FFFN35-Low Dimensional Physics 2019

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# Laboratory exercise

# OPTICS OF QUANTUM STRUCTURES

In this laboratory exercise we will use photoluminescence (PL) spectroscopy as well as photoluminescence excitation (PLE) spectroscopy to investigate electronic states in a quantum well (QW). With these two techniques we can get information on how light is absorbed in and emitted from the structure.

We will also perform Raman spectroscopy on different samples in order to determine the phonon energies that they have and we will use this information to identify the samples.

### Preparations:

Read this instruction. Look at your notes from the lectures on optics.

Sketch how the PL spectrum (excitation wavelength = 500 nm) would look for a QW sample with the structure shown in Figure 3.

Sketch the PLE spectrum for the same structure. The sample is excited with unpolarized light. You are detecting **a)** The emission from recombination between holes in the well in the valence band and electrons in the well in the conduction band. Which of the possible transitions would you choose for the detection? **b)** The emission from the GaAs substrate. Indicate in both spectra the band gaps of the materials. Does it matter from which side of the sample the light is sent in and detected? Why could it be difficult to measure the absorption of the QW by a transmission measurement?

For the laboratory exercise and the report writing you should be familiar with the following concepts:

* PL
* How to calculate the energy levels in a square potential well of finite depth.
* How the density of states looks for a 2D system (a QW) and for bulk (3D)
* Light and heavy holes
* Excitons, see 10.7.x in Davies book.
* Selection rules for interband transitions in a QW (transitions from the valence band to the conduction band).
* Raman spectroscopy and the concept of phonons.

### Absorption and emission in quantum wells:

Consider a quantum well consisting of a thin layer of (low bandgap) GaAs sandwiched in (high bandgap) AlxGa1-xAs. See Figure 1.



Figure 1. Band diagram in real and reciprocal space for a GaAs/AlGaAs QW.

Due to the restricted motion in z-direction, the 3-dimensional band structure is split into 2‑dimensional subbands. The subband splittings are given by the solution to the one-dimensional particle-in-a-box problem. The absorption of a photon is indicated by arrow A in Figure 1 and can occur for any value of *kx* and *ky*. The absorption is the probability for a transition of a given photon energy and it is mainly determined by the number of electron and hole states with the correct energy difference. This combination of electron and hole states is described by the joint density of states. Assuming parabolic bands in k-space, that is



where *m\**is the effective mass, the 2-dimensional density of states will be staircase-like with one step for each subband pair (a pair of one electron- and one hole-subband). Once the absorption has taken place, the electrons and the holes high up in the bands will rapidly relax down to the minimum of the energy band at (usually) *kx =ky* =0. The recombination process described by arrow B will therefore always take place at *k* =0.

### Experiments:

In a photoluminescence (PL) experiment, electrons and holes are created by the absorption of light. As described above, the electrons will rapidly go into the lowest possible state in the conduction band, giving off excess energy to the lattice (phonons). In a similar way the holes will go into the highest possible state in the valence band. The electrons and holes will finally recombine, emitting photons with the energy of the ground state, independent of the excitation wavelength. PL therefore gives information primarily about the ground state.

The absorption is connected to the electronic structure in a straight-forward way, as described above. It is however not always very easy to measure. In order to get information about the absorption, one can use a technique called photoluminescence excitation spectroscopy (PLE). In this technique one measures the number of photons emitted at a fixed detection wavelength (corresponding to the ground state energy) as a function of the wavelength of the excitation light. Since the created electrons and holes relax to the ground state, the number of emitted photons is proportional to the number of electron hole pairs created, that is proportional to the absorption.

The experimental setup that we will use for the PL and PLE experiments is shown in Figure 2.



Figure 2. Schematic description of the experimental setup used for the PL and PLE measurements on quantum wells. The Ar+-ion laser is used to pump the tunable Sapphire: Ti laser.



Figure 3. Schematic figure of the QW structure studied in the laboratory exercise.

We will also perform Raman scattering on different samples. Raman scattering is not well described in the book but was covered in the lectures. Here we will excite the samples with a laser and detect the scattered light. The scattered light has a frequency where  is the energy of the laser photons and  is the energy of the phonons. Raman scattering can not only detect phonons but also other excitations and is a quite general tool. The setup is very similar to that in Fig. 2 but we will here not use any cryostat since Raman scattering works well also at room temperature. We will not use a tunable laser, only a fixed He-Ne laser.

# Laboratory exercise and data analysis

### PLE spectroscopy on quantum wells

* Find the composition of the AlGaAs barrier, and the valence band and conduction band offsets using the PL spectrum (λexc = 532 nm), and appendix 3 in Davies’ book. Note that the band gaps in the appendix are for room temperature, where Eg for GaAs is 1.42 eV. Since you performed the experiments at a temperature of about 10 K it is more appropriate to use the band gap at 0 K, which is 1.52 eV for GaAs.

$$E\_{g}^{Γ}=1.52+1.247x$$

The change in band gap with temperature is about the same over the entire composition range, so the interpolation formulas for the offsets can be used without any change. The two samples have different composition of the AlGaAs.

* Calculate the energies of all the bound states in the QWs (L = 100 Å and L = 25 Å ). Appendix 3 in Davies’ book contains the effective masses you need for calculating the energies of the bound states in the QW. Use mΓ for the electrons. Calculate all the possible, that is allowed, interband transitions and compare this to the PL spectra and the PLE spectra.
* Indicate the transition corresponding to the light and the heavy hole states in the PLE spectrum. Which one is seen in the PL spectrum?
* Compare the relative intensities of the PL peak from the GaAs substrate and the QW with λexc = 532 nm and λexc = 720 nm
* Can any transitions between excited states be seen in the PLE spectrum? If so: compare to your calculated transition energies. Can you also see this transition in the PL spectrum?
* If there is time in the lab: Compare the two PLE spectra from the wider QW, where we detected the luminescence at different energies (corresponding to the QW and the GaAs substrate).

### Raman spectroscopy on AlGaAs

* Measure the Raman spectra of the QW sample. Use the phonon energies to determine the alloy composition of the AlGaAs barrier according to the article that was handed out. Compare this with the previously calculated value from the PL spectrum. Which one is more accurate?
* If there is time in the lab: Compare and describe the different Raman spectra from different materials. What can you say about the materials from the spectra.