Chapter 4

Fabrication and Characteristics of GaAs-GaAlAs Laser Diodes by LPE

4.1 Introduction

In this chapter, several data from series of GaAs-GaAlAs laser diodes with double heterostructure (DH), with four-layer heterostructure, and with separate-confinement heterostructure (SCH) have been theoretically computed and then analyzed to define material and device parameters. Consequently, these parameters are used in laser diode fabrication by Liquid Phase Epitaxy. The experiments on LPE growth of GaAs-GaAlAs heterostructure lasers using supercooling technique and combination of two-phase solution and supercooling technique has been demonstrated. SiO_2 layer have been used to limit the contact area and confine the current in the lateral direction. The characteristics of these lasers are measured at the room temperature under pulse condition.

4.2 Theoretical analysis

In this section, the lasing threshold conditions of DH, four-layer heterostructure and SCH lasers are computed by the linear gain theory (see section 2.6). The confinement factor of each structure in these computations is calculated by the effective refractive index approximation method (see section 2.4.1). The results are analyzed to derive the optimization of arbitrary laser structures with low threshold current density.

4.2.1 Double Heterostructure (DH) Lasers

DH LD is the most simple laser structure and is also widely commercially availiable. The most common applications of DH LDs are found in many office automation machines that need low power such as CD players, laser printers, CD ROM disk drivers, etc. The quality control in fabrication process of GaAs-GaAlAs DH LD could be specified by few parameters, i.e. the active layer thickness, the Al content difference of the cladding layers versus active layers, and the carrier concentration in p-cladding layer. The schematic diagram of DH structure is shown in Fig.4.1. In this section, the theoretical computation to design the GaAs-GaAlAs DH LD is presented. The results will be compared with the experimental data in the section 4.3.1.

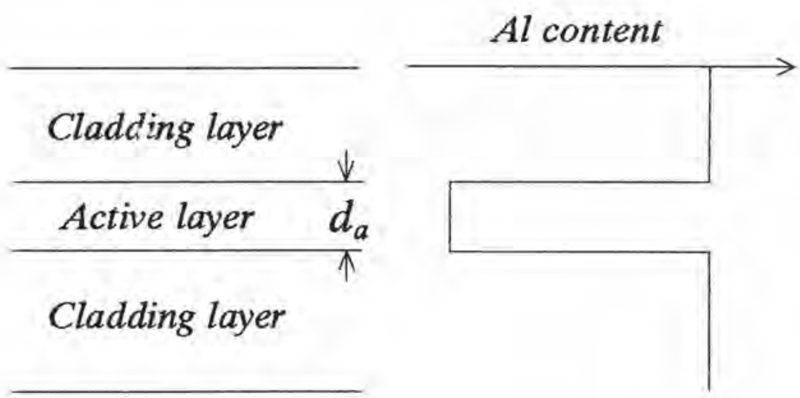


Fig.4.1 The schematic diagram of DH structure.

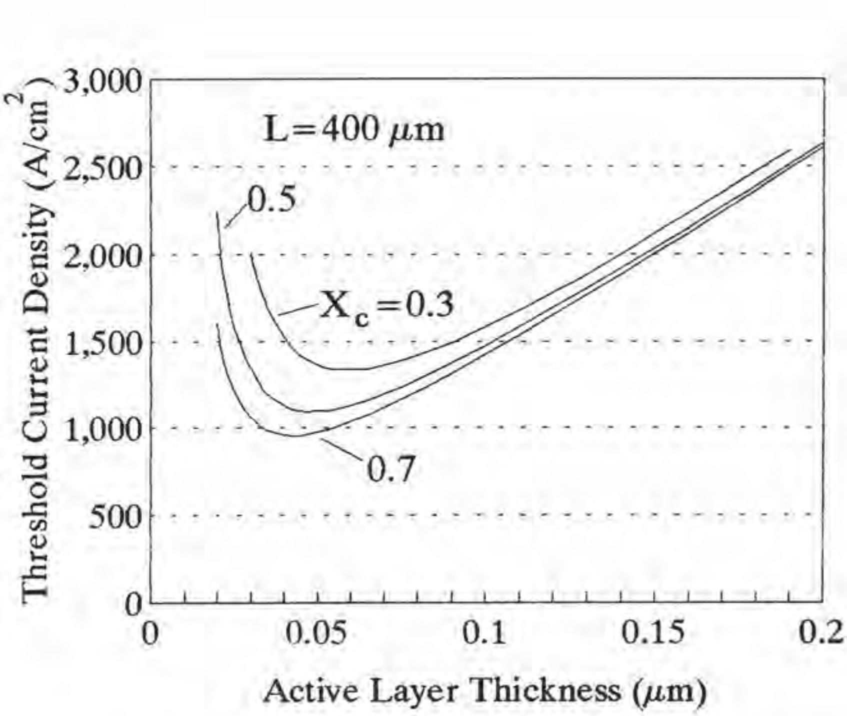


Fig.4.2 The predicted J_{th} values versus d_a (active layer thickness) of GaAs-GaAlAs DH LD's having cavity length (L) = 400 μm with different Al contents in the cladding layers (X_c).

Fig.4.2 shows the threshold current density versus the active layer thickness of GaAs-GaAlAs DH LD having cavity length of 400 μm with the different Al contents in cladding layers. The results point out that higher Al content (X_c) gives lower threshold current density. However, in the case of high Al content, the active layer thickness needs to be fairly thin. This might be the limitation of fabrication for very thin active layer in pratical LPE technology. Therefore, an appropriately Al content must be chosen.

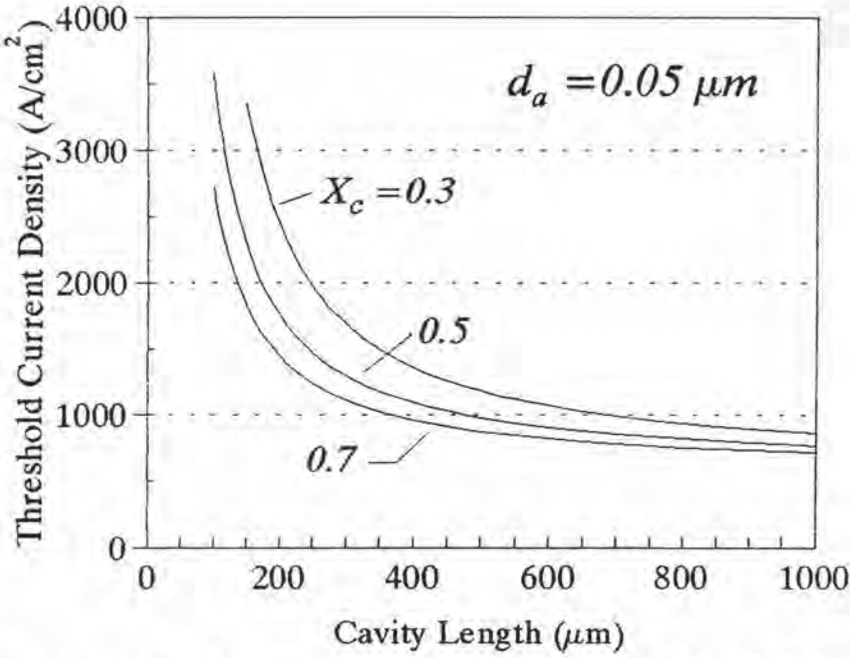


Fig.4.3 The predicted J_{th} values versus cavity length of GaAs-GaAlAs DH LD's having active layer thickness = 0.05 μm with different Al contents in the cladding layers.

In Fig.4.3, the active layer thickness is fixed at 0.05 μm. The threshold current density versus cavity length of GaAs-GaAlAs DH LDs is computed with different Al contents in the cladding layers, X_c. The computation indicates that the threshold current density rapidly increases when the cavity length is shorter than 400 μm.

4.2.2 Four-Layer Heterostructure Lasers

Four-Layer heterostructure is a promosing structure for high power light source. The most desirable applications are optical information processing system, such as optical disk memories, space communication, second-harmonic generation (SHG) elements, and so forth. The schematic diagram of four-layer heteroctrusture is shown in Fig.4.4. In this section, the dependence of threshold current in Fig.4.4. In this section, the dependence of threshold current density of four-layer heterostructure on structure parameters is studied. The results of the analysis are given with respect to the material composition and physical dimension as shown in the Fig. 4.5, 4.6, and 4.7.

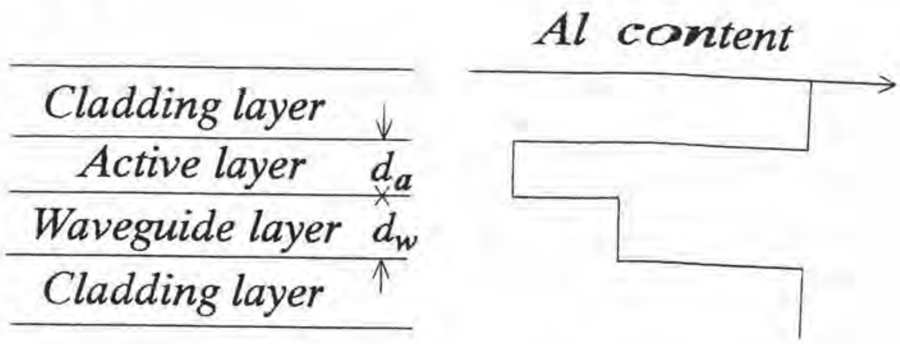


Fig.4.4 The schematic diagram of four-layer heterostructure.

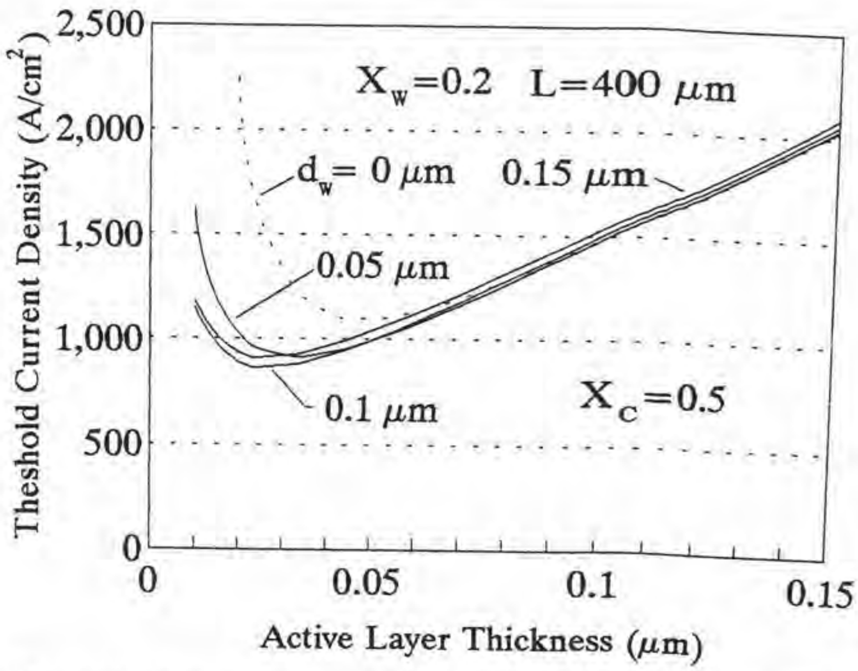


Fig.4.5 The predicted J_{th} values versus d_a of GaAs-GaAlAs four-layer heterostructure LD's having Al content in the waveguide layer (X_w) = 0.2, L = 400 μm and X_c = 0.5 with different waveguide layer thicknesses (d_w).

The dotted line in Fig.4.5 represents the DH structure comparing to the four-layer heterostructure. The computation shows that the four-layer structure with thin active layer in the range of 0.02-0.04 μm can give lower threshold current density.

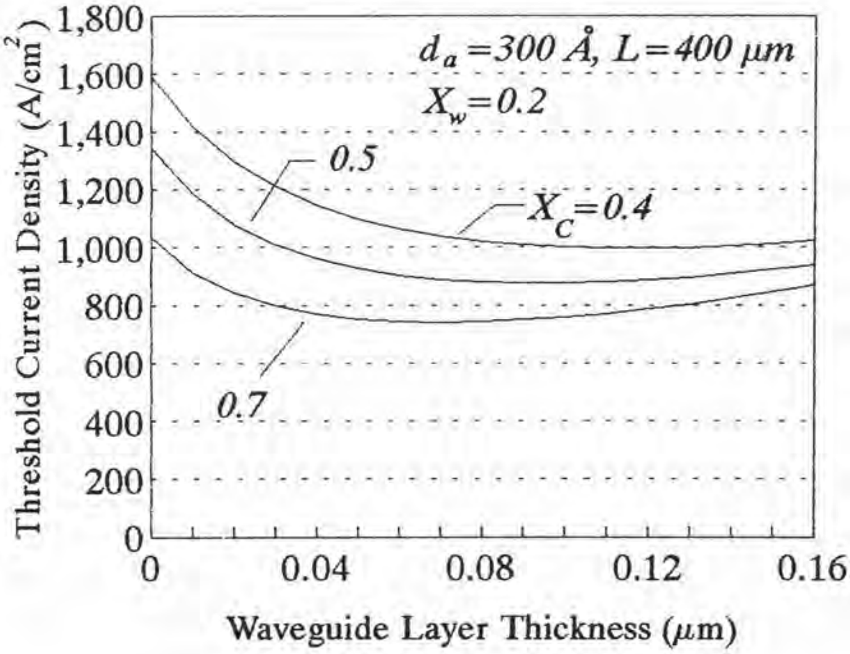


Fig.4.6 The predicted J_{th} values versus waveguide layer thickness of GaAs-GaAlAs four-layer heterostructure LD's having d_a =300 Å, X_w = 0.2 and L = 400 μm with different Al contents in the cladding layers.

With the fixed Al content in waveguide layer at X_w=0.2, the threshold current density in GaAs/GaAlAs four-layer heterostructure does not change much with the waveguide layer thickness as shown in Fig. 4.6.

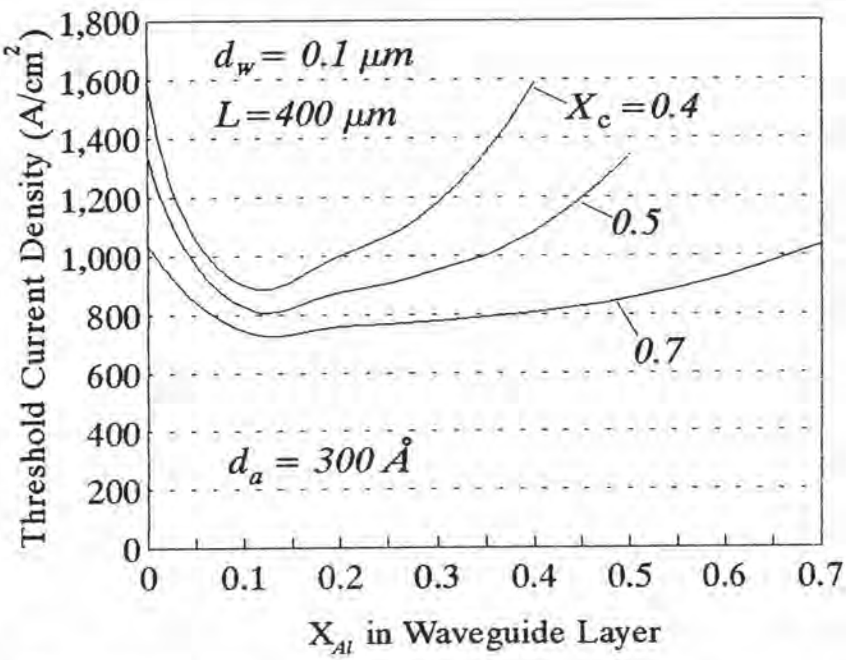


Fig.4.7 The predicted J_{th} values versus X_{Al} in waveguide layer of GaAs-GaAlAs four-layer heterostructure LD's having d_a = 300 Å, d_w = 0.1 μm, L = 400 μm with different Al contents in the cladding layers.

The curve in Fig.4.7 predict that the threshold current density is at the minimum when the Al content in the waveguide layers is around 0.1. However, in practical, the Al content in waveguide layer is chosen to be 0.2 because, at this value, the threshold current density remains nearly the same as those at the value of 0.1. This is preferable to avoid the error of Al content in the waveguide layer which may have smaller value than 0.1 and may provide rapid increase of the threshold current density.

4.2.3 Separate-Confinement Heterstructure (SCH) Lasers

The SCH is an attractive laser structure for the applications that require high power with low threshold current density and high external quantum efficiency. In this section, analytical results of SCH GaAs-GaAlAs lasers of various structure designs are presented to define material and device parameters that are suitable for subsequent modelling and threshold current optimization of arbitrary separate confinement laser structure. The modelling is computed by varying the compositions of Al contents in the barrier layers and the cladding layers, the barrier width and the active layer thickness. The schematic diagram of SCH structure is shown in Fig.4.8

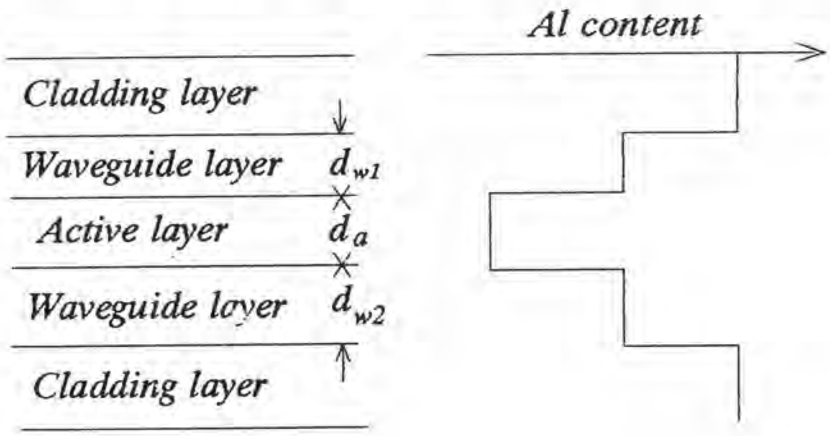


Fig.4.8 The schematic diagram of SCH structure.

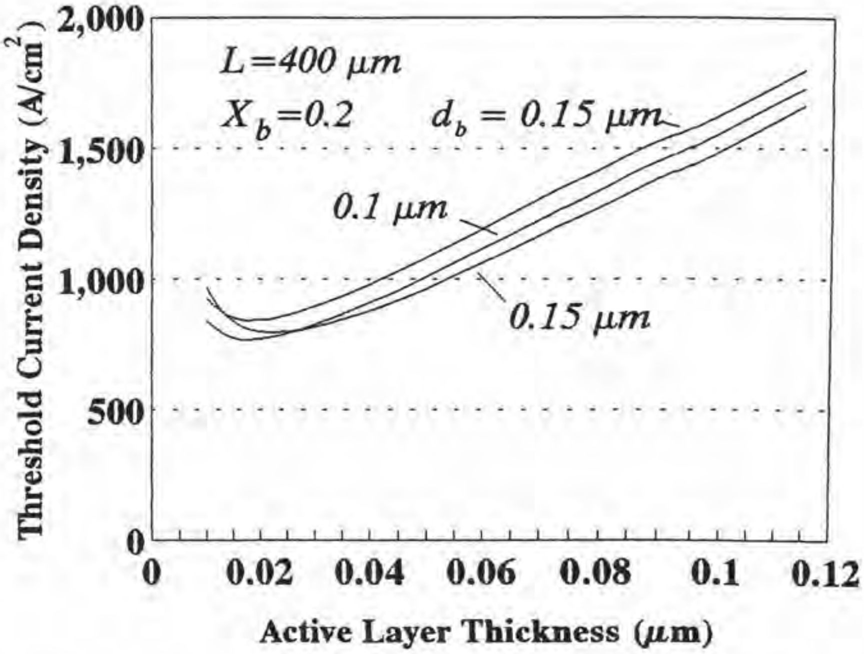


Fig.4.9 The predicted J_{th} values versus d_a of GaAs-GaAlAs SCH LD's having Al content in barrier layer (X_b) = 0.2 , L = 400 μm and X_c = 0.5 with different barrier layer thicknesses (d_b).

The results in Fig.4.9 show that SCH LD gives lower threshold current density than those of the four-layer heterostructure and the DH. The minimum threshold current density occurs at the active layer thickness of 0.01-0.02 μm. This very thin active layer may be possible in liquid phase epitaxy which needs novel technique.

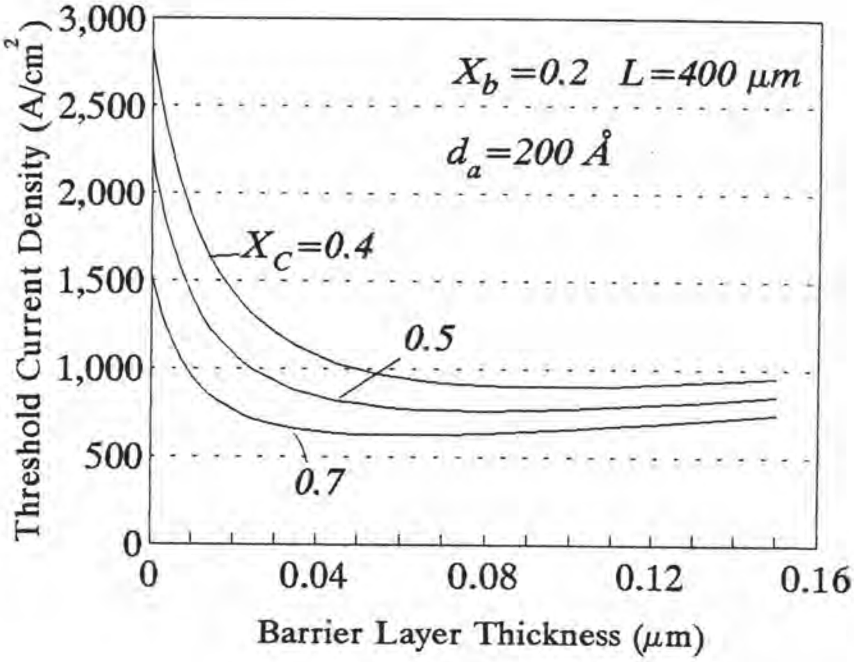


Fig.4.10 The predicted J_{th} values versus d_b of GaAs-GaAlAs SCH LD's having d_a = 200 Å, X_b = 0.2 and L = 400 μm with different Al contents in the cladding layer.

In GaAs/GaAlAs SCH LD, the barrier layer thickness exceeding 0.04 μm gives nearly constant threshold current density. Therefore, the barrier layer thickness does not seriously affect the laser performance.

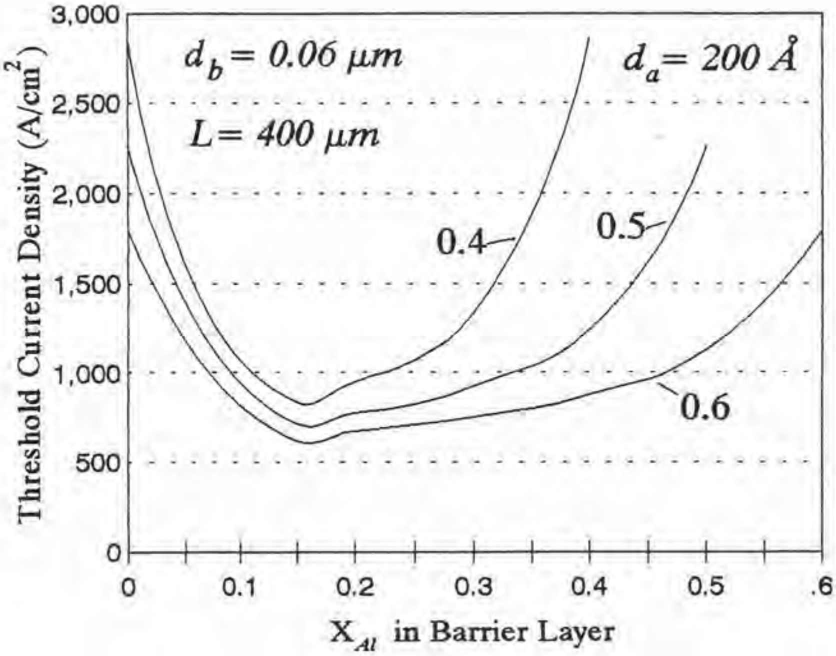


Fig.4.11 The predicted J_{th} values versus X_{Al} in barrier layer of GaAs-GaAlAs SCH LD's having d_a = 200 Å, d_b = 0.06 μm and L = 400 μm with different Al contents in the cladding layer.

The results in Fig.4.11 show that the minimum threshold current density occurs at the Al content in barrier layer around 0.15-0.2. This value is slightly higher than that of the four-layer heterostructure. The rapid increases in Threshold current density for $X_b < 0.15$ and $X_b > 0.3$ with $X_c = 0.4$, $X_b < 0.15$ and $X_b > 0.4$ with $X_c = 0.5$, $X_b < 0.15$ and $X_b > 0.5$ with $X_c = 0.6$, are due to increases in transparency current and optical losses, respectively [23].

4.3 Fabrication Procedure

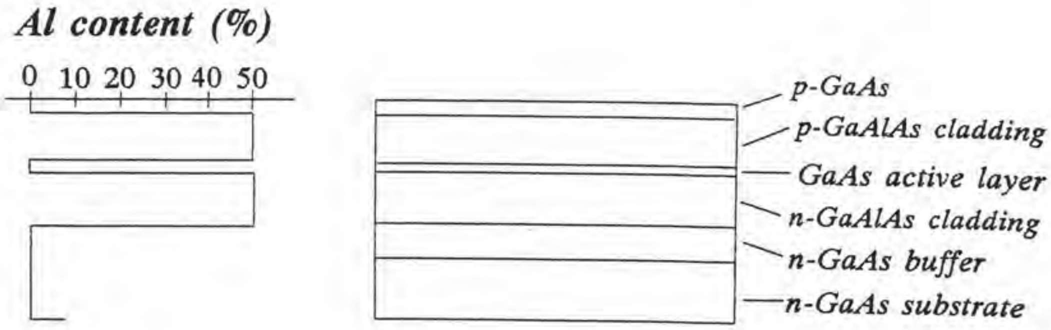
In this section, the crystal growth and device fabrication procedure in making GaAs-GaAlAs heterostructure lasers by liquid phase epitaxy is described in details.

The substrates are single crystal n-type GaAs (Si-doped). The crystallographic orientation is (100) off $0^{\circ} \pm 0.02^{\circ}$. The carrier concentration of the substrate is 1×10^{18} cm^{-3}. The E.P.D.(Etched pitch density) is 1000 cm^{-2}. The wafer thickness is 380 $\pm$ 20 μm. These substrates are the products of Mitsubishi Monsanto Chemical Company, Japan.

The epitaxial growth is carried out by liquid phase epitaxy (LPE). At the beginning of the growth, Ga melts are saturated with As, Al, and dopants at the stable temperature of 800 °C in ultra high purity of H_2 atmosphere for 4 hours. The constant cooling rate of 0.2 °C/min. is used in the fabrication. At the zero minute (t=0), the substrates are under two identical GaAs equilibrated melts at 804 °C. The surface etching of the substrate is performed at the first melt. Whereas, a buffer layer is grown under the second melts. Then, the temperature is reduced to 797 °C at the end of latter. The first cladding layer is grown at around 797 °C [24], [25]. After that the desired LD with different structures such as DH, four-layer heterostructure, and SCH are consecutively fabricated. The SiO_2 stripe-geometry was formed on the electron beam evaporated thin film of 2500 Å thickness by photolithography and wet etching. After polishing the substrate down to 100 μm in thickness, AuGe/Ni/Au and AuZn/Au ohmic contacts are deposited on the n-side and the p-side, respectively [26]. The facets are obtained by cleaving the chips having various cavity lengths. The details of laser fabrication having different structures are presented in the following sections.

4.3.1 Double Heterostructure Lasers

The GaAs-GaAl s DH LD is fabricated by LPE using supercooling technique. The GaAs active layer is grown at around 795 °C for 1 second. The thickness of active layer is about 0.1 µm. In this growth, Zn is used as the impurity for p-type and Te is used as the impurity for n-type. The SiO_2 stripe of DH laser is 10 µm wide. The SEM image and schematic structure of DH laser is shown in Fig. 4.12. The detail of each layer structure of DH LD is described in table 4.1.



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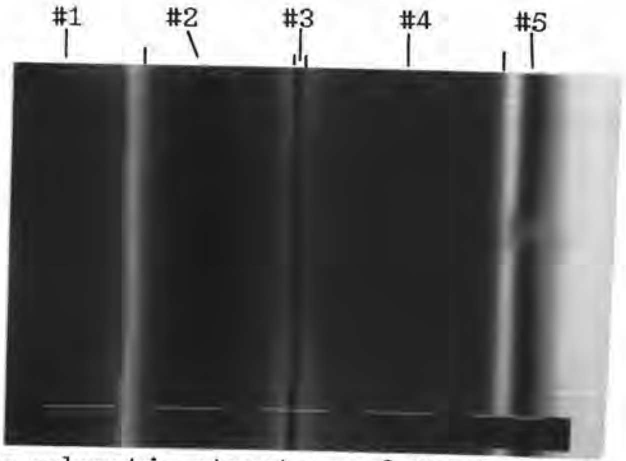


Fig.4.12 a) The schematic structure of DH structure.
b) SEM image of DH structure grown by LPE using supercooling technique. Marker represents 1 µm.

Table 4.1 Layer Structure of DH lasers.

Layer	Composition X_{Al}	Doping $[cm^{-3}]$	Thickness (μm)	Function
#1	X=0	10^{18}	6	buffer layer
#2	X=0.5	10^{18}	2.6	n-confinement layer
#3	X=0	undoped	0.1	Active layer
#4	X=0.5	$5X10^{17}$	2.8	p-confinement layer
#5	X=0	10^{19}	1	p-contact layer

The supercooling technique has limitation of growing thin active layer not less than 0.1 μm due to high initial growth rate, but it offers high crystal quality and uniformity. However, very thin active layer less than 0.1 μm is needed for low threshold current density. Therefore, the combination of diffferent techniques is proposed in this work.

The two-phase solution technique is introduced in the process to grow very thin active layer. The cross section of DH structure grown using combined techniques of two-phase solution and supercooling is shown in Fig. 4.13. These devices do not lase. The explanation will be discussed in section 4.4.1.

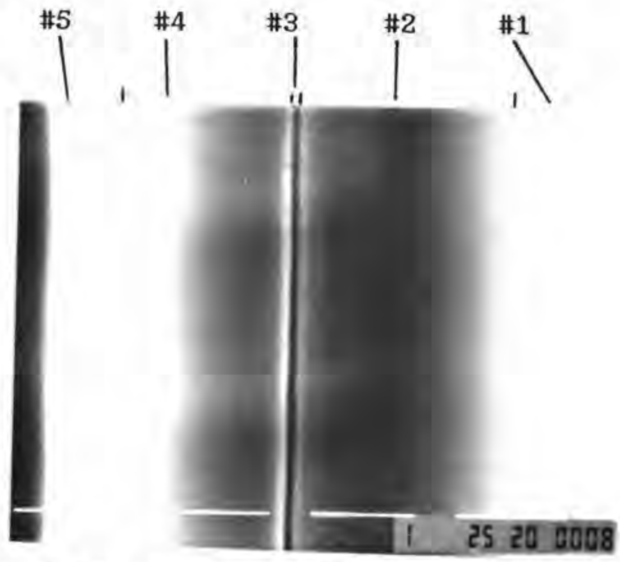


Fig.4.13 SEM image of DH structure with 500 Å active layer grown by LPE using combined techniques of two-phase solution and supercooling. The marker represents 1 μm.

4.3.2 Four-layer Heterostructure Lasers

Four-layer heterostructure of GaAs-GaAlAs lasers were fabricated by LPE using combined techniques of two-phase solution and supercooling. Supercooling technique is used for growing the passive layers such as buffer layer, cladding layer, and waveguide layer. Two-phase solution is used for growing the active GaAs layer at around 795°C. The growth time is less than 1 second to obtain very thin active layer. The waveguide layer of GaAlAs is grown for 10 seconds from supersaturated solution. In this growth, Zn is used as the impurity for p-type and Te is used as the impurity for n-type. The carrier concentration of Zn impurity in cladding layer is reduced to minimize the inter-diffusion problem. The thickness of active layer is less than 500 Å. The structural detail of four-layer heterostructure is presented in table 4.2. A 25-μm wide window of SiO_2 is used in this experiment.

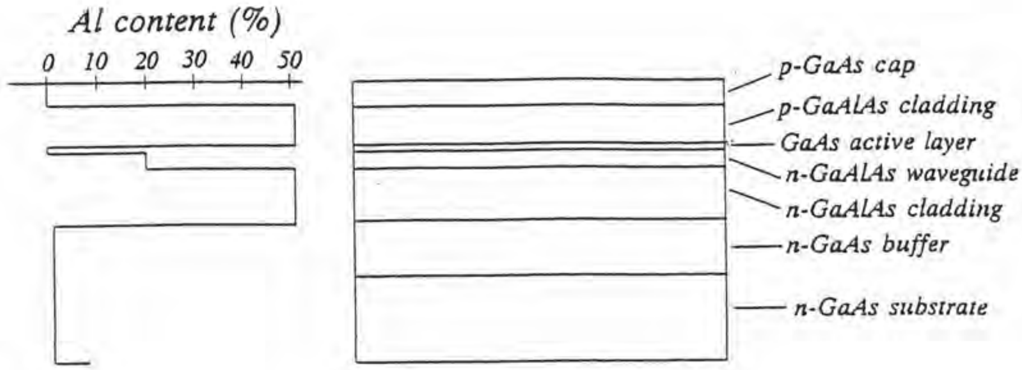


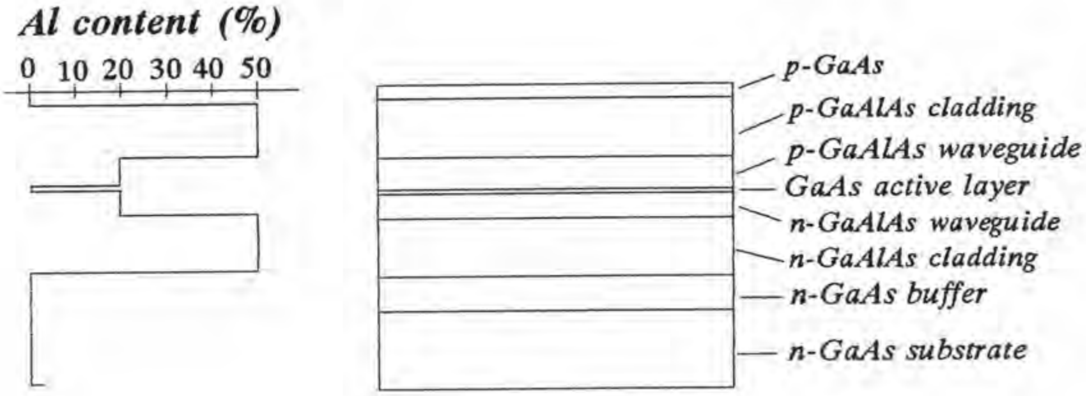
Fig.4.14 The schematic structure of four-layer heterostructure.

Table 4.2 Layer structure of four-layer heterostructure lasers.

Layer	Composition X_{Al}	Doping $[cm^{-3}]$	Thickness (μm)	Function
#1	X=0	10^{18}	6	buffer layer
#2	X=0.5	10^{18}	2.6	n-confinement layer
#3	X=0.3	$5X10^{17}$	0.5	n-waveguide layer
#4	X=0	undoped	<0.05	Active layer
#5	X=0.5	$5X10^{17}$	2.8	p-confinement layer
#6	X=0	10^{19}	1	p-contact layer

4.3.3 Separate-Confinement Heterostructure (SCH) Lasers

SCH GaAs-GaAlAs LD's are grown by LPE using combined techniques of two-phase solution and supercooling. Supercooling technique is used for growing the passive layers such as buffer layer, cladding layer and waveguide layer. Two-phase solution is used to grow an active layer. The active layer of GaAs is grown at around 795 °C. The growth is less than 1 second. The waveguide layers of GaAlAs are grown for 10 seconds from supersaturated solution. In this growth, Zn is used as the impurity for p-cap layer and p-cladding layer. In the waveguide layers, Ge and Sn are used as the impurities for p-type and n-type, respectively. Ge and Sn are selected in this process because they have low diffusion properties. Te is used as the impurity for n-buffer layer and n-cladding layer. The thickness of active layer is about 700 Å. The SEM image of SCH LD is shown in Fig. 4.11. The detail of each layer structure of SCH is presented in table 4.3. A 25-μm wide window of SiO_2 also used in this experiment.



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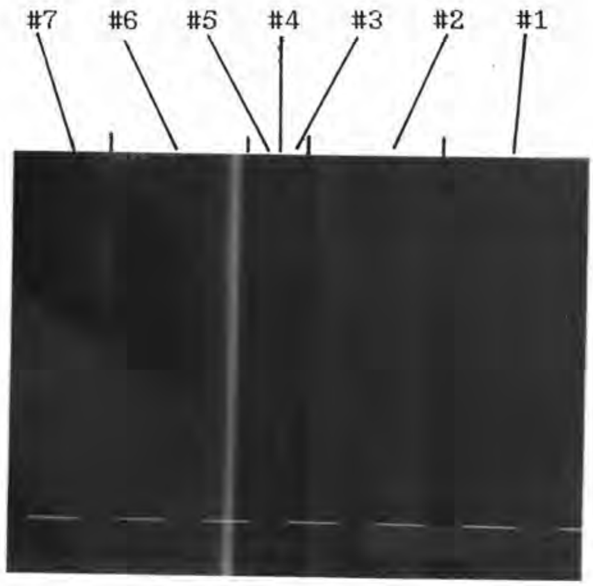

Fig.4.15 a) Schematic structure of SCH structure
b) SEM image of SCH structure grown by LPE using combined techniques of two-phase solution and supercooling.

Table 4.3 Layer structure of SCH lasers

Layer	Composition X_{Al}	Doping $[cm^{-3}]$	Thickness (μm)	Function
#1	X=0	10^{18}	6	buffer layer
#2	X=0.5	10^{18}	2.8	n-confinement layer
#3	X=0.2	$5X10^{17}$	0.7	n-waveguide layer
#4	X=0	undoped	0.07	Active layer
#5	X=0.2	$5X10^{17}$	0.7	n-waveguide layer
#6	X=0.5	$5X10^{17}$	2.6	p-confinement layer
#7	X=0	10^{19}	1	p-contact layer

4.4 Results on Characteristics of Lasers with Different Structures and Discussion

In this section, the characteristics of all samples in our work are presented. The samples are tested under pulsed condition at room temperature. The pulse width is 200 nS with the repetition rate of 10 KHz. The spectral of the samples are monitored by an optical spectrum analyzer.

4.4.1 Double Heterostructure Lasers

The threshold current density of DH LD's is in the range of 4-8 KA/cm^2 for the cavity lenghth of 200-600 μm. The threshold current density is higher than the value presented in section 4.2.1 because of the spreading current in SiO_2 stripe-geometry. An Example of I-L characteristic and spectrum of DH LD grown by supercooling technique is shown in Fig.4.16. Supercooling technique provides high initial growth rate. Therefore, the thickness of active layer in DH LD is as thick as 0.1 μm. The idea to introduce two-phase solution in DH LD fabrication is suggested in order to obtain a very thin active layer. Unfortunately, the DH structure grown by combined techniques of two-phase solution and supercooling does not lase, because Zn diffuses into GaAs active layer during the growth of p-GaAlAs cladding layer [27]. The change of impurity concentration in the active layer causes high internal loss [28] which exceeds the laser gain. The supercooling technique, is not adequate for DH structure unless Zn concentration is controlled to the appropriate level.

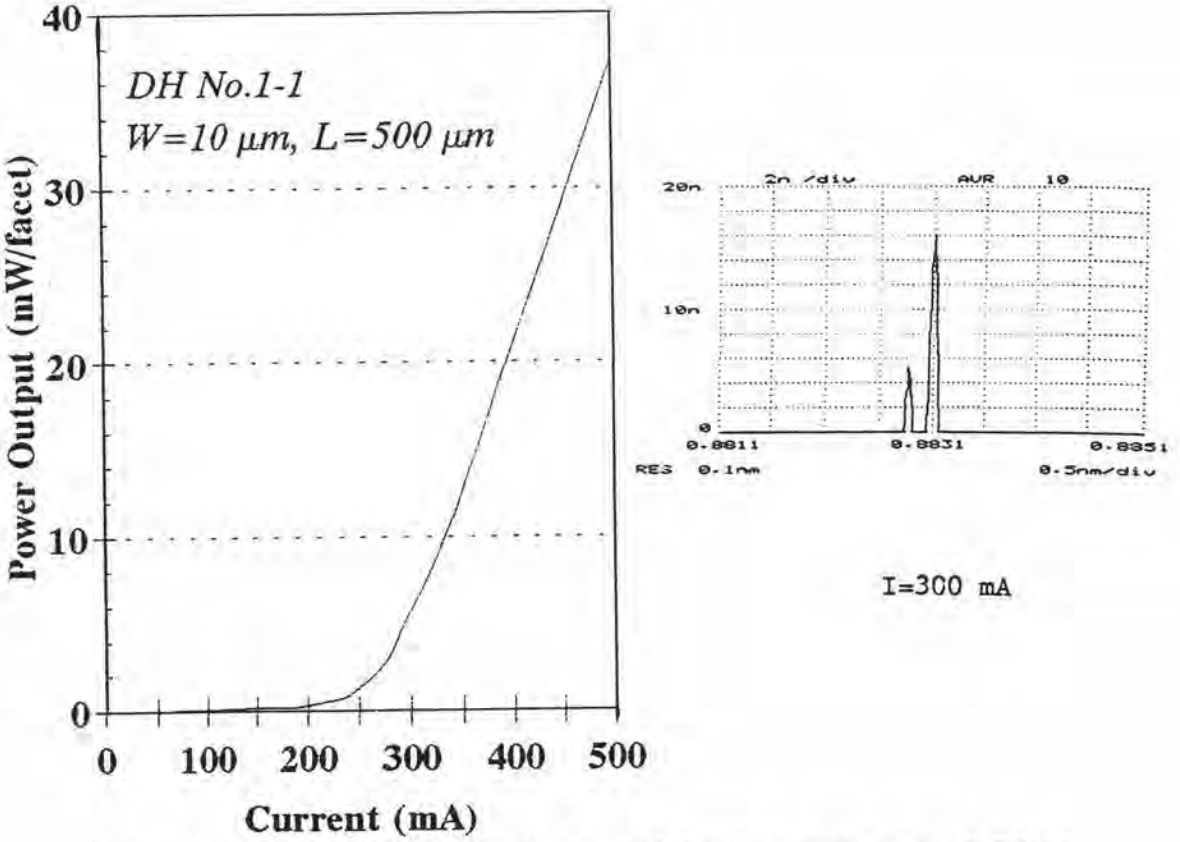

Fig.4.16 The I-L characteristic and lasing spectrum of DH LD

4.4.2 Four Layers Heterostructure Lasers

The threshold current density of four-layer heterostructure LD is in the range of 2.4-4 KA/cm^2 for the cavity length of 125-600 μm. The threshold current density is higher than the value presented in section 4.2.2 because of spreading current in SiO_2 stripe-geometry and thick waveguide layer. In this fabrication, the waveguide layer is grown by supercooling from supersaturated solution with the growth time of 10 seconds. The thickness of the waveguide layer is about 0.5 μm. An example of I-L characteristic and spectrum of four-layer heterostructure LD is shown in Fig. 4.17. The threshold current density of laser with four-layer structure is improved due to the introduction of waveguide layer.

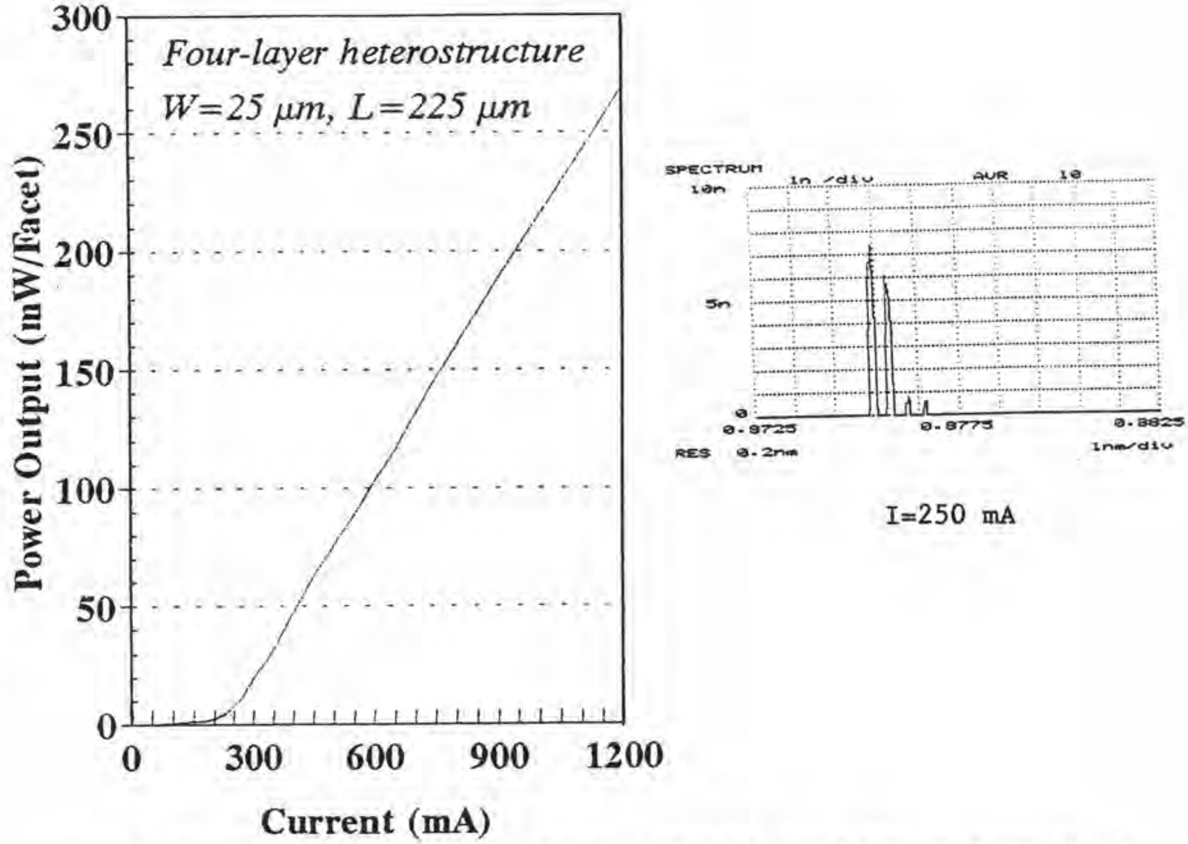

Fig.4.17 The I-L characteristic and lasing spectrum of four-layer heterostructure LD grown by combined techniques.

4.4.3 Separate-Confinement Heterostructure Lasers

The threshold current density of separate-confinement heterostructure LD is in the range of 1.8-3.2 KA/cm^2 for the cavity lenghth of 200-600 μm. The threshold current density is again higher than the value presented in section 4.2.3 because of spreading current in SiO_2 stripe-geometry and thick layer. The waveguide layer is grown by supercooling technique using supersaturated solution with the growth time of 10 seconds. The thickness of this waveguide layer is 0.7 μm. Typical example of I-L characteristic and spectrum of SCH LD is shown in Fig.4.18. The I-L curve indicates that the external quantum efficiency of these SCH LDs is improved. To confirm the increase in external quantum efficiency of SCH LD's, the inversion of external quantum efficiency versus cavity length is plotted in Fig.4.19. The internal quantum efficiency of this structure, as well as the total loss can be calculated from the plot [29]. The internal quantum efficiency is found to be as high as 96%. This result indicates that the internal quantum efficiency is not sacrificed in SCH LD grown by LPE using combined techniques.

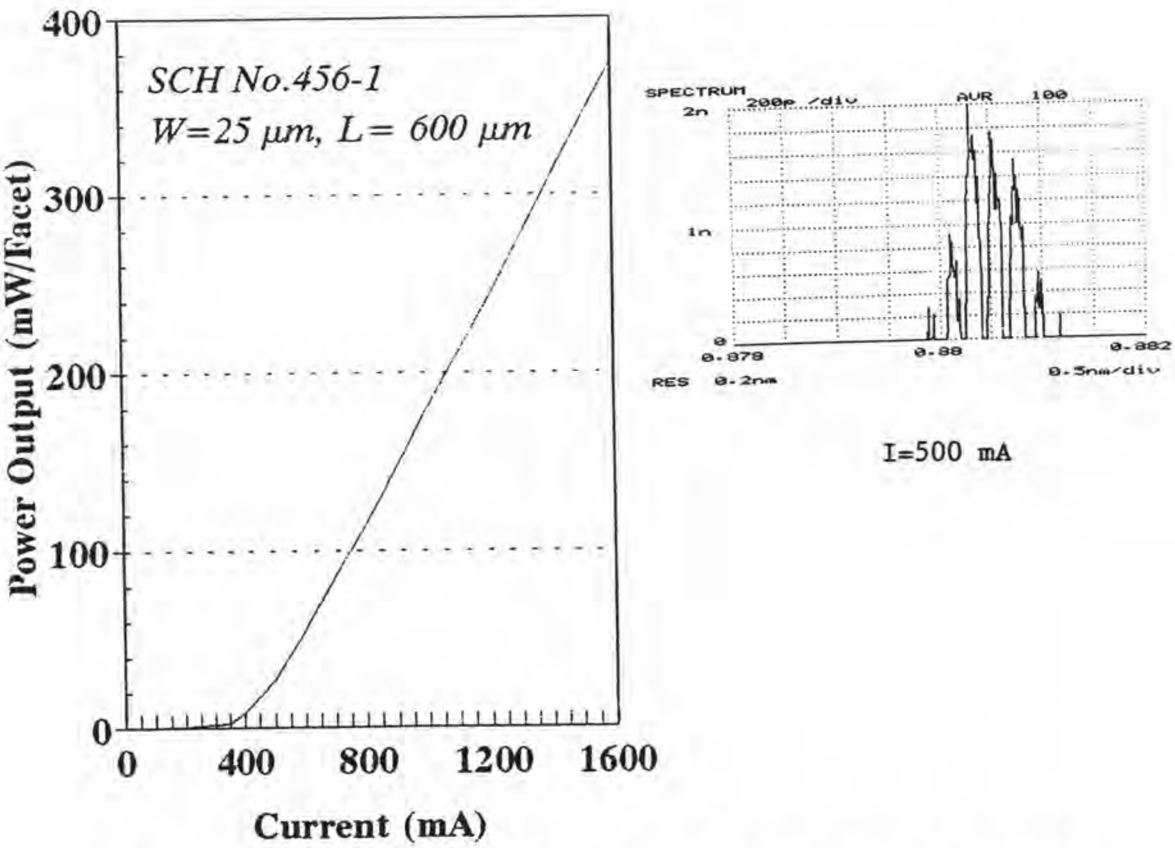

Fig.4.18 The I-L characteristic and lasing spectrum of SCH LD

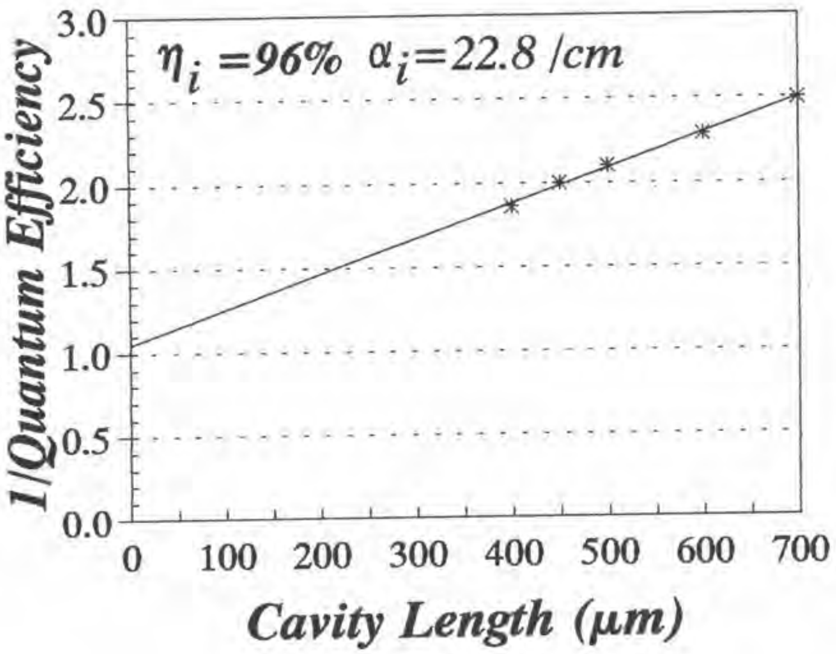

Fig.4.19 The dependence of external quantum efficiency versus cavity length.

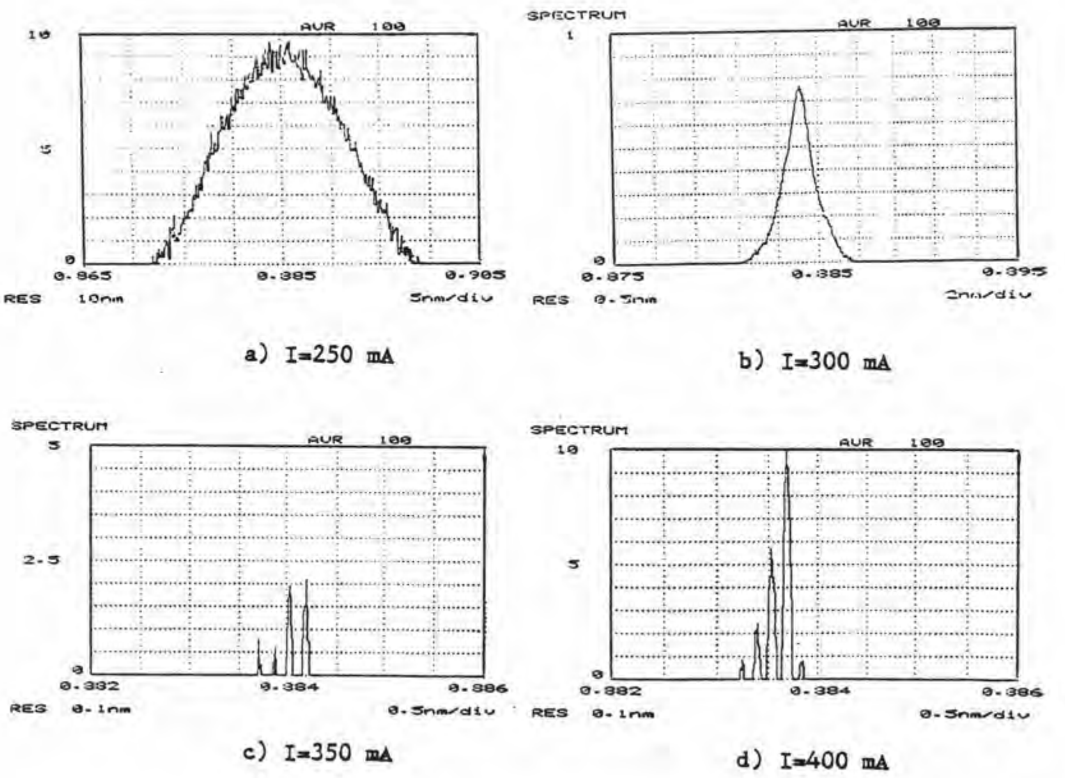

Fig.4.20 The spectrum of SCH LD under different bias conditions

The spectral behavior under the different bias current conditions is shown in Fig. 4.19. The shifting of lasing peak to shorter wavelength is observed at increasing injection current. This is called the blue shift characteristic of the laser. This blue shift characteristic happens due to the shifting of modal gain from long to short wavelength as the injection current increases.

4.5 Summary

The theoretical study have been performed to model the optimal structure of laser diodes with low threshold current. The computation gives the information concerning various design parameters which affect the threshold current density of LD's using GaAs-GaAlAs material grown by LPE technique. The information is applied in our experiment to fabricate the heterostructures with low threshold current density and having very thin active layer. The fore-mentioned characteristic can be realized by the introduction of combined techniques of two-phase solution and supercooling. The comparison of laser characteristic with different structures, i.e. DH, four layer heterostructure, and SCH is summarized in table 4.4

Table 4.4 Summary of characteristics of LPE-Grown GaAs-GaAlAs Lasers

Parameter	Structure		
	DH	Four layers Heterostructure	SCH
Cavity length (μm)	300-700	125-600	400-600
J_{th} (KA/cm^2)	4-8	2.6-4	1.8-3.2
I_{th} (mA)	200-600	150-350	200-300
$_p$ (nm) at $I = 1.1\ I_{th}$	876-892	865-874	876-890