BAND STRUCTURE ENGINEERING OF SEMICONDUCTOR LASERS

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There is tremendous room for improvement in semiconductor lasers. In the spirit of band structure engineering, we will discuss those ideas which could lower the threshold current density to \( \approx 10 \text{ Amps/cm}^2 \) and significantly improve the efficiency.

The band structure of today's semiconductor lasers is far from ideal. There is a serious asymmetry between the very light conduction band mass and the very heavy valence band mass. (Ideally both masses should be as light as possible.) 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. This is only one of a series of problems which can be addressed by band structure engineering.

Unwanted electron-hole recombination is the main enemy of all minority carrier devices including semiconductor lasers. Such recombination manifests itself as:

- Defect recombination in the bulk or at heterojunction interfaces.
- Spontaneous electron-hole radiative recombination.
- Auger recombination due to the high carrier density.

We have found in a survey of all the major growth methods, that the defect recombination rate in modern III-V epitaxy is negligible, with lifetimes > 1 \( \mu \text{sec} \) being commonplace. Therefore band structure engineering may safely concentrate on such intrinsic properties as spontaneous emission and Auger recombination, while trusting that the material quality will be adequate.

Auger recombination is proportional to carrier density cubed. Therefore one of our main goals is to reduce the threshold carrier density. Due to the heavy valence band mass, the carrier density required to satisfy the Bernard-Duraffourg condition is higher than would otherwise be the case. Proposals have been made\(^1\) to employ a combination of strain and quantum confinement to reduce the valence band effective mass and to lessen the laser threshold requirements. If the sign of the strain is such as to put compression on the quantum well active layer, then the effect on the topmost valence sub-band will be to make the effective mass heavy in the \( z \)-direction but light in the \( x-y \) plane. In this way the Bernard-Duraffourg condition may be satisfied at the lowest possible carrier density.

Spontaneous radiative recombination presents a more tricky issue. According to Einstein, any reduction in spontaneous emission must of necessity be accompanied by a corresponding reduction in stimulated gain. Therefore we must be careful to recognize that emission into the laser waveguide is unavoidable, but that there are approaches\(^3\) to inhibit spontaneous emission into modes external to the waveguide.

The basic idea behind our approach to band structure engineering is illustrated in Figures 1 and 2 at the bottom of this page. In Fig. 1(a) we compare the actual situation existing in bulk III-V semiconductors with the situation 1(b) we desire to achieve by a combination of strain and quantum confinement to artificially modify the band structure. The result is that the iso-energy contour at the top of the valence band will be shaped as in Figure 2.
The specific numerical calculations focused on the In$_x$Ga$_{1-x}$As material system since its emission wavelength is approximately optimal for optical communications, and the mole fraction $x$ could be adjusted to compensate for the strain and quantum confinement induced shifts in the band gap. The calculations were made in the effective mass approximation and incorporated the actual valence band offsets for both InP and InAlAs barrier layers. We found that it was very beneficial to maintain the highest possible potential barrier in the valence band in order to achieve the lowest effective mass and this was most readily achieved with InP barrier layers.

We will present work on both theoretical modelling and preliminary experimental results on optically pumped semiconductor quantum well lasers incorporating these concepts.


![Fig. 1](image1.png)

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).

![Fig. 2](image2.png)

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.