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A Study of Carrier Dynamics in
1.5- μm -Wavelength
Multiquantum Well Semiconductor Lasers

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September 2000

Corrigenda

Location	Error	Correct
Page 2, Table 1.1	1770s	1970s
Page 23, Eq.(2-4)	α_i	α_{int}
Page 26, Table 2.4 & 2.5	hh1, hh2	1hh, 2hh
Page 26, Table 2.5, $m_h^*(E_{1hh})$ for lattice matched LD	0.1	0.37
Page 28, Line 8	Eqs.(2-8)-(2-12)	Eqs.(2-7)-(2-12)
Page 31, Figure 2.9 horizontal axis	I/I_{th}	I_0/I_{th}
Page 50, Eq.(3-36) in the denominator	$\left(\frac{1}{L} \ln \frac{1}{R}\right)$	$\left(\frac{1}{L} \ln \frac{1}{R}\right)^{-1}$
Page 52, Figure 3.3 a) horizontal axis	I/I_{th}	I_0/I_{th}
Page 66, Lines 1, 2 and 12, Page 73, Lines 1 and 6	preposition	premise
Page 102, Line 9	[5]	[8]
Page 113, Line 24	32)	[15]
Page 119, Line 17	[23]	[2]

Abstract

The dramatic improvement has been theoretically predicted for the performances of strained multiquantum well (MQW) long-wavelength laser diodes (LDs). However, large discrepancy between the theoretical predictions and experimental results had been reported for the essential laser characteristics and thus the discrepancy was recognized as a bottleneck for further improvement. The purpose of this study is to clarify the causes of the above discrepancy and present the guidelines and methods to overcoming the bottleneck for further improvement.

At first, the key characteristics of LDs were extracted corresponding to the requirements from the recent fiber-optic transmission applications. Among them, the differential gain was shown to be one of the fundamental key characteristics in improving various laser performances. Next, the discrepancy in the key characteristics was confirmed in an experiment on AlGaInAs/GaInAs strained MQW-LDs in 1.5 μm -wavelength, in agreement with the reported results. Then, an improved theory for carrier leakage and diffusion delay was developed and adopted upon the experiments and feasibility in explaining the measured discrepancy was confirmed. Based on analysis with the theory, the discrepancy was attributed to the deterioration due to a) the thermionic carrier leakage from quantum wells (QWs) to optical confinement layers and b) the Auger carrier loss. The thermionic carrier leakage was further attributed to the low barrier height of the optical confinement layers and to the long diffusion time of carriers across the optical confinement layer. Thus the guidelines to overcoming the discrepancy were clarified and expected improvements in the performances were also predicted.

In the following step, feasible methods to suppress the thermionic carrier leakage and the Auger carrier loss were studied from the standpoint of enhancing the barrier height and maintaining smooth carrier injection. At first, multiquantum barriers (MQB), which utilize the energy stop band of superlattice in enhancing the barrier height, was taken up as a barrier height enhancing method. Strained MQW LDs with AlInAs/GaInAs MQB loaded at p-side optical confinement layer for suppressing electron leakage was fabricated. Improvements in various laser characteristics were confirmed. From the measured reduction of spontaneous emission from the optical confinement layer, barrier height enhancement over 210 meV by MQB and over

90 % reduction of leakage carriers were estimated.

In spite of those improvements, measured characteristics suggested the possibility that some part of thermionic carrier leakage and Auger carrier loss still remained or that additional cause of deterioration incorporated by MQB. Thus, the model and method of designing MQB were further investigated. Firstly, significant effect of conduction band nonparabolicity upon the reflection performance of MQB was clarified for hot electrons. Secondly, the advantage of tensile-strained-barrier MQB in realizing the enhanced high effective barrier was confirmed. Thirdly, possibility of hole-pile-up in MQB was pointed out from miniband analysis. Based on those results, improved design methods for MQB was presented. Approaches for the suppression of Auger carrier loss was discussed. Tensile-barrier MQB with high effective barrier was presented as an attractive approach.

Next, barrier height enhancement of QWs by the strained-layer was investigated for InP based materials with model-solid theory. Large enhancement effect by 1–1.5 % tensile strained AlInAs or AlInP barrier was confirmed. A strain-compensated combination of 1% tensile AlInP barrier and 1% compressive GaInAs was shown to have high barrier heights ($\Delta E_c, \Delta E_v$) = (472 meV, 433 meV) and to give sufficiently long carrier leakage lifetime. On the other hand, carrier injection problem incidental to above barrier height enhancement method was pointed out. Improved carrier injection method utilized the minibands with gradually enhanced energy levels toward QWs were presented. Improvement of the key characteristics for above strain-compensated AlInP/GaInAs QW with high barrier height was calculated assuming smooth carrier injection. Remarkable five times enhancement of differential gain at 300K was estimated as a result of the almost complete suppression of carrier leakage. T_0 around 150 K was predicted by reducing Auger coefficient down to theoretical value, 2×10^{-30} cm⁶/s in 1.55 μ m-wavelength.

In the future quantum effect devices, smooth injection and efficient confinement of carriers should be more significant due to a smaller filling factors. Superlattice as carrier energy filter should be a key concept in future devices, where control of heterobarrier height and of miniband would be a vital technology. The guidelines and knowledge developed in this study are expected to contribute to the progress of such device technology.

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Chapter 1

Introduction

In this chapter, the background, purpose and outline of this thesis are described. At first, progress in fiber-optic networks and recent requirements on the light sources are described. Then, the strained multiquantum well laser as one of promising approaches and a bottleneck problem will be introduced. Finally, the purpose and outline of this thesis are described.

1.1 Background

1.1.1 Progress in fiber-optic networks and recent requirements on the light sources

The light source and optical fiber technologies have been the essential constituents for the fiber-optic networks and close interactions between requirements from applications and those technologies have been the key driving forces for the progress. Historical topics in the fiber-optic networks and related developments in lasers and silica-fiber technologies are briefly described below. They are summarized in **Table 1.1**.

The coincided developments of the InP based GaInAsP/InP semiconductor laser diodes (LDs)[1] and the silica-fiber cables[2] opened a new era of commercial fiber-optic transmission in the 1970s. The demand for larger capacity trunk lines accelerated the development of the dynamic single axial-mode distributed feedback (DFB) LDs[3] and the dispersion-shifted fiber with reduced loss and dispersion, which realized the commercial installation of high capacity trunk networks[4], in the 1980s. Improvement of the DFB LDs for analog video transmission[5] also realized the fiber backbone cable TV combined with conventional coaxial distributions; so called Hybrid Fiber/Coax. An epoch making commercial adoption of the Er-

doped optical fiber amplifier[6] realized the all-optic long-haul trunk lines in the 1990s, where high output power pumping LDs with long term reliability[7] and Er-doped “active-fiber” as a gain medium have been the key components.

Table 1.1 Historical topics in fiber-optic transmission technology and related improvement in laser diodes and in silica-fiber technology.

Decade	System/network	laser diodes (LDs)	Silica-fiber
1770s	First commercial Fiber optic transmission	long wavelength GaInAsP/InP LDs	Low loss silica fiber
1980s	G-bps-trunk network	Dynamic single mode DFB LDs	Dispersion shifted fiber
	Hybrid Fiber/Coax CATV	DFB LDs for analog	
1990s	Optical Fiber Amp. & All optic trunk / submarine	High-output-power (fiber out) pumping LDs	Er-doped fiber / dispersion compensation fiber

Now, recent progress in fiber-optic networks and requirements on the light sources are discussed below. They could be categorized in three; 1) *high capacity trunk lines*, 2) *fiber-backbone for wireless communication*, 3) *data communication and interconnects*. The discussions below are summarized in Figure 1.1.

1)High capacity trunk lines

Greater impact of the optical fiber amplifier has been in the feasibility of simultaneous amplification of the wavelength-division-multiplexed (WDM) signals. In the gain bandwidth of Er-doped fiber amplifier, N-channel ($N > 8$) signals are multiplexed in different wavelengths. This method has realized N-times enhancement of the trunk capacity using an existing fiber and been called as dense-wavelength division multiplex (D-WDM)[9]. D-WDM has been one of the most attractive solutions for recent high capacity transmission.

Requirements on LDs for the D-WDM would be the following. For pumping LDs, higher fiber-coupled power and wavelength stabilization is required in both 980 nm and 1480 nm wavelength regions in order to realize broader and flatter gain performance of optical fiber amplifier. For higher power LDs, the key characteristics would be higher slope efficiency and higher saturation (maximum) power, where heating effect and hence the temperature stability

would also be vital[7]. For the light source LDs in D-WDM, precise control of emission wavelength and small wavelength chirping are required. Reduction of the cost for the light sources would be one of the key issues, due to an increased cost ratio of light sources in the total system cost. So far, the expensive combination of DFB LDs and the external modulator has been adopted in order to avoid the wavelength chirping in case of the direct modulation of DFB LDs. If the wavelength chirping in the direct modulation could be reduced down to a negligible level, adopting the simple direct modulation of DFB LDs should be a more attractive solution. Another important point is that for high-speed pulse modulation of LDs, large relaxation oscillation frequency f_r and short turn on delay time are required.

2)Fiber-backbone for wireless communication

Wireless transmissions are the other essential part of recent communication networks. Cellular phone handsets are evolving toward mobile Internet terminals from mere access tools for voice service. The fiber backbone has been proposed for the connection of the central control station and the local stations in those systems. As one of the most attractive solutions, the sub-carrier-multiplex (SCM) technology[11], conventionally adopted in the CATV system, has been proposed. In this technology, microwave signals received at a local station antennas can be simply multiplexed as the modulation current of a LD in the same carrier frequency as received and can be converted to the optical signals without any decoding. Thus, fiber-backbone can be adopted independently of the microwave carrier frequency or of the coding scheme, which acts as the “transparent path”.

The requirements to the light sources in this area would be following. The sub-carrier-multiplexed light signal should be transmitted in analog in time domain, although each sub-carrier would be coded in digital by phase shift keying (PSK) etc. Therefore, high performance DFB-LDs for the analog transmission are required, where the essential characteristics are large modulation band width, small distortion in wide dynamic range and small relative intensity noise (RIN), similar to those in the analog fiber-backbone transmission.

3)Data communication and interconnects

Another leading application of fiber-optic transmission is data communication and optical interconnects of the computers or the measuring instruments. The computers and the

data storage disks in the offices or on the premises are connected with the high bit rate optical data links. The links with Vertical Cavity Surface Emitting Lasers (VCSEL)[12] in 850 nm wavelength and multi-mode fiber are the prevailing combination thus far. For higher bit rate than 2Gbps and longer distance, data links with Fabry-Perrot type LDs or DFB-LDs and single-mode fiber has also been adopted. Parallel data links with over 100 fibers have also been required and proposed for fast data acquisition in measuring instruments.

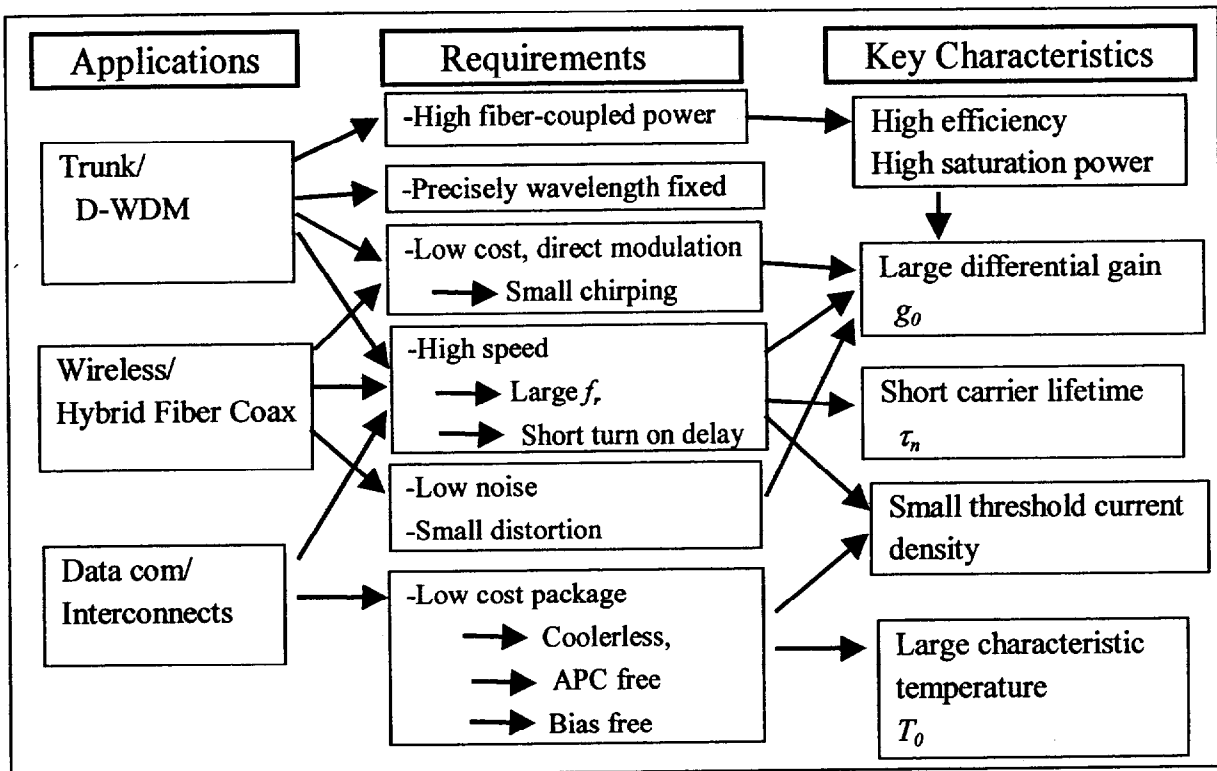


Figure 1.1

Performance requirements on LDs for recent applications and corresponding key characteristics.

For the requirements to the light sources for data communication and interconnects, not only the high-speed performance but also low cost and compact packaging are vital. For the latter requirements, coolerless, automatic-power-control (APC) free operations in wide temperature ranges are required on LDs. Bias free operation would also be required in future advanced applications. Key characteristics for such operations would be the small threshold current and the reduced temperature sensitivity in both threshold current and slope efficiency.

In realizing a compact package, narrow beam divergence is a key for easier coupling to the single mode fiber.

Here, we breakdown above extracted key characteristics for the high-speed LDs and DFB-LDs to more fundamental ones. The intrinsic high-speed pulse-modulation performance of LDs can be represented by the turn on delay time τ_d and the relaxation oscillation frequency f_r , given by Eq. (1-1) and Eq. (1-2)[13],

$$\tau_d = \tau_n \ln \left[\frac{I_p}{(I_p - I_b) - I_{th}} \right], \quad (1-1)$$

$$f_r = \frac{1}{2\pi} \sqrt{\frac{v_g g_0 S}{\tau_p (1 + \varepsilon_g S)}} \propto \sqrt{\frac{P}{\tau_p}} \sqrt{\left(\frac{\Gamma}{V_a} \right)} \sqrt{g_0}, \quad (1-2)$$

where, τ_n is carrier lifetime in the active layer, I_p , height of modulation pulse current, I_b , bias current, I_{th} , the threshold current, v_g is the group velocity, g_0 , the differential gain, i.e., the slope of optical gain against carrier density and S , the photon density, τ_p , the photon life time in the laser cavity, ε_g , the non-linear gain factor, P , the total photon number in the cavity, Γ , the confinement factor, V_a , the volume of active layer. On the other hand, the relative intensity noise (RIN) at frequency much lower than the relaxation oscillation frequency ($f \ll f_r$)[14] and the wavelength chirping line-width $\Delta\nu$ [13] is given by Eq. (1-3) and Eq. (1-4), respectively,

$$RIN_{f \ll f_r} = C \left(\frac{1 + \varepsilon_g S}{g_0 S \tau_n} + 1 \right)^2 \tau_p^2 \quad (1-3)$$

$$\Delta\nu = \frac{\alpha I_p}{2\pi q G P} \sqrt{\omega_m^2 + \Gamma_p^2} \propto \frac{\tau_p}{P^2} \frac{\Gamma}{V_a} \frac{1}{g_0} \quad (1-4)$$

where, C denotes constant coefficients, α , line-width enhancement factor, I_p , amplitude of modulating current, G , steady state modal gain, ω_m , modulation angular frequency, Γ_p , small signal photon decay rate, respectively.

In order to realize a short turn on delay time, we find from Eq.(1-1), that small carrier lifetime, small bias current and therefore small threshold current are the key fundamental characteristics. While, for the relaxation oscillation frequency f_r and the wavelength chirping line-width $\Delta\nu$, we find noticeable dependence from Eqs.(1-2) and (1.3), as shown in **Figure 1.2**.

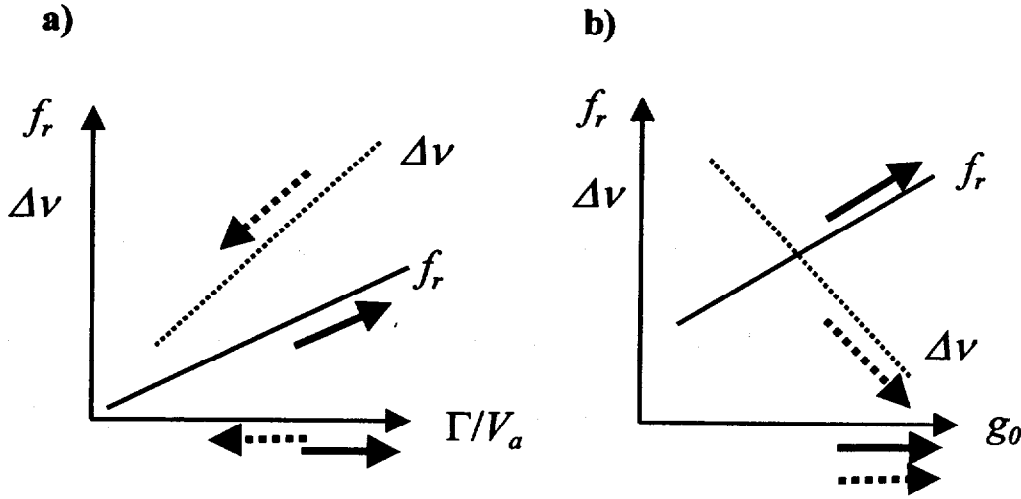


Figure 1.2
Dependencies of f_r and $\Delta\nu$ on the form factor Γ/V_a , a) and those on the differential gain g_0 , b).

Figure 1.2 shows schematically the dependencies of f_r and $\Delta\nu$ on the form factor Γ/V_a , a) and those on the differential gain g_0 , b). As shown in a), the trade off relation obstructs simultaneous improvement of f_r and $\Delta\nu$ by optimizing the form factor (Γ/V_a). While, we see in b) that larger g_0 brings improvements in both f_r , and $\Delta\nu$ at the same time. In addition, it is clear from Eq.(1-3) that larger g_0 brings lower RIN at lower frequency. It has also been reported that larger f_r results in lower composition beat distortion in sub-carrier-multiplexed transmission. Thus, we can extract the differential gain g_0 as one of the more fundamental

and essential characteristics for high-speed, low noise, low chirp, low distortion LDs.

The possibility of reducing threshold current density and enhancing both gain g and differential gain g_0 by adopting multiquantum well structure to the active layer had been theoretically predicted.[15],[16] Recent progress and a bottleneck problem along this direction will be discussed in the following subsection.

1.1.2 Advantages of recent strained quantum well lasers and a bottleneck

In this subsection, at first, the theoretically expected advantages of multiquantum well LDs, particularly, those of recent strained quantum well LDs are summarized. Then, a bottleneck problem and feasible approaches for improvement are discussed.

(1) Advantages of recent strained quantum well lasers

Since, L. Esaki and R. Tsu proposed the concept of superlattice in 1970, various kind of quantum effect devices and their advantages have been predicted and clarified [17][18]. Here, we focus our discussion on quantum well lasers (QW-LDs) and especially on strained QW-LDs from the standpoint of improving the fundamental characteristics of LDs extracted in previous subsections. Discussions below are summarized in **Figure 1.3**.

Performance improvement in quantum well lasers is basically attributed to the enhancement of gain $g(E_{ph})$, essential part of which can be expressed as[19];

$$g(E_{ph}) \propto \sum_{N_c} \sum_{N_v} \int_0^{\infty} |M_T|^2 \rho_{red}(E) \cdot [f_c(E) - f_v(E)] \cdot L(E_{ph}, E) dE, \quad (1-5)$$

where, E_{ph} denotes the photon energy, N_c , N_v denotes subband number in conduction band and valence band respectively, the summation should be taken for each subband transition pairs, $|M_T|^2$ denotes transition matrix element, $\rho_{red}(E)$, reduced density of states (DOS), $f_c(E)$, $f_v(E)$, the Fermi-Dirac distribution function for electrons and holes, respectively, $L(E_{ph}, E)$, the spectral lineshape function.

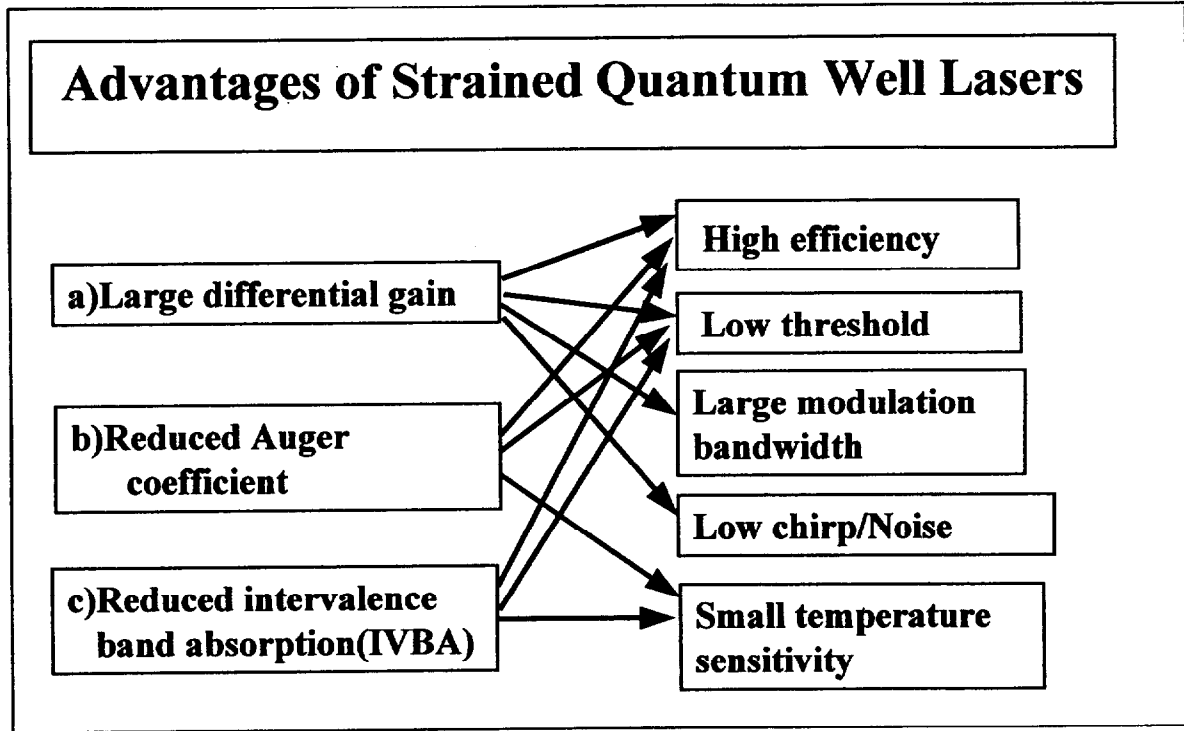


Figure 1.3

Schematic diagram showing the theoretical advantages of compressively strained quantum well lasers and expected improvements in the performances.

In Eq.(1-5), improvement arises from following factors;

- a) reduction of reduced DOS $\rho_{red}(E)$,
- b) increase of transition strength $|M_T|^2$ and
- c) energy separation of heavy-hole band and light-hole band,

all due to quantum confinement effect of carriers. Smaller $\rho_{red}(E)$ causes quicker change of Fermi-levels against an increment of well carrier density dn and so the quicker inversion of Fermi-Dirac function difference, $(f_c - f_v)$, which results in larger increment of gain, dg , or the larger differential gain $g_0 = dg/dn$.

The compressively strained QW has been theoretically predicted to add advantages in following three points [20]-[23];

- 1) enhanced differential gain,
- 2) reduced Auger recombination coefficient,
- 3) reduced intervalence band absorption.

Those are attributed to the change of valence band structure, i.e., further reduction of reduced DOS due to smaller in-plane effective mass of heavy-hole band and to larger separation energy between heavy hole band and light hole band. Above advantages should bring various improvements in laser performances such as threshold current, modulation bandwidth, linewidth and so on, as summarized in **Figure 1.3**.

For example, one of the dominant causes of the large temperature sensitivity of long-wavelength lasers has been attributed to the leakage loss of Auger hot carriers [24][25]. Auger recombination rate R_a is generally expressed as,

$$R_A = C_A N_w^3 \quad (1-6)$$

$$C_A = A \exp\left(-\frac{E_A}{kT}\right) \quad (1-7)$$

where C_A is the Auger recombination coefficient, N_w is the carrier density, E_A , the activation energy, A , the constant coefficient. The activation energy E_A is given by[26];

$$E_A = \begin{cases} \frac{m_s}{2m_h + m_c - m_s} (E_g - \Delta), & \text{CHSH} \\ \frac{m_s}{m_c + m_h} E_g, & \text{CHCC} \end{cases} \quad (1-8)$$

where, m_s is the spin-split off hole effective mass, m_h , heavy hole effective mass, m_c , conduction band effective mass, Δ is spin-split off energy, CHSH denotes hot-hole generation process to spin-split-off band, CHCC, hot-electron generation process to conduction band. Reduction in the Auger recombination coefficient arises since the compressive strain reduces in-plane heavy hole mass m_h and hence increases the activation energy. Simple calculation on 1.5 μm LDs predicts 140 meV increase in E_A and 1/200 reduction in C_A for CHCC process.[20]

(2) A bottleneck problem

After the theoretical proposals and predictions on the advantages of strained QW-LDs in late 1980s[20]-[23], successful operations of strained QW long-wavelength lasers with low threshold current and high output power were demonstrated[27] utilizing the advanced MOCVD epitaxial growth technology for InP based materials[28][29]. Sufficient reduction of intervalence band absorption in strained QW-LDs was also confirmed[30]. However, through various experiments and characterizations, following discrepancies between the measured characteristics and the theoretical predictions were pointed out;

- 1) Measured differential gain was 1/3 to 1/10 smaller than the theoretical values[31],
- 2) No remarkable improvement was obtained in temperature sensitivity of threshold current density[27].

Table 1.2 compares reported theoretical and experimental values for the differential gain. As shown here, measured values are smaller than theoretical values, two to four times for lattice matched QW LDs, five times to almost an order of magnitude for strained QW-LDs.

Table 1.2 Reported theoretical predictions and experiments on the differential gain g_0 (10^{-16} cm²) for long-wavelength LDs.

Type of active Layer	Theory	Experiment
Bulk	2.5 - 3 [24]	2.7 - 3.1 [31]
Lattice matched QW	10 - 20 ($L_z=5\text{nm}$) [22]	5 - 7 [31]
Compressive strained QW	36 - 45 (2.5%) [22]	5 - 7 (0.87%) [31]

On the causes of the above discrepancies, a theory describing the deterioration due to the carrier dynamics phenomena was proposed, where carrier leakage from QW to the optical confinement layer and carrier injection delay across the optical confinement layer were shown to play dominant role[32]-[34]. The theory, named carrier transport theory, was successful in explaining qualitatively the deterioration in differential gain and in high-frequency modulation performances. However, the theory was insufficient in terms of quantitative agreement with experimental results. Especially, the temperature sensitivity of threshold current could not be explained with the theory. In additions, it was not clear whether other possible causes such as

Auger carrier loss or the temperature sensitivity of gain were participating with above discrepancies or not. Thus, exact mechanism and therefore directions for improvement had not been clarified. In such circumstances, the above discrepancies had been recognized as the bottleneck to be overcome in order to realize the full availability of intrinsic performances of strained quantum well lasers.

Reported possible approaches for the above bottleneck problems are discussed below. The carrier transport theory pointed out the serious effect of carrier dynamics in the quantum wells lasers. Concerning suppression of the carrier leakage, it should be noted that following three approaches had been proposed. The first one is AlGaInAs material system[35],[36] with larger conduction band-edge discontinuity than that of GaInAsP system. Long-wavelength lasers in this material system had been demonstrated. The second is the artificial enhancement of the heterobarrier height by utilizing the energy stop band of superlattices[37],[38]. This method, named “multiquantum barriers” had been demonstrated in reducing leakage current and improving temperature stability in red-light lasers[39]. The third one is the concept of controlling band-edge discontinuity at the heterojunction utilizing strain effect[40]. However, few experiments had been reported on the effectiveness of above methods in overcoming the bottleneck problem in long-wavelength strained quantum well lasers.

Table 1.3 summarizes the background history of this study.

Table 1.3 The background history of this study.

Year	Strained Quantum Well Lasers	Carrier Dynamics Related Issues
1970	Proposal of Superlattice (Esaki et al.)	
1975	Demonstration of Quantum well laser (Ziel)	
1981		Temperature sensitivity on GaInAsP LD (Asada, Sugimura, Dutta)
1983	AlGaInAs MQW LD (Temkin et al.)	
1984	Improved gain in QW LDs (Asada et al.) Strained QW-LD (Laidig et al.)	
1986	Theory on strained QW lasers ; reduced DOS & Auger (Adams, Yablonovitch)	Proposal of Multiquantum Barriers (Iga et al.)
1988	Wide modulation band in strained QW LD (Suemune et al.)	
1989	Reduced linewidth in strained QW (Ohtoshi et al.)	Strain effect on ΔE_c and ΔE_v (Shuermeyer et al.)
1990	Demonstration of strained-1.5 μm QW LD: Low J_{th} & High power (Thijs et al.)	Demonstration of red-light LD with Multiquantum Barriers (TTT, Sophia Univ., Toshiba, Sanyo)
1991	High differential gain in strained QW (Suemune)	Carrier leakage & transport problem in QW LD (Nagarajan)
This study		

1.2 Purpose of this study

As described above, the background of this study is summarized as follows;

- 1) Recent progress in fiber-optic networks requires further improvement of laser performances. The dramatic improvement had been theoretically predicted for the performances of strained quantum well long-wavelength lasers. However, large discrepancy between the theoretical predictions and experimental results had been reported for the essential characteristics such as the differential gain.
- 2) As one of the dominant causes of the above discrepancy, deterioration theory due to the carrier dynamics effect had been proposed and pointed out the large deterioration from the intrinsic theoretical values. However, quantitative explanation of the discrepancy had been insufficient and hence the causes the discrepancies had not been clarified. Thus, the discrepancy had been recognized as a bottleneck to be overcome in realizing the full availability of intrinsic performance of strained quantum well lasers.

Based on the background as above described, the objectives of this study were settled as follows;

- 1) Identifying the mechanism of the discrepancy and obtaining guidelines for improvement.
 - a) Evaluating the discrepancy and the effects of carrier dynamics in 1.5- μm -wavelength quantum well lasers.
 - b) Theoretical analysis on the causes of the discrepancy focusing on the carrier dynamics phenomena.
 - c) Deriving guidelines for further improvements of LD performances.
- 2) Presenting feasible methods to overcome the discrepancy and to improve the laser performances.
 - a) Verifying the effectiveness of multiquantum barriers in long-wavelength lasers along above purpose and improving the design method.
 - b) Evaluating the effect of barrier height enhancement by strained layers.
 - c) Presenting a concrete laser structure with improved laser performances.

1.3 Outline of this thesis

This dissertation is organized as follows;

In Chapter 1, the background, the purpose and outline of this thesis are described.

In Chapter 2, characterization results for AlGaInAs/GaInAs 1.5- μm -wavelength quantum well lasers are compared with theoretical predictions. Large discrepancies are confirmed even in this material system. Further, the effects of carrier dynamics phenomena are evaluated adopting the carrier transport theory.

In Chapter 3, improved theory describing the effect of carrier dynamics in quantum well lasers will be presented. Calculated performances with the theory are compared with experiments and good agreements are demonstrated. The dominant factors of the discrepancies are identified with the theory. Directions for further improvements are derived and possible approaches are discussed.

In Chapter 4, experimental results on the effectiveness of multiquantum barriers in improving the performances of long-wavelength quantum well lasers are summarized. Evidence of carrier leakage suppression and the estimated enhanced barrier height are described. Subjects for further improvements are also discussed.

In Chapter 5, improved design methods for multiquantum barriers are described. Design method including conduction band nonparabolicity and utilizing tensile strained barriers are presented. Possibility of hole pile-up in multiquantum barriers is discussed and improved design method for smooth hole transport is presented.

In Chapter 6, a method of carrier leakage suppression with enhanced barrier height of tensile-strained-barriers and improved carrier injection method are presented. An example of laser structure and expected improvements are described.

In Chapter 7, future prospects will be discussed.

Chapter 8 concludes the study in this dissertation.

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Chapter 2

Carrier Dynamics Phenomena in 1.5- μ m-Wavelength Multiquantum Well Lasers

AlGaInAs/GaInAs 1.5- μ m-wavelength separate-confinement-heterostructure (SCH) multiquantum well LDs were fabricated and the key characteristics were compared with theoretical predictions. Large discrepancies between measured values and theory were confirmed even in this material system. Effects of carrier dynamics phenomena were evaluated with conventional carrier transport theory. The results suggested that the deterioration of intrinsic performances due to the carrier dynamics phenomena be the dominant cause of the above discrepancies. However, it was also found that the conventional carrier transport theory predicts too large deterioration.

2.1 Fabrication of GaInAs/AlGaInAs 1.5- μ m-wavelength multiquantum well lasers

2.1.1 AlGaInAs/GaInAs material system on InP

Figure 2.1 schematically shows the band-edge discontinuity for AlGaInAs/GaInAs and that of GaInAsP/GaInAs in comparison[1],[2]. As shown here, AlGaInAs/GaInAs system has a larger (smaller) conduction (valence) band edge discontinuity ΔE_c (ΔE_v) than that of GaInAsP/GaInAs system, compared at a same band gap. Larger ΔE_c would be one of the advantages in suppressing leakage of electrons from QWs. While smaller ΔE_v has been thought to be favorable in preventing phenomena such as hole-pile and non-uniform carrier distribution to QWs[3].

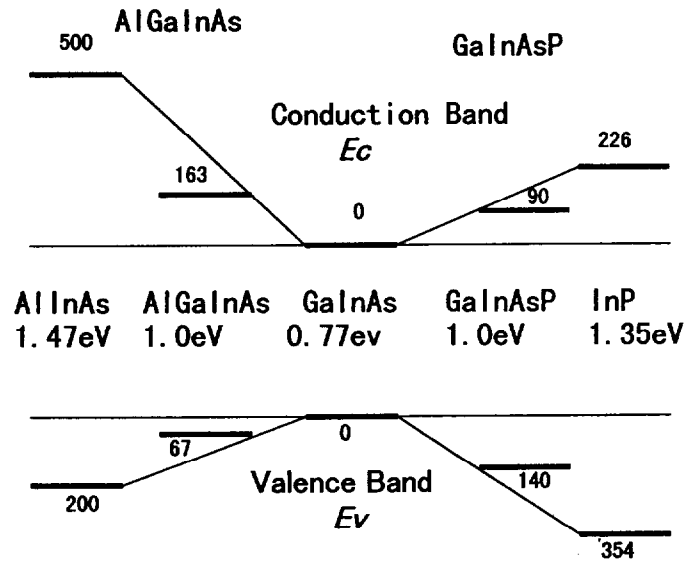


Figure 2.1

Comparison of the band edge discontinuity for AlGaInAs/GaInAs and GaInAsP/GaInAs heterojunction.

2.1.2 GaInAs/AlGaInAs 1.5- μm -wavelength SCH-MQW LDs

GaInAs well/AlGaInAs barrier 1.5- μm -wavelength SCH-MQW LDs were fabricated, where lattice matched (LM) MQW (LM-MQW) and 1 % compressive strained layer (SL) MQW (SL-MQW) were compared[4],[5]. The LD layer structures are summarized in Table 2.1 with the compositions and doping conditions.

Table 2.1 Layer structure, composition and doping conditions for the fabricated MQW LDs. N-type, (100) oriented InP substrates were used.

Layer	Thickness		Doping (cm^{-3})
p-GaInAs contact	400 nm		3×10^{19} (Be)
p-AlInAs clad	2,000 nm		1.5×10^{18} (Be)
Al _{0.24} Ga _{0.24} In _{0.52} As OC ($\lambda=1.15\mu\text{m}$)	Lattice matched MQW	1% compressive strained MQW	None
	150 nm	200 nm	
Active region	Well:Ga _{0.47} In _{0.53} As, 9 nm x 6 Barrier : Al _{0.24} Ga _{0.24} In _{0.52} As, 5 nm x 5 total 79 nm	Well:Ga _{0.32} In _{0.68} As, 3.4nm x 4 Barrier : Al _{0.24} Ga _{0.24} In _{0.52} As, 15 nm x 3 total 58.6 nm	None
Al _{0.24} Ga _{0.24} In _{0.52} As OC ($\lambda=1.15\mu\text{m}$)	150 nm	200 nm	None
n-AlInAs clad	1,000 nm		1×10^{18} (Si)

MBE was used for the epitaxial growth of laser structures on InP substrates. Sophisticated in-situ InP wafer cleaning and subsequent growth process under Arsenic pressure were developed. Growth conditions were optimized to grow high quality, low defect density materials and strained InGaAs/AlGaInAs multi-quantum well structures[6].

Table 2.2 summarizes the basic stationary state characteristic of the LDs. Threshold current density was measured with the broad area LDs. Low threshold current densities 1.5 KA/cm² and 1.1 KA/cm² were obtained at cavity length $L=800\text{ }\mu\text{m}$, both facet as cleaved states and at 300 K for lattice matched MQW LDs and 1 % compressive strained MQW LDs, respectively. Ridge waveguide (RWG) lasers with ridge width of 4 μm at the bottom were fabricated to further characterize the laser performances. Slight improvements in 1% compressive strained MQW compared to lattice matched MQW were confirmed in all characteristics. Those were almost equivalent to the best reported values in the same material system[7]-[11].

Table 2.2 Basic characteristics for the two types of MQW LDs at 300K.

Item	LM-MQW	SL-MQW
J_{th} (KA/cm ²)*	1.5	1.1
η_D (%) **	25	29
α_i (cm ⁻¹) **	19	16
T_0 (K)**	44	53

* at both facets as cleaved condition and cavity length $L=800\mu\text{m}$, broad area LDs.

** at both facets as cleaved condition and $L=400\text{ }\mu\text{m}$, at 300K, RWG LDs.

2.2 Characteristics of fabricated lasers and discrepancy from the theoretical predictions

As summarized in **Table 2.2**, remarkable improvement in the characteristic temperature T_0 was not obtained for the 1 % compressive strained MQW LDs, contrary to the expectation from theoretical predictions. Further, other essential characteristics such as carrier lifetime, differential gain were characterized and compared with theoretical values.

2.2.1 Modulation bandwidth at below threshold conditions

Small signal modulation bandwidth measurement at below threshold condition is conventionally called as the carrier lifetime measurement, since -3dB modulation bandwidth f_c is given by the carrier lifetime τ_n with following Eqs.(2-1).

$$2\pi f_c \left(\equiv \frac{1}{\tau_n} \right) = \frac{\partial R_w}{\partial N_w} = A_w + 2B_w N_w + 3C_w N_w^2, \quad (2-1a)$$

$$I_0 = qV_w (A_w N_w + B_w N_w^2 + C_w N_w^3) \equiv qV_w R_w. \quad (2-1b)$$

Figure 2.2 shows the squared modulation bandwidth as a function of normalized injection current, experiments (dots) and theoretical curves in comparison. In calculations, theoretical values[12] for bimolecular radiative recombination coefficients B_w and Auger coefficients C_w shown in the Figure were adopted to Eq.(2-1). As shown here, large discrepancy between theoretical intrinsic values and experiments was confirmed.

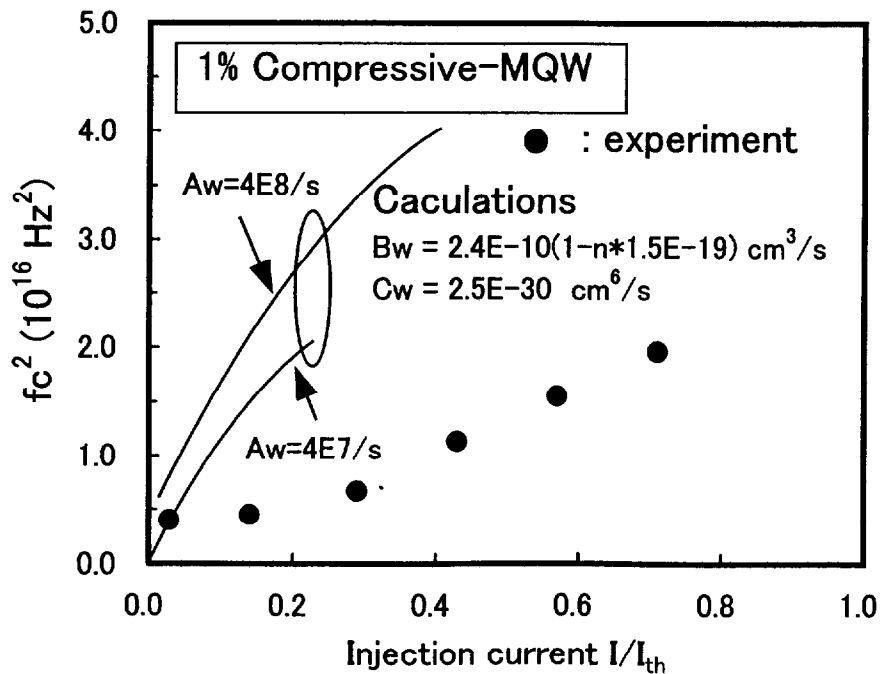


Figure 2.2

Squared modulation bandwidth as a function of normalized injection current, experiments (dots) and calculated intrinsic values (lines) in comparison.

2.2.2 Differential gain

The differential gain g_0 is one of the key characteristics for the various dynamic performances as described in **Chapter 1**[13]. In order to evaluate differential gain, relative intensity noise (RIN) spectra were measured. Examples of measured RIN spectra at various output power levels are shown in **Figure 2.3**.

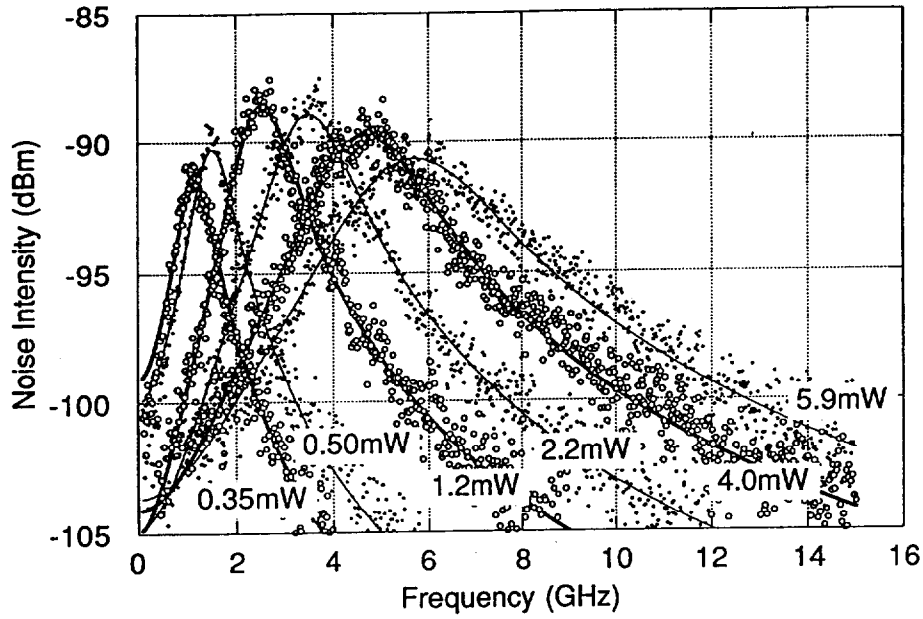


Figure 2.3

Examples of the measured RIN power spectra and fitting curves for the 1 % compressive strained MQW LD. The ridge waveguide stripe LD (width of stripe 4 μm) was used for the measurements.

The procedure to obtain the differential gain from RIN measurement is briefly described below. The RIN spectrum is given by[14],

$$\text{RIN}(f) \equiv \frac{\langle \Delta p \rangle^2}{P_0^2 \Delta f} = C \frac{f^2 + \left(\frac{\gamma^*}{2\pi} \right)^2}{(f^2 - f_r^2)^2 + f^2 \left(\frac{\gamma_e}{2\pi} \right)^2}, \quad (2-2)$$

where, $\langle \Delta p \rangle^2$ is the average value of optical noise power, p_0 , the optical output power, f , the measuring frequency, f_r , the relaxation oscillation frequency, γ^* , the damping factor, γ_e , the effective damping factor, and C the fitting coefficient. Those parameters and coefficient can be determined by fitting the measured curves with Eq.(2-2). Then, the square of relaxation oscillation frequency can be plotted as a function of facet output power as shown in Figure 2.4.

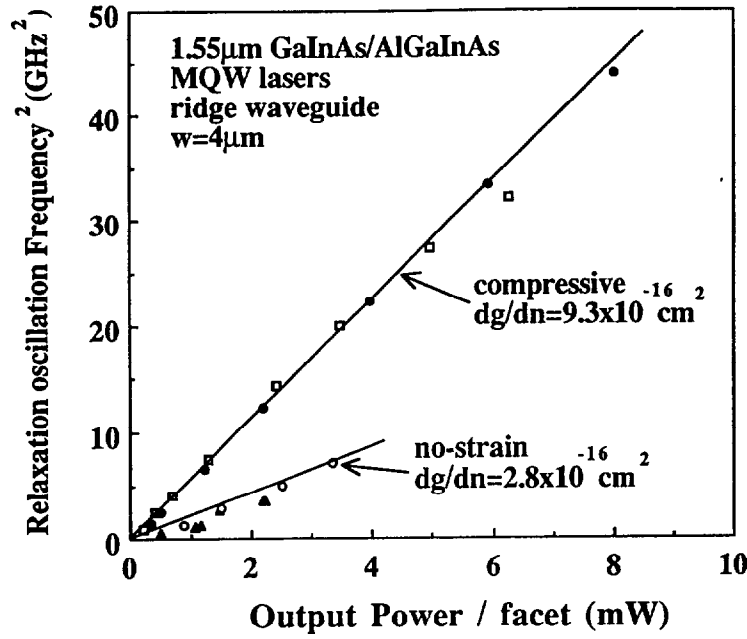


Figure 2.4

The squared relaxation oscillation frequency f_r^2 as a function of output power per facet P_{facet} for the two type of LDs, obtained from the RIN measurements.

Now, the differential gain g_0 can be deduced from slope D using following relations[15] ;

$$f_r^2 = \frac{g_0 v_g S}{4\pi^2 \tau_p} = \frac{g_0 v_g \Gamma}{2\pi^2 V_w h\nu} \left(1 + \frac{\alpha_{int}}{\alpha_m} \right) P_{facet} \equiv D P_{facet}, \quad (2-3)$$

$$g_0 = 2\pi^2 D \frac{V_w h\nu}{v_g \Gamma \left(1 + \frac{\alpha_i}{\alpha_m} \right)}, \quad (2-4)$$

where S is the photon density, τ_p , the photon lifetime, P_{facet} , the output power per facet, Γ , the optical confinement factor, v_g , the group velocity, V_w , the volume of active layer, $h\nu$, the photon energy, α_{int} , α_m denotes internal loss and total mirror loss respectively. The obtained g_0 values are remarked in **Figure 2.4**.

In **Table 2.3**, measured values for differential gain g_0^{eff} are summarized and compared with theoretical predictions[16]. For 1% compressive strained MQW LDs, the differential gain three times larger than that for lattice matched MQW was confirmed. In addition, the value for the compressive strained LDs was the highest ever reported in this wavelength region. However, those measured values are smaller than a half of the theoretical predictions for both lattice matched LDs and compressive strained LDs[16].

Table 2.3 Comparison of measured differential gain g_0 and theoretical prediction.

LD type	Measured g_0^{eff} (10^{-16} cm^2)	Theoretical g_0^{th} (10^{-16} cm^2)	Ratio g_0^{eff}/g_0^{th}
LM-MQW	2.8 (RIN)	6 [16]	0.47
SL-MQW	9.3 (RIN)	24 [16]	0.38

2.3 Estimation of the effect of carrier dynamics phenomena

2.3.1 Carrier transport theory

Carriers in the QW can be thermally excited and injected into the optical confinement layers to distribute as leakage carriers. The density of the leakage carriers in the optical confinement layer is influenced by both carrier leakage lifetime and diffusion delay time of carriers across the optical confinement layer. Those carrier dynamics phenomena have been treated by carrier transport theory and been shown to deteriorate various laser performances such as differential gain, etc.[17]-[19]. The single-quantum well model for the carrier transport theory is schematically shown in **Figure 2.5**.

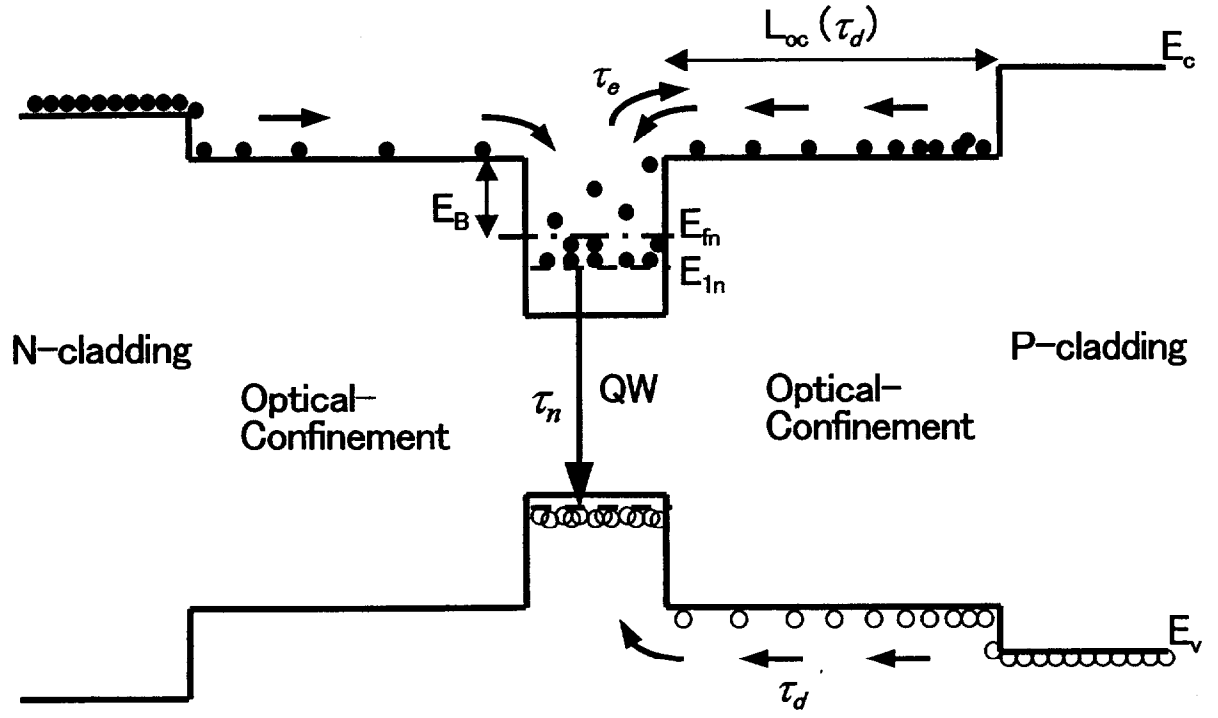


Figure 2.5

Schematic diagram showing the model for the carrier transport theory. Ambipolar diffusion in the p-side optical confinement layer is assumed.

The deterioration due to the carrier dynamics phenomena is represented by carrier transport factor χ in the carrier transport theory. For example, the carrier recombination lifetime τ_n^{eff} and the differential gain g_0^{eff} under carrier leakage effect are given by following equations;

$$\tau_n^{eff} = \chi \tau_n \quad (2-5)$$

$$g_0^{eff} = \frac{g_0}{\chi} \quad (2-6)$$

$$\chi \equiv 1 + \frac{\tau_d}{\tau_e}, \quad (2-7)$$

$$\tau_d \cong \frac{L_{oc}^2}{4D_p}, \quad (2-8)$$

$$\tau_e = N L_z \left(\frac{2 \pi m^*}{k_B T} \right)^{\frac{1}{2}} \exp \left(\frac{E_B}{k_B T} \right), \quad (2-9)$$

where, g_0 is the intrinsic differential gain without the carrier transport effect, τ_d is the diffusion delay time across the optical confinement layer where the ambipolar diffusion is assumed, τ_e is the carrier leakage lifetime, L_{oc} , thickness of the optical confinement layer, D_p , diffusion constant for hole, L_z , the well thickness, N , the well number, m^* , the effective mass for electron, E_B , the effective barrier height. Thus, both the carrier recombination lifetime and the differential gain are deteriorated by the factor χ (>1), where χ is increased by larger τ_d and smaller τ_e .

2.3.2 Band diagrams and the Fermi-levels

The band diagrams and band parameters are essential in estimating the carrier leakage lifetime with Eq.(2-9). The Fermi-level E_{fn} is also vital since the effective barrier height E_B in Eq.(2-9) is defined with the energy level of optical confinement layer $E_{C(OC)}$ as,

$$E_B = E_{C(OC)} - E_{fn}. \quad (2-10)$$

Tables 2.4 and 2.5 summarize the band parameters used for calculations. The band offset and effective mass values were calculated by the model solid theory[20],[21].

Table 2.4 Band edge discontinuity $\Delta E_{c(v)}$ and band edge effective mass $m_{ec(hv)}^*$ for perpendicular direction to QW plane determined with model solid theory^{29),30)} and subband energy levels for QWs consisting of lattice matched GaInAs well or 1% compressive GaInAs well and lattice matched AlGaInAs ($\lambda_g=1.15 \mu m$) barriers.

LD type	ΔE_c	ΔE_v	m_{ec}^*	m_{hv}^*	E_{1n}	E_{hh1}	E_{hh2}
Lattice matched	208	111	0.043	0.37	45	8.4	141
1% compressive	257	176	0.037	0.38	140	40	141

Table 2.5 Normalized DOS effective mass values used for calculations

LD type	$m_e^*(E_{1n})$	$m_e^*(E_b)$	$m_h^*(E_{hh1})$	$m_h^*(E_{hh2})$	$m_h^*(E_b)$
Lattice matched	0.048	0.067	0.1	0.37	0.37
1% compressive	0.056	0.070	0.1	0.38	0.38

The Fermi-level E_{fn} was calculated with following equations for the well carrier density N_w and the density of states (DOS) N_{QW_i} for quantum well[14];

$$N_w = \sum_i \int_{E_i}^{E_b} \frac{m_i^*}{\pi \hbar^2 L_z} \frac{1}{1 + \exp \frac{E - E_f}{k_B T}} dE = N_{QW_i} \ln \frac{1 + \exp \left(\frac{E_f - E_i}{k_B T} \right)}{1 + \exp \left(-\frac{E_b - E_f}{k_B T} \right)} \quad (2-11)$$

$$N_{QW_i} = k_B T \frac{m_i^*}{\pi \hbar^2 L_z}, \quad (2-12)$$

where, E_b denotes the energy level for i-th subband, $E_b (= \Delta E_c \text{ or } \Delta E_v)$, the barrier height, m_i^* , the DOS effective mass value for in-plane motion, L_z , the well thickness.

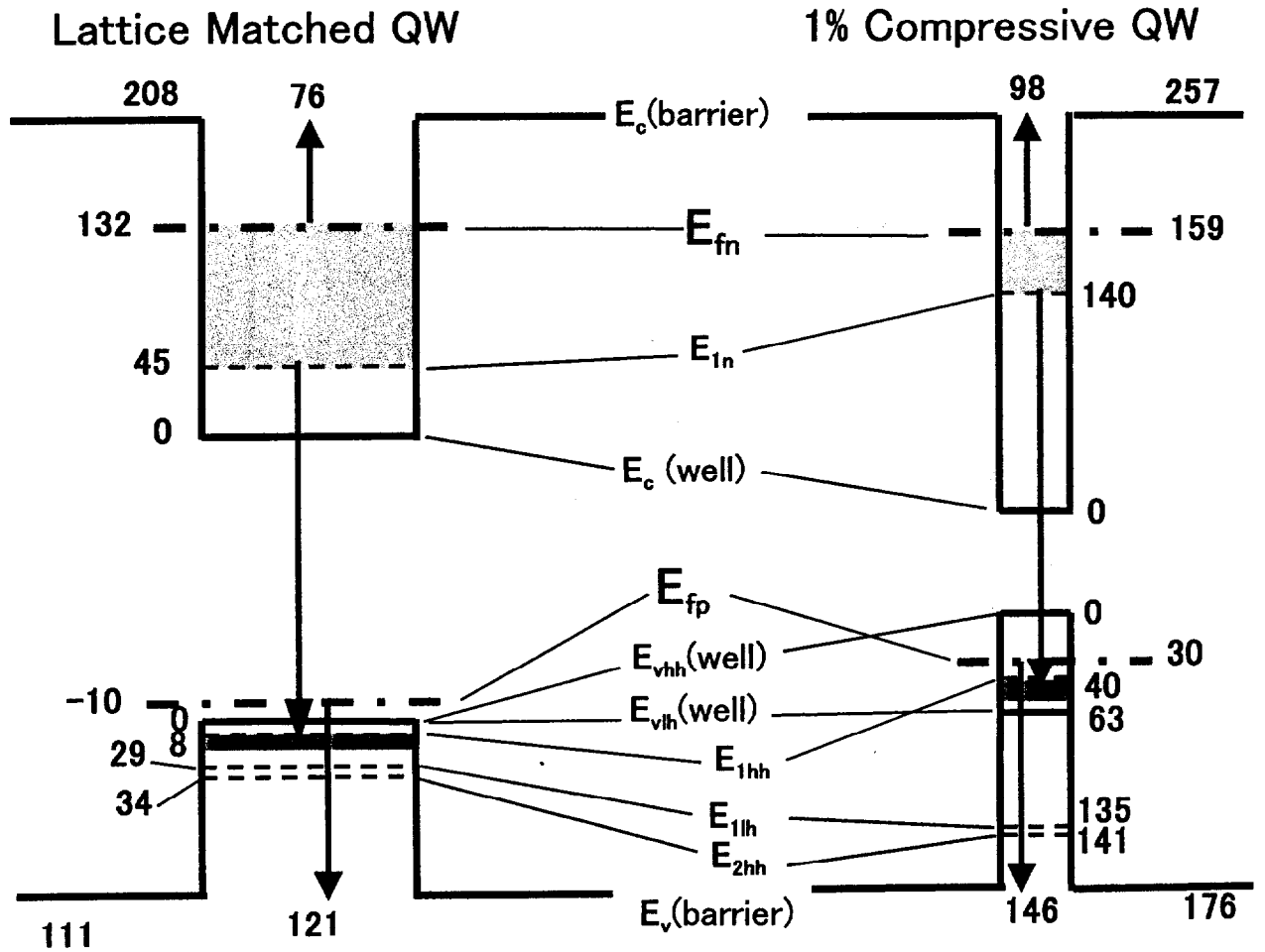


Figure 2.6

Calculated band diagrams and the subband states, Fermi levels at estimated threshold carrier density at 300 K for two type of LDs.

Figure 2.6 shows the calculated band diagrams, the subband edge energies and Fermi levels at estimated threshold carrier density at 300 K for two type of LDs. It was confirmed that in SL-MQW, the band filling in conduction band is much smaller and the separation between the first subband for light hole E_{lhh} and the one for heavy hole E_{lhh} is much larger compared to those in LM-MQW. Those differences should both contribute to the improvement of threshold current density and gain performances in SL-MQW.

2.3.3 Carrier transport factor and the effective differential gain

Carrier transport factor calculated using Eqs.(2-8)-(2-13) are shown in Figure 2.7. Large χ values were estimated for both type of LDs, which strongly suggested that the discrepancy could be attributed to the deterioration due to the carrier dynamics phenomena.

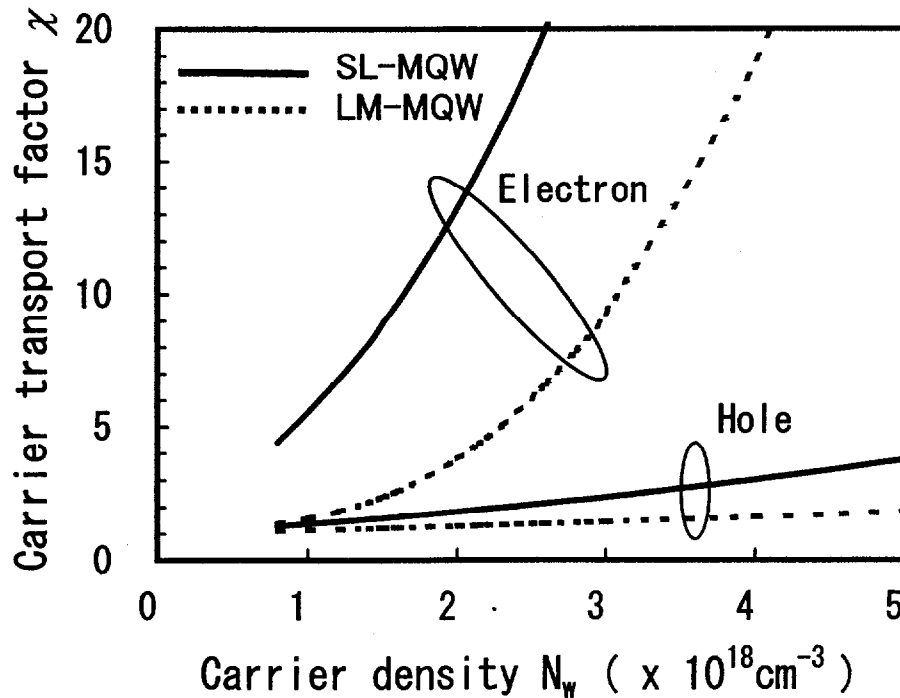


Figure 2.7

Calculated carrier transport factors as a function of well carrier density for the lattice matched (LM) MQW-LD and for the 1% compressive strained (SL) MQW-LD.

Figure 2.8 compares the intrinsic differential gain g_0 and the effective differential gain g_0/χ calculated with carrier transport theory with measured values. Measured g_0^{eff} obtained from the damping factor measurement are plotted together[22]. As shown here, carrier transport theory explains the large deterioration in the differential gain from the intrinsic values. However, in terms of quantitative agreement, it predicts too large deterioration.

In **Table 2.6**, carrier transport factors calculated from the effective barrier height with different energy references, the Fermi-level E_{fn} and the first subband edge E_{1n} are compared together with measured values. As shown here, either calculation result fails to explain consistently the measured values. Those also suggest the inadequateness of the conventional model equations together with above result in **Figure 2.8**.

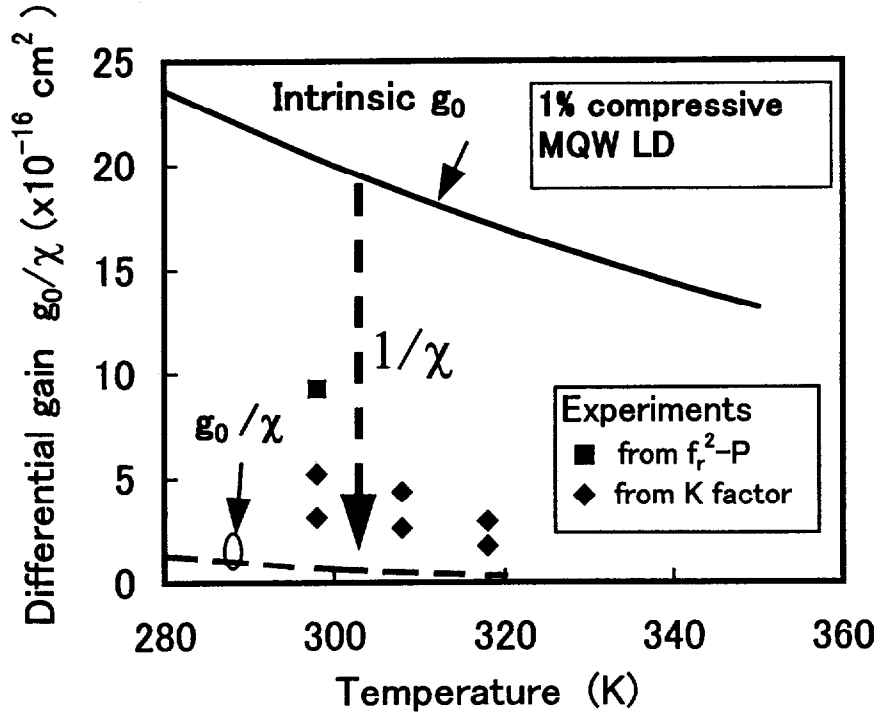


Figure 2.8

Comparison of the theoretical intrinsic differential gain g_0 , the effective differential gain g_0/χ calculated and measured values for 1% compressive strained MQW-LD.

Table 2.6 Calculated carrier transport factor χ with different energy references, E_{fn} and E_{1n} in comparison with measured values.

LD type	Calculated		Measured
	$E_B=E_{C(OC)}-E_{fn}$	$E_B=E_{C(OC)}-E_{1n}$	
Lattice matched	2.8	1.1	2.5-3.7
Compressive strained	13.3	7.3	2.6-5.2

2.3.4 Modulation bandwidth below threshold

Effect of carrier dynamics upon the small signal modulation bandwidth f_c is described with following two component rate equations[17]-[19].

$$\frac{dN_{oc}}{dt} = \frac{I}{qV_{oc}} - R_{oc}(N_{oc}) - \frac{N_{oc}}{\tau_d} + \frac{N_w}{\tau_e} \frac{V_w}{V_{oc}}, \quad (2-13)$$

$$\frac{dN_w}{dt} = R_w(N_w) + \frac{N_{oc}}{\tau_d} \frac{V_{oc}}{V_w} - \frac{N_w}{\tau_e}, \quad (2-14)$$

where, $N_{w(oc)}$ denotes carrier density in the quantum wells (optical confinement layer), I denotes the injection current, $V_{w(oc)}$ denotes the total volume of the quantum wells (optical confinement region and barriers), $R_{w(oc)}$ denotes carrier loss rate in the quantum wells (optical confinement region), τ_e represents the thermionic carrier leakage lifetime, τ_d , the ambipolar diffusion time across the optical confinement layer. By separating stationary state solutions and small signal solutions with the substitutions of, $I = I_0 + i \exp(j\omega t)$, $N_w = N_{w0} + n_w \exp(j\omega t)$, etc. and defining $\gamma_{w(oc)} \equiv \partial R_{w(oc)} / \partial N_{w(oc)}$, following relation for the small signal carrier density n_w is derived[19].

$$n_w = \frac{\left[\tau_d (\gamma_{oc} + \gamma_w) + \left(1 + \frac{\tau_d}{\tau_e} \right) \right]^{-1}}{\gamma_w \left[\tau_d \left(\gamma_{oc} - \frac{\omega^2}{\gamma_w} \right) + \left(1 + \frac{\gamma_{oc} \tau_d}{\gamma_w \tau_e} \right) \right] \left[\tau_d (\gamma_{oc} + \gamma_w) + \left(1 + \frac{\tau_d}{\tau_e} \right) \right]^{-1} + j\omega} \cdot \frac{i}{qV_w} \quad (2-15)$$

Further, noticing relations $\tau_d(\gamma_{oc} + \gamma_w) \ll 1$ and $\tau_d \omega^2 / \gamma_w \ll 1$, Eq.(2-16) is derived.

$$n_w \cong \frac{\left(1 + \frac{\tau_d}{\tau_e} \right)^{-1}}{\gamma_w \left(1 + \frac{\gamma_{oc} \tau_d}{\gamma_w \tau_e} \right) \left(1 + \frac{\tau_d}{\tau_e} \right)^{-1} + j\omega} \cdot \frac{i}{qV_w} \quad (2-16)$$

Thus, 3dB down modulation frequency f_c is given as,

$$f_c \cong \frac{1}{2\pi} \gamma_w \left(1 + \frac{\gamma_{oc} \tau_d}{\gamma_w \tau_e} \right) \left(1 + \frac{\tau_d}{\tau_e} \right)^{-1}. \quad (2-17)$$

On the other hand, the bias current I_0 is derived as;

$$I_0 = qV_w R_w + qV_{oc} R_{oc}, \quad (2-18)$$

where, $R_w = A_w N_w + B_w N_w^2 + C_w N_w^3$, $R_{oc} = A_{oc} N_{oc} + B_{oc} N_{oc}^2$ and $N_{oc} = (V_w/V_{oc})(\tau_d/\tau_e)N_w$.

Theoretical f_c^2 vs. I_0/I_{th} diagram can be obtained from Eqs.(2-17) and (2-18). **Figure 2.9** compares calculated results with measured value. In calculations, reported theoretical values were used for B_w [12] and B_{oc} [14], while A_w , A_{oc} and C_w were chosen to fit experiments. As shown here, experimental results can be well fitted with the carrier transport theory. However, for the validity of the theory to be proved, the fitted loss coefficients must consistently explain the threshold current density and its temperature sensitivity.

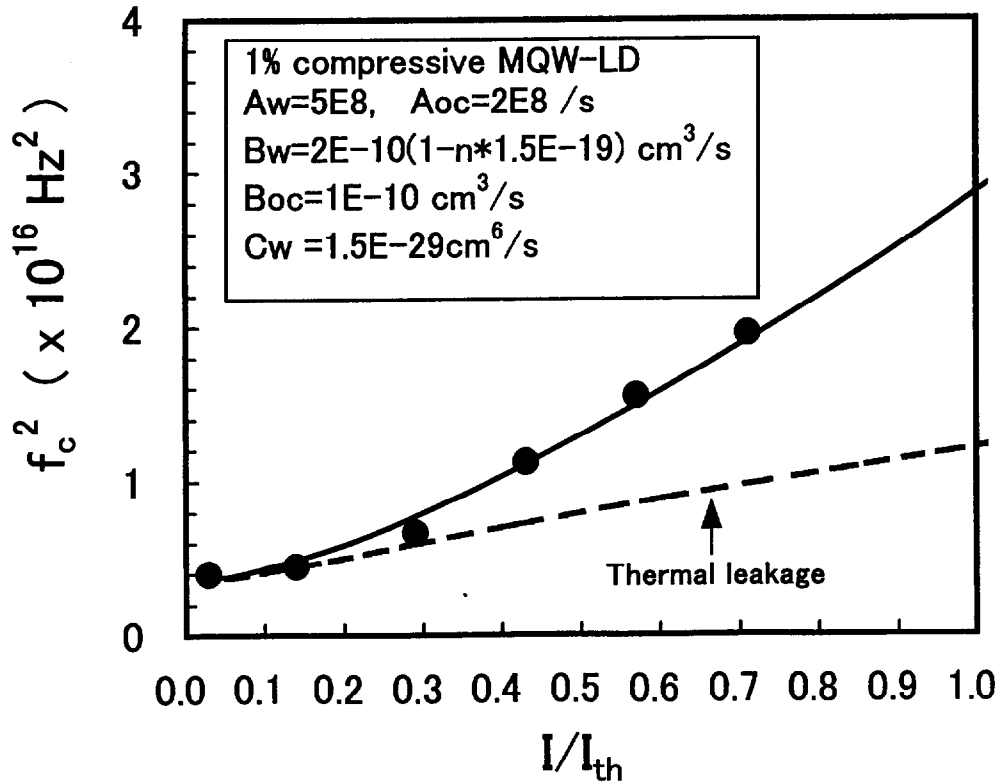


Figure 2.9

Squared modulation bandwidth frequency f_c^2 as a function of normalized injection current I_0/I_{th} . Calculated results (curves) with carrier transport theory and experiments (dots).

2.3.5 Threshold current density and temperature sensitivity

In order to examine further the validity of the carrier transport theory and the loss coefficients above determined, the threshold current density was calculated using balancing condition of gain and loss. The detail of the gain and loss model will be described in **Chapter 3** and only the calculation results are shown here. **Figure 2.10** shows calculated threshold current density as a function of temperature, together with measured results for 1% compressive strained MQW LDs. As shown here, calculated threshold current densities are twice to triple larger than experiments and characteristic temperature is about a half of the measured one. Those results again indicate that the conventional carrier transport model predicts too large deterioration in threshold current density. This also provokes the validity of the loss coefficients determined in previous subsection.

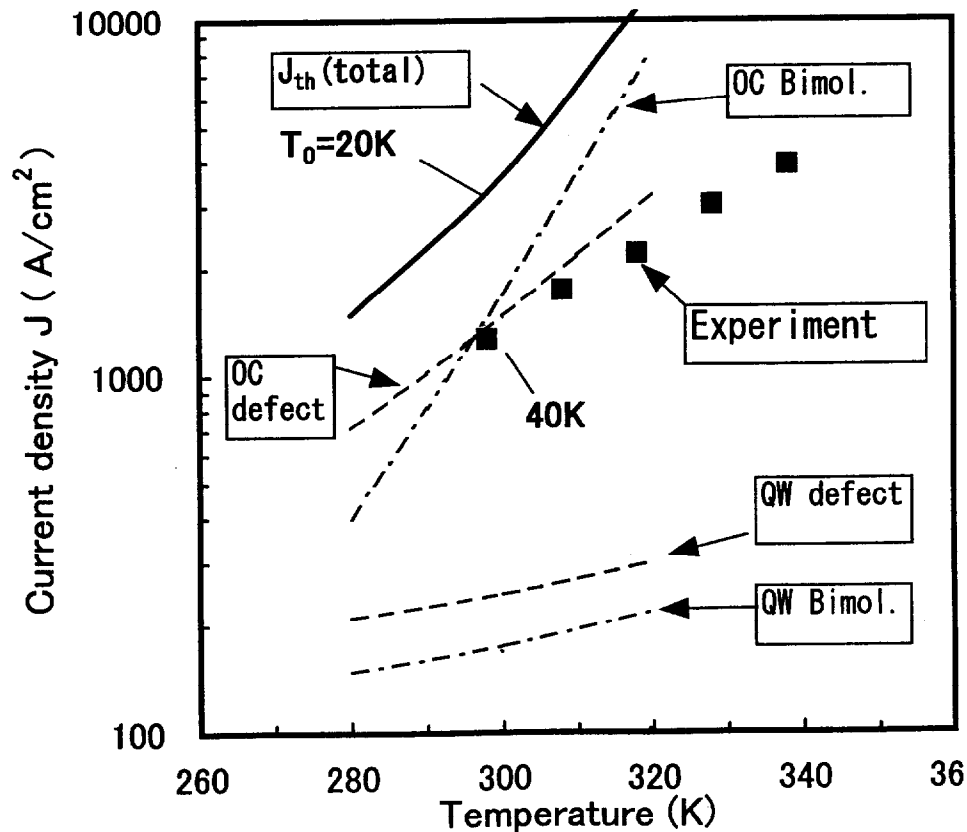


Figure 2.10

Threshold current density as a function of temperature for SL-MQW LDs. Calculated results (curves) with carrier transport theory and experiments (dots).

2.4 Summary

As a summary of this chapter, the effect of carrier dynamics phenomena in multiquantum well lasers was evaluated from experiments and with carrier transport theory.

At first, following improvement in 1% compressive strained MQW compared to lattice matched MQW was confirmed from experiments, which qualitatively agreed with theory.

- 1) Threshold current and differential quantum efficiency at room temperature and their temperature sensitivity are improved by incorporating compressive strain.
- 2) Measured differential gain g_0^{eff} for 1 % compressive strained MQW is three times larger than that of lattice matched MQW.

However, discrepancy from the theoretical predictions was clarified as follows;

- 3) No remarkable improvement is obtained in the characteristic temperature of threshold current for 1 % compressive strained MQW.
- 4) The measured modulation bandwidth below threshold is much smaller than the theoretical values.
- 5) The measured differential gain g_0^{eff} for both type of LDs are smaller than a half of the theoretical intrinsic values.

In the second step, carrier transport theory was adopted to estimate the effect of the carrier dynamics phenomena on the laser performances. Large deterioration due to the carrier dynamics effects was confirmed for the modulation bandwidth below threshold, i.e., the carrier lifetime, differential gain, and for threshold current density.

Those results suggested that the deterioration due to the carrier dynamics phenomena is the dominant cause of the above discrepancies between the experiments and theoretical intrinsic characteristics. However, at the same time, conventional carrier transport theory predicted too larger deterioration than the measured values and was found inadequate in explaining consistently the measured fundamental laser performances. Thus, improved theory for the carrier dynamics effect is required for further quantitative discussion and analysis of the deterioration mechanism.

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Chapter3

Improved Theory for Carrier Dynamics in Multiquantum Well Lasers

Improved theory for carrier dynamics phenomena in multiquantum well lasers is presented. Laser performances including their temperature sensitivities are calculated with model equations and good agreements with experimental results are demonstrated. The dominating factors of the large discrepancies between experiments and theoretical intrinsic values are discussed and attributed to 1) thermionic carrier leakage and diffusion delay effect and 2) Auger carrier loss. Directions for further improvements are also discussed.

3.1 Introduction

Problems of conventional theory and improvements introduced in this study are briefly summarized here. As shown in previous chapter, the conventional carrier transport theory proposed by Nagarajan et al. have demonstrated serious deterioration of performances due to carrier leakage and diffusion delay in SCH-MQW LDs[1]-[3]. However, in terms of quantitative explanation of experiments such as the temperature sensitivity of laser performances, those equations still involved inadequateness. Consequently, exact mechanism of the temperature sensitivity had not been fully clarified. Improved theory was required in order to identify dominating factors and to derive directions for improvements.

In this study, the author presented an improved theory that enabled further quantitative analysis[4]. Modifications were proposed on following three points;

1) A new model for thermionic carrier leakage lifetime

The conventional lifetime model by Schneider et al.[5] has recently been reported to be inadequate to explain the experiment[6],[7]. Also in this study, estimated lifetime

with conventional model was confirmed too short to explain experiments quantitatively. The conventional lifetime model is based on a simple parabolic band model and bulk density of states (DOS). In this study, the author introduced a model including the effect of nonparabolic band and DOS for strained QW.

2) Hole leakage was taken into account in addition to conventional electron leakage.

The hole leakage had been neglected in the conventional analytical model, because of much longer estimated leakage lifetime than that of the electron. However, experiment[8] and numerical analysis[9],[10] have been suggested the importance of hole leakage to OC layers. The new model adopted in this study predicted hole leakage lifetime in the same order as that of the electron. Thus, the author started from a set of rate equations including leakage of both electrons and holes from QWs to OC layers.

3) Carrier loss in the OC layers was taken into account for the first time.

The carrier loss in the OC layers had been neglected for simplicity in the analytical model. However, it was pointed out for the first time in this study that loss terms in OC layers are essential to enable more quantitative comparison of experiment and calculation.

In following section, overview of the improved theory, model and basic equations are introduced.

3.2 Improved theory for carrier leakage lifetime and rate equations

3.2.1 Overview of the improved model

Figure 3.1 shows schematically the overview of the carrier injection and leakage model presented in this study. The main features and assumptions are as follows;

1) Quasi-charge neutrality and ambipolar diffusion in OC layers under flat quasi-Fermi level[7].

Space charge in OC layer is estimated to be less than a few percent of carrier density in OC layer. This is consistent with the voltage drop in the OC layer less than 0.1V

estimated from measured current-voltage characteristics of SCH-MQW LDs.

- 2) Most parts of the diffusion flux from the OC layer are captured in each edge well.

This is consistent with the fact that reported carrier capture time of QW (0.8 (0.2) ps for electron (hole)[11]-[13] is shorter than the estimated additional ambipolar diffusion time for the edge well (>1 ps).

- 3) Leakage carriers are injected only from the edge well to the OC layer and thermionic emissions from inner wells are re-captured by QWs.

The mean free path for thermal electrons in the barrier layer is estimated at less than the barrier thickness and it should be much less in QW due to frequent coulomb scattering[14].

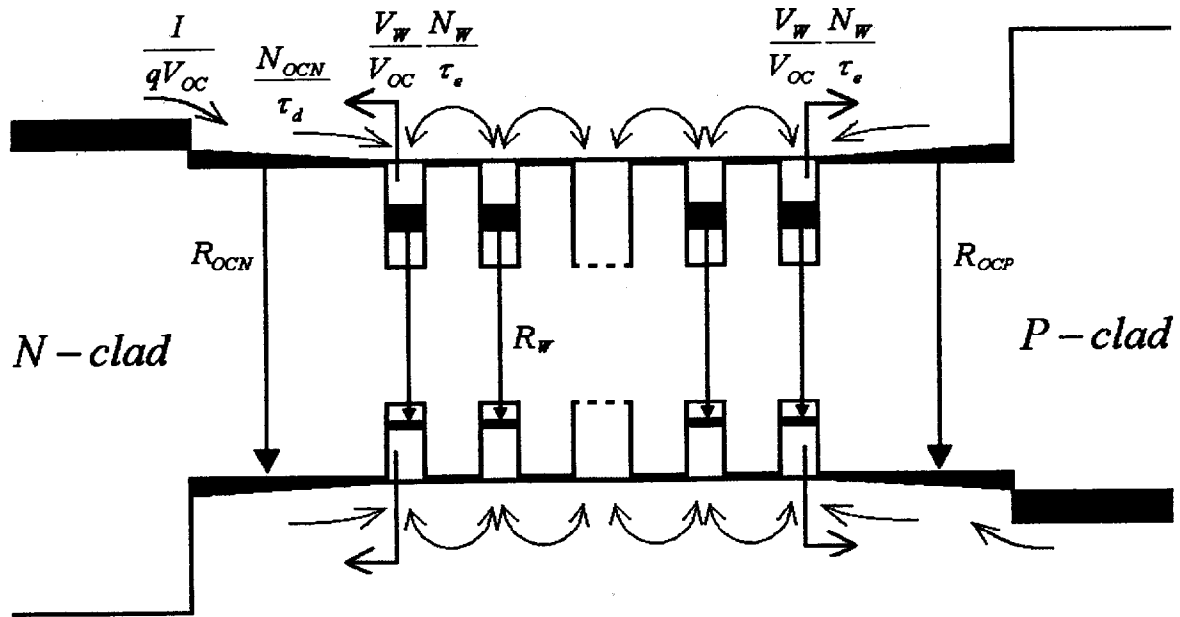


Figure 3.1

The schematic diagram showing the carrier injection and leakage model for the SCH-MQW LD. Carrier emissions from the edge wells toward OC layers result in the thermionic leakage current. R_w and $R_{ocp(ocn)}$ denotes carrier loss in QWs and p(n)-side OC layer, respectively. R_w involves defect loss, bimolecular recombination loss and Auger hot carrier loss. Auger hot carrier is assumed to result in leakage current to the cladding layer. $R_{ocp(ocn)}$ involves defect loss and bimolecular recombination loss.

4) Above injection carrier gain or leakage loss in the edge wells are readily compensated by fast carrier exchange among wells via over barrier state carriers.

Carrier transit time across the barrier layer is estimated to be less than 0.1ps[23], and carrier capture time also is less than 1 ps. Those are short enough compared to leakage carrier emission lifetime (larger than 10 ps) or to OC layer diffusion delay time (around 50 ps).

5) Auger hot electrons can pass through the QW region and reach the cladding layer as leakage current.

Hot electron leakage to the cladding layer and the effect of its suppression has been confirmed in recent SL-MQW LDs[15]. The possibility has been pointed out that a hot electron ($E > 300$ meV) has a much larger mean free path than that of low energy electron[16].

3.2.2 Carrier leakage lifetime

Here, model equations for carrier leakage lifetime are briefly summarized for conventional model and for improved model proposed in this study. Examples of calculation results are also shown in comparison.

In conventional theory, carrier leakage lifetime model Eq.(3-1), derived by Schneider et al, has been used[5];

$$\tau_e = NL_z \left(\frac{2\pi m^*}{k_B T} \right)^{\frac{1}{2}} \exp \left(\frac{E_B}{k_B T} \right), \quad (3-1)$$

where, N is the well number, L_z , the well thickness, m^* , the carrier effective mass, E_B , the effective barrier height. Eq.(3-1) was derived assuming parabolic band, bulk-like density of states (DOS). As described in previous section, above lifetime model was found inadequate to explain the experiment.

In this study an improved model equation for the leakage lifetime τ_{ei} (where, $i=e$ stands for electrons, h , for holes) was derived, starting from conventional continuous equation, Eq.(3-2), but taking into account DOS of strained QW and band nonparabolicity in calculating

leakage current, J_e^i , Eq.(3-3), and well carrier density, N_w^i , Eq.(3-4);

$$NL_z \frac{dN_w^i}{dt} = -\frac{J_e^i}{q_i} = -\frac{NL_z N_w^i}{\tau_{ei}}, \quad (3-2)$$

$$J_e^i = \frac{4\pi q (k_B T)^2}{h^3} m_i^*(E_{bi}) \exp\left(-\frac{E_{bi} - E_{fi}}{k_B T}\right), \quad (3-3)$$

$$N_w^i = \sum_j \int_{E_{ij}}^{E_{bi}} \frac{m_i^*(E_{ij})}{\pi \hbar^2 L_z} \frac{1}{1 + \exp\left(\frac{E - E_{fi}}{k_B T}\right)} dE + \int_{E_{bi}}^{\infty} \frac{4\pi (2m_i^*(E_{bi}))^{\frac{3}{2}}}{h^3} \sqrt{E} \exp\left(-\frac{E - E_{fi}}{k_B T}\right) dE, \quad (3-4)$$

where, $m_i^*(E)$ is the DOS effective mass for carriers in QW at energy level E , E_{bi} is barrier energy level, E_{ij} is j -th subband edge energy level, E_{fi} is the Fermi level, k_B , h , q , Boltzmann constant, Planck constant, elementary charge, respectively. Conduction (valence) band edge energy of QW was taken as an energy reference.

Figure 3.2 shows the example of calculation results on the carrier leakage lifetime τ_{ec} and τ_{eh} for SCH-MQW structure with 1% compressive GaInAs QW, AlGaInAs ($\lambda_g=1.15 \mu\text{m}$) barriers and OC layers. Band parameters and effective mass values determined with model solid theory[17],[18] and used for the calculation were summarized in previous chapter (**Table 2.4** and **2.5**). The effect of band nonparabolicity on DOS was taken into account by the kp method for the conduction band[19]. While for valence band DOS, a numerical calculation result was adopted for the first heavy hole subband[5],[28]. But for the higher hole subband, and over barrier hole states, bulk band edge heavy hole mass was used as an approximation. As shown in **Figure 3.2**, the conventional model gives a much longer lifetime for the hole than that for electron, while present model gives almost the same order of lifetime for electron and hole. This situation is almost similar for lattice matched (LM) LDs with a much larger well thickness. Detailed analysis indicates those difference between the two models arises from inconsistency in the conventional model, where Fermi-level and subband-energy for the QW were adopted on the bulk model equations.

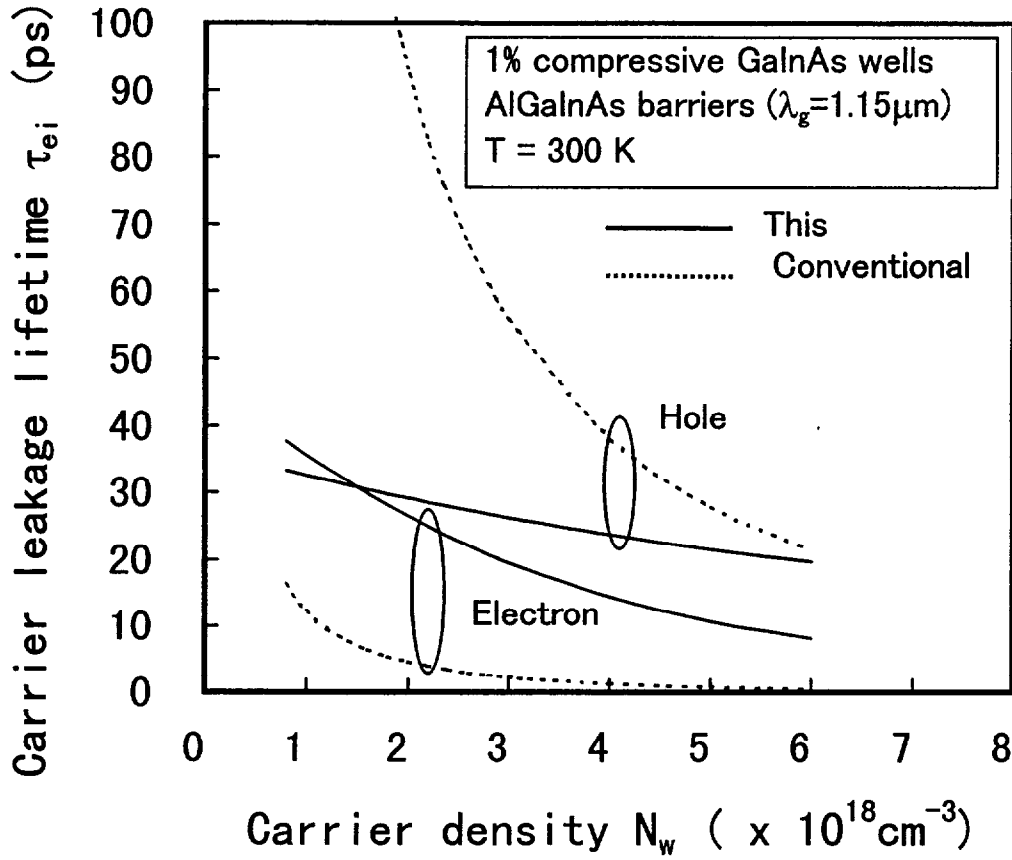


Figure 3.2

Calculated carrier leakage lifetime as a function of well carrier density for 1% compressive MQW LD at 300K.

3.2.3 Rate Equations

Rate equations for both type of carriers and photons are summarized in this subsection. Based on the model described above and taking the carrier leakage of both electrons and holes to both sides of the OC layers into account, following three level rate equations, Eqs.(3-5), (3-6), (3-7) were derived for electron density in QWs, p-OC layer and n-OC layer. Symmetric equations for holes can also be derived, which are abbreviated here. Photon density is described by Eq. (3-8).

$$\frac{dN_w^e}{dt} = -R_w(N_w^e, N_w^h) - \frac{2N_w^e}{\tau_{ee}} + \frac{V_{oc}}{V_w} \left(\frac{N_{ocn}^e}{\tau_d} + \frac{N_{ocp}^e}{\tau_d} \right) - \frac{v_g G(N_w^e) S}{1 + \varepsilon_g S}, \quad (3-5)$$

$$\frac{dN_{ocp}^e}{dt} = -R_{ocp}(N_{ocp}^e) - \frac{N_{ocp}^e}{\tau_d} + \frac{V_w}{V_{oc}} \left(\frac{N_w^e}{\tau_{ee}} \right), \quad (3-6)$$

$$\frac{dN_{ocn}^e}{dt} = \frac{I}{qV_{oc}} - R_{ocn}(N_{ocn}^e) - \frac{N_{ocn}^e}{\tau_d} + \frac{V_w}{V_{oc}} \left(\frac{N_w^e}{\tau_{ee}} \right), \quad (3-7)$$

$$\frac{dS}{dt} \equiv \frac{\Gamma v_g G(N_w^e) S}{1 + \varepsilon_g S} - \frac{S}{\tau_p}. \quad (3-8)$$

Here, V_w is total volume of QWs, V_{oc} , volume of each OC layer, τ_d , the ambipolar diffusion time[1] across the OC layer, N_{ocn}^e , N_{ocp}^e , the electron density in the n-side OC layer and that in the p-side OC layer, respectively, I , the injection current. Γ , v_g , G , S , ε_g , τ_p , denotes optical confinement factor, group velocity of the mode, optical gain, photon density, nonlinear gain factor and photon lifetime, respectively. Coefficient 2 in the second term of Eq. (3-5) arises from leakage to both side of OC layers and the third term arises from injection from both OC layers. R_w , R_{ocp} and R_{ocn} denotes carrier loss rate in QWs, P side OC layer, N side OC layer, respectively, where following relations were assumed;

$$R_w(N_w^e, N_w^h) = A_w N_w^e + B_w N_w^e N_w^h + C_w N_w^{e2} N_w^h, \quad (3-9)$$

$$R_{ocn}(N_{ocn}^e) = A_{oc} N_{ocn}^e + B_{oc} N_{ocn}^{e2}, \quad (3-10)$$

where, coefficients A_x , B_x , C_x stands for the defect loss, bimolecular radiative recombination, Auger recombination, respectively. For Auger carrier loss, CCCH process in QWs was assumed. As shown later, carrier loss in the OC layers plays an important role in determining the temperature sensitivity of lasers. The ambipolar diffusion time for the carriers across the

OC layer of thickness L_{oc} is given by,

$$\tau_d \cong L_{oc}^2 / (4D_p) = L_{oc}^2 q / (4k_B T \mu_h), \quad (3-11)$$

where the drift mobility for hole μ_h of 70 cm²/Vs at 300K and $(1/T)^2$ dependence[7] were assumed.

From the small signal analysis on modulation dynamics at the below threshold biased state, equations for injection bias current I_0 and modulation bandwidth f_c are obtained;

$$I_0 = qV_w \left\{ \left[A_w N_{w0}^e + \frac{\tau_{eh}}{\tau_{ee}} (B_w N_{w0}^{e^2} + C_w N_{w0}^{e^3}) \right] + \frac{2V_{oc}}{V_w} (A_{oc} N_{ocn0}^e + B_{oc} N_{ocn0}^{e^2}) \right\}, \quad (3-12)$$

$$f_c = \frac{1}{2\pi} \left[A_w + \frac{\tau_{eh}}{\tau_{ee}} (2B_w N_{w0}^e + 3C_w N_{w0}^{e^2}) + \frac{\tau_d}{\tau_{ee}/2} (A_{oc} + 2B_{oc} N_{ocn0}^e) \right] \left(1 + \frac{\tau_d}{\tau_{ee}/2} \right)^{-1}, \quad (3-13)$$

where,

$$N_{ocn0}^e \cong \frac{V_w}{V_{oc}} \frac{\tau_d}{\tau_{ee}} N_{w0}^e, \quad (3-14)$$

and where the subscript zero stands for the DC biased state. Those equations are adopted for the analysis of standard carrier lifetime (modulation bandwidth) measurement at below the threshold condition[21]. Eq.(3-12) also gives threshold current when threshold carrier density is given. Noticing a relation derived from the rate equations, $N_{ocn}^e \cong N_{ocp}^e$, Eqs.(3-5)-(3-8) reduce to the same form as Eqs. (7)-(9) in Ref.[1], by following substitutions;

$$\tau_e = \frac{\tau_{ee}}{2}, \quad i.e., \quad \chi \equiv 1 + \frac{\tau_d}{\tau_e} = 1 + 2 \frac{\tau_d}{\tau_{ee}}, \quad (3-15)$$

$$V_{SCH} = 2V_{oc}.$$

Therefore, for modulation performances at above threshold bias condition, the same relations as in Ref. [1] are deduced. For example, the K factor is given by,

$$K \equiv 4\pi^2 \left(\tau_p + \frac{\varepsilon_g}{v_g(g_0/\chi)} \right). \quad (3-16)$$

Here, effective differential gain, $g_0^{\text{eff}} = g_0/\chi$ appeared which is deteriorated from intrinsic g_0 by factor $\chi (>1)$. Increased K factor deteriorates the -3dB modulation bandwidth f_{max} , since f_{max} is given by, $f_{\text{max}} = \sqrt{2}(2\pi/K)$.

3.2.4 Optical gain and loss

In this subsection, model equations for optical gain and loss are described. Then, the factors relating the temperature sensitivity of laser performances will be abstracted.

Optical gain spectrum $g(E_{ph})$ can be expressed by following equations, taking into account the k-selection rule, the reduced density of states ρ_r^J and broadening effects due to intraband relaxation by Lorentzian function $L(E, E_{ph})$;[22],

$$g(E_{ph}) = \sum_n \sum_J \int_{E_{cn}^J}^{\infty} \frac{1}{E_{ph}} \frac{\pi e^2 \hbar}{\varepsilon_0 c_0 m_0^2 n_r} \rho_r^J |M_J|^2 [f_{cn}^J - f_{vn}^J] L(E, E_{ph}) dE, \quad (3-17)$$

where, E_{ph} is the photon energy, index n refers to subbands, $J=hh$ (lh) stands for heavy (light) hole, $E_{cn}^J = E_g + E_{cn} + E_{vn}^J$ is the band gap between two given subbands, n_r , the effective refractive index of the mode, $|M_J|^2$ is the transition matrix element, $f_{cn(vn)}^J$ is the Fermi-Dirac distribution for electrons in conduction (valence) band. Under parabolic band approximation, each term, ρ_r^J , $|M_J|^2$, $f_{cn(vn)}^J$ and $L(E, E_{ph})$ can be expressed as;

$$\begin{aligned} \rho_r^J &= \frac{4\pi m_r^J}{h^2 d_w} H(E - E_{cn}^J) \\ &\text{for } E_{cn}^J < E < E_g + \Delta E_c + \Delta E_v \\ \rho_r^J &= \frac{4\pi}{h^3} [2m_r^J]^{3/2} \sqrt{E - E_g} \\ &\text{for } E > E_g + \Delta E_c + \Delta E_v \end{aligned} \quad (3-18)$$

$$|M_{hh}|^2(E) = \frac{3}{4} M_{DH}^2 \left(1 + \frac{E_{cn}}{E_{cn} + \frac{m_r^J}{m_c}(E - E_{c\nu n}^J)} \right)$$

$$|M_{lh}|^2(E) = \frac{1}{4} M_{DH}^2 \left(5 - 3 \frac{E_{cn}}{E_{cn} + \frac{m_r^J}{m_c}(E - E_{c\nu n}^J)} \right) \quad (3-19)$$

$$|M_{DH}|^2(E) = \frac{m_0}{6} \left(\frac{m_0}{m_c} - 1 \right) \frac{E_g(E_g + \Delta)}{(E_g + \frac{2}{3}\Delta)}$$

$$f_{cn,\nu n}^J(E) = \frac{1}{1 + \exp\left[(E_{cn,hn}^J - E_{fc,fv})/kT\right]} \quad (3-20)$$

where,

$$E_{cn,hn}^J = E_{cn} + \frac{m_r^J}{m_c}(E - E_{c\nu n}^J), \quad E_{hn}^J = E_{\nu n}^J + \frac{m_r^J}{m_v}(E - E_{c\nu n}^J), \quad (3-21)$$

$$L(E, E_{ph}) = \frac{1}{\pi} \frac{\hbar / \tau_{in}}{(E_{ph} - E)^2 + (\hbar / \tau_{in})^2},$$

Based on direct numerical calculation results of optical gain spectrum by above equations[22] and referring also the reported results calculated by nonparabolic band model[19], the following linear gain model was adopted for the peak gain $G(N_w^e, T)$ as a function of well carrier density and temperature;[19],[22]

$$G(N_w^e, T) = g_0(T) [N_w^e - N_{wt}^e(T)], \quad (3-22)$$

where, differential gain $g_0(T)$ and transparent well carrier (electron) density $N_{wt}^e(T)$ can be expressed as[23],[24];

$$g_0(T) = g_0(300) \exp\left(-\frac{T - 300}{T_{0, dg/dn}}\right), \quad (3-23)$$

$$N_{wt}^e(T) = N_{wt}^e(300) + \gamma_g(T - 300). \quad (3-24)$$

For 1% compressive MQW LD in this study, the differential gain at 300K, $g_0(300)$ and the characteristic temperature of differential gain $T_{0,dg/dn}$ was estimated to be $(20-25) \times 10^{-16} \text{ cm}^2$ and 110-150K, respectively. Thus, $T_{0,dg/dn} = 120\text{K}$ was assumed in this study for all cases, except for the calculations to examine the effect of $T_{0,dg/dn}$. The transparent carrier density at 300K, $N_w^e(300)$ and constant coefficient γ_g was assumed as $1.1 \times 10^{18} \text{ cm}^{-3}$ and $4 \times 10^{15} \text{ cm}^3/\text{K}$, respectively. Those are consistent with the reported characteristic temperature of carrier density giving the constant gain, $T_{0,n(g)} = 180-220\text{K}$ [23] and $T_{0,dg/dn} = 115-130 \text{ K}$ for reduced carrier leakage single QW (SQW) LD on ternary substrate[25] and N_w^e [19],[25],[26]. Here we should note that we have defined the intrinsic optical gain against intrinsic (true) well carrier density. Thus, distribution effect of carriers to higher subbands should be involved. While, the apparent deterioration of the effective optical gain due to increased sheet carrier density by leakage carriers in OC layers should not be involved in this intrinsic optical gain.

For internal loss of strained QW, referring to the reported results, carrier density independent[27] but temperature dependent[28] absorption coefficient $\alpha_w(T)$ was adopted;

$$\alpha_w(T) = \alpha_w(300) + \gamma_a(T - 300), \quad (3-25)$$

where, $\alpha_w(300)$ is the absorption coefficient for the QWs at 300K, γ_a is the constant temperature coefficient measured to be $-1.3 \text{ (cm}^{-1}\text{K}^{-1})$ from Ref.[28]. While, for the absorption coefficient for OC layer, $\alpha_{oc} = cN_{oc}$ was assumed, where c is the differential absorption coefficient[29]. The value of $\alpha_w(300)$ was determined from the measured internal loss, which can be expressed generally with the transparent well carrier density N_w^e as;

$$\tilde{\alpha}_{int}(T) = \Gamma_w(\alpha_w(T) + bN_w^e) + \Gamma_{oc}c \frac{V_w}{V_{oc}} \frac{\tau_d}{\tau_{ee}} N_w^e + (1 - \Gamma_w - \Gamma_{oc})\alpha_{cl}. \quad (3-26)$$

It should be noted that τ_{ee} in Eq.(3-26) is determined by the well carrier density at threshold condition as shown later in Eq.(3-30). When $b=0 \text{ cm}^2$ [27] and $c=1 \times 10^{-17} \text{ cm}^2$ [29] are assumed and when the measured internal loss $\tilde{\alpha}_{int}(300) \cong 16 \text{ (cm}^{-1})$ is used for 1% compressive MQW

LD, $\alpha_w(300)=615 \text{ cm}^{-1}$ can be deduced, which well agrees with reported measured values.[27],[28]

As a summary of this subsection, the factors representing the temperature sensitivity of optical gain and loss were extracted from above discussions on modeling as follows;

- 1) temperature dependence of the differential gain, represented by characteristics temperature $T_{0,dg/dn}$,
- 2) temperature dependence of the transparent carrier density, represented by the coefficient, γ_g ,
- 3) temperature dependence of the absorption coefficients for QW, represented by the coefficient, γ_a .

Amount of contribution from each term and the dominant terms will be discussed in following section 3.3 based on comparison with experiment.

3.2.5 Differential quantum efficiency

Differential quantum efficiency, so called the slope efficiency is one of the essential characteristics for both light source lasers and high power pumping lasers. Leakage carriers from QWs to the OC region in the SCH-MQW LDs would add two deterioration mechanisms on the differential quantum efficiency. One is the carrier loss itself due to recombination at the OC region, the other is the increase of optical absorption loss due to free carriers in the OC layer. U. Koren et al., have derived the equation on the effect of differential gain and free carrier absorption loss at the active region upon the differential quantum efficiency[30]. With similar method, model equations describing the effect of those two processes upon the differential quantum efficiency were developed in this study. The results are briefly summarized below.

The expression for internal quantum efficiency η_{iCL} deteriorated due to the carrier loss at OC region was derived at first by adopting Eqs.(3-5)-(3-8) for two steady states, $I=I_{th}$ and $I=I_{th} + \Delta I$. It was assumed that the carrier concentration in the QW is clamped at above threshold region. Following relation was obtained for η_{iCL} at just above threshold condition:

$$\eta_{iCL}(I_{th}) = \frac{V_w \left(\frac{v_g GS}{1 + \varepsilon_g S} \right)}{V_w \left(\frac{v_g GS}{1 + \varepsilon_g S} \right) + V_{oc} [R_{oc}(N_{oc}(I)) - R_{oc}(N_{oc}(I_{th}))]}, \quad (3-27)$$

where, the first term in the denominator represents the conversion rate of carriers to the stimulated emissions in QWs, the second term, increment of carrier loss rate in the OC region, both due to the increment of injection current ΔI . Adopting approximations, $R_{oc} = A_{oc}N_{oc} + B_{oc}N_{oc}^2$, and using Eqs.(3-14), following relation is deduced;

$$\eta_{iCL}(I_{th}) = \frac{1}{1 + \tau_d [A_{oc} + B_{oc}(N_{oc}(I_{th} + \Delta I) + N_{oc}(I_{th}))]} \cong \frac{1}{1 + \tau_d \left[A_{oc} + 2B_{oc} \frac{V_w}{V_{oc}} \frac{\tau_d}{\tau_{ee}} N_{wth}^e \right]}, \quad (3-28)$$

where, N_{wth}^e denotes the well carrier density at threshold.

The differential quantum efficiency just above at threshold can be derived by estimating the internal loss $\alpha_{int}(T, I_{th})$ at threshold for the SCH LD, which is expressed generally;

$$\alpha_{int}(T, I_{th}) \cong \Gamma_w (\alpha_w(T) + bN_{wth}) + \Gamma_{oc} cN_{oc}(I_{th}) + (1 - \Gamma_w - \Gamma_{oc}) \alpha_{cl} + \alpha_{sc}, \quad (3-29)$$

where the first and the second term represents contributions from the active layer and from the OC layer respectively, the α_{cl} , α_{sc} denotes absorption loss coefficient for the cladding layer and scattering loss respectively. The coefficient b and c denotes the differential absorption coefficient for active layer and OC layer, respectively. Now, adopting linear gain model for the modal gain at threshold, $g_{th} = \Gamma_w g_0 (N_{wth}^e - N_{wt}^e)$, following equation is derived;

$$\Gamma_{oc} N_{oc}(I_{th}) = \frac{\Gamma_{oc}}{\Gamma_w} \Gamma_w \frac{V_w}{V_{oc}} \frac{\tau_d(T)}{\tau_{ee}(N_{wth}^e, T)} N_{wth}^e \equiv k_{th} \frac{\Gamma_{oc}}{\Gamma_w} \left(\frac{g_{th}}{g_0} + \Gamma_w N_{wt}^e \right), \quad (3-30)$$

where,

$$k_{th} \equiv \frac{V_w}{V_{oc}} \frac{\tau_d(T)}{\tau_{ee}(N_{wth}^e, T)}. \quad (3-31)$$

It should be noted here that k_{th} is determined by the well carrier density at threshold. Substituting Eq.(3-30) into Eq.(3-29), the internal loss at threshold can be expressed as;

$$\alpha_{int}(T, I_{th}) = \frac{\tilde{\alpha}_{int} + \left(\frac{b}{g_0} + \frac{c}{g_0} k_{th} \frac{\Gamma_{oc}}{\Gamma_w} \right) \left(\frac{1}{L} \ln \frac{1}{R} \right)}{1 - \frac{b}{g_0} - \frac{c}{g_0} k_{th} \frac{\Gamma_{oc}}{\Gamma_w}}, \quad (3-32)$$

where $\tilde{\alpha}_{int}$ is the effective internal loss given by Eq. (3-26) and the differential absorption coefficient for the QW layer b has been reported to be zero for recent strained QW LDs[27]. Thus, Eq.(3-32) indicates that the internal loss for the strained QW LDs at threshold is deteriorated due to carrier leakage by 1)increase of $\tilde{\alpha}_{int}$, 2)increase of k_{th} and 3)increase of the ratio (c/g_0). The importance of the differential gain g_0 at threshold appeared here again, since it lowers at high temperature or at large threshold carrier density. The mirror loss term appeared in the numerator originates from the threshold carrier density in Eq.(3-30).

Now, the differential quantum efficiency at threshold can be derived as;

$$\begin{aligned} \eta_D^{-1}(I_{th}) &= \eta_i^{-1}(I_{th}) \left(1 + \frac{\alpha_{int}(T, I_{th})}{\alpha_m} \right), \\ &= \eta_i^{-1}(I_{th}) \left(1 + \frac{\tilde{\alpha}_{int} + \left(\frac{b}{g_0} + \frac{c}{g_0} k_{th} \frac{\Gamma_{oc}}{\Gamma_w} \right) \left(\frac{1}{L} \ln \frac{1}{R} \right)}{\left(1 - \frac{b}{g_0} - \frac{c}{g_0} k_{th} \frac{\Gamma_{oc}}{\Gamma_w} \right) \left(\frac{1}{L} \ln \frac{1}{R} \right)} \right), \\ &= \eta_i^{-1}(I_{th}) \left(1 - \frac{b}{g_0} - \frac{c}{g_0} k_{th} \frac{\Gamma_{oc}}{\Gamma_w} \right)^{-1} \left[1 + \tilde{\alpha}_{int} \left(\frac{1}{L} \ln \frac{1}{R} \right)^{-1} \right] \equiv \tilde{\eta}_i^{-1}(I_{th}) \left[1 + \tilde{\alpha}_{int} L \left(\ln \frac{1}{R} \right)^{-1} \right], \end{aligned} \quad (3-33)$$

where,

$$\tilde{\eta}_i^{-1}(I_{th}) \equiv \eta_i^{-1}(I_{th}) \left(1 - \frac{b}{g_0} - \frac{c}{g_0} k_{th} \frac{\Gamma_{oc}}{\Gamma_w} \right)^{-1}. \quad (3-34)$$

Since transparent well carrier density N_w^e is independent of the cavity length, $\tilde{\eta}_i^{-1}$ and $\tilde{\alpha}_{int}$ in Eq.(3-33) gives effective internal quantum efficiency and effective internal loss

measured from conventional η_D^{-1} - L diagram[30], when the cavity length dependence of k_{th} can be neglected.

Substituting Eq.(3-28) instead of η_i^{-1} in Eq.(3-34), the effective internal quantum efficiency $\tilde{\eta}_i$ including the carrier leakage effect is given by,

$$\tilde{\eta}_i(I_{th}) = \frac{\left(1 - \frac{b}{g_0} - \frac{c}{g_0} k_{th} \frac{\Gamma_{oc}}{\Gamma_w}\right)}{\left[1 + \tau_d (A_{oc} + 2B_{oc} k_{th} N_{wth}^e)\right]}. \quad (3-35)$$

Substituting Eq.(3-35) into Eq.(3-33), the differential quantum efficiency at threshold condition, deteriorated due to the carrier leakage effect is given as;

$$\eta_D(I_{th}) = \frac{\left(1 - \frac{b}{g_0} - \frac{c}{g_0} k_{th} \frac{\Gamma_{oc}}{\Gamma_w}\right)}{\left[1 + \tau_d (A_{oc} + 2B_{oc} k_{th} N_{wth}^e)\right]} \frac{1}{\left[1 + \tilde{\alpha}_{int} \left(\frac{1}{L} \ln \frac{1}{R}\right)\right]}. \quad (3-36)$$

From above equations Eq.(3-36), we find that deterioration in the differential quantum efficiency due to carrier leakage near above threshold condition is caused by three terms, i.e., 1)carrier loss in the OC layers, the first term in the denominator, 2)increase of optical absorption loss at the OC layers ($b=0$ for strained QWs), the numerator, 3)increase of the effective internal loss, the second term in the denominator. Further, followings would be noteworthy. The deterioration rate due to carrier loss in the OC layer is almost linearly proportional to the diffusion delay time τ_d . On the other hand, the deterioration due to the optical absorption in the OC layer is related in the ratio (c/g_0) , hence the lowering of g_0 in high temperature or high injection condition enhances this deterioration. The concrete amount of deterioration will be discussed in **section 3.4**.

3.3 Comparison with experiments

In this section, feasibility of the theory presented in previous section will be examined by adopting the model equations on experimental results. The carrier loss coefficients are determined from experiments. Calculated temperature sensitivity for the essential laser performances will be compared with measured results.

3.3.1 Carrier lifetime measurement and carrier loss coefficients

In this subsection, carrier loss coefficients defined in Eqs.(3-9) and (3-10) are determined by adopting the equations Eqs.(3-12) and (3-13) on the standard carrier lifetime measurements[21]. **Figure 3.3** compares experiments (dots) and calculations (solid curves) for squared modulation bandwidth f_c^2 vs. normalized bias current I_0/I_{th} diagram for lattice matched (LM-) MQW LD (a) and 1% compressive strained (SL-) MQW LD (b) [4],[31]. In both Figures, curves denoted by label (A) correspond to the calculations with carrier leakage and diffusion effect. While curves with label (B) are the results when carrier leakage and diffusion delay were neglected but the same loss coefficients as those of (A) were assumed. Large discrepancy between (A) and (B) in **Figure 3.3** indicates that carrier leakage and diffusion delay seriously influence and elongate the effective recombination lifetime.

Fitting procedure employed was as follows. In case of LM-MQW LD, (a), reported values on the both coefficients B_0 and B_1 were used for the bimolecular radiative recombination coefficient $B_w = B_0(1 - N_w/B_1)$ [20]. While, in case of SL-MQW LD, (b), B_0 was determined from experiment using reported B_1 [20]. For both cases, a constant value for $B_{oc} = 1 \times 10^{-10} \text{ cm}^3/\text{s}$ was assumed[32]. A_w , A_{oc} , C_w were adjusted to fit experiments, where common A_{oc} was taken between the two type of LDs, corresponding to the same MBE growth conditions. A_w values were determined so as satisfy both low injection part and measured threshold current density. In case of “without carrier leakage”, $\tau_d/\tau_{ec} = 10^{-4}$ and $\tau_{ch}/\tau_{ec} = 1$ were assumed. Those carrier loss coefficients used in fitting experimental results are shown in the insets of both Figures and summarized in **Table 3.2** and **3.3**.

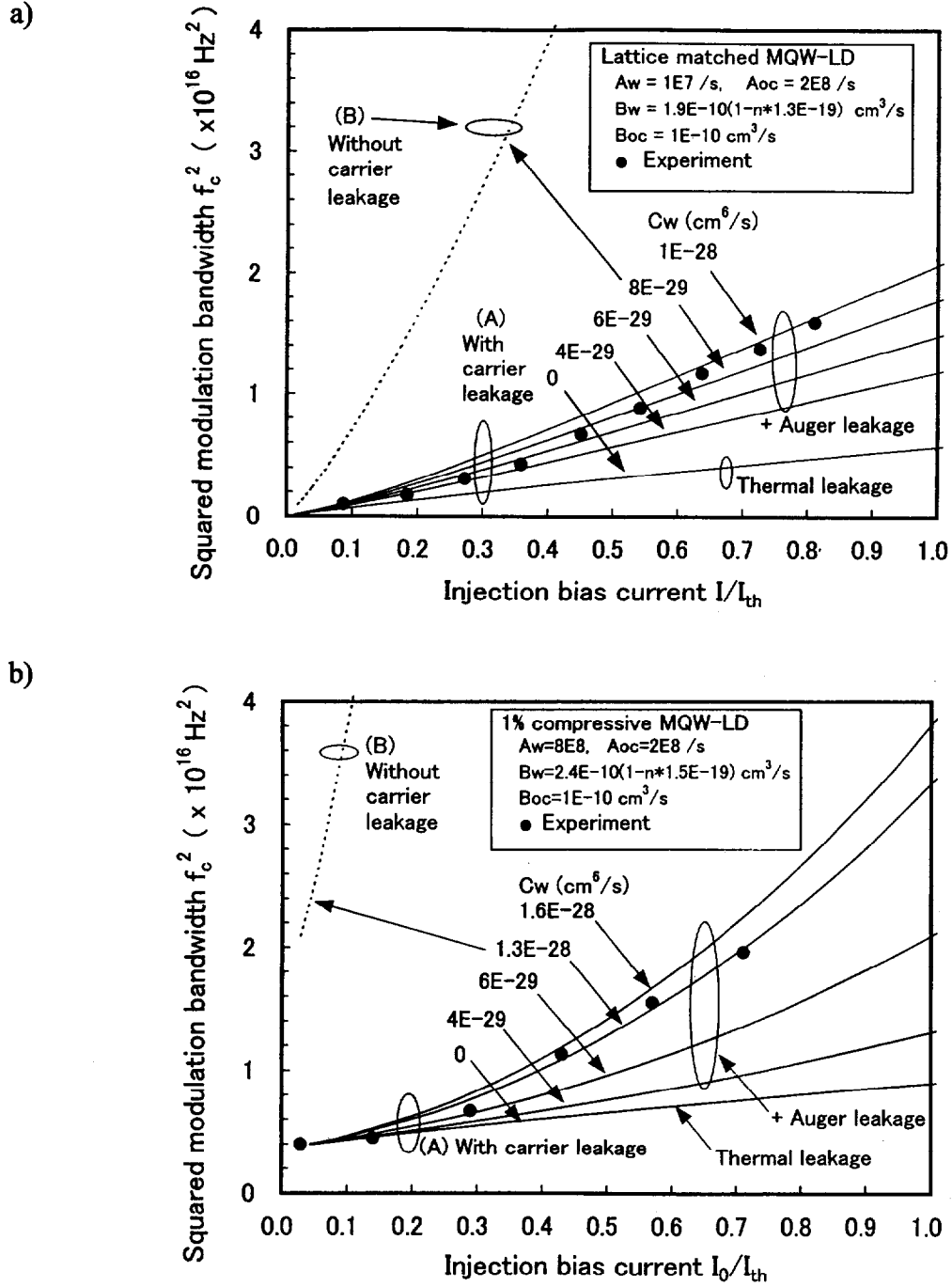


Figure 3.3

Squared modulation bandwidth f_c^2 at below threshold condition as a function of normalized injection bias current I_0/I_{th} , for lattice matched MQW LDs, a) and 1 % compressive strained MQW LDs, b).

From **Figure 3.3** and **Tables 3.2** and **3.3**, it was confirmed that measured f_c^2 vs. I_0/I_{th} diagram can be well explained by the new model using loss coefficients in reported range.

Some peculiar points in above results are discussed below. Large A_w for SL-MQW was required to explain the part of low injection current, indicating a still high defect density in QWs of SL-MQW. This large defect density could be one of the causes of the large threshold current density of this laser. However, it would not affect intrinsic B_w nor C_w values. For LM-MQW, C_w (this) at the high injection region well agrees with the reported measured values[20],[33]. For SL-MQW, C_w (this) is almost the same as that of LM-MQW within the accuracy. Similar large C_w has also been reported in Ref.[33]. However, at the small injection current, smaller C_w gives a better fit to experiments. This is also the case in LM-MQW LDs. Those would suggest that band filling is related to above large C_w [34].

Table 3.2 Carrier loss coefficients determined from the lifetime measurement by fitting (partly using reported values).

LD type	A_w (/s)	B_w (cm ³ /s, at $N_w^e=2 \times 10^{18}$ cm ⁻³)	A_{oc} (/s)	B_{oc} (cm ³ /s)
LM-MQW	1×10^7	1.4×10^{-10} a)	2×10^8	1×10^{-10} c)
SL-MQW	8×10^8	2.0×10^{-10} b)	2×10^8	1×10^{-10} c)

a)Wang et al.[20] b) B_w from Wang et al.[20] c)Agrawal et al.[32]

Table 3.3 Auger coefficients C_w (10^{-29} cm⁶/s) determined from curves (A) in Figure 3.3. Reported values are also summarized for comparison.

LM-MQW				SL-MQW			
this $I_0/I_{th} < 0.3$	this $I_0/I_{th} > 0.6$	Reported (experiment)	reported (theory)	this $I_0/I_{th} < 0.3$	This $I_0/I_{th} > 0.5$	Reported (experiment)	reported (theory)
4	(8-10)	8.6 ^{a)} , 10 ^{b)} (3-5) ^{c)} , 2 ^{d)}	2.6 ^{a)}	(4-6)	13	3 ^{a)} , 10 ^{b)} (1-6) ^{c)} , 0.06 ^{d)}	0.25 ^{a)}

a)Wang et al.[20] b)Fuchs et al.[33] c)Zou et al.[34] d)Adams et al.[35]

Importance of taking into account the carrier leakage effect in determining those recombination loss coefficients was also confirmed as shown below. **Figure 3.4** shows the example where fitting was done in approach (B), i.e., without taking the carrier leakage effect in the model equations. Coefficients determined with or without carrier leakage effect are compared in **Table 3.4**. As shown here, the fitting without carrier leakage effect gives values for B_w and C_w an order of magnitude lessor 1 or 2 than those obtained from the fitting with carrier leakage effect. Above discrepancy could be a most possible cause of the large distribution of reported measured Auger coefficient values ranged from 10^{-30} to 10^{-28} cm⁶/s.

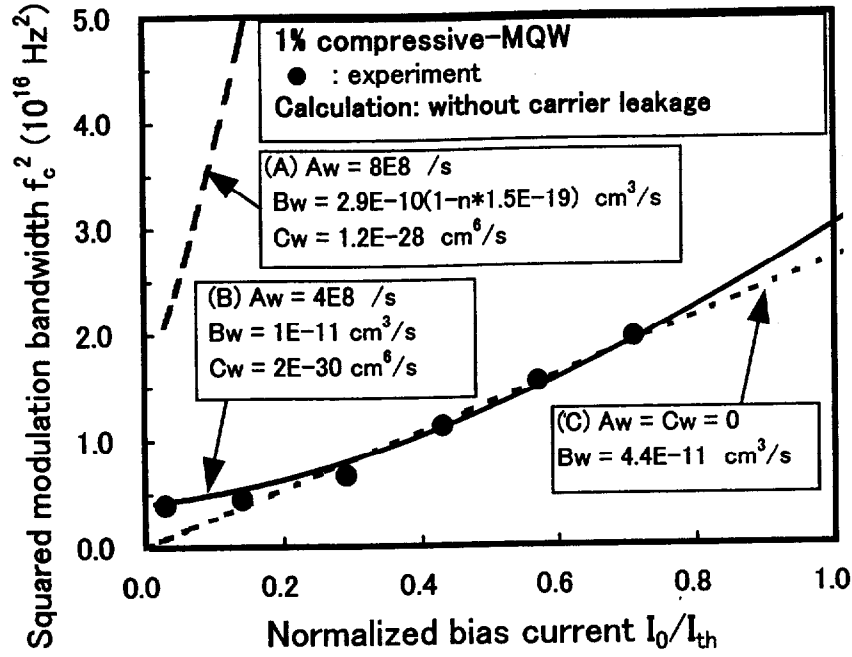


Figure 3.4

Fitting results for f_c^2 vs. I_0/I_{th} diagram when the carrier leakage effect was neglected for 1% compressive MQW-LDs. Case (A); with same loss coefficients as in Fig. 3.3 b), (B); with loss coefficients determined by fitting measured results with “without leakage” equations, (C); with only the radiative recombination loss taken into account.

Table 3.4 Radiative recombination coefficient B_w and Auger recombination coefficient C_w determined with different model equations; a) leakage effect was taken into account (with) and b) leakage effect was neglected (without).

LD type	B_w ($10^{-10}\text{cm}^3/\text{s}$, at $N_w=2\times 10^{18}\text{ cm}^{-3}$)		C_w ($10^{-29}\text{cm}^6/\text{s}$)	
	a) with	b) without	a) with	b) without
LM-MQW	1.4	0.1	(4-10)	0.75
SL-MQW	2.0	0.1	(4-13)	0.2

As a summary of this subsection, 1)Improved theory presented in this study was confirmed feasible in explaining the subthreshold carrier lifetime characteristics with loss coefficient values within reported range, 2)Measured Auger coefficient for compressive strained MQW LD was almost same as that for lattice matched MQW LDs, contrary to the reported prediction, which coincided with experiments by Fuchs, 3)Importance of taking into account the carrier leakage effect in determining the carrier loss coefficients from lifetime measurement was pointed out.

3.3.2 Threshold current density and temperature dependence

In this subsection, the improved theory is adopted on threshold current density of the lasers and compared with experiment. Eq.(3-12) was adopted to calculate the threshold current density, with the loss coefficients obtained in the previous subsection and with threshold carrier density determined by the balancing condition of gain and loss. **Figure 3.5** shows an example of the results for 1% compressive strained MQW LDs, experiments and calculations in comparison. Results for LDs with both facets as cleaved state and for ones with rear facet high reflectivity (HR) coated are compared. As shown in **Figure 3.5**, large temperature sensitivity of J_{th} can be well explained with the improved model.

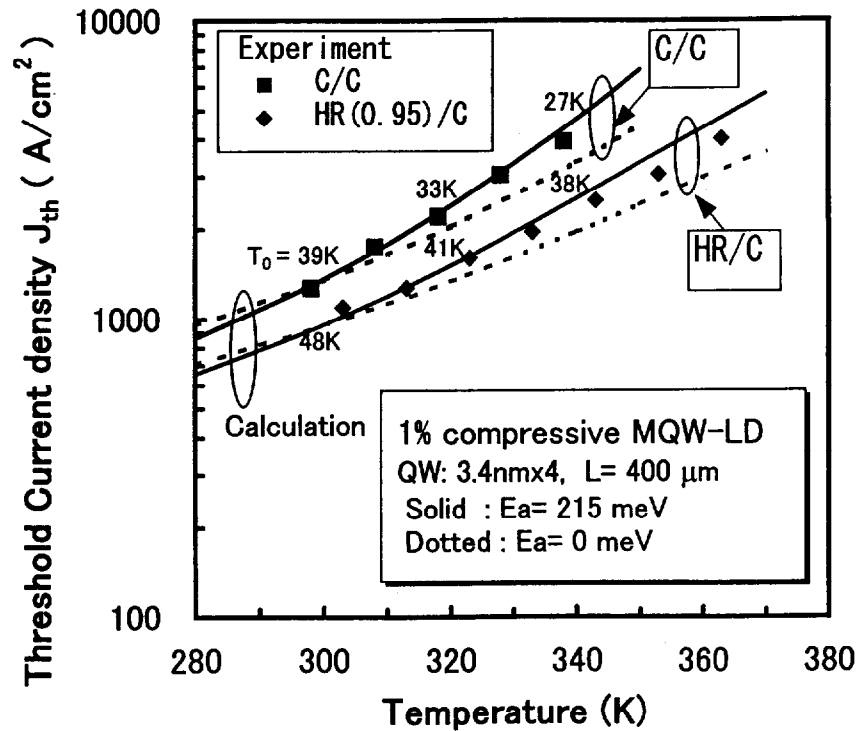


Figure 3.5

Threshold current density for 1% compressive MQW LDs as a function of temperature. C/C; both facet as cleaved state, HR/C; rear facet high-reflectivity (95 %) coated. The same carrier loss coefficients as shown in the inset of Figure 3 (b) were used. Theoretical $1/T$ dependence of B_w was included.³⁸⁾ Other assumed parameters are, for Auger coefficient, C_w , 1.3×10^{-28} (cm^6/s) at 300 K with the activation energy 215 meV (solid lines) or 0 meV (dotted lines), for optical absorption loss, $\alpha_w = 615$ cm^{-1} for QW, $c = 1 \times 10^{-17}$ cm^2 for OC layer and $\alpha_{cl} = 3$ cm^{-1} for cladding layer. Calculated values $\Gamma_w = 0.022$, $\Gamma_{oc} = 0.63$ were used.

In calculation, $T_{0, dg/dn}=120$ K was assumed and theoretical $1/T$ dependence of B_w was included[35]. For temperature dependence of C_w , reported activation energy $E_a=215$ meV was assumed in solid lines[35], while in dotted lines $E_a=0$ meV was assumed. Smaller E_a around 70 meV has also been reported[27], which would give a better fitting. Effect of possible deviation of hole drift mobility μ_h for the OC layer was examined. It was found that 30 % decrease of μ_h results in 15 to 30 % increase in J_{th} and 4 to 5K decrease in T_0 . Those would be rough indices for the accuracy of the model calculations in this study.

As a summary of this subsection, the threshold current density and the large temperature sensitivity of 1% compressive strained MQW LD was well explained with the improved theory within the accuracy. The agreement between improved theory and experiments was also conformed for the lattice matched MQW LDs.

3.3.3 K factor and temperature dependence

In this subsection, the improved theory will be adopted on K factor of the lasers and compared with experiment. K factor involves the effective differential gain g_0/χ in simple form as shown in Eq.(3-16). Thus, comparison of theory and experiment in K factor would be a good check of the theory.

K factors were determined with following procedure. RIN spectra were measured at different bias currents and temperatures. The resonance angular frequency ω_r and the effective damping factor γ_e were extracted by fitting theoretical curve Eq. (2-2) [37]. Then K factor was determined from the slope of the dependence of γ_e on squared f_r diagram, using following equation;

$$\gamma_e = \frac{1}{\chi\tau_{nw}} + 4\pi^2 \left(\tau_p + \frac{\varepsilon_g}{g_0/\chi} \right) f_r^2 \equiv \frac{1}{\chi\tau_{nw}} + Kf_r^2 \quad (3-34)$$

where, τ_{nw} denotes carrier recombination lifetime in the QWs. An example of extracted γ_e as a function of f_r^2 is shown in **Figure 3.6**.

Figure 3.7 shows K factor vs. temperature diagram for experiments and calculations on 1% compressive strained MQW LDs. Here, the nonlinear gain factor ε_g was taken as a

variable parameter. The possibility has been pointed out that the nonlinear gain factor could be increased to $(3-5) \times 10^{-17} \text{ cm}^3$ due to carrier heating effect[38]. Thus, it can be said that measured temperature dependence of K factor is well explained by present model using reasonable device parameters including the nonlinear gain factor. Here we also find serious deterioration of K factor due to carrier leakage effect. This also corresponds to a serious deterioration of the effective differential gain due to the same cause, which will be shown in following subsection.

As a summary of this subsection, measured temperature dependence of K -factor was shown well explained by the improved model.

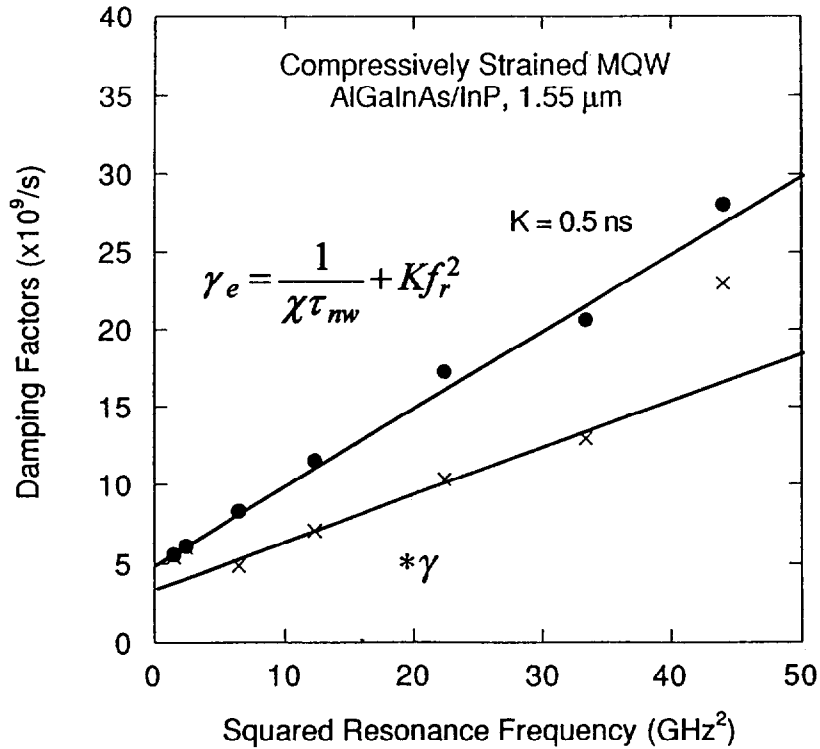


Figure 3.6

An Example of extracted effective damping factor γ_e as a function of f_r^2 for 1% compressive strained MQW-LDs.

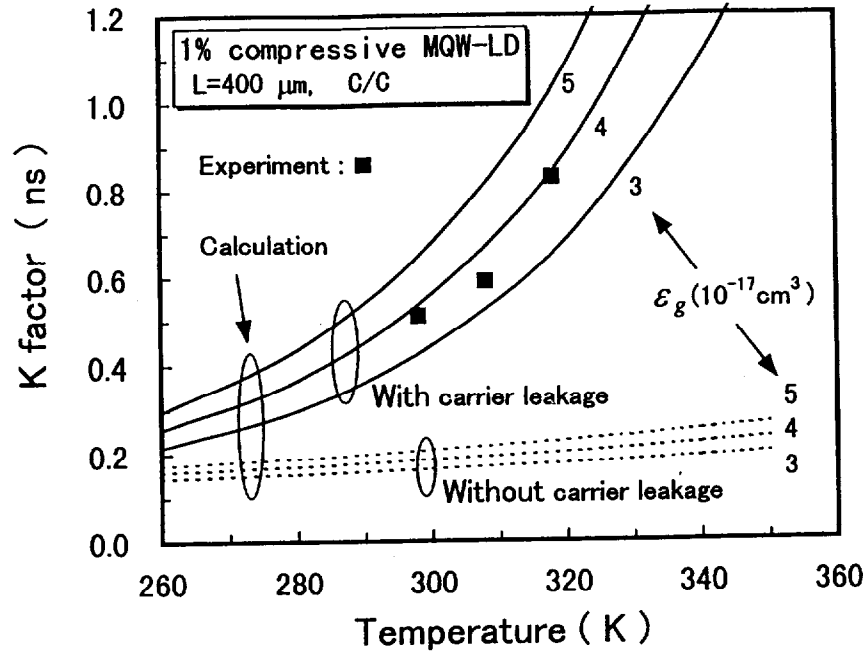


Figure 3.7

K factor as a function of temperature for 1% compressive strained MQW LDs. In calculation, the nonlinear gain factor ϵ_g was taken as a parameter.

3.3.4 Effect of carrier leakage upon differential gain

From the measured K factor, the effective differential gain, g_d/χ , deteriorated due to the carrier leakage effect was calculated, where the nonlinear gain factor was assumed to be $3.7 \times 10^{-17} \text{ cm}^3$ (lower diamonds) or $5 \times 10^{-17} \text{ cm}^3$ (upper diamonds). Figure 3.8 compared the results with theoretical intrinsic g_0 and g_d/χ value as a function of temperature. Measured values from relaxation oscillation frequency and from direct gain vs. carrier density diagram described in Chapter 2 are also plotted together. Here, although there is a factor two distribution in the measured values, the differential gain measured from K factor well agrees with theoretical g_d/χ values within the error. This clearly demonstrates that dominant part of the large discrepancy between the measured differential gain and the intrinsic theoretical value can be attributed to the deterioration due to the carrier leakage effect.

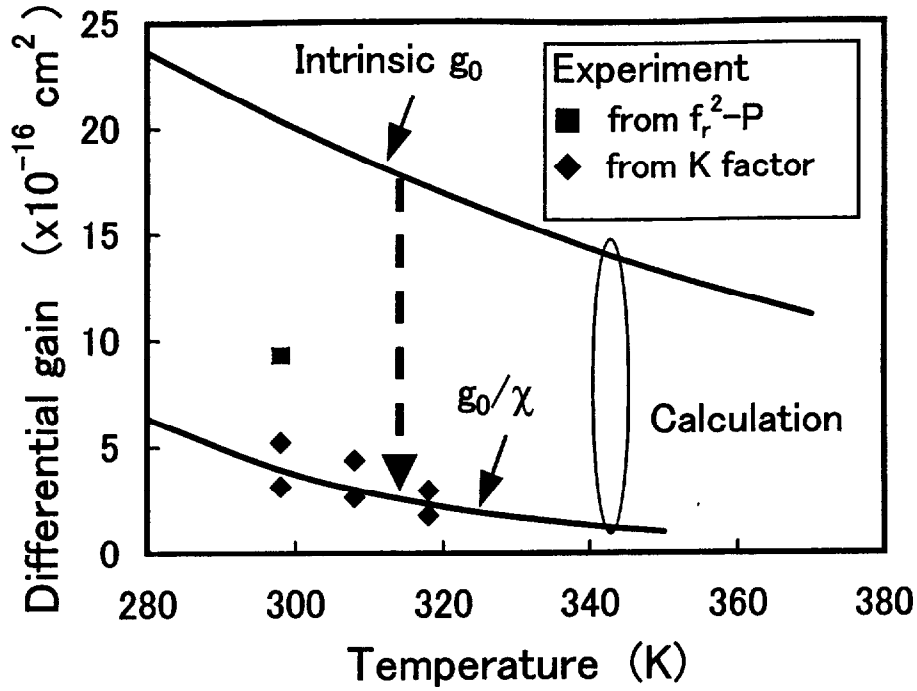


Figure 3.8

Comparison of measured values of differential gain with theoretical intrinsic value g_0 and effective value g_0/χ calculated with improved theory.

3.4 Dominant causes of temperature sensitivity and direction for further improvement

In this section, dominant causes for large temperature sensitivity of 1%-CS-MQW LD are identified and direction for improvement is discussed.

3.4.1 Effect of gain temperature sensitivity on characteristic temperature T_0

At first, we will discuss here the effect of temperature sensitivity of optical gain on T_0 . It will be shown that the low T_0 of present 1.5- μ m-wavelength strained lasers can not be attributed to the temperature sensitivity of optical gain.

In the linear gain model Eqs.(3-22)-(3-24), temperature sensitivity of gain arises from two terms, 1) deterioration of gain slope, represented by $T_{0,dg/dn}$ and 2) increase of transparent carrier density N_{wt}^e , which is represented by coefficient γ_g in Eq. (3-24). Here, when we assume, $T_{0,dg/dn}=120\text{K}$, $\gamma_g = 4 \times 10^{15} \text{ cm}^3/\text{K}$ [25],[26] and threshold gain of 2000 cm^{-1} , change in threshold carrier density caused by temperature change of 60K is estimated to be $2.4 \times 10^{17} \text{ cm}^{-3}$ for term1) and $6.7 \times 10^{16} \text{ cm}^{-3}$ for term 2), respectively. Thus, as a first approximation, the effect of gain change could be represented by the term 1), i.e., $T_{0,dg/dn}$.

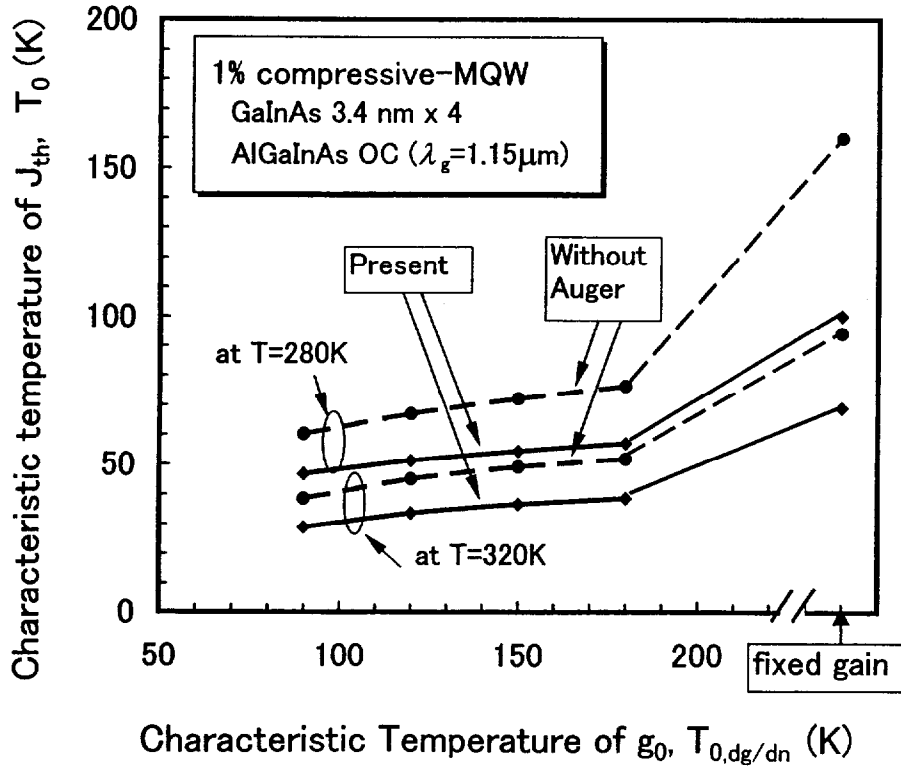


Figure 3.9

Calculated characteristic temperature of threshold current T_0 as a function of $T_{0,dg/dn}$, the characteristic temperature of differential gain. In case of “fixed gain”, temperature independent gain model ($g_0=2 \times 10^{-15} \text{ cm}^2$, $N_{wt}^e=1.1 \times 10^{18} \text{ cm}^{-3}$) was adopted. Two cases were compared; a) with same carrier loss coefficients as determined from experiments shown in Figure 3-3 (b) (“present”), and b) with Auger terms assumed to be zero (“Without Auger”).

In **Figure 3.9**, calculated T_0 is shown as a function of $T_{0,dg/dn}$. In case of “fixed gain”, temperature independent gain model ($g_0=2 \times 10^{-15} \text{cm}^2$, $N_{wt}^e=1.1 \times 10^{18} \text{cm}^{-3}$) was adopted. Two cases were compared; a) with same carrier loss coefficients as determined from experiments (present), b) same as a) except for Auger terms assumed to be zero (without Auger). As shown here, T_0 is weakly dependent on $T_{0,dg/dn}$ and estimated less than 70K in theoretically predicted range of $T_{0,dg/dn}$. Even if gain were independent of temperature, estimated T_0 is still less than 80K at above room temperature in “present” case. These imply that temperature sensitivity of intrinsic gain is not a dominating term of low T_0 . Indeed as shown later in **Figure 3.10** and **3.11**, T_0 over 150K is estimated by reducing other dominating terms even under condition of $T_{0,dg/dn} = 120\text{K}$.

3.4.2 Dominating factors of low T_0

Here, the dominating factors of low T_0 of present LD are discussed by comparing calculated current density component of each carrier loss process at threshold condition. It will be shown that 1) Auger carrier loss and 2) carrier loss in OC layers due to defect are dominating the low T_0 .

Figure 3.10 shows calculated threshold current density and each current density components for 1 % compressive LD. Improved theory described in section 3.2 and carrier loss components determined in section 3.3.1 were adopted for calculation.

From the result shown in **Figure 3.10**, followings were found;

- 1) Current components, a) Auger carrier loss, and b) carrier loss in OC layers due to defect are dominating the temperature sensitivity of the threshold current density at a temperature region higher than 300K. It should be noted that above b), carrier loss in OC layers is caused by the carrier leakage from QW to OC layers.
- 2) Carrier loss components due to bimolecular recombination in QWs and due to defects in QWs both have large T_0 ranges from 120 K to 150K even at 320K.
- 3) Carrier loss in the OC layer due to bimolecular recombination is highly temperature sensitive and even larger than the bimolecular recombination loss in QWs at high temperature region. Thus, when Auger and defect losses were substantially reduced, bimolecular

recombination loss could also have a large effect. It should be emphasized that a large bimolecular recombination at OC region has been evidenced by the spontaneous spectra in GaInAs/GaInAsP single-quantum-well (SQW) SCH LD[9],[39].

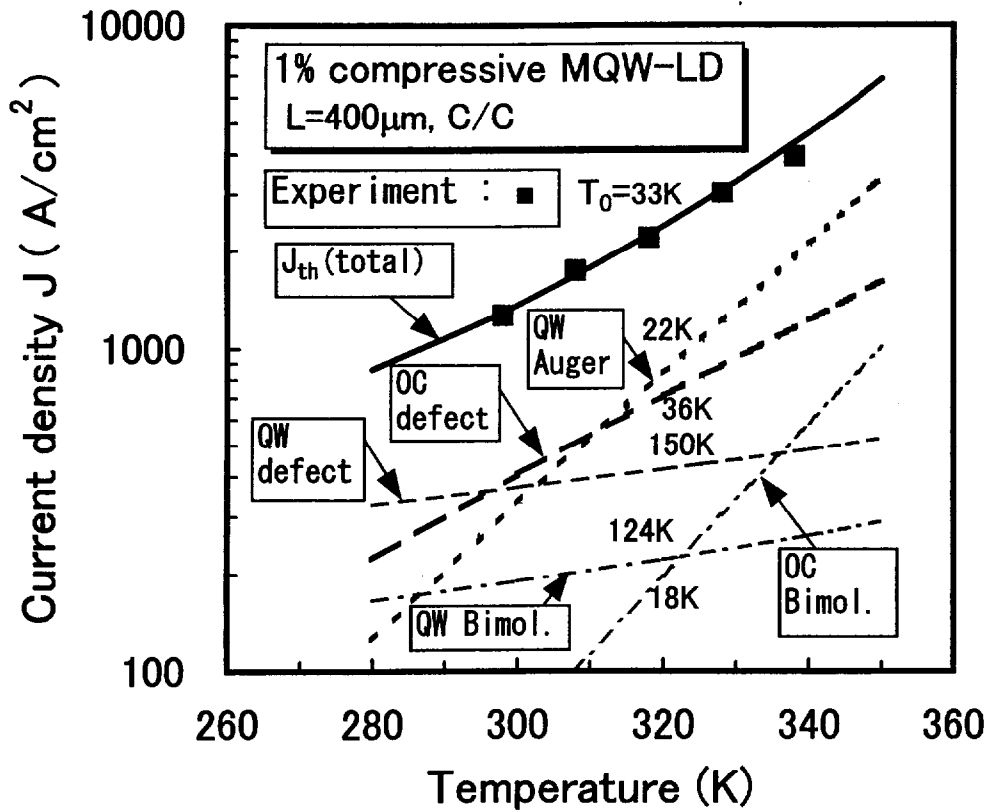


Figure 3.10

Threshold current density and each loss current component as a function of temperature for 1% compressive LDs. Loss coefficients determined from Figure 3-3(b) were used. For Auger carrier loss, $C_w = 1.3 \times 10^{-28}$ cm⁶/s at 300 K and the activation energy 215 meV were assumed.

3.4.3 Direction for improvements

Here, direction for improvements is discussed through evaluation of deterioration of laser performance due to the two dominant factors above extracted, a) Auger carrier loss and 2) carrier leakage.

Figure 3.11 summarizes the calculated T_0 for the 1% compressive LD of present study as a function of Auger coefficient. In “with carrier leakage” case, T_0 values were calculated using Eq. (3-12) and loss coefficients determined from experiments, except for C_w . In “without carrier leakage” case, $\tau_d/\tau_{ee}=1 \times 10^{-4}$ and $\tau_{eh}/\tau_{ee}=1$ were assumed.

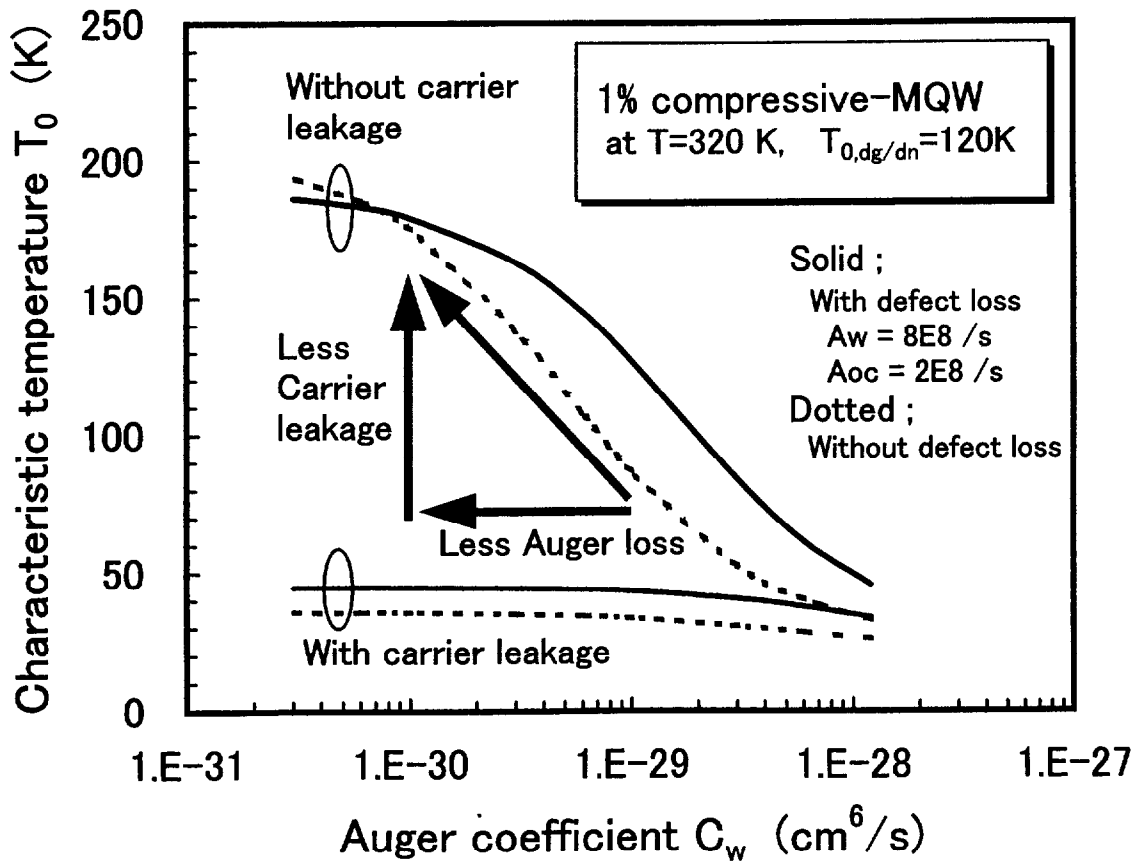


Figure 3.11

Calculated characteristic temperature T_0 at operating temperature 320 K, as a function of Auger coefficient. In “without carrier leakage” case, $\tau_d/\tau_{ee}=1 \times 10^{-4}$ and $\tau_{eh}/\tau_{ee}=1$ were assumed. Other loss coefficients and LD structure were assumed to be same as those of measured 1% compressive MQW LDs. The activation energy of Auger coefficient was assumed to be 215 meV.

As shown in **Figure 3.11**, in order to realize high T_0 over 150 K, following two conditions must be satisfied; 1) Reduction of Auger carrier loss to region where C_w is less than middle of 10^{-30} cm⁶/s. 2) Reduction of thermionic carrier leakage and diffusion delay. In another words, present 1% compressive MQW LD is doubly deteriorated in T_0 by those two causes. Elimination of either one of the two causes would not bring effective improvement. For example, in “with carrier leakage” case of **Figure 3.11**, T_0 is less than 50 K even at $C_w=1 \times 10^{-30}$ cm⁶/s. This low T_0 is caused by the carrier loss in OC layers due to carrier leakage. Thus, above two causes must be reduced at the same time. The vector triangle in the Figure indicates this situation. Additional T_0 enhance effect due to the defect loss can be attributed to the high T_0 of the defect loss component in QWs as shown in **Figure 3.10**.

3.4.4 Discussions

Here, deterioration of the differential quantum efficiency due to carrier leakage is estimated with Eq.(3-36). **Figure 3.12** shows calculated differential quantum efficiency for total output power from both facets as a function of temperature for the 1% compressive MQW LDs. Both cleaved facets were assumed and the same device parameters and loss coefficients as those described in **section 3.3** were used for calculation. As can be seen here, the deterioration at 360 K from the value at 260 K is near 5% in “without carrier leakage” case. While, it increases to almost 30% in “with carrier leakage” case. **Figure 3.13** shows the decomposed contribution of each term in Eq.(3-36) to above deterioration due to carrier leakage. Here, values were normalized by the value at 260 K for each term. As described in subsection 3.2.5, the terms CRL, AOC, AINT represents the deterioration due to carrier loss in OC layers, absorption loss at OC layers, effective internal loss increase, respectively. Deterioration of those terms at 360 K compared to values at 260 K is estimated to be 2.5% for CRL, 24% for AOC, 4.5% for AINT. Thus, dominant cause of the deterioration in the differential quantum efficiency is attributed to the term AOC, i.e., to the absorption loss due to the leakage carriers in OC layers. This result indicates that suppression of carrier leakage is essential for not only in high temperature lasers but also in high power pumping lasers, since the deterioration in the differential quantum efficiency is fatal for those lasers.

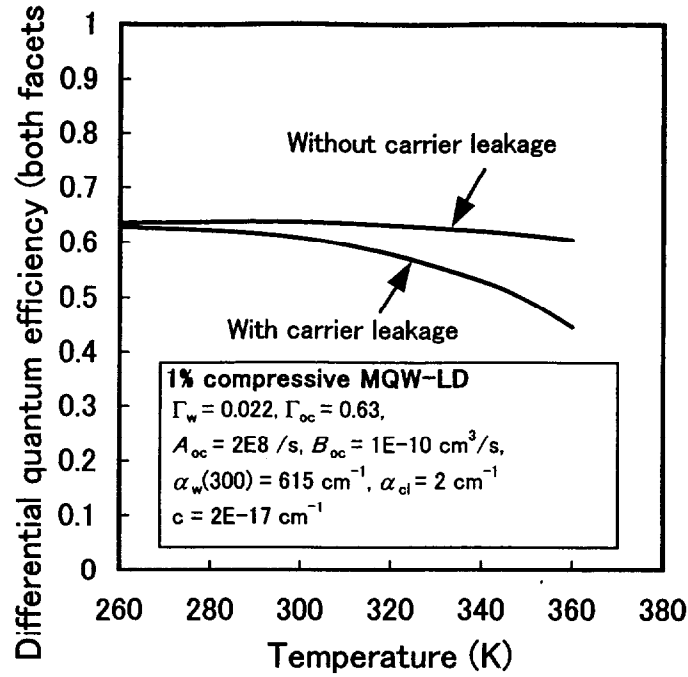


Figure 3.12

Calculated differential quantum efficiency for total output power from both facets as a function of temperature for the 1% compressive MQW LDs.

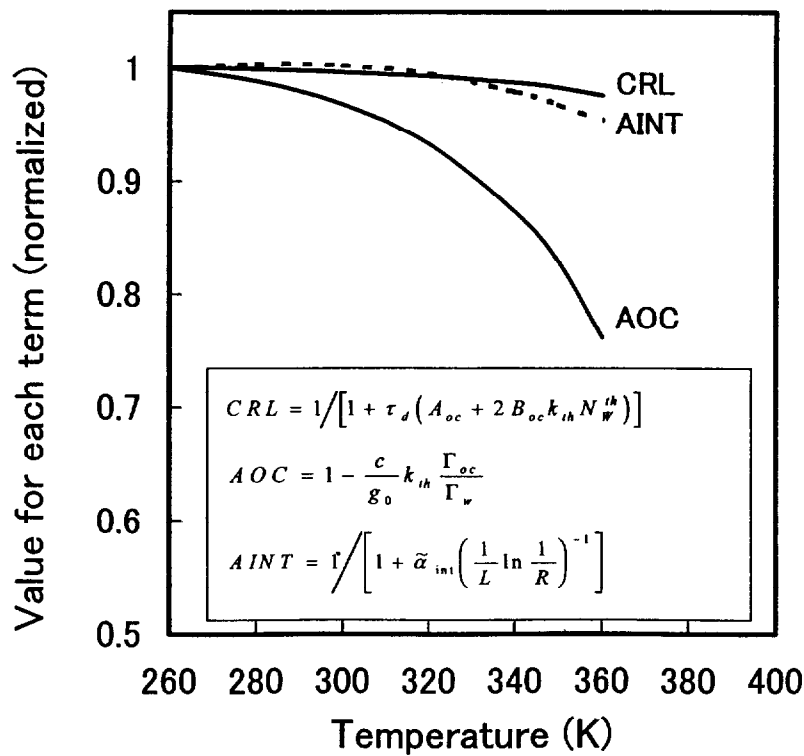


Figure 3.13

Contribution of each decomposed term to the deterioration in differential quantum efficiency due to carrier leakage in 1% compressive MQW LDs.

Next, limit of charge neutrality preposition in OC layers is discussed. In deriving Eqs.(3-12)-(3-14), charge neutrality in OC layers was assumed. Under that preposition, following relation is derived for the well carrier density for electron and that for hole;

$$N_w^h = \tau_{eh}/\tau_{ee} N_w^e \quad (3-37)$$

Since τ_{ee} is slightly shorter than τ_{eh} for the LDs so far described, above Eq.(3-37) indicates that charge neutrality in well does not hold and hole density is somewhat larger than that of electron density. However, the ratio τ_{eh}/τ_{ee} is estimated to be larger than 10 for LDs with enhanced barriers described later in chapter 6, which corresponds over an order of magnitude larger N_w^h than N_w^e . Such situation does not seem to be realistic, since the resulting space charge would cause electric potential difference over 10 V across a QW. In such situation, charge neutrality condition in QWs rather than that in OC layer would be a more realistic preposition. The change in equations under such preposition will be described in Chapter 6.

3.5 Summary

As a summary of this chapter, at first, an improved theory for the carrier dynamics phenomena in SCH-MQW LD was presented. The features of the theory are summarized as follows; 1) New model equations for the carrier leakage lifetime taking the density of states for quantum well and band nonparabolicity into account. 2) Rate equations including the leakage of both electrons and holes to both sides of OC layers. 3) Carrier loss terms not only conventional loss terms in quantum wells but also defect loss and bimolecular recombination loss in OC layers. Equations describing the effect of carrier dynamics phenomena upon modulation frequency below threshold, threshold current and differential quantum efficiency were derived.

In the following step, the improved theory was adopted to the carrier lifetime measurements in order to determine the carrier loss coefficients. Following result were confirmed; 1) The modulation bandwidth vs. bias current diagram can be well explained with

the improved theory using carrier loss coefficients in reported range. 2) Reduction of Auger coefficient for 1% compressive MQW LD was not observed near threshold condition, which coincided with the reported measured result but was inconsistent with theoretical prediction. 3) The fitting without the carrier leakage effect brings radiative recombination coefficient B_w and Auger coefficient C_w , one to two order of magnitude lesser, compared with values obtained from the fitting with the carrier leakage effect. The last point above revealed the serious effect of carrier leakage upon effective carrier lifetime of MQW LDs. The results also suggested a possible reason why the temperature sensitivity was not improved in spite of measured reduced Auger coefficient in the experiments so far reported.

In further step, the improved theory was adopted to predict the temperature sensitivity of threshold current density, K -factor and differential gain in order to examine feasibility of the theory in explaining those laser performances. It was confirmed that the proposed model equations well explain the measured large temperature sensitivity of those performances under reasonable assumptions.

As the final step of this chapter, contribution of each possible cause for the large temperature sensitivity of MQW LDs was examined using the model equations. Dominant causes were clarified and direction for improvement was discussed. Results are summarized as follows; 1) Auger carrier loss in QWs and leakage carrier loss in OC layers (due to defect for present LDs) are dominating the low T_0 at a temperature region higher than 300K. 2) Temperature dependence of optical gain is not a dominant cause of low T_0 . 3) Current component due to bimolecular recombination loss in QWs and that due to defect carrier loss in QWs has high T_0 ranges from 120K to 150K even at operating temperature 320K. Thus they are not the dominant cause of low T_0 . 4) By reducing both Auger carrier loss and thermionic carrier leakage and diffusion delay, high T_0 over 150 K is expected. Since present strained MQW LD is doubly deteriorated in T_0 by those two factors, reduction of either one of two would not bring effective improvement. 5) Large deterioration in differential quantum efficiency is caused due to the carrier leakage effect at high temperature. The dominant cause was attributed to the increase in absorption loss at the OC layers.

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Chapter 4

Experiment on Carrier Leakage Suppression by Multiquantum Barriers in 1.5- μm -Wavelength Multiquantum Well Lasers

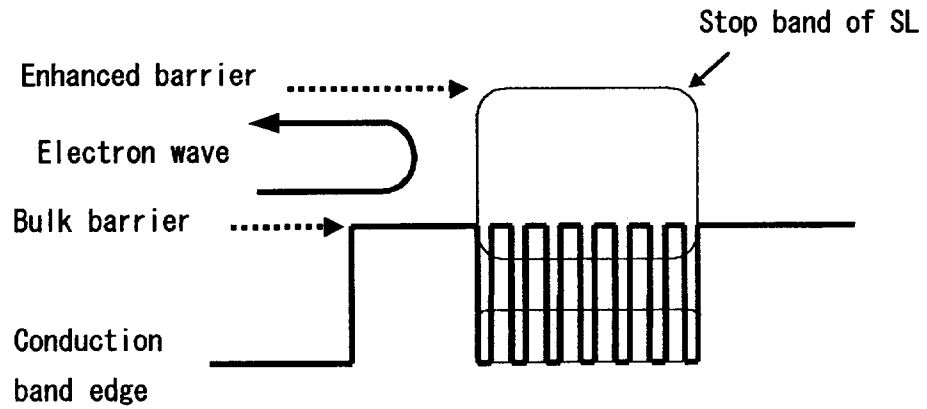
Experiments on carrier leakage suppression by multiquantum barriers (MQB)[1]-[8] in 1.5- μm -Wavelength MQW LDs are summarized. Improvements of laser performances by loading MQB at p-side optical confinement layer are described[9]. Amount of suppression ratio of leakage electrons and of barrier height enhancement with MQB are estimated from the direct spontaneous emission measurement.

4.1 Concept and research history of multiquantum barriers

The tunneling phenomenon of electron through a thin barrier in semiconductor is well known as a typical quantum mechanical effect[10]. The tunneling probability and hence the reflection probability is determined by the interference of electron waves incident to and reflected from the barrier. In the same mechanism, an electron incident to a barrier with an energy higher than the barrier height is also reflected with a finite probability. This probability can be enhanced to one in some energy regions to form energy stop bands by repeating barriers and wells as superlattice, as shown in **Figure 4.1**.

By combining above stop bands and a thick classical barrier, a continuous energy stop band ranging from zero to the energy much higher than classical heterobarrier height can be formed. Thus, artificial enhancement of heterobarrier height is realized. This is the concept of “multiquantum barrier (MQB)”, proposed by K. Iga et al. of Tokyo Institute Technology (T.I.T.) in 1986[1].

a)



b)

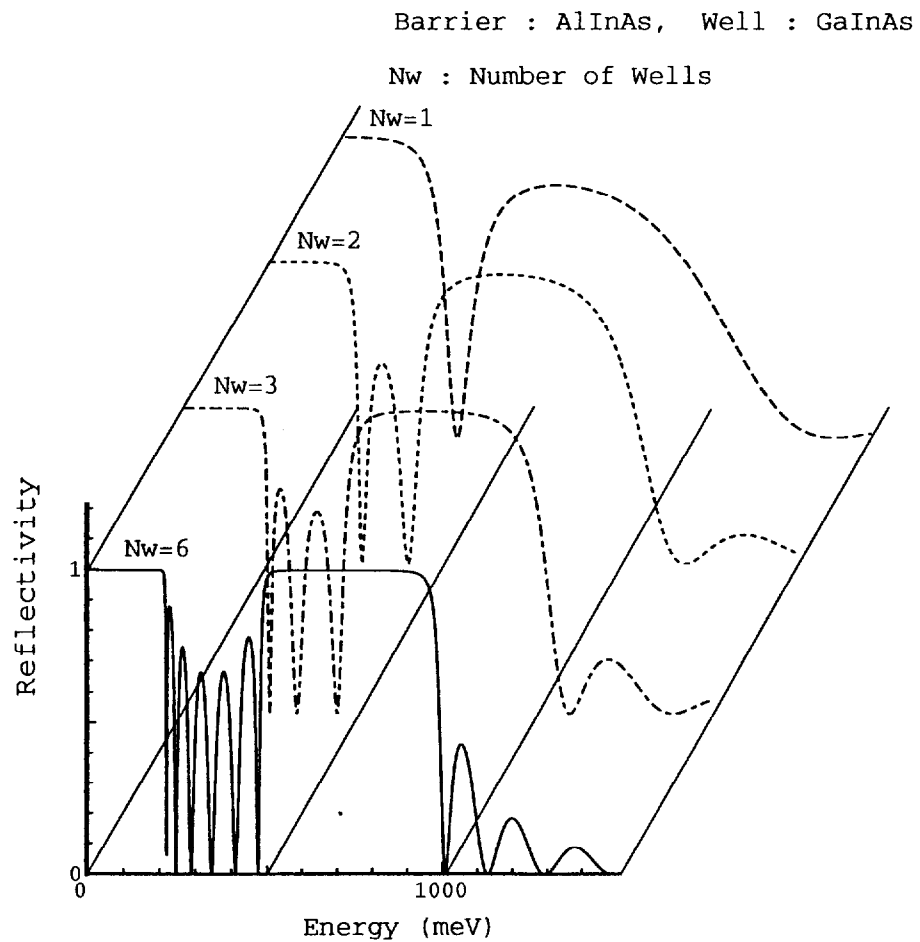


Figure 4.1

The concept of multiquantum barriers a) and an example of calculated electron wave reflectivity for superlattices with various layer numbers b).

The fundamental preposition for above interference of carrier waves is that the coherence length should be large enough compared to the total thickness of MQB. Theoretically, coherence length for electrons has been estimated to be 20 to 200 nm[11],[12], while the total thickness of MQB ranges usually 30 to 40 nm. On the other hands, near-ballistic transport across 250-500 nm has been observed in GaInAs layer at room temperature[13],[14]. Therefore, there should be a good possibility to satisfy the preposition, although the coherence length would largely depend on the material quality.

In 1991, the first experimental demonstration of the effect of MQB was reported from T.I.T. group in AlGaAs/GaAs in PL intensity enhancement[3], followed by demonstrations of performance improvements in GaInP/AlInP red-light LDs from Sophia University group[4], Toshiba group[6] and Sanyo group[7]. Marked improvements were confirmed in characteristic temperature and 20 degree C increase of maximum lasing temperature or in expansion of lasing wavelength to shorter region.

On the other hand, for InP based long-wavelength lasers, possibility to realize an effective barrier height of 500 meV was theoretically estimated in InP/GaInAsP MQB[2]. However, there was no experimental report on application of MQB to long-wavelength LDs.

4.2 Design of multiquantum barriers for long-wavelength multiquantum well lasers

4.2.1 One-dimensional potential model and effective mass approximation

The model adopted to calculate the reflectivity for MQB structure is summarized below. The multilayer structure of wells and barriers are represented by one-dimensional potential[1]. The barrier height is given by the band edge discontinuity (ΔE_c for electron). The doping condition or the carrier concentration under operating condition of the lasers is taken into account to determine the separation between the quasi-Fermi level and the band edge energy. If the electric field is applied across MQB region, it is superimposed on the potential[15]-[17].

The base of the one-dimensional model is explained as follows[15] ; the electrons excited in thermionic process or in Auger process can have random oblique incident direction

against the normal of barrier surface when we include the states after the relaxation collisions. But, if we assume isotropic parabolic conduction band, oblique wave number vector can be divided into perpendicular and parallel components. Then, the interference of the perpendicular components of the wave number vectors determines the reflection coefficient of the MQB. In such situation, the case of perpendicular injection gives the worst case, i.e., gives the largest range of incident energy.

Adopting the effective mass approximation, in other words, the parabolic band model for E - k diagram, wave number k for an electron in the j -th layer with energy E is given by Eq.(4-1),

$$k_j = \frac{\sqrt{2m_j^* (E - V_j)}}{\hbar}, \quad (4-1)$$

where, k_j , m_j^* , V_j , $\hbar$ denote wave number, effective mass, potential height and normalized Plank's constant respectively.

4.2.2 Analytical method for designing the multiquantum barriers

(1) Schrödinger equation

The Schrödinger equation under effective mass approximation is adopted for the motion of electron in the one-dimensional potential. Thus, following time-independent one-dimensional Schrödinger equation is obtained for an electron in the j -th layer with potential V_j and with effective mass m_j^* ,

$$-\frac{\hbar^2}{2m_j^*} \frac{d^2 \phi_j(x)}{dx^2} + V_j \phi_j(x) = E \phi_j(x). \quad (4-2)$$

Now, the wave function can be expressed with following equation;

$$\phi_j(x) = A_j \exp(ik_j x) + B_j \exp(-ik_j x), \quad (4-3)$$

where k_j is given by Eq.(4-1), the first term of right hand side represents plane wave which propagates toward x positive direction and the second term, x negative direction.

(2) Boundary condition

At each interface, the continuity of wave functions and continuity of flux of the probability density are adopted as boundary conditions[18] ;

$$\phi_j(x_j) = \phi_{j+1}(x_j), \quad (4-4)$$

$$\frac{1}{m_j} \frac{d\phi_j(x_j)}{dx} = \frac{1}{m_{j+1}} \frac{d\phi_{j+1}(x_j)}{dx}. \quad (4-5)$$

(3) Transfer Matrix Method

Adopting above boundary condition and the transfer matrix method, the amplitudes of wave functions for the incident first layer and the final n -th layer are connected with following equation ;

$$\begin{bmatrix} A_n \\ B_n \end{bmatrix} = \begin{bmatrix} \alpha_{11} & \alpha_{12} \\ \alpha_{21} & \alpha_{22} \end{bmatrix} \cdot \begin{bmatrix} A_1 \\ B_1 \end{bmatrix}. \quad (4-6)$$

The matrix element α_j is obtained from above boundary condition, Eqs. (4-4) and (4-5).

Now, the reflectivity R is obtained assuming $B_n=0$;

$$R = \left| \frac{B_1}{A_1} \right|^2 = \left| \frac{\alpha_{21}}{\alpha_{22}} \right|^2. \quad (4-7)$$

(4) Scattering Matrix Method

In order to take into account the effect of inelastic scattering of electrons, the scattering matrix method has been adopted by T. Loh et al.[19],[20]. In this case, the amplitude of transmission and reflection for a single barrier are given by following Eqs.(4-8)-(4-11),

$$\begin{aligned} t_B &= tt'e^{jk_B L_B} (1 - r'^2 e^{j2k_B L_B})^{-1}, \\ r_B &= r(1 - e^{j2k_B L_B}) (1 - r'^2 e^{j2k_B L_B})^{-1}, \end{aligned} \quad (4-8)$$

where t, r , are the amplitude transmission and reflection coefficients at well to barrier interface, and t', r' , at barrier to well interface. Further, wave vector is generally expressed as,

$$k^B = k_0^B + j\gamma_B, \quad k^W = k_0^W + j\gamma_W, \quad (4-9)$$

where, γ_B, γ_W are the scattering attenuation coefficients, which represent the loss of the coherent probability current due to incoherence. Loh et al. have reported a reduction of reflectivity of 3% to 15% at maximum due to inelastic scattering effect.

4.2.3 Subjects in the application of MQB to long-wavelength MQW LDs

The subjects to be taken into account in the application of MQB to long-wavelength MQW-LDs are discussed in this subsection.

(1) Optical confinement layer and MQB

Separate confinement heterostructure (SCH) with thick optical confinement (OC) layer is one of the vital structural factors in the design of long-wavelength MQW LDs, in order to prevent the lowering of optical confinement factor due to thin active layer thickness. Low barrier height of the optical confinement layer and the carrier loss in the OC layer due to the leakage electrons have been clarified as one of the dominant causes of deterioration of intrinsic laser performances[21]-[25]. However, so far in the reported studies, MQBs had been loaded in the cladding layer to suppress the carrier leakage to the cladding layer[3]-[8]. Thus in this

study, it was proposed to load MQB at the OC layer adjacent to MQW region to suppress the carrier leakage from MQW to OC layer. The average refractive index of the MQB region can be maintained almost equal to that of bulk OC layer. Therefore, MQB is expected to reflect back the leakage electrons and re-inject them to QWs, without deteriorating the optical confinement factor of SCH structure.

(2) Auger carrier loss and required barrier height

Another peculiarity of long-wavelength lasers would be the Auger process, which causes hot carrier leakage. As summarized in **Chapter 3**, the Auger hot electron leakage has been one of the dominant causes of present performance deterioration at high temperature and the effect would be further enhanced if the thermionic leakage were sufficiently suppressed in future.

The maximum energy of Auger hot electrons is given by the lasing wavelength λ_L and the Fermi-level E_{fn} as, $(E_{fn} + hc/\lambda_L + 3kT)$, which is about 1 eV, measured from the band edge of QW, for 1.5 μm LDs[17]. Thus, in order to reflect back the hot electrons, incident to the MQB not only directly via the Auger excitation but also after the relaxation process, the MQB necessarily should have sufficient reflectivity throughout the energy range of zero to above maximum energy, 1 eV. Possibility and method to realize such high effective barrier by MQB had not been discussed.

From the standpoint of material technology, a) suitable material combinations for MQB layers and b) effect of utilizing strained-layer should be discussed. While, for the design method of MQB, the parabolic band model is known to be valid only near the conduction band edge. Noticeable discrepancy from the parabolic model has been reported even at a few hundred meV above the band edge[26],[27]. Therefore, it would be essential to include the nonparabolicity of conduction band, in the application of MQB to InP based devices, for the confinement of hot electrons with energy higher than a few hundred meV. Another important point is the hole transport thorough the MQB region. As pointed out in **Chapter 3**, smooth hole transport is the key to reduce leakage carrier density in the optical confinement layer.

4.2.4 Design of MQB for 1.5- μ m-wavelength AlGaInAs/GaInAs MQW-LDs

The AlGaInAs on InP material system has a larger conduction band edge discontinuity and smaller valence band edge discontinuity compared to those of the GaInAsP on InP system[28]-[29]. Therefore, better performance can be expected in the following three aspects:

- 1) Better electron confinement to the QWs,
- 2) Higher effective barrier height of MQB,
- 3) Easier hole injection from the OC layer to QWs through such superlattice structures as the MQB.

Thus, the GaInAs/AlInAs superlattice was chosen as the material system for the MQB as the first approach to confirm the feasibility of loading MQB to OC layer, with material technology presently available.

Figure 4.2 shows the potential model and layer structure for a designed MQB loaded at the OC layer of LDs with 1% compressive strained GaInAs QWs[9]. The barriers of the MQB consist of an 80-monolayer (ML) AlGaInAs bulk barrier, three-8ML AlInAs layers and five-5ML AlInAs layers. The wells of the MQB consist of three-10ML, two-8ML and four-7ML GaInAs layers. All MQB layers are assumed to be lattice-matched to the InP substrate.

Figure 4.3 shows calculated spectral reflectivity with parabolic band model, for the MQB structure shown in **Figure 4.2**. The electron energy shown on the abscissa was measured from the conduction band edge of 1% strained QW. The enhanced barrier height of about 1000 meV is predicted, which is about 700 meV higher than the classical barrier height of the bulk OC layer. Note that this enhanced barrier height is almost the same as the maximum energy level of Auger hot electrons generated in this 1.5- μ m-wavelength LD, although the band nonparabolicity has not been taken into account.

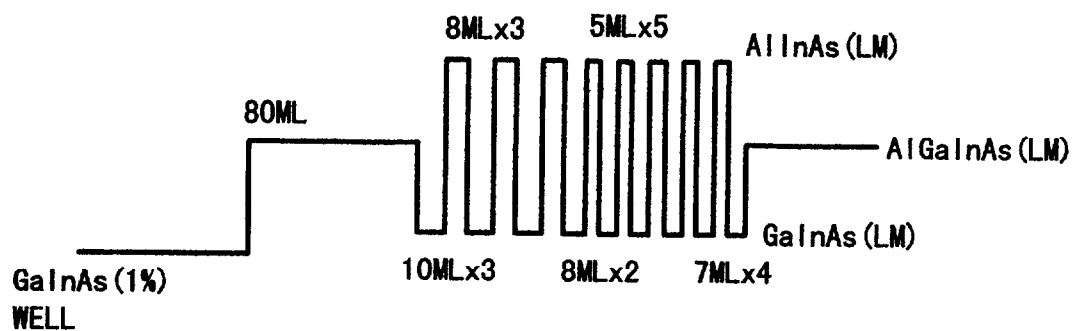


Figure 4.2

The potential model and layer structure for a designed MQB loaded at the OC layer of LDs with 1% compressively strained GaInAs QWs.

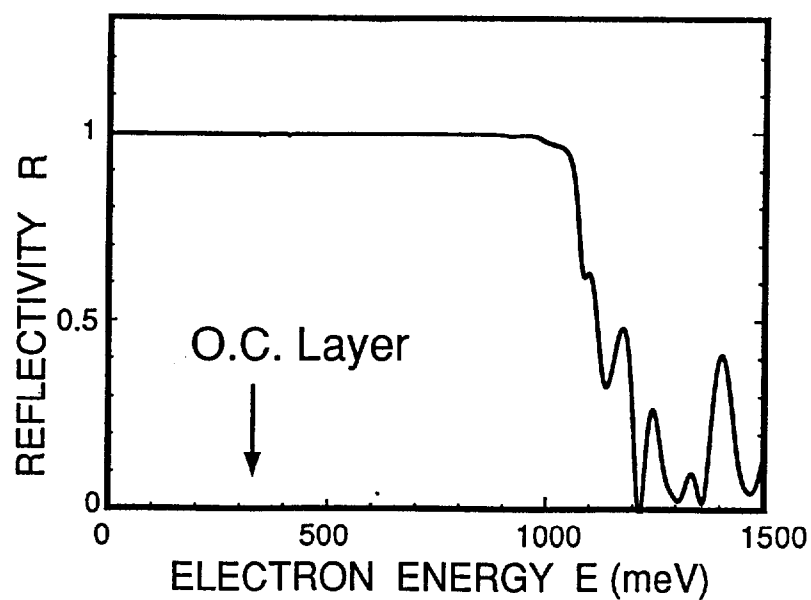


Figure 4.3

Calculated spectral reflectivity for the MQB structure shown in **Figure 4.2**.

4.3 Improved performance of multiquantum well lasers with MQB

4.3.1 Fabrication of 1% compressive MQW LDs with MQB at p-side optical confinement layer

The effects of loading MQB were evaluated by comparing the characteristics of the two types of lasers: (a) with MQB based on p-side optical confinement (OC) layer and (b) without MQB. **Figure 4.4** shows the layer structures for two types of LDs grown by MBE[9]. GaInAs/AlGaInAs 1% compressive strained MQW LDs consisted of n-AlInAs cladding layer, n-side quaternary OC layer ($\lambda_g = 1.15\mu\text{m}$, 200nm), MQW active region, p-side quaternary OC layer ($\lambda_g = 1.15\mu\text{m}$), n-AlInAs cladding layer and p-GaInAs Ohmic contact layer, grown in that order on the n-InP substrate.

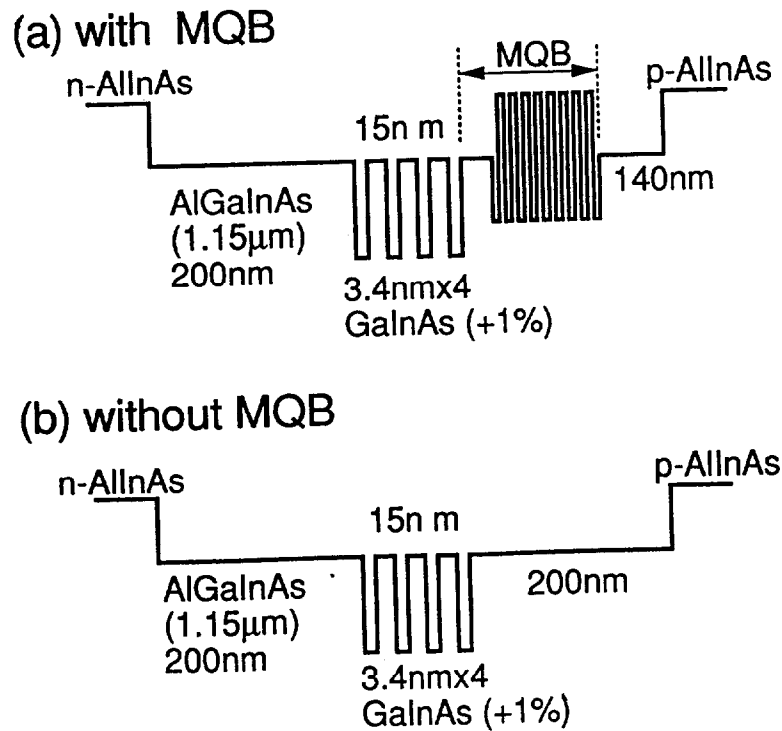


Figure 4.4

The layer structures for two types of LDs grown by MBE with MQB a), and without MQB b).

The MQW active region consisted of four 3.4 nm 1% compressive strained $\text{Ga}_{0.32}\text{In}_{0.68}\text{As}$ wells and three 15 nm quaternary-AlGaInAs-barrier layers of the same composition as the OC layer. From the transmission electron microscope measurements, abrupt and flat interfaces and the thickness deviation less than a monolayer were confirmed.

4.3.2 Improvements of laser performances by MQB

The lasers were characterized at both facet as cleaved condition. Almost equivalent threshold current densities were confirmed between the two types of LDs at 300 K. Our result is also equivalent to the reported values for LDs of same material system[31]-[34]. No essential change was observed in current-voltage characteristics by loading MQB.

By measuring the temperature dependence of the performances, clear improvements of the performances by loading MQB were confirmed for the first time in long-wavelength lasers in following points:

1) Increase of the slope efficiency at high temperature (Figure 4.5),

This result can be attributed to the reduction of carrier loss in the OC layer, as a result of suppression of carrier leakage at high temperature.

2) Increase of maximum lasing temperature of around 20 K (Figure 4.5, 4.6)

This means the leakage carrier loss and hence the threshold current density at high temperature was reduced by the MQB.

3) Decrease of the K factor more than 30 % at high temperature (Figure 4.7)[35].

The intrinsic 3 dB modulation bandwidth $f_{\max}$ is given by the K factor as [36]

$$f_{\max} = 2\pi\sqrt{2} / K, \quad (4-10)$$

where,

$$K \equiv 4\pi^2 \left(\tau_p + \frac{\epsilon_g}{v_g(g_0/\chi)} \right). \quad (4-11)$$

Thus, above reduction in K factor means the improvement in modulation bandwidth at high temperature and it is attributed to the reduction of carrier transport factor χ . It was confirmed by the calculation from Eq. (4-11) that above 30 % decrease in K -factor corresponds to 40 % increase of the effective differential gain, g_0/χ .

On the contrary to above clear improvements, the characteristic temperature T_0 was still low. However, this result agrees with theoretical consequences on the deterioration mechanism derived in **Chapter 3**. Because, in this experiment, suppressing only the electron leakage was intended. Thus, hole leakage and Auger hot carrier leakage could still be dominating the deterioration. In addition, there might be a possibility that hole injection blocking by MQB has been introduced by MQB. The amount of ratio for the suppressed leakage carriers will be discussed in following section. Other points will be discussed in later Chapter.

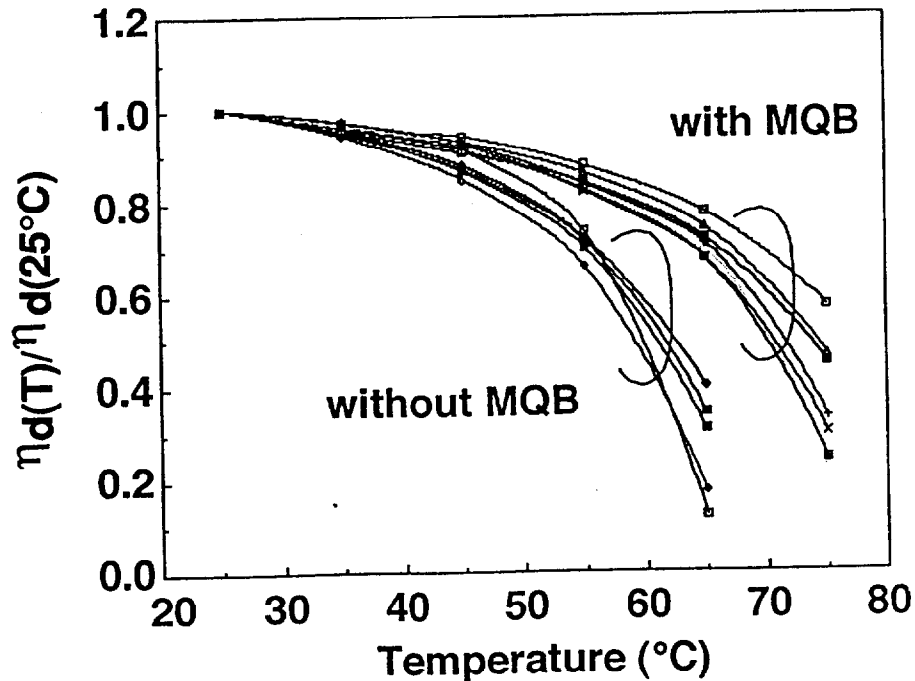
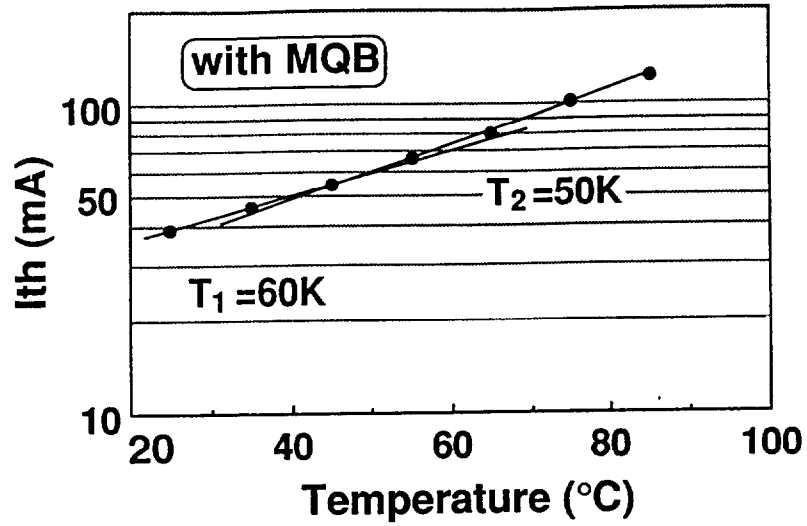


Figure 4.5

Temperature dependence of the slope efficiency for two types of LDs with both facets as-cleaved state.

a)



b)

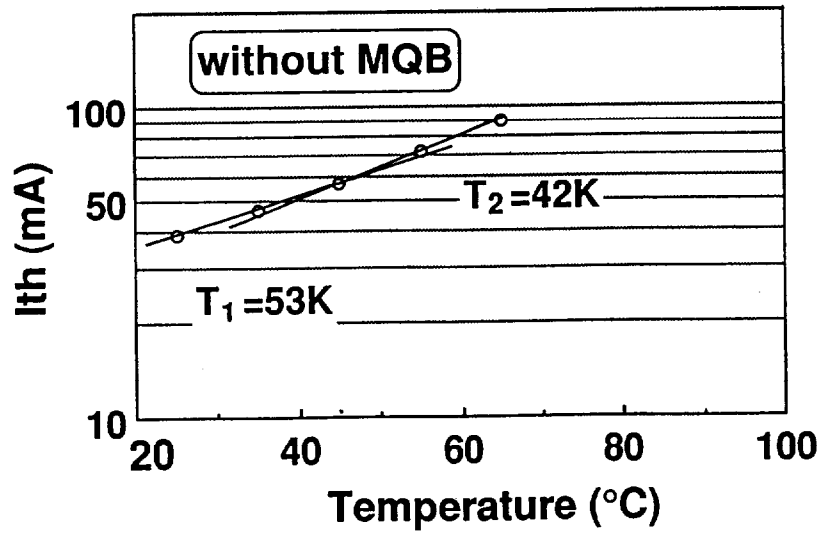


Figure 4.6

Temperature dependence for threshold current density of LDs with MQB, a) and without MQB, b).

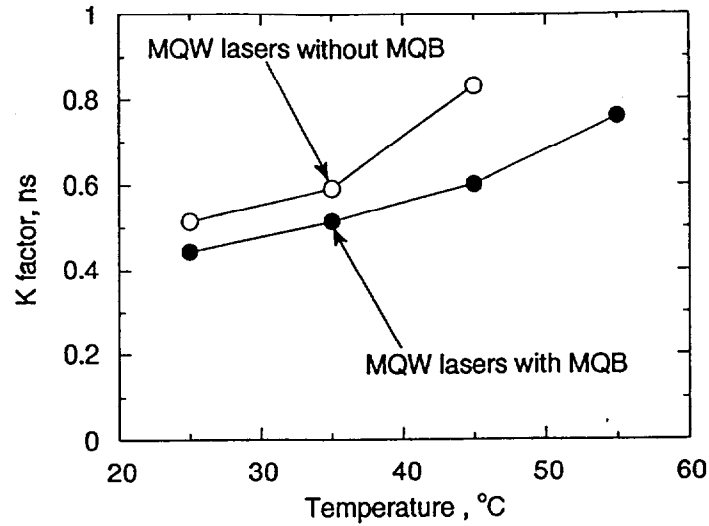


Figure 4.7

The temperature dependence of K factor obtained from RIN spectra for the two types of LDs.

4.4 Evidence for suppression of carrier leakage by MQB

4.4.1 Spontaneous emission from optical confinement layer

Spontaneous emission spectra from the optical confinement (OC) layers of LDs were measured and direct evidence for the suppression of carrier leakage by loading MQB was confirmed for the first time. Geometrical configuration for the measuring the spontaneous spectrum from LDs is shown in **Figure 4.8**. Spontaneous emission from the windows opened at substrate side was monitored. Examples of the measured results are shown in **Figure 4.9**.

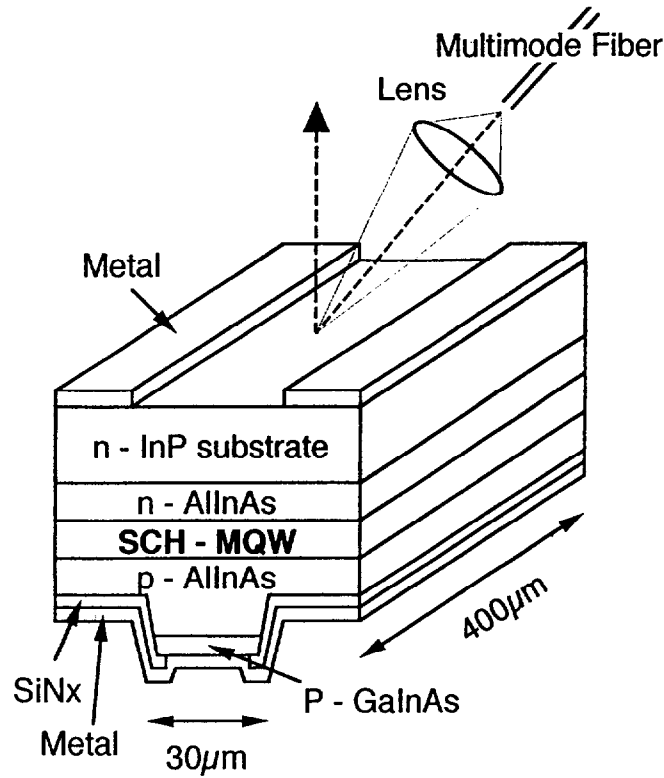


Figure 4.8

Geometrical configuration for measuring the spontaneous emission from the LDs. The emission was monitored from the substrate side, i.e., from the n-cladding side.

Comparing measured spectra from the two types LDs with MQB or without MQB, followings were confirmed;

(1) The reduction of spontaneous emission from the OC layer by loading MQB was estimated to be 2.5 to 3.5 dB at 25 degree C and 4 to 5 dB at 100 degree C. Since MQB was loaded at p-side OC layer, above difference in spontaneous emission spectra directly verified the suppression of electron leakage from QWs to OC layer by MQB. It should be noted that above reduction ratio is smaller than the apparent peak power ratio 7 to 10 dB in Figure 4.10b, because the difference in background emission intensity from the QWs at 1.5 μm -wavelength must be calibrated.

(2) The ratio P_{oc}/P_{act} increases as either injection current or operating temperature increases. This supports that thermionic leakage carriers cause the spontaneous emission from the OC layer, and that overflow increases with increasing bias current or operating temperature.

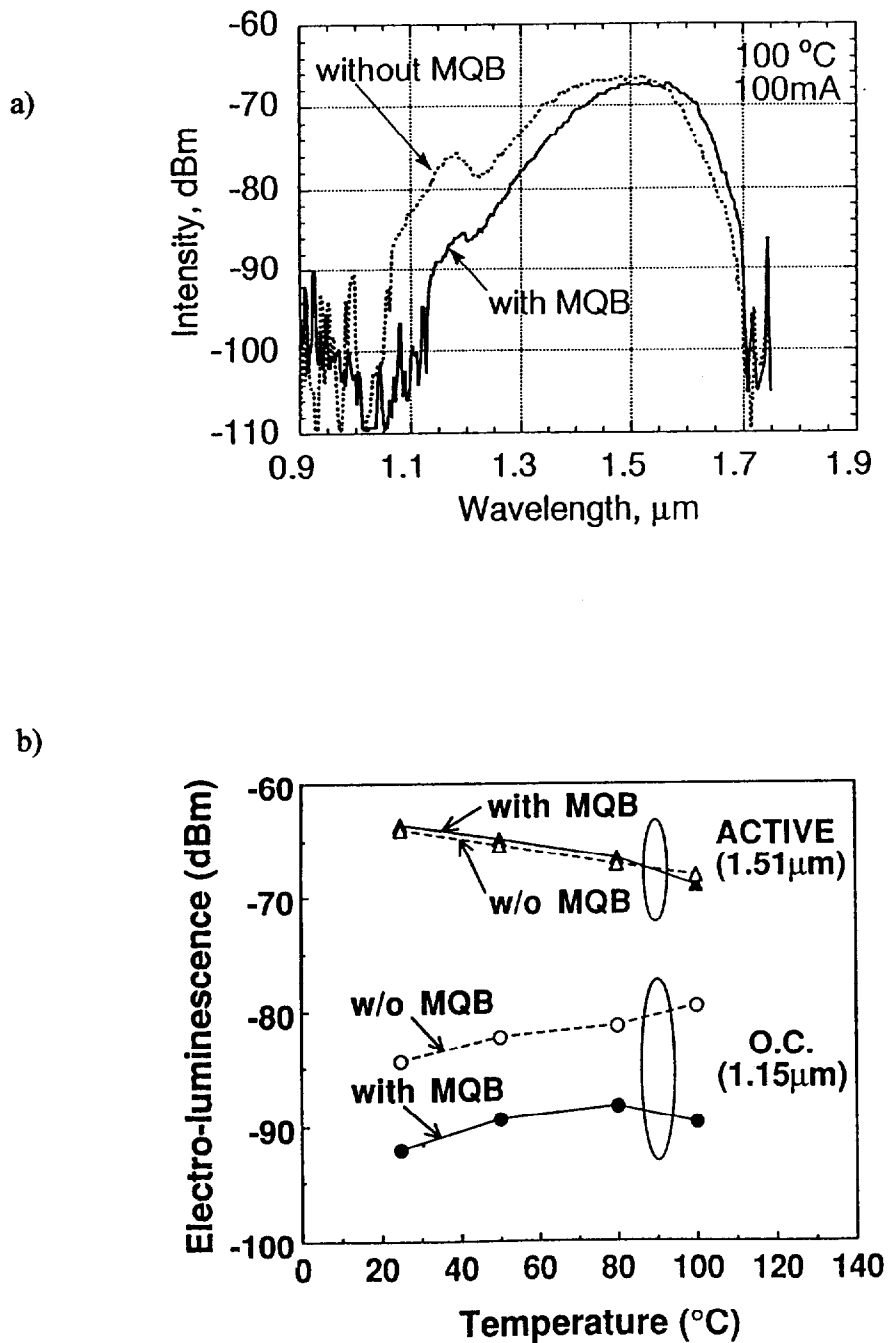


Figure 4.9

The spontaneous emission spectra for the two types of LDs, at 100 degree C a), and temperature dependence of the peak intensities b) under constant injection current of 50 mA.

4.4.2 Estimation of enhanced barrier height of MQB

Effective barrier height enhanced by MQB was estimated as follows. Since, emission was monitored from the window opened at n-cladding (substrate) side as shown in **Figure 4.8**, both emission from the n-side OC layer and that from p-side OC layer must have been detected at the same time. MQB was loaded at p-side OC layer in order to suppress the electron leakage. Therefore, it could be assumed as the first approximation that there is no change in the leakage carrier density in n-side OC layer.

In such situations, the measured emission intensity from the OC layers without MQB LDs, $P_{oc}(\text{without})$ is given by,

$$P_{oc}(\text{without}) = C2dSB_{oc}N_{oc}^e(0)^2, \quad (4-12)$$

where, $N_{oc}^e(0)$ is the carrier density in the OC layer of LDs without MQB, d , the thickness of each OC layer, S , the active area, C , the coupling coefficient. On the other hand, in LDs with MQB, the emission intensity $P_{oc}(\text{with})$ is given by,

$$P_{oc}(\text{with}) = CS[dB_{oc}N_{oc}^e(0)^2 + d_1B_{oc}N_{oc}^e(1)N_{oc}^h(1)], \quad (4-13)$$

where, $N_{oc}^{e(h)}(1)$ is the electron (hole) density in the p-side OC layer of LDs with MQB, d_1 , thickness of radiative part in p-side OC layer with MQB. Thus, the emission intensity ratio can be expressed as,

$$\begin{aligned} \frac{P_{oc}(\text{with})}{P_{oc}(\text{without})} &= \frac{[dB_{oc}N_{oc}^e(0)^2 + d_1B_{oc}N_{oc}^e(1)N_{oc}^h(1)]}{2dB_{oc}N_{oc}^e(0)^2}, \\ &= \frac{[dN_{oc}^e(0)^2 + 4d_1N_{oc}^e(1)N_{oc}^e(0)]}{2dN_{oc}^e(0)^2}, \end{aligned} \quad (4-14)$$

where, the relation $N_{oc}^h(1)=4N_{oc}^e(0)$ was adopted, assuming unipolar hole diffusion and hole flux kept unchanged by loading MQB. Since, the diffusion coefficient of holes is a quarter of

the one in ambipolar diffusion, four times larger gradient or average value would be required for hole density.

On the other hand, the loss current density in OC layer with MQB can be described as,

$$J_{LOSS}(with) = qd_1(A_{oc}N_{oc}^e(1) + B_{oc}N_{oc}^e(1)N_{oc}^h(1)) = qd_1(A_{oc}N_{oc}^e(1) + 4B_{oc}N_{oc}^e(1)N_{oc}^e(0)). \quad (4-15)$$

While, the leakage current density injected into p-side OC layer over the enhanced barrier of MQB E_{b1} is expressed as,

$$J_{LEAK} = \frac{4\pi q(k_B T)^2}{h^3} m_c(E_{b1}) \exp\left(-\frac{E_{b1} - E_{fe}}{k_B T}\right), \quad (4-16)$$

$$m_c(E_{b1}) = m_c^* \frac{E_g + 2E_{b1}}{E_g},$$

where, $m_c(E_{b1})$ is the nonparabolic DOS effective mass for the electron in the QW at enhanced barrier height E_{b1} , m_c^* is the band edge electron effective mass, E_g , the free state band gap.

Now, above loss current density $J_{LOSS}(with)$ would give the leakage current assuming that 1) re-injection of electron from the p-OC layer is negligible compared to leakage flux from the QW and that 2) all leakage carriers injected into p-OC layer are consumed in OC layer with MQB. Thus, carrier density $N_{oc}^e(1)$ can be determined from Eq.(4-14) using the quantity $N_{oc}^e(0)$ determined in **Chapter 3** and measured reduction ratio of spontaneous emission. Then with Eq.(4-15), the loss current is given, and then the leakage current, therefore the enhanced barrier height can be determined with Eq.(4-16). **Figure 4.10** shows calculated loss current density in p-side OC layer vs. peak intensity ratio. Measured reduction in the peak intensity ratio larger than 2.5 dB correspond to the reduction of the loss current from 52 A/cm² down to less than 7 A/cm², which means over 87 % reduction. While, **Figure 4.11** show calculated leakage current vs. enhanced barrier height of MQB $\Delta E_{mqb} = E_{b1} - E_b$. As shown here, leakage current less than 7 A/cm² corresponds to the enhanced barrier height ΔE_{mqb} greater than 210 meV.

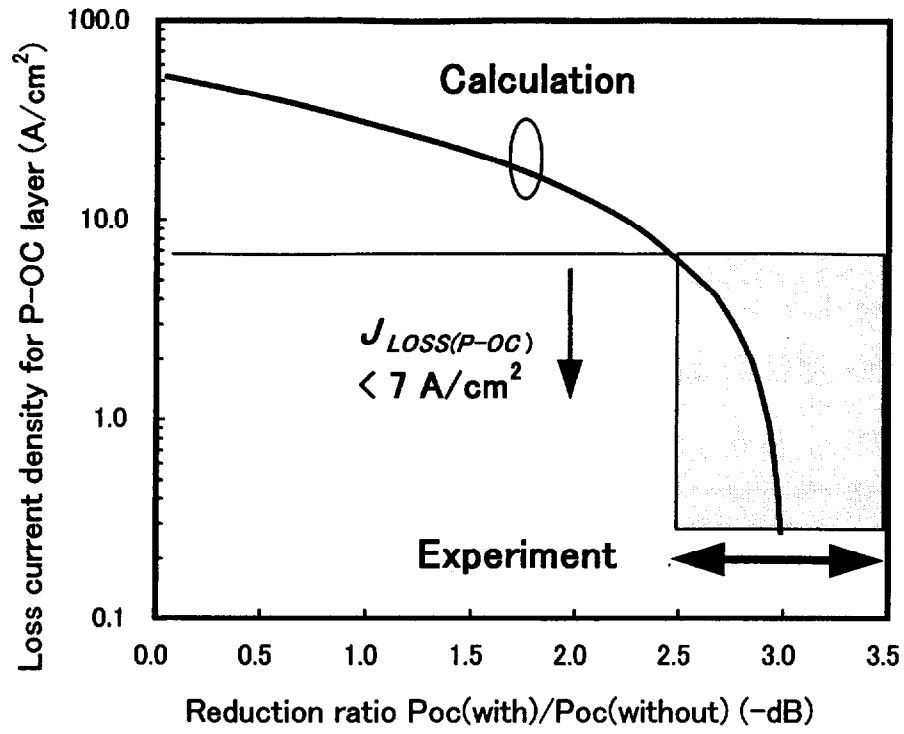


Figure 4.10

Calculated loss current density in P-side OC layer vs. spontaneous intensity reduction ratio. Measured reduction ratio in the peak intensity ratio is remarked in the Figure.

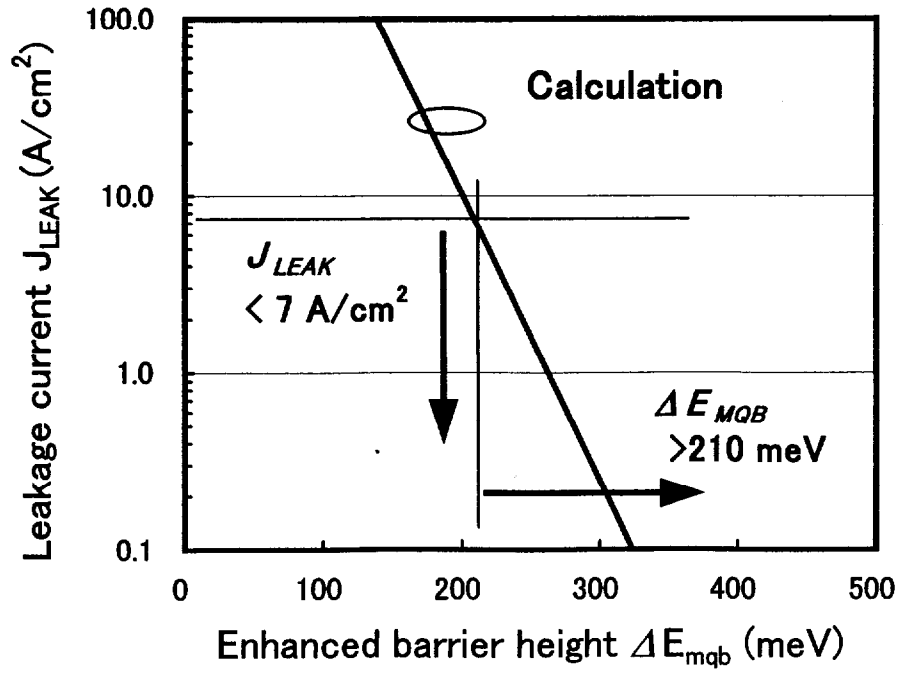


Figure 4.11

Calculated leakage current from QW to OC layer as a function of the enhanced barrier height by MQB. Estimated leakage current enhanced barrier height is remarked in the Figure.

In above analysis, we have neglected the change in n-OC side, which might be caused by loading MQB to p-OC side. As observed in **Figure 4.9**, the reduction ratio of peak intensity increases at higher temperature. This is qualitatively explained as follows. Reduction of internal loss due to the reduced leakage carriers in the p-side OC layer, causes reduction in threshold carrier density and causes the reduction of the carrier transport factor and eventually reduces leakage carrier density in n-side OC layer. This effect is enhanced at higher temperature, since the carrier density in the OC layer influences more seriously at higher temperature.

4.5 Summary

In summary, suppression of the carrier leakage in long-wavelength lasers by MQB was demonstrated for the first time. Strained GaInAs/AlGaInAs MQW lasers were fabricated with MQB structure at the p-side optical confinement layer, by using MBE. As evidences of the suppression of carrier leakage by loading of MQB, followings were confirmed;

- 1) Temperature dependence of slope efficiency was improved so that the efficiency was increased at high temperature and the maximum operating temperature was raised about 15 degree C. A slight improvement in the characteristic temperature T_0 was observed.
- 2) Temperature dependence of the K factor was improved, and the K factor was reduced more than 30 % at high temperature, which corresponds to the 40 % increase in differential gain,
- 3) Reduction in the peak intensity of spontaneous emission from OC layers 2.5 dB to 3.5 dB was confirmed, as for more direct evidence of MQB effect. Enhanced barrier height by MQB over 210 meV was estimated from the above reduction ratio. Almost complete suppression of over 87 % of thermionic electron leakage was estimated.

Slight increase in T_0 agrees with theoretical consequences on the deterioration mechanism derived in **Chapter 3**. That is, carrier leakage to n-side OC layer, hole leakage and Auger hot carriers must also be eliminated. The obtained results suggest those processes are still dominating the temperature sensitivity. On the other hand, the effect of MQB upon hole transport in p-OC region also needs further investigation.

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Chapter 5

Improved Design Method for Multiquantum Barriers

Improved design method for multiquantum barriers (MQB) in the application to long-wavelength lasers is presented. Design models are discussed from following viewpoints; 1) effect of nonparabolic dispersion of conduction band, 2) effective barrier height enhancement of MQB using strained-layer and 3) hole transport in MQB region.

5.1 Effect of band nonparabolicity upon MQB performance

5.1.1 Nonparabolic model for conduction band

As for the conduction band dispersion, noticeable difference from the parabolic model has been reported even at an energy a few hundreds meV above the conduction band edge[1],[2]. Therefore, there is a large possibility that such a difference in the dispersion model would cause a deviation of the phase matching condition and result in the indispensable change of the reflection spectrum of MQB. Thus, the effect of nonparabolicity upon the electron reflection performance of MQB was examined theoretically, using *kp* perturbation method[3][4].

In order to incorporate the nonparabolicity in transfer matrix method, following two relations must be defined;

- 1) a nonparabolic *E-k* dispersion relation,
- 2) an energy dependent electron effective mass.

For the latter, the differential effective mass definition was adopted[5],

$$m^*(E) = \left[\frac{1}{\hbar^2} \frac{d^2 E(k)}{dk^2} \right]^{-1} \quad (5.1)$$

The nonparabolic $E-k$ dispersion was derived using kp perturbation method[3][4]. The interaction between conduction band and upper valence band and that between conduction band and the spin-split-off band cause the nonparabolicity of conduction band, as shown in appendix. From the secular matrix equation, following nonparabolic dispersion relation is obtained for lattice matched material;

$$E = \frac{\hbar^2 k^2}{2m} + \frac{1}{2} \left\{ -E_g + \left[E_g^2 + 2\hbar^2 k^2 \left(\frac{1}{m_c^*} - \frac{1}{m} \right) \frac{E_g (E_g + \Delta_0) \left(E + E_g - \frac{\hbar^2 k^2}{2m} + \frac{2}{3} \Delta_0 \right)}{\left(E_g + \frac{2}{3} \Delta_0 \right) \left(E + E_g - \frac{\hbar^2 k^2}{2m} + \Delta_0 \right)} \right]^{1/2} \right\}, \quad (5-2)$$

where, E , E_g , Δ_0 are energy level measured from the conduction Γ band edge, band gap energy, spin-split-off energy, respectively, and m , m_c^* are electron rest mass and effective mass at the conduction Γ band edge, respectively.

Figure 5.1 compares the $E-k$ dispersions for conduction Γ band of GaAs calculated from kp method, Eq.(5-2), with those from parabolic model (effective mass approximation) and from reported nonparabolic dispersions[4]. In terms of deviation from parabolicity, nonparabolicity gives a larger wave number and a larger effective mass at a given energy, where higher the energy, larger the deviation. In comparison with other models, formula in this study gives a dispersion close to one from nonlocal pseudopotential calculation by Chelikowsky et al.[6], in the energy region of present concern, $0 \leq E \leq 1\text{eV}$. While for higher energy region than 500 meV, both curves from Raymond et al.[1] and from Miller et al.[2] give too large nonparabolicity when compared with the results by Chelikowsky et al.[6], where peak energy appears at around 1.8 eV. Those discrepancies can be attributed to the fact that the two models by Raymond and Miller were deduced from the experiments in rather low energy region.

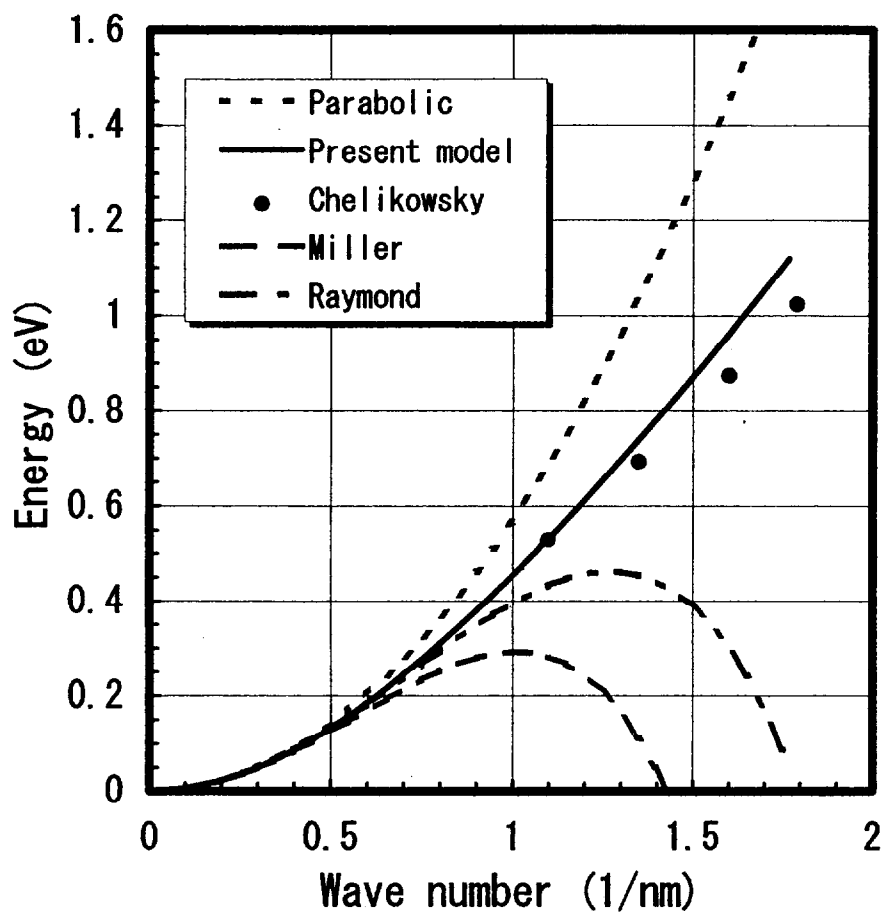


Figure 5.1

Comparison of dispersion relations for the conduction band of GaAs, calculated with parabolic model, nonparabolic models including present study and other formula. Circles are reported results from nonlocal pseudopotential calculations. The normalized effective mass value of 0.067 for the electron in GaAs was assumed.

5.1.2 Effect of nonparabolicity on MQB performances

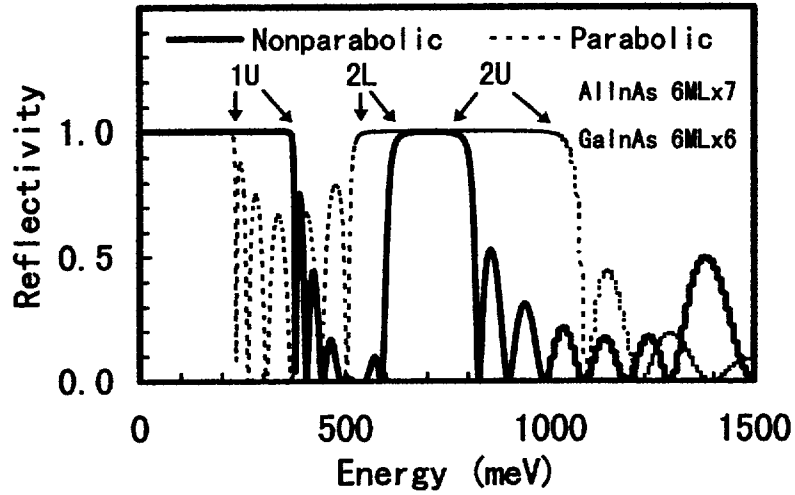
Figure 5.2 compares the typical electron reflection spectra calculated with transfer matrix method (TMM) under parabolic model (dotted line) and nonparabolic model (thick solid line) for MQBs consisting of GaInAs wells and AlInAs barriers with constant period. Typical two cases are shown here.

Changes of stop band positions were examined in detail for various layer structures. **Figure 5.3** shows the extracted stop band edge energies as a function of barrier thickness a) and as a function of well thickness b).

From those results, following effects induced by the band nonparabolicity were found ;

- 1) the first stop band is enhanced in all the cases. Enhanced amount varies depending on layer thickness from 80 meV to 180 meV.
- 2) Narrowing of bandwidth for the second stop band is induced. This also strongly depends on layer structure and in some layer structures, the second stop band disappears.

a)



b)

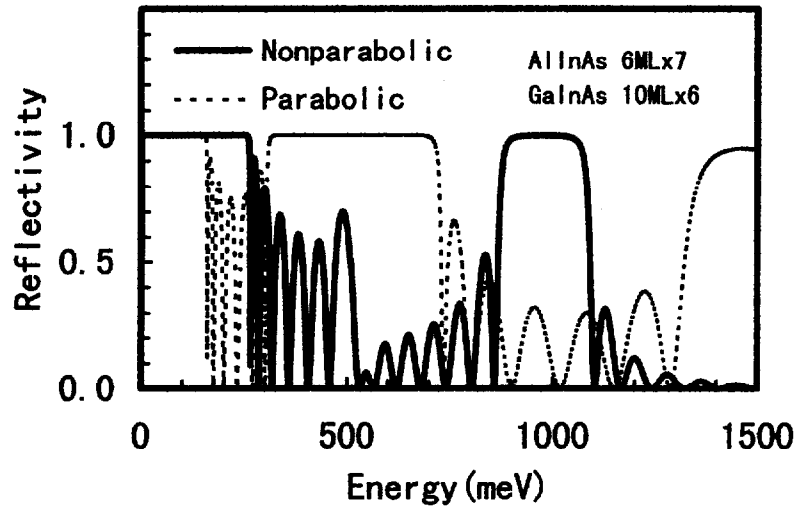
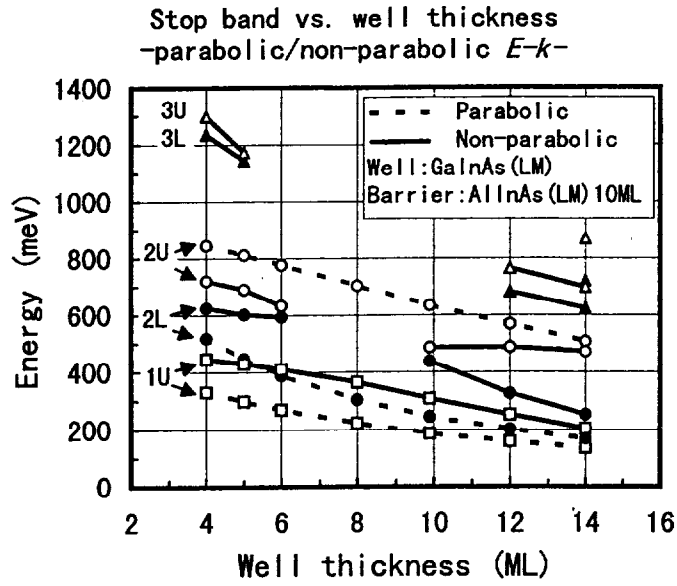


Figure 5.2

Typical electron reflection spectra of MQB calculated with parabolic dispersion model (dotted line) and with nonparabolic model (thick solid line). In case a), MQB is consisting of six 6 ML GaInAs wells and seven 6 ML AlInAs barriers, and in case b), consisting of six 10 ML GaInAs wells and 6 ML AlInAs barriers. All layers were assumed lattice matched to InP. The band parameters used for calculations were ; the normalized effective mass of electron for GaInAs and AlInAs 0.0427 and 0.0758, respectively, the spin split-off energies for GaAs, InAs, AlAs, 0.34 eV, 0.38 eV, 0.29 eV, respectively, where parabolic interpolation was used for ternary materials, the band edge discontinuity ΔE_c , 497 meV.

a)



b)

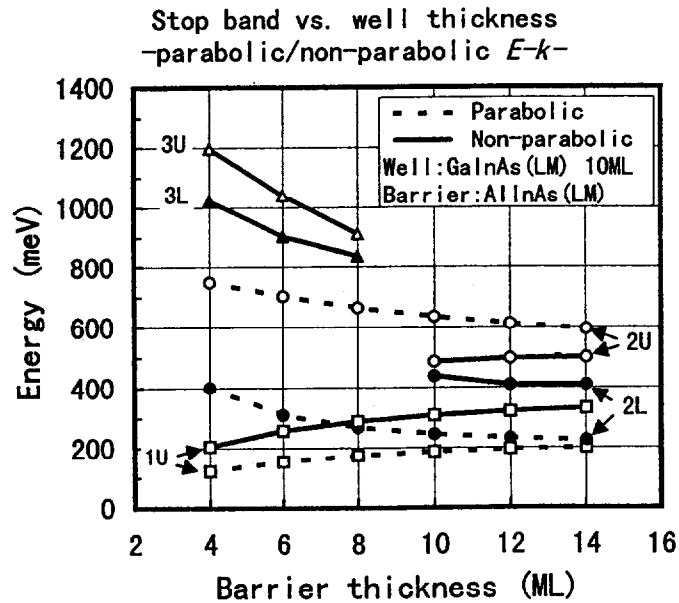


Figure 5.3

Stop band edge energies for MQBs calculated using the parabolic band model (dotted line) or the nonparabolic band model (solid line) as functions of well thickness a) and as a function of barrier thickness b). MQBs were assumed to consist of six GaInAs wells and seven AlInAs barriers, all lattice matched to InP. The lowest three stop bands are plotted here.

The effect of nonparabolic $E-k$ dispersion itself and that of the change of differential effective mass was separately evaluated by comparing two cases; a) with nonparabolic dispersion but constant effective mass and b) with nonparabolic dispersion and differential effective mass. **Figure 5.4** shows the results.

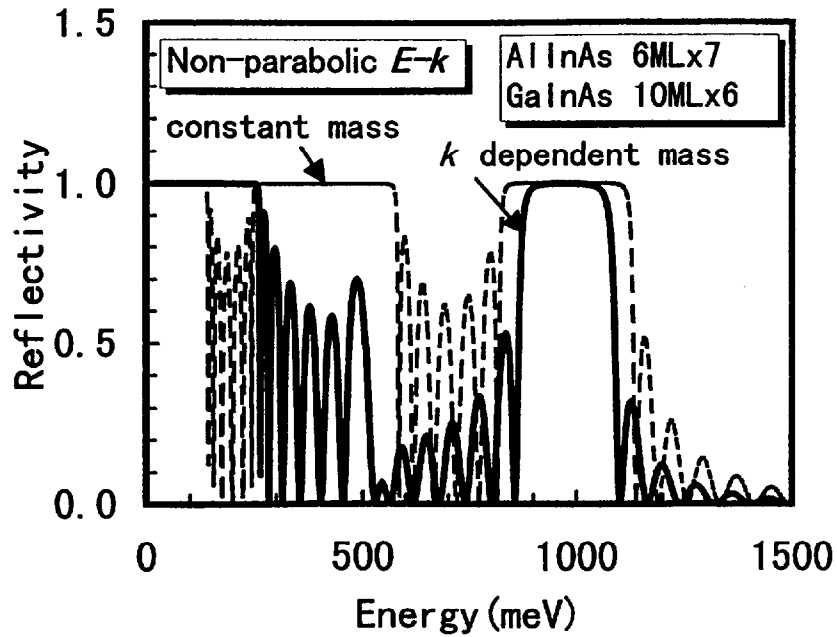


Figure 5.4

Comparison of reflection spectra for an MQB calculated using nonparabolic $E-k$ but constant effective mass (dotted line) and nonparabolic $E-k$ and energy-dependent differential effective mass. Band parameters used were the same as those described in Figure 5.2.

Comparing **Figure 5.4** with the result from parabolic model **Figure 5.2 b)**, followings were found for the effect of E - k dispersion.

- 1) the enhancement of the first stop band is attributed to the change of effective mass,
- 2) the change of positions of the second and the third stop bands are mainly determined by the nonparabolic dispersion, while the drastic deterioration of the second stop band is attributed to the effective mass change.

Those suggested that a possibility of a significant change in the reflection spectrum of MQB could be induced by the nonparabolicity of the conduction band, particularly in high energy region. Indeed, in the design of MQB for 1.5 μ m MQW-LDs, large effect upon the effective barrier height by adopting the nonparabolic model was confirmed in high energy region.

In summary of this subsection, the effect of the conduction band nonparabolicity upon the reflection performance of MQB was examined theoretically for the first time. In the electron wave reflection spectrum, nonparabolicity causes a large narrowing or even vanishing of the second stop band in some thickness regions of superlattice. While, the first stop band region is always enhanced. Taking into account the nonparabolicity in the design model would be a key to the full realization of MQB effect, especially in the application of MQB for the confinement of Auger hot electrons.

5.2 Strained-layer for enhancing the barrier height of MQB

In this section, change of band edge discontinuity in the strained-layer structure is discussed at first. Based on the knowledge, enhancement method of the effective barrier height of MQB by using the tensile strained-barriers was presented in this study for the first time[7].

5.2.1 Effect of strain on band edge discontinuity and effective mass

In designing MQB structure, the band edge discontinuity and the band parameters such as effective mass of electron and so on are required for the constituent materials. The model-solid theory is known to be a method to give those values systematically[5],[9]. It is based on the results from the first principle calculations on the average valence band energies and deformation potentials for binary materials. The band parameters for lattice matched or strained materials are obtained by combining experimental results on the band gap energy, spin-orbit splitting and the parameters for calculating shear deformation potential. Interpolation scheme is used for ternary and quaternary materials. Good agreement has been reported on the band edge discontinuity between calculations from the model-solid theory and experiments.

Figure 5.5 shows the calculated in-plane strain dependencies of the band edge discontinuity for conduction band ΔE_c for heterojunctions between three typical ternary barrier materials and lattice matched GaInAs well[7]. As shown here, by introducing 1-2 % in-plane tensile strain into barriers, increase in ΔE_c of 150-200 meV can be expected. A clear advantage of AlInAs is confirmed here in realizing a high ΔE_c by the tensile strain

At the same time, the inherent advantage of AlInP barrier to AlInAs barrier was newly found from this diagram as described below. **Figure 5.6** compares the strain related aluminum contents for AlInAs and AlInP on InP substrates[7]. We find here AlInP/GaInAs system requires much less aluminum content than that of AlInAs/GaInAs system to realize the same conduction band edge discontinuity.

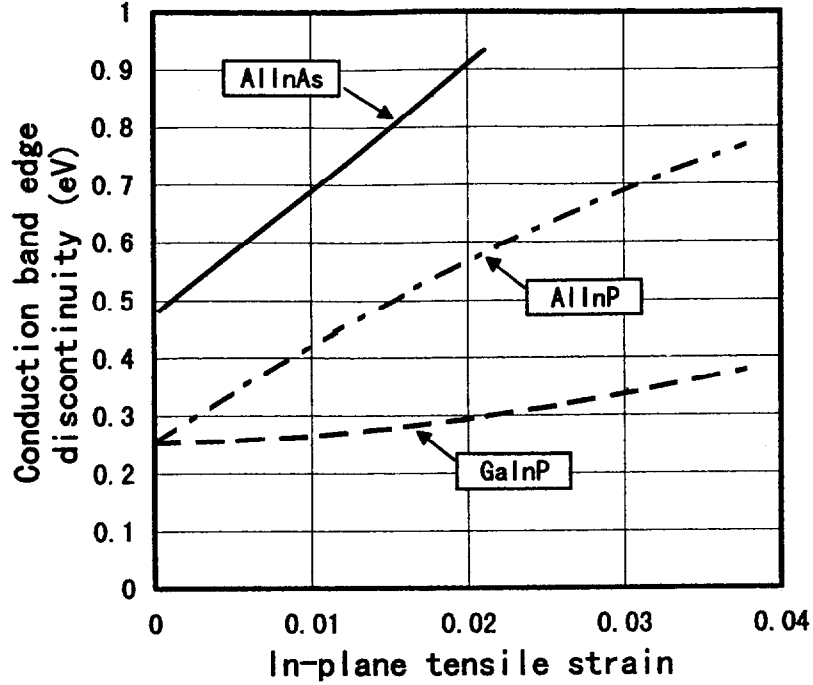


Figure 5.5

Calculated strain dependence of conduction band edge discontinuity for three ternary materials against GaInAs lattice matched to InP. The model solid theory was used for calculation.

For example, lattice matched $\text{Al}_x\text{In}_{1-x}\text{As}$ ($x = 0.48$)/GaInAs gives ΔE_c of 485 meV. Almost equivalent ΔE_c of 421 meV can be realized by 1 % tensile strained $\text{Al}_x\text{In}_{1-x}\text{P}$ ($x = 0.14$)/GaInAs. From the point of view of epitaxial growth, we experience drastic deterioration of crystal quality of AlInAs with increasing the aluminum content. Taking such state of the art of epitaxial growth technology into account, the tensile strained AlInP barrier on InP should have the inherent advantage.

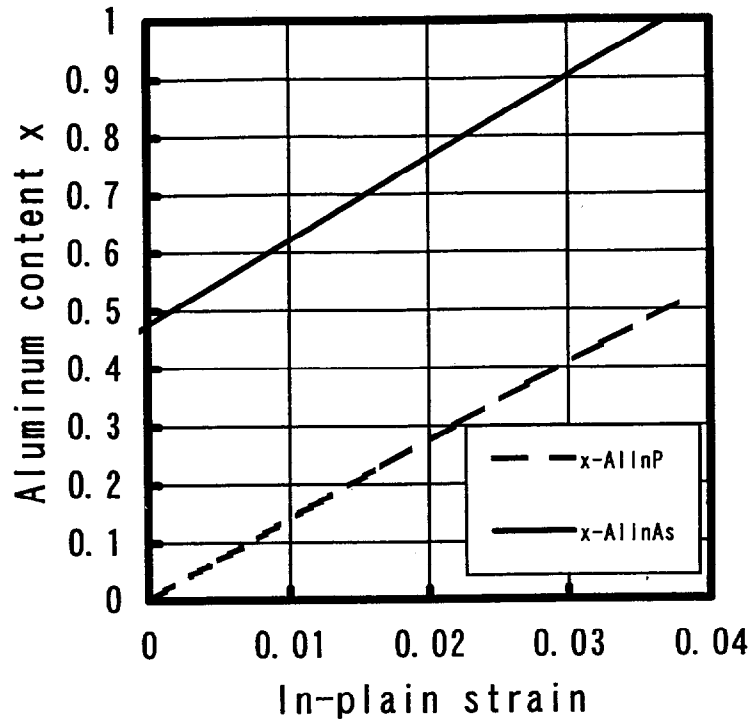


Figure 5.6

The aluminum content as a function of in-plane tensile strain for AlInAs and AlInP on InP.

5.2.2 Enhancing the effective barrier height of MQB by strained-layer

The effects of using tensile barriers in MQB are discussed here at first. **Figure 5.7** summarizes the precise comparison of barrier and well thickness dependencies of the reflection spectra for AlInAs/GaInAs MQBs with lattice matched barriers or with 1% tensile barriers[7]. Following advantages of introducing tensile barriers were confirmed for the stop band energy;

- 1) tensile barrier enhances the high edge of the second stop band energy
- 2) tensile barrier enhances also the width of the first stop band,
- 3) tensile barrier basically lowers the low edge of the second stop band, so as to slightly enhance the width of the second stop band, except for the case of thick barriers,
- 4) tensile barrier reduces the width of the energy tunneling channel between the first and the second stop bands.

5) tensile barrier increases tolerance of layer thickness deviation, which is apparent from the high edge of the second stop band in **Figure 5.7**.

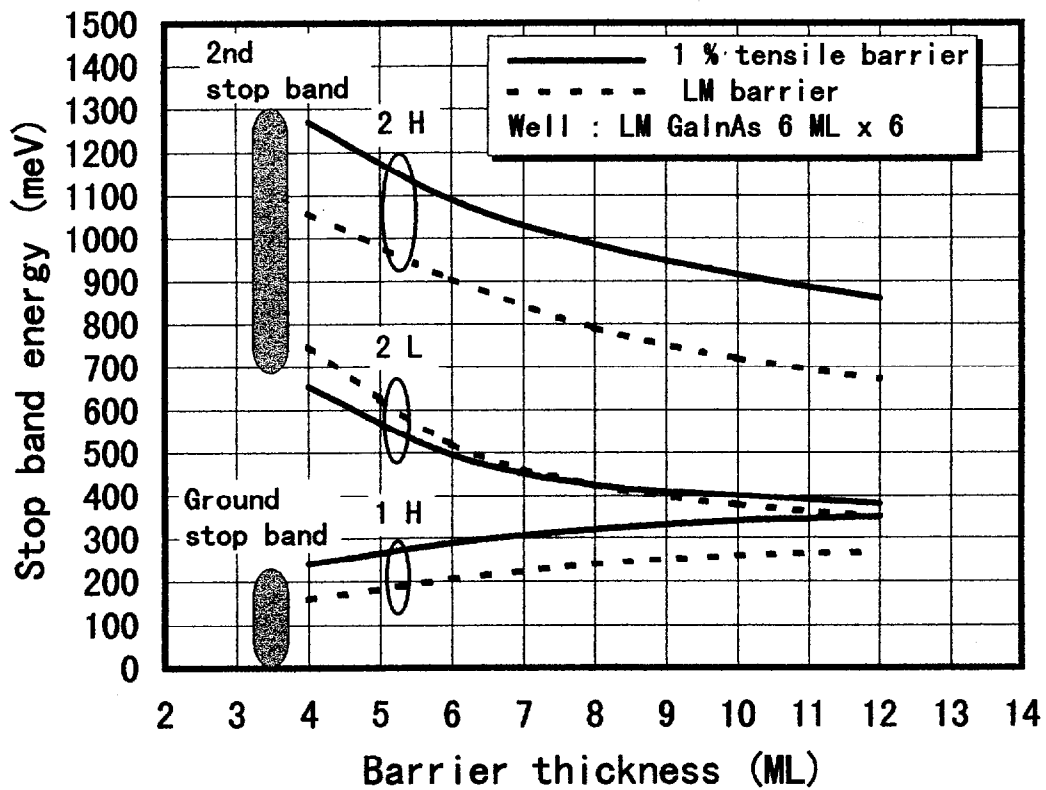


Figure 5.7

Stop band positions extracted from the calculated reflection spectra of MQB, as a function of barrier thickness. Two types of MQBs with lattice-matched AlInAs barrier and 1% tensile strained AlInAs barrier were compared. For all cases, lattice-matched GaInAs wells were assumed. Band parameters used are as follows: normalized electron effective mass for lattice-matched and 1% tensile AlInAs, 0.075 and 0.089, respectively, and for lattice matched GaInAs, 0.044. Conduction band edge discontinuity ΔE_c for lattice matched (1% tensile) barrier, 485 (690) meV.

As a summary of this section, following advantages of incorporating tensile strained barriers in MQB were confirmed from calculations;

- 1) tensile strained barrier enhances the width of the energy stop band of MQB,
- 2) tensile strained barrier opens possibility to use a new material such as AlInP with low aluminum content,
- 3) tensile strained barrier increases tolerance of layer thickness deviations.

Those advantages would be useful in designing MQB with high effective barrier height for the suppression of Auger hot electrons in long-wavelength MQW-LDs.

5.3 Hole transport in MQB

Hole transport in MQB is discussed taking into account the valence band minibands and density of states (DOS) of valence band for MQB as the superlattice. The effects of introducing strain-compensated (SC) structure in MQB upon those valence band states are also discussed. Improved structure for MQB avoiding the hole pile-up phenomena is presented.

5.3.1 Miniband and DOS for the valence band of MQB

In order to estimate the hole density in MQB at lasing conditions, miniband levels and DOS for the valence band of MQB were investigated. **Figure 5.8** shows calculated hole tunneling probability as a function of barrier thickness. As shown here, hole can tunnel through the barriers in those thickness regions, although the probability largely depends on the barrier height and effective mass of hole in the barrier. More specifically, the tunneling probability is remarkably enhanced when a hole experiences a light hole mass in the barrier region, which is one of the features of tensile strained barriers. Thus, the tensile strained barrier has the advantage in larger hole tunneling probability.

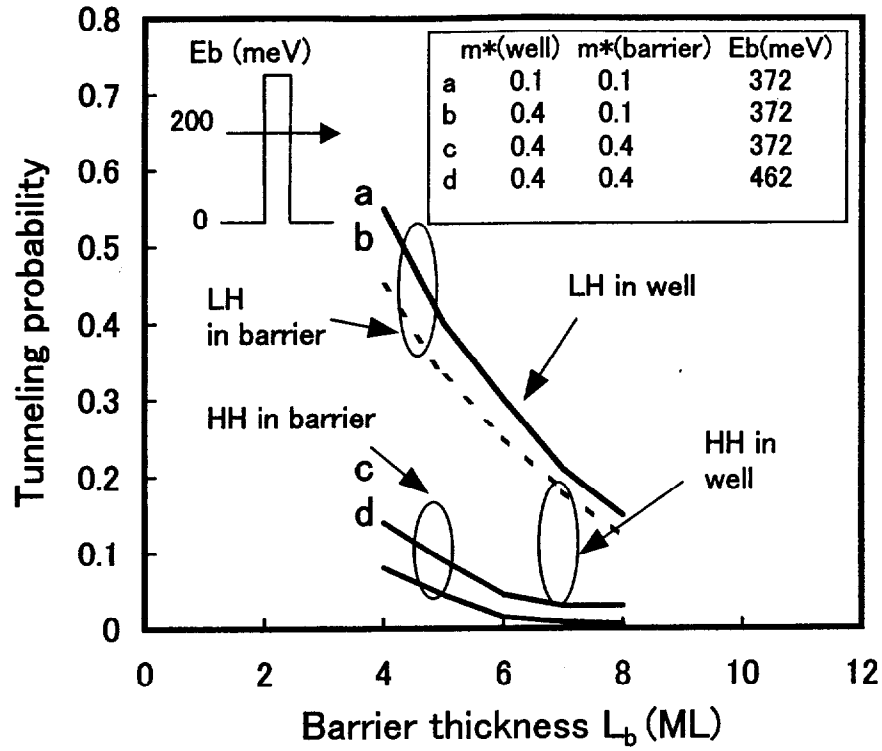


Figure 5.8

Tunneling probability for holes against a single barrier calculated by TMM. Injection energy for hole of 200 meV was assumed. Transfer matrix method was used for calculation.

In such circumstances, hole wave functions in wells can penetrate into the neighbor wells and continuous miniband is formed. **Figure 5.9** shows the calculated miniband levels for AlInP/GaInAs superlattice on InP. The model solid method and the Krönig-Penny model were used for calculations[10]. Those results revealed the existence of the miniband in MQB and suggested the possibility of injection and pile-up of holes into those minibands.

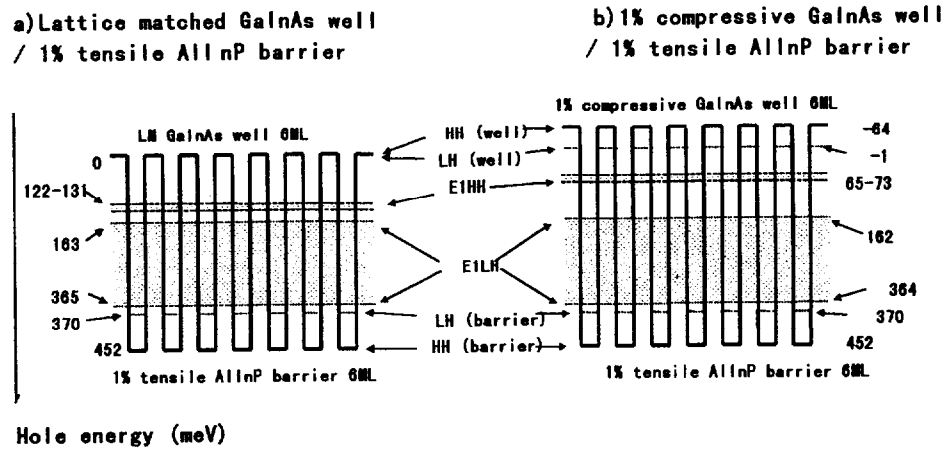


Figure 5.9

Valence band diagrams and minibands for 1% tensile AlInP/GaInAs superlattices, calculated from model solid theory and the Krönig-Penny model. Lattice matched GaInAs wells were assumed in case a) and 1% compressive GaInAs in b). Valence band edge of LM GaInAs was taken as the energy reference.

Thus, in the following step, DOS for the miniband and hole density in MQB was calculated. The DOS of superlattice miniband $g_{SL}(E)$ is given by following Eq. (5-3) as shown in appendix[11]-[13];

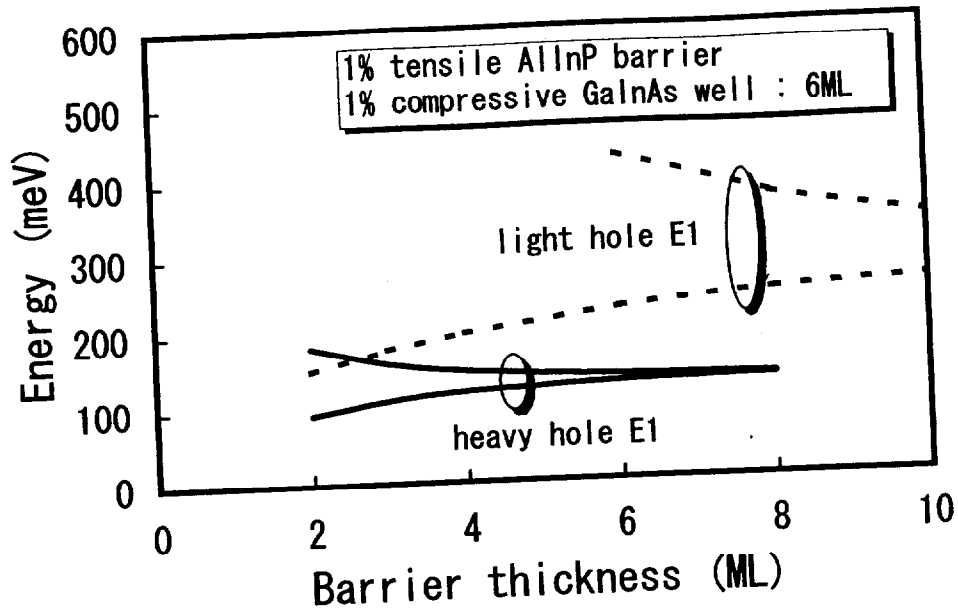
$$g_{SL}(E) = \sum_i \frac{m_w^{*i}}{\pi^2 \hbar^2 d} \begin{cases} 0, & 0 \leq E \leq E_{ia}, \\ \cos^{-1}\left(1 - 2 \frac{E - E_{ia}}{E_{ib} - E_{ia}}\right), & E_{ia} \leq E \leq E_{ib}, \\ \pi, & E \geq E_{ib}, \end{cases} \quad (5-3)$$

where $g_{SL}(E)$ is the DOS per unit volume, m_w^{*i} , the in-plane effective mass of hole in the well layer for i-th miniband of superlattice, $d = L_w + L_b$ the period of the superlattice, and the energy region $E_{ia} \leq E \leq E_{ib}$ corresponds to the i-th miniband.

As is clear in Eq.(5-3), a thinner well thickness gives a larger DOS of SL, which results in a larger hole concentration. While, a thinner well should give a higher miniband level, which leads to a lower hole concentration. That trade off suggests an importance of the well thickness dependence of the miniband energy. Thus, the allowed lowest miniband energy levels for heavy holes and light holes were calculated as functions of barrier thickness (a) and well thickness (b). The results are shown in **Figure 5.10** for SC-superlattice consisting of 1% tensile AlInP/ 1% compressive GaInAs[14]. In calculation, it was assumed that heavy (light) holes in the well only experience heavy (light) hole barrier levels. Followings were confirmed;

- 1)the thinner barrier brings the broader energy band width of the miniband, which results in the lowering of the low edge of the miniband (**Figure 5.10 a**),
- 2)the thinner well generates the higher miniband energy level (**Figure 5.10 b**).

a) as a function of barrier thickness



b) as a function of well thickness

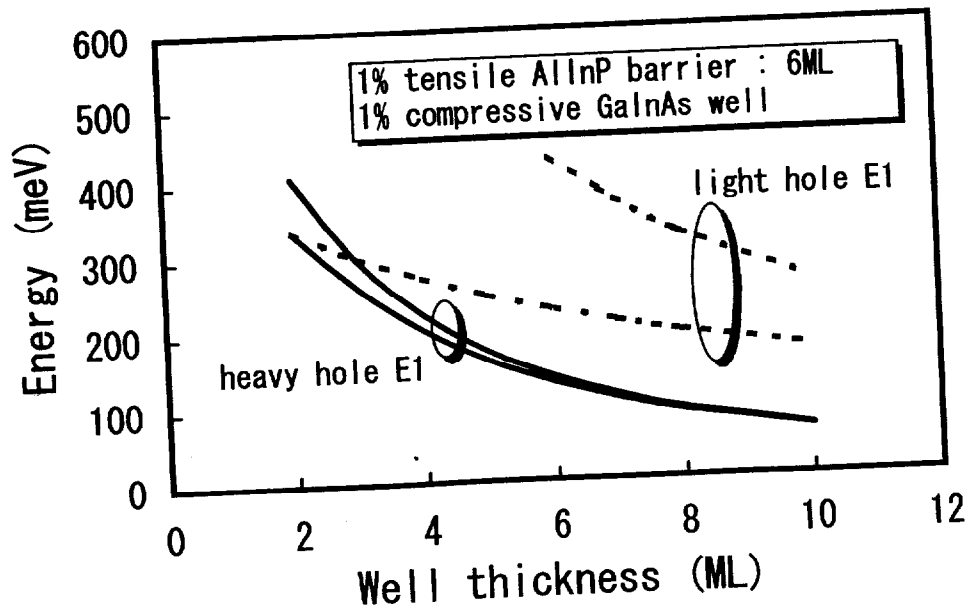


Figure 5.10

Allowed lowest miniband energy for heavy holes and light holes as a function of barrier thickness a) and well thickness b). The Kronig-Penny model was used for the calculation. The effective mass for heavy (light) hole was approximated to be $0.4m_0$ ($0.1m_0$).

5.3.2 Hole density in MQB and hole pile-up

Now hole density in MQB region under lasing condition was calculated as follows[14]. In the application of MQB to SCH MQW-LD, MQB is loaded adjacent to the MQW active region. In such situation, the quasi-Fermi level for hole E_{fp} determines both the hole density in wells of MQW, p_w and that in MQB region, p_{MQB} . Thus p_{MQB} and p_w can be calculated as a function of E_{fp} using following equations;

$$p = \sum_i \int_{E_i}^{E_b} g_{SL}(E) f(E) dE + \frac{L_w}{d} \int_{E_b}^{\infty} g_b^{wel}(E) f(E) dE + \frac{L_b}{d} \int_{E_b}^{\infty} g_b^{bar}(E - E_b) f(E) dE, \quad (5-4)$$

where, $g_{SL}(E)$ is given by Eq. (5-3) and

$$\begin{aligned} g_b^{wel}(E) &= \frac{1}{2\pi^2} \left(\frac{2m_w^*}{\hbar^2} \right)^{\frac{3}{2}}, \\ g_b^{bar}(E) &= \frac{1}{2\pi^2} \left(\frac{2m_b^*}{\hbar^2} \right)^{\frac{3}{2}}, \\ f_p(E) &= \frac{1}{1 + \exp\left(\frac{E - E_{fp}}{k_B T}\right)}, \end{aligned} \quad (5-5)$$

where, $g_b^{wel}(E)$ and $g_b^{bar}(E)$ denote the bulk DOS for well and barrier material respectively, $f_p(E)$, the Fermi-Dirac distribution function for hole.

Calculated results are shown in Figure 5.11, where the hole density in MQB region p_{MQB} was plotted as a function of hole density in well p_w . Here, MQB with lattice matched well and strain compensated 1% tensile AlInP barrier/ 1% compressive GaInAs well MQB were compared for various layer thickness. In calculation, the quasi-Fermi level and the valence band edges of MQW and MQB were assumed to be flat (flat band approximation).

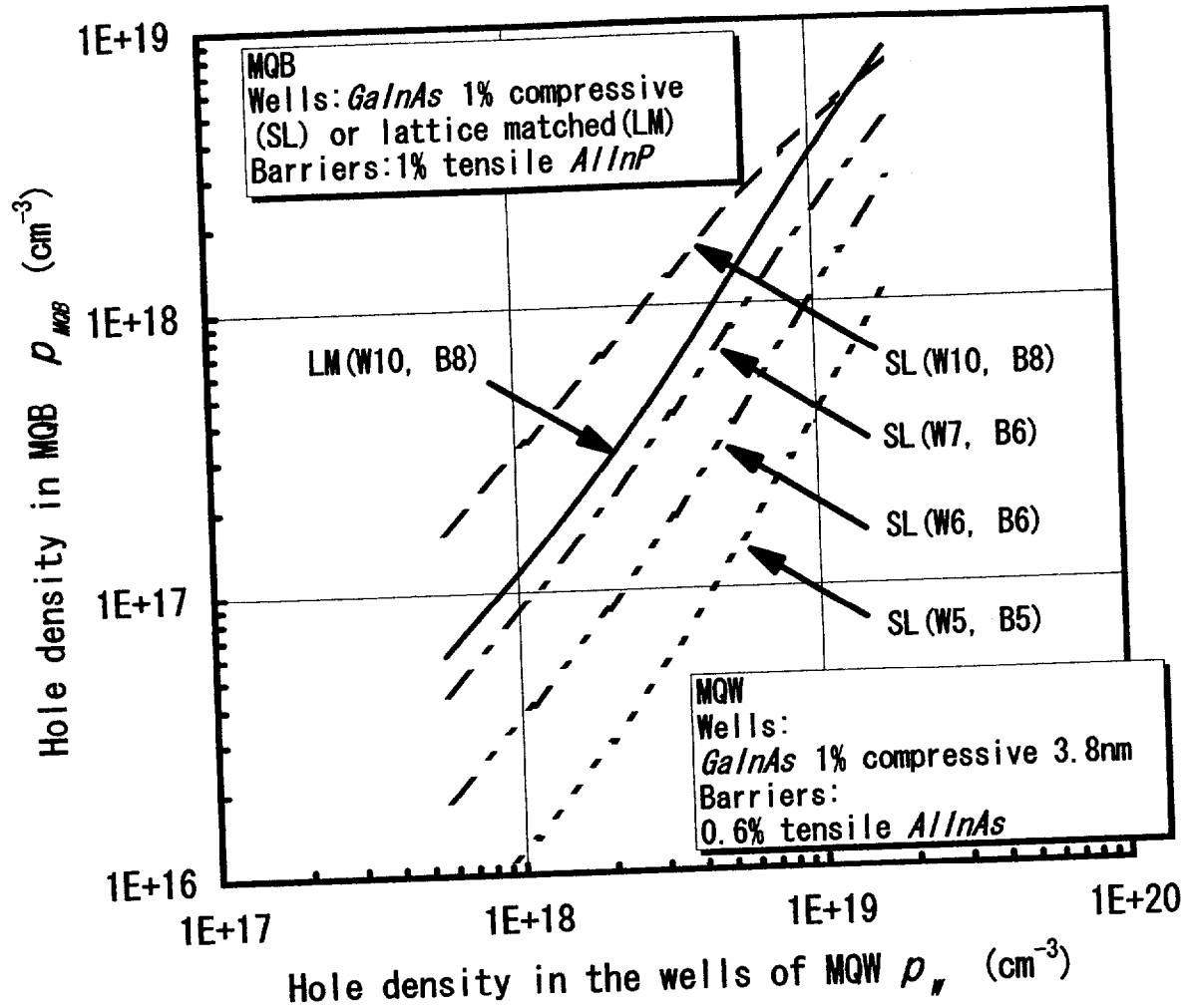


Figure 5.11

The hole density in MQB minibands as a function of hole density in well of MQW under lasing condition and flat band assumptions. For MQW, 1% compressive GaInAs wells, each 3.8nm thick were assumed. The barriers of MQB is 1% tensile strained AlInP, while wells are either GaInAs lattice matched (LM) or 1% compressively strained (SL). The bracket (W10, B8) denotes the well thickness 10 ML, barrier thickness 8ML. In the calculation, the DOS of lowest minibands for heavy hole and light hole for MQB was taken into account, where in-plane effective mass for hole in well was assumed to determine the DOS of superlattice and heavy (light) hole in-plane effective mass was approximated to be $0.4 m_0$ ($0.1 m_0$) for the lattice matched well and $0.1 m_0$ ($0.4 m_0$) for the compressive strained well. The supposed layer structures are described in the insets.

From **Figure 5.11**, followings were found;

- 1) Hole density in MQB p_{MQB} reaches almost to $1 \times 10^{18} \text{ cm}^{-3}$ in case of MQB with well thickness larger than 7 ML in lasing condition (p_w range of 1×10^{18} to $6 \times 10^{18} \text{ cm}^{-3}$).
- 2) MQB with compressively strained well gives larger p_{MQB} than that of lattice matched well MQB at same layer thickness.
- 3) However, p_{MQB} can be suppressed to less than middle of 10^{17} cm^{-3} by reducing the layer (well) thickness of MQB.

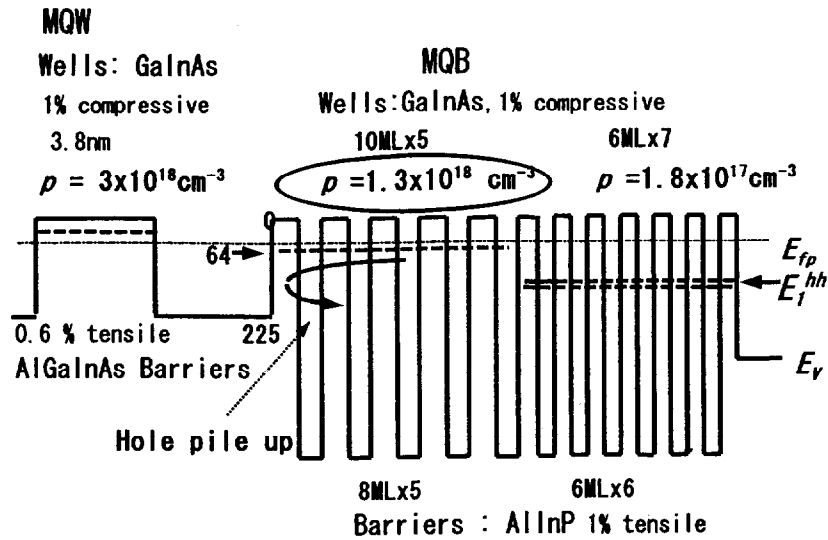
The value p_{MQB} corresponds to the doping carrier concentration required to satisfy the assumed flat band condition without generating the space charge effect, at a given injection condition p_w . Therefore, lower p_{MQB} value is more desirable. Thus, the layer thickness of MQB should be kept as thin as possible (less than 6ML in case of present SL-MQB). On the other hand, the large hole concentration in MQB miniband described in above item 1) suggests that a large amount of hole pile-up would occur in MQB region. The improved hole injection to active layer of MQW LD through MQB will be discussed in following subsection.

5.3.3 Improved hole injection through MQB

Hirayama et al.[15], have pointed out that a serious non-uniformity in hole density among wells of MQW LDs is caused as the holes have to be injected by drift and diffusion and not via the tunneling through the barriers. Similar hole-pile-up phenomena would occur in MQB if the energy level of the lowest hole miniband of MQB is much lower than the bulk barrier level.

Figure 5.12 a) schematically shows the situation in conventional MQW LDs loaded with MQB at p-side OC layer. Here, thicker layers have been used at closer position to MQW in conventional design of MQB. In this case, $1 \times 10^{18} \text{ cm}^{-3}$ of hole pile up in MQB region is estimated when hole density in MQW well is $3 \times 10^{18} \text{ cm}^{-3}$. If the inhomogeneous injection occurs, the pile up density in MQB would be twice of above value.³²⁾ Such pile up should be avoided as it would cause space charge effect which prevents hole injection and also would cause recombination loss of carriers in MQB.

a) Conventional MQB



b) MQB with improved carrier injection structure

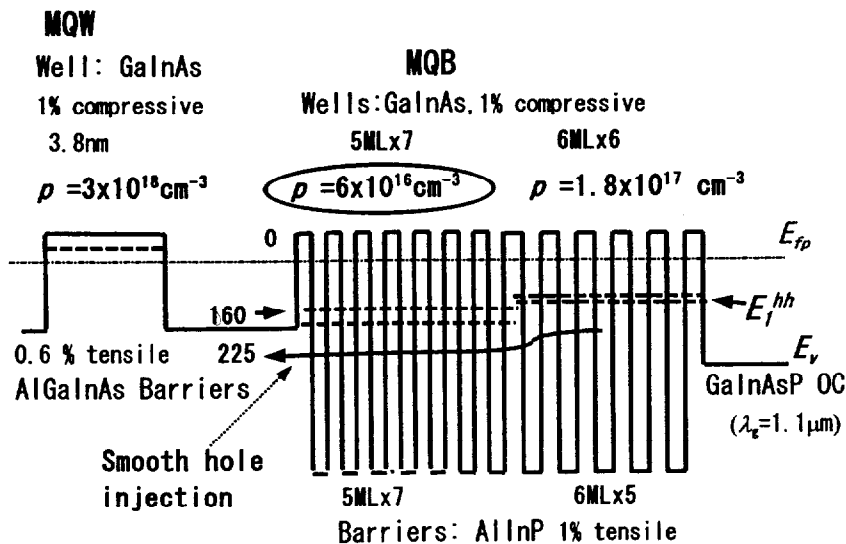


Figure 5.12

Valence band diagrams and hole injection aspects for MQW LDs loaded MQBs at p-side OC layer under lasing condition and flat band assumption. Conventional MQB with large hole density a) and MQB with improved carrier injection and with far less hole density b).

An improved carrier injection method was proposed to avoid such hole blocking phenomena. **Figure 5.12 b)** shows the MQB structure with improved hole injection, where such hole-pile-up can be suppressed. Here thinner layers are used at closer position to MQW to gradually increase the heavy hole sub band energy from p-OC layer side toward MQW active region, which prevents hole blocking by bulk barrier and piling up in MQB region. Estimated hole density in MQB for this case is below middle of 10^{17} cm^{-3} under lasing, flat band condition. Thus reduction of hole density over a figure is expected with this method.

5.4 Summary

As a summary of this chapter, design method for MQB in the application to long-wavelength lasers was discussed and from following improved method was presented.

1) Large effect of nonparabolic dispersion of conduction band on MQB performances was clarified.

For the confinement of higher energy electrons, nonparabolicity was shown to be a key issues.

2) Enhancement of the effective barrier height of MQB by using tensile strained barriers was revealed for the first time. Additional advantages of using strained layers were pointed out in a) adding a possibility of using new strained-layer materials such as AlInP and b) increase design tolerance.

3) Possibility of hole-pile-up in conventional MQB was pointed out. Improved design method of MQB to increase the miniband level toward active region was presented.

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Chapter 6

Barrier Height Enhancement of Quantum Wells by Strained-Layer and Improved Carrier Injection

In this Chapter, suppression of carrier leakage by enhanced barrier height of strained barriers will be discussed. A strain compensated QW with tensile strained barriers will be presented as one of the promising approaches with concrete candidate materials. Carrier injection problem, incidental to the above approach, will be pointed out and improved injection method will also be discussed. Combination of MQB with above approach to suppress the Auger carrier loss will also be discussed. Expected improved performance will be presented.

6.1 Barrier height enhancement in strain-compensated MQW

The advantage of tensile strained barriers on InP such as AlInAs or AlInP with enhanced barrier height (band edge discontinuity) was demonstrated in previous Chapter 5 [1],[2]. Since compressive strained well such as GaInAs on InP has lower band edge levels than those of lattice matched (LM) QW, SC-MQW would further increase the barrier height ΔE_c and ΔE_v [3].

Table 6.1 summarized the band diagrams for combinations of 1 % compressive GaInAs well and three typical barrier materials, LM-AlGaInAs ($\lambda_g=1.15 \mu\text{m}$) a), 0.4 % tensile barrier AlGaInAs ($\lambda_g=1.0 \mu\text{m}$) b) [3] and 1 % tensile barrier AlInP ($\lambda_g=0.8 \mu\text{m}$) c) [4]. Here, case a) is the same structure as described in the experiment in Chapter 3. Model solid theory was adopted for calculation [5],[6]. As shown here, tensile AlInP has the large barrier height both against electrons and against holes.

Table 6.1 Comparison of the barrier height for LM barriers and tensile strained barriers against 1 % compressive strained GaInAs well.

case	barrier	well	ΔE_c (meV)	ΔE_v (meV)
a)	LM- $\text{Al}_x\text{Ga}_y\text{In}_{1-x-y}\text{As}$ ($x=0.24, y=0.24, \lambda_g=1.15\mu\text{m}$)	1%-compressive $\text{Ga}_x\text{In}_{1-x}\text{As}$ ($x=0.32$)	257 (0)	175 (0)
b)	0.4%-tensile- $\text{Al}_x\text{Ga}_y\text{In}_{1-x-y}\text{As}$ ($x=0.33, y=0.2, \lambda_g=1.0\mu\text{m}$)		355 (98)	214 (39)
c)	1%-tensile- $\text{Al}_x\text{In}_{1-x}\text{P}$ ($x=0.14, \lambda_g=0.80\mu\text{m}$)		472 (215)	433 (258)

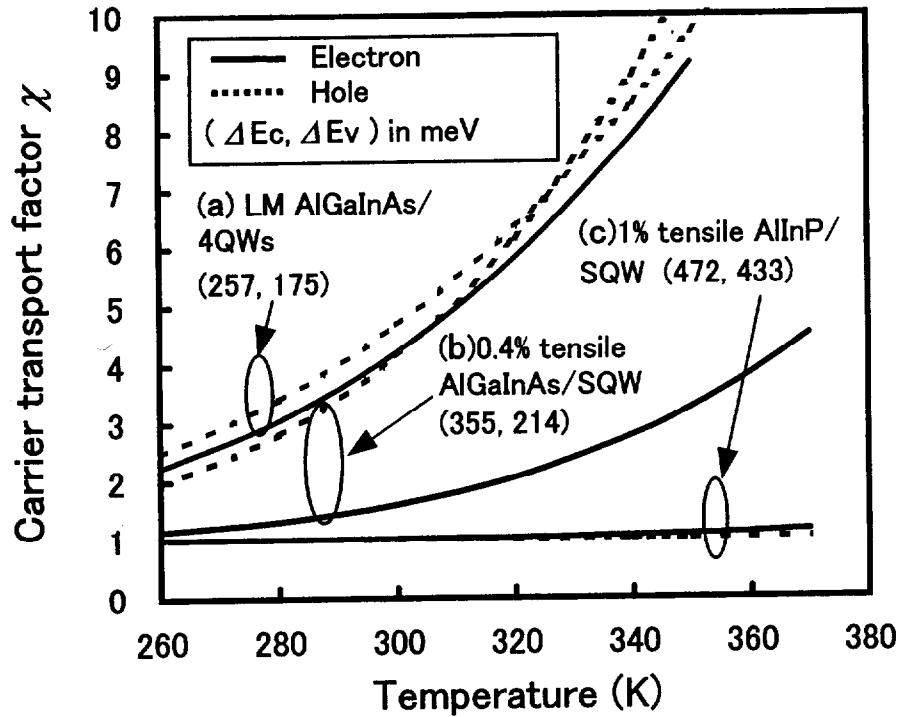


Figure 6.1

Calculated carrier transport factors for three types of LDs with 1% compressive GaInAs QWs and different barrier/SCH structures. In case (a), same structure as present 1% compressive LD was taken as a reference, while in (b) and (c), tensile barriers shown in the figure were assumed. The OC layers in case (b) were assumed to be same as those of (a), and in case (c), $\text{Al}_x\text{Ga}_y\text{InAs}$ ($x=0.4, y=0.075, \lambda_g=0.95\mu\text{m}$), 200nm thick each side was assumed. Well thickness was adjusted to 3.4 nm, 3.9 nm and 4.1 nm for case (a), (b) and (c), respectively, so as to give same lasing wavelength.

Figure 6.1 shows the carrier transport factor χ calculated with Eq.(3-15) as a function of temperature. Here, for case a), 1% compressive MQW LD presented in Chapter 3 was taken as a reference. While for case b) and case c), single quantum well LDs were assumed, since the difficulty in uniform carrier distribution among wells is expected in case of MQW. As shown here, in case c) with tensile AlInP barriers, sufficient reduction of χ is expected, while in case b), estimated reduction is insufficient for hole .

6.2 Carrier pile-up and improved injection through minibands

Figure 6.2 schematically shows the band diagrams for the combination of strain-compensated MQW of case c) in **Figure 6.1** with two types of OC layers, from the viewpoint of examining smooth carrier injection. The model solid theory was adopted for the calculations of band edge energy levels [5],[6]. Here, LM-Q at the OC layer denotes the quaternary material AlGaInAs lattice matched to InP. As shown here, smooth electron injection can be established by adopting $\lambda_g=0.95 \mu\text{m}$ LM-Q for OC layer, since ΔE_c between 1%-tensile AlInP and OC layer is less than kT . While, for hole injection (**Figure 6.2 b**), a high barrier ΔE_v , close to 200 meV is formed at the interface between 1% tensile AlInP and OC-layer. This would cause hole pile-up and subsequent deterioration such as inhomogeneous carrier injection etc.[23].

It should be noted that similar hole transport problem has been reported in GaInAs/AlInAs photo detector (PD), where the tailing phenomenon in high speed pulse response has been attributed to the hole pile up at the heterointerface [7],[8]. It is known that about 50 ps additional switching-off time for PD is imposed due to slow sweep out of piled-up carriers[8]. In the SCH LDs in this study, the carrier diffusion time across the OC layer τ_d is estimated to be in the same order (55ps) and additional increase in τ_d would cause further deterioration in χ value. Thus, the above concerned hole pile-up due to the barrier at the p-OC/1% tensile AlInP barrier interface would cause deterioration not only in DC performances but also in high frequency performances.

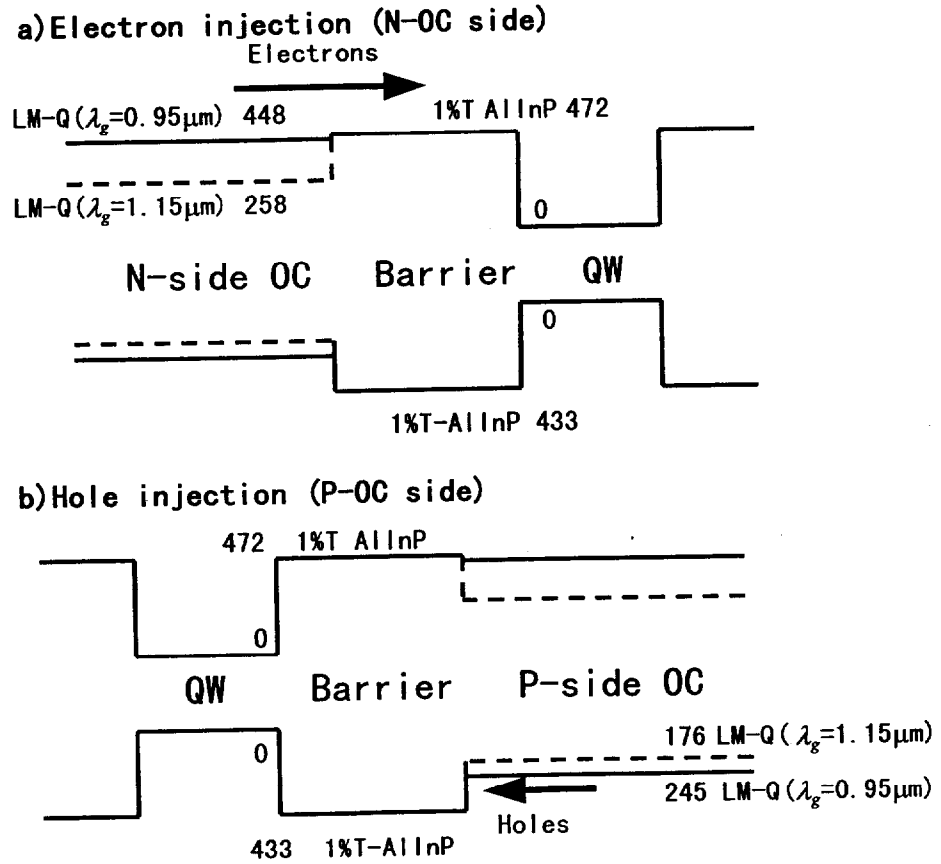


Figure 6.2

Schematic aspect of carrier injection near the heterointerface between the OC layer and 1% tensile AlInP barrier, for electron injection a) and for hole injection b). The OC layer material LM-AlGaInAs was denoted as “Q”.

In order to avoid such hole-pile up phenomenon and enable to utilize the high barrier of strained layer, a combination of barrier height enhancement with strain layer and a new carrier injection through the miniband of superlattice was proposed. **Figure 6.3** shows schematically the concept the combination of carrier injection through the miniband of superlattice and barrier height enhancement with strained layer or with multiquantum barriers(MQB)[2]. As shown here, hole minibands are connected to gradually increase energy level toward the quantum well. When lower band gap material such as $\lambda_g=1.15\mu\text{m}$ LM-Q is used for the OC layer[3], which has advantage in giving higher optical confinement factor, similar injection method would also be useful for electron injection.

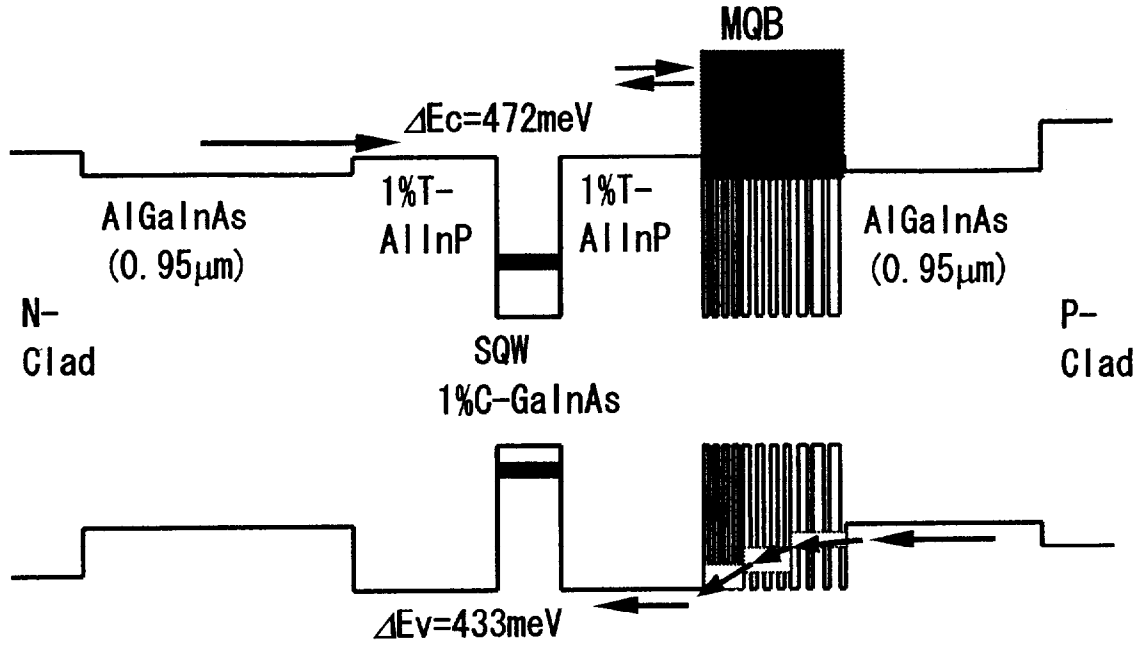


Figure 6.3

Schematic diagram showing the concept of combination of carrier injection through minibands of superlattice and tensile barriers/MQB with enhanced barrier height.

Reduction of Auger carrier loss by the compressive QW has not been fully successful, as described in **Chapter 3**. Along this direction, optimization of strain amount and well size etc. should be further investigated together with correct determination method of Auger coefficient. On the other hand, other reduction schemes are also strongly expected. Essential factor is, by all means, the reduction of threshold well carrier density, since the Auger carrier loss and bimolecular recombination loss is proportional to N_w^3 and N_w^2 , respectively [9]. While, MQB for reflecting and confining Auger hot electrons would also be one of the attractive candidates. In loading MQB to p-side OC layer, MQB could also be above superlattice for smooth hole injection.

6.3 Estimation of improved laser performances

The effective differential gain and threshold current density were estimated for the combination of above presented SC-QW, type c) and LM-OC layers ($\lambda_g=0.95 \mu\text{m}$) assuming smooth carrier injection. As discussed in **subsection 3.4.4**, adoption of equations in **Chapter 3** should be carefully examined, since the charge neutrality condition would not hold in OC layers. From the rate equation Eq.(3-4), electron density in well, N_w^e and one in OC layers $N_{OCp(N)}^e$ are related in DC state with following equation;

$$-R_w - \frac{2N_w^e}{\tau_{ee}} + \frac{V_{oc}}{V_w} \left(\frac{N_{ocn}^e}{\tau_d} + \frac{N_{ocp}^e}{\tau_d} \right) = 0. \quad (6-1)$$

Since, the recombination loss in well, R_w is given by N_w^e/τ_n and $\tau_n(\cong 1 \text{ ns})$ is much smaller than $\tau_{ee}(\cong 10 \text{ ns})$ in present case, the leakage term in above Eq.(6-1) can be neglected and reduces to;

$$-R_w + \frac{V_{oc}}{V_w} \frac{N_{ocn}^e}{\tau_d} = 0, \quad (6-2)$$

where, injection from the p-side OC due to leakage carriers was neglected. Eq.(6-2) gives the simple balance condition between recombination carrier loss rate in QWs and carrier supply rate by injection current. Assuming $N_w^e=2 \times 10^{18} \text{ cm}^{-3}$, $\tau_n \cong 1 \text{ ns}$, $V_{oc}/V_w=200/4.1=48.7$, $\tau_d=56 \text{ ps}$ (i.e., ambipolar diffusion), N_{ocn}^e is estimated to be $2.3 \times 10^{15} \text{ cm}^{-3}$ at 300K. If the diffusion process were not ambipolar, τ_d would be around 5-10 ps for electron and 110 ps for hole respectively, which give N_{ocn}^e of low 10^{14} cm^{-3} region and N_{ocp}^e of near $5 \times 10^{15} \text{ cm}^{-3}$. Thus, we find that the charge neutrality would not be maintained and that carrier loss in OC layer can safely be neglected at present case. Thus, threshold current can be simply expressed as;

$$I_{th} = qV_w(A_w N_w + B_w N_w^2 + C_w N_w^3). \quad (6-3)$$

Figures 6.4 and 6.5 shows calculated results for the effective differential gain g_0/χ and the threshold current density J_{th} as a function of temperature. The defect loss coefficients were assumed to be $A_w=A_{oc}=1 \times 10^8$ /s. HR coating to both facets $R_r/R_f=0.95/0.8$ was assumed. Other characteristics such as, gain, internal loss and bimolecular recombination were assumed to be same as those for type a) described in Chapter 3.

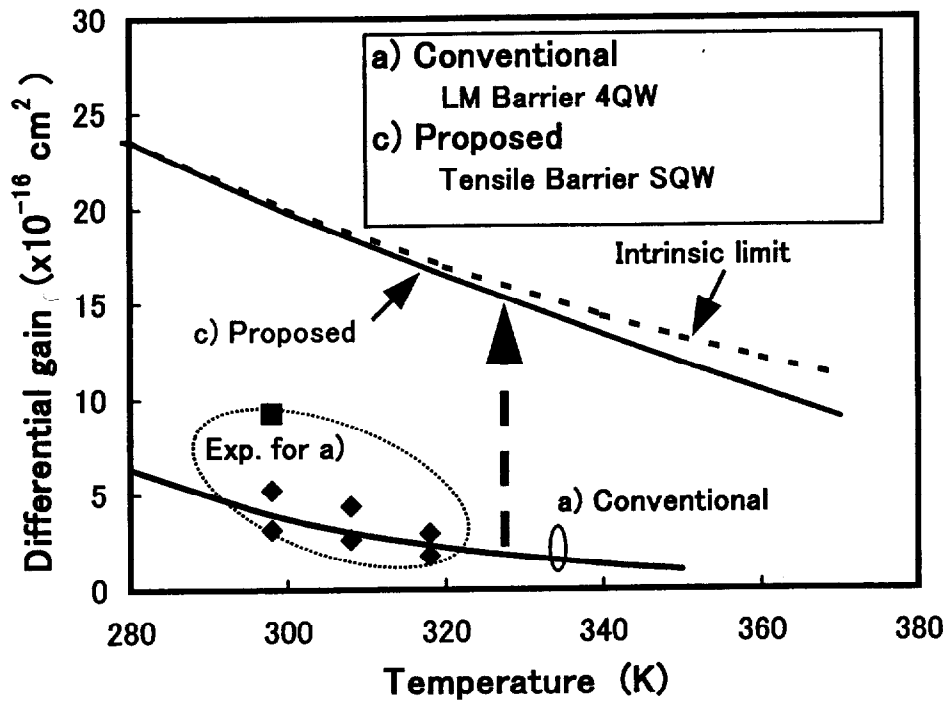


Figure 6.4

Effective differential gain g_0/χ as a function of temperature for SQW-LD shown in Figure 6.3 and in case (c) in Figure 6.1. The barrier height $\Delta E_c=472$ meV and $\Delta E_v=433$ meV was assumed. The 1 % compressive GaInAs well was assumed, where thickness was tuned to 4.1 nm so as to give same 1.5 μ m lasing wavelength as case a). All other fundamental characteristics such as gain and internal loss etc. were assumed same as those for 1% compressive type a) LDs, reported in Chapter 3.

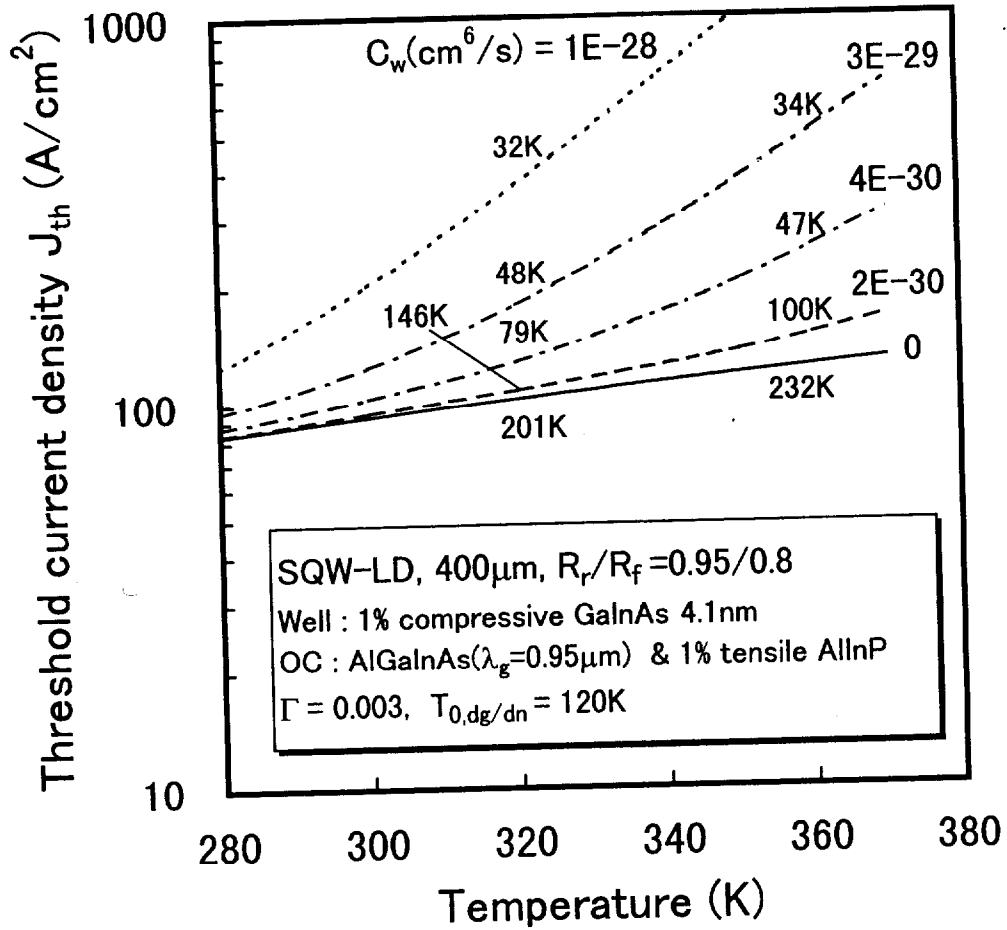


Figure 6.5

Calculated threshold current density as a function of temperature for SQW-LD of case (c) in Figure 6.1. Device parameters are shown in the inset. Defect loss coefficients were assumed to be $A_w=A_{oc}=10^8$ /s. Auger coefficient was taken as a variable parameter.

Following improvements were predicted from above results;

- 1) Deterioration of the differential gain due to the carrier leakage can be almost eliminated (Figure 6-4). The deterioration from the intrinsic value is negligible at 300 K and it is less than 10% even at 360 K. Thus, five time larger differential gain than that of type a) should be available.

2) Threshold current density for LDs would be dramatically reduced. However, the temperature dependence is highly dependent on the Auger coefficients. If the Auger coefficients is reduced down to less than $2 \times 10^{-30} \text{ cm}^6/\text{s}$, the characteristic temperature should be around 150 K and it increases to 200 K at zero Auger limit. Thus, it was confirmed again that the sufficient reduction of both the thermionic carrier leakage and the Auger carrier loss is the vital approach to realize the high T_0 performance.

6.4 Summary

As a summary of this Chapter, suppression of carrier leakage by enhanced barrier height by strain effect was discussed. Followings were clarified.

1) A large enhancement effect of barrier height in the combination of tensile barrier and compressive QW on InP was clarified. A strain compensated (SC) QW with 1 % tensile-strained barrier and compressive GaInAs was shown to have an enough high barrier height over 400 meV to eliminate the carrier leakage effect.

2) Carrier pile-up problem due to the band edge discontinuity at the interface between the OC layer and the AlInP barrier was pointed out. Improved carrier injection through minibands of superlattice with gradually enhanced energy levels was presented. Combination of MQB with above superlattice was also presented as a method to suppress the Auger carrier loss.

3) Effects of above enhanced barrier height over 400 meV were calculated with the improved theory described in chapter 3. Remarkable five time larger effective differential gain was predicted, which corresponds reduction of the chirping down to one fifth in case of DFB LDs. Temperature sensitivity was estimated largely dependent on Auger carrier loss and a high characteristic temperature over 150 K was estimated for the reported theoretical Auger coefficient $2 \times 10^{-30} \text{ cm}^6/\text{s}$.

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Chapter 7

Design Consideration for Further Improvement and Future Prospects

Causes for the serious deterioration in the performances of strained quantum well lasers have been revealed in this study. Feasible approaches for improvement have also been proposed. By overcoming the deterioration due to the carrier dynamics effect, dramatic improvement of the performance can be expected. In this chapter, progresses in strained quantum well lasers after the start of this study are overviewed and design considerations for further improvement are summarized focusing on the carrier dynamics related issues. Then, future prospects on the possible applications of this study will be described.

7.1 Progress in strained quantum well lasers after the start of this study

Table 7.1 summarizes the progress in strained quantum well lasers after the start of this study, focusing on the carrier dynamics related issues. As shown here, adoption of the tensile barrier Al(Ga)InAs proposed in this study in 1992 in order to enhance the barrier height and to suppress the carrier leakage, has become one of the essential constituents in the design of strained quantum well lasers. Demonstration of high differential gain in AlGaInAs strained MQW LDs in this study in 1994 led up the recent high temperature LDs with the characteristic temperature over 120 K in the same material systems. Demonstration of MQB for long-wavelength lasers in AlGaInAs material system in 1995 in this study has also been succeeded to recent high temperature LD with tensile-barrier strain compensated MQB.

Table 7.1 Progress in strained quantum well lasers and in carrier dynamics related issues after the start of this study

Legend :		
Topics from other groups		<i>This study</i>
Year	Strained Quantum Well Lasers	Carrier Dynamics Related Issues
1991	Prediction on high differential gain in strained QW (I. Suemune)	Carrier transport theory in long-wavelength quantum well LDs (UCSB*)
1992		<i>Proposal on barrier height enhancement of MQB by tensile strained barriers (this)</i>
1993		-Low T_0 attributed to temperature sensitivity of differential gain (Zou, Ackerman) -Auger coefficients for strained QW LDs (Adams, Fuchs, Wang)
1994	<i>High differential gain in compressive strained AlGaInAs 1.5 μm QW LDs (this)</i>	<i>Carrier dynamics effect in compressive strained AlGaInAs 1.5 μm QW LDs (this)</i>
1995		<i>Demonstration of improved performance in MQB loaded strained AlGaInAs 1.5 μm QW LDs (this)</i>
1997		
1998	Tensile-barrier strain-compensated AlGaInAs QW LDs with high T_0 (Ortel, Fujitsu, NEC, Oki, National Tsing Hua Univ.)	Strain compensated GaInAs/GaInP MQB (TIT**)
1999	Tensile-barrier strain-compensated AlGaInAs QW LDs with tensile-barrier MQB (TIT**)	<i>Tensile AlInP barrier MQW LDs loaded MQB with improved carrier injection structure (this)</i>
2000		<i>Improved theory for carrier dynamics in QW LDs (this)</i>

* UCSB ; University of California Santa Barbara, Professor Bowers group.

** TIT ; Tokyo Institute of Technology, Professor Iga group.

7.2 Design considerations for further improvements

Figure 7.1 summarizes key issues in overcoming the carrier dynamics effect and relating factors and directions for further improvement of strained quantum well lasers. The key issues could be summarized as; 1)reduced carrier leakage from quantum wells to optical confinement layers, where larger carrier leakage lifetime and shorter time for carrier injection from the cladding layers to the quantum wells are essentially important, 2)reduced carrier loss in the optical confinement layers, 3)reduced absorption loss in the optical confinement layers, 4)reduced defect loss in quantum wells and 5)reduced Auger carrier loss. As shown in **Figure 7.1**, there are factors in the trade-off relation for all thickness factors, well thickness L_w , total well thickness NL_w , and thickness of optical confinement layer L_{oc} . This indicates the existence of the optimum conditions and at the same time the limitation of improvement by the optimization of those amounts. On the other hand, no trade-off relations are accompanied in following approaches; a)enhancement of the barrier height E_b by the strain effect or by MQB effect or by a new material system and b)hole injection improvement by superlattice or new material (with larger hole mobility). Thus, those approaches would bring the essential improvement. For reducing the Auger carrier loss, there would still be a possibility to lower the Auger coefficient by optimizing the strain, although the reduction of threshold carrier density is essentially important. It should be noted that suppression of leakage by the enhancement of the barrier height would increase the difficulty in homogeneous injection of carriers to multiquantum wells. Higher the barrier height, fewer the well number would be desirable from the point of view of uniform carrier injection. Regarding the above issue 3), large intrinsic differential gain is essential also in reducing the deterioration in slope efficiency due to the absorption loss in OC layers, as shown in **Figure 3.13**.

The proposed combination of tensile barrier/compressive well MQW and carrier injection through the minibands would be one of the most promising solutions to overcome the deterioration due to the carrier dynamics phenomena in long-wavelength strained quantum well lasers. The MQB, optimized with improved design would also effective in suppressing the hot-electron leakage. As shown in **Figure 6.4**, over five times-larger differential gain than

those so far reported is expected. The large differential gain would realize LDs with ultra narrow linewidth, small wavelength-chirp and large bandwidth, which are essential for the applications. It would also be essential for high power lasers in realizing a) larger slope efficiency at high injection condition and b) lower internal loss by adopting thinner total active layer thickness, both brings larger saturation power.

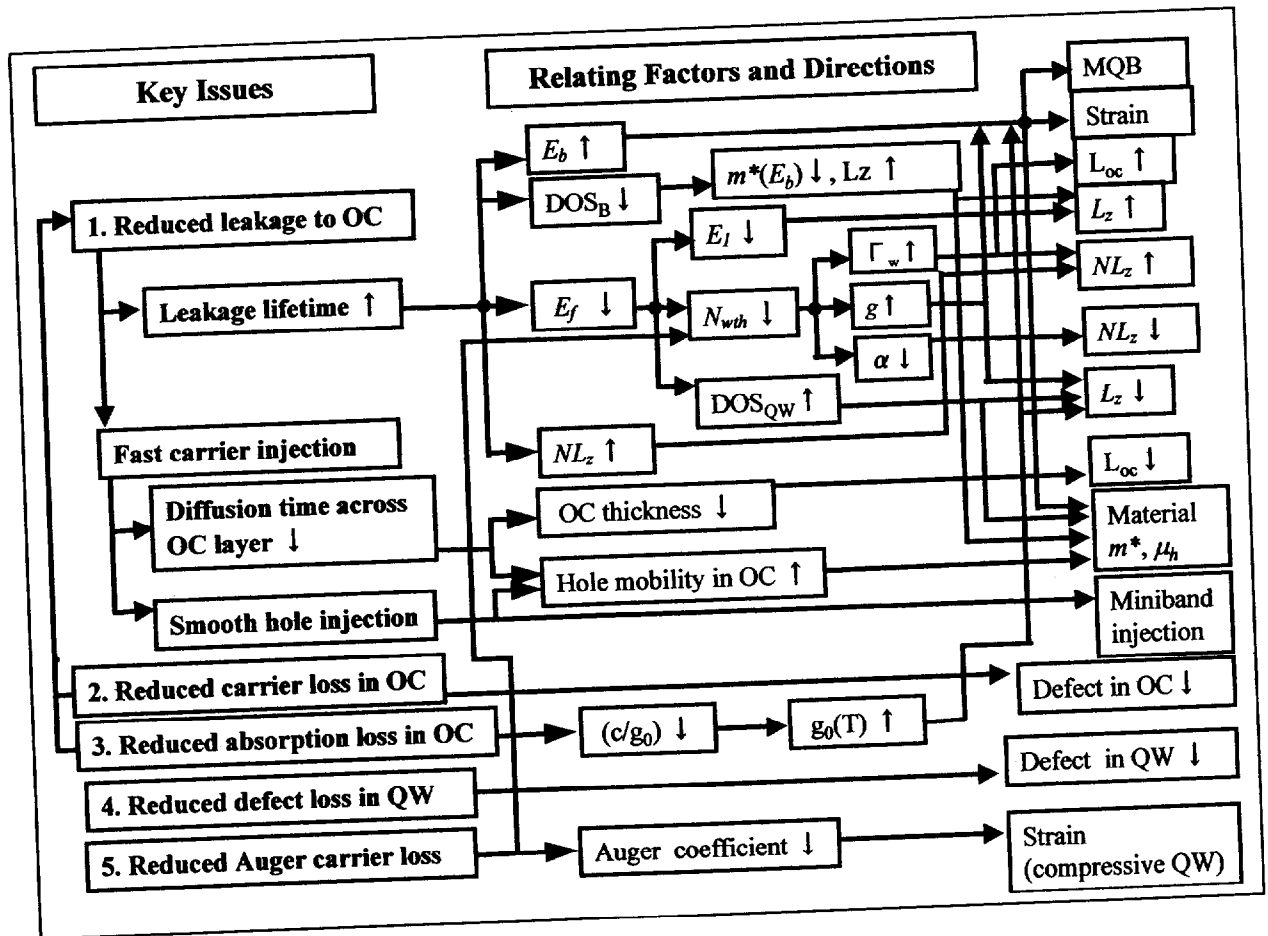


Figure 7.1

Key issues in overcoming the carrier dynamics effect, relating factors and directions for improvement of strained quantum well lasers.

7.3 Future prospects

Explosive spread of the Internet has been pushing up the required capacity of fiber-optic networks to over 1 Tbps region. D-WDM has been one of the most attractive solutions for such high capacity transmission. Bit through rate capacity of 40Gbps x 40 channels/fiber (1.6 Tbps/fiber) has already been realized. D-WDM technology is now evolving from trunk lines to metropolitan networks, where the D-WDM ring networks with wavelength allotted optical add/drop multiplexing (OADM) nodes would be adopted and those rings would be connected to each other via the OADM. Thus, D-WDM would evolve from “lines” to “surface” in future.

In such future networks, further advanced devices would be required. Those would include a)wavelength tunable lasers, b)fast speed wavelength converters, c)large scale optical switches and so on. In realizing those advanced quantum effect devices, quantum wire or quantum dot devices[1] and the electron wave interference devices[2]-[8] would be the noticeable candidates. They will bring not only ultra fast switching operations[3] but also further novel functions such as optical bistable switch[4],[5],[6], multi-channel switch[6] or memory device[8]-[9]. Resonant Tunneling Diodes(RTD)[2],[10] is recently emerging as one of the key devices for future generations of high performance microwave and optoelectronic system. Resonant-tunneling photodiode, which can be optically switched at low power and at 2Gb/s has also been demonstrated. For such application of photodiode to photonic IC, the waveguide type photodiode would be a promising solution, on which a low dark current and high reliability performances have also been demonstrated recently[11]. Superlattice as an energy filter for the electron wave would be a basic concept in those resonant-tunneling devices. The knowledge of barrier height and miniband control including strained superlattice, developed in this study would also contribute to the progress in such devices. Integration of those optical devices would realize the next generation devices such as ultra fast optical-optical switching devices for optical communications and optical signal processing.

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Chapter 8

Conclusions

Large discrepancy between the theoretical predictions and experiments on the performances of recent strained quantum well lasers had been reported and recognized as the bottleneck for further improvements. This dissertation described the study on the causes of the discrepancy and on possible solutions for improvements. Results obtained in this study are summarized as follows;

1) Identifying the mechanism of the discrepancy and obtaining directions for improvement.

1.a) Evaluation of the discrepancy and effects of carrier dynamics in 1.5- μm -wavelength quantum well lasers.

Large discrepancy between experiments and theoretically predicted values was confirmed through characterization of AlGaInAs/GaInAs long-wavelength multiquantum well lasers. Adopting conventional carrier transport theory, it was confirmed that discrepancy can be explained qualitatively as the deterioration due to the carrier dynamics phenomena, i.e., carrier leakage and diffusion delay effect. However, it was also pointed out that conventional theory predicts too large deterioration to analyze the deterioration mechanism and to derive directions for improvements.

1.b) Analysis on effects of carrier dynamics and the causes of the discrepancy.

Improved theory on the carrier dynamics effect was presented and confirmed to well explain the discrepancy. Good agreements with the experimental results were confirmed for the differential gain, carrier lifetime measurement, threshold current density and its temperature sensitivity, K factor and its temperature sensitivity. The causes of the discrepancy were analyzed with the theory and revealed that the discrepancy was attributed to the deterioration due to the thermionic carrier leakage of both electrons and holes, and the Auger carrier loss. The differential gain was shown deteriorated by the thermionic leakage of

electrons and holes from QWs to the optical confinement layers. While, the temperature sensitivity of threshold current was shown doubly deteriorated by Auger carrier loss and thermionic carrier leakage, where, large contribution of carrier loss in the optical confinement layers and hole leakage were pointed out. Thus, it was shown theoretically that high differential gain and high temperature stability could be realized by suppressing those two carrier loss processes. The intrinsic gain characteristic was shown to have little influence on temperature sensitivity of LDs.

1.c) Deriving directions for further improvements.

From above discussions, directions for further improvements were derived. The key issues are summarized as; (1) reduction of carrier leakage from quantum wells to optical confinement layers, where larger carrier leakage lifetime and shorter time for carrier injection from the cladding layers to the quantum wells are essentially important, (2) reduction of carrier loss in the optical confinement layers, (3) reduction of optical absorption loss in the optical confinement layers, (4) reduction of defect loss in quantum wells and (5) reduction of Auger carrier loss.

2) Presenting effective methods to overcome the discrepancy and to improve the laser performances.

2.a) Verifying the effectiveness of multi-quantum barriers in long-wavelength lasers and presenting improved design methods.

The improvements of laser performance and direct evidence of carrier leakage suppression were confirmed in 1.5 μm -wavelength GaInAs/AlGaInAs strained quantum well LDs with multi-quantum barriers loaded at the optical confinement layer in following points. (1) Reduction in K factor more than 30 % at high temperature, which corresponds to improvement in effective differential gain (g_0/χ) over 40 %. (2) Increase of maximum operating temperature by 15 degrees C and large increase of slope efficiency at high temperatures, although increase of characteristic temperature T_0 was slight. (3) As an evidence of suppression of carrier leakage, reduction of spontaneous emission from OC layer by 2.5 dB

was confirmed. From the reduction rate, the enhanced barrier height by MQB was estimated larger than 210 meV and near 90 % of leakage electrons were suppressed by MQB.

From the viewpoint of improving design method of MQB, the following points were investigated and improved methods were presented. (1)Effect of conduction band nonparabolicity upon reflection performance of MQB was investigated theoretically for the first time. A significant narrowing of the second stop band of MQB due to the nonparabolicity was confirmed. Thus, importance of taking into account the band nonparabolicity in MQB design was clarified. (2)Hole transport in MQB was discussed based on analysis of miniband and density of states for valence band of MQB. An improved design concept of MQB to prevent such hole-pile up was presented. (3)The barrier height enhancement of MQB by adopting tensile strained barrier was examined and proposed for the first time.

2.b)Evaluation of barrier height enhancement effect by strained layers and of incidental problem in carrier injection.

Large enhancement effect in 1–1.5 % tensile strained AlInAs barrier or AlInP barrier was confirmed. An inherent advantage of AlInP in low aluminum content compared to AlInAs was pointed out. From the viewpoint of smooth carrier injection, hole pile-up problem incidental with this approach was also pointed out.

2.c)Presenting an improved carrier confinement and injection method utilizing strain effect and superlattices.

A combination of 1% tensile AlInP barrier and 1% compressive GaInAs was presented and was shown to have high barrier heights $(\Delta E_c, \Delta E_v) = (472 \text{ meV}, 433 \text{ meV})$ and long enough carrier leakage lifetime. An improved carrier injection method was presented for SCH-LDs with the high tensile barriers as described above. Carrier injection through the minibands with gradually enhanced energy levels toward QWs was presented.

Improvement of the key characteristics for the above strain-compensated AlInP/GaInAs QW with high barrier height $(\Delta E_c, \Delta E_v) = (472\text{meV}, 433\text{meV})$ was calculated with improved theory assuming smooth carrier injection. Remarkable five times enhancement of differential gain at 300K was estimated as a result of almost complete suppression of carrier leakage. The

characteristic temperature T_0 was shown to largely depend on the Auger coefficient, where T_0 around 150 K was predicted by reducing C_A down to the theoretical value, 2×10^{-30} cm⁶/s.

Quantum wire or quantum dot lasers and further novel function devices such as optical switches utilizing electron wave interference are emerging as the key devices for future photonic networks. In those devices, efficient carrier injection and confinement would be more significant due to less filling factors. Superlattice as energy filter for electrons would be one of the essential constituents for those devices. Control of heterobarrier height and minibands of superlattice would be a key issue in realizing full intrinsic performances of those advanced quantum effect devices. The author hopes that the guidelines and knowledge developed in this study could contribute to the progress of such device technology.

Appendix

Appendix 1: Derivation of E - k dispersion relation from $k \cdot p$ method

In $k \cdot p$ method, Schrödinger equation for the perturbed system including the spin-orbital interaction is expressed as;

$$(H_0 + H' + H_{SO})u_{nk}(\mathbf{r}) = \lambda u_{nk}(\mathbf{r}), \quad (\text{A1})$$

where,

$$\lambda \equiv E_{nk}(\mathbf{k}) - \frac{\hbar^2 k^2}{2m}, \quad (\text{A2})$$

$$u_{nk}(\mathbf{r}) = \sum_{i,j} u_i(\mathbf{r}) s_j, \quad (\text{A3})$$

$$H_0 = -\frac{\hbar^2}{2m} \nabla^2 + V(\mathbf{r}), \quad (\text{A4})$$

$$H_{SO} = \frac{\mu_0}{4\pi} \frac{Ze^2}{2m} \frac{1}{r^3} (\mathbf{l} \cdot \mathbf{s}) \quad (\text{A5})$$

where, $u_{nk}(\mathbf{r})$ represents the Bloch eigenfunctions for the perturbed system consisting of two conduction bands and six valence bands involving spin functions, $u_i(\mathbf{r})s_j$ represents base functions for the unperturbed system, λ , the eigenvalues for the perturbed eigenstates, H_0 denotes unperturbed Hamiltonian, H' , the $k \cdot p$ perturbation term, H_{SO} , the spin-orbital interaction term.

The 8x8 secular matrix equation is doubly degenerated and reduced to 4x4 matrix equation to be expressed as follows when $k_x=k_y=0$ and $k_z=k$;

$$\begin{vmatrix} (E_c - \lambda) & 0 & \sqrt{\frac{2}{3}}Pk & \frac{1}{\sqrt{3}}Pk \\ 0 & (E_v + \frac{\Delta_0}{3} - \lambda) & 0 & 0 \\ \sqrt{\frac{2}{3}}P^*k & 0 & (E_v + \frac{\Delta_0}{3} - \lambda) & 0 \\ \frac{1}{\sqrt{3}}P^*k & 0 & 0 & (E_v - \frac{2\Delta_0}{3} - \lambda) \end{vmatrix} = 0, \quad (\text{A7})$$

where, the base function set is as follows;

$$|u_c\alpha\rangle = |Y_0^0\alpha\rangle, \quad (\text{A8})$$

$$|u_{v1}\beta\rangle = |Y_1^{-1}\beta\rangle, \quad (\text{A9})$$

$$|u_{v2}\alpha\beta\rangle = \sqrt{\frac{2}{3}}|Y_1^0\alpha\rangle + \frac{1}{\sqrt{3}}|Y_1^1\beta\rangle, \quad (\text{A10})$$

$$|u_{v3}\alpha\beta\rangle = \frac{1}{\sqrt{3}}|Y_1^0\alpha\rangle - \sqrt{\frac{2}{3}}|Y_1^1\beta\rangle, \quad (\text{A11})$$

$$|u_c\beta\rangle = |Y_0^0\beta\rangle, \quad (\text{A12})$$

$$|u_{v1}\alpha\rangle = |Y_1^1\alpha\rangle, \quad (\text{A13})$$

$$|u_{v2}\beta\alpha\rangle = \sqrt{\frac{2}{3}}|Y_1^0\beta\rangle + \frac{1}{\sqrt{3}}|Y_1^{-1}\alpha\rangle, \quad (\text{A14})$$

$$|u_{v3}\beta\alpha\rangle = \frac{1}{\sqrt{3}}|Y_1^0\beta\rangle - \sqrt{\frac{2}{3}}|Y_1^{-1}\alpha\rangle, \quad (\text{A15})$$

and where, E_c , E_v is the unperturbed eigenenergy for the conduction band and that for the valence band, respectively, Δ_0 is the spin-split off energy of the valence band given by following spin-orbital interaction integral,

$$\Delta_0 = 3\langle u_{v1}\beta | H_{SO} | u_{v1}\beta \rangle = -\frac{3}{2}\langle u_{v3}\alpha\beta | H_{SO} | u_{v3}\alpha\beta \rangle, \quad (\text{A16})$$

and where, P is an interaction integral between the conduction band and valence bands given by following equation,

$$P \equiv -\frac{i\hbar^2}{m} \langle Y_0^0 | -\frac{i\hbar^2}{m} \frac{\partial}{\partial z} | Y_1^0 \rangle, \quad (\text{A17})$$

$$|P|^2 = \frac{\hbar^2}{2} \left(\frac{1}{m_c^*} - \frac{1}{m} \right) \frac{E_g (E_g + \Delta_0)}{\left(E_g + \frac{2}{3} \Delta_0 \right)}. \quad (\text{A18})$$

From the secular equation (A7), following equation is derived;

$$(\lambda - E_c) \left(\lambda - E_v - \frac{\Delta_0}{3} \right) \left(\lambda - E_v + \frac{2}{3} \Delta_0 \right) - |P|^2 k^2 \left(\lambda - E_v + \frac{1}{3} \Delta_0 \right) = 0. \quad (\text{A19})$$

Here we focus on the conduction band and define energy E as;

$$E \equiv \lambda - \left(E_v + \frac{\Delta_0}{3} \right). \quad (\text{A20})$$

Then, following quadratic equation is derived.

$$E^2 - E_g E - |P|^2 k^2 \frac{\left(E + \frac{2}{3} \Delta_0 \right)}{(E + \Delta_0)} = 0, \quad (\text{A21})$$

where, $E_g \equiv E_c - (E_v + \Delta_0/3)$ is the band gap energy for the perturbed states. Solving above quadratic equation on E , following dispersion relation $E_c(k)$ for the conduction band is obtained,

$$E_c(k) = E - E_g + \frac{\hbar^2 k^2}{2m}$$

$$= \frac{\hbar^2 k^2}{2m} + \frac{1}{2} \left\{ -E_g + \left[E_g^2 + 2\hbar^2 k^2 \left(\frac{1}{m_c^*} - \frac{1}{m} \right) \frac{E_g(E_g + \Delta_0) \left(\Delta E_c + E_g - \frac{\hbar^2 k^2}{2m} + \frac{2}{3} \Delta_0 \right)}{\left(E_g + \frac{2}{3} \Delta_0 \right) \left(\Delta E_c + E_g - \frac{\hbar^2 k^2}{2m} + \Delta_0 \right)} \right]^{\frac{1}{2}} \right\}$$

(A22)

Here, parabolic relation near the band edge is confirmed as;

$$E_c(k) = \frac{\hbar^2 k^2}{2m_c^*} \quad (k \rightarrow 0) \quad (A23)$$

Appendix 2: Density of states (DOS) for superlattice and hole concentration as a function of quasi-Fermi level

The DOS of superlattice (SL) is derived here. Following prepositions are assumed; 1) the width of miniband is smaller than the energy separations between the subbands of SQW and 2) only the next-neighbor couplings of wave functions is dominating. The dispersion relation for the perpendicular motion of carriers in miniband of SL is given as [1][2];

$$E_{perp} = E^{SQ} - \Delta_1 - \Delta_2 \cos(kd), \quad (A24)$$

where, E^{SQ} is the corresponding subband energy for the SQW, Δ_1 is a positive constant, Δ_2 denotes the half width of the miniband, $d \equiv L_w + L_b$ is the period of SL. Then, the DOS for SL $g_{SL}(E)$ is derived for energy region within the miniband, from following area integration;

$$\begin{aligned}
 g_{SL}(E)dE &= \int_{E_a}^E g_{perp}(E_{perp})dE_{perp} \int_{E-E_{perp}}^{E-E_{perp}+dE} g_{para}(E_{para})dE_{para} \\
 &= \int_0^k \frac{L}{\pi} dk \left(\frac{m_{para}^* L^2}{\pi \hbar^2} dE \right) \\
 &= \frac{m_{para}^* L^3}{\pi^2 \hbar^2 d} \cos^{-1} \left(\frac{E^{SQ} - \Delta_1 - E}{\Delta_2} \right) dE.
 \end{aligned} \tag{A25}$$

Noticing that the same DOS for two-dimensional in-plane motion as SQW appears above the miniband energy, following equation for DOS of SL per unit volume ($L^3=1$) for each energy range is derived as;

$$g_{SL}(E) = \sum_i \frac{m_w^{*i}}{\pi^2 \hbar^2 d} \begin{cases} 0, & 0 \leq E \leq E_{ia}, \\ \cos^{-1} \left(1 - 2 \frac{E - E_{ia}}{E_{ib} - E_{ia}} \right), & E_{ia} \leq E \leq E_{ib}, \\ \pi, & E \geq E_{ib}, \end{cases} \tag{A26}$$

where, the effective in-plane mass for i -th miniband of SL was approximated by the in-plane effective mass of carrier in the well layer m_w^{*i} and where E_{ia} and E_{ib} denotes the low edge energy, high edge energy for the i -th miniband, respectively.

Using equation (A26), averaged hole concentration in SL is given by following equation as a function of quasi-Fermi level for hole E_{fp} ;

$$P = \sum_i \int_{E_i}^{E_b} g_{sl}(E) f(E) dE + \frac{L_w}{d} \int_{E_b}^{\infty} g_b^{wel}(E) f(E) dE + \frac{L_b}{d} \int_{E_b}^{\infty} g_b^{bar}(E - E_b) f(E) dE \quad (A27)$$

where,

$$\begin{aligned} g_b^{wel}(E) &= \frac{1}{2\pi^2} \left(\frac{2m_w^*}{\hbar^2} \right)^{\frac{3}{2}}, \\ g_b^{bar}(E) &= \frac{1}{2\pi^2} \left(\frac{2m_b^*}{\hbar^2} \right)^{\frac{3}{2}}, \\ f(E) &= \frac{1}{1 + \exp\left(\frac{E - E_{fp}}{k_B T}\right)}, \end{aligned} \quad (A28)$$

and where $g_b^{wel}(E)$ and $g_b^{bar}(E)$ denotes the bulk DOS for well and barrier material respectively, $f(E)$, the Fermi-Dirac distribution. In the calculation using equation (A26), only $i=1$ miniband for heavy hole and that for light hole were taken into account for energy range smaller than the barrier height E_b . Further, the DOS was approximated to be constant in the miniband energy region for simplicity, i.e., following approximation was applied;

$$\cos^{-1}\left(1 - 2 \frac{E - E_{ia}}{E_{ib} - E_{ia}}\right) \approx \frac{\pi}{2}, \quad \text{for } E_{ia} \leq E \leq E_{ib}. \quad (A29)$$

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Publication List

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D. Patents

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