MSE 5460/ECE 5570, Spring Semester 2016
Compound Semiconductors Materials Science

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Assignment 3

Policy on assignments: Please turn in this assignment by 5pm, **Thursday, April 14th, 2016**.

General notes: Present your solutions *neatly*. Do not turn in rough unreadable worksheets - learn to **take pride in your presentation**. Show the relevant steps, so that partial points can be awarded. BOX your final answers where applicable. Draw figures wherever necessary. Please print out this question sheet and staple to the top of your homework. Write your name and email address on the cover.

Problem 3.1) Band Alignments and Energy-Band Diagrams

a) Solve problems 1-6 from Lundstrom's notes Page T3-42 posted on the class website.

b) Solve problems 8 & 9 from Lundstrom's notes Page T3-42 posted on the class website.

c) Verify your analytical solutions for part (b) above with a self-consistent 1D Poisson-Schrodinger simulation.

Problem 3.2) High Electron Mobility Transistors (HEMTs)

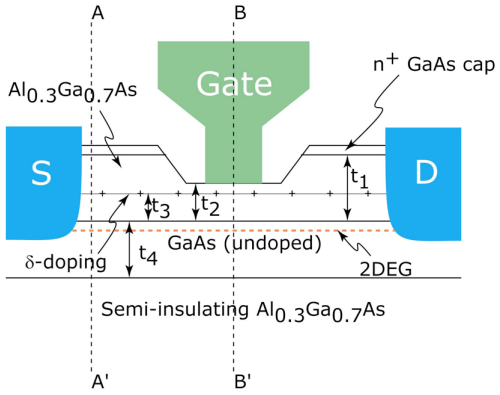

Figure 1: AlGaAs/GaAs $\delta-$doped HEMT.

Consider the AlGaAs/GaAs HEMT structure in Figure 1. The structure is grown by MBE. The thicknesses and doping of the layers are: the cap layer: $t_{cap} = 5$ nm and $N_D = 7 \times 10^{17}/\text{cm}^3$, $Al_{0.3}Ga_{0.7}As$ layer thickness $t_1 = 25$ nm, after the gate-recess etch, AlGaAs thickness $t_2 = 17$ nm, $\delta-$doped layer thickness=1 nm and effective 3D doping $= 3.5 \times 10^{19}/\text{cm}^3$, $t_3 = 5$ nm, and the GaAs quantum well thickness $t_4 = 10$ nm. Assume the surface barrier height is pinned at $q\Phi_s = 0.6$ eV below the conduction band edge for both GaAs and AlGaAs.

a) Calculate the 2DEG sheet density in the GaAs QW below the gate. Draw the charge-field-band diagram along line B-B' for finding the sheet density. Verify your calculated value with 1D Poisson-Schrodinger simulation of the charge-field-band diagram [1]. Is there any quantum-confinement? How many quantum-confined states are formed in the GaAs QW? What are the eigenvalues?.

[1] Run the "schrodingerstart", and "schrodingerstop" functions, and use the "*.status" file in 1-D Poisson.

b) Calculate the 2DEG sheet density in the GaAs QW below the source-and drain-access regions. Draw the charge-field-band diagram along line A-A' for finding the sheet density. Verify your calculated value with 1D Poisson simulation of the charge-field-band diagram. Comment on quantum confinement and eigenvalues.

c) What is the gate-capacitance C_g? Verify your analytical result with a 1D Poisson-Schrodinger simulation of C_g vs the applied gate voltage V_g.

d) Calculate the threshold voltage V_{th} for the HEMT. Verify your analytical result with a 1D Poisson-Schrodinger simulation of the sheet density n_s vs the applied gate voltage V_g; plot this in both linear and log scales.

Problem 3.3) Polar III-Nitride Semiconductor Heterostructures

Consider an $Al_{0.3}Ga_{0.7}N$/GaN HEMT structure. Assume that the surface Schottky barrier height is $q\phi_s = 1.7$ eV on AlGaN and $q\phi_s = 0.9$ eV on GaN. The $Al_{0.3}Ga_{0.7}N$ layer is coherently strained to the GaN lattice constant.

a) Calculate the net polarization sheet charge $Q_\pi(x)$ at a strained $Al_xGa_{1-x}N$/GaN heterojunction for barrier Al composition x. Use the value for $x = 0.3$ for the rest of the problem.

b) How does the *mobile* sheet charge at the AlGaN/GaN junction vary with the thickness t_b of the AlGaN barrier? Plot the sheet charge n_s for AlGaN thicknesses up to $t_b = 40$ nm.

c) Plot the energy band diagram of an AlGaN/GaN HEMT with a $t_b = 30$ nm AlGaN cap at zero gate bias, and at pinch-off. What is the pinch-off voltage? Verify your analytical calculation with a self-consistent 1D Poisson-Schrodinger solution.

d) Now, a $t_{cap} = 5$ nm layer of GaN is added above the AlGaN barrier. Calculate and plot the band diagram of this structure at zero bias and at pinch-off. What is the effective Schottky-barrier height in these two cases? Do you expect the gate leakage of this diode to be different from the AlGaN/GaN structure? Why (not)?

Problem 3.4) LEDs and Lasers

In class, we discussed that a negative absorption coefficient implies emission, and optical gain. The absorption coefficient of a bulk semiconductor under non-equilibrium conditions is given by $\alpha(\hbar\omega) = \alpha_0(\hbar\omega) \times [f_v(k_0) - f_c(k_0)]$, where $\alpha_0(\hbar\omega)$ is the equilibrium absorption coefficient, $f(...)$ are the non-equilibrium Fermi-Dirac distribution functions of the valence and conduction bands, and $k_0 = \sqrt{2m_r^\star(\hbar\omega - E_g)/\hbar^2}$ is the wavevector of electron states that allow interband transition of energy $\hbar\omega$. The Bernard-Duraffourg conditions for optical gain were discussed. Following up on the discussion, choosing GaN as an example and assuming a separation of quasi-Fermi levels larger than the bandgap by 0.2 eV ($F_c - F_v = E_g + 0.2$ eV), make quantitative plots the following as a function of photon energy $\hbar\omega$ at room temperature :

a) The equilibrium absorption coefficient $\alpha_0(\hbar\omega)$,

b) The Fermi difference function $f_v(k_0) - f_c(k_0)$,

c) The net absorption coefficient $\alpha(\hbar\omega)$, and

d) The gain spectrum.
Give a numerical estimate of the maximum gain (in cm^{-1}), and the energy at which it occurs. Look up reports of GaN-based lasers (they typically always involve quantum wells!) and compare numbers with your simple calculations.