Reduction of Lasing Threshold Current Density by the Lowering of Valence Band Effective Mass

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Abstract—**In present day semiconductor lasers, there is a serious asymmetry between the very light conduction band mass and the very heavy valence band mass. Under laser threshold conditions, the hole occupation remains classical even while the electrons are degenerate. This results in a significant penalty in terms of threshold current density, carrier injection level, and excess Auger and other nonradiative recombination. We propose a combination of strain and quantum confinement to reduce the valence band effective mass and to lessen the laser threshold requirements.**

I. Introduction

In the III–V CLASS of semiconductor lasers, there is a serious asymmetry between the very light conduction band mass and the heavy valence band mass. As a result, the usual semiconductor laser picture [1] of a degenerate distribution of both electrons and holes does not actually apply. The upper laser levels in the conduction band are indeed filled with degenerate electrons but the lower lasing levels in the valence band are not empty. Due to the heavy valence band mass, the hole quasi-fermi level is above the top of the valence band and the hole distribution is classical. (This situation is illustrated in Fig. 1(a).) Therefore, the hole occupation probability at the top of the valence band is small, i.e., the lower laser levels are almost completely filled with electrons.

Present day semiconductor lasers find themselves in the awkward position of lasing down from filled states to almost filled states. This is far from optimal. The more ideal situation of equal conduction and valence band mass is illustrated in Fig. 1(b). In the first part of this paper we will estimate the penalty associated with the effective mass asymmetry and in the second part of the paper we will analyze the effectiveness of a strain perturbation in shifting the light hole band above the heavy hole band, thereby reducing the valence band edge effective density of states and minimizing this asymmetry.

The penalty associated with the effective mass asymmetry is especially severe in a three-dimensional active layer. The ratio of density of states between valence and conduction band is proportional to $(m_h/m_c)^{3/2}$ where m_c is the light conduction band mass and m_h is the heavy valence band mass. (We neglect, for now, the light valence band mass m_l, since its contribution is overwhelmed by the heavy band.) In a quantum confined active layer, the density of states asymmetry is less severe but still proportional to (m_h/m_c). We will analyze the penalty associated with a two-dimensional (x, y) active layer having quantum confinement in the z direction. The two-dimensional density of states per unit carrier energy per unit area is $m/\pi\hbar^2$ and is independent of carrier energy.

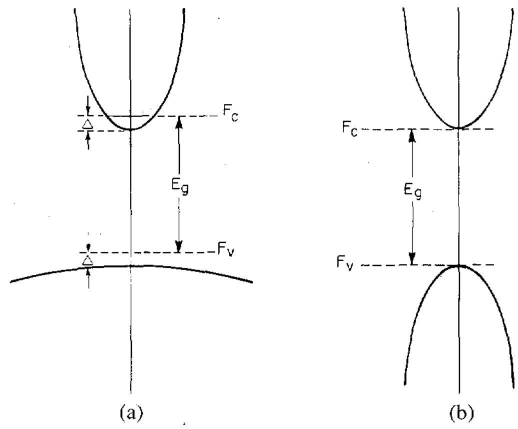

Fig. 1. (a) An ordinary III–V semiconductor at gain threshold in which the conduction band carrier density is degenerate and the valence band carrier density is nondegenerate due to the effective mass asymmetry. (b) An idealized semiconductor with equal effective masses that arrives at gain threshold with a lower carrier injection density than case (a).

The threshold condition for gain is the well-known Bernard–Duraffourg [2] condition

$$(F_c - F_v) > \hbar\omega \geq E_g \cdots \quad (1)$$

which requires that the separation of quasi-Fermi levels $(F_c - F_v)$ should be greater than the band gap. In both Fig. 1(a) and (b), this condition is minimally satisfied. In practice, the quasi-Fermi level separation should exceed the minimal value by 1 or 2 kT in order to overcome cavity losses, etc., but this would not change any of our conclusions. The carrier injection level n per unit area required to produce the quasi-Fermi level separation in Fig. 1(b) is

$$n = \int_0^\infty \frac{1}{\exp\{E/\mathrm{kT}\} + 1} \frac{m_c}{\pi\hbar^2}\, dE$$

$$n = \frac{\mathrm{kT}\, m_c}{\pi\hbar^2} \ln 2.$$

The situation in Fig. 1(a) is more complex. The electrons are degenerate and their density is given by $n = m_c\Delta/\pi\hbar^2$, where Δ is the degeneracy energy. The holes are nondegenerate and their density p can be approxi-

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$$p = \frac{\mathrm{kT}\, m_h}{\pi \hbar^2} \exp\left\{-\frac{\Delta}{\mathrm{kT}}\right\}.$$

Equating n and p results in an equation for Δ/kT which can be solved iteratively on a hand calculator

$$\left(\frac{\Delta}{\mathrm{kT}}\right)\left(\frac{m_c}{m_h}\right) = \exp\left\{-\frac{\Delta}{\mathrm{kT}}\right\} \cdots . \qquad (2)$$

A reasonable value for (m_c/m_h) is $\frac{1}{6}$, which results in a value for $\Delta = 1.43$ kT. Therefore, the ratio of injection level in case 1(a) over case 1(b) is 1.43/ln 2 which is a factor greater than two. In a fully three-dimensional active region the penalty is even more severe.

The threshold current J_{th} in a semiconductor laser must compensate a) spontaneous emission J_{sp}, b) nonradiative surface recombination on the two faces of the active region $2qnS$, and c) nonradiative Auger recombination $q\gamma n^3 d$

$$J_{\mathrm{th}} = J_{\mathrm{sp}} + 2qnS + q\gamma n^3 d \cdots \qquad (3)$$

where q is the electronic charge, S is the surface recombination velocity, γ is the Auger recombination coefficient, and d is the thickness of the active layer. It is clear from the second and third terms of (3) that any reduction in carrier injection level n will immediately result in a reduction of threshold current density. This is especially true for Auger recombination, which is particularly serious for longer wavelength lasers.

It might also seem that J_{sp} would also benefit from a reduction in n, but this would be largely incorrect. The spontaneous emission is directly linked to the required laser gain by a fundamental formula [3], [4] which is analogous to the Einstein A and B relations and which is largely independent of any microscopic properties of the gain medium

$$J_{\mathrm{sp}} = 8\pi q g\, d\, \Delta\nu/\lambda^2 \cdots \qquad (4)$$

where g is the gross gain in the active region uncorrected for absorption, λ is the wavelength in the medium, and $\Delta\nu$ is the spontaneous emission bandwidth. For a given gain, the main leverage on J_{sp} is via the emission bandwidth, but this tends to always be a few kT/h wide. For example, at the room temperature injection levels required for lasing, quantum confined excitons tend to have broad emission bands smeared together with the band-to-band emission. Nevertheless, quantum confined active layers do tend to have somewhat narrower spontaneous emission bandwidths $\Delta\nu \approx 3$ or 4 kT/h than do thick layers.

The main conclusion from the above discussion is that a reduction of valence band effective mass can reduce injection levels required for lasing and have a favorable effect on the threshold current via (3). Now let us see how the effective mass can be reduced by strain in a quantum confined layer. We have in mind to lift the $k = 0$ degeneracy between light and heavy holes in the valence band of a ternary or quaternary semiconductor. If the light valence band can be shifted upward then its effective mass

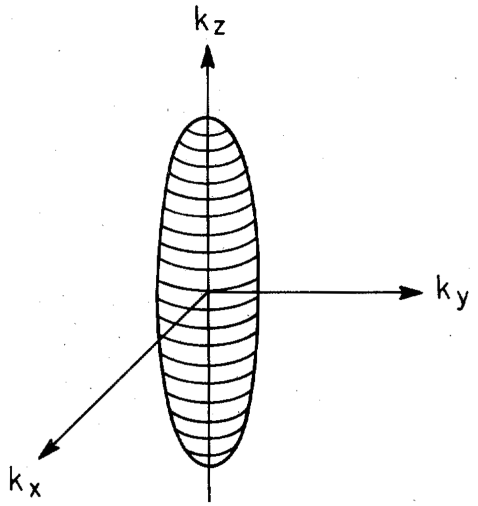

Fig. 2. The iso-energy contour of the highest lying valence band of a semiconductor subject to compressive strain in the x and y directions. In the z direction, the mass is the heavy hole mass. In the x and y directions, the mass is much less.

would determine the band edge density of states. This will occur in a strained active layer [5] grown on a substrate whose lattice constant is smaller than the active layer would ordinarily prefer to grow.

The effect of strain on the valence band structure of semiconductors was first analyzed by Pikus and Bir [6]. As is usual, we neglect band structure terms linear in k which are very small in the III–V semiconductors. The effect of strain is to mix the light and heavy valence bands whose energy is now given by

$$E = A|k|^2 \pm (E_k^2 + E_e^2 + E_{ek}^2)^{1/2} \cdots \qquad (5)$$

$$E_k^2 = B^2|k|^4 + C^2(k_x^2k_y^2 + k_x^2k_z^2 + k_y^2k_z^2) \cdots \qquad (5a)$$

$$E_e^2 = b^2(e_{xx} - e_{zz})^2 \cdots \qquad (5b)$$

$$E_{ek}^2 = Bb(e_{xx} - e_{zz})(k_x^2 + k_y^2 - 2k_z^2) \cdots \qquad (5c)$$

where we have specialized to the case of strain $e_{xx} = e_{yy}$ and have ignored shear strain and the hydrostatic term that shifts both bands uniformly. The plus and minus before the square root represent the heavy and light bands, respectively. A, B, and C are the reciprocal effective mass coefficients and b is the deformation potential. If the strain in the x–y plane is compressive, then the iso-energy surface in k-space is as shown in Fig. 2. The highest valence band will be heavy in the z-direction and relatively light in the x–y plane.

Since the quantum confined layer cannot be grown arbitrarily thick, let us introduce quantum confinement in the z direction by restricting k_z to the values $\pm l\pi/d$, when l is an integer. This is equivalent to assuming infinitely high-potential barriers. Then (5) can be expanded [7] in a power series in $k_\parallel^2 \equiv k_x^2 + k_y^2$.

$$E = A(l\pi/d)^2 \pm \{B(l\pi/d)^2 - b(e_{xx} - e_{zz})\} + (A \pm T)k_\parallel^2 \qquad (6)$$

and where

$$\pm T = \frac{(2B^2 + C^2)(l\pi/d)^2 + Bb(e_{xx} - e_{zz})}{\pm 2\{B(l\pi/d)^2 - b(e_{xx} - e_{zz})\}} \cdots . \qquad (7)$$

TABLE I
A TABLE OF NUMERICAL CONSTANTS REPRESENTATIVE OF A QUATERNARY SEMICONDUCTOR WITH BAND EDGE NEAR THE 1.5-μm WAVELENGTH

m_h	$= 0.25\ m_e$
m_c	$= 0.045\ m_e$
A	$= -13\ \hbar^2/2m_e$
B	$= -9\ \hbar/2m_e$
$\lvert C \rvert$	$= 10\ \hbar^2/2m_e$
d	$= 100$ Å
b	$= -2$ eV
e_{xx}	$= -0.037$
e_{zz}	$= -2\ (C_{12}/C_{11})\ e_{xx}$
C_{12}/C_{11}	$= 0.45$

Since the valence bands turn down, A is negative and we desire to make the reciprocal effective mass $A \pm T$ as negative as possible. In addition, we seek out the highest lying valence band for which $\pm \{B(l\pi/d)^2 - b(e_{xx} - e_{zz})\}$ must be positive. Therefore, the only term in $\pm T$ that has any chance of being negative is $Bb(e_{xx} - e_{zz})$. Since b and B are both negative as shown in [8], it follows that the strain $(e_{xx} - e_{zz})$ must be negative and sufficient to counteract the $2B^2 + C^2$ quantum confinement term. Unfortunately, the quantum confinement acts to partially cancel the effective mass reduction in the highest lying band. Therefore, a large strain is necessary to produce the smallest possible effective mass.

To proceed further, we have numerically evaluated the parallel effective mass in x-y plane using (6) and (7). In Table I, an assumed set of numerical coefficients is given which are thought to be representative of a quaternary semiconductor with a band edge near the 1.5-μm wavelength. The assumed strain 3.7 percent is for a semiconductor with the lattice constant of InP grown on a substrate of GaAs. The quantum well was selected to be 100 Å wide, which is probably the maximum permissible thickness [5] for such a high strain. Even under such extreme conditions, the strain barely counteracts the quantum confinement yielding $T = -0.9\ m_e^{-1}$. The effective mass in the plane of the active layer is $m_\| = -(A + T)^{-1} = 0.07\ m_e$ where m_e is the free electron mass. This is a considerable improvement but it does not completely fulfill our goal of equal electron and hole effective masses. Furthermore, the higher quantum confined sublevels represented by $l > 1$ are separated from the lowest sublevel $l = 1$ by less than kT due to the heavy mass perpendicular to active layer. Therefore, the sublevels with $l > 1$ are likely to be populated and add unnecessarily to the injection level and to the threshold current burden. Therefore, a considerable improvement occurs but there is room for further improvement.

II. CONCLUSION

In conclusion, the effect of a valence band effective mass reduction is to lower the injection level and threshold current requirements in semiconductor laser. If the nonradiative terms in (3) can thereby be completely eliminated, the threshold current density will be given by (4). In a graded index-separate confinement heterostructure [9] with a single-quantum well-active layer, g can be 200 cm^{-1} for a net gain in the mode of $\Gamma g = 10\ \text{cm}^{-1}$, which might be enough to overcome losses in a cavity that is 2 mm long. (Γ is the mode filling factor assumed to be 0.05 in this instance.) Substituting these values into (4) suggests that under these ideal circumstances the lasing threshold current density might be as low as 10 or 20 A/cm^2 compared with current technology [10] which is about ten times higher.

Another approach toward reducing threshold requirements might be even more successful. For example, full three-dimensional quantum confinement would make the band masses irrelevant and would put the upper and lower lasing levels on a more equal footing.

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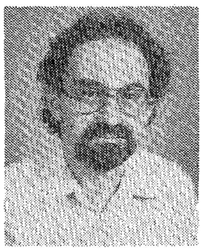

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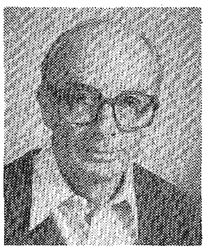

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