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P7 SOLID-STATE PHYSICS

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P7.1.1
CRYSTAL STRUCTURE

P7.1.1.1
Structure of a body-centered cubic and face-centered cubic lattice

In the field emission microscope, the extremely fine tip of a tungsten monocrystal is arranged in the center of a spherical luminescent screen. In the vicinity of the tip, the electric field between the crystal and the luminescent screen reaches such a high field strength that the conducting electrons can "tunnel" out of the crystal and travel radially to the luminescent screen. Here, an image of the emission distribution of the crystal tip is created, magnified by a factor of

\[ V = \frac{R}{r} \]

\[ R = 5 \text{ cm: radius of luminescent screen} \]

\[ r = 0.1 - 0.2 \text{ \(\mu\)m: radius of tip} \]

In the first part of the experiment P7.1.1, the tungsten tip is purified by heating it to a white glow. The structure which appears on the luminescent screen after the electric field is applied corresponds to the body-centered cubic lattice of tungsten, which is observed in the (110) direction, i.e. the direction of one of the diagonals of a cube face. Finally, a minute quantity of barium is vaporized in the tube, so that individual barium atoms can precipitate on the tungsten tip to produce bright spots on the luminescent screen. When the tungsten tip is heated carefully, it is even possible to observe the thermal motion of the barium atoms.
P7.1.2

X-RAY SCATTERING

P7.1.2.1
Bragg reflection: determining the lattice constants of monocrystals

P7.1.2.2
Laue diagrams: investigating the lattice structure of monocrystals

P7.1.2.3
Debye-Scherrer photography: determining the lattice plane spacings of polycrystalline powder samples

P7.1.2.4
Debye-Scherrer Scan: determining the lattice plane spacings of polycrystalline powder samples

X-rays are an essential tool to determine the structure of crystals. The lattice planes inside a crystal are identified by their Miller indices \( h, k, l \) and reflect the X-rays only if the Laue or Bragg conditions are fulfilled. The distribution of reflexes allows to calculate the lattice constant and crystal structure of the investigated crystal.

In the experiment P7.1.2.1, the Bragg reflection of Mo-\( \text{K}_\alpha \) radiation \( (\lambda = 71.080 \text{ pm}) \) at NaCl and LiF monocrystals is used to determine the lattice constant. The \( \text{K}_\beta \) component of the X-ray radiation can be suppressed using a zirconium filter.

Laue diagrams from NaCl and LiF monocrystals are created in the experiment P7.1.2.2 using the "bremsstrahlung" of the X-ray apparatus as "white" X-radiation. The positions of the "multicolored" reflections on an X-ray film behind the crystal and their intensities can be used to determine the crystal structure and the lengths of the crystal axes through application of the Laue condition.

In the experiment P7.1.2.3, Debye-Scherrer photographs are produced by irradiating samples of a fine crystal powder with Mo-\( \text{K}_\alpha \) radiation. Some of the randomly oriented crystallites conform to the Bragg condition and diffuse X-rays into cones for which the aperture angles \( \Theta \) can be derived from a photograph. This experiment determines the lattice spacing corresponding to \( \Theta \) as well as its Laue indices \( h, k, l \), and thus the lattice structure of the crystallite.

The experiment P7.1.2.4 records the Debye-Scherrer pattern with an end window counter instead of X-ray film. The diffracted reflections of a fine powder sample are recorded as a function of diffraction angle. The intensity peaks in the diffraction spectrum allow the calculation of the separations of adjacent lattice planes.

---

**Table:**

<table>
<thead>
<tr>
<th>Cat. No.</th>
<th>Description</th>
<th>P7.1.2.1</th>
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* additionally recommended
P7.1.2
X-RAY SCATTERING

P7.1.2.5
Digital Laue diagrams: investigating the lattice structure of monocrystals

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<tr>
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<tr>
<td>554 8381</td>
<td>Pinhole collimator with Laue crystals</td>
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<td>554 828</td>
<td>X-ray image sensor</td>
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<td>554 829</td>
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<tr>
<td></td>
<td>PC with Windows XP/Vista/7/8/10 (x86 or x64)</td>
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</table>

To create Laue diagrams of NaCl and LiF monocrystals, the bremsstrahlung of the X-ray apparatus is used in the experiment P7.1.2.5 as a “white” spectrum of X-rays. The positions of the “multicolored” diffraction spots on an X-ray image sensor behind the crystal and their intensities can be used to determine the crystal structure and the dimensions of the unit cell through application of the Laue condition. The X-ray image sensor allows capturing the Laue pattern in one minute (much faster than conventional film) and the digital evaluation eases the determination of the diffraction angles on the computer.

Laue diagram of NaCl and Debye-scherrer photograph of NaCl

The X-ray image sensor is sensitive enough to expose the discrete reflexes behind a crystal. The zero order is shielded by a metal plate.
P7.1.4
ELASTIC AND PLASTIC DEFORMATION

P7.1.4.1
Investigating the elastic and plastic extension of metal wires

P7.1.4.2
Investigating the elastic and plastic extension of metal wires – recording and evaluating with CASSY

The shape of a crystalline solid is altered when a force is applied. We speak of elastic behavior when the solid resumes its original form once the force ceases to act on it. When the force exceeds the elastic limit, the body is permanently deformed. This plastic behavior is caused by the migration of discontinuities in the crystal structure.

In the experiments P7.1.4.1 and P7.1.4.2, the extension of iron and copper wires is investigated by hanging weights from them. A precision pointer indicator or the rotary motion sensor S attached to a CASSY measures the change in length $\Delta s$, i.e., the extension

$$e = \frac{\Delta s}{s}$$

$s$: length of wire

After each new tensile load

$$\sigma = \frac{F}{A}$$

$F$: weight of load pieces
$A$: wire cross-section

the students observe whether the pointer or the rotary motion sensor returns to the zero position when the strain is relieved, i.e., whether the strain is below the elasticity limit $\sigma_e$. Graphing the measured values in a tension-extension diagram confirms the validity of Hooke’s law

$$\sigma = E \cdot \varepsilon$$

$E$: modulus of elasticity

up to a proportionality limit $\sigma_p$.

![Load-extension diagram for a typical metal wire](image-url)
P7.2.1

HALLEFFECT

P7.2.1.1

Investigating the Hall effect in silver

P7.2.1.2

Investigating the anomalous Hall effect in tungsten

In the case of electrical conductors or semiconductors within a magnetic field $B$, through which a current $I$ is flowing perpendicular to the magnetic field, the Hall effect results in an electric potential difference

$$U_h = R_h B I \cdot \frac{1}{d}$$

$d$: thickness of sample

The Hall coefficient

$$R_h = \frac{1}{e} \left( \frac{p \mu_p^2 - n \mu_n^2}{(p \mu_p + n \mu_n)^2} \right)$$

depends on the concentrations $n$ and $p$ of the electrons and holes as well as their mobilities $\mu_n$ and $\mu_p$ and is thus a quantity which depends on the material and the temperature.

The experiments P7.2.1.1 and P7.2.1.2 determine the Hall coefficient $R_h$ of two electrical conductors by measuring the Hall voltage $U_h$ for various currents $I$ as a function of the magnetic field $B$. A negative value is obtained for the Hall coefficient of silver, which indicates that the charge is being transported by electrons. A positive value is found as the Hall coefficient of tungsten. Consequently, the holes are mainly responsible for conduction in this metal.
P7.2.1

HALL EFFECT

P7.2.1.3
Determining the density and mobility of charge carriers in n-Germanium

P7.2.1.4
Determining the density and mobility of charge carriers in p-Germanium

P7.2.1.5
Determining the band gap of germanium

<table>
<thead>
<tr>
<th>Cat. No.</th>
<th>Description</th>
<th>P7.2.1.3</th>
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<th>P7.2.1.5</th>
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</tbody>
</table>

Additionally required:
PC with Windows XP/ Vista/7/8/10 (x86 or x64)

The experiments P7.2.1.3 and P7.2.1.4 explore the temperature-dependency of the Hall voltage and the electrical conductivity

$$\sigma = e \left( \mu_p + \mu_n \right)$$

using doped germanium samples. The concentrations of the charge carriers and their mobilities are determined under the assumption that, depending on the doping, one of the concentrations n or p can be ignored.

In the experiment P7.2.1.5, the electrical conductivity of undoped germanium is measured as a function of the temperature to provide a comparison. The measurement data permits determination of the band gap between the valence band and the conduction band in germanium.

Hall voltage when heating up the p-Gc sample
P7.2.2
ELECTRICAL CONDUCTIVITY IN SOLIDS

P7.2.2.1
Measuring the temperature-dependency of a noble-metal resistor

P7.2.2.2
Measuring the temperature-dependency of a semiconductor resistor

The temperature-dependency of the specific resistance $\rho$ is a simple test for models of electric conductivity of conductors and semiconductors. In electrical conductors, $\rho$ increases with the temperature, as the collisions of the quasi-free electrons from the conduction band with the atoms of the conductor play an increasingly important role. In semiconductors, on the other hand, the specific resistance decreases as the temperature increases, as more and more electrons move from the valence band to the conduction band, thus contributing to the conductivity.

The experiments P7.2.2.1 and P7.2.2.2 measure the resistance values as a function of temperature using a Wheatstone bridge. The computer-assisted CASSY measured-value recording system is ideal for recording and evaluating the measurements. For the noble metal resistor, the relationship

$$ R = R_0 e^{\frac{T}{\Theta}} $$

where $\Theta = 240 \text{ K}$: Debye temperature of platinum is verified with sufficient accuracy in the temperature range under study.

For the semiconductor resistor, the evaluation reveals a dependency with the form

$$ R = e^{kE} $$

where $k = 1.38 \cdot 10^{-23} \text{ J} K^{-1}$: Boltzmann constant with the band spacing $E = 0.5 \text{ eV}$. 
P7.2.3
PHOTOCONDUCTIVITY

P7.2.3.1
Recording the current-voltage characteristics of a CdS photoresistor

<table>
<thead>
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<td>450 60</td>
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<td>460 20</td>
<td>Condenser with diaphragm holder</td>
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<td>460 14</td>
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Photoconductivity is the phenomenon in which the electrical conductivity $\sigma$ of a solid is increased through the absorption of light. In CdS, for example, the absorbed energy enables the transition of activator electrons to the conduction band and the reversal of the charges of traps, with the formation of electron holes in the valence band. When a voltage $U$ is applied, a photocurrent $I_{ph}$ flows.

The object of the experiment P7.2.3.1 is to determine the relationship between the photocurrent $I_{ph}$ and the voltage $U$ at a constant radiant flux $\Phi_c$ as well as between the photocurrent $I_{ph}$ and the radiant flux $\Phi_c$ at a constant voltage $U$ in the CdS photoresistor.
P7.2.4 LUMINESCENCE

P7.2.4.1 Exciting luminescence through irradiation with ultraviolet light and electrons

Exciting luminescence through irradiation with ultraviolet light and electrons (P7.2.4.1)

Luminescence is the emission of light following the absorption of energy. This energy can be transmitted in the form of e.g. high-energy electrons or photons which have an energy greater than that of the emitted photons. Depending on the type of decay, we distinguish between fluorescence and phosphorescence. In fluorescence, the emission of photons fades exponentially very rapidly when excitation is switched off (i.e. about $10^{-8}$ s). Phosphorescence, on the other hand, can persist for several hours.

In the experiment P7.2.4.1, the luminescence of various solids following irradiation with ultraviolet light or electrons is demonstrated. These samples include yttrium vanadate doped with europium (red fluorescent), zinc silicate doped with manganese (green fluorescent) and barium magnesium aluminate doped with europium (blue fluorescent).

Note: It is possible to recognize individual emission lines within the band spectrum using a pocket spectroscope.
P7.2.5
THERMOCHELLECTRICITY

P7.2.5.1
Seebeck effect: Determining the thermoelectric voltage as a function of the temperature differential

When two metal wires with different Fermi energies $E_F$ touch, electrons move from one to the other. The metal with the lower electronic work function $W_0$ emits electrons and becomes positive. The transfer does not stop until the contact voltage

$$U = \frac{W_{a_1} - W_{a_2}}{e}\alpha$$

is reached. If the wires are brought together in such a way that they touch at both ends, and if the two contact points have a temperature differential $T - T_1 - T_2$, an electrical potential, the thermoelectric voltage

$$U = U(T_1) - U(T_2)$$

is generated. Here, the differential thermoelectric voltage

$$\alpha = \frac{dU}{dT}$$

depends on the combination of the two metals.

In the experiment P7.2.5.1, the thermoelectric voltage $U_T$ is measured as a function of the temperature differential $T$ between the two contact points for thermocouples with the combinations iron/constantan, copper/constantan and chrome-nickel/constantan. One contact point is continuously maintained at room temperature, while the other is heated in a water bath. The differential thermoelectric voltage is determined by applying a best-fit straight line

$$U_T = \alpha \cdot T$$

to the measured values.
P7.2.6
SUPERCONDUCTIVITY

P7.2.6.1
Determining the transition temperature of a high-temperature superconductor

P7.2.6.2
Meissner-Ochsenfeld effect for a high-temperature superconductor

In 1986, K A Müller and J G Bednorz succeeded in demonstrating that the compound YBa$_2$Cu$_3$O$_{7-x}$ becomes superconducting at temperatures far greater than any known up to that time. Since then, many high-temperature superconductors have been found which can be cooled to their transition temperature using liquid nitrogen. Like all superconductors, high-temperature superconductors have no electrical resistance and demonstrate the phenomenon known as the Meissner-Ochsenfeld effect, in which magnetic fields are displaced out of the superconducting body.

The experiment P7.2.6.1 determines the transition temperature of the high-temperature superconductor YBa$_2$Cu$_3$O$_{7-x}$. For this purpose, the substance is cooled to below its critical temperature of $T_c = 92$ K using liquid nitrogen. In a four-point measurement setup, the voltage drop across the sample is measured as a function of the sample temperature using the computer-assisted measured value recording system CASSY.

In the experiment P7.2.6.2, the superconductivity of the YBa$_2$Cu$_3$O$_{7-x}$ body is verified with the aid of the Meissner-Ochsenfeld effect. A low-weight, high field-strength magnet placed on top of the sample begins to hover when the sample is cooled to below its critical temperature so that it becomes superconducting and displaces the magnetic field of the permanent magnet.
Diamagnetism is the phenomenon in which an external magnetic field causes magnetization in a substance which is opposed to the applied magnetic field in accordance with Lenz's law. Thus, in an inhomogeneous magnetic field, a force acts on diamagnetic substances in the direction of decreasing magnetic field strength. Paramagnetic materials have permanent magnetic moments which are aligned by an external magnetic field. Magnetization occurs in the direction of the external field, so that these substances are attracted in the direction of increasing magnetic field strength. Ferromagnetic substances in magnetic fields assume a very high magnetization which is orders of magnitude greater than that of paramagnetic substances.

In the experiment P7.3.1.1, three 9 mm long rods with different magnetic behaviors are suspended in a strongly inhomogeneous magnetic field so that they can easily rotate, allowing them to be attracted or repelled by the magnetic field depending on their respective magnetic property.
P7.3.2 FERROMAGNETIC HYSTERESIS

P7.3.2.1 Recording the initial magnetization curve and the hysteresis curve of a ferromagnet

In a ferromagnet, the magnetic induction

\[ B = \mu_r \cdot \mu_0 \cdot H \]

\[ \mu_0 = 4\pi \cdot 10^{-7} \ \text{Vs/Am} \]

reaches a saturation value \( B_s \) as the magnetic field \( H \) increases. The relative permeability \( \mu_r \) of the ferromagnet depends on the magnetic field strength \( H \), and also on the previous magnetic treatment of the ferromagnet. Thus, it is common to represent the magnetic induction \( B \) in the form of a hysteresis curve as a function of the rising and falling field strength \( H \). The hysteresis curve differs from the magnetization curve, which begins at the origin of the coordinate system and can only be measured for completely demagnetized material.

In the experiment P7.3.2.1, a current \( i \) in the primary coil of a transformer which increases (or decreases) linearly over time generates the magnetic field strength

\[ H = \frac{L_i}{L} \]

\( L \): effective length of iron core

\( N_i \): number of windings of primary coil

The corresponding magnetic induction value \( B \) is obtained through integration of the voltage \( U_2 \) induced in the secondary coil of a transformer.

\[ B = \frac{1}{N_2 \cdot A} \int U_2 \, dt \]

\( A \): cross-section of iron core

\( N_2 \): number of windings of secondary coil

The computer-assisted measurement system CASSY is used to control the current and to record and evaluate the measured values. The aim of the experiment is to determine the relative permeability \( \mu_r \) in the magnetization curve and the hysteresis curve as a function of the magnetic field strength \( H \).
P7.4.1
SCANNING TUNNELING MICROSCOPE

P7.4.1.1
Investigating a graphite surface using a scanning tunneling microscope

P7.4.1.2
Investigating a gold surface using a scanning tunneling microscope

P7.4.1.3
Investigating a MoS₂ sample using a scanning tunneling microscope

The scanning tunneling microscope was developed in the 1980’s by G. Binnig and H. Rohrer. It uses a fine metal tip as a local probe; the probe is brought so close to an electrically conductive sample that the electrons “tunnel” from the tip to the sample due to quantum-mechanical effects. When an electric field is applied between the tip and the sample, an electric current, the tunnel current, can flow. As the tunnel current varies exponentially with the distance, even an extremely minute change in distance of 0.01 nm results in a measurable change in the tunnel current. The tip is mounted on a platform which can be moved in all three spatial dimensions by means of piezoelectric control elements. The tip is scanned across the sample to measure its topography. A control circuit maintains the distance between tip and sample extremely precisely at a constant distance by maintaining a constant tunnel current value. The controlled motions performed during the scanning process are recorded and imaged using a computer. The image generated in this manner is a composite in which the sample topography and the electrical conductivity of the sample surface are superimposed.

The experiments P7.4.1.1, P7.4.1.2 and P7.4.1.3 use a scanning tunneling microscope specially developed for practical experiments, which operates at standard air pressure. At the beginning of the experiment, a measuring tip is made from platinum wire. The graphite sample is prepared by tearing off a strip of tape. When the gold sample is handled carefully, it requires no cleaning; the same is valid for the MoS₂ probe. The investigation of the samples begins with an overview scan. In the subsequent procedure, the step width of the measuring tip is reduced until the positions of the individual atoms of the sample with respect to each other are clearly visible in the image.
The experiment P7.4.1.4 uses an AFM to investigate several different surface structures from a CD stamper to blood cells. In contrast to a STM non-conductive samples can be used. A microscopic „needle“ is touching the surface and scans it. In static mode, the needle just scratches along the surface and records the height variations. Using extended modes, not only topography can be recorded, but also local properties like elasticity or magnetism. For example the needle is set into vibration and slightly touches the surface. Hard and soft areas of the sample will dampen the oscillation of the needle differently and can be imaged.
**P7.5.1**

**X-RAY FLUORESCENCE ANALYSIS**

**P7.5.1.1**
Application of X-ray fluorescence for the non-destructive analysis of the chemical composition

**P7.5.1.2**
Determination of the chemical composition of a brass sample by X-ray fluorescence analysis

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X-ray fluorescence is a very useful tool for a non-destructive analysis of the chemical composition of a target alloy. When irradiating a sample with X-rays, all the different elements it contains emit characteristic X-rays due to fluorescence, which are fingerprints of every single element.

In the experiment P7.5.1.1, X-ray fluorescence is used to do qualitative analysis by identifying the substances in four alloy samples, made from chrome-nickel steel, two different kinds of brass and rare earth magnet.

In the experiment P7.5.1.2, the composition of one brass alloy is analysed quantitatively. The weight percentage of each component in the alloy is calculated from the strength of different fluorescence lines.

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Additionally required:
- PC with Windows XP/Vista/7/R10 (x86 or x64)

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*X-Ray fluorescence spectrum of a brass sample*