Effect of Strained Quantum Wells of Enhanced Performance for Quantum Well Lasers in Direct Modulation

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Abstract

Strained-layer quantum wells are interesting for applications in semiconductor lasers , because they allow both, a wider range of material combinations, and a certain amount of band structure and gain engineering. This layer is effected on frequency shift of the gain spectrum ,but gain increase also possible. The major advantages of strained quantum wells in the modulated quantum well lasers diodes are a very high modulation speed, a low frequency chirp (α-parameter) , a narrow line-width, and a low threshold carriers concentration. Strained quantum well lasers are better than the semiconductor lasers , which have a modulation band-width in upper teens and low twenties of gigahertz.

I. Introduction

A strained quantum wells is very important in a direct modulated quantum well lasers which this strains are applied to semiconductor crystals, symmetry of the crystals is reduced, and degeneracy of the energy bands is removed [1]. According to the compressive or tensile strains, the band structures change in different ways. Based on this principle, band-structure engineering, which modifies the band structures by intentionally controlling the strains, has been developed [2]. By introducing the strains into the active layers, we can obtain excellent characteristics, such as a low threshold current, a high differential quantum efficiency, high-speed modulation, low chirping, and a narrow spectral line width in semiconductor lasers, as in the quantum well laser diodes[1,2].

II. Theory and analysis

A. Resonance frequency analysis of semiconductor laser:

The analysis of the dynamic behaviour of semiconductor laser starts from the interaction between photon number and carrier number [3, 4].

$$\frac{dN}{dt} = \frac{J}{ed} - \frac{N}{\tau_S} - vg(N)S \qquad (1)$$

$$\frac{dS}{dt} = \Gamma vg(N)S - \frac{S}{\tau_P} + \beta R_{SP} \qquad (2)$$

Where N is the carrier density, S is the photon density in a mode of the laser cavity , Γ is the optical confinement factor, J is the pump current density, d is the thickness of the active region, τ_S is the recombination lifetime of the carriers, τ_P is the photon lifetime, g(N) is the optical as a function of the carrier density, v is the group velocity($v = c/\mu_g$),c is the light speed, μ_g is the group refractive index, β is the fraction of spontaneous emission entering the lasing mode, R_{SP} is the spontaneous emission rate, and e is the electronic charge. When optical gain is normalized ($G = vg$) where g is the gain at lasing frequency, therefore, at steady state g(N) become [4]

$$G(N) = \frac{G_0 + G^{/} n}{1 + \varepsilon S} \qquad (3)$$

Where $G(N)$ is the normalized optical gain as a function of the carrier density at steady state, $G^{/}$ is the normalized differential optical gain i.e. $\left[G^{/} = \frac{\partial G}{\partial N} \right]$,G_0 is average optical gain , n is the small signal deviation of the electron density from the steady state value, and ε is the gain compression , εS , is very small compared with 1 even at very high optical power . A small signal analysis of the rate equations gives the following modulation response function for the photon density:

$$S(\omega)=\Gamma G^{/} S_0 (J/ed) f(\omega) \quad \text{4a}$$

Where

$$f(\omega)=[(i\omega+\beta R_{SP}/S_0+\varepsilon S_0/\tau_P) \times (i\omega+1/\tau_S+G^{/} S_0)]+\frac{G^{/} S_0}{\tau_0 (1+\varepsilon S_0)} \quad \text{4b}$$

Where $S(\omega)$ is the small signal photon density, S_0 is the average photon density, J is the small signal modulation current. , and under the assumption of a small ε the resonance frequency is approximately given by

$$\omega_r=\sqrt{\frac{G^{/} S_0}{\tau_P}}=\sqrt{\frac{vg^{/} S_0}{\tau_P}} \quad \text{5}$$

The photon lifetime is related to the optical gain ($1/\tau_P=\Gamma vg=\Gamma G$), therefore, the relaxation oscillation frequency is

$$f_r=\frac{1}{2\pi} v\sqrt{\Gamma g g^{/} S_0} \quad \text{6}$$

The product quantity ($gg^{/}$) is very important, which the differential optical gain is related with line-width enhancement factor [$\alpha=-2k_0(\frac{\partial\mu/\partial N}{\partial g/\partial N})$], where μ is refractive index ,k_0 is the vacuum wave number, $\frac{\partial g}{\partial N}$ is the differential optical gain ($g^{/}$), and $\frac{\partial\mu}{\partial N}$ is depended on the joule heating of the active layer [5].Therefore, by using k-selection rule[5], the gain is

$$g(E)=-\frac{e^2 h}{2\in_0 m_0^2 c\bar{\mu}E} \times\int_{-\infty}^{\infty}\{\rho_C(E_C)\rho_V(E_C+E_V)|M|^2 \times[1-f_V(E_C+E_V)-f_C(E_C)]\}dE_C \quad \text{7}$$

Where $\xi=\frac{\hbar e^2|M|^2}{2\in_0 m_0^2 c\bar{\mu}E}$ is a material parameter, m_0 is the free electron mass ,c is the speed of light in vacuum, $\bar{\mu}$ is the effective refractive index of the mode and $|M|^2$ is the transition matrix element , $\hbar=h/2\pi$, h is plank's constant, $E=\hbar\omega-E_g=E_C+E_V$, E_C and E_V and ρ_C and ρ_V are , for the conduction and valence bands respectively , the densities of states per units volume per unit energy . f_C and f_V are fermi-dirac probability function for conduction and valence bands as shown in Table (1)[5].Table (2) shows the parameters values of 1.3µm Burid Letero structure laser[4].

B. Strained Quantum wells

To understand why, we need to examine the effects of strain, particularly in a quantum well. Introducing compressive strain into a quantum well configuration is particularly simple [7]: just grow the well layer out of a material with a larger native lattice constant than the barrier layers. Because the quantum well layer is typically very thin, instead of forming misfit dislocations the lattice actually compresses in the plane of the well to match that of the barrier layers [6, 7]. In addition, the lattice constant in the direction normal to the plane becomes elongated (in an effort to keep the volume of each unit cell the same), as shown in Fig. 1[6].Because the energy gap of a semiconductor is related to its

Table(1)
The densities of states and fermi-dirac probability function for conduction and valence bands ,and Nc and N_V expressions [5]

Parameter	Expression
Fermi-Dirac probability function for conduction band	$f_C(E_C)=\frac{n}{N_C}e^{(-\frac{E_C}{KT})}$
Fermi-Dirac probability function for valence band	$f_V(E_V)=\frac{P}{N_V}e^{(-\frac{E_V}{KT})}$
Density of State for conduction band	$\rho_C(E)=4\pi(\frac{2m_C}{h^2})^{3/2}E^{1/2}$
Density of State for valence band (ρ_{Vj})	$P=\sum_{i=l,h}\int\frac{\rho_{Vj}(E)dE}{1+e^{\frac{E-E_V}{KT}}}$
N_C	$2(\frac{2\pi m_C KT}{h^2})^{3/2}$
N_V	$2(\frac{2\pi KT}{h^2})^{3/2} \times(m_{lh}^{3/2}+m_{hh}^{3/2})$

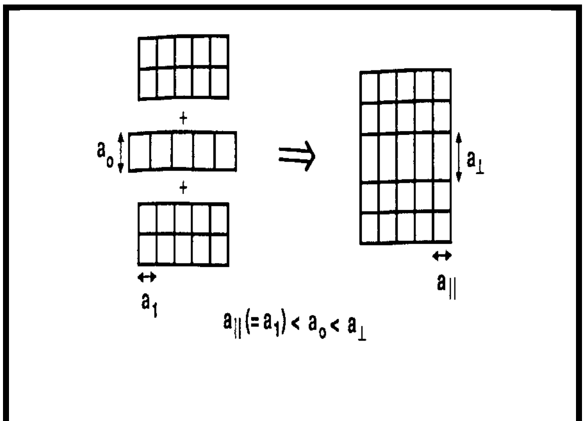

Fig.(1) Illustration of the crystal lattice deformation resulting from the epitaxial growth of a thin layer of material with a native lattice constant a_0 between two thick layers with lattice constant $a_1 < a_0$ [6

a semiconductor is related to its lattice spacing, we might expect that distortions in the crystal lattice should lead to alterations in the band gap of the strained layer (putting aside for the moment the changes created simply by quantum confinement). In fact, there are two types of modifications that occur. The first effect produces an upward shift in the conduction band as well as a downward shift in both valence bands, increasing the overall band gap by an amount $\delta\varepsilon_{\mathrm{H}}$ (which is positive for compressive strain and negative for tensile strain). The H subscript indicates that this shift originates from the hydrostatic component of the strain [8,9]. The second, more important effect separates the HH and LH bands, each being pushed in opposite directions from the center by an amount res. The S subscript indicates that this shift originates from the shear component of the strain. Thus, the band edge degeneracy of the two valence bands is removed and two energy gaps must now be defined. The total strained band gap can be written as $E_g + \delta\varepsilon_{\mathrm{H}} \pm \delta\varepsilon_S$, where the upper sign refers to the C-LH band gap Eg(LH), and the lower sign refers to the C-HH band gap Eg(HH). $\delta\varepsilon_{\mathrm{H}}$ as defined is positive for compressive strain, since Eg(LH) > Eg(HH).For tensile strain, $\delta\varepsilon_{\mathrm{H}}$ would be negative, and the band gap ordering would be reversed[8,9].

In a quantum well, the splitting of the HH and LH bands can have dramatic consequences, since the large nonparabolicity of the subband structure is a direct result of the HH and LH band mixing. If we place the strained band gaps into a quantum well, the situation becomes as shown in Fig. 2, where the depth of the quantum well as seen by light holes is reduced by the splitting energy (S) which this energy is presented the interaction between the LH band and the split-off hole (SO) band where $S = 2\delta_S(1 - \delta\varepsilon_S / \Delta)$ and Δ is the spin-orbit splitting energy . To predict the valence subband structure of the strained quantum well in Fig. 2, we simply need to add a potential offset(V) to the effective mass equation describing the LH band in the well , where V is zero inside the well, and S is zero outside the well [2].

Table(2)
the parameters values of 1.3µm Burid Letero structure laser[4]

Parameter	Symbol	Value
Active-layer thickness	d	0.2 µm
Cavity length	L	250 µm
Active-region width	w	2 µm
Group velocity	$v = c / \mu_g$	
Effective refractive index	$\overline{\mu}$	3.4
Group refractive index	μ_g	5
Recombination lifetime of the carriers (radiative and nonradiative)	τ_S	2.2ns
Photon lifetime	τ_P	1.6ps
Confinement factor	Γ	0.3
Threshold current	I_{th}	15.8mA
Fraction of spontaneous emission entering the lasing mode	β	$10^7\ s^{-1}$
Spontaneous emission rate	R_{SP}	$1.28\times10^{12}\ s^{-1}$
Gain compression factor	ε	$3\times10^{-12}\ m^2/s$
Matrix element/Rest mass of electron	$\frac{\lvert M\rvert^2}{m_0}$	19.7+5.6y x=0.47y for $In_{1-x}Ga_xAs_yP_{1-y}$

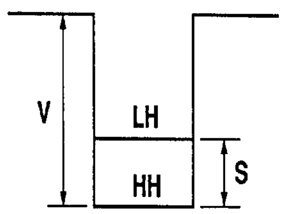

Fig.2 The modified potential barrier of a quantum well, when the well material is under compressive strain [2].

we see that the LH bands have been pushed deep into the band. As a result, the density of states in the conduction(ρ_C) and valence (ρ_V)bands in the strained quantum well is reduced significantly, and matching between ρ_C and ρ_V is greatly improved. Both of these features should lead to lower transparency levels as well as higher differential gain than the un-strained quantum well [2,7]. Therefore , The gain spectrum of the strained quantum well.

$$g(E) = \xi\rho_r\left(\frac{1}{1+e^{\frac{E_C-E_{fC}}{KT}}}+\frac{1}{1+e^{\frac{E_V-E_{fV}}{KT}}}-1\right) \quad (8)$$

Where Eg is the equivalent band gap of the quantum well material, which is the sum of the lowest quantization energies of the electrons and that of the holes, and the band gap of the parabolic band. The quantity $\rho_r(E)$ is the reduced density of states, which in the case of a two dimensional quantum well [1,5] (staircase approximation) is

$$\frac{1}{\rho_r}=\sum_i\left(\frac{1}{\rho_C}+\frac{1}{\rho_{ui}}\right) \quad (9)$$

The summation is over all heavy- and light-hole bands. It can be easily seen that the maximum of this gain curve occurs at E=0 i.e. E_C=Ev = 0. Thus, the peak gain g_P is given by

$$g_P = \xi\rho_r\left(\frac{1}{1+e^{\frac{-E_{fC}}{KT}}}+\frac{1}{1+e^{\frac{-E_{fV}}{KT}}}-1\right) \quad (10)$$

Let the hole density of states be D times that of the electron density of states. Then, equating N and P under the charge neutrality condition yields the following relation between E_{fC} and E_{fV} i.e.{ $e^{\frac{E_{fC}}{KT}}+1=(e^{\frac{E_{fV}}{E_{KT}}}+1)^D$ }[5]:

$$g_P = \xi\rho_r\left(\frac{1}{(e^{\frac{E_{fC}}{KT}}+1)^D}+\frac{1}{e^{\frac{E_{JV}}{KT}}+1}-1\right) \quad (11)$$

Assume that the electron mass is unchanged, and different values of D reflect different hole masses. One of the principal effects of inducing strain is to lower the value of D. The current density where g_P crosses zero is the transparency level, and it decreases with decreasing D, as expected. The peak achievable gain is also slightly reduced for small D[1,5]. We have

$$g^{/} = \frac{\xi}{\rho_C+\rho_V}\left(\frac{\rho_C}{(e^{\frac{E_{fC}}{KT}}+1)^{1/D}}+\frac{\rho_V}{e^{\frac{E_{fC}}{KT}}+1}\right) \quad (12)$$

C. Modulation response analysis of Dynamic Quantum well laser diode

In quantum well laser , a part of the carrier density in the separate confinement heterostructure (SCH) region will be captured in the well and another part will be escaped from the well which this two cases appears due to Strained Quantum Wells **,** therefore rate equations can then be written that describe exchange of carriers between the confined and unconfined carriers densities in the well, and between photon density. The small signal rate equations are[10,11]

$$\frac{dS}{dt}=\Gamma G^{/}S_0 n \quad (13)$$

$$\frac{dn_2}{dt}=\left(\frac{n_3}{\tau_{Cap}}-\frac{n_2}{\tau_{esc}}\right)-G^{/}S_0 n-\frac{S}{\Gamma\tau_P}-\frac{n_2}{\tau_2} \quad (14)$$

$$\frac{dn_3}{dt}=-\left(\frac{n_3}{\tau_{Cap}}-\frac{n_2}{\tau_{esc}}\right)+j_{pump}-\frac{n_3}{\tau_3} \quad (15)$$

Where s, n_2, and n_3 are the (small signal) photon density, carrier density in confined quantized states, and carrier density in the unconfined states in SCH regions respectively, S_o is the photon density at the bias point τ_2 and τ_3 are the recombination times, τ_P is the photon lifetime, and j_{pump} is the pumping current density., The effective gain compression coefficient ε_{cap} deduced from these equations is purely due to the carrier capture effect. The total ε is then the sum of the effective ε_{cap} and ε_{other}, where ε_{other} is due to other mechanisms, such as spectral hole burning, carrier heating, and standing wave effect.

The recombination terms in Eqs. (14) and (15) are neglected for simplicity as the recombination times (τ_2 and τ_3) are typically a few nanoseconds and, therefore, larger than the time scale of interest. From Eq. (15) [11], we obtain an expression for net capture current as follows:

$$\frac{n_3}{\tau_{Cap}}-\frac{n_2}{\tau_{esc}}=\frac{n_2}{\tau_{esc}}\left(\frac{-\omega\tau_{Cap}}{1+i\omega\tau_{Cap}}\right)+\frac{j_{pump}}{1+i\omega\tau_{Cap}} \qquad 16$$

Following a standard analysis of the rate equations, (13) and (14), we obtain the modulation response:

$$\frac{S}{j_{pump}}=\frac{\Gamma G^{/}S_0}{-\omega^2(1+R+i\omega\tau_{cap})+(1+i\omega\tau_{cap})(i\omega G^{/}S_0+\omega_r^2)}=\frac{\Gamma G^{/}S_0}{F(\omega)} \qquad 17$$

Where $\omega_r=\sqrt{\frac{G^{/}S_0}{\tau_P}}$ and $R=\frac{\tau_{cap}}{\tau_{esc}}$, when the limit of extremely small capture time($\omega\tau_{cap}\to 0$) and small but finite τ_{cap} ($\omega\tau_{cap}\langle\langle 1$), the modulation response can be obtained using a differential gain constant $G_0^{/}(1-\varepsilon S)$ in the conventional rate equations:

$$F(\omega)=-\omega^2+i\omega G_0^{/}S_0\left[1+\frac{\varepsilon_{cap}}{G_0}\left(\frac{1}{\tau_P}\right)\right]+\omega_r^2 \qquad 18$$

Where ε_{cap} is the effective gain compression due to the effective carrier capture time

$$\varepsilon_{cap}=\tau_{cap}\frac{R}{1+R}G_0^{/}=\tau_{cap}\frac{R}{1+R}\nu(g^{/})_{eff}$$ } and

$(g^{/})_{eff}$ is the effective differential optical gain $\{(g^{/})_{eff}=g^{/}/(1+R)\}$.

Table(3)
Some Parameters values of InGaAsP/InP quantum well laser[10]

Parameter	Symbol	Value
Operating wave length	λ	1.3µm
Current injection efficiency	η_i	0.86
Dipole moment	dm	9×10^{-29} c·m
Dipole relaxation time	τin	0.1×10^{-12} s
Electrons inter-aband relaxation time	τ_c	0.3×10^{-12} s
Holes inter-aband relaxation time	τ_v	0.07×10^{-12} s
Effective mass of electron /Rest mass of electron	$\frac{m_e}{m_0}$	0.11 for x<0.7 0.35 for x>0.7
Effective mass of heavy hole/Rest mass of electron	$\frac{m_{hh}}{m_0}$	0.62+0.0 5x
Effective mass of light hole/Rest mass of electron	$\frac{m_{lh}}{m_0}$	0.11+0.03x
Quantized energy gap of heavy hole band	E_g(HH) = E_g ($In_{0.49}$ $Ga_{0.51}$) – E_g ($In_{0.49}$ $Ga_{0.51}$ P)	As shown in Fig.(3)
Quantized energy gap of light hole band	E_g(LH) =1-E_g(HH)	As shown in Fig.(3)
Splitting energy	S= E_g(LH) - E_g(HH)	
Spin-Orbit Splitting energy	Δ(eV) =0.34 ×(1-x) +0.371x	
Quantum well size	L_z	5nm
Quantum well capture lifetime	τcap	45 ps
escape lifetime	τesc	400 ps

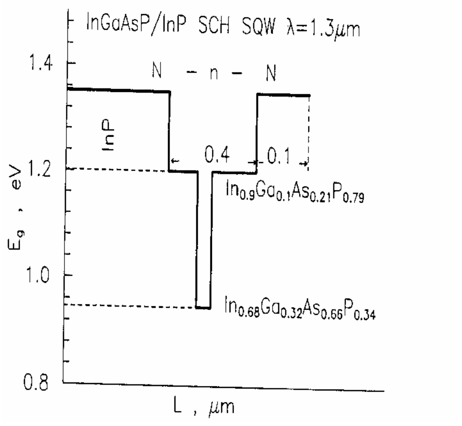

Fig. 3. Band schemes of N-n-N InGaAsP/lnP SCH SQW structures [10].

III. Results and Discussions

By using Eq.(12)as normalized (i.e. $G^{/} = \partial G / \partial N = vg^{/}$),Table(1), Table(2),Table(3) and as illustrated in Fig. 4, the differential optical gain $\partial G/\partial N$ in the quantum well laser is larger than that in the semiconductor laser diode. The absolute value of α in the quantum well laser is small, which leads to a narrow spectral line-width.

By using Eq.(12) and the relation of the line width enhancement factor ((i.e. $\alpha = -2k_0 (\frac{\partial \mu / \partial N}{\partial g / \partial N})$)) , Fig. (5) shows calculated (α) values as a function of the quasi-Fermi level of the conduction band E_{fc}. It is found that α in the quantum well laser is smaller than that in the semiconductor laser diode. Moreover, a small α leads to low chirping during modulation, which is suitable for long-haul, large-capacity optical fiber communication systems.

As shown in Fig.6, the quantum well laser, the differential optical gain $\partial G/\partial N$ is larger than that in the semiconductor laser diode. Hence, f_r in the quantum well laser is larger than that in the semiconductor laser diode, which leads to high-speed modulations in the quantum well laser.

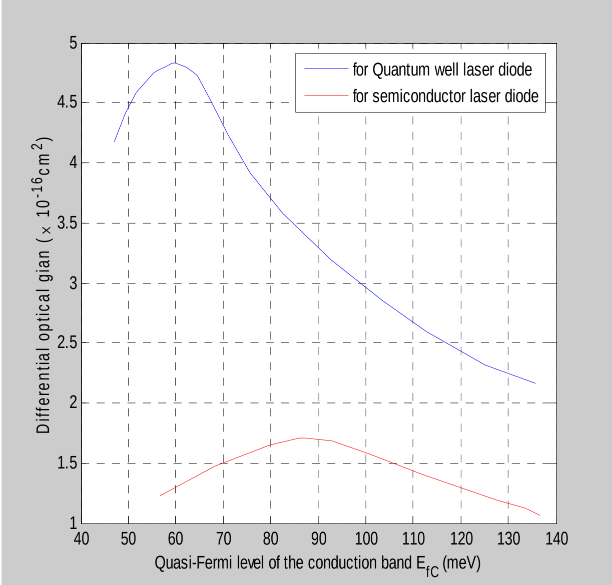

Fig. 4 Differential optical gain variation with Quasi-Fermi level of the conduction band

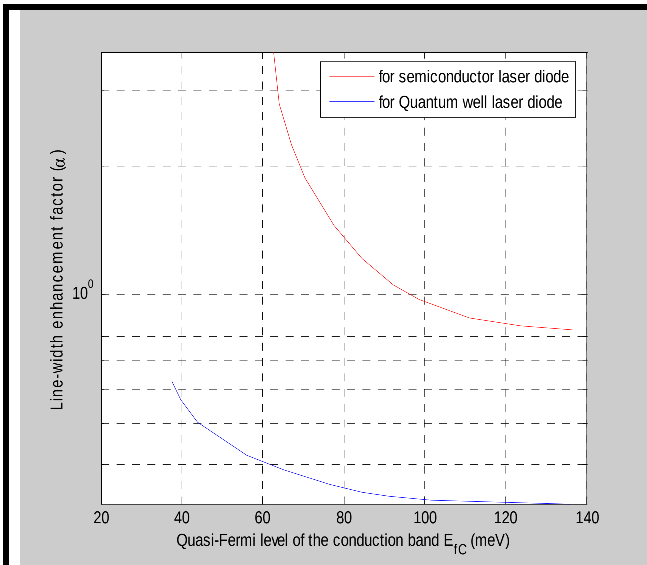

Fig. 5 Spectral line-width enhancement factor as a function of Quasi-Fermi level of conduction band

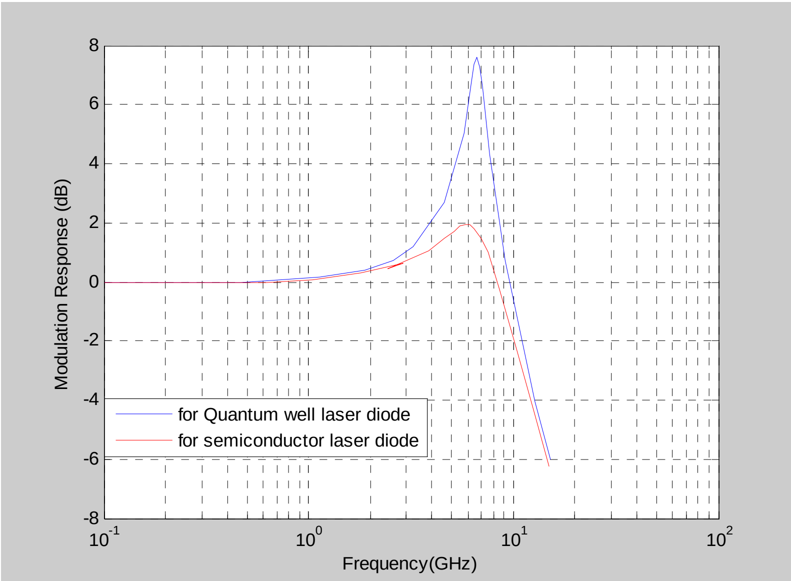

Fig.6 Modulation Response of Semiconductor and Quantum well Lasers Diodes as a function of frequency modulation

V. Conclusions

1. The low threshold current

Strains in the active layer decrease the radius of the curvature of the heavy hole band in the vicinity of the band edge, which reduces the effective mass of the heavy hole. As a result, the threshold carrier concentration decreases, and therefore the Auger recombination rate is also reduced. Furthermore, from the momentum conservation law and the energy conservation law, the Auger transitions are going to be inhibited. Hence, the Auger processes are drastically reduced. As a result, a high light emission efficiency and a low threshold current density are simultaneously obtained. The strains in the active layers also enhance the differential optical gain $\partial G/\partial N$, which further reduces the threshold carrier concentration.

2. High-speed modulation

The strains in the active layers enhance the differential optical gain $\partial G/\partial N$, which leads to high-speed modulations. The compressive strains result in large gain saturation, while the tensile strains lead to low gain saturation with a large optical gain. Hence, the tensile strains are expected to improve high-speed modulation characteristics.

3. Low chirping and Narrow spectral line width

The strains increase the differential optical gain $\partial G/\partial N$ and decrease α. Therefore, a narrow spectral line-width The compressive.

References

[1] R. People, and S. K. Sputz, " Band nonparabolicities in lattice-mismatch-strained bulk semiconductor layers", Phys. Rev. B, vol. 41, no. 12, pp. 8431-8439, 1990 .

[2] J. J. Coleman, "Strained layer quantum well lasers", in Peter S. Zory, Jr. (Ed.): Quantum Well Lasers, Academic Press, ISBN 0-12-781890-1, 1993.

[3] S. Betti, E. Bravi, M. Giaconi , "Comparison betweem optical SCM systems or multimedia applications",IEEE PhotonicsTechn. Lett.,Vo1.8,no.7 , 1998,pp.536-543.

[4] C. Y. Kuo, "Fundamental Second-Order Nonlinear Distortions in Analog AM CATV Transport Systems Based on Single Frequency Semiconductor Lasers", J. of Light wave Techn., vo1.10, vo1.2. February 2002,pp.235-243.

[5] J. Piprek, "Semiconductor Optoelectronic Devices Introduction to Physics and Simulation" , University of California at Santa Barbara, This book is printed on acid-free paper, This book is printed on acid- free paper, Elsevier Science (USA) ,Copyright 2003.

[6] O. Svelto, "Principles of Lasers" , Fourth Edition, Springer Science and Business Media, Inc.1998.

[7] D. J. Dunstan, “Strain and strain relaxation in semiconductors”,J. Materials Science: Materials in Electronics, vol. 8, no. 6, pp. 337-375, 2001.
[8] X. W. Liu, A. A. Hopgood, B. F. Usher, H. Wang, and N. St. J. Braithwaite, “ Formation of misfit dislocations during growth of InxGa1-xAs/GaAs strained-layer heterostructures”, Semicond. Sci. Technol., vol. 14, pp. 1154-1160, 2002.
[9] H. H. Tan, P. Lever, and C. Jagadish, “Growth of highly strained InGaAs quantum wells on GaAs substrates-effect of growth rate”, J. Cryst Growth, vol. 274, pp. 85-89, 2005.
[10] S. Ghoniemy, L. MacEachern, and S. Mahmoud, “Enhanced large signal laser modeling including thermal effects for analog communications,” 4th laser and fiberoptical networks modeling, 2002. Proceedings of the 2002 Laser and Fiber-optical Networks Modeling, pp. 21-24, 2002.
[11] L. V. T. Nguyen, A. J. Lowery, P.C. R. Gurney, and D. Novak, “A time domain model for high-speed quantum well lasers including carrier transport effects,” IEEE Journal of Selected Topics in Quantum Electronics, vol. 1, no. 2, pp. 494-504, 2004.

ليزرات الحاجز الكمي ذات التضمين المباشر

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الخلاصة
يتم إقحام طبقة تعرف بطبقة الإجهاد في ليزرات أشباه الموصلات حيث تتكون هذه الطبقة من عدة مواد مما يؤدي إلى تكون كمية معينة من تراكيب الحزمة. هذه الطبقة تؤثر على تردد الربح الطيفي فتزاحفه مما يؤدي إلى زيادة بالربح . اكبر الفوائد لهذه الطبقة في ليزرات التضمين البئر المكمم وهي سرعة التضمين عالية جدا" ، تقليل تردد الزقزقة (عنصر ألفا) ، عرض الخط ضيق ،وتقليل تركيز حاملات شحنة حد العتبة . ليزرات اجهادات البئر المكمم هي أفضل من ليزرات أشباه الموصلات، حيث تمتلك عرض خط تضمين من أعلى عشرات و اقل عشرينات من الكيكا هرتز