ECE 536 – Integrated Optics and Optoelectronics
Lecture 19 – March 30, 2021

Spring 2021
Tu-Th 11:00am-12:20pm
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Lecture 19 Outline

- Finish Strain Effects
- Brief comments of Quantum Dot Lasers
- Semiconductor Optical Amplifiers
Strain Effects
Strain Effects in Quantum Wells

- For unstrained material, bandgap is the same for HH and LH. The energy levels in a quantum well, corresponding to HH and LH, differ because of unequal effective masses.
Strain Effects in Quantum Wells

• For strained materials HH and LH bandgaps and the energy offsets in CB and VB are different. HH and LH are in different potential wells.

• QW under tensile strain brings HH and LH quantum levels closer to each other (LH has deeper well but higher energy levels)
Recall that

- C1-HH1 transition is mostly favored by TE
- C1-LH1 transition is mostly favored by TM

- Tensile strain can improve balance between TE and TM gain
- Trade-off is maximum gain linked to joint density of states through the ratio of effective masses
Momentum Matrix Elements

Recall the matrix element depends on transverse wave vector $k_t$

For $k_t = 0$,

**TE Polarization:**

$$|\hat{x} \cdot M_{c-hh}|^2 = |\hat{y} \cdot M_{c-hh}|^2 = \frac{3}{2} M^2_b$$

$$|\hat{x} \cdot M_{c-lh}|^2 = |\hat{y} \cdot M_{c-lh}|^2 = \frac{1}{2} M^2_b$$

**TM Polarization:**

$$|\hat{z} \cdot M_{c-hh}|^2 = 0$$

$$|\hat{z} \cdot M_{c-lh}|^2 = 2 M^2_b$$

Reminder: Empirical Fit of optical momentum matrix element

$$M^2_b = \frac{m_0}{6} E_p$$

Tabulated from experimental data for various materials

Gain depends on surface (sheet) carrier concentration

$$n_S = n \times L_Z$$
Momentum Matrix Element

- Normalized as $2|M_{nm}(k_t)|^2/M_b^2$ with $n = C1$, $m = HH1$ for compressive strain and $m = LH1$ for tensile strain
Modal gain versus sheet concentration

For In$_{1-x}$Ga$_x$As / In$_{1-x}$Ga$_x$As$_y$P$_{1-y}$ quantum well laser working near 1.55μm

\[ n_s = n \times L_z \]
Band Distortion in Strained Quantum Wells

In$_{1-x}$Ga$_x$As

Summarizing comments

• As we have seen, LH can become heavier, HH can become lighter

• Compressively-strained materials may have lower valence band density of states (because HH at the top of the VB may have effective mass lower than LH at the top of the VB in the case of tensile strain)

\[ n_s = n \times L_z \]
Modal Gain versus Current Density

- Modal Gain

\[ \Gamma g \propto \frac{L_z}{W_{\text{mode}}} g \]

- Empirical relationship

\[ G = n_w \Gamma_w g_w = n_w \Gamma_w g_0 \left[ \ln \left( \frac{n_w J_w}{n_w J_0} \right) + 1 \right] \]

**Compressive strain**
Smaller transparency carrier density but it saturates faster.

**Tensile strain**
Larger transparency carrier density but it increases faster (higher differential gain).

**Loss mechanisms** (Auger, recombination, intervalence band absorption) need to be factored in when considering current density.
Quantum Dot Lasers
SPSL = Short Period Superlattice

(Alternate monolayers of GaAs & AlAs instead of growing AlGaAs gives less fluctuation in QW width)
“adatom” (adsorbed atom) is an atom lying on a surface and is the opposite of a surface vacancy.
Formation of 2D layers: *adatoms* attach preferentially to surface sites. Formation of atomically smooth layers.
Stransky-Krastanov: layer-plus-island formation

Formation of clusters: intermediate process with 2D and 3D island growth. Transition from layer-by-layer to island growth occurs at a critical layer thickness.
InAs QD array in an InGaAs QW on GaAs

Can form 3D strained islands (growth of sheets of dots on top of each other, with vertical coupling of the dots)
Tunnel injection allows better carrier collection by the QW with reduced $J_{th}$, faster modulation, smaller linewidth enhancement.
Semiconductor Optical Amplifier (SOA)
Basic Characteristics of SOA

• SOAs are typically optical active regions in a semiconductor that are used without any optical feedback.

• An optical signal input experiences gain through stimulated emission.

• Spontaneous emission is added to the signal and then amplified through stimulated amplification while propagating in the structure.
Basic Characteristics of SOA

- Noise is added by spontaneous emission and amplified spontaneous emission.

- Carrier density and gain are not clamped if there is no feedback in the cavity. A larger fraction of carriers recombine through spontaneous emission, compared to a laser.

- SOAs are used mainly for photonic integration, but discrete SOAs also exist.
## Specifications\(^a\)

<table>
<thead>
<tr>
<th>Item #</th>
<th>SOA1013SXS</th>
<th>BOA1004PXS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating Wavelength</td>
<td>1528 - 1562 nm</td>
<td>1500 - 1600 nm</td>
</tr>
<tr>
<td>Optical Isolation (P_{IN} / P_{OUT})(^b)</td>
<td>≥42 dB</td>
<td>≥40 dB</td>
</tr>
<tr>
<td>Extinction Ratio(^c)</td>
<td>60 dB</td>
<td>70 dB</td>
</tr>
<tr>
<td>Switching Speed</td>
<td>1 ns</td>
<td>1 ns</td>
</tr>
<tr>
<td>Max Output Power for CW Input Signal</td>
<td>17 dBm</td>
<td>18 dBm</td>
</tr>
<tr>
<td>Max Output Power for Modulated Input Signal</td>
<td>9 dBm</td>
<td>10 dBm</td>
</tr>
</tbody>
</table>

\(^a\) Typical values. For complete specifications, please see Specs tab.

\(^b\) At 0 mA and 1550 nm

\(^c\) At \(P_{IN} = -20\) dBm and 1550 nm
Four important parameters characterize the performance of SOA:

- Signal gain
- Frequency bandwidth
- Saturation output power
- Noise figure

The measured signal gain of an SOA, in decibels, is given by

\[ G = 10 \log[\frac{P_{out}}{P_{in}}] \]

If it refers to a single light path from input to output (Travelling Wave Amplifier, TWA) the resulting gain is known as “single pass gain” \( G = G_s \). If positive feedback is provided by reflections from end-facets (Fabry-Pérot amplifier)

\[ G = \frac{G_s}{1 + F_B G_s} \]

\( F_B = \) proportion of output signal fed back to the input
The signal gain of an optical amplifier is limited by a finite range of input and output power. Experimentally, once the input power is increased to a certain level, the gain starts to drop.

\[ G_s = \exp(g_m L) = \exp\left[ g_0 L / (1 + I_{\text{out}} / I_{\text{sat}}) \right] \]

The pumping source creates a fixed amount of population inversion. As we increase the input power, as some point the rate of draining due to amplification is greater than the rate of pumping and the population inversion level starts to fall.

Gain saturation simply arises because of conservation of energy.
SOA Gain (Section 8.2.5 in Coldren, Corzine and Mašanović)

Gain of an SOA of Length $L$:

$$G_0 = e^{\Gamma g(N)L}$$

Rate Equation:

$$\frac{dN}{dt} = \frac{\eta_i I}{qV} - \frac{N}{\tau} - \frac{\Gamma_{xy}}{wd} \frac{g}{hv} P$$

($V$ is volume of active region)

Steady State:

$$\frac{dN}{dt} = 0$$

$$\frac{dN}{dt} \approx \frac{\eta_i I}{qV} - \frac{N}{\tau} = 0$$

$$N = N_0$$

$$\frac{\eta_i I}{qV} = \frac{N_0}{\tau}$$
SOA Gain

At low optical powers:

\[ N = N_0 = \frac{\eta_i I \tau}{qV} \]

\[ g_0 = a \left( N - N_{tr} \right) = a \left[ \frac{\eta_i I \tau}{(qV)} - N_{tr} \right] \]

differential gain

At large input/output powers, stimulated emission is included:

\[ N = \frac{\eta_i I \tau}{qV} - \frac{\Gamma_{xy} g \tau}{wd} \frac{P}{hv} \rightarrow g = \frac{wdhv}{\Gamma_{xy} \tau P} \left( \frac{\eta_i I \tau}{qV} - N \right) \]

\[ g = \frac{g_0}{1 + P / P_s} \quad \text{and} \quad P_s = \frac{wdhv}{a \Gamma_{xy} \tau} \quad \left( P_s \text{ typically 1-20 mW, depends upon } \Gamma \right) \]

\[ \frac{dN}{dt} \approx \frac{\eta_i I}{qV} - \frac{N}{\tau} = 0 \]

\[ N = N_0 \]

\[ \frac{\eta_i I}{qV} = \frac{N_0}{\tau} \]
SOA Amplifier Response

Net Amplifier Response:
Integrate over gain length for amplifier response:

\[
\frac{dP}{dz} = gP = \frac{g_0}{1 + P/P_s} P = g_0 \left( \frac{1}{P} + \frac{1}{P_s} \right)^{-1}
\]

\[
G = \frac{P(L)}{P(0)} = \frac{P_{out}}{P_{in}} = G_0 \exp \left[ -\frac{G - 1}{G} \frac{P_o}{P_s} \right]
\]

\[
G_0 = e^{gL} = e^{g_0 L} \text{ is the unsaturated gain when } P_o \ll P_s
\]
SOA Amplifier Response

Proof:

\[ \int \left( \frac{1}{P} + \frac{1}{P_s} \right) dP = \int g_0 dz \]

\[ \ln \left( \frac{P(L)}{P(0)} \right) + \frac{P(L) - P(0)}{P_s} = g_0 L \]

\[ \ln (G) + \frac{P(0)}{P_s} (G - 1) = g_0 L \]

\[ \ln (G) + \frac{P(L)}{P_s} \left( \frac{G - 1}{G} \right) = g_0 L \]

\[ \ln (G) = g_0 L - \left( \frac{G - 1}{G} \right) \frac{P(L)}{P_s} \]

\[ G = G_0 \exp \left[ - \left( \frac{G - 1}{G} \right) \frac{P(L)}{P_s} \right] \text{ where } G_0 = e^{g_0 L} \]
SOA Amplifier Response

Output Saturation Power:
The output saturation power $P_{o,sat}$ is defined as the power that causes the gain $G$ to drop to half of $G_0$:

$$G = G_0 \exp \left[ - \frac{G - 1}{G} \frac{P_{o,sat}}{P_s} \right] = \frac{1}{2} G_0$$

$$P_{o,sat} = \frac{G_0 \ln 2}{G_0 - 2} P_s$$

Proof:

$$G = G_0 \exp \left[ - \left( \frac{G - 1}{G} \right) \frac{P(L)}{P_s} \right]$$

$$P(L) = -P_s \left( \frac{G}{G - 1} \right) \ln \left( \frac{G}{G_0} \right)$$

$$P_{o,sat} = -P_s \left( \frac{G_0 / 2}{G_0 / 2 - 1} \right) \ln \left( \frac{1}{2} \right)$$

Neglecting facets feedback

SOA Noise Figure:

$$F_A = 2n_{sp} \left( \frac{g}{g - \alpha_i} \right) = 2 \frac{f_2 (1 - f_1)}{f_2 - f_1} \left( \frac{g}{g - \alpha_i} \right)$$

(typically $\sim 5$dB)
SOA Noise Figure:

\[ F_A = 2n_{sp} \left( \frac{g}{g - \alpha_i} \right) = 2 \frac{f_2 (1 - f_1)}{f_2 - f_1} \left( \frac{g}{g - \alpha_i} \right) \] (typically \( \sim 5 \text{dB} \))

(Neglecting facets feedback)


• For photonic integrated circuits including optical receivers, SOAs should not have polarization dependence. Structures needs to be designed for gain and optical confinement factors are similar for TE and TM modes.
• Inclusion of strain in the active region is an approach commonly used to achieve this.