QCL Fundamentals

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Outline

- Motivation
- Basic QCL design/function
- Improvements over traditional semiconductor lasers
- Theoretical framework
- Design overview
QCL Motivation

- No convenient semiconductor sources in mid and far infrared wavelengths
- QCL’s properties result of design of epitaxial layers
  - Semiconductor lasers rely on intrinsic material properties to produce emission wavelength
  - Population inversion created in QCL’s by design of wavefunctions
- High quantum efficiency (one electron can emit more than one photon)
Electron confinement

- Dimensionality of material reduced by sandwiching between two layers of different materials
- Confinement changes density of states of incoming electrons
Multiple Quantum Well Structure
Inter-band vs. Inter-sub-band
Resonant tunneling

- Conducted current of quantum well peaks when resonance achieved between energy of incoming electrons and energy levels of quantum well.
QCL structure: injector / active region
Theoretical Framework - I

- Numerical solution of 1D, time-independent Schrödinger equation
- Determination of various scattering rates by applying Fermi’s Golden Rule
  - Spontaneous, stimulated emission
  - Electron-phonon, electron-electron, etc.
- Determination of level populations by applying rate equations
- Calculate population inversion
- Determine waveguide properties
- Calculate gain
Numerical Solution of Equations - I

- Schrödinger equation: \[
\frac{d}{dz} \left[ \frac{1}{m^*(z)} \frac{d}{dz} \right] \psi(z) = - \frac{2}{\hbar^2} (E - V(z)) \psi(z)
\]

- Poisson equation: \[
\frac{d}{dz} \left( \epsilon(z) \frac{d\phi(z)}{dz} \right) = \rho(z)
\]

- Solved using numerical methods
- Iterative solution is obtained
Scattering rates

- Rates have to be determined for all types of scattering
- Fermi’s Golden Rule for transition rate:
  \[
  W_{i\to f} = \frac{2\pi}{\hbar} |\langle f | H' | i \rangle|^2 \delta(E_f - E_i)
  \]

- Photon scattering: \( H' = -\frac{e}{m^* c} \vec{A} \cdot \vec{P} \)

- Phonon scattering: \( H' = \sum \alpha(q) \left( e^{iq \cdot r} \vec{b}_q^+ + e^{-iq \cdot r} \vec{b}_q^\dagger \right) \)

- Electron-electron scattering: \( H' = \frac{e^2}{4\pi \varepsilon |\vec{r}_i - \vec{r}_j|} \)
Rate Equations

- Populations for each level can be found by solving rate equations

\[
\frac{dn_2}{dt} = \frac{n_3}{\tau_{32}} - \frac{n_2}{\tau_{21}}
\]

\[
n_3 \approx \frac{n_3}{n_2} = \frac{\frac{1}{\tau_{21}} - \frac{1}{\tau_{12}}}{\frac{1}{\tau_{32}} - \frac{1}{\tau_{23}}}
\]
THz issues - I

- Difficulty: engineer system where lower level depopulated without also depopulating upper level
- At low temperatures, e-e scattering dominates
THz issues - II

- Difficulty: low-loss waveguide
- Long wavelength increases free-carrier absorption
- Losses characterized by:
  \[ \Gamma g_{th} = \alpha_W + \alpha_m \]
- SI-SP and MM waveguides used presently
Active region design

- Goal: maximum gain while minimizing losses
- Maintain population inversion by engineering wavefunctions and transition rates

\[ G_P = \frac{4\pi q^2}{\epsilon_0 n\lambda} \frac{z_{ij}^2}{2\gamma_{ij} L_P} (n_j - n_i) \]
Chirped Superlattice (CSL)
Bound-To-Continuum (BTC)
Resonant-Phonon (RP)
Summary

- QCL’s are semiconductor devices which use inter-sub-band transitions within the conduction band to create radiation
- They can be made to emit radiation at longer wavelengths than traditional band-gap lasers
- Longer wavelength emission requires special design considerations
Full Quantum Well Structure

\[ \Delta \Phi_{\text{applied}} : \text{Externally applied voltage drop (V)} \]

\[ \Phi(z) : \text{Built-in potential (V)} \]

\[ E_c(z) : \text{Conduction band edge energy in bulk (eV)} \]

\[ V(z) : \text{Effective conduction band edge energy (eV)} \]

\[ \Psi_n^r(z) : \text{Wave functions (nm}^{1/2}) \]

\[ E_n : \text{Energies of possible quantum states (eV)} \]

\[ E_F(z) : \text{Fermi energies (eV)} \]

\[ E_v(z) : \text{Valence band edge energy in bulk (eV)} \]

\[ E_g(z) : \text{Band-gap energies in bulk (eV)} \]