

6.977 Semiconductor Optoelectronics – Fall 2002

Problem Set 3 – Electroabsorption Modulators

Reading: Chuang, Section 3.5 in Chapter 3

This problem set will lead you through the design of a quantum well electroabsorption modulator. The key figure of merit is the modulation depth (change in transmission of light) for a given applied voltage. The length of the modulator and the thickness of the quantum well are critical dimensions that affect the performance of these devices.

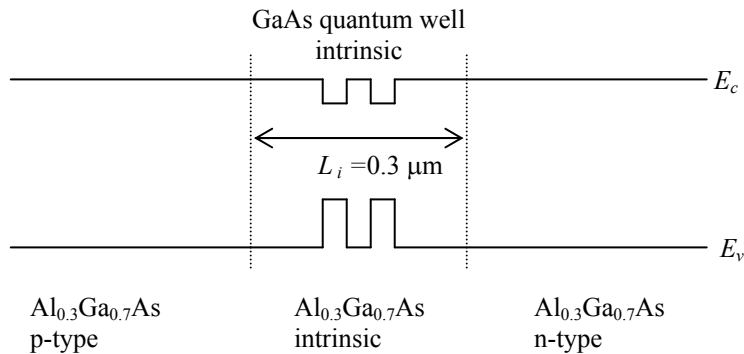
The modulator consists of GaAs quantum wells in the depletion region of an $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ p-i-n junction. The built-in potential is $V_o=1$ eV. The width of the intrinsic region is $0.3 \mu\text{m}$.

The conduction band discontinuity between GaAs and $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ is 250 meV. The valence band discontinuity between GaAs and $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ is 120 meV.

The effective mass for electrons in the GaAs quantum well is $m_e^*=0.067$ and the effective mass for the heavy-holes in the quantum wells is $m_h^*=0.34$. The bandgap of GaAs is 1.424 eV.

The effective mass for electrons in the $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ barrier is $m_e^*=0.091$ and the effective mass for the heavy-holes in the $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ barrier is $m_h^*=0.38$.

Note that the hole mass in the confinement direction for a quantum well is much smaller than the mass of a hole in bulk GaAs or $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$.



Problem #1 *This problem explores the critical length scales for an electroabsorption modulator.*
Throughout Problem #1 assume infinite quantum well.

- Given the built-in potential ($V_o=0.8$ eV), calculate the electric field in the intrinsic region as a function of the applied voltage (V_A). What is the internal electric field for applied voltages from $V_A = -5$ to 0 Volts. Note that the electric field is uniform throughout the intrinsic region and assume the depletion width is equal to the width of the intrinsic region.
- For a quantum well width of $L_w=10$ nm, calculate the shift in the first electron subband state ($n=1$) and the first hole subband state. Plot the lowest energy interband transition as a function of electric field. Vary the electric field from $E=0$ to 150 kV/cm. Calculate energies to second order in perturbation theory and keep only the first two non-vanishing terms in the perturbation expansion.
- Derive an expression for the wavefunction of the electron and hole to first order in perturbation theory. Use only the coupling between the quantum well ground state and first excited state.
- Derive an expression for the overlap integral between electron and hole envelope functions.
- Plot the magnitude of the band-edge absorption (in units of cm^{-1}) as a function of the applied electric field. Vary the applied electric field from $E=0$ to 150 kV/cm.
- For an incident photon with energy 1.475 eV, plot the absorption as a function of the internal electric field (from $E=10$ kV/cm to 150 kV/cm)

The transmission through a modulator is $T = e^{-\Gamma\alpha(V_A)L}$ where $\alpha(V_A)$ is the absorption calculated above and Γ is the confinement factor which is the fraction of the incident light beam that overlaps the quantum wells. Assume a confinement factor of $\Gamma = 0.02$

- For the same incident photon energy as part (f), plot the transmission as a function of the applied voltage. Vary the voltage from $V_A = -5$ to 0 Volts.
- Plot ΔT , where $\Delta T = T(V_A=0) - T(V_A) = e^{-\Gamma\alpha(V_A=0)L} - e^{-\Gamma\alpha(V_A)L}$, of the modulator as a function of the modulator length. For only this part of the problem, assume that $\alpha(V_A=0)=500$ cm^{-1} and that $\alpha(V_A)=1000$ cm^{-1} . What is the optimal length of the modulator? What is the extinction ratio of the modulator (ΔT measured in dB)?

Problem #2 *This problem explores the effect of finite quantum wells on the Quantum Confined Stark Effect.* In Problem #1, the quantum well was assumed to have infinite barrier height. While analytic solutions for the Stark shift of the energy levels can be derived for finite quantum wells, the calculations are often cumbersome. Also, the discontinuity in the effective mass between GaAs and $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ must be taken into account for an accurate calculation of the energy levels and wavefunctions. For this reason this problem explores finite-difference solutions of the effective mass Schrodinger Equation.

- a. Using the finite difference approach, repeat the calculation of electron and hole ground state energy levels and wavefunctions for finite quantum well. Note that the effective mass in the barrier and quantum well are different. Assume there is no electric field applied to the quantum well.
- b. What is the overlap integral for the electron and hole wavefunction? How does it compare to the infinite well approximation? Why?
- c. If you make the electron and hole effective mass equal in the quantum well and the barrier how much does that change the electron and hole ground state energies?
- d. Consider an applied electric field of 100 kV/cm. What are the new eigenenergies and wavefunctions for the ground state electrons and holes?
- e. What is the overlap between electron and hole wavefunctions under the applied field (100 kV/cm)?

Problem #3 *Choose the device that you would like to analyze for the term project.*

Suggested topics include:

Lasers

Gain coupled DFB laser
High power lasers (Al free)
1550 nm VCSELs
Widely tunable lasers (DBR)
1300 nm quantum dot lasers
1550 nm intersubband laser

Optical amplifier

Polarization independent SOA
Wavelength conversion

Detectors

Avalanche photodiode
Waveguide pin photodetector

Modulators

Traveling wave EA modulator
InP Mach-Zehnder modulator

Passive

Variable optical attenuator
Arrayed waveguide grating

The italics indicate devices that are not yet deployed in communications systems.