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Author: Gudat, Jan
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Chapter 2

Experimental Setup

Temperature dependent photoluminescence spectroscopy (PL) is a method for characterizing optically active materials. In this thesis we are particularly interested in the optical properties of InGaAs/GaAs semiconductor quantum dots for which we measure the PL at low temperatures. A PL setup requires various devices such as a stable and powerful monochromatic light source, optics to focus light onto the sample, a sample holder, collection optics, a spectrometer and a detector for the spectral analysis. For low temperature measurements the sample additionally needs to be mounted in a cryostat in order to potentially cool it down to 4.2K, the boiling point for Helium (He). These are the basic components of any low temperature PL setup. For more advanced studies, such as exciting and measuring specific areas on the sample at very low light intensities or carry out exciton lifetime measurements, the standard setup has to be modified and equipped with additional devices, such as pulsed laser systems, avalanche photodiodes (APDs), and motorized stages. In the overall design, physical stability of the final system is in particular an important requirement when measurements need long integration times.

This chapter gives an overview of the components used for almost all experiments discussed in this thesis. Modifications are addressed in each chapter. Details on practical and design issues as could be of importance for anyone building a similar setup are addressed in appendix A.

2.1 Optical setup

The main components of the setup are illustrated in Fig. 2.1. The setup can be used for different purposes such a PL measurements, resonant spectroscopy at very low pump intensities, and surface defect induced strain experiments. For PL measurements mirror **M1** is in place so the pump laser can excite the

sample which is located in the cryostat. The sample itself can be moved in x, y and z by using a stack of three micro-positioners which allows to easily address specific regions on the sample and focus the laser onto the surface (z-direction). For this purpose there is a CCD camera installed that images via beamsplitter **BS2**. Beamsplitter **BS1** causes the collection path to direct the light, with beamsplitter **BS3** being removed, to a high resolution spectrometer with an attached CCD array. The system can be improved by replacing beamsplitter **BS1** by a dichroic mirror and by removing **BS2** during measurements. With the objective (or an aspheric lens) mounted on a nano-positioning stage it is possible to scan over the surface of the sample with a resolution of several nanometers. In this basic configuration the setup is used to analyze spectra, Stark-shift scans and carry out spatial scans (see Chap. 3 and 5). For permanent cavity tuning (see Chap. 4) high powers are focused onto the sample using different laser options in the excitation path. For that purpose beamsplitters **BS1** and **BS2** are taken out of the path to prevent damage on the CCD cameras (or on the grating of the spectrometer) and to maximize the available power. For resonant measurements (see Chap. 8) the collection path with the spectrometer can be turned into the excitation path. With this excitation path and with mirror **M1** removed, the reflected signal can be recorded via the two APDs or photodiodes for optical correlation measurements.

2.2 Laser and detector options

Depending on the application, different lasers are used for the different measurements. A standard diode laser at 780nm (in a few cases a Helium-Neon (HeNe) laser at 633nm was used instead) allows to pump the sample above the GaAs bandgap and image the sample surface. For high-power operations we utilize a continuous-wavelength (CW) pump laser (Millennia Vs) at 532nm with a maximum output power of 5W. This laser allows to pump a Ti-sapphire CW ring-laser that can output up to 800mW power when tuned to 770nm. This particular laser is used for the hole burning technique described in Chap. 4. With the same pump laser we can also operate a tunable $(650 - 1100nm)$ Ti-sapphire Tsunami laser that can generate 20ps pulses when being mode-locked. This picosecond mode system is used for lifetime-measurements. For resonant measurements (Chap. 8) we make use of an external-cavity tunable $(930 - 945nm)$ diode laser (Velocity, Model 6319). It allows for fast linear sweeps at narrow linewidths $(< 300kHz)$.

For analysis of the emission from the sample the optical setup allows to couple the light via optical fibers (or free-space) into a high resolution spec-
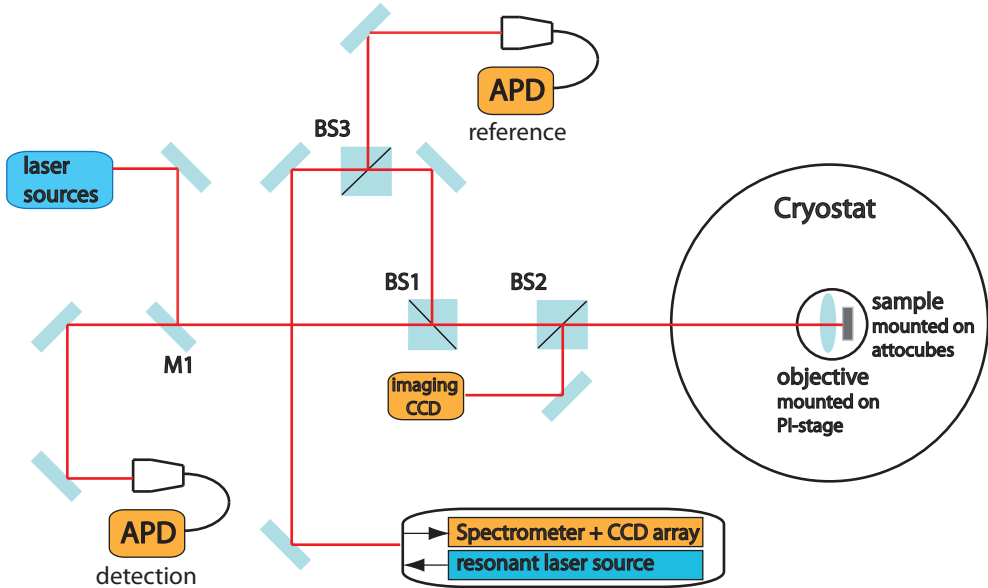
Figure 2.1: *Scheme of the experimental setup. This is the basic layout of the optical setup. Different laser sources can probe the sample in the emission path by being reflected on mirror **M1**. The sample is located in a 4K flow cryostat mounted on a micro-positioning stack. With beamsplitter **BS2** in place, the sample can be imaged onto a CCD camera. In the usual case of photoluminescence spectroscopy beamsplitter **BS3** is not located in the path and beamsplitter **BS1** is replaced by a dichroic mirror. For low and very high power measurements **BS2** can be taken out of the path in order to increase the collection efficiency or avoid damage to the CCD. The spectrum is recorded with a high resolution (1m) spectrometer with an attached CCD array. For resonant measurements the collection path just described can be turned into the resonant excitation path where it is useful to collect the emission with the two APDs having beamsplitters **BS1** and **BS3** in place and mirror **M1** removed. For precise scanning of the sample surface it is possible to control the objective mounted on a nano-positioning stage in x and y direction. The same objective can also be replaced with an aspheric lens.*

trometer (by Horiba Jobin Yvon, Model FHR-1000, focal length 1m). In the spectrometer the grating reflects the light onto a charge-coupled device (CCD). The grating can be rotated and covers the wavelength range of $0 - 1100nm$. In combination with the 1024(x127) pixels CCD array we obtain a simultaneous recording range of about 17nm or (5.6THz) resulting in a resolution of 0.016nm (5.5GHz) per pixel. The spectrometer is usually operated with a $5\mu m$ slit opening. The CCD (by Andor, back-illuminated, deep depleted) is optimized for near infrared applications corresponding to the emission wavelength of our QDs. It is operated at $-70°$ Celsius. The quantum efficiency at 940nm, the wavelength of interest, is 40 to 50% when operated at $-100°$ Celsius. The spectra are calibrated with a Neon spectral calibration lamp where at least three lines are identified on the given range of one recorded spectrum to get an accurate reading for each pixel given the linear fit through the three or more lines.

Si-photodiodes (PD) allow to directly measure light intensities and are helpful for alignment and optimization of in particular the reflection measurements (Chap. 8). For more sensitive measurements these can be switched to a femtowatt-receiver or avalanche photodiodes (APDs).

2.3   Cryostat

For stability considerations a He-flow cryostat (customized and manufactured by Janis) was chosen. It allows for a minimum amount of helium flow vibrations. See Fig. 2.2 for schematic side-view of the cryostat. The liquid helium boils within the cryostat and is continuously replenished by a steady flow of liquid helium from the storage dewar. It enters the cryostat from the side and cools the 4K pot by running through a few coils underneath the sample mount. Subsequently it cools the 60K pot with more coils that are vertically aligned on the side. The sample mount is the coldest point in the cryostat. On top of it rests a stack of three positioners (by Attocube, model ANPx100 and ANPz100) that allow to independently move the sample holder on top of them in all three directions. This eases investigating specific areas of a sample without having to re-align the whole optical path. Cooper braids connecting the sample mount with the sample holder help increasing the speed of the cooling process but also make sure there is enough cooling power to get the sample cold enough. The sample usually cools down to around 5K but only if being glued onto the sample holder with silver paint. The Attocube positioners are only used for rough alignment while a nano-positioning stage (by Physik Instrumente (PI), model P-733.3UD) mounted in the upper part

of the cryostat allows precise scanning of the sample by moving an objective or for some applications an aspheric lens. Though the attocubes are only used for rough alignment purposes, motions of 10nm at 4K can be realized. The nano-positioning PI-stage has a resolution of less than 0.3nm and a range of $100\mu m$ in x and y and $10\mu m$ in z. Because it can be controlled closed-loop and operates at room temperature, it is the preferred device for precision measurements. Its repeatability depends on the load and the PID settings of the stage. We usually measured a repeatability of ±2.5nm. The whole cryostat usually operates at 10^{-7}mbar when being pumped over night and cooled down to 4K. A rapid decrease of the pressure can be perceived below 120K when the so called 'cryo-cooling' causes remaining gas molecules to freeze out. At room temperature a typical pressure reading is around 10^{-4}mbar. For an accurate reading a vacuum gauge is attached to the cryostat as close as possible perpendicular to the pump direction. The pump is an oil-free turbo-pump (by Leybold, model TW70H) that is decoupled from the whole optical setup through flexible hoses. All components, the flanges, the hoses, the seals and the cryostat are designed to operate at ultra-high vacuum (UHV) (10^{-9}mbar). During cooled measurements the pump system can be completely decoupled from the cryostat and even the optical table.

A difficult design choice was to pick the right objective which allows high collection efficiency at the wavelength of the QD emission $900 - 950$nm and measure other characteristics of the sample (like i.e. the wetting layer) from $800 - 900$nm. Only a few commercially available objectives with rather short working distances seemed suitable and are described in the specific chapters. The blackbody radiation inducing heat on the sample and the sample holder turned out to be non-negligible. Therefore special radiation heat shields with very small openings for the light to pass through have been designed and allowed reasonable cooling down to 5K (see appendix A for more details). The cryostat was customized with 20 electrical wires attached to UHV rated electrical feedthroughs. These were sufficient to control the positioners, the temperature sensors, the heaters and electrically contact one sample. Later, we added additional feedthroughs and wires in order to electrically contact several samples during one cooldown and carry out more complicated and precise measurements (e.g. 4-point contact schemes and on sample temperature measurements).
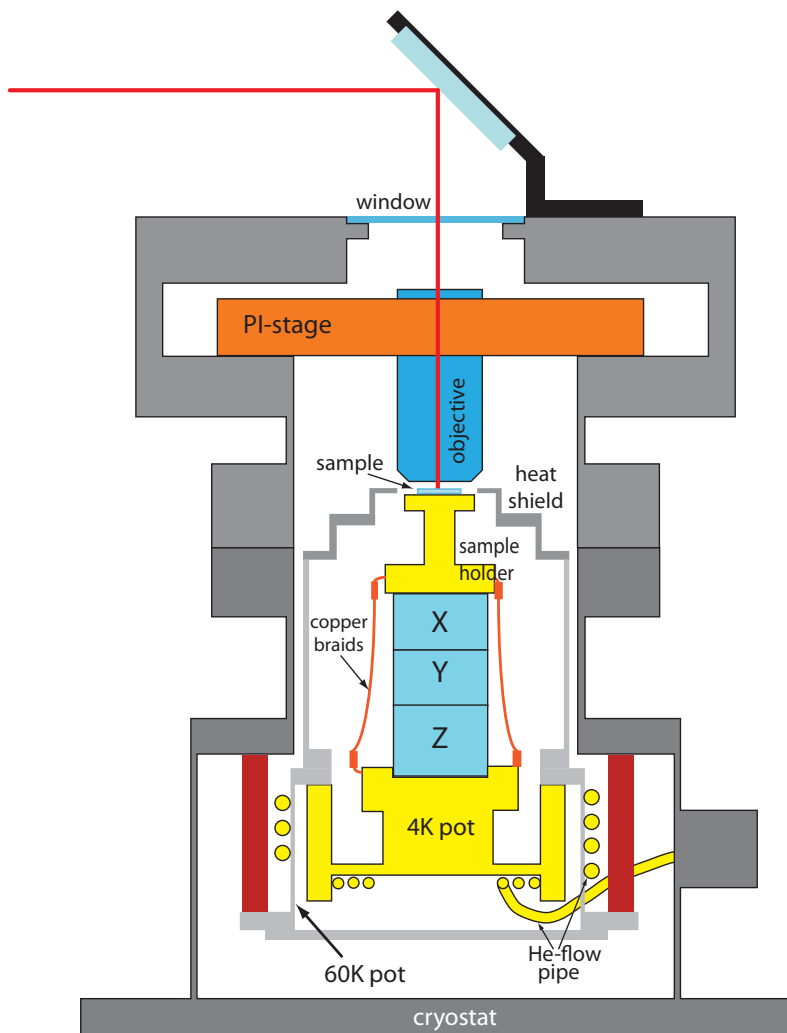
Figure 2.2: *Schematic view of the liquid He flow cryostat. The 4K pot is connected to the sample holder via cooper braids. The sample holder itself rests on a XYZ stack of positioners. The 4K pot is cooled by the liquid He entering the cryostat in three coils underneath the pot before it cools the 60K pot on the side. Above the sample rests a nano-positioning stage with a mounted objective focusing the light onto the sample surface. The nano-positioning stage is at room temperature but located inside the cryostat at high-vacuum. Not depicted in the scheme are the various electrical wires allowing to control temperature sensors, heaters, positioners and electrically contact several samples.*