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980 nm Pump Laser for Erbium-Doped Fiber Amplifiers

This project explores the design of a 980 nm quantum-well semiconductor laser diode for use in erbium-doped fiber amplifiers (EDFAs). The goal is to determine a physically realistic material system and well thickness that achieves emission at the target wavelength while satisfying lattice-matching constraints for high-quality epitaxial growth.

Material Selection and Lattice Matching

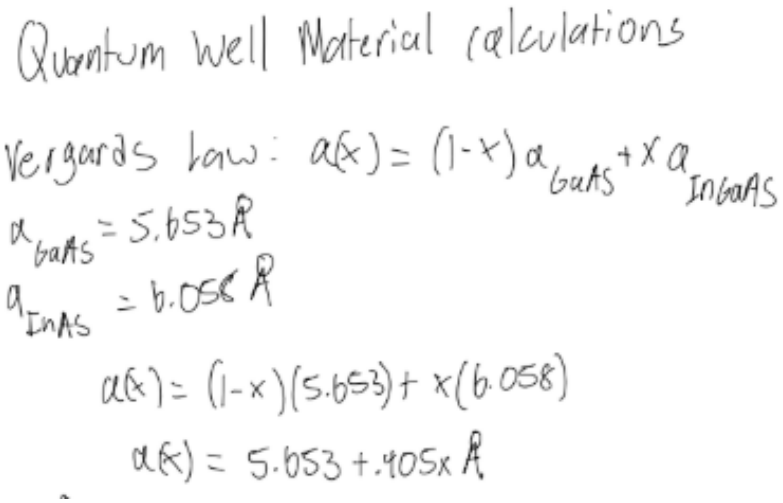
GaAs is selected as the substrate material due to its well-established epitaxial growth processes, availability of lattice-compatible ternary alloys (such as InGaAs and AlGaAs), and widespread use in semiconductor laser fabrication.

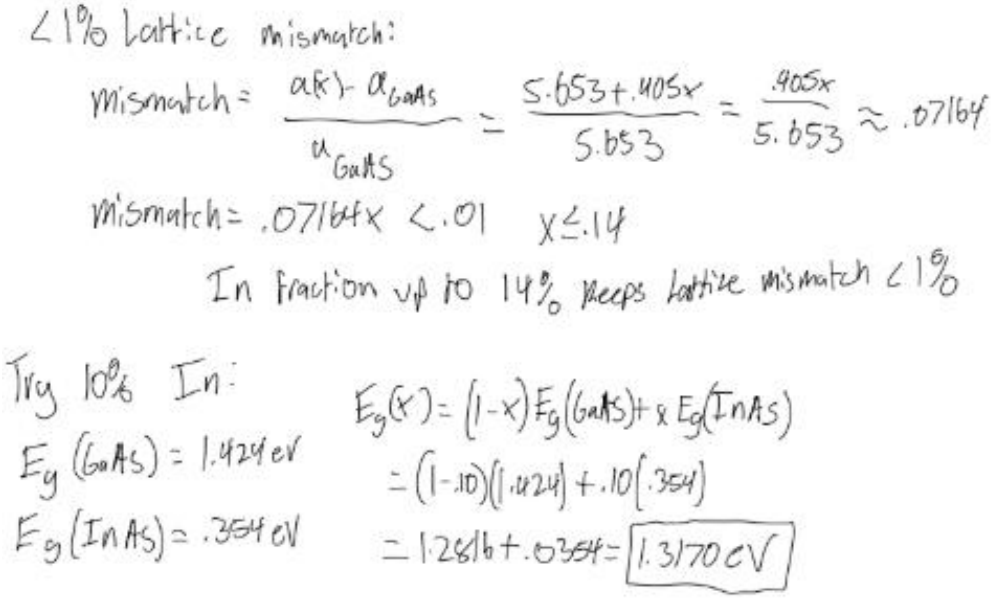
- GaAs has a lattice constant of 5.65325 A (iofee.ru)
- GaAs has a bandgap of 1.424 eV (iofee.ru)

Quantum Well Material

To emit at 980 nm, the quantum well must have a smaller bandgap than GaAs. Incorporating indium into GaAs to form InGaAs lowers the bandgap and slightly increases the lattice constant.

InAs has a lattice constant of 6.0583 A (iofee.ru)





Using Vegard's law, the indium composition was evaluated under the constraint that lattice mismatch remains below 1%. This analysis shows that the indium fraction must be less than 14 percent of the material. An initial design value of 10 percent was selected. For this composition, the calculated bandgap is 1.3170 eV which is less than that of GaAs (1.424 eV), ensuring carrier confinement within the quantum well.

Barrier Material

The barrier material must possess a larger bandgap than the quantum well to ensure proper carrier confinement. A lattice-matched and technologically straightforward choice is GaAs itself. Using GaAs as the barrier material simplifies epitaxial growth and automatically satisfies the lattice-matching constraint.

The bandgap difference between GaAs and the InGaAs well defines the band offsets. The total bandgap difference is partitioned according to a typical offset ratio:

- 60% allocated to the conduction band offset
- 40% allocated to the valence band offset

These offsets determine the confinement strength for electrons and holes within the quantum well. The detailed calculation is shown below.

Barrier Material Calculations

$E_g(GaAs) = 1.424\ eV$

$E_g(In_{.10}Ga_{.90}As) = 1.317\ eV$

$\Delta E_g = E_g(GaAs) - E_g(InGaAs)$

$\Delta E_g = 1.424 - 1.317 = \boxed{.107\ eV}$

$\Delta E_c = .6 \cdot \Delta E_g = .6 \cdot .107 = .0642\ eV$

$\Delta E_v = .4 \cdot \Delta E_g = .4 \cdot .107 = .0428\ eV$

The total bandgap discontinuity between GaAs and InGaAs is:

ΔEg=0.107 eV

Partitioning this discontinuity according to the assumed band offset ratio yields the corresponding conduction and valence band offsets.

Quantum Well Modeling

With the InGaAs well bandgap established at 1.317 eV and the corresponding band offsets defined as ΔEc = .0642eV and ΔEv = .0428eV, the next step is to model the quantum well and determine the ground-state confinement energies for electrons and holes.

A trial well thickness is selected, and the infinite square well approximation is used to estimate the n = 1 confinement energies. Although this model slightly overestimates confinement compared to a true finite well, it provides a reasonable first-order approximation that can be compared against the available well depths.

The ground-state confinement energies for electrons and heavy holes are calculated using:

Well thickness calculations

Electron confinement Energy E_{C_1}:

Try $L = 10nm = 10 \cdot 10^{-9} m$ (typical order of magnitude for quantum wells in type III-IV semiconductors)

Ground state for an electron:

$$E_{C1}^{(\infty)} = \frac{\pi^2 \hbar^2}{2 m_c^* L^2}$$

$\hbar$ = reduced planks constant

m_c^* = effective mass of electron in well

L = well thickness

Approximated effective electron mass for $In_{.10}Ga_{.90}As = .06m_0$

$$E_{C1}^{(\infty)} = \frac{(3.14)^2 (1.054 \cdot 10^{-34})^2}{2(.06)(9.11 \cdot 10^{-31})(10 \cdot 10^{-9})^2} = \frac{1.096 \cdot 10^{-67}}{1.0932 \cdot 10^{-47}} = 1.002 \cdot 10^{-20} J$$

$1eV = 1.602 \cdot 10^{-19} J$

$1.002 \cdot 10^{-20} J = .0626eV$

$E_{C1}^{(\infty)} = .0626eV$

Hole Confinement Energy E_{V1}

$$E_{V1}^{(\infty)} = \frac{\pi^2 \hbar^2}{2 m_{hh}^* L^2}$$

$m_{hh}^* = .45 m_0$

$$E_{V_1}^{(\infty)} = \frac{(3.14)^2 (1.054 \cdot 10^{-34})^2}{2(.45)(9.11 \cdot 10^{-31})(10 \cdot 10^{-9})^2} = \frac{1.096 \cdot 10^{-67}}{8.199 \cdot 10^{-47}} = 1.337 \cdot 10^{-21} J$$

$1.337 \cdot 10^{-21} J = .00835eV$

$E_{V_1}^{(\infty)} = .00835eV$

The calculated ground-state confinement energies are:

Ee1=.0626eV

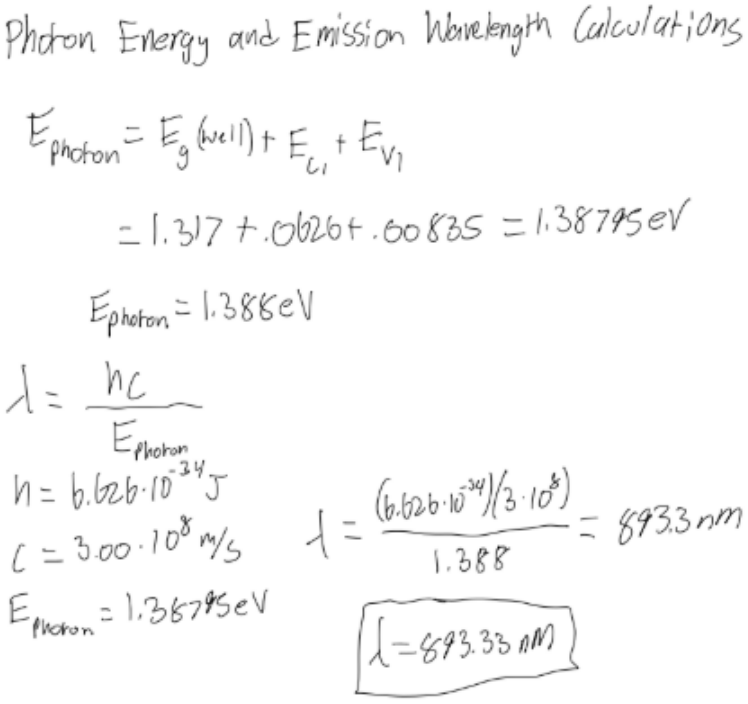
Eh1=.00835eV

Photon Energy and Emission Wavelength

With the well bandgap and confinement energies determined, the emitted photon energy is given by the sum of the well bandgap and the ground-state confinement energies for electrons and holes:

Eph=Eg+Ee1+Eh1

Where: Eg is the InGaAs well bandgap, Ee1 is the electron confinement energy, and Eh1 is the heavy hole confinement energy.



The resulting emission wavelength is calculated to be:

λ=893.33 nm

This value is shorter than the 980 nm target, indicating that the initial structure produces a photon energy that is higher than desired.

Design Iteration to Achieve 980 nm Emission

The initial structure produced an emission wavelength of 893.33 nm, which is shorter than the 980 nm target. Since photon energy is inversely proportional to wavelength, this

indicates that the total transition energy (bandgap + confinement) is higher than required. Achieving 980 nm emission therefore requires reducing the effective photon energy of the structure.

Two primary design variables influence the emission wavelength:

1. Quantum Well Thickness

Increasing the well thickness reduces electron and hole confinement energies. This lowers the total transition energy and shifts the emission wavelength toward longer values.

2. Indium Composition (x)

Increasing the indium fraction reduces the intrinsic bandgap of $In_xGa_{1-x}As$, further decreasing the photon energy.

However, the lattice-matching constraint limits the indium fraction to:

$x \leq 0.14$, to maintain less than 1% lattice mismatch with GaAs.

To satisfy both the physical constraints and the wavelength requirement, the design was adjusted by:

- Increasing the indium fraction to $x=0.14$
- Increasing the quantum well thickness to reduce confinement energy

These combined adjustments enable precise tuning of the emission wavelength to 980 nm.

Numerical Parameter Sweep

To systematically identify the optimal structure, a MATLAB-based parameter sweep was implemented. The model evaluates emission wavelength as a function of well thickness while incorporating:

- Composition-dependent bandgap with bowing parameter
- Conduction and valence band offsets
- Confinement energy calculations with physical well-depth limits

The InGaAs bandgap is modeled using the bowing relation:

$$E_g(x) = (1-x)E_g(GaAs) + xE_g(InAs) - bx(1-x)$$

This accounts for the non-linear dependence of bandgap on alloy composition.

Modeling Assumptions

Ground-state confinement energies are estimated using the infinite square well approximation as a first-order model. Because this approximation slightly overestimates confinement relative to a true finite well, the calculated energies are constrained not to exceed the available well depths (ΔEc and ΔEv). This preserves physical realism while maintaining analytical simplicity.

The iterative model converges to a structure that produces emission at approximately 980 nm.

MATLAB Implementation

```
%% 980 nm Quantum Well Laser Calculator
clear; clc;
%% Values
hbar = 1.054e-34;
m0 = 9.11e-31;
eV = 1.602e-19;
hc = 1240;
%% Updated well bandgap using bowing
Eg_well = 1.216; % eV (for x = 0.14)
%% Band offsets
Delta_Ec = 0.0642; % eV
Delta_Ev = 0.0428; % eV
%% Effective masses
me_eff = 0.06 * m0; % electron mass
mhh_eff = 0.45 * m0; % heavy hole mass
%% Thickness sweep (nm)
L_vals = 10:1:40;
lambda = zeros(size(L_vals));
for i = 1:length(L_vals)
L = L_vals(i) * 1e-9; % convert nm to m
% Infinite well electron and hole energies
Ec1 = (pi^2 * hbar^2) / (2 * me_eff * L^2) / eV;
Ev1 = (pi^2 * hbar^2) / (2 * mhh_eff * L^2) / eV;
% Cap energies by actual well depth
Ec1 = min(Ec1, Delta_Ec);
```

```
Ev1 = min(Ev1, Delta_Ev);
% Photon energy
Eph = Eg_well + Ec1 + Ev1;
% Convert to wavelength
lambda(i) = hc / Eph;
end
%% Display result table
disp(' L (nm) Wavelength (nm)');
disp([L_vals' lambda']);
%% Best match to 980 nm
[~, idx] = min(abs(lambda - 980));
fprintf('\nClosest to 980 nm: L = %d nm gives lambda = %.2f nm\n', ...
L_vals(idx), lambda(idx));
```

Optimization Result

Executing the parameter sweep yields:

L=12 nm and λ=980.03 nm

This well thickness produces emission within 0.03 nm of the 980 nm target.

Final Design Parameters

The optimized structure is summarized below:

Substrate: GaAs

Barrier Material: GaAs

Quantum Well Material: In(.14)Ga(.86)As

Indium fraction (x): 0.14 (maximum allowed while staying within 1% lattice mismatch)

Quantum Well Thickness: L=12 nm

Well Bandgap (with bowing): Eg =1.216 eV

Conduction Band Offset: Delta Ec =0.0642 eV

Valence Band Offset: Delta Ev =0.0428 eV

Under these parameters, the model predicts a photon emission wavelength of:

λ=980.03 nm

The indium fraction corresponds to the maximum allowable value under the 1% lattice-mismatch constraint with GaAs.

Summary

This project presents a parametric design approach for a 980 nm InGaAs/GaAs quantum well laser structure. The process incorporates material selection, lattice-matching constraints, band offset modeling, and confinement energy estimation.

The composition-dependent bowing parameter is included to accurately model the InGaAs bandgap. Ground-state confinement energies are calculated and combined with the well bandgap to determine photon energy. A numerical parameter sweep over well thickness identifies the structure that achieves the desired emission wavelength.

The optimized design — $In_{0.14}Ga_{0.86}As$ with a 12 nm well thickness — produces emission at 980.03 nm while maintaining physical realism and lattice compatibility