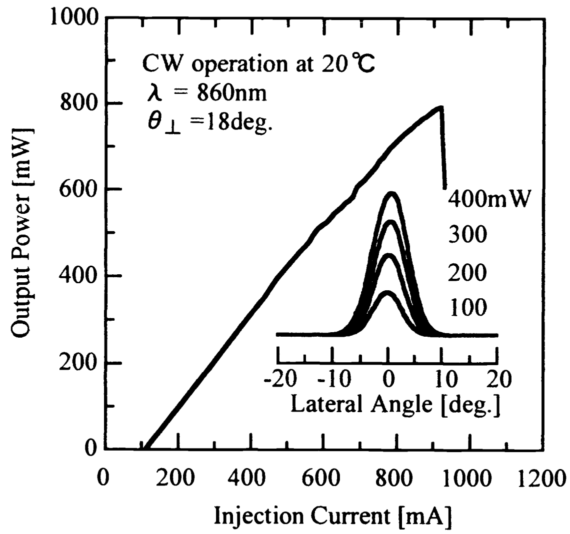

Fig.10 Output characteristics of 860nm single mode laser diode.

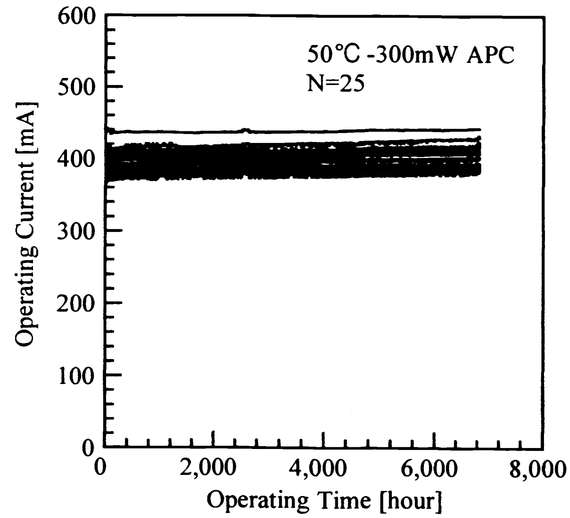

Fig.11 Life test at the conditions of 300mW and 50°C

Fig.11 shows the life test of 860nm single mode laser diodes at the conditions of 300mW - 50℃. All the 25 tested devices showed stable operation up to 7,000 hours. Several ten thound hours median life was extraplated defining a failure by 20% increase of injection current at this condition. Very high power and reliable operation of DCH single mode laser has been realized. This may be ascribed partly to the improvement of COD level, and partly to the reduction of electrical and thermal resistance, and also partly to the increase of process stability.

5. PRELIMINARY RESULTS ON InGaAs/AlGaAs DCH LASER DIODES

InGaAs strained quantum well can provide laser diodes at the wavelength range of 900nm~1100nm.[3] These wavelength range covers many important applications such as pumping of Erbium doped fiber amplifier (EDFA) and pumping of Er or Yb solid state laser system. On the other hand InGaAs strained quantum well can decrease threshold current density of the laser diode by modifying the valence band structure.[3,15] Especially, InGaAs/AlGaAs laser diode with DCH structure can be made with low Al-content alloy which has better electric, thermal and chemical characteristics. This means that DCH structure will bring more exciting results for high power laser diodes.

Fig.12 shows CW output characteristics of 980nm 100μm-aperture InGaAs/AlGaAs DCH laser at 10℃. The active layer was composed of InGaAs strained quantum well layers, the well width is 7.8nm, and In-content is 18%. The maximum output power was 7.6W at the current of 10A. This value was limited by supply current of our measuring system, so the real maximum output power should be much higher. The maximum energy conversion efficiency, 62% was achieved around 4A. Incidentally the maximum CW output power of 50μm-aperture laser diode was 4.7W, and COD level measured by 50μsec. pulse was over 8W.
InGaAs/AlGaAs DCH laser diode has higher COD level and higher energy conversion efficiency than GaAs/AlGaAs DCH laser diode. Many profitable features of DCH structure will be maximized in the InGaAs/AlGaAs system, especially, at the 980nm laser diode.

Fig.13 shows output characteristics of 980nm single mode laser diode with real index guided structure. The structure is nearly same with the structure in Fig.9, but the active layer was composed with 7.8nm InGaAs strained quantum well layers with In-content, 18%. More than 1W output power and single mode operation up to 500mW have been achieved with a several μm stripe width device. The life tests of broad-area and single mode laser diodes are now on progress.

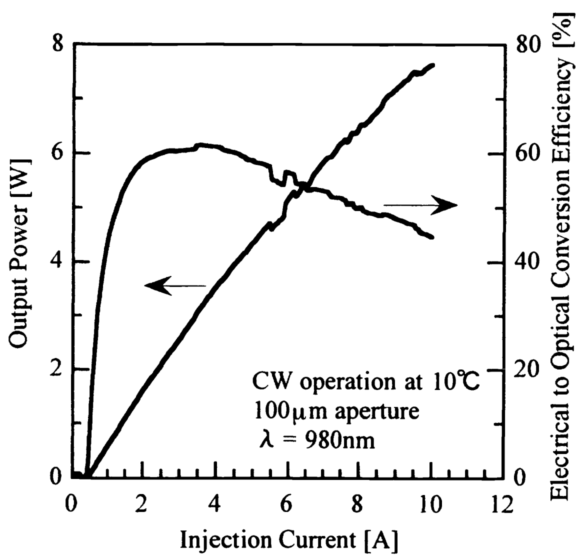

Fig.12 Characteristics of 980nm 100μm-aperture DCH laser.

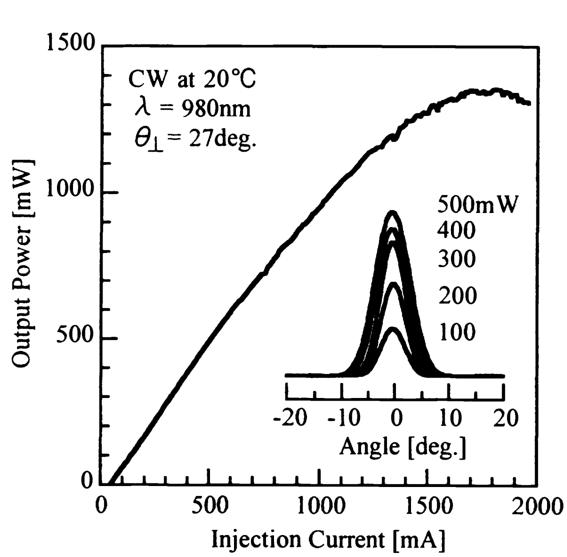

Fig.13 Characteristics of 980nm single mode DCH laser.

6. SUMMARY

Al free technologies have been received a lots of attention as a method to realize laser diodes with much high brightness and much high reliability[17,18,19], for emerging new applications. GaAs/AlGaAs and InGaAs/AlGaAs laser diodes with DCH structure have quite similar effects, especially, InGaAs/AlGaAs laser can be substantially Al-free.

Which is more promising technology? It is very difficult to answer.

Anyway, decoupling confinement heterostructure gives us a new freedom in designing laser diode. These new technologies will join, rather than compete. In fact, Hausser et al[12] and Kazarinov et al[16] have examined the improvement of the temperature characteristics in the 1.3μm InGaAs/InP material system with DCH technology.

We have demonstrated the great potential of DCH structure in the GaAs/AlGaAs material system. We believe that over 1W single mode laser diode is not just a dream, when we see the excellent basic characteristics of InGaAs/AlGaAs DCH laser diode. Now laser diodes are going to be integrated.[9] The process stability and high efficiency of DCH laser diode will help the integration. Fiber coupled module will become more popular for the future application. The better beam quality of DCH laser diode guarantees the higher coupling efficiency.

DCH structure seems to have the chance to be the major epitaxial profile of a semiconductor laser, at least, for a high power laser diode.

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REFERENCES

1. S.Adachi, Properties of Aluminium Gallium Alsenide, EMIS Datareviews Series No.7, INSPEC, 1993
2. H. C. Casey, Jr and M. B. Panish, Heterostructure Lasers, Academic Press, Inc., 1978
3. P. S. Zory, Jr., Quantum Well Lasers, Academic Press, Inc., 1993
4. D. Welch, R. Craig, W. Streifer, D. Scifres, "High Reliability, High Power, Single Mode Laser Diodes", Electronics Lett.,**26**, pp.1481-1483, 1990
5. H. Jaeckel, G.-L. Bona, P. Buchmann, H. P. Meier, P. Vettiger, W. J. Kozlovsky, and W. Lenth, "Very High-Power (425mW) AlGaAs SQW-GRINSCH Ridge Laser with Frequency-Doubled Output (41mW at 428nm)", IEEE J. Quantum Electron., **27**, pp.1560-1567, 1991
6. O. Imafuji, T. Takayama, H.Sugiura, M.Yuri, H.Naito, M.Kume, and K.Itoh, "600mW CW Single-Mode GaAlAs Triple-Quantum-Well Laser with a New Index Guided Structure", IEEE J. Quantum Electron., **29**, pp.1889-1984, 1993
7. M. Sakamoto, D. F. Welch, H. Yao, J. G. Endriz, D. R. Scifres, "High Power, High Brightness 2W (200μm) and 3W (500μm) CW AlGaAs Laser Diode Arrays with Long Lifetimes", Electronics Lett., **26**, pp.729-730, 1990
8. H. P. Meier and V. Graf, "Research Lab Converts to Diode-Laser Manufacturer", Laser Focus World, Octorber, pp.51-56, 1996
9. S. O'Brian, D. F. Welch, R. A. Parke, D. Mehuys, K. Dzurko, R. J. Lang, R. Waarts, and D. Scifres, "Operating Characteristics of a High-Power Monolithically Integrated Flared Amplifier Master Oscillator Power Amplifier", IEEE J. Quantum Electron., **29**, pp.2052-2057, 1993
10. D. P. Bour, D. W. Treat, R. L. Thornton, R. S. Geels, and D. F. Welch, "Drift Leakage Current in AlGaInP Quantum Well Lasers",IEEE J. Quantum Electron., **29**, pp.1337-1343, 1993
11. A. P. Ongstad, M. L. Tilton, E. J. Bochove, and G. C. Dente, "Carrier Spillover at 300, 195, and 77K in InGaAs and GaAs Single Quantum Wells", J. Appl. Phys., **80**, pp.2866-2872, 1996
12. S. Hausser, H. P. Meier, R. Germann, and Ch. S. Harder, "1.3μm Multiquantum Well Decoupled Confinement Heterostructure (MQW-DCH) Laser Diodes", IEEE J. Quantum Electron., **29**, pp.1596-1600, 1993
13. A. E. Siegman, Optical Resonator 2, New Developments in Laser Resonators, SPIE, **1224**, pp.2-14, 1990
14. A. Moser, "Thermodynamics of Facet Damage in Cleaved AlGaAs Lasers" Appl. Phys. Lett., **59**, pp.522-524, 1991
15. H. K. Choi and C. A. Wang, "InGaAs/AlGaAs Strained Single Quantum Well Diodes Lasers with Extremely Low Threshold Current Density and High Efficiency", Appl. Phys. Lett., **57**, pp.321-323, 1990
16. R. F. Kazarinov, G. L. Belenky, "Novel Design of AlGaInAs-InP Lasers Operating at 1.3μm", IEEE J. Quantum Electron, **31**, pp.423-426, 1995
17. J. K. Wade, L. J. Mawst, D. Botez, M. Jansen, F. Fang, and R. F. Nabiev, "High Continuous Wave Power, 0.8μm-Band , Al-Free Active Region Diode Lasers" Appl. Phys. Lett., **70**, pp.149-151, 1997
18. T. Ijichi, M. Ohkubo, A. Iketani, and T. Kikuta, "High-Power 0.98-μm Strained-Layer Quantum-Well Lasers with InGaP Cladding", Microwave and Optical Technology Lett., **7**, pp.139-143, 1994
19. L. J. Mawst, A.Bhattacharya, J. Lopez, D. Botez, D. Z. Garbuzov, L. DeMarco, J. C. Connolly, M. Jansen, F.Fang, and R. F. Nabiev, "8W Continuous Wave Front-Facet Power from Broad-Waveguide Al-Free 980nm Diode Lasers", Appl. Phys. Lett., **69**, pp.1532-1534, 1996
20. T. Fujimoto, Y. Yamada, Y. Oeda, A. Okubo, Y. Yamada, and K. Muro, "High Power GaAs/AlGaAs Laser Diodes with a Decoupled Confinement Heterostructure", CLEO Pacific Rim '97, Postdeadline 2.7