ALC-Experiment B12
Low Energy Electron Diffraction
Supervisor team B12

June 26, 2020

Solid state physics, FAU Erlangen-Nuremberg
# Contents

1 Introduction 3

2 Basics 4
   2.1 Physical principles 4
   2.2 Experimental setup 6
      2.2.1 The vacuum chamber 6
      2.2.2 Sample holder and manipulator 7
      2.2.3 LEED Optics 9
      2.2.4 Electronic equipment 11

3 Manual 13
   3.1 Preparation and literature work 13
   3.2 Conduction and evaluation 14
      3.2.1 Clean reconstructed Ir(001) 14
      3.2.2 Oxygen covered surface 16
      3.2.3 Preparation of an unreconstructed Ir(100)-surface 16
      3.2.4 I(E) measurements 18

4 Appendix 19
   4.1 Collection of literature 19

Bibliography 20
1 Introduction

The surface of a crystal is the interface between the solid and its environment. Processes on the surface are subject of an interdisciplinary field between physics, chemistry and material science. This experiment shall introduce you to the basic concepts and some experimental methods of surface science.

Here, Low Energy Electron Diffraction (LEED) is used to study the bare surface of an Iridium single crystal as well as the adsorption of oxygen and hydrogen on it. After thermal activation the adsorbates form self-assembled structures, so-called superstructures and can therefore be identified via the appearance of additional diffraction spots.

The Ultra High Vacuum (UHV) environment prevents the surface from uncontrolled adsorption of residual gases resulting in typical contamination rates well below one single atomic layer per hour. Therefore, a side aspect of this experiment is to gain some knowledge about functionality and handling of UHV equipment.
2 Basics

2.1 Physical principles

A solid is a rigid assembly of atoms on a macroscopic scale. We distinguish between amorphous and crystalline solids. The latter have a periodic arrangement of atoms that can be described by the mathematical concept of a lattice with a specific configuration of atoms as basis.\textsuperscript{1–3} In contrast, amorphous solids do not fulfill this requirement but show short-range ordering at maximum. An intermediate class are polycrystalline materials that are build up from microscopic or mesoscopic single crystal grains which are more or less randomly orientated with respect to each other. Physicists have an unbroken interest in crystals, since their properties can be derived merely from the content of one single unit cell and the rules for its periodic continuation.

A surface is the boundary of a solid towards its environment. This fact sounds trivial, but in particular crystalline structures may and will undergo severe structural modifications as a consequence of the truncation of chemical bonds at the surface in order to reach an energetic minimum.\textsuperscript{4} Hereby either whole atomic layers may locally move towards a new equilibrium position (surface relaxation) or a completely different crystallographic structure with new periodicity, density and/or composition evolves within the outermost layers (reconstruction). Of course these structural modifications will have a strong impact on any other physical or chemical property of the surface. Usually, the expression “surface” refers to all atomic layers that deviate in a particular property of interest from the respective bulk value. Hence, the width of the surface regime not only depends on the special property under investigation but also on the accuracy of measurement.

Furthermore, any interaction of a solid with its environment happen right at the surface. The most obvious example is the adsorption of atoms and molecules. Such adsorbates may modify or even switch the crystallographic structure of the surface. Via diffusion into the bulk the adsorbates may even become part of the solid and new compounds with completely different structures may evolve.\textsuperscript{4} A common example for this is corrosion, where oxygen or oxygen-containing molecules first adsorb and dissociate on a metal surface and eventually interdiffuse forming a thick oxide film.

Low Energy Electron Diffraction (LEED) is a well-established method in surface science to investigate the structure and ordering of surfaces.\textsuperscript{4,5} The DeBroglie wavelength of low energy electrons (typical: 10 eV–1000 eV) is in the range of the lattice parameter and the penetration
The atomic structure, however, i.e. the exact position and chemical nature of the atoms within the unit cell, can only be deduced from the intensity of the diffraction spots, but here the consideration of multiple scattering is essential, which is numerically complex. For this purpose, in experiment the integral spot intensities are measured as a function of the kinetic energy of the electrons (see figure 2.1). In a second step, these so called I(E) spectra are calculated for various plausible structural models and many, many parameter variations within each model, until the best possible match to the experiment is achieved. With this method, surface structures can be determined within picometer accuracy today.5

A compact description of relevant physics concerning surface crystallography and low-energy electron diffraction can be found in the textbook "Fauster et al.: Surface Physics"4 (also in German: Fauster et al.: "Oberflächenphysik") in sections 1.1, 2.1.2, 4.1, and 4.2. The book is available in the library of the Dept. of Physics. On request the supervisor can provide you with copies of the relevant chapters.

---

Figure 2.1: Symbolic comparison of a measured I(E)-spectrum of the (1 0)-reflex for a clean Rh(100) surface (red) with a theoretically calculated “best-Fit” spectrum (blue). The R-factor is a measure for the goodness of the fit (the lower, the better).
2 Basics

2.2 Experimental setup

To guarantee a clean crystal surface the experimental setup is located in an ultra-high-vacuum (UHV)-chamber. The sample under investigation is an Iridium single crystal slice with the surface oriented along the [100] direction. Iridium has a face center cubic (fcc) crystal structure with a lattice constant of 3.84 Å. The sample is mounted on a sample holder that allows for translation in all three space directions and a rotation around an axis lying within the surface plane. The sample can be heated up to 2400 °C with simultaneous temperature measurement.

2.2.1 The vacuum chamber

The vacuum chamber is the central part of the apparatus with numerous functional elements attached. The sample manipulator (sample holder and drive) resides vertically on top of the chamber, while the LEED-optics is located at the rear. A large viewport at the front side allows a clear view into the chamber. Below this viewport there is a leak valve for controlled dosing of small amounts of gas from the attached gas reservoir into the main chamber. A pressure gauge is mounted in the small T-part on the left side. There are in total four pumps, which are mounted as follows: A roughing pump is placed below the table, a turbo molecular pump on the back side below the metal plate, an ion getter pumps (IGP) right below the main chamber and a titanium sublimation pump (TSP) on the left behind the large 90° elbow piece.

The standard way to generate UHV is nowadays a two stage pumping system, which consist of a turbo molecular pump (“turbo pump”) and a roughing pump (“pre-pump”). The turbo
pump can generate a pressure \(<1 \times 10^{-10}\) mbar but it needs also a vacuum at the outlet side. This "pre-vacuum" \((\geq 1 \times 10^{-3}\) mbar\) is generated by the roughing pump. Turbo pumps are very efficient to pump larger amounts of residual gas out of the chamber, as occurring during sample preparations or while pumping the chamber down from ambient pressure, but they have also some disadvantages. They produce unpleasant noise, vibration, and in case of a failure they form direct connection of the UHV side to the "pre-vacuum" at the outlet. Therefore, there are other pumps just to maintain the UHV inside the chamber after it has been generated. IGPs and TSPs are working exclusively under at least high vacuum (HV) conditions, but they have no connection to the outside, so it is possible to close up the whole UHV part.

An ion pump is a clever combination of a strong magnet and a capacitor made out of titanium. The magnetic field inside the ion pump forces free electrons on cycloid trajectories. They will ionize residual gas molecules or atoms entering the pump. Due to their much larger mass the ionized particles react hardly on the magnetic field but are accelerated by the applied electric field to the Titanium electrodes, where they get implanted (gettered).

Instead, a TSP is a fully passive pump. Its central part are massive titanium filament rods (diameter 2 mm), which are heated by a high current \((\sim 50\) A\) and thus sublimate titanium towards the surrounding walls forming fresh metallic Titanium films there. Reactive gases are strongly chemisorbed on the Titanium (i.e. the gas particles form strong chemical bonds to titanium) and therefore the number of remaining molecules in the chamber is reduced (sorption pump). From time to time, the titanium layer has to be refreshed. Therefore, the filaments are operated in cycles with off-periods depending on the chamber pressure. During this cycle bound gas particles are covered by fresh titanium layers and thus are embedded forever. TSPs are normally mounted in a remote part of the chamber to avoid direct sublimation from the pump to the main part of the chamber (especially sample, manipulator and measurement devices).

A Bayard-Alpert ion gauge for pressure measurement\(^9\) consists of an positively charged electrostatic cage with a negative collector in its center and a filament outside. The filament emits a constant flux of electrons, which are accelerated inside the cage. There they ionize residual gas particles, which are attracted by the collector in the center of the gauge. The collector current is then proportional to the density of gas particles in the cage volume and thus proportional to the chamber pressure. The pressure readout also depends on the atomic mass and the ionization cross-section of the respective residual gas. For special gas compositions, correction values for the different ionization cross sections have to be applied.

### 2.2.2 Sample holder and manipulator

Figure 2.3 depicts a sketch of the sample holder. The sample is fixed with small Tantalum strips (thickness 0.1 mm) spot welded on a Molybdenum carrier. The carrier is mounted between Titanium clamps, which are electrically and thermally contacted by massive 5 mm thick Copper...
rods. The whole electrical circuit is insulated from the support via Alumina ceramics and thin Mica slices.

The sample can be heated by applying an AC current through the sample carrier. The resistance of the carrier is at any temperature rather low. Therefore, a supply with high output current at low voltage is needed: $I_{\text{eff}} \approx 100\,\text{A}$, $U_{\text{eff}} < 7\,\text{V}$. It is strongly recommend to heat the sample to temperatures $T > 1000\,^\circ\text{C}$ for very short time intervals only (flash). The absolute time limit is about 2 min. Otherwise, the manipulator temperature drastically increases and heavy degassing starts (pressure increase due to desorption from hot surfaces).

The sample temperature is measured by a thermocouple, which is a pair of wires made from different alloy materials. In a closed circuit made up by the two wires there is a voltage created, when the two junctions are at different temperatures (Seebeck effect\textsuperscript{2}). The magnitude of this voltage depends on the temperature difference and on the material combination. In the experiment, one junction touches the rear of sample carrier, while the second is just at the meter and thus at room temperature. Both thermocouple wires have also to be fully isolated from the contact point at the sample to the readout device outside of the chamber. We use a so-called “Type D” thermocouple made from high melting Tungsten-Rhenium alloys (positive leg $W_{97}\text{Re}_{3}$; negative leg $W_{75}\text{Re}_{25}$), which is perfectly suited for the use at extremely high temperatures.

**Important note:** The thermocouple is touching the sample carrier and not the crystal itself.
Thus, the temperature reading is always ahead of the true sample temperature until a steady state is reached (within a few seconds). It is recommended to keep the final temperature for around five seconds to ensure that the crystal has reached the indicated temperature as well.

An external three-axis micrometer stage allows for precise spatial movement of the setup. Similarly, the rotation angle around the vertical axis (parallel to the sample’s surface) can be set within a single degree. The length of the flexible electrical connections to the sample holder limits the rotation angle. Therefore, stop positions are installed to avoid over-winding of the setup.

### 2.2.3 LEED Optics

A LEED optics consists of an electron gun, four grids and a fluorescent screen all concentrically arranged around the sample (see Figure 2.4). The electron gun can be divided into two functional parts: a beam generation unit (filament, Wehnelt cylinder and anode) and a beam focusing system (lens elements L1–L4) to focus the beam on the screen. The energy of the electrons - when leaving the gun - depends only on the potential difference between the filament (cathode), where the electrons have only negligible thermal energies, and the (grounded) sample. Any local electrostatic potential along the way through the gun do not influence the final electron energy (as long as the electrons can pass at all)! The electron source is either a thori-
ated Tungsten filament or a Lanthanum hexaboride (LaB$_6$)-single crystal filament. The electron emission from a filament depends on its temperature according to the Richardson equation:

$$j = A \cdot T^2 \cdot e^{-\phi/k_B T} ,$$

with $j$ the emitted current density, $A$ the Richardson constant, $T$ and $\Phi$ the cathode’s temperature and work function, and $k_B$ the Boltzmann factor.$^{10}$

The Wehnelt cylinder surrounds the filament. Set to a negative potential the Wehnelt cylinder repels the emitted electrons, thus forming an electron cloud around the filament. The positive electrical field of the anode penetrates this region, extracts electrons from a well-defined area close to the aperture and accelerates them towards the anode. The equipotential lines are curved like a lens and they also act in that way forming a crossover (point of smallest beam size) close to the anode. Only electrons with a small angular spread can pass the double slit of the anode. As a consequence, a directed electron beam is formed (see Figure 2.5a). As a second function the Wehnelt cylinder allows for a fast regulation of the beam intensity by low control voltages. The whole beam source (filament, Wehnelt and anode) should be operated at fix voltage settings independent from the energy of the primary beam.

The combination of lens elements L1–L3 form a so-called electrostatic ”einzell lens” (see Figure 2.5b). A sharp diffraction pattern is achieved by focusing the crossover point to the fluorescent screen (either with or without an intermediate focus), whereby the sample acts like a mirror. The lens voltages should be (in first approximation) proportional to the electron energy in order to keep the focus length independent of energy. The lens element L4 has to be grounded to ensure a field-free space between gun and sample.

The scattered electrons pass the grids on their way to the fluorescent screen. The grids G2
and G3 act as a high-energy pass filter, that can only be surmounted by elastically or quasi-elastically scattered electrons. This is achieved by applying a retarding potential somewhat smaller than the filament potential to these grids, whereby the energy cut off characteristics of this filter is significantly improved by the doubling of the grids. In contrast, the grids G1 and G4 are grounded. G1 shall shield the penetration of the high electric field of the fluorescent screen into the retarding grid area, while the grid G4 shall ensures a field free space around the sample to achieve undistorted electron trajectories.

The fluorescent screen is made out of glass and is coated with a fluorescent material, here (Zn,Cd)S : Ag, which can be excited by electrons. The photon yield rises disproportionately with the applied voltage. Consequently, a voltage as high as possible is recommended, but it is limited by the breakdown voltage of the setup. A typical value for the screen voltage is 5 kV–7 kV.

### 2.2.4 Electronic equipment

The rack on the right of the chamber contains all electronics necessary for operation and control of the apparatus (see Figure 2.6). The readouts for sample temperature and pressure in the rough vacuum part are placed on top of the rack. The other components from top to bottom are: The
controller of the Bayard-Alpert pressure gauge, the LEED optics control unit, the power supply for the sample heating, the TSP controller and the IGP supply. A CCD camera is mounted behind the LEED screen (outside the vacuum) to record the diffraction patterns. It will be controlled from the PC on the left. The measurement software uses an AD/DA card for remote control of the electron energy and recording of the beam current.
3 Manual

3.1 Preparation and literature work

Read the introductory chapters carefully and provide a written preparation. In the advanced lab course you shall also train yourself to do literature work and to write own scientific texts. Thus, the section on fundamental physics (Sect. 2.1) is intentionally held very dense, so that you will need additional literature for proper preparation. **Hint:** In principle, you can find all necessary information in the textbook cited at the end of Sect.2.1. However, you are encouraged to have a look into other sources as well. An extended collection of useful literature is given in the Appendix 4.1.

As a rough guideline, your written preparation should cover the following topics:

- Basics of crystal lattices and surface orientations
- Surface crystallography: 2D-Bravais lattices, superstructures (description and notation), relaxation and reconstruction.
- Interaction of low energy electrons with solids: Scattering and diffraction, penetration depth.
- Basics of diffraction at surfaces: Kinematic theory, reciprocal lattice and Ewald construction
- LEED experiment: Setup and operating mode.

*The written preparation is intended to be the introductory part of your final report. As a guideline for the layout of such a report you can take this manual as a template.*

**Remark:** The section 2.2 contains not only information about the LEED optics itself, but also about the whole instrumental equipment (chamber, manipulator, electronics). This is mostly secondary information and should help you in conducting the experiment. Beside the LEED optics, you do not have to mention technical details in your written preparation, but you should have read it at least once before starting the experiment.
3.2 Conduction and evaluation

SAFETY INSTRUCTION

Despite some safety precautions, improper operation of the parts can be dangerous or even lethal or may damage the experiment! You are therefore requested to treat this experiment carefully. In principle, you shall inform yourself about the functionality and handling of individual components before you act! **If you have any doubts, ask your supervisor!**

If the pressure reading increases beyond $1 \times 10^{-6}$ mbar or if the ion pump shuts off automatically (red light “trip” on), immediately turn off all power supplies except the ion getter pump and notify the supervisor.

Don’t make any modifications at the following parts of the apparatus for your own safety:

- The HV plug of the ion getter pump underneath the table.
- Electrical connections of the LEED optics on the rear of the vacuum chamber.
- Connectors on the rear of the power supplies.
- Gas inlet system.

SAFEty INSTRUCTION

For a normal conduction of the experiment you have to change exclusively settings at the LEED controller and the sample heating! All other devices in the rack are well adjusted and you only have to read the values if necessary.

3.2.1 Clean reconstructed Ir(001)

1. Heat the crystal quickly with maximum power (“flash”) until 1500 °C is reached and keep the temperature for 5 s.

2. **Check** that the fluorescent screen voltage is set to 5 kV (requires no further change!) and the filament current adjustment potentiometer is turned to minimum (knob turned fully to the left)! Turn on the LEED supply (3 main switches, in the order Mains, Screen, Filament), slowly increase the filament current up to 2.5 A and set the primary electron energy to around 100 eV. Align (laterally, vertically, angle) the crystal in front of the electron gun. Now you should be able to see a diffraction pattern of the crystal’s surface, otherwise check again for the crystal position. Changing the voltages of the lens element (L1/3, L2) varies the size and shape of the electron beam. Ideally, the beam is focused
on the fluorescent screen, which results in a sharp diffraction pattern. To maintain this condition over a wide energy range the lens voltages are made to vary linearly (defined by offset and gain) with the primary electron energy. Adjust the corresponding potentiometers in order to obtain a sharp diffraction pattern over a wide energy range. Hint: At low energies the focus strongly depends on the offset settings, while at higher energies the adjustment of the gains becomes dominant. (Why?)

3. What influence does a lateral movement or a rotation of the sample have on the diffraction pattern and why?

4. Adjust the incidence of the electron beam as perpendicular as possible by using the four-fold symmetry of the sample. Now take pictures of the diffraction pattern for several energies between 20 eV and 500 eV. Determine for one appropriate picture the \textit{primitive} (reciprocal) unit cells of both the Ir(100) bulk structure and the superlattice of the surface reconstruction. Mark both cells and name the spots (in terms of the bulk unit cell).

\textbf{Hints:}

1) Typically, not all spots are simultaneously visible at the very same energy. Therefore, you have to make sure that you have at least one image showing all appearing spots for a correct determination of the superstructure.

2) The surface reconstruction has a rectangular cell (with unequal sides). Thus, on a square substrate there must be two equivalent orthogonal domains in equal numbers. The LEED pattern will then be a superposition of both diffraction patterns (provided that the domains are large compared to the coherence length of the electrons).

Determine in your report the diffraction angles of various spots for two appropriate images (taken at different energies). Use this to calculate the size of the primitive unit cell of the substrate (in real space) and compare your results with the corresponding value found in literature. Discuss possible statistical and systematic errors of your measurement.

Explain the reconstruction of the surface. Draw a tentative structural model and mark the unit cells (primitive and superstructure) in the model.

\textbf{Note:} Radius of the screen: 66 mm; opening angle: $2 \times 50^\circ$
3.2.2 Oxygen covered surface

SAFETY INSTRUCTION
Operate the gas inlet of the UHV chamber only after instruction by your supervisor!
Before opening the gas valve you have to turn off both the filament and the screen at the LEED control unit.

1. After instruction by your supervisor refill the gas line with oxygen. Open the valve carefully (in order not to exceed the desired pressure) until a partial oxygen pressure of $1 \times 10^{-6}$ mbar is reached. Heat the crystal to $1000\,^\circ\text{C}$–$1100\,^\circ\text{C}$ for 30 s. Let the crystal cool down to at least $250\,^\circ\text{C}$ in oxygen atmosphere. Now, close the oxygen valve. Describe the changes of the diffraction pattern.

2. Heat the crystal to $300\,^\circ\text{C}$ for 5 s. Do you see any change in the diffraction pattern? Repeat this procedure for higher annealing steps: $600\,^\circ\text{C}$, $900\,^\circ\text{C}$, $1200\,^\circ\text{C}$, and $1500\,^\circ\text{C}$. Let the crystal cool down in between and record the obtained LEED pattern. Use energies, which give a clear image of the new superstructures. Observe and describe the change of the superstructure with increasing annealing temperature. Ensure, that you have a clean reconstructed surface after the last step, otherwise anneal again to $1500\,^\circ\text{C}$ for 5 s.

Calculate in your report how many oxygen molecules have hit one surface atom on average with this dosage? Which processes are going on the surface during the annealing steps? Make a tentative real space model of the initial superstructure. Can you expand the model for the phases observed after the annealing steps? Why is it important to cool down the crystal in oxygen atmosphere? Name all observed structures using the Wood notation and try to give a consistent explanation.

3.2.3 Preparation of an unreconstructed Ir(100)-surface

The clean Ir(100) surface is reconstructed in its ground state, but there is a way to prepare a metastable, unreconstructed Ir(100)-surface by exposing the oxygen covered Ir(100)-surface to hydrogen and by that reducing the oxygen to water, which desorbs.
Before starting the experiment read first all steps. In case of any doubts ask your supervisor first!

1. Repeat the initial preparation of the oxygen covered surface, set the electron energy to a value, where you can well observe the diffraction pattern of the oxygen superstructure. Take a reference image and then turn off the LEED.

2. Pump the oxygen out of the gas line and refill the line with hydrogen.
3. Ensure that the LEED unit is still off and the crystal temperature is below 250 °C.

4. Set the image recorder to I(t) measurement and start an record of about 15 min with a time step of 1 s (LEED still off).

5. Open the leak valve and stabilize the partial pressure of hydrogen at $5 \times 10^{-8}$ mbar.

SAFETY INSTRUCTION

Operating the LEED optics under gas atmosphere is dangerous for the device! Switch on the LEED first after the pressure is stable! Do not change the valve setting while the LEED is running. This also includes the closing of the valve!

6. Switch on the LEED optics and observe whether the superstructure start to vanish. If you do not see any change within 1 min, flash the sample for 1 s to 350 °C and observe again. You may have to repeat this step one or two times until the conversion to the unreconstructed surface proceeds.

7. After the conversion has finished, turn off the LEED, stop the hydrogen flow and also stop the record.

8. Now take LEED images of the unreconstructed surface for different electron energies.

9. Export from the I(t)-movie a couple of frames, that show different states of the conversion. Extract an I(t) spectrum for one set of symmetrically equivalent beams of the superstructure.

10. Flash 5 s at 1500 °C. You should now observe the reconstructed surface again. Take another LEED image for reference.

Is the measured reaction time plausible? Average the I(t) spectra and determine the reaction time. Calculate the time which is needed that a unit cell of the oxygen phase is hit once by a hydrogen molecule on average. This is the theoretical minimum time to remove all oxygen from the surface? What would be the conditions for that?

Calculate the lattice constant from your LEED images and show that this fits your expectations for unreconstructed Ir(100).

Explain in your report, why the oxygen superstructure is suited to prepare an unreconstructed Ir(100) surface? What is the role of the hydrogen in this conversion? Why is it necessary to anneal the crystal in order to start the conversion? The reconstructed surface is recovered from the unreconstructed surface by annealing in the last step. What can you learn from this experiment about the energy landscape of both phases?

**Hint:** You may find it helpful to have an look into the cited literature.
3.2.4 I(E) measurements

The hydrogen-covered Ir(100) surface shows the same superstructure period as the clean reconstructed surface. The goal of this experiment is to reveal a clear structural difference of the two structures via their I(E) spectra.

**Remark:** Normalize all I(E) spectra to the beam current $I_0$. Make sure that the beam current is recorded during the measurements.

1. Re-adjust the normal incidence and focus the LEED optics as good as possible.
   **Hint:** For example the diffraction pattern around 95 eV is suitable to recognize already minor deviations from normal incidence via deviating intensities of symmetry-related diffraction spots. Let the supervisor check the result and do some test measurements together.

2. Take a LEED video in the energy range of 10 eV–400 eV and measure I(E)-spectra for the (1,0) and (1,1) beams. Use first the "follow mode" to track the spot trajectories and later the "repeat mode" to extract less noisy spectra. Useful energy ranges for recording intensities are:
   - (1,0) equivalent beams from 45 eV to 250 eV
   - (1,1) equivalent beams from 85 eV to 400 eV

3. The sample temperature should have reached 150 °C (better $T \lesssim 100$ °C) in the meantime. Expose the sample to $5 \times 10^{-7}$ mbar hydrogen for 120 s. Do not move the sample during this procedure (Why?). Record another video and measure again the I(E) spectra for the (1,0) and (1,1) beams. Since you did not move the sample, you can try to use just the "repeat mode".

4. Inspect the spectra of both phases and look for energies with a clear difference. Export frames from both videos at some of these energies.

   Discuss in your report the observed difference of symmetry equivalent spectra. What are the experimental errors?

   Average the spectra of symmetrically equivalent beams in order to obtain a characteristic spectrum. If the average leads to non-meaningful results, choose the beam with the best spectrum for further analysis. Highlight the differences between the I(E)-spectra of the two phases. Discuss the spectra together with the images.

   Compare your results to the literature and explain in a few sentences the difference between the two superstructures.
4 Appendix

4.1 Collection of literature

All mentioned literature in this collection should be accessible from the university network or as a textbook in the library.

1. Very good overview about surface science methods including LEED (German and English edition available in the library of the Dept. of Physics):
   - Th. Fauster, L. Hammer, K. Heinz, und M.A. Schneider: Oberflächenphysik
   - Th. Fauster, L. Hammer K. Heinz, and M.A. Schneider: Surface Physics

2. Some standard textbooks (German and English) about solid state physics:
   - Kittel – Einführung in die Festkörperphysik
   - Gross und Marx – Festkörperphysik
   - Ibach und Lüth – Festkörperphysik
   - Ashcroft und Mermin – Solid State Physics

3. Advanced textbook chapter about LEED:
   - K. Heinz, Electron Based Methods: 3.2.1 Low-Energy Electron Diffraction (LEED)

4. Information about Iridium:
   - Arblaster et al., Crystallographic properties of iridium

5. LEED analysis of the clean reconstructed Ir(100) surface:
   - E.Lang et al., LEED intensity analysis of the (1 × 5) reconstruction of Ir (100)
   - A. Schmidt et al., Deep-going reconstruction of Ir(100)-5 × 1

6. Oxygen and Hydrogen on the Ir(100)-surface:
   - L. Hammer et al., Hydrogen-induced self-organized nanostructuring of the Ir(100) surface
   - P. Ferstl et al., Structure and ordering of oxygen on unreconstructed Ir(100)
Bibliography