Performance improvement in quantum well lasers by optimizing band gap offset at quantum well heterojunctions

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(Received 30 November 1992; accepted for publication 24 May 1993)

We analyze the influence of the band gap offset at the quantum well (QW) heterojunctions on the performance of QW lasers. It is shown that, in addition to the strain, optimization of the band gap offset also leads to improved performance in QW lasers, especially in enabling a simultaneous attainment of ultralow threshold current and high speed. The improvement stems from the reduction of state filling in the QW lasers since the asymmetry between the conduction band and the valence band structures in the optical confining region is compensated by the corresponding optimal band gap offset at the QW heterojunctions. The results provide general guidelines to the design of high performance of QW lasers as well as suggest applications to other active laser devices.

In a quantum well (QW) laser, there exists, due to the fundamental Fermi distribution, an inevitable carrier population in the optical confining region of the QW structure. This state filling effect has been shown to have a significant impact on the threshold current,[1,2] modulation dynamics,[3,4] amplitude-phase coupling, and spectral linewidth[5,6] in QW lasers. The state filling effect on the modulation dynamics and spectral linewidth can be reduced by employing multiple quantum wells (MQW) for the active region[6,7] but the attendant penalty is an increase in threshold current due to the need to maintain the transparency density of carriers in a larger active volume. It would be highly desirable to realize both ultralow threshold and high speed performance simultaneously. This is especially important when the semiconductor lasers are used in high density applications such as optical interconnects. To achieve ultralow threshold current, a single quantum well (SQW) structure needs to be used. To achieve high speed performance, the state filling effect has to be reduced.

It has been shown that the state filling effect can be reduced by increasing the band gap offset at the QW.[3–5] But this is limited by the choice of materials available for the optical confining region. Addition of strain to the active QW region will lead to performance improvement in the QW lasers due to the reduction of effective mass of holes and the resultant larger energy separation between the ground lasing subbands and the other upper subbands.[3,8,9] However, the amount of strain added to the QW is limited by the critical thickness of the strained QW.

It has been shown that band gap offset engineering can significantly improve the performance of electronic devices and passive photonic devices such as photodetectors whose performance (responsivity, dark current) depends exponentially on the band discontinuities.[10] In general, band gap offset engineering includes the choice of semiconductor material to form the optimized heterojunction and artificially modifying the band gap offset. Two methods have been proposed to artificially control the band gap offset at a semiconductor heterojunction. The first employs a doping dipole sheet at the heterojunction, which is formed by ultrathin ion layers. Changes of the band gap offset at the heterojunction by as much as 140 meV were demonstrated at $GaAs/Al_{0.26}Ga_{0.74}As$ heterojunction.[11] The second one is based on the incorporation of an ultrathin atomic interlayer at the heterojunction, which modifies the charge distribution creating an interface dipole sheet. Changes of the band gap offset from -380 to 380 meV were reported by incorporation of ultrathin Si interface layers at GaAs/AlAs heterojunction.[12] In this letter, we show theoretically how the performance of QW lasers can be significantly improved by optimization of the band gap offset at QW heterojunctions.

In a III-V semiconductor, there exists a very large asymmetry between the conduction band and the valence band structures. In a separate confinement heterostructure (SCH) QW laser, the larger effective mass of holes (compared to electrons) is responsible for a much larger number of energy states in the optical region in the valence band compared to the conduction band. Usually, the band gap offset at a heterojunction between two III-V semiconductors is smaller in the valence band than that in the conduction band. These two facts result in that the state filling effect is due mainly to the holes in the valence band in typical III-V QW lasers.

The state filling effect dominated by the holes can be reduced by increasing the valence band gap offset at the QW heterojunction. To show how the state filling effect is affected by the band gap offset at the QW heterojunction consider a simple four-level model as shown in Fig. 1. We assume that the lasing transition occurs between the two ground states ($n=1$) in the conduction band and valence band. m_e and m_h represent the effective masses of electrons and holes, respectively. E_d is the total band gap discontinuity at the QW heterojunction. R_d is the ratio of conduction band gap offset to E_d. For simplicity, we assume the energy separations between the ground states and the states in the optical confining region to be approximately $E_d \times R_d$ and $E_d(1-R_d)$ for the electrons and holes, respectively; i.e., we neglect the quantization energy of the $n=1$ electron and hole levels. D_e and D_h represent the effective number of states within one kT in the optical confining region for electrons and holes, respectively, where T is the tempera-

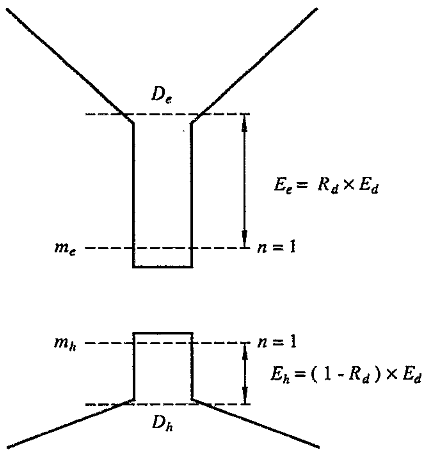

FIG. 1. Schematic diagram for the four-level model.

ture and k is the Boltzmann constant. Parabolic and isotropic band structures have been assumed for both electrons and holes in this simple model.

The maximum optical gain will be experienced at a frequency corresponding to the separation between the two ground states ($n=1$) of Fig. 1 if we neglect the dephasing collision broadening. We can express it as

$$G = A_0 \rho_r (f_e + f_h - 1), \tag{1}$$

where A_0 is a material-dependent parameter, $\rho_r = (\rho_e \rho_h)/(\rho_e + \rho_h)$ is the reduced density of states for the ground state optical transition, $\rho_e = m_e/(\pi \hbar^2)$ and $\rho_h = m_h/(\pi \hbar^2)$. The Fermi function is given by

$$f_{e,h} = \left[1 + \exp\left(-\frac{E_{fe,fh}}{kT}\right)\right]^{-1}, \tag{2}$$

where E_{fe} and E_{fh} are the Fermi energy levels for electrons and holes measured from their ground states ($n=1$), respectively. Given E_{fe} and E_{fh}, the corresponding carrier density is obtained from an integration of the density of states as

$$N = \rho_{e,h} kT \left\{ \ln\left[1 + \exp\left(\frac{E_{fe,fh}}{dT}\right)\right] + D_{e,h} \ln\left[1 + \exp\left(\frac{E_{fe,fh} - E_{e,h}}{kT}\right)\right]\right\}. \tag{3}$$

From Eqs. (1)–(3) the differential gain is written explicitly as

$$\frac{dG}{dN} = \frac{A_0}{kT} \rho_r \sum_{j=e,h} \frac{1}{\rho_j} \frac{1}{1 + \exp(E_{fj}/kT)} \times \left(1 + D_j \frac{1 + \exp(E_{fj}/kT)}{\exp(E_j/kT) + \exp(E_{fj}/kT)}\right)^{-1}, \tag{4}$$

where $E_e = E_d R_d$ and $E_h = E_d(1 - R_d)$.

In Fig. 2, we show the carrier density and differential gain at transparency ($E_{fe} + E_{fh} = 0$) as a function of the band gap offset ratio for different values of E_d. $m_e{:}m_h = 1{:}7$ has been taken and other parameters taken are shown in Fig. 2, which are based on a typical GaAs/AlGaAs QW laser structure. It is shown that there exist optimal band gap offset ratios to obtain the lowest transparency carrier density and highest differential gain. A larger value of D_h presents a larger number of states of holes within one kT in the optical confining region due to the larger effective mass of the holes. When R_d is large (i.e., smaller band gap offset for the valence band), the state filling effect is dominated by the hole population in the optical confining region. As R_d decreases, the energy separation between the ground state and the states in the optical confining region in the valence band increases. The state filling for holes will be reduced, which leads to a smaller transparency carrier density and higher differential gain. However, if R_d is too small the state filling will be dominated by the electrons in the conduction band, resulting in a larger transparency carrier density and a lower differential gain.

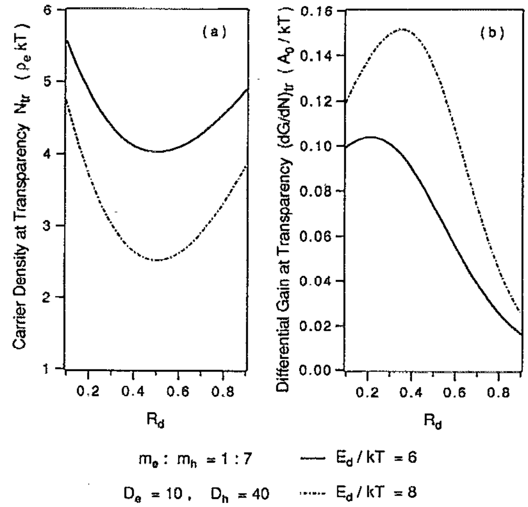

FIG. 2. Calculated carrier density (a) and differential gain (b) at transparency as a function of band gap offset ratio R_d.

In Fig. 3, we show the transparency carrier density and corresponding differential gain as a function of R_d for

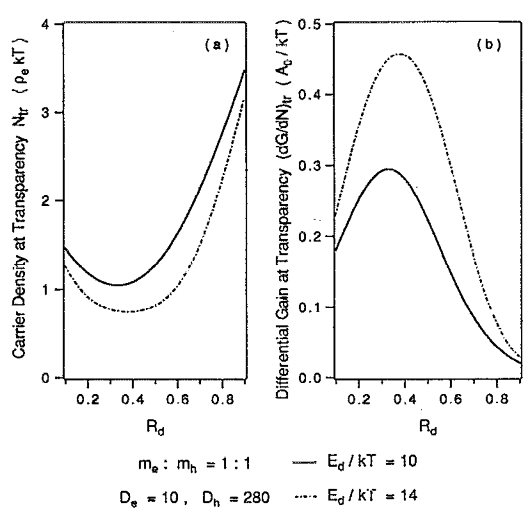

FIG. 3. Calculated carrier density (a) and differential gain (b) at transparency as a function of band gap offset ratio R_d for reduced effective mass of holes in the QW and a deeper QW (larger value of E_d).

m_e:m_h=1:1 and larger E_d values. These parameters highlight the consequence of strain in the QW, such as InGaAs strained QW structure. The strain causes a reduction in the hole effective mass as well as an increase in the depth of the quantum well. Since the effective mass of holes in the optical confining region does not change, the D_h [see Eq. (3)] should be taken as $7/1\times 40=280$, where 7/1 is the effective mass reduction ratio for the holes in the ground state of the strained QW and 40 is the D_h value in Fig. 2. Comparing Figs. 2 and 3, we can see that at the nominal band gap offset ratio $R_d\sim 0.7$ the addition of strain to the QW results in a reduction in transparency carrier density, whereas the differential gain is enhanced by a factor of 2–3. Figure 3 shows that tuning the band gap offset ratio R_d may lead to further reduction in transparency carrier density and the differential gain can be further enhanced by a factor of 2–3.

Although the above analysis is based on a simple model, it illustrates the basic physics underlying the reduction of state filling by tuning the band gap offset at the QW heterojunctions. The state filling effect is reduced because the asymmetry in the conduction band and valence band structures in the optical confining region is compensated by the corresponding optimal band gap offset at the QW heterojunctions.

A more accurate gain calculation has been carried out for a typical GaAs/AlGaAs SQW structure. The QW structure is assumed to have a 75 Å GaAs QW and a pair of 2000 Å $Al_{0.2}Ga_{0.8}As/Al_{0.5}Ga_{0.5}As$ optical confining layers. The conduction band is assumed to be a parabolic and the valence band structures were obtained by solving the 4×4 Luttinger–Kohn Hamiltonian[13] via the axial approximation,[14] i.e., the valence band mixing effect has been taken into account. In Fig. 4 we show the calculated carrier density and corresponding differential gain as functions of the band gap offset ratio R_d for different values of modal gain g. It is shown that the differential gain can be increased if the R_d is reduced from its nominal value ~ 0.7. For instance, the differential gain is doubled at R_d at 0.5 for the modal gain of 30 cm^{-1} while the carrier density is also reduced. This analysis also applies to other material system, such as the InGaAs/AlGaAs and the quaternary InGaAsP/InP or InGaAsAs/InP QW structures. Detailed results will be presented elsewhere.

In summary, we have shown that, in addition to the strain, a control of the band gap offset will lead to improved performance in QW lasers, especially in the SQW lasers to achieve simultaneous operation of ultralow threshold and high speed (at low injection current). The improvement stems from the reduction of state filling in the QW lasers through optimizing the band gap offset at the QW heterojunctions since the asymmetry between the conduction band and the valence band structures in the optical confining region is compensated by the corresponding optimal band gap offset at the QW. The results provide general guidelines to the design of high performance QW lasers as well as suggest applications to other active laser devices.

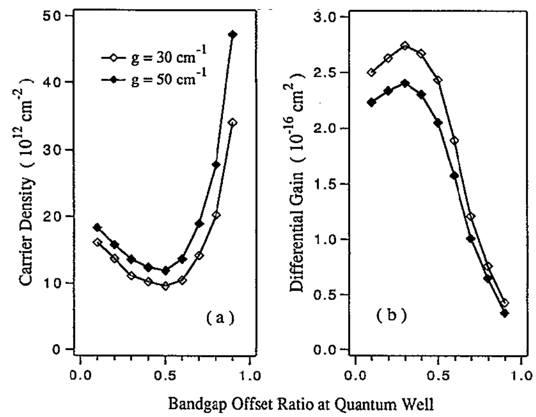

FIG. 4. Computed carrier density (a) and differential gain (b) as a function of band gap offset ratio R_d for a typical GaAs/AlGaAs SCH SQW laser by a more accurate model, where the valence band coupling effects have been taken into account. g is the modal gain.

This work was supported by the Advanced Research Project Agency, by the Air Force Office of Scientific Research and by the Office of Naval Research.

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