ELECTRONIC STRUCTURE ENGINEERING OF THE LINEWIDTH ENHANCEMENT FACTOR IN MID-INFRARED SEMICONDUCTOR LASER ACTIVE REGIONS

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ABSTRACT

The linewidth enhancement factor is a fundamental parameter that characterizes the limit of spectral purity and the tendency for filamentation in a semiconductor laser. For either narrow-line or high-power operation, it is generally desirable that the linewidth enhancement factor be minimized. This parameter depends primarily on the shape of the differential gain spectrum of the active region material. In mid-infrared laser materials, band structure engineering has been used routinely to minimize the effects of nonradiative recombination. This same approach can be used to tailor the differential gain spectrum of these materials to minimize the linewidth enhancement factor.

Favorable features of the electronic structure of the material include 1) band-edge dispersion in the conduction band which shifts the peak of the gain away from the band edge and 2) intersubband absorption resonances, which can be designed to lie above the peak gain in energy. Both of these strategies shift the peak of the differential gain closer to the peak gain, and thus reduce the linewidth enhancement factor. These electronic structure design strategies can be used to reduce the linewidth enhancement factor in type-II InAs/GaInSb systems to almost 1.0, which is significantly smaller than typical values of 2.5-5 in type-I strained quantum wells. We note that a linewidth enhancement factor close to 1 is much smaller even than a typical linewidth enhancement factor in visible or near-infrared semiconductor lasers. Furthermore in some materials the peak of the differential gain lies in a region of positive gain, indicating that a grating could be used to select a mode with negligible linewidth enhancement factor.

INTRODUCTION

Many of the potential applications for mid-infrared semiconductor lasers, in particular those involving molecular spectroscopy and remote sensing, require coherent sources with narrow linewidths. Spectral purity in a semiconductor laser is degraded by the coupling between phase and amplitude noise, and thus the linewidth is broadened beyond the Schawlow-Townes limit according to $\Delta \nu = \Delta \nu_0 (1 + \alpha_{\text{twe}}^2)$, where $\Delta \nu_0$ is the Schawlow-Townes linewidth and $\alpha_{\text{twe}}$ is the linewidth enhancement factor.\[1\] The linewidth enhancement factor is also a measure of the likelihood of formation of optical filaments. At high powers, optical filamentation can lead to catastrophic facet damage in the localized optical fields. Devices with small linewidth enhancement factors have the capability of producing larger output powers without facet damage.

The linewidth enhancement factor ($\alpha_{\text{twe}}$) is defined as the ratio of the density derivative of the real ($\chi_r$) and imaginary ($\chi_i$) parts of the complex susceptibility. However, when the fractional change in the index of refraction is small compared to the fractional change of the absorption coefficient, the linewidth enhancement factor can be written in terms of the density derivatives of the index of refraction ($n$) and the net gain ($\gamma_{\text{net}}$). Because $dn/dN$
can be related to the differential gain spectrum by a Kramers-Kröng transformation, the linewidth enhancement factor can be written entirely in terms of the differential gain spectrum,

\[ \alpha_{\text{lwe}} = \frac{dX_r/dN}{d\chi_i/dN} \sim -\frac{4\pi}{N} \frac{dn/dN}{d\gamma_{\text{net}}/dN} = \frac{4e}{\lambda} \int_0^\infty (\omega^2 - \omega^2)^{-1} \frac{(d\gamma_{\text{net}}(\omega')/dN)d\omega'}{(d\gamma_{\text{net}}(\omega)/dN)}, \]

(1)

where \( N \) is the carrier density and \( \omega \) is the photon energy. Whereas \( dn/dN \) (and hence \( \alpha_{\text{lwe}} \)) vanishes near the peak of the differential gain spectrum, lasers operate at the frequency of the peak of the gain spectrum. In interband semiconductor lasers, unlike atomic lasers, the peak of the differential gain is shifted away from the peak of the gain due largely to the imbalance between conduction and valence band densities of states.[2] Because of this, semiconductor lasers typically have \( \alpha_{\text{lwe}} \)'s significantly different from zero. Typical values for near-infrared semiconductor lasers range from 2 – 6.[3]

Three primary strategies have been employed for reducing the linewidth enhancement factor in near-infrared lasers.[2,4,5] The first is to reduce the imbalance between the conduction and valence band densities of states through the use of strain and quantum confinement. The second is to p-dope the active region, which helps to offset the density of states imbalance. Third, a distributed feedback grating (DFB) can be used to detune the lasing energy from the peak of the gain towards the peak of the differential gain. The amount of detuning that can be used is limited by the range of energies over which there is positive gain. When the peak of the differential gain spectrum lies in the region of positive gain, it is possible to reduce the linewidth enhancement factor to near zero.

The situation is more challenging in the mid-infrared since the conduction band effective mass (of a bulk material) decreases roughly proportionally with the band gap, increasing the density of states imbalance. In addition, p-doping the active region aggravates existing problems with Auger recombination. Thus, producing semiconductor lasers with small linewidth enhancement factors requires careful attention to the problem of density of states mismatch. There have been relatively few reports of linewidth enhancement values for wavelengths beyond 1.55 \( \mu \)m. Meyer, et al., report 300K calculated values of 1.7 and 4.2 for early mid-infrared type-II quantum wells and superlattices, and VurgafaLand Meyer report a 100K calculated value of 1.1 for a system considered here.[6,7] Intersubband quantum cascade lasers are expected to have ultra-low linewidth enhancement factors (< 0.1) due to the extremely narrow joint density of states characteristic of atomic-like systems.[8] Recently, Anson, et al. reported measurements of small linewidth enhancement factors (< 1.0) in a 4 \( \mu \)m type-II superlattice.[9]

Here we report calculations of the linewidth enhancement factor at room temperature in a selection of mid-infrared active region materials. The linewidth enhancement factor is correlated with three features of the electronic structure: conduction and valence densities of states balancing, conduction band dispersion, and judiciously placed intersubband absorption features. Calculations were performed on a 4.2 \( \mu \)m strained InAsSb/AlInAsSb quantum well structure[10], a 4.4 \( \mu \)m strained InAsSb/InAsP quantum well structure[11], a 4.0 \( \mu \)m InAs/GaInSb/InAs/AlGaInAsSb superlattice[12,13], and a 4.1 \( \mu \)m InAs/GaInSb/InAs/AlSb superlattice[7]. Bulk InAs0.91Sb0.09 (lattice matched to GaSb) is included as a reference. Although the linewidth enhancement factor of a real device is affected by the optical cavity, the value is dominated by the inherent linewidth enhancement factor of the active region material. Comparison of the linewidth enhance-
ment factor of the different materials allows for the evaluation of these materials as active regions for either spectrally pure or high-power applications.

THEORY

The optical properties of the materials were calculated using a superlattice $K \cdot p$ formalism with a fourteen-band bulk basis. This method is an extension of the eight-band $K \cdot p$ formalism that has been previously used to calculate the optical properties of several mid-infrared materials.\[12\] Excellent agreement has been seen between a variety of theoretical calculations and experimental measurements. Gain and intersubband absorption spectra were calculated for TE polarization as a function of carrier density using the highly non-parabolic band structure and momentum dependent matrix elements. A Kramers-Krönig transformation of the change in absorption spectra for each density was performed to obtain the nonlinear change in the index of refraction. The differential gain, differential index, and linewidth enhancement factor were calculated for the transition energy corresponding to the peak of the gain spectrum.

Strictly, the Kramers-Krönig transformation should be applied over the entire energy spectrum, whereas we use a finite energy range (transition energies out to $\sim 0.8$eV). However, calculating the change in index from the change in absorption spectrum is a very different problem than calculating the index of refraction from the absorption spectrum. The index of refraction is dominated by the magnitude of the absorption spectrum at Van Hove singularities away from zone center, but the change in absorption spectra is only non-zero where the nonequilibrium carriers are (near zone center for the direct gap materials discussed here). We can approximate the effect of using a finite energy range in our calculations by repeating the calculations using a substantially larger energy range. From this procedure, we estimate the error introduced by the use of a finite energy range in the calculation of the change in index spectrum at the expected lasing energy to be less than 10%.

RESULTS

<table>
<thead>
<tr>
<th>System</th>
<th>$E_g$ (µm)</th>
<th>$\rho_v/\rho_c$</th>
<th>$\Delta E_{CB}$ (meV)</th>
<th>$\alpha_{LWE}$ peak</th>
<th>$\alpha_{LWE}$ DFB</th>
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</thead>
<tbody>
<tr>
<td><strong>Bulk</strong></td>
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<tr>
<td>(a) InAs$<em>{0.91}$Sb$</em>{0.09}$</td>
<td>4.2</td>
<td>25.7</td>
<td>N/A</td>
<td>6.5</td>
<td>1.8</td>
</tr>
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<td><strong>Type-I Quantum Wells</strong></td>
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<tr>
<td>(b) InAsSb/AlInAsSb</td>
<td>4.2</td>
<td>9.9</td>
<td>0.3</td>
<td>5.4</td>
<td>2.0</td>
</tr>
<tr>
<td>(c) InAsSb/InAsP</td>
<td>4.4</td>
<td>7.6</td>
<td>21.2</td>
<td>2.5</td>
<td>1.7</td>
</tr>
<tr>
<td><strong>Type-II Superlattices</strong></td>
<td></td>
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<tr>
<td>Ref. 13</td>
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</tr>
<tr>
<td>(d) InAs/GaInSb/InAs/AlSb</td>
<td>4.1</td>
<td>2.0</td>
<td>2.5</td>
<td>1.1</td>
<td>0.4</td>
</tr>
<tr>
<td>(d) InAs/GaInSb/InAs/AlGaInAsSb</td>
<td>4.0</td>
<td>2.3</td>
<td>36.2</td>
<td>0.97</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Table 1: Calculated values of $\alpha_{LWE}$ for five mid-infrared active region materials at room temperature. $E_g$ is the band gap, $\rho_v/\rho_c$ is a measure of the ratio of the valence to conduction band densities of states, and $\Delta E_{CB}$ is the miniband width of the lowest conduction subband.
Figure 1: Gain, differential gain, differential index and $\alpha_{LW}(\omega)$ as a function of transition energy for (a) bulk InAs$_{0.91}$Sb$_{0.09}$, (b) an InAsSb/AlInAsSb quantum well, (c) an InAsSb/InAsP quantum well, and (d) an InAs/GaInSb/InAs/AlGaInAsSb type-II superlattice. The vertical line indicates the energy of the peak gain. The densities chosen are those which minimize $\alpha_{LW}$ at the peak gain.

The results of our calculations of linewidth enhancement factors are listed in Table 1. Figure 1 shows the gain, differential gain, differential index, and linewidth enhancement factors as a function of transition energy for four of the systems. It is apparent in Fig. 1 that the differential gain spectrum for systems (a) and (b) is most unbalanced about the peak of the gain spectrum. The barriers in systems (c) and (d) are much higher, both for electrons and holes, and thus the differential gain spectrum is peaked closer to the band edge. This is a mark of improved balance in the density of states. The imbalance between the densities of states can be quantified using the ratio of the valence and conduction band-edge Fermi occupation functions at a density where the sum of the Fermi functions is 1.0 (which is a minimal condition for gain). Calculated values are shown in Table 1 for all of the materials.

Within each type of structure (quantum well or superlattice), those with larger conduction band dispersion (listed in Table 1) have smaller linewidth enhancement factors. The presence of dispersion in the conduction band shifts the peak of the gain spectrum (and hence, the lasing energy) from the band edge to an energy roughly the miniband width above the band edge. The region of positive differential gain between the band edge and the shifted gain spectrum peak reduces the density-dependence of the index of refraction and the value of the linewidth enhancement factor at the peak of the gain spectrum.

An additional optimization can be used to reduce the linewidth enhancement factor in the type-II superlattices. Intersubband absorption features in these superlattices are relatively sharp due to the highly structured nature of the valence subbands. It is possible to adjust the energy of the subbands by modifying the layer thicknesses and alloy compositions in such a way as to place a large absorptive feature above the peak of the gain spectrum. The presence of this large density-dependent absorption feature just above the
lasing energy will reduce the density dependence of the index of refraction at the lasing energy without reducing the differential gain. Thus the linewidth enhancement factor will be reduced. An example of this is shown in Fig. 2 for two 4.5 μm type-II superlattices. The placement of the resonance at 305 meV in one structure (solid line) rather than 255 meV in the other (dashed line) leads to a 34% reduction of α_{LWE} at the peak of the gain spectrum. For both systems, the curves shown represent the density at which α_{LWE} is a minimum.

Figure 2: (a) Intersubband absorption, (b) differential gain, and (c) α_{LWE} for two superlattices. One (solid line), 18Å InAs/30Å Ga_{0.55}In_{0.45}Sb/18Å InAs/65Å Al_{0.30}Ga_{0.42}In_{0.28}As_{0.5}Sb_{0.5}, has an optimally placed intersubband absorption feature, while the other (dashed line), 20Å InAs/38Å Ga_{0.75}In_{0.25}Sb/20Å InAs/65Å Al_{0.30}Ga_{0.42}In_{0.28}As_{0.5}Sb_{0.5}, does not.

The discussion to this point has focused on the linewidth enhancement factor at the peak of the gain spectrum. We can estimate the minimum linewidth enhancement factor that can be obtained through detuning of the lasing frequency with a DFB structure by calculating the minimum linewidth enhancement factor over the energy range where the gain is greater than some minimum value. The results for a minimum gain value of 50 cm⁻¹ are shown in Table 1. It is possible to obtain linewidth enhancement values as low as 0.3 with the type-II superlattices. This represents a very attractive value for spectrally pure or high power laser operation.

CONCLUSIONS

α_{LWE} has been calculated for five mid-infrared materials. Electronic structure engineering strategies for reducing α_{LWE} have been identified, including the influence of conduction miniband dispersion and the proper placement of intersubband absorption peaks. Type-II superlattices have α_{LWE}’s near 1 at the peak of the gain spectrum, and near 0.3 for reasonable material gains.

ACKNOWLEDGMENTS

This research was supported in part by the United States Air Force, Air Force Materiel
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11. The structure (including bulk constituent energies) is taken from Fig. 1 of S. R. Kurtz, A. A. Allerman, and R. M. Biefeld, Appl. Phys. Lett. 70, 3188 (1997).
