University of Regensburg

Advanced Physics Laboratories

Experiment:
Photoluminescence

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Abstract:
Quantum wells in material systems with GaAs as starting material are technologically relatively easy to manufacture and are mainly used in modern optoelectronic devices. Besides the purely technical application, a semiconductor quantum well is also a well-suited system to experimentally illustrate the "particle in the box potential" model.

Contents

Learning Goals

In this lab experiment, GaAs quantum wells embedded in AlGaAs will be investigated with photoluminescence spectroscopy. This will give you the opportunity to perform experiments on current topics in semiconductor technology and to learn the fundamentals of modern optical semiconductor devices. The problem of quantized energy states of a particle in a box, otherwise known from various textbooks on theoretical physics, is applied here in reality, which you can also reproduce in the laboratory itself. In addition, you will gain information about the quality of the epitaxial fabrication process of the GaAs quantum wells from the measured data.
During this lab experiment you will become familiar with the following topics:

- What are direct and indirect semiconductors and their optical properties?
- What is photoluminescence and how is it detected?
- What are excitons?
- What is a quantum well and how to calculate the quantization energy?

In order to complete this experiment successfully, you should already have basic knowledge in the field of solid state physics, in particular semiconductors, or acquire this knowledge during the preparation phase of the experiment. The literature recommendations can help you with this.

1 Basics

1.1 Photoluminescence

If light of a suitable wavelength is irradiated onto semiconductors, photons are absorbed under consideration of the conservation of momentum if their energy is greater than the band gap of the semiconductor. Those electrons which have been lifted from the valence band into free states of the conduction band then relax into the energetically most favorable state at the conduction band edge. From there, radiative recombination with a hole in the valence band is possible, and a photon can be emitted. This entire process is called photoluminescence and is shown in Figure INSERT REFERENCE HERE **??** schematically.

INSERT FIGURE HERE

For direct semiconductors, i.e., semiconductors in which the minimum of the conduction band and the maximum of the valence band are at the same $\vec{k}$, no change in momentum due to phonons has to occur upon emission or absorption of a photon. This makes direct semiconductors such as gallium arsenide (GaAs) suitable materials for modern optoelectronic devices. If one evaluates the calculated band structures for pure GaAs (Fig. INSERT REFERENCE HERE **??**, right) in detail, one sees that at

the Γ-point[1] there are several dispersion relations $E(\vec{k})$ for the valence band. The most important of these are the curves of different curvature which are degenerate at $\vec{k} = 0$ and are assigned to light and heavy holes[2].

1.2 Heterostructures in reduced dimensions

The previous considerations initially apply only to pure bulk semiconductors, i.e. semiconductor crystals whose spatial extent is large compared to the relevant length scales. However, if one reduces the spatial extent in one or more dimensions, the situation changes significantly. Consider first an abrupt transition between two semiconductor materials, e.g., aluminum gallium arsenide ($Al_xGa_{1-x}As$, depending on the Al fraction x)and gallium arsenide (cf. Figure INSERT REFERENCE HERE **??**, left). At the interface of the materials, the bands align such that band discontinuities ΔE_{LB} and ΔE_{VB}, respectively, arise because GaAs has a smaller band gap than $Al_{0.32}Ga_{0.68}$. Regardless of the Al concentration x, the following applies to the partitioning of the difference in bandgap energy:

$$\frac{\Delta E_{LB}}{\Delta E_{VB}} \approx \frac{65}{35} \tag{1}$$

INSERT FIGURE HERE

Going one step further and embedding a thin layer of GaAs in $Al_xGa_{1-x}As$, we obtain potential wells for both the electrons in the conduction band and the holes in the valence band (Figure INSERT REFERENCE HERE **??**, right). Since the spatial constraint occurs only in the growth direction z and neither electrons nor holes undergo a constraint in the xy plane, this is the realization of the „particle in the one-dimensional box "problem. Incidentally, this two-dimensional system is called a quantum well. Analogously, one can also think of heterostructures in which the electrons are constrained in two or even three dimensions and thus can move freely only in one dimension or not at all. This kind of systems is then called quantum wire or quantum dot.

1.3 Energy levels in the quantum well

The calculation of the energy values is shown exemplarily for electrons in the conduction band, but with adjusted parameters it is valid just as well for holes in the valence band. If the thickness d of the quantum well is of the order of the De Broglie wavelength of the electron, quantization effects due to the spatial confinement of the electrons in the quantum well become noticeable. In the xy-plane, the motion of the electrons is still free, while the energy in the z-direction is quantized. This allows us to express the wave function in the form

[1] point of high symmetry in the crystal with $\vec{k} = 0$
[2] light hole (lh) and heavy hole (hh)

$$\Psi(x, y, z) = \psi(x, y)\, \varphi(z) \tag{2}$$

and thus to solve the Schrödinger equation for $\psi(x, y)$ and $\varphi(z)$ separately. The states of the system are then described with two parameters: a two-dimensional wave vector $\vec{k}$ for the motion in the xy-plane and a quantum number n as an indicator for the energy eigenvalue in the z-direction. For the total energy of a particle then applies

$$E_{ges}(n, \vec{k}) = E_n + E(\vec{k}) \quad , \tag{3}$$

where E_n is the quantized energy of the n-th level. To obtain this, we have to solve the one-dimensional Schrödinger equation

$$\left[-\frac{\hbar^2}{2m^*(z)} \frac{d^2}{dz^2} + V(z) \right] \varphi(z) = E\varphi(z) \tag{4}$$

for a particle in the quantum well. The effective mass m^* of the particle in equation 4 depends on the location, since the particle in the GaAs quantum well has a different effective mass than in the surrounding barrier material. We denote the mass in the well by m_w^*, in the barrier by m_b^*. To simplify the calculation, we first assume an infinitely deep potential well of width d. With the boundary condition that the wave function cannot penetrate into the barrier, it is sufficient to consider the region of the quantum well, so that as solutions of equation 4 we obtain the energy eigenvalues

$$E_n = \frac{\hbar^2}{2m_w^*} \left(\frac{n\pi}{d} \right)^2 \tag{5}$$

If we now consider the case where a real quantum well has only a finite potential depth V_0, we will obtain only a finite number of quantization energies $E_n < V_0$ as solutions. The Schrödinger equation (Eq. 4) is still valid. With a suitable choice of the zero point of the z-axis, it is defined section-wise as follows:

$$\left[-\frac{\hbar^2}{2m_w^*} \frac{d^2}{dz^2} \right] \varphi(z) = E\varphi(z) \quad \text{für} \quad |z| \leqslant d/2 \quad \text{(in the quantum well)} \tag{6}$$

$$\left[-\frac{\hbar^2}{2m_b^*} \frac{d^2}{dz^2} + V_0 \right] \varphi(z) = E\varphi(z) \quad \text{für} \quad |z| > d/2 \quad \text{(in the barrier).} \tag{7}$$

In the quantum well, the electron can be described by a standing plane wave, so we take the following approach:

$$\varphi_w(z) = A\cos(k_w z) \quad \text{for even symmetry} \tag{8}$$
$$\varphi_w(z) = A\sin(k_w z) \quad \text{for odd symmetry} \tag{9}$$
$$k_w = \sqrt{\frac{2m_w^*}{\hbar^2}E}$$

Similar to the infinite potential well, the energy E can take only discrete values E_n. Equation 8 describes symmetric wave functions for odd index n, equation 9 the asymmetric wave functions for even n.
In the barriers, the wavefunction of the electron decays exponentially, here holds:

$$\varphi_b(z) = B\exp(-k_b z) \quad \text{for} \quad z > d/2 \tag{10}$$
$$\varphi_b(z) = B\exp(+k_b z) \quad \text{for} \quad z < -d/2 \tag{11}$$
$$k_b = \sqrt{\frac{2m_b^*}{\hbar^2}(V_0 - E)}$$

The coefficients A and B are determined by the boundary conditions: At the interface between the quantum well and the barrier, both the wave function and the particle flux must be preserved:

$$\varphi_w(\pm d/2) = \varphi_b(\pm d/2) \tag{12}$$
$$\frac{1}{m_w^*}\left.\frac{d\varphi_w(z)}{dz}\right|_{z=\pm d/2} = \frac{1}{m_b^*}\left.\frac{d\varphi_b(z)}{dz}\right|_{z=\pm d/2} \tag{13}$$

Finally, taking all the information together, two equations can be established that describe the relationship between the quantum well width d and the quantization energy E_n:

$$\sqrt{\frac{m_b^* E_n}{m_w^*(V_0 - E_n)}}\tan\left(\sqrt{\frac{2m_w^* E_n}{\hbar^2}}\frac{d}{2}\right) = +1 \quad \text{für} \quad n = 1.3,\ldots \tag{14}$$
$$\sqrt{\frac{m_b^* E_n}{m_w^*(V_0 - E_n)}}\cot\left(\sqrt{\frac{2m_w^* E_n}{\hbar^2}}\frac{d}{2}\right) = -1 \quad \text{für} \quad n = 2.4,\ldots \tag{15}$$

The results of the calculations are shown schematically in Figure INSERT REFERENCE HERE **??**: On the left, the situation is shown for a quantum well with an infinitely

high barrier, and on the right for the realistic case of a finitely deep quantum well. The wave functions of the first three quantized states are shown in each case.

INSERT FIGURE HERE

The quantization energies of the holes in the valence band of the quantum well are calculated in the same way. Since the effective mass is explicitly included in the calculation, light and heavy holes have different quantization energies. The energy degeneracy present in the bulk semiconductor (cf. INSERT REFERENCE HERE Fig.**??**) is cancelled by the quantum well. Table **??** lists some values of the quantization energy in a 10 nm GaAs-$Al_{0.3}Ga_{0.7}As$ quantum well for electrons and for heavy and light holes.

Table 1: Trajectory of an electron in the antidot lattice for magnetic field values corresponding to (a) $R_c = a$ and (b) $2R_c = a$. The trajectory tangles around the antidots cause the resistance maximum in the series resistance. (From [18]).

	n	V_0 finite	V_0 infinite
Electron	1	32 meV	57 meV
	2	120 meV	227 meV
	3	247 meV	510 meV
Heavy hole	1	7 meV	11 meV
	2	30 meV	44 meV
	3	66 meV	100 meV
Light hole	1	21 meV	40 meV
	2	78 meV	160 meV

1.4 Excitons

If a photon is absorbed and thus an electron is excited from the valence band into the conduction band, a hole remains in the valence band. An attractive force acts between the negatively charged electron and the positively charged hole due to the Coulomb interaction. This leads to the electron and the hole forming a bond, which can be described analogously to the bond of an electron to the proton in the hydrogen atom. The electron-hole pair is called an exciton. To calculate the exciton binding energy, the hydrogen model can be used with some corrections[3]:

$$E^{exc} = \frac{m^* e^4}{8\epsilon^2 \epsilon_0^2 h^2} \quad . \tag{16}$$

The spatial constraint of electron and hole wave function in the quantum well leads to the fact that the binding energy for excitons in the quantum well (2D excitons) depends

[3]e.g. effective masses of the binding partners, since they are crystal electrons; description of charge shielding in the crystal by dielectric constant

on the width of the quantum well. The relationship is shown in Figure INSERT REFERENCE HERE **??**.

INSERT FIGURE HERE

1.5 Optical properties of a quantum well

An important issue when considering luminescence phenomena is whether all possible transitions between quantized energy levels are also allowed. Intraband transitions, i.e. transitions within a band (e.g. from the electron state E_2 to E_1), are far in the infrared spectral range and shall not be considered further here. For interband transitions, parity conservation[4] (n and m are the quantum numbers for electrons in the conduction and for holes in the valence band, respectively):

$$\Delta n \;=\; |n-m| \quad \text{even} \tag{17}$$

For $\Delta n = 0$, the transitions are the most probable (arrows shown in bold in Fig.INSERT REFERENCE HERE **??**) and thus clearly visible as a luminescent line. Transitions with $\Delta n = 2$ are also allowed, but much less likely (thinly printed arrows in Fig. INSERT REFERENCE HERE **??**). By the way, the selection rules also apply to the absorption of photons.

If its energy is greater than the band gap of the barrier material, a photon can be absorbed, exciting an exciton in the barrier. At low temperatures, electrons and holes relax into the most energetically favorable states ($n = 1$, $m = 1$) in the quantum well. Note that a heavy hole has a lower quantization energy E_1 than a light hole, so that mainly heavy holes are involved in this process. The charge carriers (electron and heavy hole) recombine either non-radiatively via interaction with phonons or by emitting a photon. This variant is preferred especially in semiconductors with direct energy gap at low temperatures. In luminescence experiments, therefore, a spectral line with the energy

$$E^{photon} \;=\; E_{gap} + E_1^{LB} + E_1^{VB} - E^{exc} \tag{18}$$

is observed. Here E_1^{LB} denotes the energy of an electron in the first level in the conduction band and E_1^{VB} the energy of a heavy hole in the first level in the valence band.

1.6 Recommended literature

The following books can contribute to a better understanding of the subject:

- Franz Schwabl: *Quantenmechanik (QM I)*
  for: Particles in finite and infinite potential wells

[4]The parity conservation reflects the spatial overlap of the wavefunctions, which enters into the calculation of the transition matrix elements,

- Harald Ibach and Hans Lüth: *Festkörperphysik*
  for: Excitons, electrons in the potential well, photoluminescence spectroscopy in general.

- Charles Kittel: *Einführung in die Festkörperphysik*
  for: Band gap, exciton, direct & indirect semiconductors, effective mass, heterostructures in general.

2 Experimental setup

2.1 Overview

The overall experimental setup is schematically shown in Figure INSERT REFERENCE HERE **??**. A laser diode is directly coupled to an optical fiber[5] and emits light that is directed to the sample. A second optical fiber collects the luminescent light from the sample and couples it directly into the spectrometer. There it falls, spectrally decomposed, onto a suitable detector, where it is converted into an electrical signal. This signal is directly processed by a computer and displayed as a spectrum.

INSERT FIGURE HERE

2.2 Laser and power supply

The laser diode emits light of wavelength 638 nm and is directly coupled to an optical fiber. Since this is quite filigree, however, it is attached to a permanently installed fiber coupler from which work continues. The diode is controlled by the power supply, where the current is regulated by a knob. For the experiment, please select an operating current of maximum 68 mA.

2.3 Semiconductor sample and sample rod

The samples are prepared by molecular beam epitaxy. For this purpose, the components of the crystal are evaporated in a high vacuum, usually as pure elements, and deposited layer by layer on a wafer. This ensures maximum purity and precision. However, it is still not completely avoidable that impurities of carbon occur in small quantities. A 100 nm thick GaAs layer is first grown on a commercially available 350 μm thick GaAs substrate (called „buffer“). This and the subsequent 100 times repeated layer sequence 7 nm $Al_{0.32}Ga_{0.68}As$ - 3 nm GaAs („overlattice“) serve to improve the crystal quality. The ‚optically active‘part of the photoluminescence sample is then grown on top of it: 100 nm GaAs (optional) and multiple GaAs quantum wells separated by 20 nm thick barriers of $Al_{0.32}Ga_{0.68}As$ each. A 2 nm thin, optically inactive GaAs layer on the surface serves as oxidation protection. Pieces of about 2 mm $\times$ 3 mm are cut out from the substrate and incorporated in the sample rod so that the sample is about 2 mm from the end of the glass fibers. The optically active layers of the sample are thus located exactly at the intersection of the center axes of the glass fibers, which are slightly inclined to each other. The head of the sample rod itself is located inside a can and is immersed in a bath of liquid helium.

[5] multimode fiber with 600 μm core diameter

3 Experimental preparation

The following questions or tasks serve to prepare you for the content of the experiment. You should be able to answer them and respond to any follow-up questions at the preliminary discussion. The literature recommendations and the small collection of formulas in the appendix may be useful for your work.

1. Briefly explain what is meant by the term ‚semiconductor' Ėxplain the difference between direct and indirect semiconductor. Why are direct semiconductors better suited for semiconductor optical devices?

2. What is meant by a semiconductor quantum well and how can it be made?

3. What is meant by the terms ‚photoluminescence' or ‚electroluminescence'? Sketch the energy diagram $E(z)$ in the quantum well and barrier and draw the process of photoluminescence.

4. What is an exciton? Why does the binding energy of an exciton in a quantum well depend on its width?

5. Explain the outlined experimental setup shown in Figure INSERT REFERENCE HERE **??**. Describe in a few sentences what happens in the semiconductor sample during the measurement. How can the measurement results be used to make statements about the layered structure of samples?

6. Make a qualitative consideration for the relationship between the thickness of the quantum well and the wavelength of the associated emission.
   In the luminescence spectrum, the peaks of a 17 nm and a 20 nm wide quantum well are closer together than those of a 4 nm and a 7 nm wide quantum well. What could be the reason for this?

7. Make a rough estimate for a minimum and a maximum wavelength of photons that can be emitted during photoluminescence at GaAs-$Al_{0.32}Ga_{0.68}As$ quantum wells. Consider for this purpose two reasonably chosen extreme cases of the energy levels in equation INSERT REFERENCE HERE (**??**). They may neglect the exciton energy at this point.

8. Sketch qualitatively the spectrum of a hypothetical sample. For this purpose, assume that it is constructed from 5 quantum wells of different thicknesses waxed onto a GaAs wafer with a superlattice and a buffer layer. Incorporate the results of the previous tasks. Consider that photoluminescence can also occur outside the quantum wells.

9. In a sample, the thinnest quantum wells are incorporated just below the surface and the other quantum wells are incorporated in deeper layers, sorted by thickness. Make an educated guess as to why this is done.
   Tip: The emitted photons from the deeper layers must pass the higher quantum wells on their way out of the sample!

10. What changes in the luminescence spectrum do you expect if you do not measure at 4.2 K, but at a higher temperature?

11. Read the safety instructions carefully.

12. Read through the implementation and evaluation tasks. If you have any questions about them, you can bring them right into the preparation. Some of the tasks for the protocol are designed to be completed prior to the implementation. Whether you want to do this is up to you.

Remember as well to bring a USB stick for data storage to the experiment.

4 Execution

4.1 Safety notes

- **You are working here with a laser of laser class 3R. The radiation emitted by a laser of this class can cause irreparable damage to the eyes. During operation, the beam path is completely inside the fiber optic cables, but you should still work with caution and always switch off the laser before changing anything in the setup.** Optical fibers are expensive, delicate and can break if subjected to excessive mechanical stress. Therefore, handle them with care.

- **GaAs is a hazardous substance. Avoid contact with skin and eyes and use tweezers for handling. Take care when handling GaAs, even dusts or chipped particles are hazardous to health! Wash your hands after finishing the experiment**

- **Take care when handling cryogenic gases! Check whether the He can into which you insert the sample rod is connected to the return line and whether the corresponding shut-off valves are open. Slowly immerse the sample rod into the can to avoid overpressure caused by evaporating He. Avoid contact with the cryogenic liquid and the objects cooled in it. Use the available protective equipment! Gas escaping unnoticed can displace atmospheric oxygen and cause asphyxiation. If in doubt, contact the supervisor immediately. In case of emergency, open the windows and make sure that no one else is in the room.**

4.2 Execution and evaluation

Do not start the experiments until you have been instructed about the experimental setup by your supervisor. Please handle the instruments with care.

1. Measuring the spectrum of sample P1 at 4.2 K
   Let the supervisor show you how the installation and removal of samples works. Together, install sample P1, cool it in liquid helium. Connect the fiber optic cables, turn on the laser and regulate it to its operating current of 68 mA. View the spectrum on the PC using the ‚SpektraSuite'software. This sample contains 10 quantum wells and is made with an aluminum concentration of x = 0.32. Briefly discuss with the supervisor whether the measured spectrum matches your expectations from the preparation. Save the measurement [6].

2. Measurement of the spectrum of the sample P2A - P2E
   In the following, record the spectra of the samples P2A - P2E independently. These 5 samples all originate from the same wafer, which, however, was not rotated during growth. Consider how this circumstance could manifest itself in the observed spectrum and check whether the expectation is confirmed in the measurement results.

3. Influence of the temperature on the measurement Install the sample P3. When they have reached the point where the gas evolution increases strongly for the first time during cooling, measure the relative height of the sample rod to the lowest possible point (from the brass sleeve to the square sleeve). When the sample rod is fully cooled, select the serial save function[7]. Record a spectrum every 10 seconds and set the limit to 36 spectra (6 minutes). After starting the measurement, pull out the sample rod until it is approximately centered between the previously measured height and the maximum height ($\approx$ 100 cm) and fix it with the brass sleeve. At the end of the measurement, almost no peaks should be visible. If the sample has not warmed up enough, cool it down again and repeat the measurement for a higher position.

4. Leave the workplace clean. Switch off the laser completely and disconnect the optical fibers. Put covers on all fiber couplers and open ends of fiber optic cables, please rewind them carefully and store them in the boxes provided. Shut down the PC, remove the sample rod, and store the samples back in the box. Store any individual parts lying around in the drawers and hang the sample rod back in its place.
   Thank you.

[6]For further processing, e.g. with qtiplot, the recommended format is „tab separated“
[7]Under „Datei“⇒ „Speichern“⇒ „Spektrum speichern “

5 Preparation of the protocol for the experiment

5.1 Introduction to the topic

Your protocol should be a compact little scientific paper on the physics of photoluminescence on one-dimensional quantum wells. Your introduction to the topic should cover the following questions:

- What is the difference between direct and indirect semiconductors?
- How can a one-dimensional potential well be realized on a semiconductor basis? What is the difference between this and the theoretical model of the infinite potential well?
- What happens in photoluminescence? Also briefly address electroluminescence.
- What is meant by an exciton? How do excitons affect the emitted radiation? Why does their energy depend on spatial dimensions?
- What determines the energy of the emitted photons?
- What role does temperature play in photoluminescence? Why does the experiment take place in liquid helium?

Before you start the evaluation, please also describe in a few sentences how the experiment you are working with is structured.
The questions you worked on in preparation for the preliminary meeting do not necessarily have to appear in the protocol. However, the insights gained from them should be included in the processing.

5.2 Preparatory tasks for evaluation

In order to be able to evaluate the measurement results appropriately, first some relations between emitted wavelengths and physical conditions of the quantum wells have to be derived. These cannot be determined exactly analytically, but can be approximated well by graphical or numerical methods. The following steps should help you to do this:

1. First consider which quantities in equation **??** depend on the width of the quantum well. Then solve equation 14 for d, give yourself reasonable values for E for one of the two bands, and calculate d from this. Assume an aluminum concentration of x= 0.32.

2. Perform the same calculation for the other band. Try to find energy values that lead to the same values for d in a good approximation by varying the initial parameters.

3. For these values of d, determine the energies for the excitons from Figure INSERT REFERENCE HERE **??**. Add all pairs of values as in equation INSERT REFERENCE HERE **??** to create an $E(d)$ graph. Use this to graphically assign slice thickness to the measured wavelengths during the analysis.

4. For the evaluation, a relationship between the wavelength of the photoluminescence line and the temperature is also necessary. To do this, equate the equation of the temperature dependence of the band gap energy from the appendix. From this, form a $T(E)$ function for a fixed quantum well.

5.3 Evaluation

Now evaluate the results of your measurements. Use the previously determined correlations for this.

1. Plot the luminescence spectrum of sample P1 in a reasonable range using a program of your choice. Interpret the result. Which lines can be assigned to quantum wells and what is their thickness? How much would the deviations be if you used the infinitely deep potential well model instead of the exact model? Also, give explanations for the other observed maxima in the spectrum.

2. Select an appropriate quantum well of the P2 samples and compare the location of the associated luminescence line in the 5 different pieces. Discuss the differences in the results. In which parameters do the different sample pieces differ? Notes: Figure INSERT REFERENCE HERE **??** shows where the samples were taken from the wafer. The substrate from which the sample pieces were separated was not rotated during sample growth. However, the thickness of the layers at P2A, P2B, and P2C can be assumed to be the same

   INSERT FIGURE HERE

3. What changes in the spectrum of sample P3 do you observe? What are the physical causes behind them? Select 10 suitable spectra from the recorded spectra to estimate the respective temperature of the sample at the time of measurement using the shift of the luminescence line of the GaAs buffer. Match the intensities of the peaks to the temperatures and use this data to plot how temperature affects photoluminescence. Attach the corresponding graph to your protocol.

Appendix

Changing the sample

The following steps should serve as a reminder when changing samples.

1. Switch off the laser with the ‚Laser On‘button.
2. Uncouple both fiber optic cables from the sample rod and carefully set them aside.
3. Put on the cold protection gloves.
4. Open the brass locking sleeve (Fig. INSERT REFERENCE HERE **??**, in the second image above) and carefully pull the sample rod out upwards. If it freezes halfway up, be sure to continue holding the rod so that it does not fall back. Wait a moment before pulling it out completely. Screw the sleeve tight.
5. You can now take the gloves off again. Close the red tap leading into the can. Use the heat gun to bring the sample rod evenly to room temperature. When no more ice is deposited on the rod and it only feels metal cold, you can proceed.
6. Loosen the clamping sleeve and dismantle the sample rod. Place the red cap on the helium can to prevent contaminants from falling into it. Place the sample rod on the table and loosen the screw of the sample holder. Remove the sample holder and use the tweezers to take down the sample and place it in the box provided.
7. Check that there is still enough high-vacuum grease on the sample holder. A single, light application of grease should actually be sufficient for the entire procedure. Only now, please open the box of the next sample and place it on the sample holder with the tweezers. The shiny side of the sample must face upwards. Set the box aside and reattach the sample holder to the lower end of the rod.
8. Reassemble the sample rod onto the can. Remember to open the red tap again before cooling the sample. Keep an eye on the helium clock (Fig. INSERT REFERENCE HERE **??**, right) while doing this to avoid putting excessive stress on the feedback system. The ball in the gauge should always be in its lower third. If there is excessive gas, pull the sample rod back a bit and continue when the gas flow has decreased.
9. After successful cooling, reconnect the fiber optic cables and turn the laser back on with „Laser On“.

INSERT FIGURE HERE

Exciton energy

To better read the values for ground state energy of excitons in GaAs-AlGaAs, in figure INSERT REFERENCE HERE **??** is once again a section of figure INSERT REFERENCE HERE **??** shown enlarged.

INSERT FIGURE HERE

Small formula collection

Energy gap for Γ electrons of GaAs as a function of temperature:

$$E_{gap} = (1.5192 - 5.408 \times 10^{-4} \frac{T^2}{T + 204}) \,\mathrm{eV} \quad (\mathrm{T\ in\ K}) \tag{F1}$$

Energy gap for Γ electrons in $Al_xGa_{(1-x)}As$ at 4.2 K:

$$E_{gap} = (1.5192 + 1.247\, x) \,\mathrm{eV} \tag{F2}$$

Effective masses at the Γ point in $Al_xGa_{(1-x)}As$ (m_0 mass of the free electron):

$$\text{Electron:} \quad m_e^* = (0.067 + 0.084\, x) m_0 \tag{F3}$$
$$\text{Light hole:} \quad m_{lh}^* = (0.087 + 0.063\, x) m_0 \tag{F4}$$
$$\text{Heavy hole:} \quad m_{hh}^* = (0.34 + 0.175\, x) m_0 \tag{F5}$$

Conversion of energy into wavelength:

$$E\,[\mathrm{eV}] = \frac{1239.85}{\lambda\,[\mathrm{nm}]} \tag{F6}$$

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