Invited Paper

High power InGaAs/AlGaAs laser diodes with decoupled confinement heterostructure

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Abstract

High power InGaAs/AlGaAs laser diodes with decoupled confinement heterostructure(DCH) have been developed. Almost Al-free waveguide and cladding layers were realized in 980nm DCH laser diodes without degrading temperature characteristics. The extremely low electrical and thermal resistances allowed high power and efficient operation.

The maximum CW output power as high as 9.5W was obtained with 100-μm-aperture broad area DCH laser diode. The maximum efficiency was 55% at 2.5W. The series resistance of 1.8-mm long cavity was 0.04Ω and internal loss was 1.5cm^{-1}. The characteristic temperature(T_0) was 155K.

The substantially Al-free DCH structure enables easy fabrication of various index guided laser diodes. We have developed two types of real index guided laser diodes, buried-ridge and self-aligned structure.
Buried-ridge laser diode presented 1.3W maximum CW output power and 500mW single mode operation. Self-aligned structure laser diodes showed 1.4W CW output power and 700mW single mode operation with better reproducibility.

Keywords: High power laser diode, InGaAs/AlGaAs laser diode,Decoupled confinement heterostructure

1. Introduction

A lot of applications, such as solid state laser or fiber amplifier pumping, printing, soldering, and material heat treatments, demand much higher power laser diodes. Recent studies to raise the available output power of a laser diode developed various new technologies, e.g., thin active layer, facet passivation, window structure and use of Al-free materials.[1,2,3,4,5,6]

We proposed high power GaAs/AlGaAs laser diode with decoupled confinement heterostructure(DCH) nowadays.[7,8,9] DCH structure features broadened waveguide layer and thin carrier block layers sandwiching an active layer. The thin carrier block layers realize the decoupling of carrier- and optical-confinement, which is impossible in separated confinement heterostructure(SCH). In DCH laser diode the optical intensity at the active layer can be suppressed without increasing total epitaxial thickness. High catastrophic optical damage(COD) level is obtained together with the decrease of gain coupling factor(Γ_{QW}). The decoupling of the optical confinement from the carrier confinement enables the reduction of Al-content in the waveguide and cladding layers without degrading temperature characteristics. Since the reduction of Al-content decreases electrical and thermal resistances of epitaxial structure, the DCH laser diode has low series resistances compared to the SCH laser diode. This is essential for high power operation.

DCH structure is also advantageous for index-guided laser diode. Higher single mode power can be obtained, because low Γ_{QW} suppresses spatial hole burning and low resistances reduce thermal disturbance. The reduction of Al-content decreases the chemical-activity of AlGaAs epitaxial layer and relieves the process difficulties related to chemical etching and selective re-growth. The wide waveguide layer which is free from minority carrier accepts a direct modification to lateral index guided structure, and the broadened optical mode gives large allowance for the fabrication process.[9]

These advantages of DCH laser diode are performed most effectively in InGaAs/AlGaAs system. In this paper, we report InGaAs/AlGaAs DCH laser diodes at the wavelength of 980nm.

All DCH laser diodes were grown by low pressure MOVPE and made by a conventional fabrication process.

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2. InGaAs/AlGaAs DCH structure

The epitaxial profiles of DCH laser diodes at wavelength of 809 and 980nm are schematically shown in Fig.1. Both laser diodes were designed to make the beam divergence angle to be 35 degrees in FWHM, and the normalized frequencies based on 3-layer slab waveguide approximation were π. Almost Al-free(<0.2) epitaxial structure is realized at the wavelength of 980nm by elaborately designed carrier block layers. And it is clear that the total Al-content of 980nm laser diode is much lower than that of 809nm.

GaAs broadened waveguide layer has been examined in the 980nm SCH laser diode by M.Gokhale et al., however, they encountered a degradation of temperature characteristics due to the carrier flooding into GaAs waveguide layer.[10] Here we have realized broadened GaAs waveguide without degrading temperature characteristics, because well designed carrier block layers solved the problem.

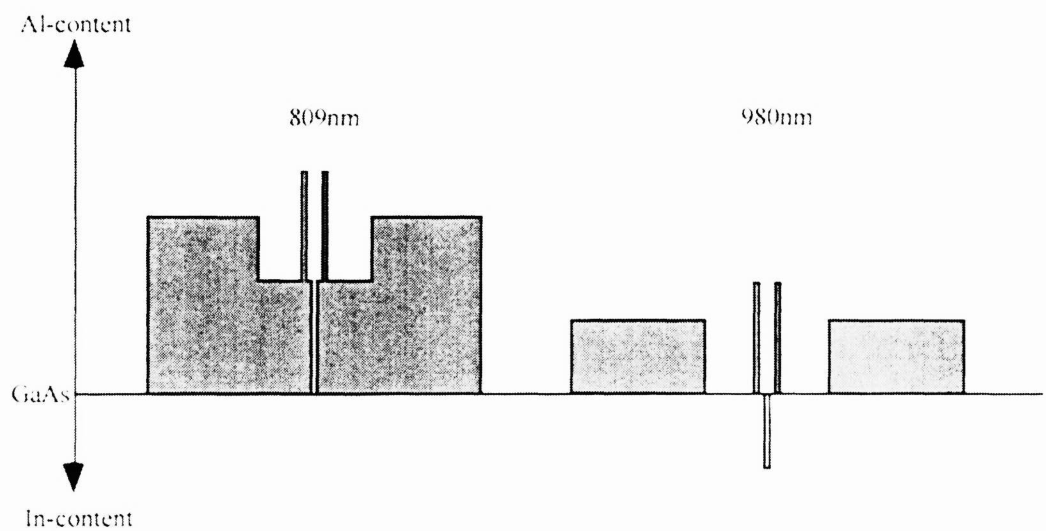


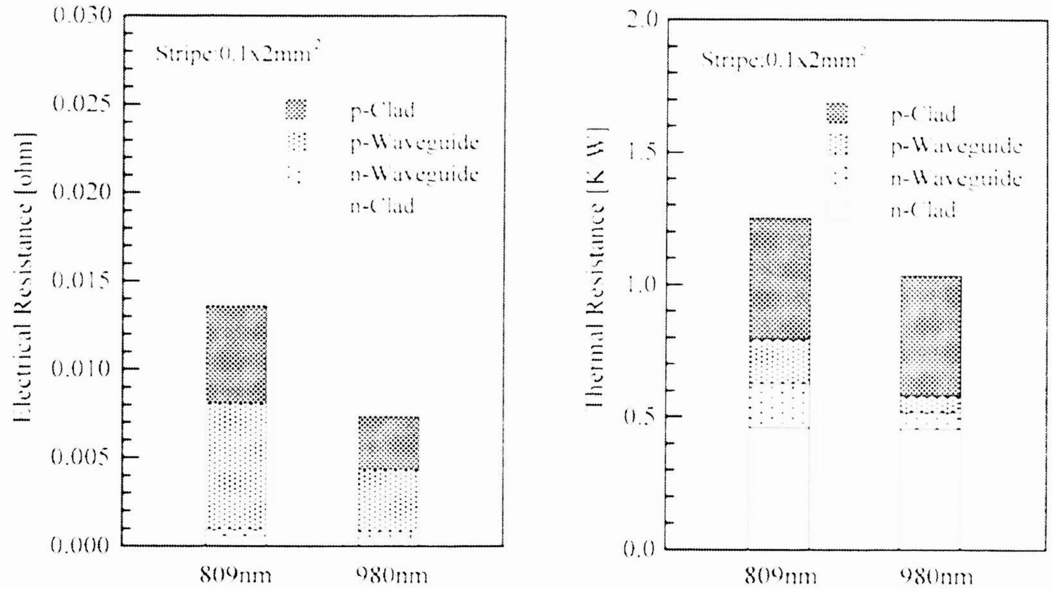
Fig.1 Epitaxial profiles of DCH laser diodes at wavelength of 809 and 980nm

In DCH laser diode which has a high normalized frequency, the optical mode is confined only in wide waveguide layer completely. So simultaneous reduction of electrical resistance and free carrier absorption can be realized by a modulation doping which incorporates low doping in waveguide layer and high doping in cladding layer. DCH laser diode accepts long cavity design, because internal loss is decreased by the suppression of free carrier absorption in the GaAs waveguide.

The electrical resistance of the devices with 100μm aperture and 2.0mm cavity length, calculated from the resistivity of AlGaAs alloy is shown in Fig.2(a). The doping concentrations of waveguide and cladding layers are 1×10^{17} and $1\times10^{18}cm^{-3}$, respectively. Almost Al-free epitaxial structure at 980nm brings low electrical series resistance, which is half of that at 809nm as seen in Fig.2(a). Thermal resistance of each layer in the devices is shown in Fig.2(b). Series thermal resistance of 980nm device can be decreased, comparing to that of 809nm, even though the total epitaxial thickness is increased. And low thermal resistance of GaAs waveguide layer can disperse the heat generated at the facet, so facet degradation may be suppressed. Significantly reduced electrical and thermal resistances allow high power operation and bring high mode stability in the case of index guided laser diode.

980nm DCH laser diode has InGaAs strained quantum well. So, high power kink-free operation can be expected, because InGaAs quantum well has lower linewidth enhancement factor.[13,14] Also the COD level is higher compared to GaAs/AlGaAs DCH laser diode, since InGaAs has lower surface recombination velocity compared to GaAs,.[11,12]

InGaAs/AlGaAs DCH structure has these ideal features for high power laser diode.



(a) (b)

Fig.2 Electrical and thermal series resistances of 809and 980nm DCH laser diodes

3. 980nm Broad-area laser diodes

Low optical confinement factor raise COD level, but it brings increase of threshold current. The high threshold current is a problem for a broad-area laser diode where the thermal load is a critical issue. However, this problem can be compensated by strained quantum well effect. Low threshold current and low resistances guarantee a higher power operation of 980nm DCH laser diode, compared to 809nm laser.[8]

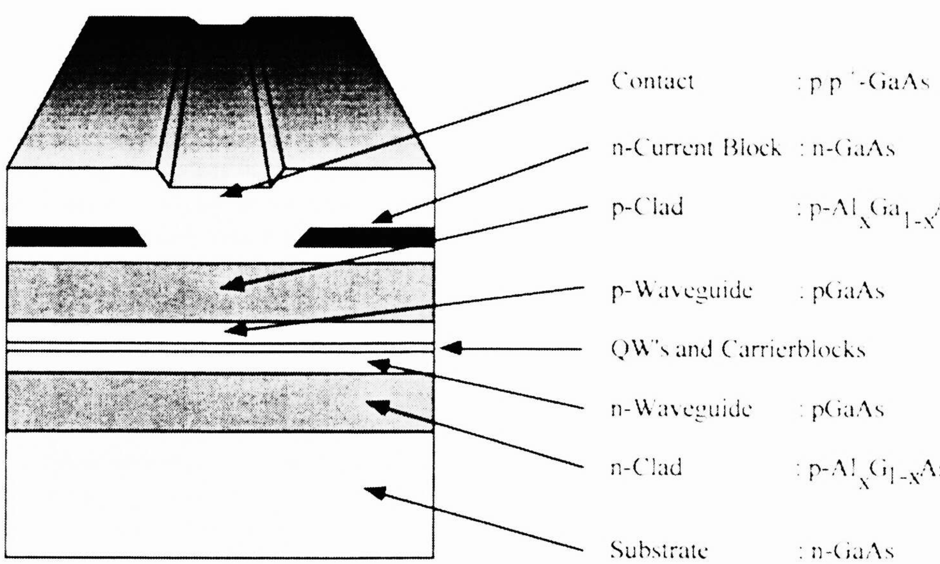


Fig.3 Cross sectional view of 980nm InGaAs/AlGaAs broad-area DCH laser diode

A cross sectional view of 980nm InGaAs/AlGaAs broad-area DCH laser diode is shown in Fig.3. The stripe was formed by n-type GaAs current-block layer that was buried in the p-type GaAs contact layer. The thick contact layer allowed stable junction down die-bonding. The active layer was composed of twin 7nm $In_{0.18}Ga_{0.82}As$ strained quantum well layers. The front/back facets were coated by Al_2O_3 and Si/SiO_2 without any special passivation, and the reflectivities of facets were 2% and 96% respectively.

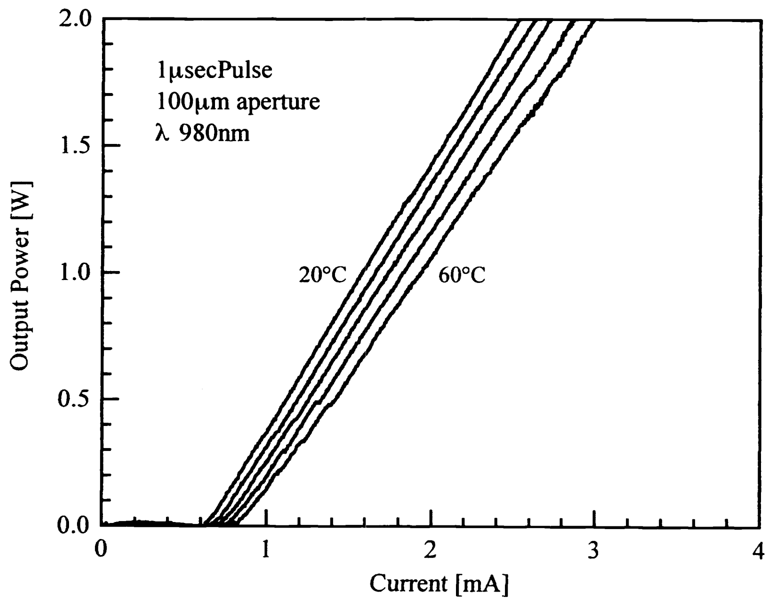


Fig.4 Temperature dependence of I-L characteristic of 980nm InGaAs/AlGaAs broad-area DCH laser diode

The temperature dependence of I-L characteristics is shown in Fig.4. The device with 100μm aperture and 1.8mm-long cavity was mounted on Cu-W submount p-side down and was characterized under 0.1% duty pulsed operation. The characteristic temperature for threshold current and slope efficiency were 150K and 260K, respectively. Fairly good carrier confinement was realized even for GaAs broadened waveguide.

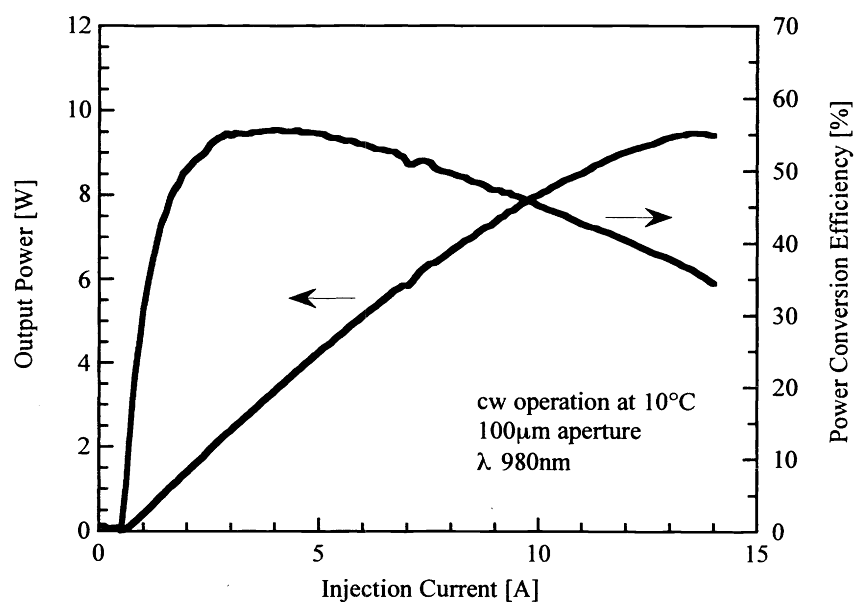


Fig.5 CW output characteristics of 980nm InGaAs/AlGaAs broad-area DCH laser diode

CW output characteristics of the device which was mounted on diamond submount p-side down is shown in Fig.5. The series resistance was 0.04Ω, which was 60% of the value for 809nm DCH laser diode. The internal-loss estimated from the cavity length dependence of the slope efficiency was $1.5cm^{-1}$. The vertical and lateral beam divergence were 35 degrees and 6 degrees in FWHM respectively. The maximum CW output power reached 9.5W at 10°C and the maximum power conversion efficiency achieved 55% at 2.5W.

We have no systematic result of aging test for 100μm aperture broad-area laser diode, but for 50μm devices with the same DCH structure, all the 14 devices are operating over 13000 hours at the condition of 50°C-1.0W without failure.[12]

3. 980nm Real index guided laser diodes

Significantly reduced Al-content also leads to easy fabrication of index guided laser diodes. We have fabricated two types of real index guided laser diodes, buried-ridge(BR) and self-aligned(SA) structure. The BR-laser diode doesn't have regrowth interface in the stripe region, so it is believed to have high reliability.[15] In fact, we have demonstrated stable operation over 7000 hours at 50°C-300mW in the 860nm GaAs/AlGaAs BR-DCH laser diode.[9]

The cross sectional view of 980nm InGaAs/AlGaAs BR-DCH laser diode is shown in Fig.6. Employment of GaAs waveguide allowed very low Al-content(y~0.1) AlGaAs current block layer for lateral optical confinement. That made the selective growth easy even by standard MOVPE. The front/back-facet coatings and the mounting were the same as broad-area laser diode.

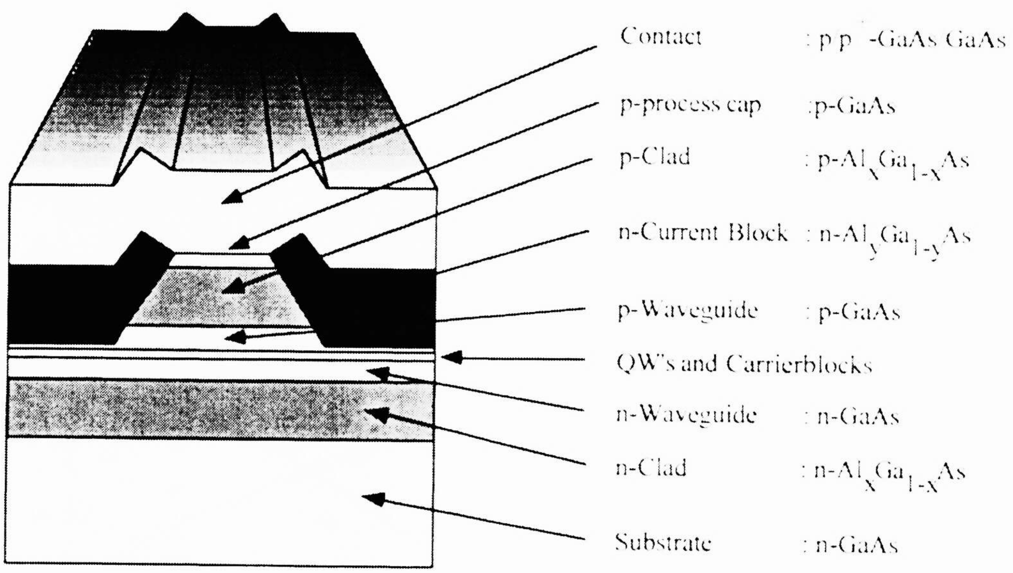


Fig.6 Cross sectional view of 980nm InGaAs/AlGaAs BR-DCH laser diode

CW output characteristics of BR-DCH laser diode are shown in Fig.7. The vertical beam divergence was designed to be 27 degrees in FWHM. The maximum output power of the laser diode with 6μm stripe width and 1.8mm long cavity length reached 1.3W, which was limited by thermal saturation. The inset in Fig.7 shows lateral FFP as a function of output power. Single mode operation was kept up to 500mW. This value was higher than that of GaAs/AlGaAs BR-DCH laser diode. Above mentioned prediction based on the low thermal disturbance and low linewidth enhancement factor has been demonstrated.

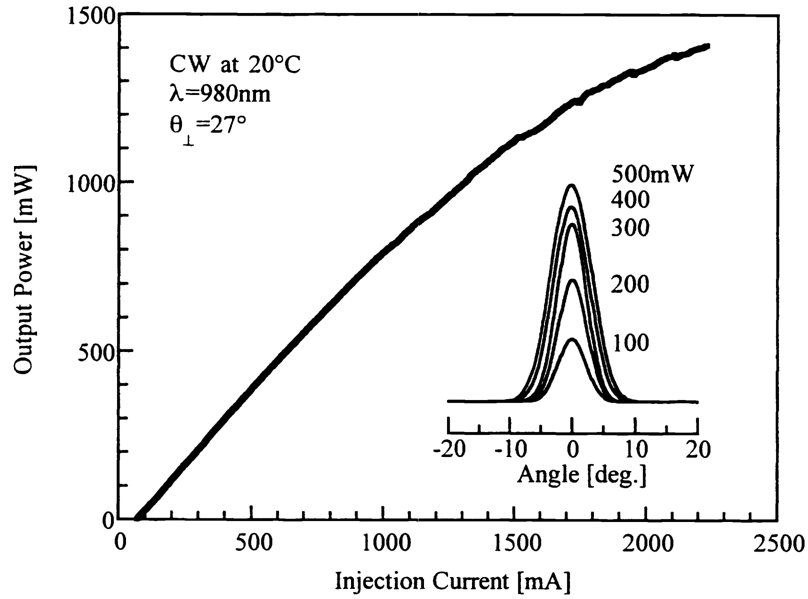


Fig.7 CW output characteristics of 980nm InGaAs/AlGaAs BR-DCH laser diode

The dependence of electrical series resistance on stripe width is shown in Fig.8. The series resistance of BR-DCH laser diode increases rapidly with decreasing stripe width, and this is ascribed to the current channel squeezing. As seen in Fig.6, the current squeezed through the high resistivity p-type cladding layer. It seems difficult to make the stripe width less than 4μm especially in a laser diode with low beam divergence. This restriction on stripe width makes optimization to realize high power single mode operation difficult.

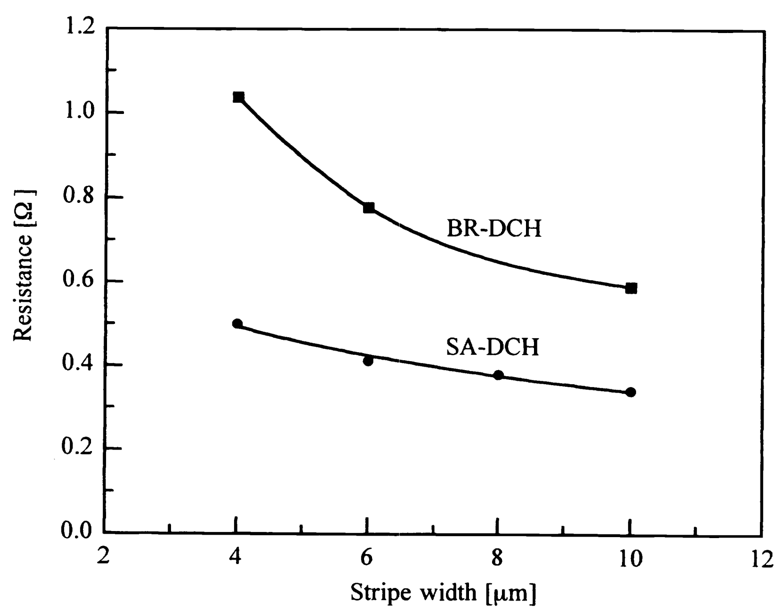


Fig.8 Electrical series resistance of 980nm InGaAs/AlGaAs BR(■)- and SA(●)-DCH laser diode

On the other hand, series resistance showed weak dependence in SA-DCH laser, since the current block layer is in the waveguide layer and thin enough. Consequently, SA-DCH structure seems to be suitable for the optimization of stripe width and effective index difference in order to realize a very high power single mode operation. The cross sectional view of 980nm InGaAs/AlGaAs SA-DCH laser diode is shown Fig.9.

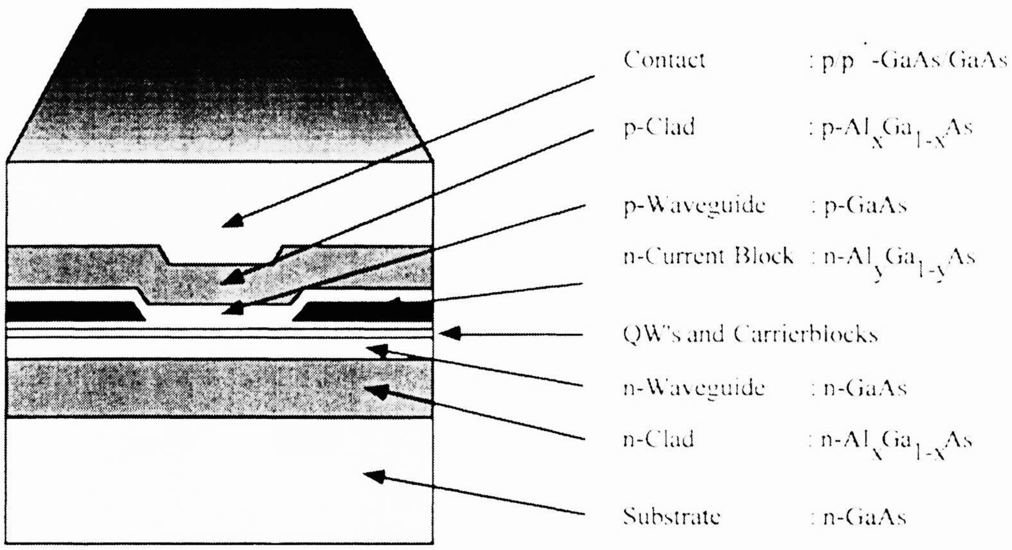


Fig.9 Cross sectional view of 980nm InGaAs/AlGaAs SA-DCH laser diode

The current block and real index guided structure were formed by burying a thin AlGaAs(y~0.1) current block layer in the GaAs waveguide layer. Although SA-DCH laser diode has regrowth interface in stripe region, high reliability was attained by using GaAs waveguide layer which is free from surface oxidation. The shallow groove was formed reproducibly and it was reclaimed flatly by the regrowth. Flat surface structure is favorable for p-side down die-bonding, which is necessary for a high power operation. The front/back-facet coating was same as the broad-area laser diode.

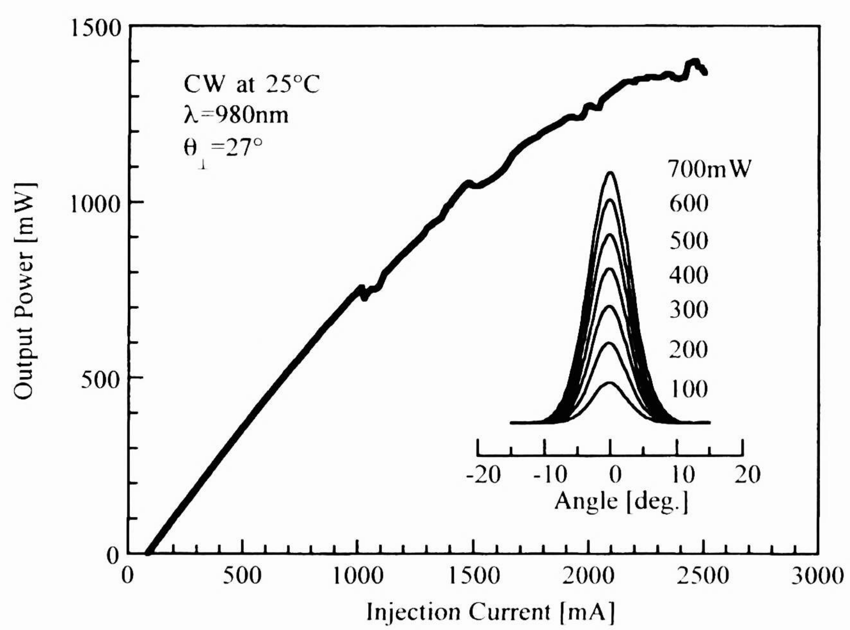


Fig.10 CW output characteristics of 980nm InGaAs/AlGaAs SA-DCH laser diode

CW output characteristics of980nm SA-DCH laser diode is shown in Fig.10. The vertical beam divergence was 27 degrees. The maximum output power achieved 1.3W, and it was thermally saturated. The cavity length was 1.8mm-long, and the maximum power conversion efficiency was 47% at 300mW. Single mode operation was extended up to 700mW as shown in the inset of Fig.10. Also we were able to obtain over 500mW kink-free output reproducibly.

A preliminary fiber coupling experiment with this SA-DCH laser diode showed the fiber output of about 400mW at the coupling efficiency of 75 %.

Aging test ofthis device is just in start, however, SA-DCH laser diodes with a similar structure showed stable operation for 3000 hours at the condition of 50°C -300mW.

4. Conclusion

We have reported the great potential of InGaAs/AlGaAs DCH laser diodes. The maximum power and efficiency of InGaAs/AlGaAs DCH laser diode surpassed that of GaAs/AlGaAs DCH laser diode.

Higher single mode output power has been demonstrated in SA-DCH laser diode with better reproducibility. Preliminary fiber coupling experiment and aging test showed that 980nm SA-DCH laser diode is a promising candidate as a pump source of Erbium doped fiber amplifier where higher power is strongly demanded for next generation DWDM optical communication network.

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References

1. H. Jaechel et al., IEEE J. Quantum Electron., 27, 1560(1991)
2. O. Imafuji et al., IEEE J. Quantum Electron., 29, 1889(1993)
3. H. P. Meier et al., Laser Focus World, Octorber, 51(1996)
4. J. Wade et al., Appl. Phys. Lett., 70, 149(1997)
5. T. Ijichi et al., Microwave and Optical Technology Lett., 7, 139(1994)
6. L. J. Mawst et al., Appl. Phys. Lett., 69, 1532(1996)
7. T. Fujimoto et al., CLEO Pacific Rim '97, Postdeadline 2.7
8. Y. Oeda et al., CLEO '98, Technicl Digest Vol.6,10(1998)
9. T. J. Fujimoto et al., SPIE 3285,80,(1998)
10. M.Gokhale et al., IEEE J. Quantum Electron., 33, 2266(1997)
11. L.J.Mawst et al., Appl. Phys. Lett., 69, 1532(1990)
12. Y.Yamada et al, SPIE 3626, (1999)
13. Y.Kan et al., IEEE J. Quantum Electron., 23, 2167(1987)
14. D.S.Chemla et al, J. Opt.Soc.Amer., B2, 1153(1985)
15. A.Sima et al.,14th IEEE Int.Semicond.Laser Conf.,(1994)