Modern Physics Laboratory Manual

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Contents

Experiment 1

MILIKAN’S OIL DROP EXPERIMENT

Purpose

The purpose of this experiment is to measure the charge of the electron, and show that it is quantized with smallest value of 1.6×10^{-19} C.

Introduction

Historical Background

Greek philosophers debated whether matter is infinitely divisible or is, instead, composed of discrete atoms (in Greek $\alpha\tau o\mu o\sigma$ meaning “uncuttable”) as taught by Democritus in the fifth century B.C. During the nineteenth century A.D. the atomic idea was the basis for various successful theories of chemistry and physics, most notably the theory of chemical combination (Dalton) and the kinetic theory of gases (Maxwell). Yet there remained competent scientists who doubted the reality of atoms as late as 1900. They followed Ernst Mach (1836–1916) in adherence to the philosophical principle of empiricism whereby physical theory must exclude any concept that is not directly observable. In fact, it was not until the present century that the atomicity of matter or of any of its attributes (e.g. charge) was directly observed. After all, one atom of lead weighs only 3.2×10^{-22} g; one electronic charge is 4.8×10^{-10} statcoulombs; the quantum of angular momentum is $6.7 \times 10^{-27}\,\mathrm{cm}^2\,\mathrm{s}^{-1}$; and the energy of one quantum of red light is 3.2×10^{-12} ergs. Whereas the units of these measures are physical quantities of palpable magnitude, readily measured with the instruments invented by nineteenth century physicists, the atomic quantities are such minute fractions of their units of measure as to have defied measurement by the best experimentalists of that century.

Then, in 1907, Robert Millikan’s young collaborator, Harvey Fletcher, got the idea of watching the motion of a single, charged, microscopic oil droplet under the influence of gravity and a uniform electric field between two parallel metal plates. He produced microscopic droplets with an “atomizer”, like a common nasal spray, illuminated the droplets from behind, observed individual droplets as unresolved pinpoints of diffracted light, and timed their motion between fiducial marks in the focal plane of a horizontal microscope as they switched the voltage between the plates on and off. Some droplets carried a few more electrons than protons, or vice versa, and could be suspended or drawn upward against the force of gravity by application of an electric field of the order of a thousand volts per cm. Droplets were tracked up and down many times, sometimes for hours, to reduce random errors in the measurements of the terminal velocities of the motions under the forces of gravity, viscous drag, and electricity in the presence of the fluctuations of Brownian motion.

The oil drop experiment proved the atomicity of electricity (i.e. that the droplets always carried integer multiples of a charge quantum e), determined the value of e with an estimated error of $\pm 0.2\%$, provided thereby the key to the accurate determination of the mass of the electron and Avogadro's number (from the previously measured values of e/m and $F = Ne$), and won Millikan the Nobel Prize. It turned out that his result was off by a systematic error of -0.6% due to an error in the viscosity of air which was corrected in 1930. The uncertainty of the currently accepted value is $\pm 0.0003\%$ (3 ppm).

For an interesting presentation of the physics and history of the discoveries of the electron and other fundamental particles, these sources in the reference part of this experiment section may be found attractive and supportive [1,2,3,4].

Theory of the experiment

Consider a spherical oil droplet of radius a and density ρ falling at a terminal velocity v through air of density ρ' and viscosity coefficient η. If a is large compared to the mean free path of the air molecules, then the gravity and buoyancy forces acting on the droplet are balanced by a drag force $6\pi\eta av$ according to Stoke's law for the streamline motion of a sphere through a viscous medium. Actually, the experiment must employ oil droplets which are light enough to be suspended or drawn upward by the electric force exerted on just a few (1 to ~ 10) electronic charges by a field of a thousand volts/cm. Such droplets have radii that are typically not very large compared to the mean free path of air molecules, which is 2.2×10^{-6} cm at normal temperature and pressure according to the CRC Table. The equation of motion for a spherical oil drop can be written as

$$m\frac{dv}{dt} = \frac{4}{3}\pi a^3(\rho - \rho')g - qE - 6\pi\eta av \tag{1.1}$$

where g is the acceleration of gravity. If the droplet carries a charge ne and is moving upward with terminal velocity v under the influence of an electric field V/d between two parallel plates separated by the distance d and a potential difference V, the equation of motion is

$$m\frac{dv}{dt} = \frac{4}{3}\pi a^3(\rho - \rho')g - ne\frac{V}{d} - 6\pi\eta av \tag{1.2}$$

This equation can be easily solved:

1. If there is no applied electric field ($E = 0$) and the oil drop moves with terminal velocity,

$$v = \frac{\frac{4}{3}\pi a^3(\rho - \rho')g}{6\pi\eta a} = \frac{2a^2(\rho - \rho')g}{9\eta} \tag{1.3}$$

The radius of oil drop is

$$a = 3\sqrt{\frac{\eta v}{2(\rho - \rho')g}} \tag{1.4}$$

2. If the oil drop has been held stationary ($\eta = 0$) using an electric field,

$$\frac{4}{3}\pi a^3(\rho - \rho')g = qE \tag{1.5}$$

We find

$$q = \frac{4}{3}\pi a^3(\rho - \rho')g\frac{d}{V} \tag{1.6}$$

using equation (1.4) and (1.6) and solving for and solving for q, we obtain

$$q = \frac{9\sqrt{2}\pi\eta^{3/2}}{(\rho - \rho')^{1/2}g^{1/2}}\frac{d}{V}v^{3/2} = c\frac{v^{3/2}}{V} \tag{1.7}$$

where $c = 2 \times 10^{-10}$. Many measurements of $q = ne$ for drops of various radii will yield a collection of values; presumably, each is close to an integer multiple of the fundamental unit of charge. When the numbers of unit charges involved in each of the measurements have been figured out, then each measurement, divided by the proper integer number, yields a value of e. A plot of $cv^{3/2}$ against V should show data points clustered around lines with slopes equal to ne ($n = 1, 2, 3, \ldots$).

Preparatory Questions

The Millikan apparatus in Modern Physics Lab has two parallel plates separated by approximately 0.6 cm and a high-voltage power supply (0 to 600 Volts). Each time you start a new observation with zero field and a squirt from the atomizer, you will see a myriad of droplets falling through the field of view. Your problem will be to pick a droplet that is of a size such that, if it carries a charge of a few electrons (e.g. 1–3e), you will be able to pull it upward with the available electric force. To judge which droplet to pick you must estimate the terminal fall velocity and holding voltage of a suitable droplet. The velocity of a droplet is determined from a measurement of the time it takes it to fall a distance which can be seen in the eyepiece reticle. The distance has to be taken about $z = 0.1\,\text{cm}$.

Problem 1: Calculate the time of fall of a droplet ($z = 0.1\,\text{cm}$) which, if it carries a charge of $1e$, can be held stationary with a voltage of 200 Volts.

Problem 2: Describe another completely independent method for determining the value of the electron charge.

You can obtain results of impressive accuracy in this experiment provided you take care in reducing random errors of measurement. The most important thing of all is to select appropriately sized droplets carrying very few elementary charges — $1e$ to $3e$ or $4e$. Make a preliminary analysis of the data for each droplet immediately after you obtain it so that you can perfect your judgment as to which droplets to select and what voltages to use. The timing measurements are like a video game in which practice makes perfect. N repetitions of any given measurement will reduce the random error of the mean in proportion to $(N)^{1/2}$. The most important source of systematic error is probably the voltage measurements. To estimate the error you should check the voltmeter against other similar ones and against the electrostatic voltmeter.

Procedure

A schematic diagram of the apparatus is shown in Figure 1.1.

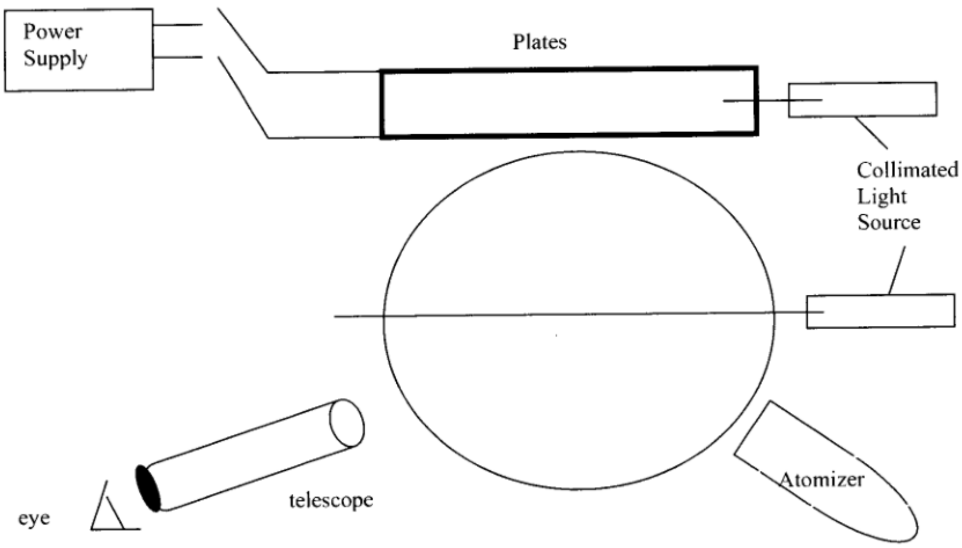

Figure 1.1: Schematic side and top view of the Millikan's Oil Drop apparatus

1. Adjust the eyepiece so the reticle is in sharp focus for your eye.
2. Spray droplets of oil from the atomizer through the port into the top chamber. As the droplets drift down, some pass through the tiny hole into the fiducial volume where they are illuminated by a collimated light as illustrated. When you see a droplet through the microscope as an unresolved point of diffracted light drifting slowly downward, attempt to arrest the droplet's fall by applying a voltage across the parallel plates. If the droplet moves downward more slowly under the influence of the electric force, then clearly the droplet is charged and an increase in voltage may arrest or reverse its motion. If the droplet accelerates downward under the action of electric force, the voltage should be reversed. If the electric field has no

effect, then the droplet is not charged at all. Try another droplet. When you catch one that works, i.e. it drifts slowly downward ($\sim 30\,\mathrm{s}$ fall time indicates the drop has about the optimum weight) with no voltage and can be pulled up by applying a voltage ($\sim 180\,\mathrm{V}$ indicates that there are only a few charge quanta on the drop).

3. Using as your race track the gap between horizontal lines of the reticle in the focal plane of the telescope, measure the free-fall times with the voltage off and record the voltage that keeps it stationary on one drop. Repeat as many times as possible or as long as you have patience. When you think you have your first really good set of repeatable data for one droplet, stop and analyze it, and derive the value of the charge on the droplet. If everything seems reasonable and your value is close to a small ($\sim$ 1–5) integer multiple of the known value of e, proceed to get data on more drops, working with each one as long as possible, and analyzing the data after each droplet is finished. Try to observe several with the shortest free-fall time (largest radius) you can measure accurately in order to have a good basis for extrapolating your values of e.

Air currents can be a problem in this experiment. Take care that the chamber is well sealed, and reduce as much as possible any movement of air in the room.

If you are working alone you may find the following procedure more convenient:

1. Pull the droplet above the top line by adjusting the voltage;
2. Switch the voltage to zero and measure the time to fall from the top to the bottom line of the reticle. Keep your left hand on the timer controls and your right hand on the voltage controls;
3. After the droplet has passed the bottom line arrest the downward motion by switching on the voltage;
4. Read and record the fall time, taking care that you will be able to identify the droplet after you have looked away for a moment to read and record the clock;
5. Measure and record the voltage that renders the droplet exactly stationary ($v = 0$);
6. Pull the droplet up and above the top line;
7. Repeat the sequence many times to reduce the random errors of the time and voltage measurements.

Tabulate your data in a format that will allow you to reduce it in an orderly fashion in adjacent columns.

You will find that it takes a considerable amount of practice to achieve high accuracy in this experiment. Both members of a team should perfect their skill at making all the various measurements. The more droplets you measure and the more data you accumulate on each droplet, the more accurate will be your final result.

Data and Calculations

Table 1.1

$V_{stop}(V)$	$x(m)$	$t(s)$	$v_t(=x/t)(m/s)$	$q = 2\times10^{-10}v_t^{3/2}/V_{stop}(C)$

Constants For Our Apparatus:

$$\begin{aligned}\rho\ &;\ \text{density of oil } = 800\,\mathrm{kg/m^3}\\ \rho'\ &;\ \text{density of air } = 1.29\,\mathrm{kg/m^3}\\ \eta\ &;\ \text{viscosity of air } = 1.827\times10^{-5}\,\mathrm{N\,s/m^2}\end{aligned}$$

For each droplet find the value of v and q and the errors. Plot $cv^{3/2}$ against V. Determine the slope (ne), and errors by linear regression. A linear fit program can be used for this purpose. From these results compute e and the errors. Take special care in understanding and evaluating the random and systematic errors.

Questions

1. Calculate the constant value in Equation (1.7).
2. What is viscosity and how can it be measured?
3. What is Stoke's law, and how can you verify it?
4. Quarks have charges of $\pm(1/3)e$ and $\pm(2/3)e$. What is the explanation for the fact that such charges have never been observed?
5. In the oil drop experiment a capacitor is used with a plate separation of 2.5 mm. A droplet is observed falling without electric field through a distance of 1.00 mm in 25.3 s. When a potential difference of 154.8 V raises the same droplet, it travels a distance of 1.00 mm in 18 second. The density of the oil is given as $\rho = 920\,\mathrm{kg/m^3}$, the viscosity of air as $\eta = 1.827\times10^{-5}\,\mathrm{Ns/m^2}$. How large is the electric charge on the droplet?

References

[1] P. R. Bevington and D. K. Robinson, *Data Reduction and Error Analysis for the Physical Sciences*, 2nd Edition, McGraw-Hill, (1992).

[2] R. A. Millikan, “On the Elementary Electrical Charge and the Avogadro Constant,” *Physical Review*, **32**, 349 (1911).

[3] S. Weinberg, *The Discovery of Subatomic Particles*, Scientific American Books, New York, (1983).

[4] Common Apparatus, “Novel Experiments in Physics,” *American Institute of Physics*, (1964), pp. 237–241.

Experiment 2

e/m FROM ELECTRIC AND MAGNETIC DEFLECTION

Purpose

- to measure the ratio of charge/mass (e/m) for electrons,
- to discuss about the phenomena of electric and magnetic deflection,
- to use the application of vector product.

Introduction

In electric discharges through gases at low pressure, there are observed cathode (or negative) rays and positive rays, both of which are found to be corpuscular (discrete particle). The charge / mass ratio, e/m, of these corpuscles gives evidence of their nature.

Historical Context: Cathode Rays

An electric discharge tube consists of two spherical glass bulbs connected through a narrow neck (Figure 2.1). The discharge is produced in the right bulb between the anode (the plate connected with the positive terminal of a power supply) and the cathode (the cylinder occupying the neck, connected with the negative terminal). A power supply provides several thousands or tens of thousands of volts. The gas consists, for example, of hydrogen or mercury vapor at a pressure of a few thousands of a millimeter of mercury. A discharge fills the whole right bulb uniformly with dim light. Furthermore, a straight ray, brighter than the discharge, emanates from the front surface of the cathode, crosses the bulb, and produces fluorescence of the opposite glass surface. This ray is called a 'cathode ray'. An obstacle placed in its path casts a shadow on the glass surface and so demonstrates that the ray emanates from the cathode.

The nature of this ray is revealed when a magnet is brought near. Even the weak magnetic field surrounding a steel magnet causes a deflection. Its direction indicates that the cathode ray

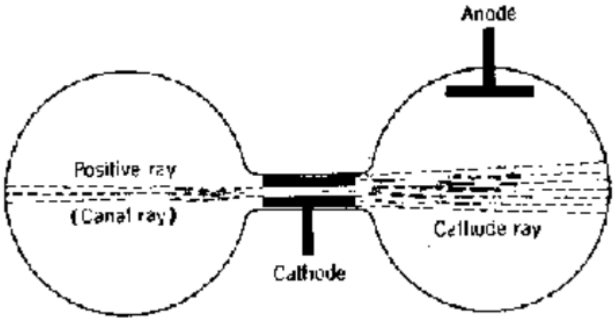

Figure 2.1: Dielectric Discharge.

consists of negatively charged particles. This is confirmed when the ray is allowed to pass through the space between two parallel metal plates connected to a battery. The electric field between the metal plates deflects the cathode ray in a direction that indicates that negative charges are coming from the cathode.

J. J. Thomson's Method (Electromagnetic Deflection)

A quantitative study of the deflections caused by magnetic and electric fields was made by J.,J.,Thomson. By way of introduction, let us review the forces exerted on electric charges by such fields.

1. The magnitude of electric field $\boldsymbol{E}$ between plane plates of a capacitor (separation s) connected to a battery is

$$|\boldsymbol{E}| = \frac{\Delta V}{s} \tag{2.1}$$

The electric force exerted by this field $\boldsymbol{E}$ on a charge q is

$$\boldsymbol{F} = q\boldsymbol{E}. \tag{2.2}$$

For an electron ($q = -e$), $\boldsymbol{F} = -e\boldsymbol{E}$ and the force is opposite to $\boldsymbol{E}$. Equations (2.1)–(2.2) summarize the action of a uniform electric field on a charge.

2. A wire of length l carrying a current I when placed in a magnetic field directed perpendicular to the wire is acted upon by a force. In general (vector form) the magnetic force on a current-carrying segment is

$$\mathbf{F} = \mathbf{I}\boldsymbol{\ell} \times \mathbf{B}, \tag{2.3}$$

where $\boldsymbol{\ell}$ is a vector of magnitude l along the wire, and $\mathbf{B}$ is the magnetic induction. For the perpendicular arrangement used here, $\boldsymbol{\ell} \perp \mathbf{B}$, so the magnitude reduces to

$$\mathbf{F} = \mathbf{I}l\mathbf{B}. \tag{2.4}$$

The direction of $\mathbf{F}$ is perpendicular to that of the wire and that of the magnetic field, as expressed by (2.3).

Applying this basic law to the cathode ray, which consists of n electrons per meter of length moving with velocity $\mathbf{v}$, we first note the single-particle (Lorentz) magnetic force in vector form:

$$\mathbf{F}_B = e\mathbf{v} \times \mathbf{B}. \tag{2.5}$$

Hence the magnitude in the general case is

$$F = evB \sin\theta, \tag{2.6}$$

where θ is the angle between $\mathbf{v}$ and $\mathbf{B}$. In the perpendicular field configuration used experimentally ($\theta = 90°$), (2.6) simplifies to $F = evB$.

We obtain

$$\text{Current} = nev, \tag{2.7}$$

so that

$$\text{Force on length } l = nevlB, \tag{2.8}$$

where nl = number of electrons contained in l. Hence

$$\text{Force on one electron} = evB. \tag{2.9}$$

Again the force is perpendicular to both $\mathbf{v}$ and $\mathbf{B}$, in agreement with (2.5).

For his quantitative study of the magnetic and electric deflections Thomson, in 1897, applied uniform fields limited to a well-defined space.

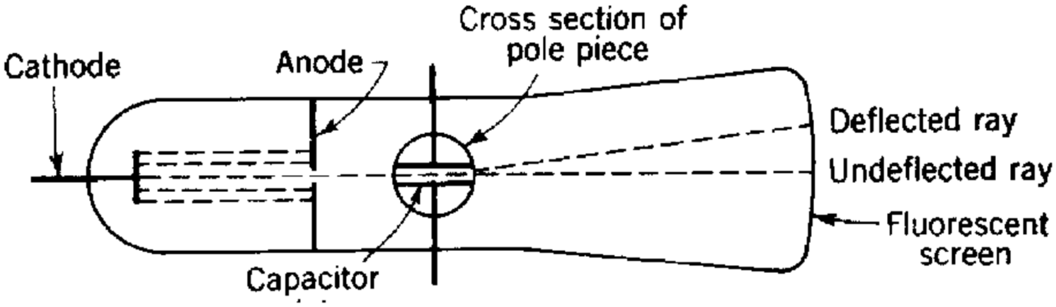

Figure 2.2: Deflection of cathode rays.

First Measurement (Velocity Selection)

Thomson combined the results of two consecutive measurements. The cathode ray is deflected by an electric field E_1, and a magnetic induction B_1 is adjusted to cancel the electric force.

$$\textit{Hence, } E_1 e = evB_1.$$

The velocity v is determined as:

$$v = E_1/B_1 \tag{2.10}$$

This velocity is very high, depending on the potential difference applied between cathode and anode.

Second Measurement (Magnetic Deflection)

Only a magnetic induction B_2 is applied. *The theory predicts a circular path of the charged particles within the range of the magnetic field. The centripetal force required for the circular path equals the magnetic force exerted by* B_2:

$$\frac{mv^2}{r} = evB_2 \tag{2.11}$$

The radius of curvature r is computed from the observed slight deflection. Solving for the specific charge e/m:

$$\frac{e}{m} = \frac{v}{rB_2} \tag{2.12}$$

Thomson's result showed that the specific charge is always the same, identifying the particles as **free electrons**. The accepted numerical result is $e/m = 1.75888 \times 10^{11}$ coulombs/kg.

Electric Acceleration and Magnetic Deflection (The Practical Lab Method)

This alternative determination of e/m utilizes electron emission from glowing filaments (discovered by T. A. Edison in 1883).

Energy Acceleration

In the setup (Figure 2.4), a glowing filament (F) is made negative with respect to a cylinder (A). The kinetic energy (T) gained by the particles accelerated by a potential difference ΔV is computed:

$$T = \frac{1}{2}mv^2 = \int_{V_a}^{V_b} e dV = e\Delta V \tag{2.13}$$

Magnetic Deflection and e/m Calculation

The particles enter a region subjected to a uniform magnetic field B perpendicular to their direction, where they are bent into a circular path of radius r. The magnetic force provides the centripetal acceleration:

$$\frac{mv^2}{r} = evB \tag{2.14}$$

Solving the energy equation and Equation (2.14) for e/m in terms of measurable quantities (ΔV, B, r):

$$\frac{e}{m} = \frac{2\Delta V}{B^2 r^2} \tag{2.15}$$

The numerical result $e/m = 1.759 \times 10^{11}$ C/kg identifies the same free electrons.

Helmholtz Coils

Helmholtz coils (Figure 2.3) consist of two circular coils of the same radius (R), with a common axis, separated by a distance R. They are used to produce a relatively uniform magnetic field (B) over a small region. The magnetic induction at the midpoint is:

$$B = \frac{8\mu_o NI}{5^{3/2}R} \tag{2.16}$$

For the coils used in this experiment, the relationship between current (I) and magnetic induction (B) is:

$$B = 7.8 \times 10^{-4} I \quad (B \text{ in T}, I \text{ in A})$$

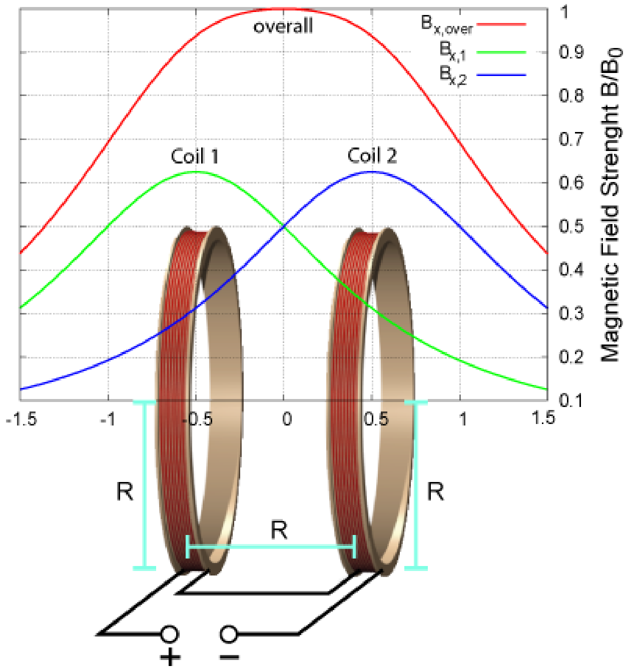

Figure 2.3: Helmholtzs coils and magnetic field strength

Procedure

Part 1: Electromagnetic Deflection

This part checks the understanding of the magnetic force on a charged particle, which is governed by the Lorentz force law: $F_B = qv \times B$. *This force is perpendicular to both the magnetic field and the velocity*. For a particle moving perpendicular to a uniform magnetic field, results with a circular orbit because the magnetic force equals the centripetal acceleration:

$$evB = \frac{mv^2}{R}$$

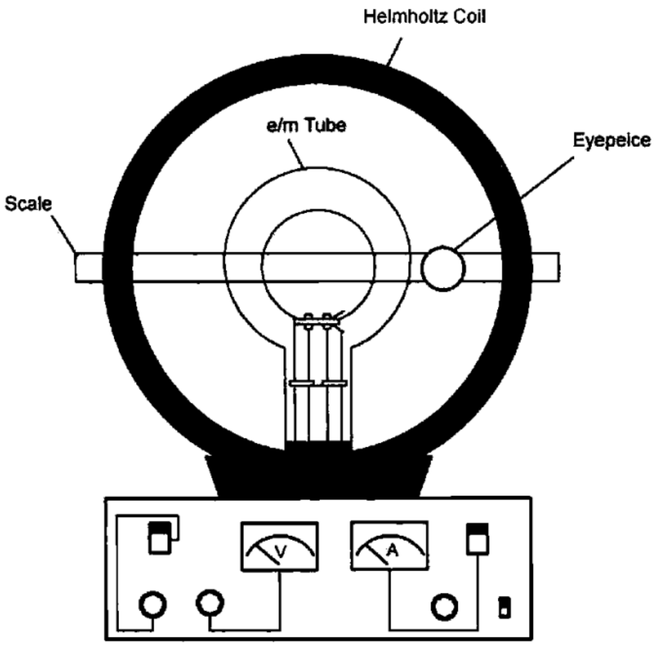

Figure 2.4: Experimental Setup

You can use this rule, along with the knowledge that electrons have negative charge, to figure out the direction of the magnetic field inside the Helmholtz coils. In the special case of a particle moving perpendicular to a uniform magnetic field, it is easy to see that this leads to a circular orbit. The acceleration is perpendicular to the velocity and so will change only its direction, and since v and B are both constant the magnitude of the acceleration will also be uniform.

Part 2: Electrostatic Deflection

This is another method of getting at the e/m value for the electron. If the Helmholtz coils are off and a potential difference V_d is put across the parallel plates, then the electrons moving through the cathode ray tube are affected by a "constant" electric field and so experience a "constant" force. Over the region of the grid this is very close to true, but outside the grid the field weakens. This may affect your results significantly and is worth investigating. Turn the switch to the "electrical deflection" position to observe a deflection.

Since the electrons are experiencing a constant force, they travel just like projectiles fired from a cannon. This lets you write down the x and y coordinates as a function of the force, initial velocity, and time:

$$x = v_e t \tag{2.17}$$

$$y = a_y t^2/2 = (F_E/m)t^2/2 \tag{2.18}$$

The time can be substituted for any x coordinate by rewriting Equation (2.17) as $t = x/v_e$. The force on the electron is just eE, and the electric field is V_d/s, where s is the seperation between the plates. We can take the last step only because the field is uniform. Combining all this information into Equation (2.18) gives us the following.

$$y = \frac{1}{2}\left(\frac{e}{m}\right)\left(\frac{V_d}{s}\right)\left(\frac{x}{v_e}\right)^2 \tag{2.19}$$

Part 3: Determination of e/m by Magnetic Deflection

Turn the switch to the ”e/m measure” position to observe a circular orbit. Keep accelerating voltage at 200V. Apply bias to the Helmholtz coils. Measure the radius (r) of the electron’s orbit for various magnetic field intensities. Fill the Table 2.1.

Data and Calculations

Table 2.1: *Experimental Data*

I (A)	*r (m)*	*B (T)*	ΔV *(V)*	$1/r^2$ (m^{-2})	B^2 (T^2)
0.9			200		
1.0			200		
1.1			200		
1.2			200		
1.3			200		
1.4			200		
1.5			200		
1.6			200		

Data Analysis and Plotting

The quantitative calculation relies on the formula: $\frac{e}{m} = \frac{2\Delta V}{B^2 r^2}$. When plotting $Y = 1/r^2$ versus $X = B^2$, the slope (S) is:

$$S = \frac{e/m}{2\Delta V}$$

Plot $1/r^2$ versus B^2, find its slope, calculate e/m and compare it with the results given in the introduction part.

Questions

Questions for Part 1: In Part 1, if you increase the velocity of the electrons by turning up the accelerating voltage, you should see the radius of the trajectory increase proportionally. Do you see a helix or circular orbit? What is the difference between them? Find the direction of magnetic field.

Questions for Part 2: In Part 2, we will only observe electric deflection without taking any data. Draw deflection of electrons. After reversing the bias, what do you see?

1. Is it possible to find your direction by use of a cathode ray tube, electron gun or an osscilloscope? If it is possible, explain how you can perform it?

2. In an experiment a cathode ray passes between plates 1 cm apart, connected with a power supply of 790V; the electrostatic deflection is compensated by a magnetic induction of 3×10^{-3} Wb/m^2. In a second experiment the same cathode ray is bent by a magnetic induction of 1.250×10^{-3} Wb/m^2 into a circular path of 12.00 cm radius. Compute e/m of the cathode-ray particles.

3. Electrons are accelerated from a glowing filament toward a plate by a potential difference of 100 V. After passing through a slit, they enter a space free of electric fields in which they are subjected to a magnetic induction of 3.00×10^{-4} Wb/m^2 directed perpendicular to their velocity. Find their linear velocity v beyond the slit and the radius R of their path in the magnetic field.

References

[1] Thomas A. Edison, "On a peculiar behaviour of glow lamps when raised to high incandescence," *Proceedings of the Royal Society of London*, 1883.

[2] D. J. Griffiths, *Introduction to Electrodynamics*, 4th ed., Pearson Education, 2013.

Experiment 3

ELECTRON DIFFRACTION

Purpose

- Observe the wave behaviour of particles (electrons) from diffraction.
- Determine the interplanar spacings in graphite.

Introduction

In 1924, Louis de Broglie proposed that matter, just like light, has a dual character behaving in some circumstances like particles and in others like waves. In 1927 Davisson and Germer in the United States and G.P. Thomson in England independently confirmed the existence of de Broglie waves, and demonstrated that the electron beams are diffracted, when they are scattered by the regular atomic arrays of crystals. G.P. Thomson used a monoenergetic beam of electrons through a thin metal target foil. The target was not a single large crystal (as in the Davisson and Germer experiment), but was made up of a large number of tiny, randomly oriented crystallizes. With this arrangement, there will always, by chance, be a certain number of crystallizes oriented at the proper angle to produce a diffracted beam. It is well known that a photon of light of frequency ν has the momentum

$$p = \frac{h\nu}{c} \tag{3.1}$$

To explain in the interference phenomenon, a wavelength λ which depends on momentum, is assigned to the electrons in accordance with the de Broglie wavelength:

$$\lambda = \frac{h}{p} \tag{3.2}$$

where $h = 6.625 \times 10^{-34}$ Js, Planck's constant.

The momentum can be calculated from the velocity that the electrons acquire under acceleration voltage U_A:

$$\frac{1}{2}mv^2 = \frac{p}{2m} = eU_A \tag{3.3}$$

The wavelength is thus:

$$\lambda = \frac{h}{\sqrt{2meU_A}} = \frac{1.23}{\sqrt{U_A}} nm \tag{3.4}$$

where $e = 1.602 \times 10^{-19}$ C (electron charge) and $m = 9.109 \times 10^{-31}$ kg (rest mass of electron).

Since our apparatus is operated below 10 kV, the electrons are non-relativistic. Relativistic corrections are not required for the above relations.

At the voltages U_A used, the relativistic mass can be replaced by the rest mass with an error of only 0.5%.

The electron beam strikes a polycrystalline graphite film deposited on a copper grating and is reflected according to the Bragg condition (Figure 3.1):

$$2d \sin\theta = n\lambda, \quad n = 1, 2, 3 \ldots \tag{3.5}$$

where d denotes the spacing between the planes of carbon atoms and θ represents the Bragg angle (the angle between the incident electron beam and the lattice planes).

In polycrystalline graphite, the weak van der Waals bonds between the individual layers (Figure 3.2) are broken, leading to a random orientation of these layers. As a result, the incident electron beam is diffracted into a conical pattern, producing a series of interference rings on the fluorescent screen. In a single crystal, the atomic planes are well oriented and the diffraction forms along specific aligments. Consequently, a sharp and vertically aligned interference pattern is produced.(Figure 3.3).

The Bragg angle θ can be calculated from the radius of the interference ring but it should be remembered that the angle of deviation α (see Figure 3.1 and Figure 3.4) is twice as great:

$$\alpha = 2\theta \tag{3.6}$$

From Figure 3.4 we read off:

$$\sin(2\alpha) = \frac{r}{R} \tag{3.7}$$

where $R = 65$ mm, radius of the glass bulb. Now:

$$\sin 2\alpha = 2 \sin\alpha \cos\alpha \tag{3.8}$$

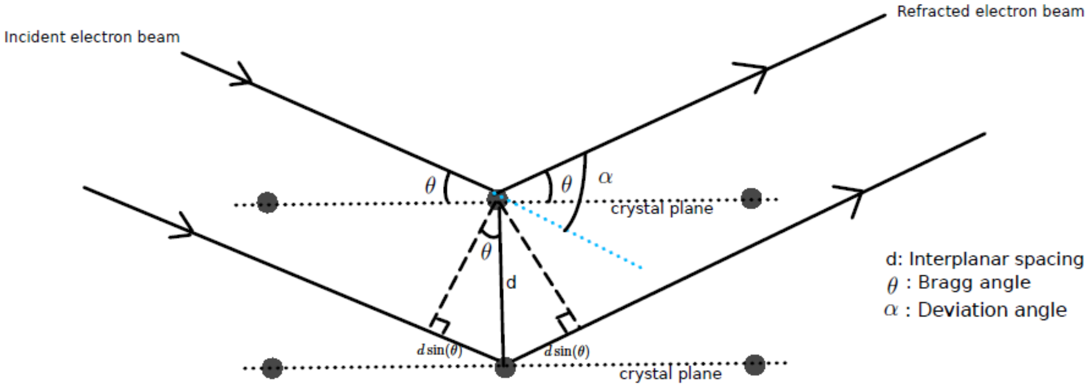

Figure 3.1: Bragg's Law.

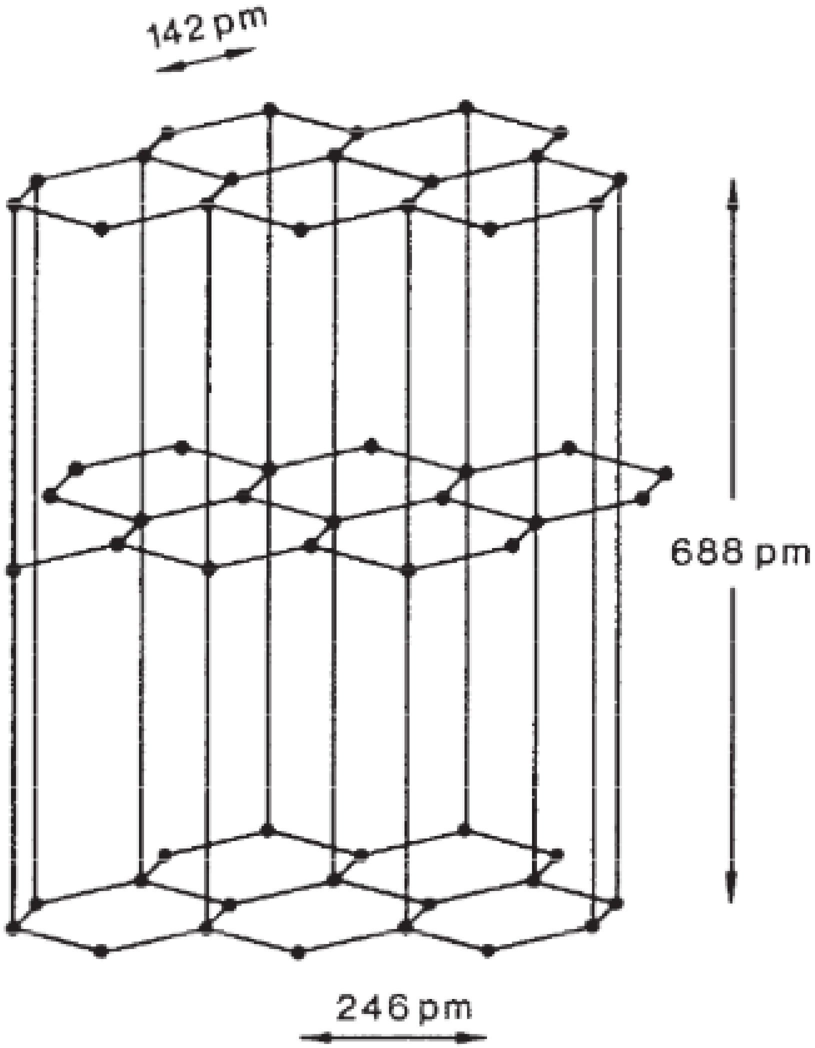

Figure 3.2: Crystal lattice of graphite.

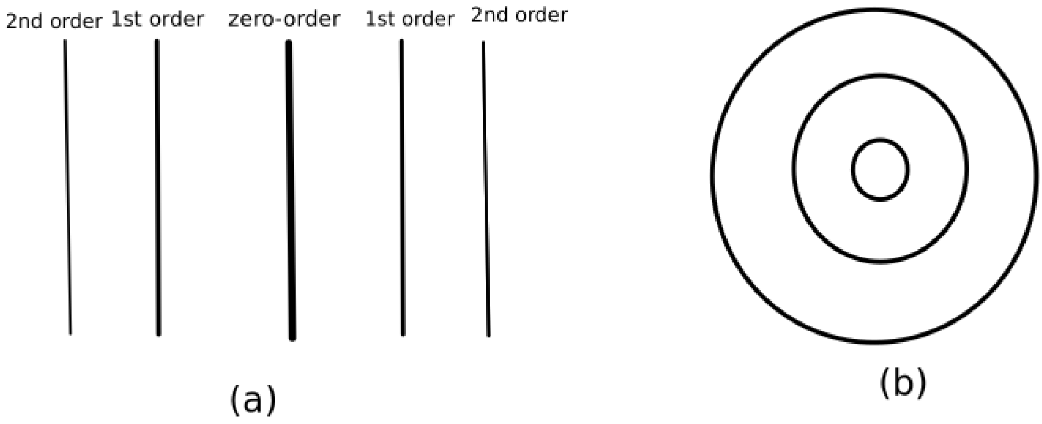

Figure 3.3: (a) Vertical line interference pattern (b) Concentric circular interference pattern

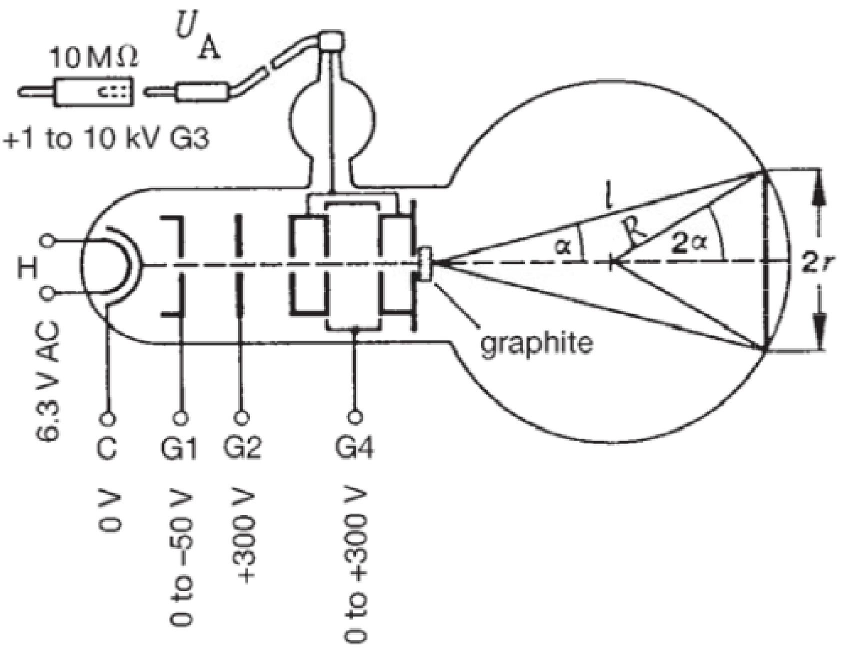

Figure 3.4: Setup and Power Supply to the Electron Diffraction Tube

For small angles α ($\cos 10^\circ = 0.985$) we can put:

$$\sin(2\alpha) \simeq 2\sin(\alpha) \tag{3.9}$$

so that for small angles θ we obtain:

$$\sin(\alpha) = \sin(2\theta) \simeq 2\sin(\theta) \tag{3.10}$$

With this approximation we obtain:

$$r = \frac{2R}{d} n\lambda \tag{3.11}$$

The two inner interference rings occur through reflection from the lattice planes of spacing d_1 and d_2 (Figure 3.5), for $n = 1$ in Equation (3.11).

Related Topics

Bragg reflection, Debye-Scherrer method, lattice planes, graphite structure, material waves, de Broglie equation.

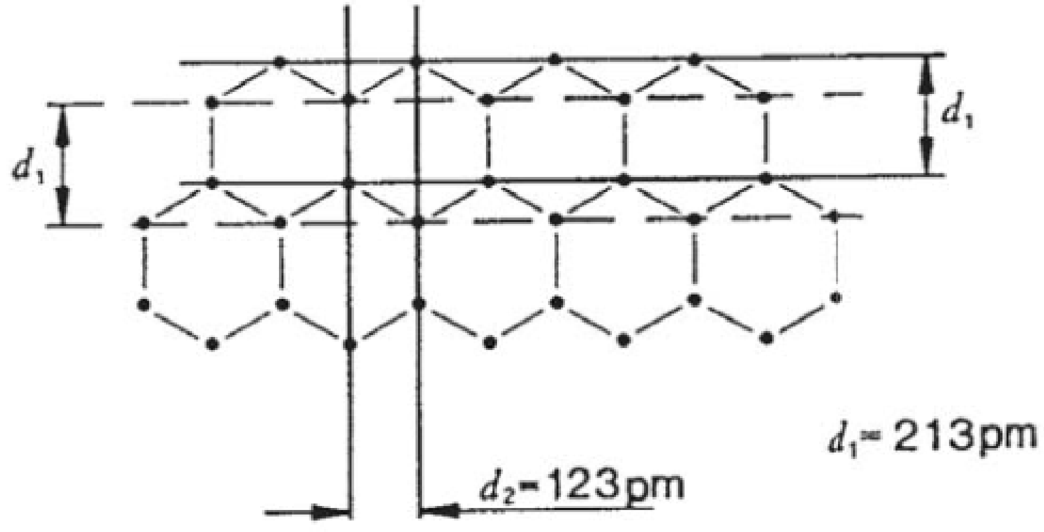

Figure 3.5: Graphite planes for the first two interference rings

Equipments

- Electron diffraction tube and mounting
- High voltage supply unit, 0–10 kV
- High-value resistor, 10 MΩ
- Connecting cord, 50 kV, 500 mm
- Power supply, 0–600 VDC
- Vernier caliper, plastic

Procedure

1. Set up the experiment as shown in Figure 3.6. Connect the sockets of the electron diffraction tube to the power supply as shown in Figure 3.7. Connect the high voltage to the anode G3 through a 10 MΩ protective resistor.

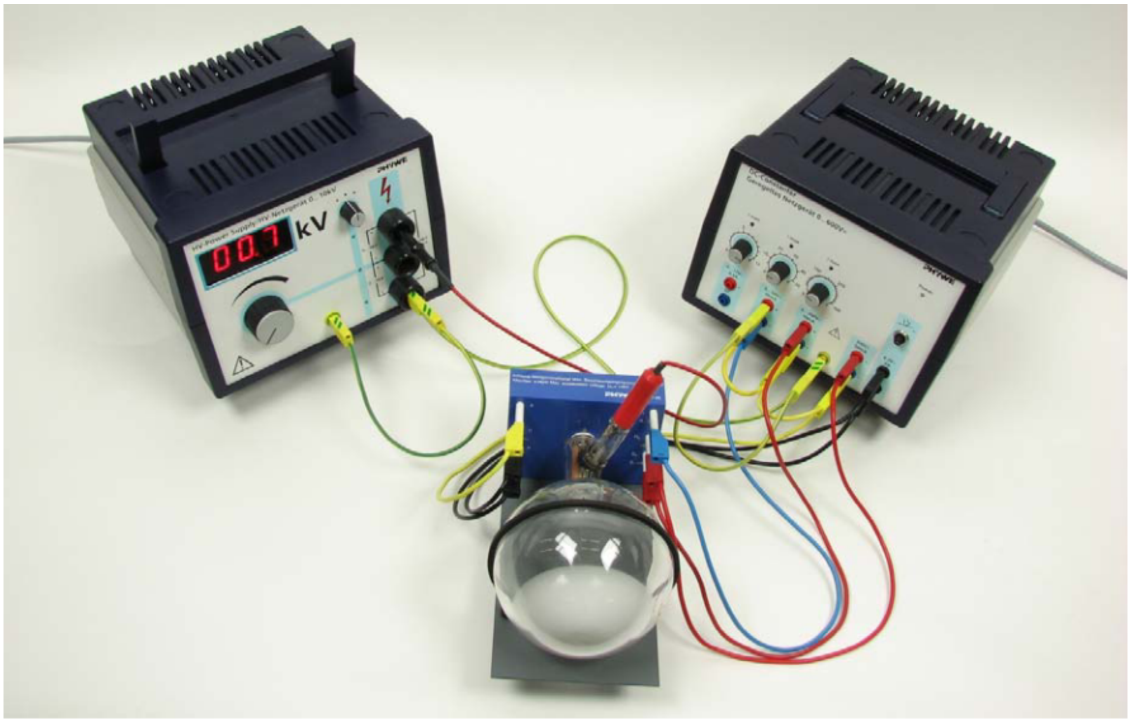

Figure 3.6: Set-up of the experiment.

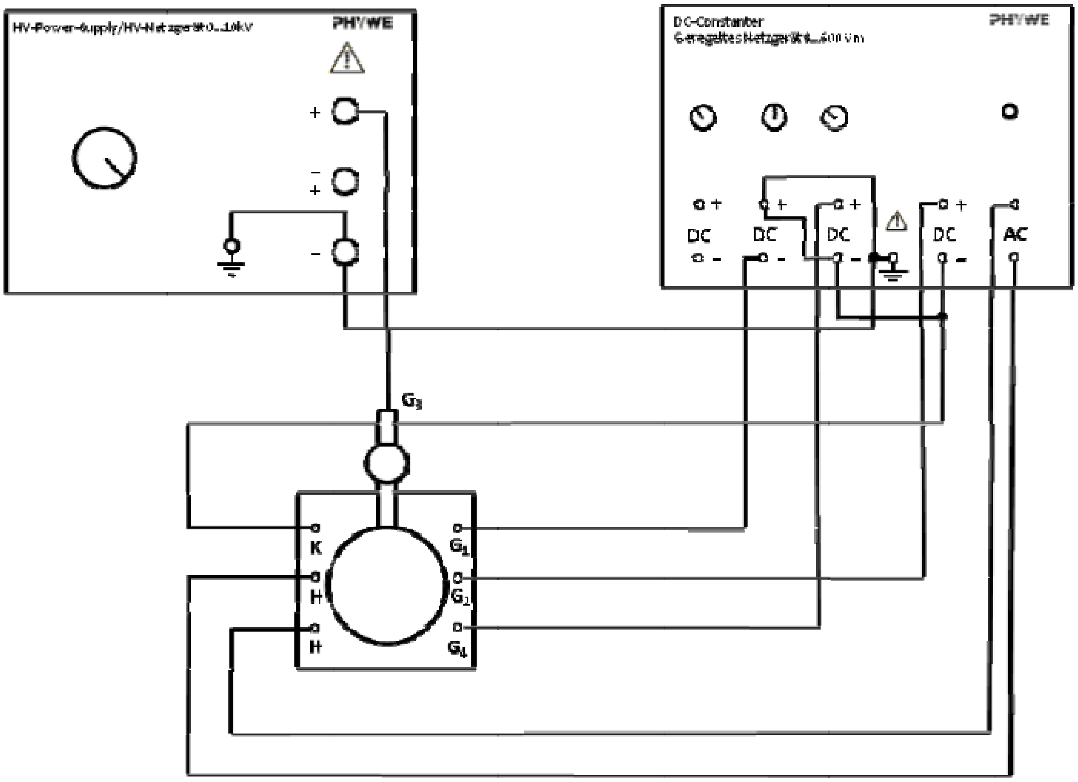

Figure 3.7: Electrical connection for the experiment

2. Set the Wehnelt voltage G1 and the voltages at grids G4 and G3 so that sharp, well-defined diffraction rings appear. Read the anode voltage at the HV display.
3. To determine the diameter of the diffraction rings, measure the inner and outer edge of the rings with the vernier caliper in a darkened room and take an average. Note that there is another faint ring immediately behind the second ring.

Notes

- Intensity of higher order interference rings is much lower than first order.
- Visibility depends on lab light intensity and voltages applied to G1 and G4.
- Bright spot in the center can damage fluorescent layer. Reduce intensity after each reading.

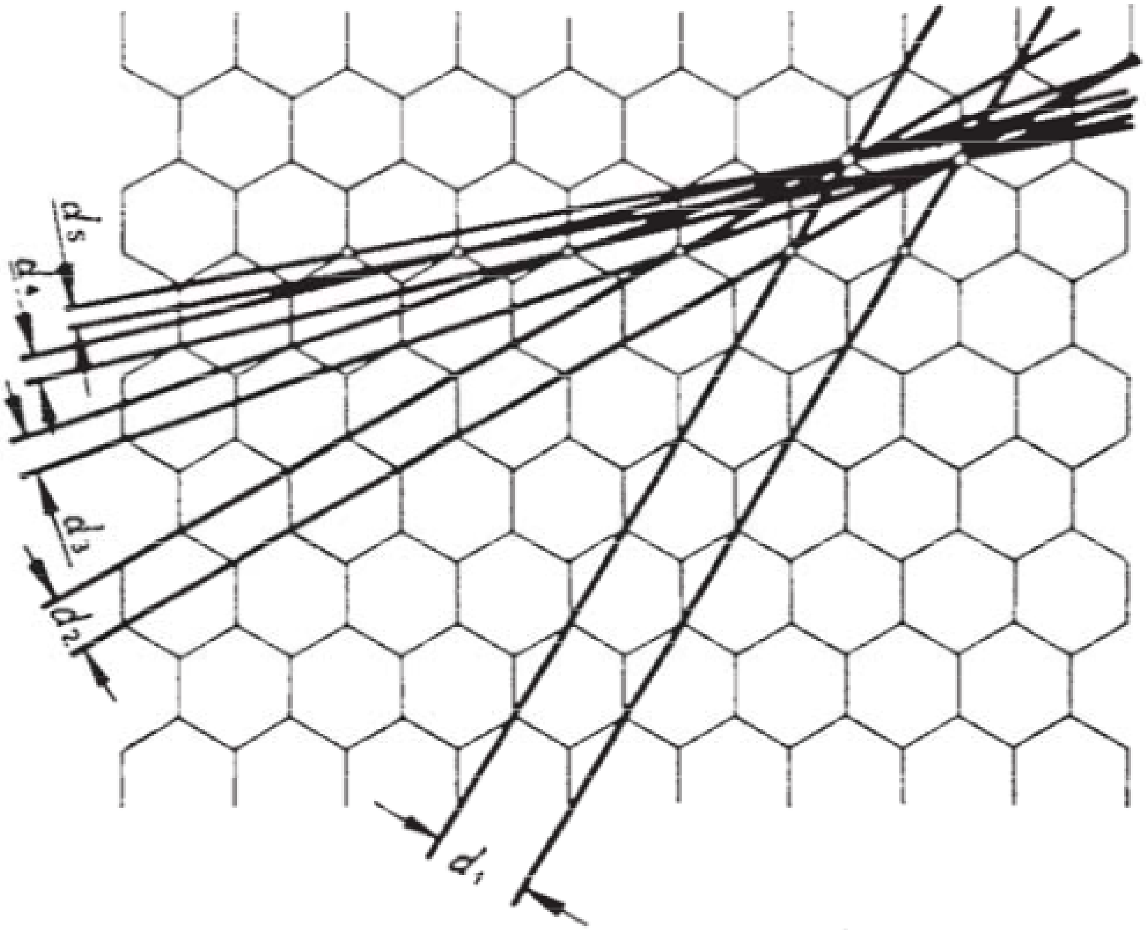

Figure 3.8: Interplanar spacing in graphite, d1=213 pm, d2=123 pm, d3=80.5 pm, d4=59.1 pm, d5=46.5 pm

EXPERIMENT 3: ELECTRON DIFFRACTION

Data and Calculations

Table 3.1

U_A (kV)	λ (pm)	r_{1in} (mm)	r_{1out} (mm)	r_{1ave} (mm)	r_{2in} (mm)	r_{2out} (mm)	r_{2ave} (mm)
4.00							
4.50							
5.00							
5.50							
6.50							
7.00							
7.40							

Calculate the wavelength from the anode voltage in accordance with Equation (3.4). For two interference rings, plot r versus λ, use linear fit to find slope, and calculate lattice constants.

Questions

1. What is the de Broglie wavelength of electrons of an energy 20 000 eV in the beam of a TV tube? Is classical mechanics likely to be a satisfactory approximation for the operation of TV tubes?
2. A beam of electrons of energy 64.0 eV is incident on an aluminium foil containing many microcrystals. The interference pattern produced by the scattered beams is observed on a fluorescent screen placed 15.0 cm beyond the foil. The pattern consists of several concentric circles. Calculate the radii of the circles that result from Bragg reflections by a set of planes with a spacing of 4.04 Å.
3. An electron moves along a circular path 0.5 cm in radius in a uniform magnetic field of strength H = 46 Oe. What is the de Broglie wavelength of the electron?
4. Calculate the theoretical magnitude of the resolving power to be expected in an electron microscope when an accelerating voltage of 100 kV is applied. What will be the de Broglie wavelength of the electrons?

References

1. `https://dlf.ug.edu.pl/wp-content/uploads/2014/03/Electron-diffraction.pdf`
2. `https://www.unm.edu/~mph/307/EDiffraction_UNM1.pdf?utm_source`
3. *Physics*, Halliday, Resnick, and Krane, 5th Edition (Volume 2), Chapters 42–43.

Experiment 4

THERMAL RADIATION SYSTEMS

Purpose

- Measure radiative intensities using the Radiation Sensor, Radiation Cube (Leslie's Cube), and the Stefan–Boltzmann Lamp to verify the theoretical relationship between temperature and emitted power.
- Examine how surface characteristics (color and texture) affect emissivity and radiative heat transfer efficiency.

Introduction

Thermal radiation is the transfer of energy through electromagnetic waves that are emitted by matter as a result of its temperature. Unlike conduction and convection, it does not require a material medium and can take place even in a vacuum. This mechanism allows heat from a hot body to travel through empty space, as in the energy reaching Earth from the Sun[1]. Blackbody radiation is the electromagnetic radiation emitted by an idealized object that absorbs all incident energy. Classical physics failed to describe its observed spectrum, predicting infinite radiated energy at short wavelengths, a problem known as the ”ultraviolet catastrophe” [1]. This discrepancy was resolved by Max Planck in 1900, who proposed that energy is quantized, introducing the concept of energy quanta [2].

The Thermal Radiation System includes three items: the Radiation Sensor, the Radiation Cube (Leslie's Cube), and the Stefan–Boltzmann Lamp. The thermal radiation emitted depends strongly on the temperature and surface properties of the body, which form the basis for the Stefan–Boltzmann and inverse square relationships investigated in this experiment. This manual contains operating instructions for each of these items plus instructions and worksheets for the following four experiments:

1. Introduction to Thermal Radiation
2. Inverse Square Law

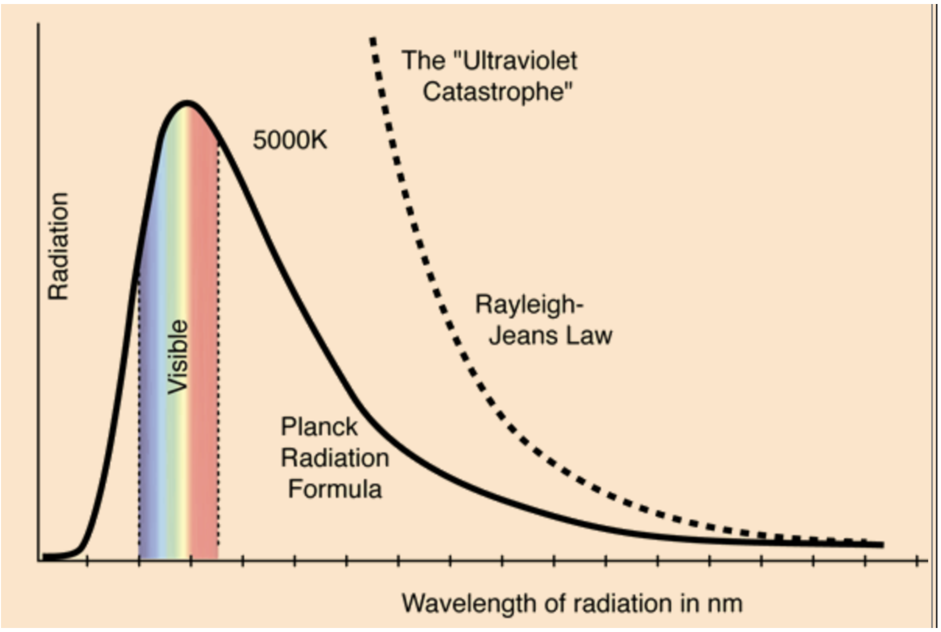

Figure 3.1: Comparison of the classical Rayleigh–Jeans prediction with the quantum mechanical Planck radiation formula for blackbody radiation at 5000 K [3].

3. Stefan–Boltzmann Law* (at high temperatures)
4. Stefan–Boltzmann Law* (at low temperatures)

Note: The descriptions of the equipment, operating procedures, and experimental setup in this report are based primarily on the *Thermal Radiation System Instruction Manual* provided by PASCO Scientific for models TD-8553 (Radiation Sensor), TD-8554A (Radiation Cube), and TD-8555 (Stefan–Boltzmann Lamp) [4]. The content has been adapted for instructional and non-commercial laboratory use.

Radiation Sensor

The Radiation Sensor (Figure 3.2) measures the relative intensities of incident thermal radiation. The sensing element, a miniature thermopile, produces a voltage proportional to the intensity of the radiation. The spectral response of the thermopile is essentially flat in the infrared region (from 0.5 to 40 μm), and the voltages produced range from the microvolt range up to around 100 millivolts. (A good millivolt meter is sufficient for all the experiments described in this manual.)

The sensor can be hand-held or mounted on its stand for more accurate positioning. A spring-clip shutter is opened and closed by sliding the shutter ring forward or back. During experiments, the shutter should be closed when measurements are not actively being taken. This helps reduce temperature shifts in the thermopile reference junction which can cause the sensor response to drift.

Note: When opening and closing the shutter, it is possible you may inadvertently change the sensor position. Therefore, for experiments in which the sensor position is critical, two small

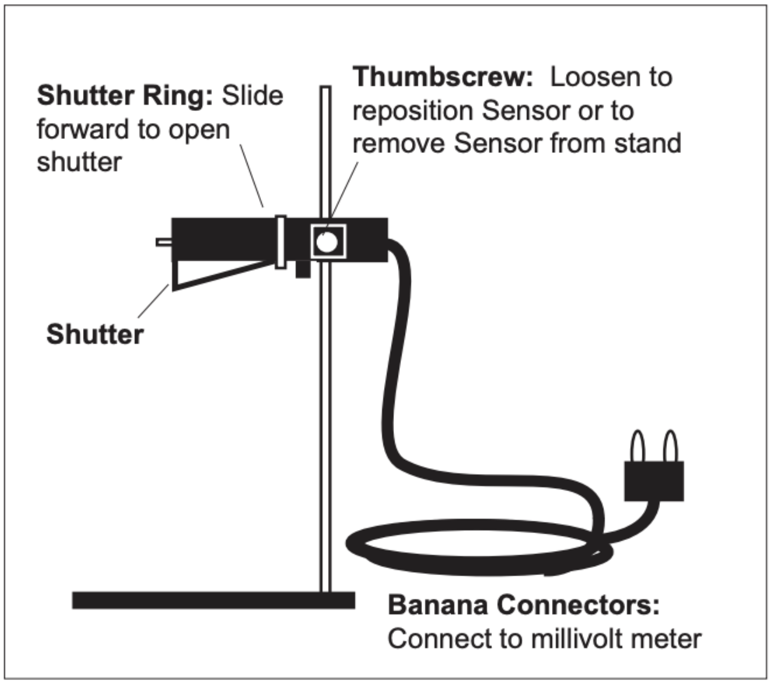

Figure 3.2: Radiation Sensor setup.

sheets of opaque insulating foam have been provided. Place this heat shield in front of the sensor when measurements are not actively being taken.

The two posts extending from the front end of the Sensor protect the thermopile and also provide a reference for positioning the sensor a repeatable distance from a radiation source.

Specifications

- Temperature Range: $-65\,^\circ\mathrm{C}$ to $85\,^\circ\mathrm{C}$
- Maximum Incident Power: $0.1\,\mathrm{W\,cm^{-2}}$
- Spectral Response: 0.6 to 30 μm
- Signal Output: Linear from 10^{-6} to 10^{-1} $\mathrm{W\,cm^{-2}}$

Radiation Cube

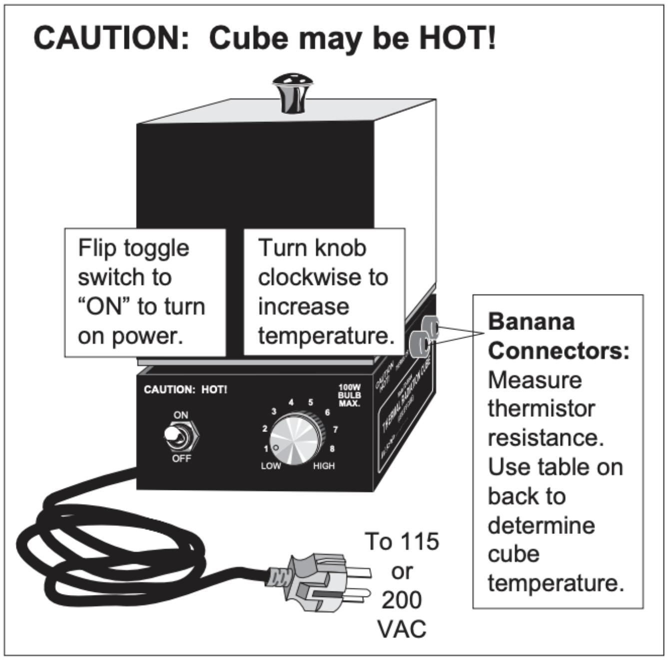

Figure 3.3: Radiation Cube (Leslie's Cube).

The Radiation Cube (Figure 3.3) provides four different radiating surfaces that can be heated from room temperature to approximately 120 °C. The cube is heated by a 100 watt light bulb. Just plug in the power cord, flip the toggle switch to "ON", then turn the knob clockwise to vary the power. Measure the cube temperature by plugging your ohmmeter into the banana plug connectors labeled THERMISTOR. The thermistor is embedded in one corner of the cube. Measure the resistance, then use Table 4.1 to translate the resistance reading into a temperature measurement. **Note:** For best results, a digital ohmmeter should be used.

Table 4.1: Resistance versus Temperature for the Thermal Radiation Cube

Term. R(Ω)	**T(°C)**	**Term. R(Ω)**	**T(°C)**	**Term. R(Ω)**	**T(°C)**	**Term. R(Ω)**	**T(°C)**
207,850	10	39,605	46	10,110	82	3,215.8	118
197,560	11	37,995	47	9,767.2	83	3,123.0	119
187,840	12	36,458	48	9,437.7	84	3,033.3	120
178,650	13	34,991	49	9,120.8	85	2,946.5	121
169,950	14	33,591	50	8,816.0	86	2,862.5	122
161,730	15	32,253	51	8,522.7	87	2,781.3	123
153,950	16	30,976	52	8,240.6	88	2,702.7	124
146,580	17	29,756	53	7,969.1	89	2,626.6	125
139,610	18	28,590	54	7,707.7	90	2,553.0	126
133,000	19	27,475	55	7,456.2	91	2,481.7	127
126,740	20	26,409	56	7,214.0	92	2,412.6	128
120,810	21	25,390	57	6,980.6	93	2,345.8	129
115,190	22	24,415	58	6,755.9	94	2,281.0	130
109,850	23	23,483	59	6,539.4	95	2,218.3	131
104,800	24	22,590	60	6,330.8	96	2,157.6	132
100,000	25	21,736	61	6,129.8	97	2,098.7	133
95,447	26	20,913	62	5,936.1	98	2,041.7	134
91,126	27	20,136	63	5,749.3	99	1,986.4	135
87,022	28	19,386	64	5,569.3	100	1,932.8	136
83,124	29	18,668	65	5,395.6	101	1,880.9	137
79,422	30	17,980	66	5,228.1	102	1,830.5	138
75,903	31	17,321	67	5,066.6	103	1,781.7	139
72,560	32	16,689	68	4,910.7	104	1,734.3	140
69,380	33	16,083	69	4,760.3	105	1,688.4	141
66,356	34	15,502	70	4,615.1	106	1,643.9	142
63,480	35	14,945	71	4,475.0	107	1,600.6	143
60,743	36	14,410	72	4,339.7	108	1,558.7	144
58,138	37	13,897	73	4,209.1	109	1,518.0	145
55,658	38	13,405	74	4,082.9	110	1,478.6	146
53,297	39	12,932	75	3,961.1	111	1,440.2	147
51,048	40	12,479	76	3,843.4	112	1,403.0	148
48,905	41	12,043	77	3,729.7	113	1,366.9	149
46,863	42	11,625	78	3,619.8	114	1,331.9	150
44,917	43	11,223	79	3,513.6	115		
43,062	44	10,837	80	3,411.0	116		
41,292	45	10,467	81	3,311.8	117		

Stefan–Boltzmann Lamp

Important: The voltage into the lamp should **NEVER** exceed 13 V. Higher voltages will burn out the filament.

The Stefan–Boltzmann Lamp (Figure 3.4) is a high temperature source of thermal radiation. The lamp can be used for high temperature investigations of the Stefan–Boltzmann Law. The high temperature simplifies the analysis because the fourth power of the ambient temperature is negligibly small compared to the fourth power of the high temperature of the lamp filament. When properly oriented, the filament also provides a good approximation to a point source of thermal radiation. It therefore works well for investigations into the inverse square law. By adjusting the power into the lamp (13 V max, 2 A min, 3 A max), filament temperatures up to approximately 3000 °C can be obtained. The filament temperature is determined by carefully measuring the voltage and current into the lamp. The voltage divided by the current gives the resistance of the filament.

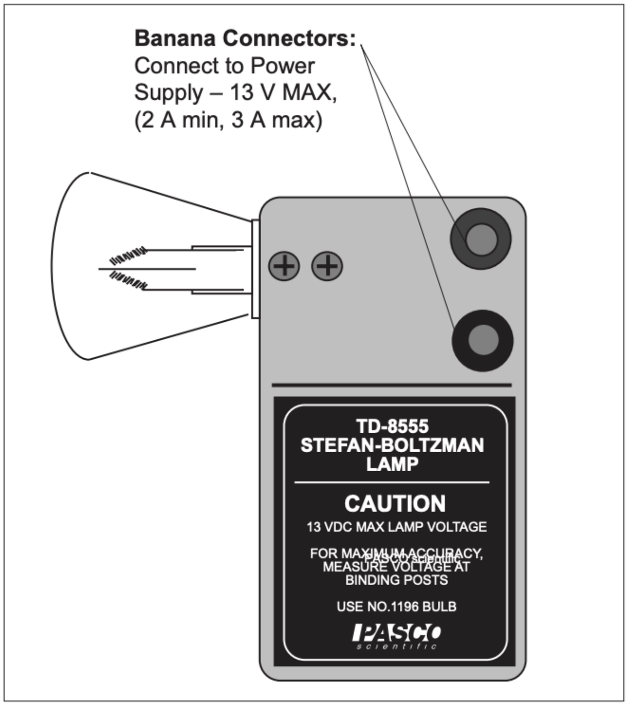

Figure 3.4: Stefan–Boltzmann Lamp.

For small temperature changes, the temperature of the tungsten filament can be calculated using α, the temperature coefficient of resistivity for the filament:

$$T = \frac{R - R_{\mathrm{ref}}}{\alpha R_{\mathrm{ref}}} + T_{\mathrm{ref}}$$

where,

T = Temperature
R = Resistance at temperature T
T_{ref} = Reference temperature (usually room temp.)
R_{ref} = Resistance at temperature T_{ref}
α = Temperature coefficient of resistivity for the filament ($\alpha = 4.5 \times 10^{-3}\ \text{K}^{-1}$ for tungsten)

For large temperature differences, however, α is not constant and the above equation is not accurate. For large temperature differences, therefore, determine the temperature of the tungsten filament as follows:

1. Accurately measure the resistance (R_{ref}) of the tungsten filament at room temperature (about 300 K). Accuracy is important here. A small error in R_{ref} will result in a large error in your result for the filament temperature.
2. When the filament is hot, measure the voltage and current into the filament and divide the voltage by the current to measure the resistance (R_T).
3. Divide R_T by R_{ref} to obtain the relative resistance (R_T/R_{ref}).
4. Using your measured value for the relative resistivity of the filament at temperature T, use Table 4.2 or the associated graph to determine the temperature of the filament.

The Stefan–Boltzmann Law, for high temperatures, relates R, the power per unit area radiated by an object, to T, the absolute temperature of the object. The equation is:

$$R = \sigma T^4 \quad (\sigma = 5.6703 \times 10^{-8}\ \text{W}\,\text{m}^{-2}\,\text{K}^{-4}).$$

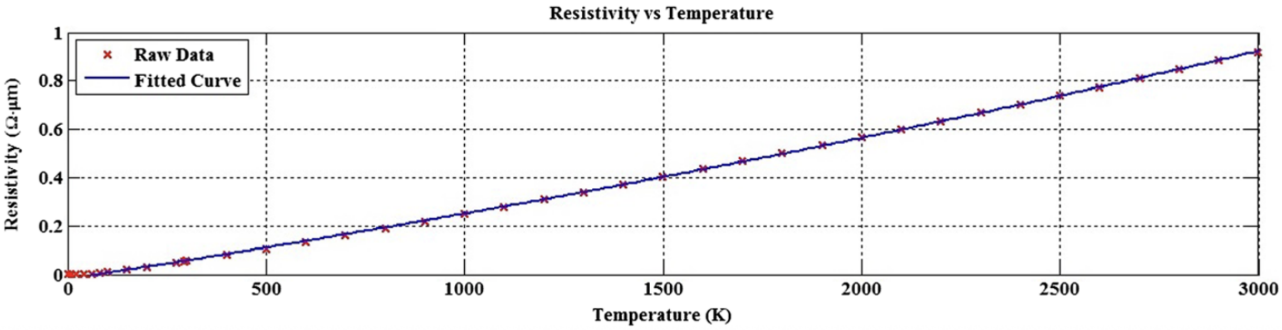

Figure 3.5: Empirical curve fit of measured resistivity of tungsten as a function of temperature [5].

You will make relative measurements of the power per unit area emitted from a hot object, namely the Stefan–Boltzmann Lamp, at various temperatures. From your data you will be able to test whether the radiated power is really proportional to the fourth power of the temperature.

Table 4.2: Temperature and Resistivity for Tungsten

R/R_{300K}	**Temp (K)**	**Resistivity ($\mu\Omega\,$cm)**
1.00	300	5.65
1.43	400	8.06
1.87	500	10.56
2.34	600	13.23
2.85	700	16.09
3.36	800	19.00
3.88	900	21.94
4.41	1000	24.93
4.95	1100	27.94
5.48	1200	30.98
6.03	1300	34.08
6.58	1400	37.19
7.14	1500	40.36
7.71	1600	43.55
8.28	1700	46.78
8.86	1800	50.05
9.44	1900	53.35
10.03	2000	56.67
10.63	2100	60.06
11.24	2200	63.48
11.84	2300	66.91
12.46	2400	70.39
13.08	2500	73.91
13.72	2600	77.49
14.34	2700	81.04
14.99	2800	84.70
15.63	2900	88.33
16.29	3000	92.04
16.95	3100	95.76
17.62	3200	99.54
18.28	3300	103.3
18.97	3400	107.2
19.66	3500	111.1
26.35	3600	115.0

Most of the thermal energy emitted by the lamp comes from the filament of the lamp. The filament temperature can be determined using the procedure given in this manual.

At high temperatures (approximately 1000 K to 3000 K), the ambient temperature is small enough that it can be neglected in the analysis. When you investigate the Stefan–Boltzmann relationship at much lower temperatures using the Thermal Radiation Cube, you will see that at these lower temperatures the ambient temperature cannot be ignored.

If the detector in the Radiation Sensor were operating at absolute zero temperature, it would produce a voltage directly proportional to the intensity of the radiation that strikes it. However, the detector is not at absolute zero temperature, so it is also radiating thermal energy. According to the Stefan–Boltzmann law, it radiates at a rate

$$R_{\text{det}} = \sigma T_{\text{det}}^4.$$

The voltage produced by the sensor is therefore proportional to the radiation striking the detector minus the radiation leaving it. Mathematically, the sensor voltage is proportional to

$$R_{\text{net}} = R_{\text{rad}} - R_{\text{det}} = \sigma (T^4 - T_{\text{det}}^4).$$

As long as you are careful to shield the Radiation Sensor from the Radiation Cube when measurements are not being taken, T_{det} will be very close to room temperature (T_{rm}).

Procedure

Experiment 1: Introduction to Thermal Radiation

Equipments

- Radiation Sensor
- Thermal Radiation Cube
- Window glass
- Millivoltmeter
- Ohmmeter

Notes:

1. If lab time is short, it's helpful to preheat the cube at a setting of 5.0 for 20 minutes before the laboratory period begins. (A very quick method is to preheat the cube at full power for 45 minutes, then use a small fan to reduce the temperature quickly as you lower the power input. Just be sure that equilibrium is attained with the fan off.)
2. Part 1 and Part 2 of this experiment can be performed simultaneously. Make the measurements in Part 2 while waiting for the Radiation Cube to reach thermal equilibrium at each of the settings in Part 1.

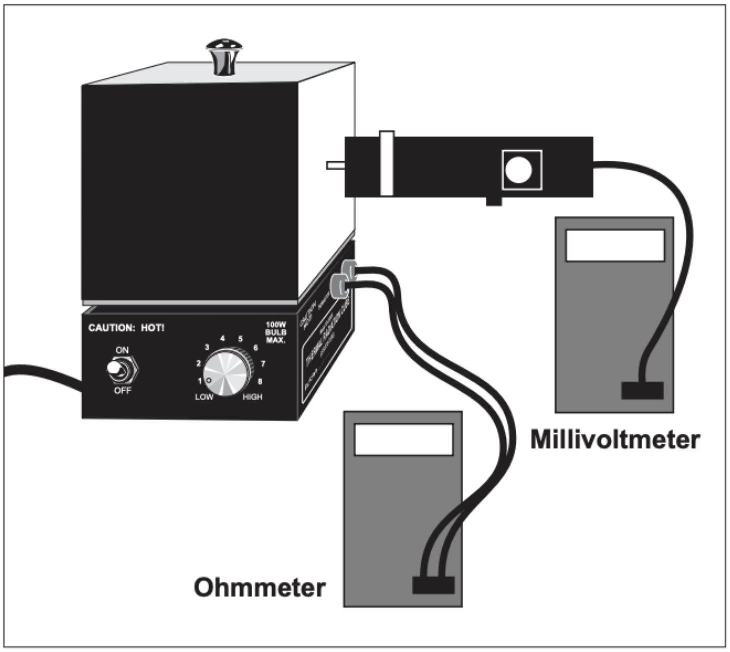

Figure 3.6: Experimental setup for Introduction to Thermal Radiation (Experiment 1).

3. When using the Radiation Sensor, always shield it from the hot object except for the few seconds it takes to actually make the measurement. This prevents heating of the thermopile, which will change the reference temperature and alter the reading.

Radiation Rates from Different Surfaces

Part 1

1. Connect the Ohmmeter and Millivoltmeter as shown in Figure 3.6.

2. Turn on the Thermal Radiation Cube and set the power switch to “HIGH”. Keep an eye on the ohmmeter reading. When it gets down to about 40 kΩ, reset the power switch to 5.0. (If the cube is preheated, just set the switch to 5.0.)

3. When the cube reaches thermal equilibrium, the ohmmeter reading will fluctuate around a relatively fixed value — use the Radiation Sensor to measure the radiation emitted from each of the four surfaces of the cube. Place the Sensor so that the posts on its end are in contact with the cube surface (this ensures that the distance of the measurement is the same for all surfaces). Record your measurements in Table 3.3. Also measure and record the resistance of the thermistor. Use the table on the base of the cube to determine the corresponding temperature.

4. Increase the power switch setting, first to 6.5, then to 8.0, and finally to “HIGH”. At each setting, wait for the cube to reach thermal equilibrium, then repeat the measurements of step 1 and record your results in the appropriate table.

Part 2

Use the Radiation Sensor to examine the relative magnitudes of the radiation emitted from various objects around the room. On a separate sheet of paper, make a table summarizing your observations. Make measurements that will help you to answer the questions.

Absorption and Transmission of Thermal Radiation

1. Place the Sensor approximately 5 cm from the black surface of the Radiation Cube and record the reading. Place a piece of window glass between the Sensor and the bulb. Does window glass effectively block thermal radiation?
2. Remove the lid from the Radiation Cube (or use the Stefan–Boltzmann Lamp) and repeat the measurements of step 1, but using the bare bulb instead of the black surface. Repeat with other materials.

Experiment 2: Inverse Square Law

Equipments

- Radiation Sensor
- Stefan–Boltzmann Lamp
- Millivoltmeter
- Power Supply (12 VDC; 3 A)
- Meter stick

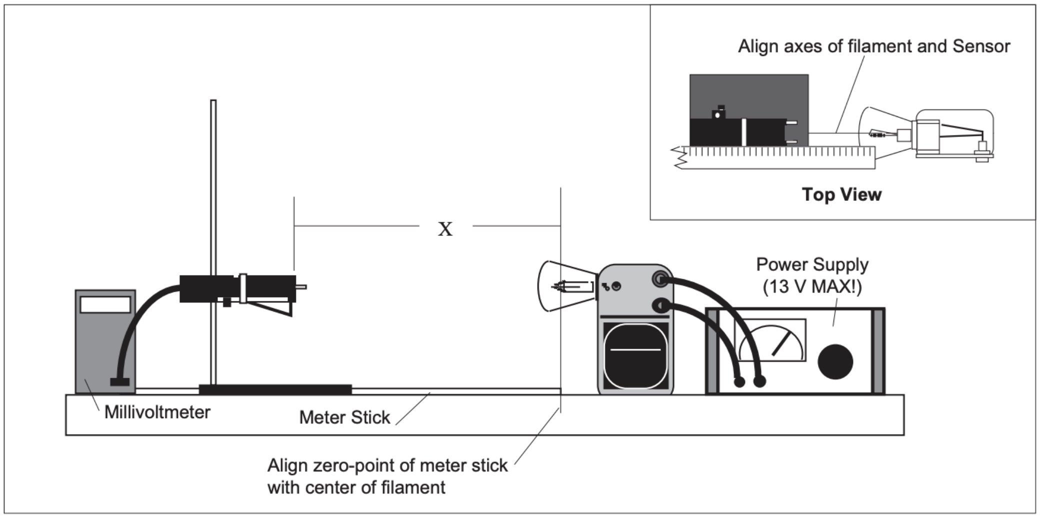

Figure 3.7: Experimental setup for the Inverse Square Law. Align the zero point of the meter stick with the center of the filament, and ensure the axes of the filament and the sensor are collinear.

Procedure

1. Set up the equipment as shown in Figure 3.7.
    (a) Tape a meter stick to the table.
    (b) Place the Stefan–Boltzmann Lamp at one end of the meter stick as shown. The zero-point of the meter stick should align with the center of the lamp filament.
    (c) Adjust the height of the Radiation Sensor so it is at the same level as the filament of the Stefan–Boltzmann Lamp.
    (d) Align the lamp and sensor so that, as you slide the Sensor along the meter stick, the axis of the lamp aligns as closely as possible with the axis of the Sensor.
    (e) Connect the Sensor to the millivoltmeter and the lamp to the power supply as indicated in the figure.
2. With the lamp **OFF**, slide the sensor along the meter stick. Record the reading of the millivoltmeter at 10 cm intervals. Record your values in Table 3.5. Average these values to determine the ambient level of thermal radiation. You will need to subtract this average ambient value from your measurements with the lamp on, in order to determine the contribution from the lamp alone.
3. Turn on the power supply to illuminate the lamp. Set the voltage to approximately 10 V.
4. Adjust the distance between the Sensor and the lamp to each of the settings listed in Table 3.4. At each setting, record the reading on the millivoltmeter.

    Important: Do not let the voltage to the lamp exceed 13 V.

Make each reading quickly. Between readings, move the sensor away from the lamp or place the reflective heat shield between the lamp and the sensor, so that the temperature of the Sensor stays relatively constant.

Experiment 3: Stefan–Boltzmann Law (High Temperature)

Equipments

- Radiation Sensor
- Stefan–Boltzmann Lamp
- Ohmmeter
- Ammeter (0–3 A)
- Voltmeter (0–12 V)
- Millivoltmeter
- Thermometer

Procedure

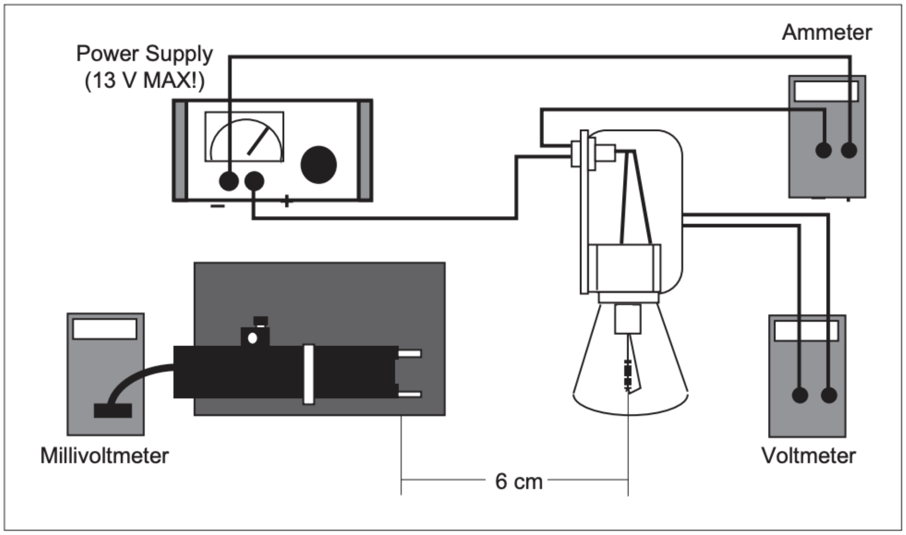

Figure 3.8: Equipment setup for the Stefan–Boltzmann Law (High Temperature).

1. **Before turning on the lamp**, measure T_{ref}, the room temperature in degrees Kelvin, using the relation $(K = {}^\circ C + 273)$, and R_{ref}, the resistance of the filament of the Stefan–Boltzmann Lamp at room temperature. Record your results.
2. Set up the equipment as shown in Figure 3.8. The voltmeter should be connected directly to the binding posts of the Stefan–Boltzmann Lamp. The Sensor should be at the same height as the filament, with the front face of the Sensor approximately 6 cm away from the filament. The entrance angle of the thermopile should include no close objects other than the lamp.
3. Turn on the power supply. Set the voltage V to each of the settings listed in Table 6. At each voltage setting, record I (the ammeter reading) and Rad (the millivoltmeter reading).

   Important: The voltage into the lamp should never exceed 13 V. Higher voltages will burn out the filament.

Make each Sensor reading quickly. Between readings, place both sheets of insulating foam between the lamp and the Sensor, with the silvered surface facing the lamp, so that the temperature of the Sensor stays relatively constant.

Experiment 4: Stefan–Boltzmann Law (Low Temperature)

Equipments

- Radiation Sensor
- Thermal Radiation Cube
- Millivoltmeter
- Ohmmeter

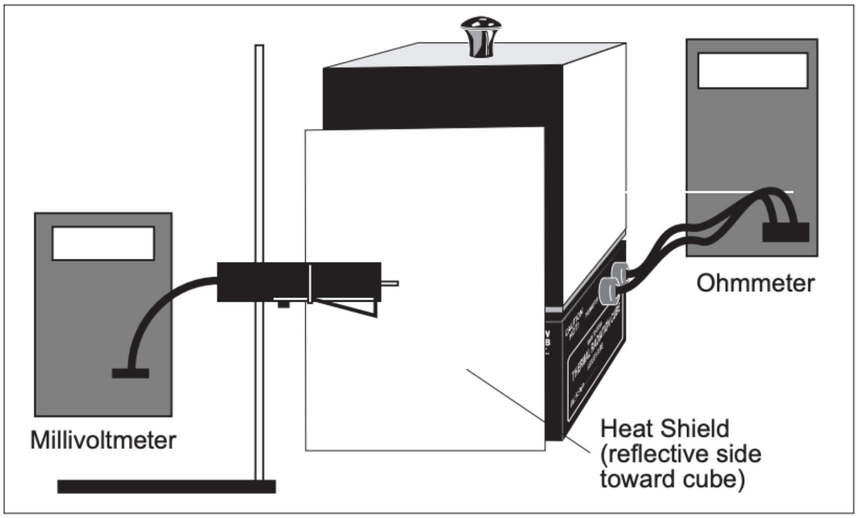

Figure 3.9: Equipment setup for the Stefan–Boltzmann Law (Low Temperature).

Procedure

1. Set up the equipment as shown in Figure 3.9. The Radiation Sensor should be pointed directly at the center of one of the better radiating surfaces of the cube (the black or white surface). The face of the Sensor should be parallel with the surface of the cube and about 3 cm to 4 cm away.
2. With the Thermal Radiation Cube off, measure R_{rm}, the resistance of the thermistor at room temperature. Record this data.
3. Shield the Sensor from the cube using the reflecting heat shield, with the reflective side of the shield facing the cube.
4. Turn on the Radiation Cube and set the power switch to 10.
5. When the thermistor resistance indicates that the temperature is about 12 °C above room temperature, turn the power down so the temperature is changing slowly. Read and record R (the ohmmeter reading) and Rad (the millivoltmeter reading). The readings should be taken as nearly simultaneously as possible while briefly removing the heat shield. Record these values in Table 7.
6. Replace the heat shield, and turn the cube power to 10. When the temperature has risen an additional 12 °C–15 °C, repeat the measurements of step 5. Repeat this procedure at about 12 °C–15 °C intervals until the maximum temperature of the cube is reached.

Important: Make each reading quickly, removing the heat shield only as long as it takes to make the measurement. Take care that the position of the sensor with respect to the cube is the same for all measurements.

Report Sheet

EXPERIMENT 4: THERMAL RADIATION SYSTEM

Student's Name: ______________________________
Experiment Date: ______________________________
Group Member Name(s): ______________________________
Laboratory Bench Number: ______________________________
Assistant's Name and Signature: ______________________________

Data and Calculations

Experiment 1: Introduction to Thermal Radiation

Radiation Rates from Different Surfaces

Table 4.3: Radiation rates from different surfaces at various power settings.

Power Setting 5.0

Therm. Res. __________ Ω
Temperature __________ °C

Surface	**Sensor Reading (mV)**
Black	
White	
Polished Al	
Dull Al	

Power Setting 6.5

Therm. Res. __________ Ω
Temperature __________ °C

Surface	**Sensor Reading (mV)**
Black	
White	
Polished Al	
Dull Al	

Power Setting 8.0

Therm. Res. __________ Ω
Temperature __________ °C

Surface	**Sensor Reading (mV)**
Black	
White	
Polished Al	
Dull Al	

Power Setting 10.0

Therm. Res. __________ Ω
Temperature __________ °C

Surface	**Sensor Reading (mV)**
Black	
White	
Polished Al	
Dull Al	

Questions (Part 1)

1. List the surfaces of the Radiation Cube in order of the amount of radiation emitted. Is the order independent of temperature?
2. It is a general rule that good absorbers of radiation are also good emitters. Are your measurements consistent with this rule? Explain.

Questions (Part 2)

1. Do different objects, at approximately the same temperature, emit different amounts of radiation?
2. Can you find materials in your room that block thermal radiation? Can you find materials that do not block thermal radiation? (For example, do your clothes effectively block the thermal radiation emitted from your body?)

Questions (Absorption and Transmission of Thermal Radiation)

1. What do your results suggest about the phenomenon of heat loss through windows?
2. What do your results suggest about the Greenhouse Effect?

Experiment 2: Inverse Square Law

Table 4.4: Radiation Level versus Distance

x (cm)	*Rad (mV)*	$1/x^2$ *(cm^{-2})*	*Rad – Ambient (mV)*
2.5			
3.0			
3.5			
4.0			
4.5			
5.0			
6.0			
7.0			
8.0			
9.0			
10.0			
12.0			
14.0			
16.0			
18.0			
20.0			
25.0			
30.0			
35.0			
40.0			
45.0			
50.0			
60.0			
70.0			
80.0			
90.0			
100.0			

Table 4.5: Ambient Radiation Level

x (cm)	*Ambient Radiation Level (mV)*
10	
20	
30	
40	
50	
60	
70	
80	
90	
100	

Average Ambient Radiation Level = ________________________

1. For each value of x, calculate $1/x^2$. Enter your results in Table 4.4.
2. Subtract the Average Ambient Radiation Level from each of your Rad measurements in Table 4.4. Enter your results in the table.
3. On a separate sheet of paper, make a graph of Radiation Level versus Distance from the source, using columns one and four from Table 4.4. Let the radiation level be the dependent (y) axis.
4. If your graph from step 3 is not linear, make a graph of Radiation Level versus $1/x^2$, using columns three and four from Table 4.4.

Questions

1. Which of the two graphs is more linear? Is it linear over the entire range of measurements?
2. The inverse square law states that the radiant energy per unit area emitted by a point source of radiation decreases as the square of the distance from the source to the point of detection. Does your data support this assertion?
3. Is the Stefan–Boltzmann Lamp truly a point source of radiation? If not, how might this affect your results? Do you see such an effect in the data you have taken?

Experiment 3: Stefan–Boltzmann Law (High Temperature)

$\alpha = 4.5 \times 10^{-3}\ \mathrm{K}^{-1}$

T_{ref} (room temp.) = _______________ K

R_{ref} (filament resistance at T_{ref}) = _______________ Ω

Table 4.6: Data and Calculations

Data			**Calculations**		
$V\,(V)$	$I\,(A)$	$Rad\,(mV)$	$R\,(\Omega)$	$T\,(K)$	$T^4\,(K^4)$
1.00					
2.00					
3.00					
4.00					
5.00					
6.00					
7.00					
8.00					
9.00					
10.00					
11.00					
12.00					

1. Calculate R, the resistance of the filament at each of the voltage settings used ($R = V/I$). Enter your results in Table 4.6.
2. Use the procedure in this manual to determine T, the temperature of the lamp filament at each voltage setting. Enter your results in the table.
3. Calculate T^4 for each value of T and enter your results in the table.
4. On a separate sheet of paper, construct a graph of Rad versus T^4. Use Rad as your dependent variable (y-axis).

In place of calculations 3 and 4, some may prefer to perform a power regression on Rad versus T to determine their relationship, or graph on log–log paper and find the slope.

Questions

1. What is the relationship between Rad and T? Does this relationship hold over the entire range of measurements?
2. The Stefan–Boltzmann Law is perfectly true only for ideal black body radiation. A black body is any object that absorbs all the radiation that strikes it. Is the filament of the lamp a true black body?
3. What sources of thermal radiation, other than the lamp filament, might have influenced your measurements? What effect would you expect these sources to have on your results?

Experiment 4: Stefan–Boltzmann Law (Low Temperature)

Room Temperature:

$R_{\mathrm{rm}} =$ _______________ Ω

$T_{\mathrm{rm}} =$ __________ °C = __________ K

Table 4.7: Data and Calculations

Data		Calculations			
R (Ω)	Rad (mV)	T_c (°C)	T_k (K)	T_k^4 (K^4)	$T_k^4 - T_{rm}^4$ (K^4)

1. Using the table on the base of the Thermal Radiation Cube, determine T_c, the temperature in degrees Centigrade corresponding to each of your thermistor resistance measurements. For each value of T_c, determine T_k, the corresponding value in degrees Kelvin ($K = {}^\circ C + 273$). Enter both sets of values in Table 4.7. In the same manner, determine the room temperature, T_{rm}.
2. Calculate T_k^4 for each value of T_k and record the values in the table.
3. Calculate $T_k^4 - T_{\mathrm{rm}}^4$ for each value of T_k and record your results in the table.
4. On a separate sheet of paper, construct a graph of Rad versus $(T_k^4 - T_{\mathrm{rm}}^4)$. Use Rad as the dependent variable (y-axis).

Questions

1. What does your graph indicate about the Stefan–Boltzmann law at low temperatures?
2. Is your graph a straight line? Discuss any deviations that exist.

Discussion

References

1. Halliday, D., Resnick, R., & Walker, J. (2018). *Fundamentals of Physics* (11th ed., Chapter 18). Wiley. Section on heat transfer by radiation.
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5. Hu, F., & Lucyszyn, S. (2014). Emerging thermal infrared 'THz Torch' technology for low-cost security and defence applications. In C. Corsi & F. Sizov (Eds.), *THz and Security Applications: Detectors, Sources and Associated Electronics for THz Applications* (pp. 239–275). Springer Netherlands. (NATO Science for Peace and Security Series B: Physics and Biophysics). Empirical tungsten resistivity data used for comparative analysis.

Experiment 5

THE PHOTOELECTRIC EFFECT

Purpose

- To demonstrate the particle behaviour of light.
- To measure Planck's constant *h* and the work function of the cathode material.

Introduction

The emission and absorption of light was an early subject for investigation by German physicist Max Planck. As Planck attempted to formulate a theory to explain the spectral distribution of emitted light based on a classical wave model, he ran into considerable difficulty. Classical theory (Rayleigh-Jeans Law) predicted that the amount of light emitted from a black body would increase dramatically as the wavelength decreased, whereas experiment showed that it approached zero. This discrepancy became known as the ultraviolet catastrophe.

Experimental data for the radiation of light by a hot, glowing body showed that the maximum intensity of emitted light also departed dramatically from the classically predicted values (Wien's Law). In order to reconcile theory with laboratory results, Planck developed a new model for light called the **quantum model**. In this model, light is emitted in small, discrete bundles or quanta.
The relationship between the classical and quantum theories for the emission of light can be investigated using the scientific h/e Apparatus. Using the apparatus, in combination with the Mercury Vapor Light Source allows an accurate determination of the h/e ratio and thus a determination of h, Planck's constant.

Planck's Quantum Theory

By the late 1800's many physicists thought they had explained all the main principles of the universe and discovered all the natural laws. But as scientists continued working, inconsistencies that couldn't easily be explained began showing up in some areas of study. In 1901 Planck published his law of radiation. In it he stated that an oscillator, or any similar physical system, has a discrete set of possible energy values or levels; energies between these values never occur. Planck went on to state that the emission and absorption of radiation is associated with transitions or jumps between two energy levels. The energy lost or gained by the oscillator is emitted or absorbed as a quantum of radiant energy, the magnitude of which is expressed by the equation:

$$E = h\nu \tag{5.1}$$

where E equals the radiant energy, ν is the frequency of the radiation, and h is a fundamental constant of nature. The constant, h, became known as Planck's constant. Planck's constant was found to have significance beyond relating the frequency and energy of light, and became a cornerstone of the quantum mechanical view of the subatomic world. In 1918, Planck was awarded a Nobel prize for introducing the quantum theory of light.

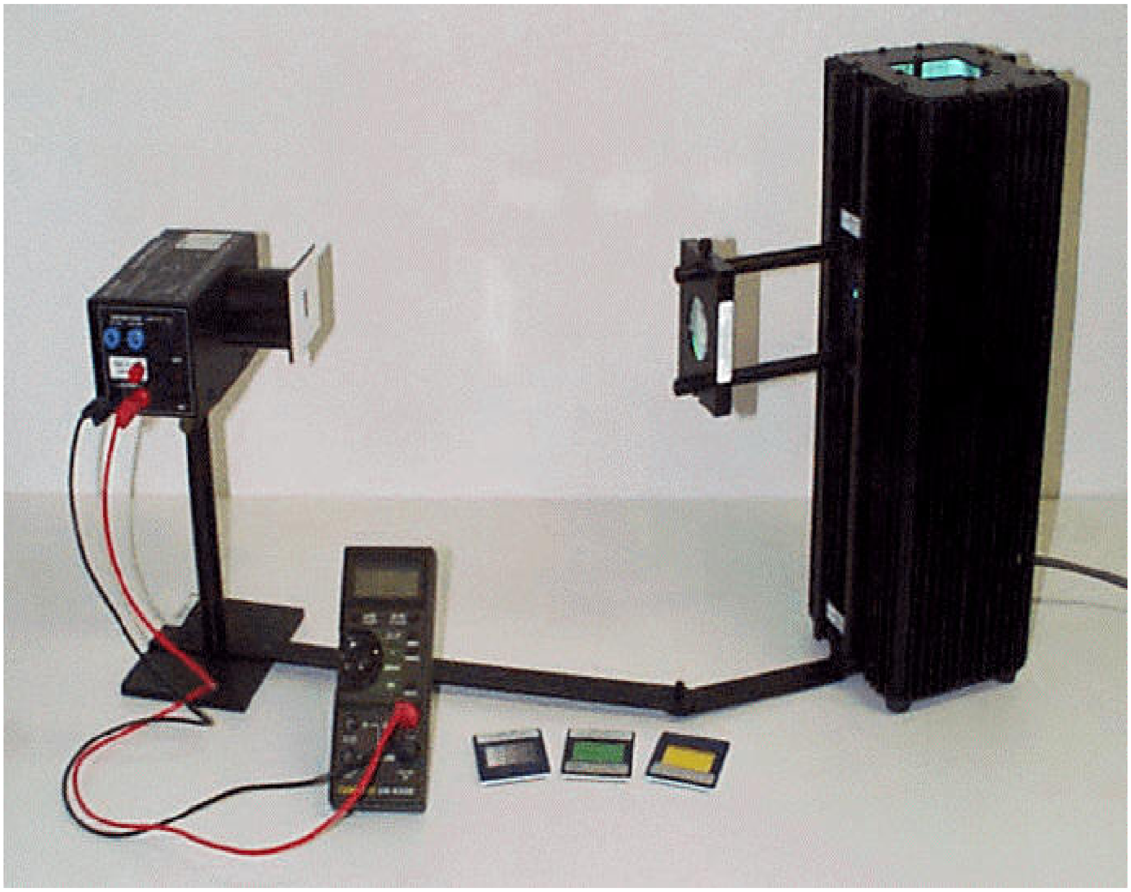

Figure 5.1: The h/e Apparatus shown with the Accessory Kit and Mercury Vapor Light Source.

The Photoelectric Effect

In photoelectric emission, light strikes a material, causing electrons to be emitted. The classical wave model predicted that as the intensity of incident light was increased, the amplitude and thus the energy of the wave would increase. This would then cause more energetic photoelectrons to be emitted. The new quantum model, however, predicted that higher frequency light would produce higher energy photoelectrons, independent of intensity, while increased intensity would only increase the number of electrons emitted (or photoelectric current). In the early 1900s several investigators found that the kinetic energy of the photoelectrons was dependent on the wavelength, or frequency, and independent of intensity, while the magnitude of the photoelectric current, or number of electrons was dependent on the intensity as predicted by the quantum model. Einstein applied Planck's theory and explained the photoelectric effect in terms of the quantum model using his famous equation for which he received the Nobel prize in 1921:

$$E = h\nu = KE_{max} + W_0 \tag{5.2}$$

where KE_{max} is the maximum kinetic energy of the emitted photoelectrons; and Wo is the energy needed to remove them from the surface of the material (the work function). E is the energy supplied by the quantum of light known as a photon.

The h/e Experiment

A light photon with energy $h\nu$ is incident upon an electron in the cathode of a vacuum tube. The electron uses a minimum W_0 of its energy to escape the cathode, leaving it with a maximum energy of KE_{max} in the form of kinetic energy. Normally the emitted electrons reach the anode of the tube, and can be measured as a photoelectric current. However, by applying a reverse potential V between the anode and the cathode, the photoelectric current can be stopped. KE_{max} can be determined by measuring the minimum reverse potential needed to stop the photoelectrons and reduce the photoelectric current to zero.* Relating kinetic energy to stopping potential gives the equation:

$$KE_{max} = eV \tag{5.3}$$

Therefore, using Einstein's equation,

$$h\nu = eV + W_0 \tag{5.4}$$

When solved for V, the equation becomes:

$$V = \frac{h}{e}\nu - \frac{W_0}{e} \tag{5.5}$$

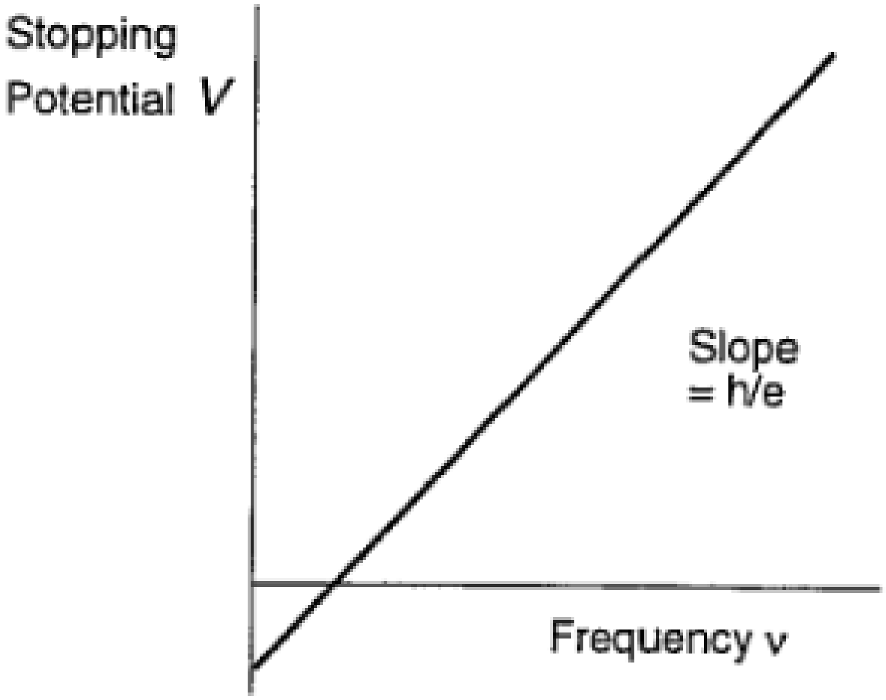

Figure 5.2: Graph of stopping potential V versus frequency ν.

If we plot V versus ν for different frequencies of light, the graph will look like Figure 5.4. The V intercept is equal to W_0/e and the slope is h/e.Coupling our experimental determination of the ratio h/e with the accepted value for e, 1.602×10^{-19} coulombs, we can determine Planck's constant, h.

The Mercury Vapor Light Source

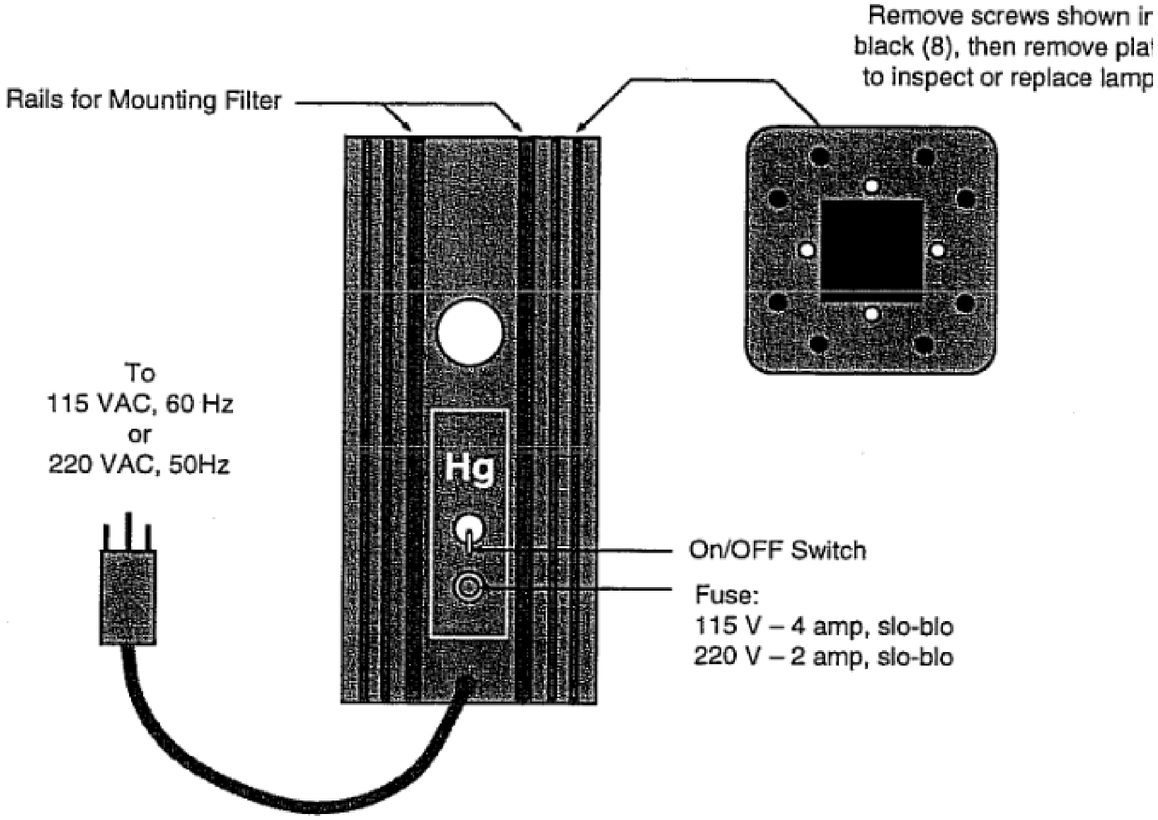

Figure 5.3: The Mercury Vapor Light Source.

The Mercury Vapor Light Source provides approximately 3,000 lumens of light in the mercury spectrum. The 100 watt light source comes ready to use, with a built-in power supply. Cooling fins and air vents on the sturdy aluminium case ensure cool, safe operation. In addition, rails on the front and rear of the case can be used for mounting standard 2-inch by 2-inch filters, so that monochromatic light can be obtained.

Mercury Vapor Light Source Notes and Safety

Note:
For maximum life of the mercury vapor lamp:

1. Always operate the light source in its upright position.
2. If you are going to use the light source more than once during the day, leave it on. Lamp wear results more from turning the light source on and off than from steady operation.

Table 5.1: Wavelength of the Mercury Spectral Lines

Color	Frequency (Hz)	Wavelength (nm)
Yellow	5.18672×10^{14}	578.0 and 580.0
Green	5.48996×10^{14}	546.074
Blue	6.87858×10^{14}	435.835
Violet	7.40858×10^{14}	404.656
Ultraviolet	8.20264×10^{14}	365.483

Note: The yellow line is actually a doublet with wavelengths of 578 and 580 nm.

Caution I: The outer glass tube of the mercury vapor lamp blocks harmful ultraviolet radiation produced by the lamp. If the outer tube is cracked or broken, this radiation can cause severe skin burn and produce eye inflammation. Regularly inspect the outer tube for cracks, especially if the light source has received a significant jolt. If the glass bulb is broken, immediately turn the lamp off and remove it to avoid possible injury. Replace the bulb prior to next use.

Caution II: Do not open the light source with the unit plugged in.

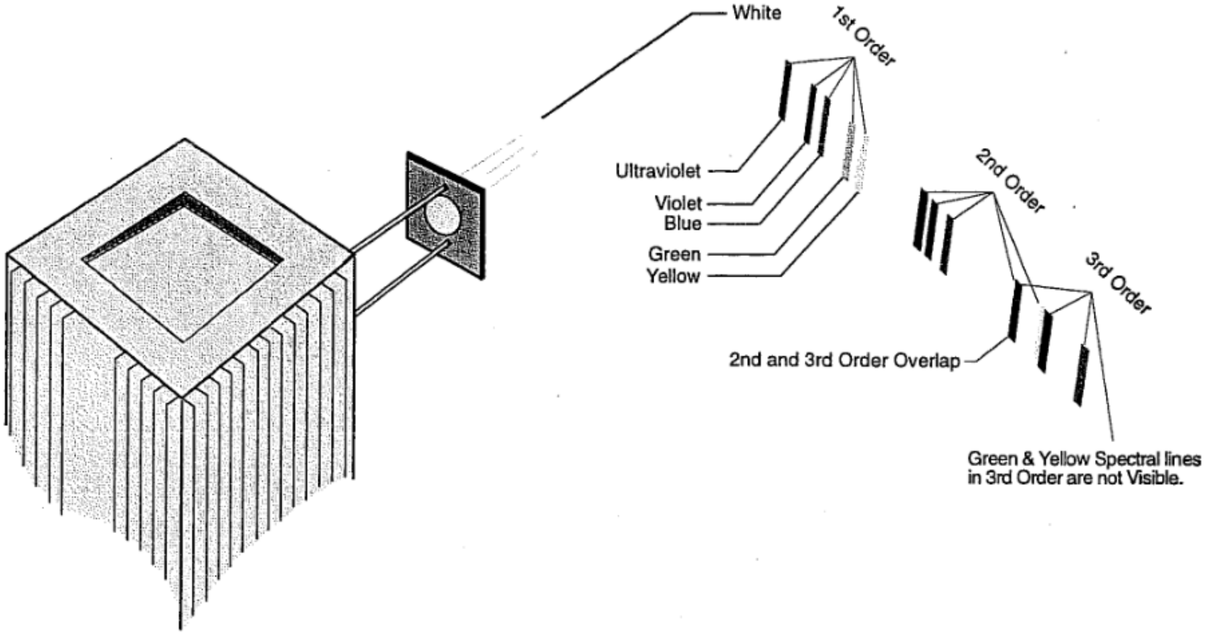

Figure 5.4: The Three Orders of Light Gradients.

Note: The grating is blazed to produce the brightest spectrum on one side only. During your experiment, you may need to turn the Lens/Grating Assembly around in order to have the brightest spectrum on a convenient side of your lab table.

Note: The white reflective mask on the h/e apparatus is made of a special fluorescent material. This allows you to see the ultraviolet line as a blue line, and it also makes the violet fine appear more blue. You can see the actual colors of the light if you hold a piece of white non-fluorescent material in front of the mask. (The palm of your hand works in a pinch, although it fluoresces enough, that UV line will still be visible.)

Note: When making measurements it is important that only one color falls on the photodiode window. There must be no overlap from adjacent spectral maxima.

Note: For some apparatus, the stopping potential will temporarily read high and then drop down to the actual stopping potential voltage.

Using the Filters

The h/e Apparatus includes three filters: one green and one yellow, plus a variable transmission filter. The filter frames have magnetic strips and mount to the outside of the white reflective mask of the h/e Apparatus. Use the green and yellow filters when you're using the green and yellow spectral lines. These filters limit higher frequencies of light from entering the h/e apparatus. This prevents ambient room light from interfering with the lower energy yellow and green light and masking the true results. It also blocks the higher frequency ultraviolet light from the higher order spectra which may overlap with lower orders of yellow and green.

The Variable Transmission Filter consists of computer generated patterns of dots and lines that vary the intensity (not the frequency) of the incident light. The relative transmission percentages are 100%, 80%, 60%, 40%, and 20%.

Equipments

- h/e Apparatus
- h/e Apparatus Accessory Kit
- Mercury Vapor Light Source
- Digital voltmeter

Procedure

1. Set up the equipment as shown in Figure 5.1. Focus the light from the Mercury Vapor Light Source onto the slot in the white reflective mask on the h/e Apparatus. Tilt the Light Shield of the Apparatus out of the way to reveal the white photodiode mask inside the Apparatus. Slide the Lens/Grating assembly forward and back on its support rods until you achieve the sharpest image of the aperture centred on the hole in the photodiode mask. Secure the Lens/Grating by tightening the thumbscrew.

2. Align the system by rotating the h/e Apparatus on its support base so that the same color light that falls on the opening of the light screen falls on the window in the photodiode mask, with no overlap of color from other spectral lines. Return the Light Shield to its closed position.

3. Check the polarity of the leads from your digital voltmeter (DVM), and connect them to the OUTPUT terminals of the same polarity on the h/e Apparatus.

Experiment 5.1: The Wave Model of Light vs. the Quantum Model

According to the photon theory of light, the maximum kinetic energy, KE_{max}, of photoelectrons depends only on the frequency of the incident light, and is independent of the intensity. Thus the higher the frequency of the light, the greater its energy. In contrast, the classical wave model of light predicted that KE_{max} would depend on light intensity. In other words, the brighter the light, the greater its energy. This laboratory investigates both of these assertions. Part A selects two spectral lines from a mercury light source and investigates the maximum energy of the photoelectrons as a function of the intensity. Part B selects different spectral lines and investigates the maximum energy of the photoelectrons as a function of the frequency of the light.

Part A: Maximum Energy of the Photoelectrons as a Function of the Intensity

1. Adjust the h/e Apparatus so that only one of the spectral colors falls upon the opening of the mask of the photodiode. If you select the green or yellow spectral line, place the corresponding colored filter over the White Reflective Mask on the h/e Apparatus.
2. Place the Variable Transmission Filter in front of the White Reflective Mask (and over the colored filter, if one is used) so that the light passes through the section marked 100% and reaches the photodiode. Record the DVM voltage reading in the table below. Press the instrument discharge button, release it, and observe approximately how much time is required to return to the recorded voltage.
3. Move the Variable Transmission Filter so that the next section is directly in front of the incoming light. Record the new DVM reading, and approximate time to recharge after the discharge button has been pressed and released. Repeat Step 3 until you have tested all five sections of the filter.
4. Repeat the procedure using a second color from the spectrum.

Part B: Maximum Energy of the Photoelectrons as a Function of the Frequency of the Light

1. You can easily see five colors in the mercury light spectrum. Adjust the h/e Apparatus so that only one of the yellow colored bands falls upon the opening of the mask of the photodiode. Place the yellow colored filter over the White Reflective Mask on the h/e Apparatus.
2. Record the DVM voltage reading (stopping potential) in the table below.
3. Repeat the process for each color in the spectrum. Be sure to use the green filter when measuring the green spectrum.

Note: While the impedance of the zero gain amplifier is very high (↑ 10^{13}), it is not infinite and some charge leaks off. Thus charging the apparatus is analogous to filling a bath tub with different water flow rates while the drain is partly open.

Experiment 5.2: The Relationship between Energy, Wavelength and Frequency

According to the quantum model of light, the energy of light is directly proportional to its frequency. Thus, the higher the frequency, the more energy it has. With careful experimentation, the constant of proportionality, Planck's constant, can be determined.
In this laboratory, you will select different spectral lines from mercury and investigate the maximum energy of the photoelectrons as a function of the wavelength and frequency of the light.

1. You can see five colors in two orders of the mercury light spectrum. Adjust the h/e Apparatus carefully so that only one color from the first order (the brightest order) falls on the opening of the mask of the photodiode.
2. For each color in the first order, measure the stopping potential with the DVM and record that measurement in the table below. Use the yellow and green colored filters on the Reflective Mask of the h/e Apparatus when you measure the yellow and green spectral lines.
3. Move to the second order and repeat the process. Record your results in the table below.

X-Ray Photoemission Spectroscopy (XPS)

X-ray Photoemission Spectroscopy (XPS) is an application of the Photoelectric Effect. It is used to determine the binding energies of core electrons under high-vacuum conditions, which allows for the identification of the elements and their chemical states on the surface of a material. In the XPS, a monochromatic X-ray source illuminates the surface of the material. The incident photons interact with the surface atoms, and their energy is absorbed by core-level electrons. These electrons become excited, overcome the surface potential barrier, escape from the material, and are subsequently detected as photoelectrons (Figure 5.5).The kinetic energies of these photoelectrons are measured and converted into electrical signals by a detector system. By studying these signals on a computer, the binding energies of the electrons are determined, providing information about the elemental composition and chemical states of the material surface. The energy conservation relationship for XPS is given by:

$$E = E_{binding} + \Phi + E_{kinetic} \tag{5.6}$$

Where E is the incoming photon energy from the X-ray source, E_{binding} is the binding energy of the core electron, Φ is the work function of analyzer, and E_{kinetic} is the maximum kinetic energy of the emitted photoelectron.

In the above equation (5.6), the X-ray source energy is generally known (for example, Al Kα radiation: $h\nu = 1486.6$ eV). The work function of analyzer (Φ) is also known, while the kinetic energy of the emitted photoelectrons is measured by the hemispherical electron energy analyser.A schematic diagram illustrating the main components of the XPS system is shown in Figure 5.6.

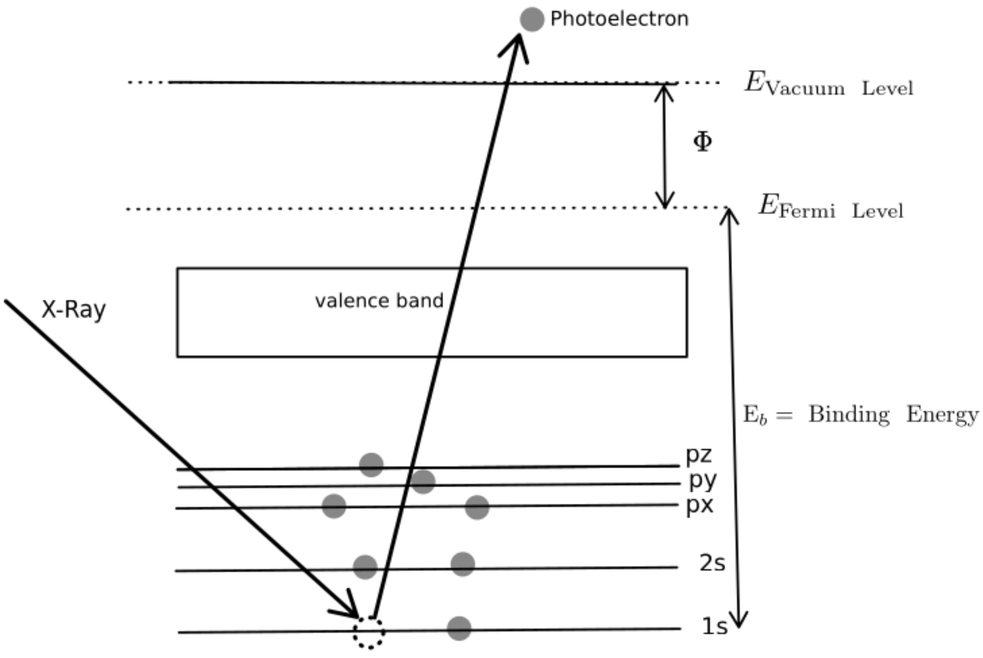

Figure 5.5: Energy diagram for the Photoelectric Effect.

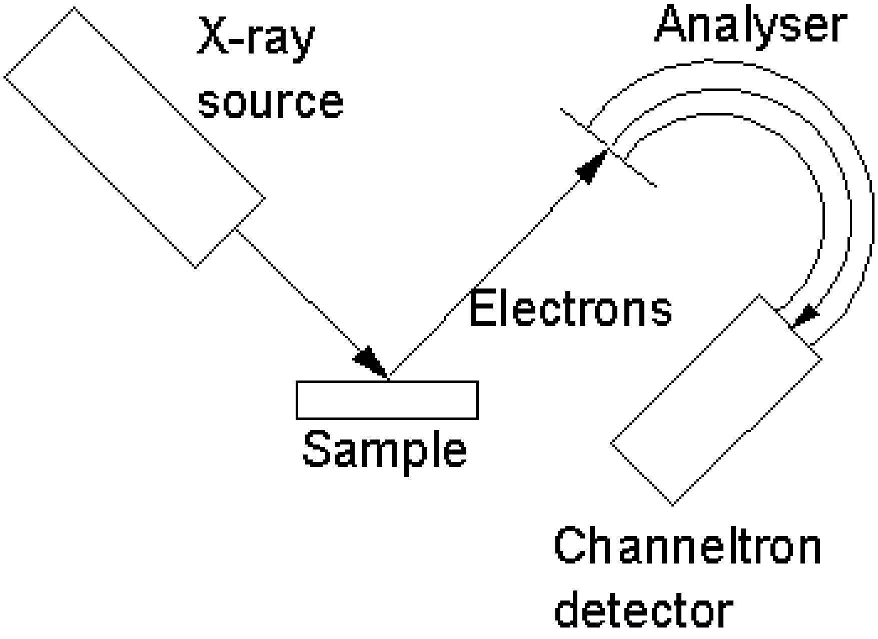

Figure 5.6: Schematic diagram of the XPS system.

REPORT SHEET

EXPERIMENT 5: THE PHOTOELECTRIC EFFECT

Data and Calculations

Experiment 5.1: The Wave Model of Light vs. the Quantum Model

Part A: Maximum Energy of the Photoelectrons as a Function of the Intensity

Table 5.2:

Color	% Transmission	Stopping Potential (V)	Approx. Charge Time (s)
	100		
	80		
	60		
	40		
	20		
Color	% Transmission	Stopping Potential (V)	Approx. Charge Time (s)
	100		
	80		
	60		
	40		
	20		

Part B: Maximum Energy of the Photoelectrons as a Function of the Frequency of the Light

Table 5.3

Light Color	Stopping Potential (V)
Yellow	
Green	
Blue	
Violet	
Ultraviolet	

1. Describe the effect that passing different amounts of the same colored light through the Variable Transmission Filter has on the stopping potential and thus the maximum energy of the photoelectrons, as well as the charging time after pressing the discharge button.

2. Describe the effect that different colors of light had on the stopping potential and thus the maximum energy of the photoelectrons.

3. Defend whether this experiment supports a wave or a quantum model of light based on your lab results. Explain why there is a slight drop in the measured stopping potential as the light intensity is decreased.

Experiment 5.2: The Relationship between Energy, Wavelength and Frequency

Table 5.4:

First Order Color	Wavelength (nm)	Frequency ($\times 10^{14}$ Hz)	Stopping Potential (V)
Yellow	578.0 and 580.0	5.18672	
Green	546.074	5.48996	
Blue	435.835	6.87858	
Violet	404.656	7.40858	
Ultraviolet	365.483	8.20264	
Second Order Color	Wavelength	Frequency ($\times 10^{14}$ Hz)	Stopping Potential (V)
Yellow	578.0 and 580.0	5.18672	
Green	546.074	5.48996	
Blue	435.835	6.87858	
Violet	404.656	7.40858	
Ultraviolet	365.483	8.20264	

1. Determine the wavelength and frequency of each spectral line. Plot a graph of the stopping potential vs. frequency.
2. Determine the slope and y-intercept. Interpret the results in terms of the h/e ratio and the Wo/e ratio. Calculate h and Wo.
3. Report your values and discuss your results with an interpretation based on a quantum model for light.

Questions

1. What is the most important statement you can make from your experiment results?
2. Even if the bias voltage is zero, you can still measure a photocurrent. Explain why.
3. When the anode is positive with respect to the cathode, why doesn't the current immediately rise to its saturation value?

References

1. `https://portal.if.usp.br/labdid/sites/portal.if.usp.br.labdid/files/he%20Apparatus.pdf`
2. `https://www.physics.purdue.edu/~jones105/phys34000_Fall2009/PhotoelectricEffect.pdf`
3. `http://nattrass.utk.edu/Phys250Spring2020Web/Laboratories/photoelectric%20effectTEST.htm`
4. `https://www.chm.bris.ac.uk/pt/diamond/jamespthesis/chapter2.htm`

Experiment 6

ELECTRON SPIN RESONANCE

Purpose

- Introducing the concept of electron spin and its magnetic properties.
- Investigating electron spin resonance (ESR) using a DPPH (*diphenylpicryl hydrazyl*) sample, which is a stable chemical free radical.
- Examining the dependence of the resonance condition on the strength of the external magnetic field and the applied frequency.
- Measuring the resonance magnetic field at two different resonance frequencies.
- Calculating the Landé g-factor from the experimental results.

Introduction

Magnetic Properties of Materials

- **Diamagnetic materials:** Substances in which all electrons are paired, resulting in no permanent magnetic moment. When placed in an external magnetic field, they are weakly repelled. Examples include copper, bismuth, and silver.
- **Paramagnetic materials:** Substances that contain unpaired electrons, giving rise to small permanent magnetic moments. These materials are weakly attracted by an external magnetic field, and their magnetization disappears when the field is removed. Typical examples are aluminum, magnesium, and DPPH used in this experiment.

DPPH Sample

DPPH is an organic compound commonly used as a reference material in electron spin resonance experiments. It is a stable **paramagnetic free radical** that contains one unpaired electron primarily localized on the nitrogen atom. This unpaired electron is delocalized across the aromatic rings, providing remarkable stability against oxidation and dimerization, which makes DPPH ideal for accurate ESR calibration and determination of the Landé g-factor. In an external magnetic field, this unpaired electron interacts with the field and produces a sharp and measurable resonance signal. The molecular structure of DPPH, shown in **Figure 6.1**, illustrates the delocalized unpaired electron responsible for its paramagnetic behavior.

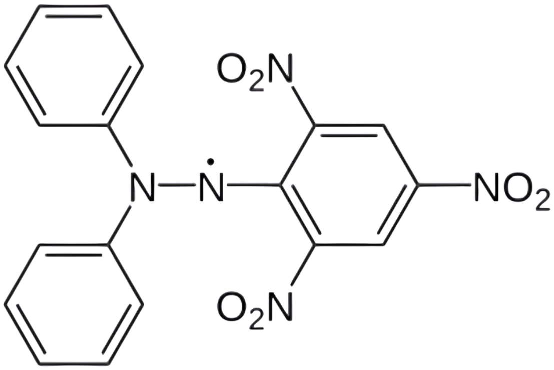

Figure 6.1: Chemical structure of DPPH (*diphenylpicryl hydrazyl*). The unpaired electron is delocalized over the aromatic rings, leading to stable paramagnetism. Adapted from *DPPH*, Wikipedia (`https://en.wikipedia.org/wiki/DPPH`).

- **Ferromagnetic materials:** Substances with strong interactions between atomic magnetic moments, leading to spontaneous alignment even without an external field. They exhibit high magnetic susceptibility and can retain magnetization. Examples include iron, cobalt, and nickel.
- **Antiferromagnetic and ferrimagnetic materials:** In antiferromagnetic substances, adjacent atomic moments align in opposite directions, cancelling each other. In ferrimagnetic materials, the opposite moments are unequal, producing a net magnetization. Common examples are manganese oxide (MnO) and magnetite (Fe_3O_4).

Theoretical Background of ESR

The Zeeman effect causes the splitting of electron energy levels when a magnetic field is applied (Figure 6.2). In the absence of a field, the two spin orientations have the same energy, but the external field removes this degeneracy and creates two distinct energy states. As the magnetic field strength increases, the separation between these states also increases. In electron spin resonance, electromagnetic radiation of a suitable frequency induces transitions between these spin states, resulting in an absorption signal. This phenomenon forms the fundamental principle of ESR and establishes a direct relationship between the resonance frequency and the magnetic field strength.

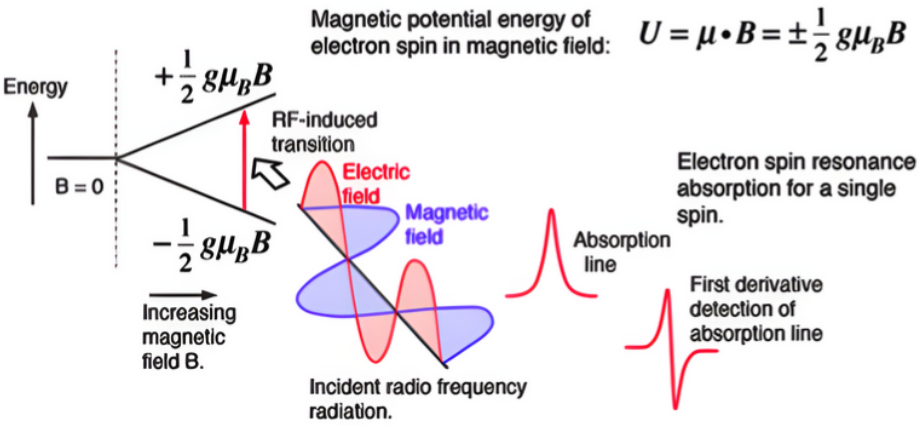

Figure 6.2: Schematic representation of the Zeeman splitting of electron spin energy levels and the ESR absorption process. The diagram illustrates how an incident radio frequency field induces transitions between the spin states when the photon energy matches the Zeeman energy difference, leading to an absorption signal whose first derivative is typically detected in ESR experiments (HyperPhysics, n.d.).

Since electrons have charge e and are 'spinning' on their axis, they have a magnetic dipole moment $\boldsymbol{\mu}$. In the presence of an external magnetic field **B**, a free electron will therefore acquire a potential energy given by:

$$E = -\boldsymbol{\mu} \cdot \mathbf{B} \tag{6.1}$$

The relationship between magnetic moment $\boldsymbol{\mu}$ and the spin angular momentum **S** can be written as:

$$\boldsymbol{\mu} = \gamma \mathbf{S} \tag{6.2}$$

where γ is the gyromagnetic ratio. You may show that if an electron is a uniform sphere with homogeneous charge distribution, one expects $\gamma = e/2m$. Real electrons have a larger magnetic moment than this simple model predicts, and the discrepancy is often written in terms of the Landé g factor:

$$g \equiv \frac{\gamma}{e/2m} > 1 \tag{6.3}$$

If we consider the magnetic field **B** to be pointing in the z direction, the potential energy is:

$$E = \mu_z B_z \tag{6.4a}$$
$$E = \gamma S_z B_z \tag{6.4b}$$

Since we know from quantum mechanics that S_z can only have two values:

$$S_z = \pm\frac{\hbar}{2} \tag{6.5}$$

the potential energy will only have two values:

$$E = \pm\frac{1}{2}\gamma\hbar B_z \tag{6.6}$$

The difference in the two energies is then:

$$\Delta E = \gamma \hbar B_z \tag{6.7}$$

For single electron ;

- The two spin states have the same energy in the absence of a magnetic field
- The energies of spin states diverge linearly as the magnetic field increases

Therefore;

- Without a magnetic field, there is no energy difference to measure
- The measured energy difference depends linearly on the magnetic field

If a photon incident on an electron has an energy corresponding to this energy difference and the electron is in the lower energy state, the photon may be absorbed, inducing the electron to ‘flip’ its orientation: this phenomenon is electron spin resonance. Since the photon energy is just $h\nu$, we can re-write Equation (7) in terms of the frequency of the incident radiation:

$$\nu = \frac{1}{2\pi} \gamma B_z \tag{6.8}$$

In ESR technique; sample is placed in a microwave cavity (i.e. high frequency em radiation) in an electromagnet. The trapped electrons in the material either align with or against the magnetic field in which they find themselves. The magnetic field is slowly changed, for a given frequency, there is a certain value of magnetic field at which the electrons resonate i.e. change direction of alignment. In so doing, microwave energy is absorbed and no trapped electrons. Therefore, measure of age i.e. time since signal zeroed. Each type of electron trap has a characteristic g value which is related to microwave frequency and magnetic field strength.

$$g = 0.7144 \times \frac{\text{microwave frequency}}{\text{magnetic field strength}} \tag{6.9}$$

Resonance occurs when the reactance of an inductor balances the reactance of a capacitor at some given frequency. In such a resonant circuit where it is series resonance, the current will be maximum and offering minimum empedance. In parallel resonant circuits the opposite is true. The rf coil is part of a high quality parallel resonance circuit. In the resonance case the sample absorbs rf energy, thus changing the AC resistance (damping) of the oscillatory circuit. By triggering the two-channel oscilloscope with the modulation signal of the magnetic field it is possible to simultaneously display the curves for field modulation and ESR absorption. The resonance frequencies f at differnet field strengths B are directly indicated on a digital frequency counter, built-in to the ESR Control unit.

So far we have only discussed free electrons. However in chemical free radicals there is one unpaired electron per molecule and these substances are paramagnetic. These unpaired electrons are almost entirely uninfluenced by their orbital motion. Thus it is possible to obtain a good value for the free electron gyromagnetic ratio from measurements on a free radical. This in turn will allow you to calculate the Landé g factor. The free radical you will use in this experiment is diphenylpicryl hydrazyl (DPPH, $(C_6H_5)_2NN(\bullet)C_6H_2(NO_2)_3$); it is contained in the small 'test-tube'. Note that it fits neatly inside each of the 3 small copper coils.

An unpaired electron interacts with its envirenment and the details of ESR spectra depend on the nature of those interactions. Two ways are conceivable for scanning an absorption spectrum;

1. To sweep the microwave at a constant magnetic field
2. To sweep the magnetic field at a constant microwave frequency.

Since it is technical much more feasible to realise the second way, the external magnetic field is commonly swept at a constant microwave frequency. Due to amplification technique the absorption signal is recorded as the first derivative. $\Delta E = h\nu = g\mu_B B_z$. g is the proportionality constant approximately equal to 2 for most samples, but varies depending on the electronic configuration of the radical or ion.

The magnetic field B_z will be supplied by the 2 Helmholtz coils. Rather than a fixed B_z, you will use an AC current (60 Hz is very slow compared to atomic times, so the fact that the field is varying doesn't matter) as the field sweeps through the resonance point you will then see the absorption of the high frequency photons. **Never exceed 1 A current through the coils!** Recall that the field is most uniform when the distance between the coils is equal to their radius. Also, the central field generated by a pair of coils is given by:

$$B = \left(\frac{4}{5}\right)^{3/2} \frac{\mu_0 n I}{R} \text{ Tesla} \tag{6.10}$$

where: $\mu_0 = 4\pi \times 10^{-7}\,\mathrm{Wb\,A^{-1}\,m^{-1}}$,
R = radius of the coils,
n = number of turns,
I = current.

You should monitor the current going into the coils both with an ammeter and by looking at the voltage drop across the supplied $1\,\Omega$ resistor with a scope.

The heart of the apparatus are the 2 units from Leybold (Figure 6.3). One, called the ESR Basic Unit, contains a socket for mounting one of the small copper coils containing the DPPH sample, a DIN cable, and two small knobs for controlling the strength and frequency of the high-frequency photons. The unit will generate a RF field inside the copper coil. The 3 different copper coils give you 3 different ranges of frequencies. Can you predict which of the copper coils will give the maximum frequency?

The other is the ESR Control Unit which provides all the required voltages and also digitally indicates the frequency of the oscillatory circuit.

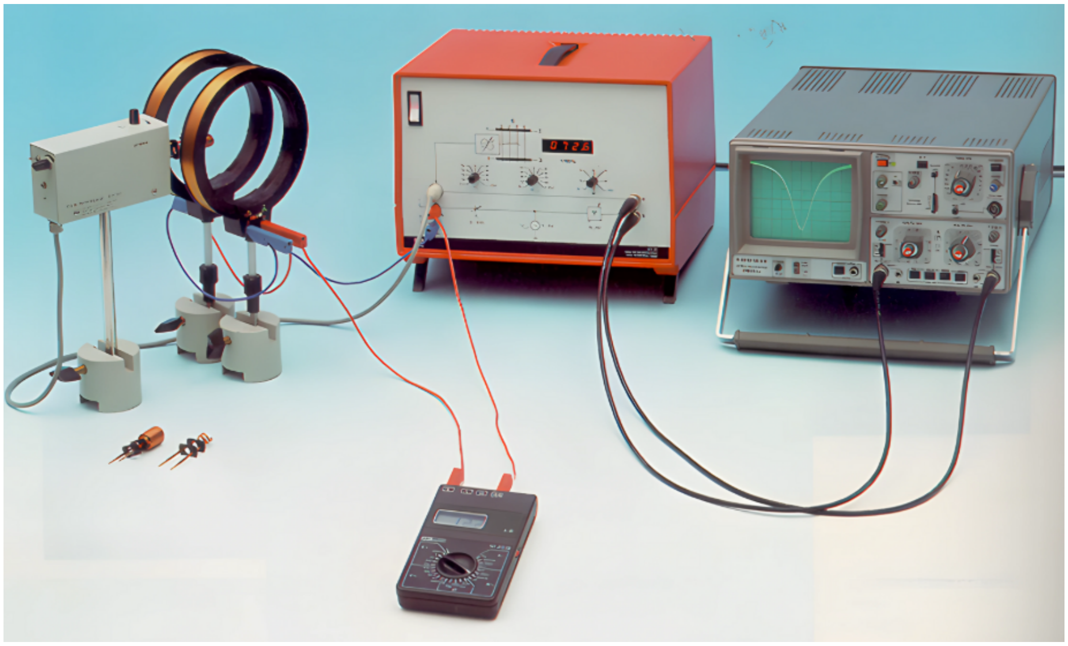

Figure 6.3: Experimental setup of the electron spin resonance (ESR) apparatus. The system consists of the ESR Basic Unit with an inserted RF coil containing the DPPH sample, the pair of Helmholtz coils providing a homogeneous magnetic field, and the ESR Control Unit that supplies and modulates the magnetic field. A digital multimeter monitors the current through the coils, while a dual-trace oscilloscope displays the resonance absorption signal as the magnetic field sweeps through the resonance condition.

Finally, a couple of experimental tips:

- the axis of the copper coil should be perpendicular to the extern field B_z.
- if you can find a combination of frequency and current so that the two peaks have just merged into one, then the corresponding current at resonance is just the peak current going through the coils.

You may also wish to ponder and/or investigate the following:

- The ESR signal may not be exactly symmetric about the maximum current point. Why?
- Is the relation Equation (8) true over a wide range of frequencies, ie: is the effect truly linear?
- What is the physical interpretation of the width of the peak?
- How does the Basic Unit work? What is the knob that adjusts the frequency connected to? What parameter of the circuit is being fed out of the Y socket?

Applications

ESR has a wide range of applications in research, industry, and daily technology. It is extensively used to identify and study free radicals in chemical and biological systems, providing insight into reaction mechanisms and oxidation processes. In materials science, ESR helps characterize lattice defects, impurities, and dopant behavior in semiconductors and crystals. In medicine, ESR-based dosimetry allows measurement of radiation exposure, while ESR imaging contributes to the study of oxygen distribution and tissue characterization. Further applications include food quality monitoring, polymer degradation analysis, and age determination in archaeological or geological samples.

ESR spectra are characterized by several measurable features:

- the form of the absorption curve,
- the position of the resonance field,
- the line width,
- the area under the absorption curve.

From these spectral parameters, important physical quantities can be derived:

- the Landé g value,
- the relaxation rates $1/T_1$ and $1/T_2$,
- the spin susceptibility χ_s.

Equipments

- ESR Basic Unit with base
- ESR Control Unit
- Two RF coils and a DPPH sample in a vial
- Passive resonant circuit
- Current measuring lead
- Pair of Helmholtz coils with base
- Multimeter
- Dual-trace oscilloscope
- Connecting wires

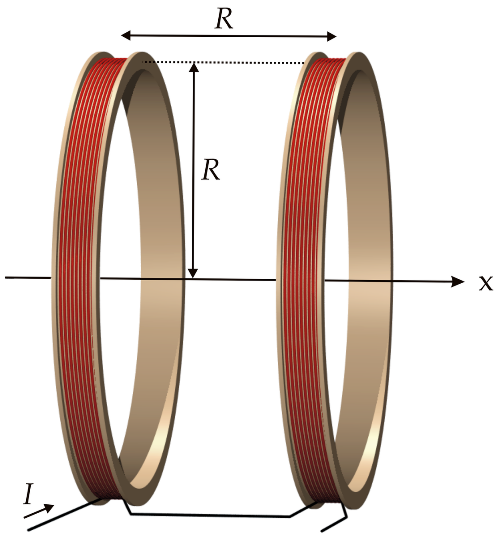

Figure 6.4: Schematic representation of a pair of Helmholtz coils used to generate a nearly uniform magnetic field at the midpoint between the coils. Each coil has radius R and carries an identical current I flowing in the same direction. The separation between the coils is equal to their radius, ensuring optimal field homogeneity along the central axis. This configuration is commonly used in electron spin resonance experiments to produce a stable and well-defined magnetic field. Adapted from *Helmholtz coils*, Wikipedia (`https://en.wikipedia.org/wiki/File:Helmholtz_coils.png`).

Technical Parameters of the Helmholtz Coils

These coils (Figure 6.4) can be used as field and induction coils or as inductive resistor. They can be fitted either – with defined “Helmholtz distance” for generating an approximately homogeneous magnetic field – into the stand for electron tubes or into stand equipment.

Number of turns: 320 per coil
DC resistance: approx. $6.5\,\Omega$ per coil
Maximum load: 1.5A (continuous), 2A (for short period)
Coil diameter: 13.5 cm
Mean coil distance for Helmholtz arrangement: 6.8 cm
Field strength $H = 34 \times 10^2\,\mathrm{m}^{-1}\,I$ (I coil current, in Helmholtz arrangement)
Connections: Two 4mm sockets, with identification of beginning (A) and end (Z) of winding

Do not exceed the maximum permissible current and observe it.
Connect the pair of coils so that they have the same winding sense. If the coil connections are at the outside, proceed as follows:
For series connection, connect socket Z of coil 1 with socket Z of coil 2.
For parallel connection, connect socket A of coil 1 with socket Z of coil 2 and socket Z of coil 1 with socket A of coil 2.

Procedure

1. Set the Helmholtz coils at the proper spacing of 1/2 diameter. Connect the ESR Basic Unit with the middle-sized rf coil, as well as the Helmholtz coils to the ESR Control unit, and turn on both power switches (Figure 6.5). Watch the dedector output on the scope. Adjust the tuning knob on top of the ESR Basic Unit to get a frequency reading near the high end (say 60–70 MHz). Be sure the DPPH sample is in the coil.

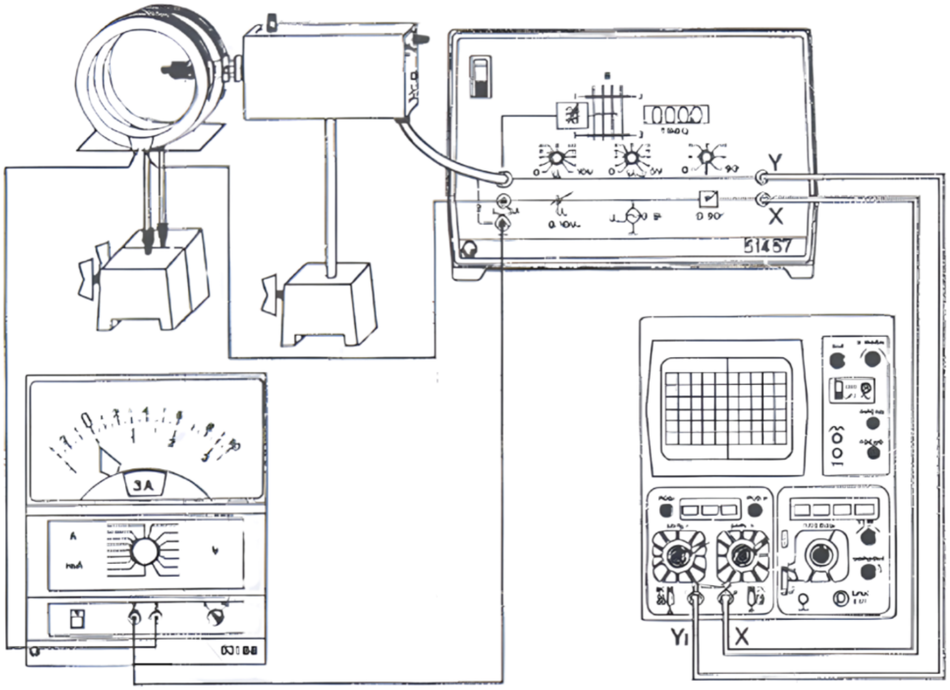

Figure 6.5: Schematic wiring diagram of the ESR experimental setup. The Helmholtz coils are connected to the ESR Control Unit, which provides both DC and AC current to generate the magnetic field. The ESR Basic Unit is coupled to the coils and the oscilloscope for detecting the resonance signal, while a multimeter monitors the coil current.

2. Three knobs on the ESR Control Unit control the dc and ac current to the Helmholtz coils, and the phase shift of the signal sent to the scope (for convenience and viewing). Set a moderate ac level and adjust the dc current until you see indication of a resonance (somewhere near mid-range). This should show up as a dip in the somewhat noisy Y output from the detector each time the modulation takes the total field through resonance, the dip indicating a decrease in the level of oscillation due to absorption of power in the DPPH. Adjust the amplitude knob on the back of the ESR Basic Unit for the best signal to noise ratio.

3. Determine the magnetic field at resonance. This is the field due to the dc current, provided you adjust things so that the dip occurs at the zero crossing of the modulation. There are two good ways to do this: Adjust for symmetric dips in a time trace (MTB), or for a symmetric dip pattern with the scope in XY mode (X-DEFL). For the latter, reduce the modulation

level until you see only half the dip; the phase shift may also be useful here. Check that the coil spacing is correct for the Helmholtz formula to be appropriate. Do this for a number of frequencies over as wide a range as possible.

4. Determine the with of the resonance (in magnetic field units). Is it frequency dependent? A limitation of these relatively low-field measurements is that the intrinsic width must be quite small; at least smaller than the field used.

Safety Precautions

- Never exceed the maximum current limit of the Helmholtz coils (1 A during continuous operation, 2 A for short periods).
- Avoid touching the coils or connecting leads while current is applied, as they may become hot during operation.
- Ensure all electrical connections are secure before switching on the ESR Basic and Control Units.
- Do not operate the apparatus with wet hands or near liquids to prevent electrical hazards.
- Keep the DPPH sample vial intact; avoid direct skin or eye contact with the chemical.
- Turn off the power supply immediately if abnormal noise, overheating, or smoke is observed.
- Allow the coils to cool down between long measurement sessions to prevent insulation damage.
- Handle the oscilloscope and frequency counter cables carefully to avoid short circuits or grounding faults.
- Verify that the Helmholtz coil spacing corresponds to the correct experimental configuration before energizing the system.
- After completing the measurements, reduce the current to zero and switch off all power supplies before disconnecting any components.

Data

Table 7.1: ESR measurements for each coil

Coil No.	Frequency (MHz)	Current (mA)
1		
2		

Questions

1. What is the magnetic moment of free electrons?
2. What is the Landé *g* factor? Why is it needed?
3. How does *g* depend on the envirenment of the electron?
4. If the magnetic moment of the electron is aligned along the z-axis with no external magnetic field, describe the effect of turning on an external field aligned along the x-axis.
5. What is Larmor frequency and γ, the gyromagnetic ratio?
6. Show that for a free electron in a 5 kG magnetic field the Larmor frequency is 14 GHz.
7. Why are microwaves necessary to study the electron spin resonance?
8. How do microwaves differ from light?
9. What is the quantum mechanical coupling probed by ESR?
10. What selection rules are important in determining the experimental frequency and/or the magnetic field? and why?
11. Do you expect the resonance frequency to change if the sample is changed?

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Experiment 7

ELECTRICAL CONDUCTION IN SOLID BODIES

Purpose

- To study the temperature dependence of electrical resistance in a noble metal (platinum) resistor and a semiconductor (NTC) resistor, and to compare their conduction mechanisms.
- To determine the temperature coefficient of resistance for the noble metal and to estimate the energy band gap of the semiconductor using experimental data.

Introduction

Energy Band Theory of Solids

The differences in behavior of a conductor, semiconductor, and insulator can be explained by the electron energy band theory of solids.

Only electrons in the conduction band and holes in the valence band will contribute to the conduction of current. No electron can have an energy in the "forbidden" energy gap. In an insulator, the energy gap is large and essentially no electrons have sufficient energy to reach the conduction band. At absolute zero, all the electrons would reside in the valence band and would be tightly bound to the individual atoms. In a good conductor, there is no energy gap and the conduction and valence bands may overlap. Hence, electrons can readily be available for conduction of current—even at considerably low temperatures.

If the temperature of a solid is raised, the resistance is likely to change because of two opposing tendencies:

(a) An increase in temperature increases the vibration amplitudes of the atoms in the crystal lattice. This causes an increased frequency of collisions between the charge carriers and

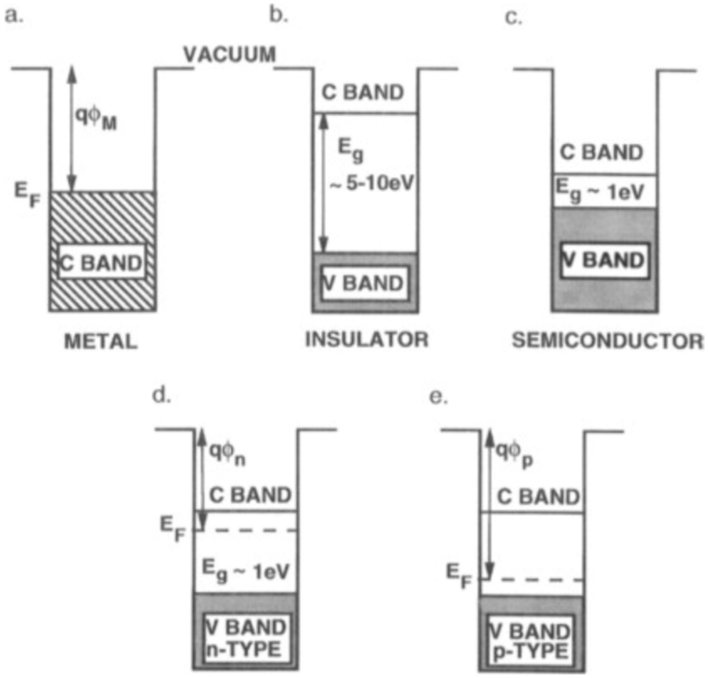

Figure 5.1: Schematic band structures for (a) a metal, (b) an insulator, (c) an intrinsic semiconductor, (d) an *n*-type semiconductor, and (e) a *p*-type semiconductor. Metals exhibit overlapping or partially filled conduction bands, resulting in high conductivity. Insulators possess a wide band gap ($E_g \approx 5$–$10\,\text{eV}$), inhibiting electron excitation. Semiconductors have narrower band gaps ($E_g \approx 1\,\text{eV}$), allowing limited carrier excitation, while doping shifts the Fermi level (E_F) upward in *n*-type and downward in *p*-type materials [1].

the lattice, thus reducing the average drift velocity of the carriers. For a constant applied potential difference, the reduced motion of the carriers implies a reduced current, and hence resistance is increased.

(b) The increased amplitudes of vibration may break some bonds between the valence electrons and the lattice atoms, hence releasing more charge carriers and reducing the resistance.

Electrical Conduction in Metals

Electron Mobility

Electrons are accelerated in an electric field E, in the opposite direction to the field because of their negative charge. The force acting on the electron is $-eE$, where e is the electric charge. This force produces a constant acceleration so that, in the absence of obstacles (in vacuum, like inside a TV tube), the electron speeds up continuously in an electric field. In a solid, the situation is different. The electrons scatter by collisions with atoms and vacancies that change drastically their direction of motion. Thus, electrons move randomly but with a net drift in the direction opposite to the electric field. The drift velocity is constant, equal to the electric field times a constant called the mobility μ:

$$v_d = -\mu_e E \tag{5.1}$$

which means that there is a friction force proportional to velocity. This friction translates into energy that goes into the lattice as heat. This is the way that electric heaters work. The electrical conductivity is:

$$\sigma = n|e|\mu_e, \tag{5.2}$$

where n is the concentration of electrons (n is used to indicate that the carriers of electricity are negative particles).

Electrical Resistivity of Metals

The resistivity depends on collisions. Quantum mechanics tells us that electrons behave like waves. One of the effects of this is that electrons do not scatter from a perfect lattice. They scatter by defects, which can be:

- atoms displaced by lattice vibrations (phonons),
- vacancies and interstitials,
- dislocations and grain boundaries,
- impurities.

The total resistivity can be expressed using Matthiessen's rule as

$$\rho_{\mathrm{tot}}(T) = \rho_{\mathrm{ph}}(T) + \rho_{\mathrm{imp}} + \rho_{\mathrm{disl}}, \tag{5.3}$$

where the phonon term dominates at high T, while impurities and dislocations contribute nearly temperature-independent terms.

In a metal, the number of conduction electrons is approximately independent of temperature. Hence mechanism (a) dominates, and resistance increases with T. For moderate ranges of T, the resistance can be approximated by

$$R(T) = R_0[1 + \alpha(T - T_0)], \tag{5.4}$$

where R_0 is the resistance at reference temperature T_0 (e.g. 0 °C or 20 °C) and α is the temperature coefficient of resistance.

Electrical Conduction in Semiconductors

There are materials in which resistance decreases with increasing temperature. A thermistor is an example of such a material. Thermistors are very sensitive to even small changes of temperature, therefore they are often used as thermometers. It is made of semiconductors, such as oxides of manganese, nickel and cobalt mixed in the desired proportion with a binder and pressed into shape.

Semiconductors may be *intrinsic* or *extrinsic*. Intrinsic means conductivity arises from the pure lattice, while extrinsic conductivity depends on dopants (impurities).

Conduction occurs by both electrons and holes. In an electric field, electrons and holes drift in opposite directions. The conductivity of a semiconductor is

$$\sigma = n|e|\mu_e + p|e|\mu_h, \tag{5.5}$$

where n (p) are the electron (hole) concentrations and μ_e (μ_h) are their mobilities. Typically,

$$\mu_e > \mu_h. \tag{5.6}$$

In an intrinsic semiconductor, each electron promoted to the conduction band leaves behind a hole in the valence band; thus $n = p$, and eq. (5.5) simplifies accordingly. Thus,

$$\sigma = n|e|(\mu_e + \mu_h) \qquad \text{(only for intrinsic semiconductors).} \tag{5.7}$$

The thermal vibration of the atoms can impart energy ($\sim kT$) to the electrons such that some of them break free from their covalent bonds and can migrate through the crystal as part of the conduction current. From Fermi-Dirac statistics, the number ne of electrons per m^3 which are thermally excited to the conduction band at a temperature $T(K)$ is given by the expression

$$n = N_c e^{-E_g/2kT} = 4.83 \times 10^{21} T^{3/2} e^{-E_g/2kT}, \tag{5.8}$$

where E_g is the energy gap between the valence and conduction band, k is Boltzmann's constant $(1.38 \times 10^{-23} J/K)$ and N_c is the effective density of states in the conduction band. Equation (8) is only valid for a pure (intrinsic) semiconductor where the number of conduction electrons equals the number of positive holes in the valence band. As the temperature increases, the number of electrons (and holes) increases so the resistance of the semiconductor decreases and tendency (b) is said to dominate. Since the exponential term $e^{(-E_g/2kT)}$ far outweighs any other factors, it follows that the resistance R at a temperature $T(K)$ can be approximately given by the equation

$$R = R_0 e^{(1/T - 1/T_0)E_g/2k}, \tag{5.9}$$

where R_0 is the resistance of the semiconductor at reference temperature T_0 (often 273 K). Extrinsic semiconductors have, in addition to this dependence, one due to the thermal promotion of electrons from donor levels or holes from acceptor levels. The dependence on temperature is also exponential but it eventually saturates at high temperatures where all the donors are emptied or all the acceptors are filled.This means that at low temperatures, extrinsic semiconductors have larger conductivity than intrinsic semiconductors. At high temperatures, both the impurity levels and valence electrons are ionized, but since the impurities are very low in number and they are exhausted, eventually the behavior is dominated by the intrinsic type of conductivity.

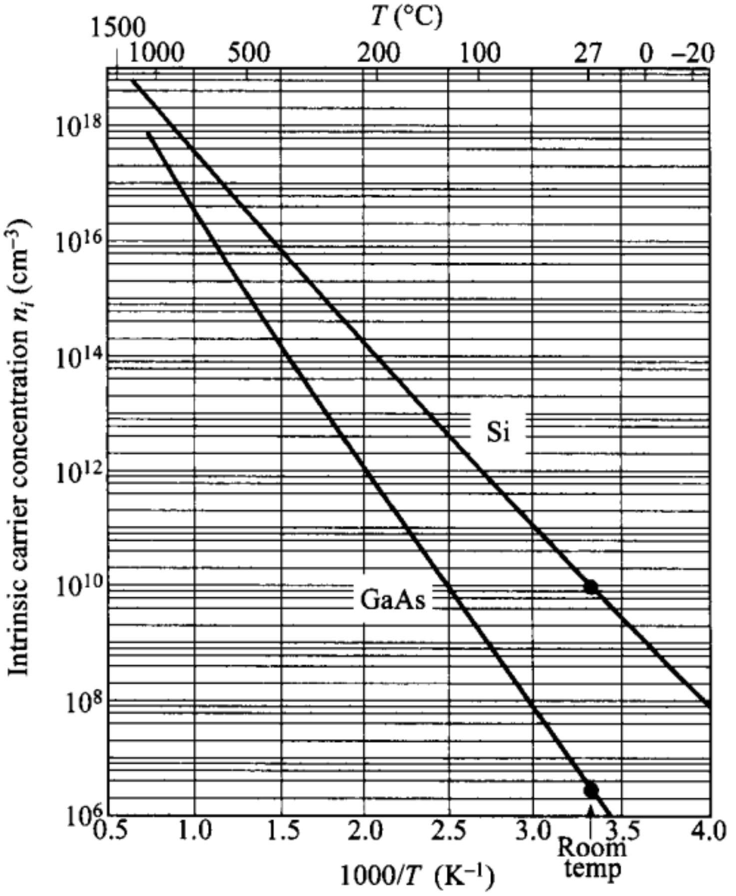

Figure 5.2: Intrinsic carrier concentration (n_i) of Si, and GaAs as a function of temperature, showing the exponential increase in carrier density with temperature [2].

Technical Data

Noble Metal and Semiconductor Resistors

These resistors are used for quantitative investigation of the temperature dependency of the ohmic resistance of two solid bodies with different types of conductivity. Hence, they enable experiments to be carried out on the conductivity in solid bodies.

Noble metal resistor: It is a platinum wire, sealed in a glass tube.

Semiconductor resistor: It is a NTC (Negative Temperature Coefficient) resistor, sealed in a glass tube.

4 mm sockets, connected with resistors. Borehole, diameter 8 mm, for positioning of a thermometer as required for the measurements, in the immediate vicinity of resistors while they are heated in the electric oven.

Table 7.1: Technical specifications of noble metal and semiconductor resistors.

	Noble metal resistor	Semiconductor resistor
Temperature range	$-100°C$ – $+400°C$	$-100°C$ – $+200°C$
Resistance range	approx. $60\,\Omega$ – $240\,\Omega$	approx. $20\,k\Omega$ – $5\,\Omega$
Resistance at $20°C$	approx. $100\,\Omega$	approx. $200\,\Omega$

Dewar Flask

The Dewar flask (see Figure 8.3) featuring low thermal absorption and very good insulation against heat losses are used in calorimetric measurements for immersion of solid test specimens into liquids.

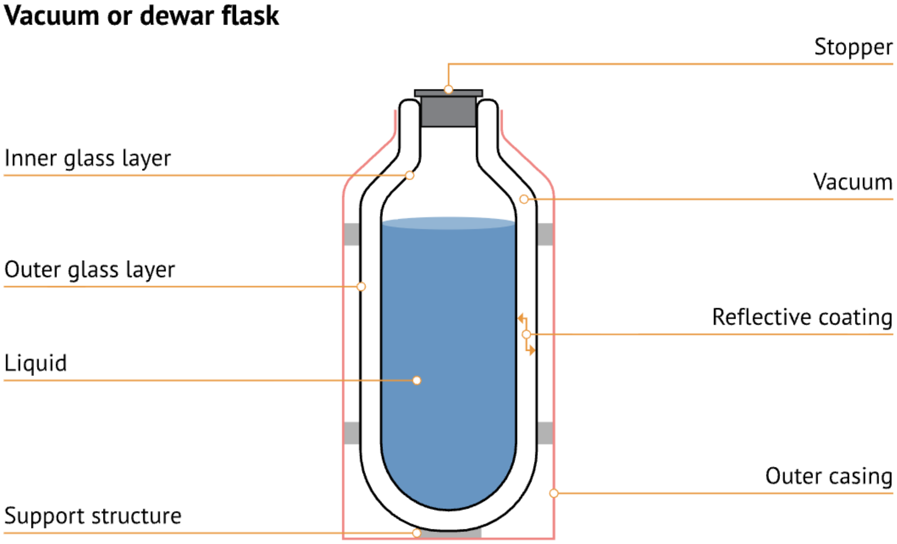

Figure 5.3: Schematic representation of a Dewar (vacuum) flask showing its double-walled glass structure, vacuum insulation, and reflective coating used to minimize heat transfer and maintain the liquid temperature [3].

It consists of a plastic base and Dewar flask, 250 ml, double-walled glass jacket, highly evacuated, silver-coated, internal diameter 7 cm, depth 9 cm.

Safety note: Do not let hard objects fall into the Dewar flask. Protect its walls against scratches by sharp objects. Risk of breakage. Risk of implosion.

Demonstration Bridge

The apparatus (Figure 8.4) is used together with standard resistors and an ammeter as a zero indicator to determine unknown resistances in a Wheatstone bridge circuit. It is also suitable for investigating voltage drop along a resistance wire.

Resistance wire: constantan

Specifications:

- Length: 1 m
- Resistance: approx. 4Ω
- Maximum allowable voltage: 2 V
- Maximum allowable current: 0.5 A
- 4 mm sockets for power supply and resistors
- Sliding contact with 4 mm sockets
- Baseplate with scale; length: 1 m
- Scale: 10 cm divisions with cm and mm graduations

Determining the Resistance by means of a Wheatstone Bridge Circuit

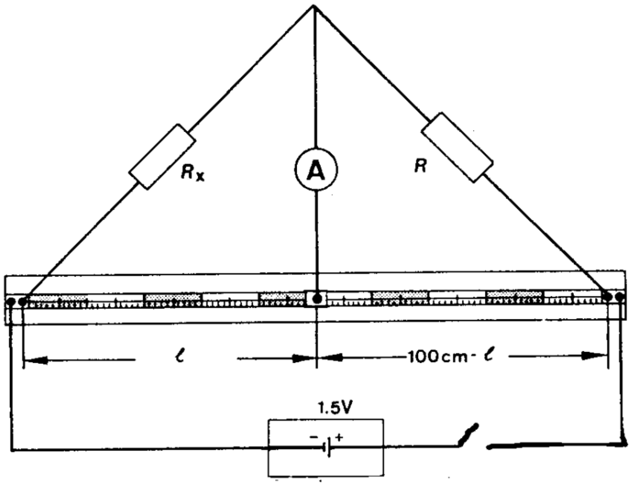

Figure 5.4: Wheatstone bridge circuit for determining an unknown resistance R_x.

Choose a standard resistor approximately equal to, or at least of the same order of magnitude as the unknown resistance R_x (smallest measurement inaccuracy for l when the sliding contact is centrally positioned).

For determining a resistance value: balance the bridge with the sliding contact so that the ammeter shows no deflection. The unknown resistance is then

$$R_x = \frac{l}{100\,\mathrm{cm} - l} R, \tag{5.10}$$

where l is the length measured along the bridge wire and R is the standard resistor.

Equipments

- Noble metal resistor
- Semiconductor resistor
- Demonstration bridge
- Electric oven
- Morse key
- Measuring junction box
- Ammeter, zero point in centre
- Standard resistors
- Thermometer
- Dewar vessel with cooling agent (liquid nitrogen)
- Single cell battery, 1.5 V
- STE battery holder
- Plugboard

Procedure

Set the equipments as shown in Figure 8.4.
It is advisable to study the resistance as a function of temperature in the following sequence:

1. at room temperature,
2. during heating in an electric oven,
3. during cool-down in a freezing bath.

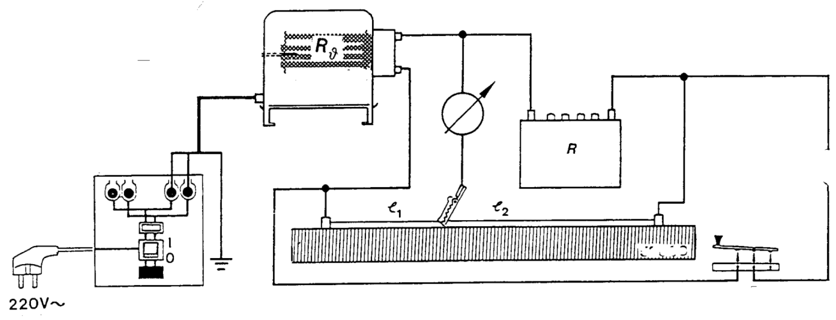

Figure 5.5: Experimental setup for measuring resistance as a function of temperature.

Heating in the Electric Oven

1. Introduce the thermometer into the borehole at the rear of the oven until the thermometer is in the immediate vicinity of resistors (noble metal or semiconductor).
2. Before recording any pair of temperature/resistance values, wait until temperature has balanced with the oven voltage switched off, each time measuring the reversal point of temperature.
3. When the thermometer indicates the maximum permissible value (200°C for semiconductor resistor, 400°C for noble metal resistor), immediately remove the resistor from the oven.

Cool-down in the Freezing Bath

1. Before immersing the heated resistor into the freezing bath, precool it by means of a fan.
2. Cool down the resistor to approximately $-50°$C to $-100°$C directly above the surface of liquid nitrogen.
3. Measure the resistor while it is slowly heated to room temperature.
4. Arrange the thermometer in close vicinity to the resistor (it is advisable to use heat conducting paste to improve contact).

Report Sheet

Experiment 8: Electrical Conduction in Solid Bodies

Student's Name: **Experiment Date:**

Group Member Name(s):

Laboratory Bench Number: **Assistant’s Name and Signature:**

Data and Calculations

Conductor 1

T(^oC)	$l_1(cm)$	$l_2(cm)$	$R_o(\Omega)$	$R_x(\Omega)$

Figure 5.6: Data sheet table for Conductor 1.

Conductor 2

T(^oC)	$l_1(cm)$	$l_2(cm)$	$R_o(\Omega)$	$R_x(\Omega)$

Figure 5.7: Data sheet table for Conductor 2.

1. Which device behaves as a metal? As a semiconductor? Discuss.

2. For the metal, plot a graph to test the validity of Equation (4) and obtain an experimental value for α. Is there any evidence that α changes with temperature? Graphically determine a value for R_0. At what temperature would the resistance R become zero according to Equation (4.4)? What does this suggest about the validity of Equation (4.4) for all temperature ranges?

3. For the semiconductor, plot a graph of $\ln R$ versus $1/T$ to test Equation (4.9). Graphically determine the value of the energy gap E_g. What would the resistance of the semiconductor be at absolute zero? Why?

Is your value for E_g reasonable, given that for many semiconductors near room temperature?

Questions

1. Draw energy band structures for insulators, conductors and semiconductors and describe their characteristics.

2. Describe the difference between Bose–Einstein statistics and Fermi–Dirac statistics. Which are at play in this lab? Describe how they vary as a function of temperature. *(Note: a picture is worth a thousand words!)*

Discussion

References

1. Ohring, M. (2002). *Chapter 1 – A Review of Materials Science*. In M. Ohring (Ed.), *Materials Science of Thin Films* (2nd ed., pp. 1–56). Academic Press, San Diego. https://doi.org/10.1016/B978-012524975-1/50004-5
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Experiment 8

PHOTOCONDUCTIVITY

Purpose

- Recording the current-voltage curve of a CdS photoresistor, which is a n-type semiconductor, at different illuminance values and constant wavelength.
- The behavior of the current flowing through the CdS photoresistor will be investigated when a voltage is applied.
- During each measuring series, the luminous intensity acting on the photoresistor from a light source will remain constant.
- Each measurement series will then be used to produce a current-voltage curve for the respective irradiance.

Introduction

A **light dependent resistor (LDR)**, also known as a photoresistor, is a semiconductor device whose resistance changes according to the intensity of incident light. Typically made of materials such as cadmium sulfide (CdS) or cadmium selenide (CdSe), an LDR exhibits a very high resistance in darkness because only a few charge carriers are available (Figure 8.1). When light falls on its surface, photons excite electrons from the valence band to the conduction band, generating additional free charge carriers. As a result, the electrical conductivity of the material increases, and its resistance decreases. Due to their simplicity, low cost, and reliability, LDRs are widely used in various light-sensing applications such as automatic lighting controls, street lamps, photographic exposure meters, and alarm systems.

CdS cells are a type photoconductive device. They are semiconductor sensors that utilize the photoconductive effect in which light entering the photoconductive surface reduces the resistance. A voltage is applied to both ends of a CdS cell and the change in resistance due to light is output as a current change signal. Despite of small size, the output current per photoconductive surface area is large enough to drive relays directly. For this reason, CdS cells are used in a variety of fields.

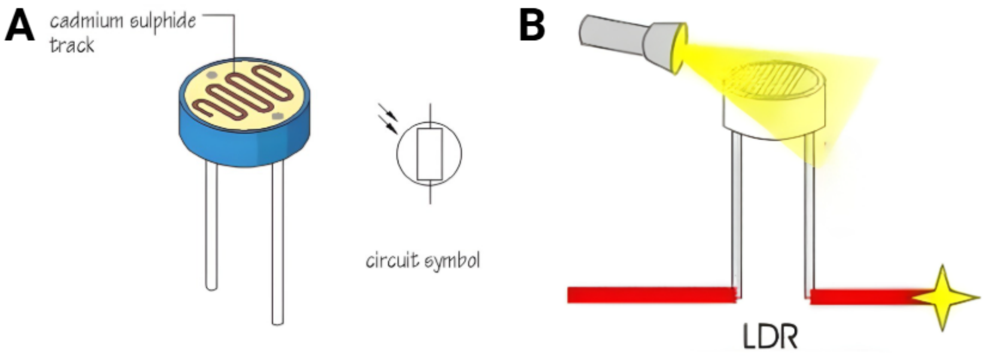

Figure 8.1: (A) Structure and circuit symbol of a light-dependent resistor (LDR), composed of a cadmium sulphide (CdS) track. (B) Working principle of an LDR: when light falls on the CdS surface, its resistance decreases, allowing more current to pass. This effect, known as photoconductivity, is commonly used in automatic light control and sensing applications. Source: WatElectronics. (n.d.). *Light Dependent Resistor (LDR) – Working Principle and Its Applications*. Retrieved October 12, 2025, from https://www.watelectronics.com/light-dependent-resistor-ldr-with-applications/

Photoconductive Effect

Figure 8.2 is a schematic diagram of a CdS cell and its operation circuit. An electrode is set at each end of the photoconductor. In darkness, the photoconductor resistance is very high and when a voltage is applied, the ammeter shows only only a small dark current. This is the CdS photoconductor's characteristic thermal equilibrium current. When light is incident on this photoconductor, a current (I) flows. Figure 8.3 shows the current that flows when the amount of light is increased.

Here are the basic principles of the photoconductive effect.

I) Directly beneath the conduction band of the CdS crystal is a donor level and there is an acceptor level above the valence band. In darkness, the electrons and holes in each level are almost crammed in place in the crystal and the photoconductor is at high resistance.

II) When light illuminates the CdS crystal and is absorbed by the crystal, the electrons in the valence band are excited into the conduction band. This creates pairs of free holes in the valence band and free electrons in the conduction band, increasing the conductance.

III) Furthermore, near the valence band is a separate acceptor level that can capture free electrons only with difficulty, but captures free holes easily. This lowers the recombination probability of the electrons and holes, and increases the number for electrons in the conduction band for N-type conductance.

The increase in conductance in (II) requires that the light energy be greater than the band gap E_g. For CdS with a band gap of $2.42\,\text{eV}$, the absorption edge wavelength λ is

$$\lambda = \frac{hc}{E_g} \simeq 515\,\text{nm} \tag{8.1}$$

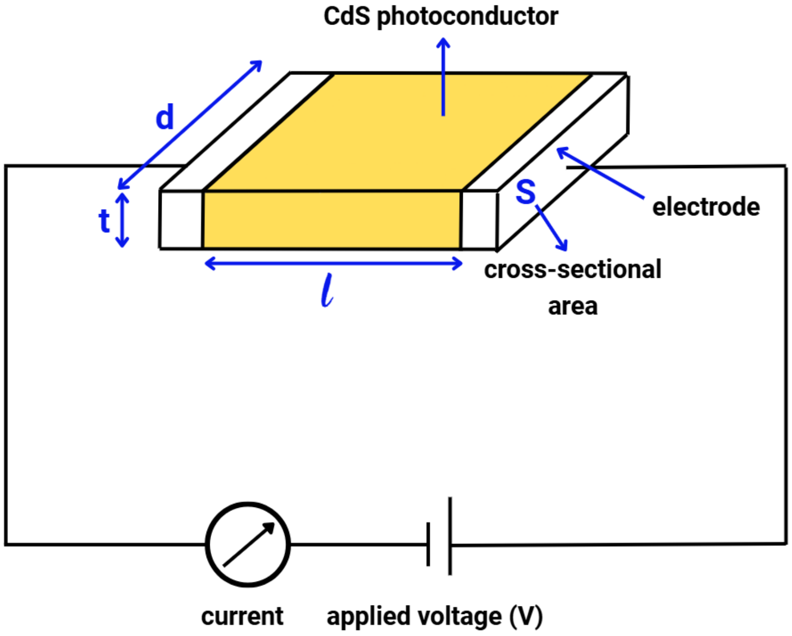

Figure 8.2: A schematic diagram of a CdS cell and its operation circuit

Therefore, the CdS crystal absorbs light with a wavelength shorter than 515 nm and lets light with a wavelength longer than 515 nm be transmitted. Therefore, the photoconductor's absorption edge wavelength determines the spectral response characteristic on the long wavelength side. The sensitivity of CdS drops at wavelength shorter than 515 nm. This is because at short wavelengths, the light is absorbed near the surface of the crystal, increasing the local charge density and inducing electron hole recombination, and also because there are lattice defects at the crystal surface, they promote the recombination.

Until the carries generated in (II) and (III) recombine, electrons are injected from one electrode and pulled out by the other. When these carriers last longer and they move more, the conductance increases greatly. The conductance $\Delta\sigma$ is given by the following equation.

$$\Delta\sigma = en(\mu_e\tau_e + \mu_p\tau_p) \tag{8.2}$$

where μ_e, μ_p; free electron and free hole movement ($\mathrm{cm^2/V\,s}$),
τ_e, τ_p; free electron and free hole life (s),
n; number of generated carriers per second per cubic volume.

For a CdS cell, $\mu_e\tau_e \gg \mu_p\tau_p$ and conductance by free holes can be ignored. Then it becomes an N-type semiconductor. Thus,

$$\Delta\sigma = en\mu_e\tau_e \tag{8.3}$$

Here, the gain G is defined as how many electrons flow between the electrodes due to excitation by one photon in the CdS photoconductor (until the carrier lifespan is over).

$$G = \frac{\tau_e}{t_t} \tag{8.4}$$

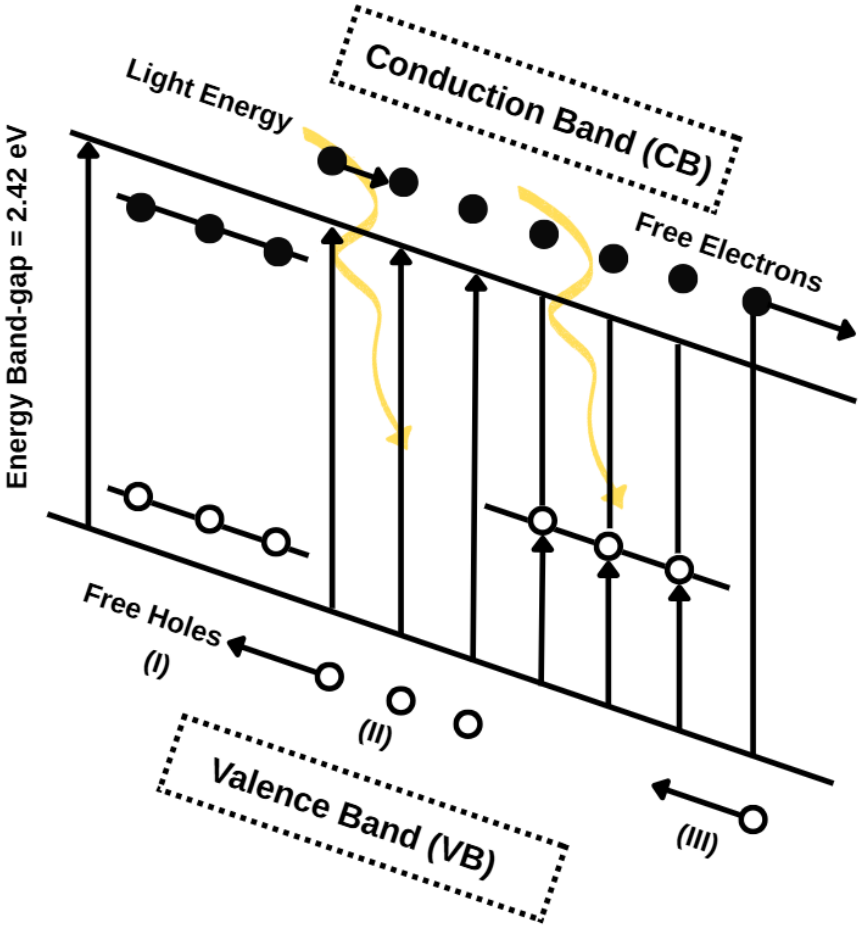

Figure 8.3: Band diagram illustrating the photoconductive effect in a CdS crystal

where t_t (transit time between electrodes) $= \dfrac{l^2}{V\mu_e}$,

l; distance between electrodes,

V; voltage applied.

Therefore,

$$G = \frac{\mu_e \tau_e V}{l^2} \tag{8.5}$$

If, for example, $\mu_e = 300\,\mathrm{cm^2/V\,s}$, $\tau_e = 1\times10^{-3}\,\mathrm{s}$, $l = 0.2\,\mathrm{mm}$ and $V = 1.2\,\mathrm{V}$, then the gain is 900. This means that there is multiplication in the CdS photoconductor and that the CdS is highly sensitive.

The sensitivity of CdS is the change in resistance, i.e. the change in current in response to change in light. As Figure 8.2 shows, if the distance between the electrodes is l, the cross-sectional area of the photoconductor is S and the voltage applied is V, then from Ohm's law;

$$\Delta I \propto \Delta\sigma \frac{SV}{l} = \Delta\sigma \frac{tdV}{l} \tag{8.6}$$

If the conductance $\Delta\sigma$ and the photoconductor thickness t are held constant, then,

$$\Delta I \propto \frac{d}{l} \quad \rightarrow \quad \Delta R \propto \frac{l}{d} \tag{8.7}$$

This l/d is an important factor in designing the electrode configuration. In other words, the shorter distance between the electrodes and the greater the electrode length, the higher the sensitivity and the lower the cell resistance. Thus, the electrode patterns for high-sensitivity CdS cell consist of many zig-zags.

Everyday Applications

Photoconductivity has several practical uses in daily life. It is commonly employed in light sensors and automatic street lighting systems, where the electrical conductivity of materials changes with light intensity. Photoconductive materials are also used in solar cells to convert light into electrical energy, and in photodiodes for optical communication and safety systems. These applications demonstrate how photoconductivity plays a vital role in modern technology and energy efficiency.

Equipments

- Power supply unit for tube experiments
- Lamp housing and a lamp 6V/30W
- Aspherical condenser with diaphragm slider
- Adjustable slits
- Projection objective
- Flint glass prism and prism table
- Pair of polarizing filters
- Lens, $f = 100\,\text{mm}$
- Photoresistor LDR
- Small optical bench with short holder
- Small optical bench with long holder
- Swivel joint with protractor scale

- Stand bases, stand rods and multiclamps
- Multimeter
- Connecting leads

Procedure

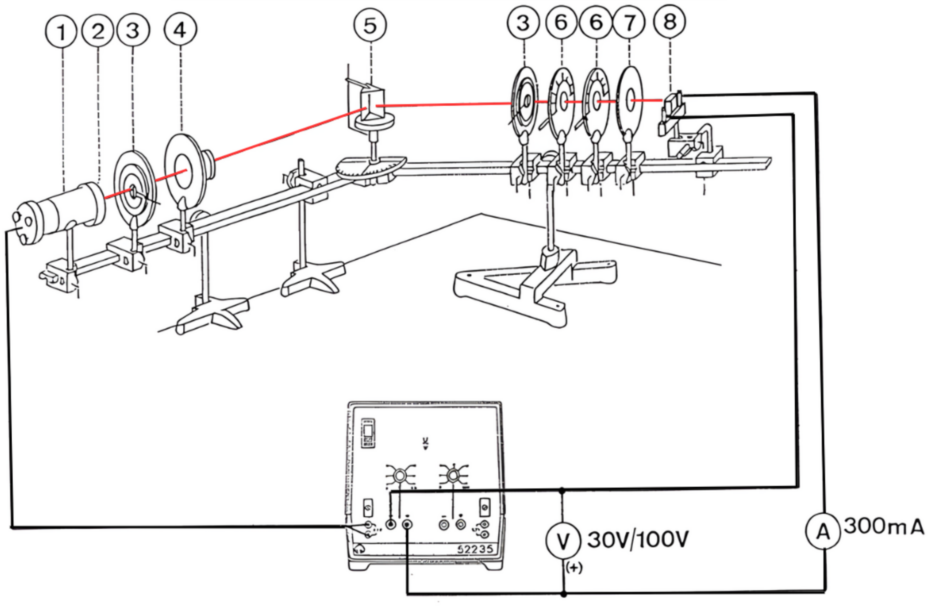

Figure 8.4: The experimental setup: (1) Light source (2) Condenser (3) Entrance or emergence slits (4) Projection objective (5) Flint glass prism (6) Polarizer or analyzer (7) Conversion lens $f = 100\,\mathrm{mm}$ (8) Photoresistor LDR

1. Measurements should be carried out with the room darkened to suppress the influence of room light on the photocurrent (not a total black-out so that it is still possible to read off the instrument display). It is also recommended to place a black cover on the photoresistor which is only open towards the ray path. In this way, the “dark photocurrent” can easily be kept negligibly small.
2. Set the entrance and emergence slits arbitrarily, but remember that the smaller the gap width, the sharper the color separation. It is advantageous to select the gap width of the entrance slit so that it is at least as large as the emergence slit.
3. With slit widths of 0.3 mm and less, the colors yellow, green, blue and violet, amongst others, can be separated at least as exactly as when using the filter set for these colors.
4. Before reading off each measurement value, it is recommended to allow a certain waiting period, approximately 20 s, until the photocurrent has reached a stationary value.

5. Using lens (2), fully illuminate entrance slit (3). Form a sharp image of the entrance slit on the emergence slit using the projection objective (without prism). Finally, place the prism in the ray path, adjusting for minimum deflection. Using the lens (7), focus the desired color on the receiver through the emergence slit by moving the mobile path of the optical setup (Figure 8.4).

6. Set the polarizer to the angle 0° and the analyzer to the desired angle (α). The radiance J determined in this way is given by; $J = J_0 \cos^2 \alpha$.

7. The photocurrent (I_{ph}) is now measured step-by-step as a function of voltage (V) with fixed wavelength (λ) and irradiation (J),

   $$I_{ph} = I_{tot} - I_0$$

   since I_0 (dark current) is significantly low in respect of I_{tot},

   $I_{ph} \simeq I_{tot}$.

8. Repeat the experiment for different irradiances, i.e. different angles for α, keeping the same wavelength range.

Safety Precautions

- Do **not touch the prism** or any other sensitive optical components. Handle only the **polarizer** and **analyzer** elements.
- Ensure that all optical components are properly aligned before turning on the power supply.
- **Do not exceed 40 volts** during the experiment. Higher voltages may damage the sample or equipment.
- Always switch off the power supply before changing any connections in the circuit.
- Keep liquids, metal objects, and conductive materials away from the setup to prevent short circuits.
- Avoid looking directly into the light beam to protect your eyes from intense illumination.
- Use insulated cables and ensure all electrical contacts are secure before operation.
- Report any damaged cables, components, or unusual behavior of the setup to your teaching assistant immediately.
- Maintain a clean and stable workspace to prevent accidental displacement of optical components.

Data and Calculations

Table 8.1: Dark and total currents at different angles under various voltages in the CdS photoresistor

Voltage (V)	I_0 **(µA),** $\alpha = 0°$	I_{tot} **(µA),** $\alpha = 0°$	I_{tot} **(µA),** $\alpha = 30°$	I_{tot} **(µA),** $\alpha = 60°$	I_{tot} **(µA),** $\alpha = 75°$
0					
5					
10					
15					
20					
25					
30					
35					
40					

Using the current values recorded in Table 8.1, calculate the photocurrents (I_{ph}) for each voltage and angle.

The photocurrent is determined using the formula:

$$I_{ph} = I_{tot} - I_0$$

where I_{tot} is the total current and I_0 is the corresponding dark current. For each measurement, subtract the dark current from the total current and record the resulting photocurrent values. After completing the calculations, present the results in a new table (Table 8.2).

Table 8.2: Photocurrents at different angles under various voltages in the CdS photoresistor

Voltage (V)	I_{ph} **(µA),** $\alpha = 0°$	I_{ph} **(µA),** $\alpha = 30°$	I_{ph} **(µA),** $\alpha = 60°$	I_{ph} **(µA),** $\alpha = 75°$
0				
5				
10				
15				
20				
25				
30				
35				
40				

After completing Table 8.2, plot the voltage (V) versus photocurrent (I_{ph}) for each analyzer angle used in the experiment. Make sure to label both axes clearly with their corresponding symbols and units, and include a legend indicating each analyzer angle. From the plotted data, determine the resistance from the slope of each linear region in the V–I_{ph} graphs. Since the relationship between voltage and photocurrent follows Ohm's law,

$$V = I_{ph} R,$$

the resistance R for a given angle corresponds to the slope of the fitted line:

$$R = \frac{\Delta V}{\Delta I_{ph}}.$$

Be careful with units: when calculating R, convert I_{ph} from microamperes to amperes to obtain resistance in ohms (Ω). Report your results in kilohms (kΩ) or megohms (MΩ) where appropriate.

In addition, express the radiance J in terms of the reference radiance J_0 for all analyzer angles according to Malus' law:

$$J = J_0 \cos^2 \alpha.$$

As an example, for the analyzer angle of 30°, the radiance can be expressed in terms of the reference radiance J_0 using Malus' law:

$$J(30^\circ) = J_0 \cos^2(30^\circ).$$

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Experiment 9

I–V CHARACTERISTICS OF SOLID STATE DEVICES

Purpose

The purpose of this lab is to become familiar with the modern laboratory equipment for experimental physics and to measure the I–V characteristics of a test diode and resistance using the LabVIEW program.

Introduction

The current–voltage (I–V) curve is a basic method for characterizing electrical materials. In solid-state devices, the I–V curve provides information about the electronic properties of the junctions, as well. In this experiment, you will use a LabVIEW program to measure the I–V characteristics of a resistor and a test diode.

LabVIEW Program

LabVIEW (Laboratory Virtual Instrumentation Engineering Workbench) is a graphical programming environment from National Instruments, commonly used for data acquisition, instrument control, and automation. Its language, is based on dataflow: a function executes as soon as all its inputs are available.

LabVIEW programs are called virtual instruments (VIs) because they look and act like real instruments (e.g., oscilloscopes, multimeters). A VI consists of three parts:

1. **Front panel** – the user interface. Built with controls (knobs, buttons, sliders) that provide input, and indicators (graphs, LEDs, meters) that display output.
2. **Block diagram** – the graphical source code. Functions, loops, and case structures are connected with wires to define behavior. Front panel objects appear here as terminals.

3. **Icon and connector pane** – identify the VI so it can be used in another VI as a subVI (similar to a subroutine in text-based code).

Key elements in the block diagram: **Terminals** – represent controls and indicators. **Nodes** – objects that perform operations when a VI runs. **Wires** – transfer data between elements. **Structures** – graphical forms of loops and conditional statements.

A subVI behaves like a function: it takes inputs, performs a task, and returns outputs. Complex programs are often built by combining many subVIs.

Note: In this course, you are not expected to build or program your own LabVIEW interfaces. You will use the pre-developed VI provided.

Review of Scientific Principles

For an electrical current to flow through a material, three basic requirements must be satisfied:

1. An **electric field** must be present.
2. **Charge carriers** must exist in the material.
3. The charge carriers must be able to **move** through the material.

An electric field is created when a voltage is applied across a circuit. The charge carriers depend on the material:

- In **metals**, they are the valence electrons.
- In **semiconductors** or **insulators**, they include both electrons promoted into the *conduction band* and the *holes* left behind in the *valence band*.

The ease with which these charge carriers move—their **mobility**—is affected by the material's crystal structure and by temperature.

Conductor

In metals (conductors), the outermost (valence) electrons are not tightly bound to individual atoms. Instead, they occupy a set of energy levels called the *valence band*, which is only partially filled. Because of this partial filling, these electrons can move freely through the crystal structure of the metal when an electric field is applied.

As temperature increases, the metal's atoms vibrate more strongly around their equilibrium positions. These vibrations scatter the moving electrons, which reduces their mobility. At very low temperatures (approaching absolute zero), scattering is minimal, so mobility reaches its maximum.

Semiconductor

In semiconductors and insulators, the valence band is **completely filled** under normal conditions, and the conduction band is **empty**. For electrical conduction to occur, some electrons must gain enough energy to move from the valence band to the conduction band.

- An electron in the conduction band acts as a charge carrier.
- The "hole" it leaves behind in the valence band (an empty state where an electron could exist) also acts as a charge carrier.

The number of these carriers depends on the material and its temperature. As temperature increases, more electrons acquire enough energy to cross into the conduction band.

Important clarification: When we say electrons move "from the valence band to the conduction band," this does **not** mean they change their physical position in the crystal. Instead, it means they change their **energy state**—from the energy associated with the valence band to that of the conduction band.

Doping

The electrical properties of semiconductors can be controlled by **doping**, which means adding small amounts of other elements to the crystal:

- If an atom with **one more valence electron** than the base material is added (for example, arsenic (As), which has 5 valence electrons, into silicon (Si), which has 4), the extra electron becomes available as a charge carrier. This creates an **n-type** semiconductor, where "donor" energy levels are introduced just below the conduction band.
- If an atom with **one fewer valence electron** is added (for example, gallium (Ga), with 3 valence electrons, into silicon), it creates a "hole" where an electron is missing. This produces a **p-type** semiconductor.

Resistor

When a voltage is applied across a resistor, it creates an **electric field** inside the material. This electric field "pushes" the charge carriers, giving them a **drift velocity** — a net motion in the direction from higher potential energy to lower potential energy.

As the voltage increases, the electric field becomes stronger, increasing the drift velocity. Since the electrical current is directly proportional to the drift velocity, this means that the current increases proportionally with voltage. This proportional relationship is expressed as **Ohm's Law**, which is the fundamental principle describing resistor behavior.

Diode

A diode behaves differently from a resistor because its current depends on overcoming an **energy barrier** at the junction between two differently doped semiconductor regions (the *p-n junction*).

The number of charge carriers able to cross the p-n junction depends on whether they have enough energy to “climb” this energy barrier. The size of the barrier depends on the amount and type of dopants in the semiconductor.

When a voltage is applied in the forward bias direction, this barrier is reduced, allowing more electrons to cross the junction. The number of electrons able to cross increases **exponentially** with the applied voltage, so the current increases exponentially with voltage as well.

Resistor I–V Characteristics

The simplest current–voltage (I–V) relationship can be observed with a resistor. According to Ohm’s Law, a resistor shows a linear relationship between the applied voltage and the resulting electric current. This means that if you increase the voltage, the current increases proportionally. Mathematically, Ohm’s Law is expressed as

$$V = IR,$$

where V is the voltage across the resistor, I is the current through it, and R is the resistance.

This equation describes a straight line when plotting V versus I, with a slope equal to the resistance R and a Y-intercept equal to zero. In other words, the slope of the line is $\frac{V}{I} = R$.

In real experimental conditions, the I–V curve may not be perfectly linear. Factors such as changes in temperature, mechanical stress, or the specific material properties of the resistor can cause slight deviations from ideal behavior, producing a small amount of curvature in the graph. These effects are important to recognize when interpreting measurements in the laboratory.

Diode I–V Characteristics

Before we can use a PN-junction as a practical device, such as a rectifier, we must first “bias” the junction — that is, apply an external voltage across it. On a voltage axis, the term “Reverse Bias” refers to applying a voltage that increases the potential barrier at the junction, while “Forward Bias” refers to applying a voltage that reduces the potential barrier.

There are three possible biasing conditions for a standard PN-junction diode:

- **Zero Bias** — No external voltage is applied to the PN-junction.
- **Reverse Bias** — The negative terminal of the voltage source is connected to the P-type material, and the positive terminal is connected to the N-type material. This increases the width of the depletion region.

- **Forward Bias** — The positive terminal of the voltage source is connected to the P-type material, and the negative terminal is connected to the N-type material. This decreases the width of the depletion region.

Zero Bias

In the Zero Bias condition, no external voltage is applied to the PN-junction. Despite this, there is a natural movement of charge carriers due to thermal energy.

In the P-type region, the majority carriers are *holes*. Some holes have enough energy to overcome the potential barrier and move across the junction — this produces a **Forward Current** (I_F). In the N-type region, electrons are the majority carriers, but *minority carriers* (holes) also exist. These minority carriers can move in the opposite direction across the junction, producing a **Reverse Current** (I_R).

At equilibrium, these two currents are equal in magnitude and opposite in direction, resulting in no net current flow through the diode. This state is called **Dynamic Equilibrium**.

Increasing the temperature increases the number of thermally generated carriers, slightly raising the leakage current even in Zero Bias conditions.

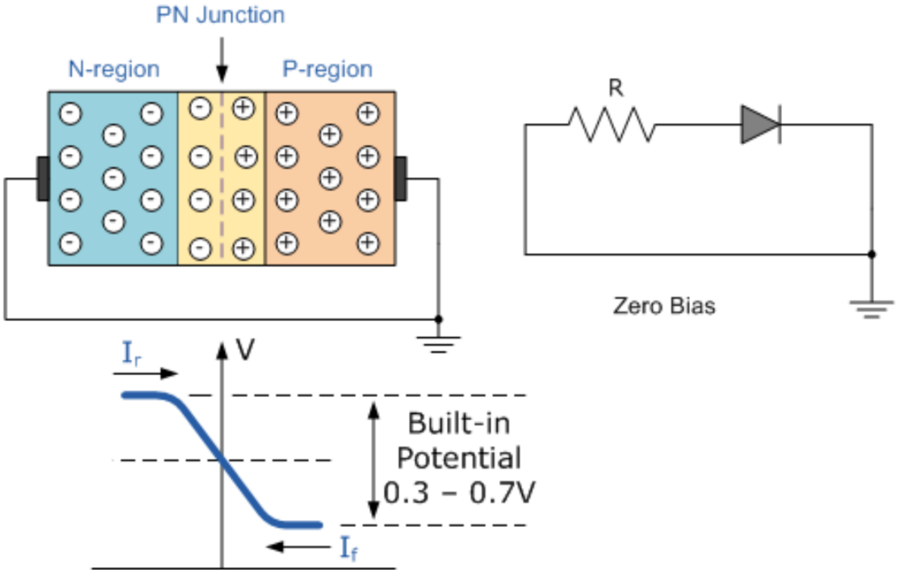


Figure 5.1: Zero Biased Junction

Reverse Bias

In Reverse Bias, the positive terminal of the voltage source is connected to the N-type material and the negative terminal to the P-type material. This configuration pushes electrons and holes away from the junction, widening the depletion region and increasing the potential barrier.

The depletion region acts like a high-resistance barrier, effectively preventing current flow. Only a small *leakage current* (often in the microampere range) remains due to minority carriers crossing the junction.

If the reverse bias voltage V_r becomes sufficiently large, the junction may break down due to the **avalanche effect**, generating excessive current and potentially damaging the diode.

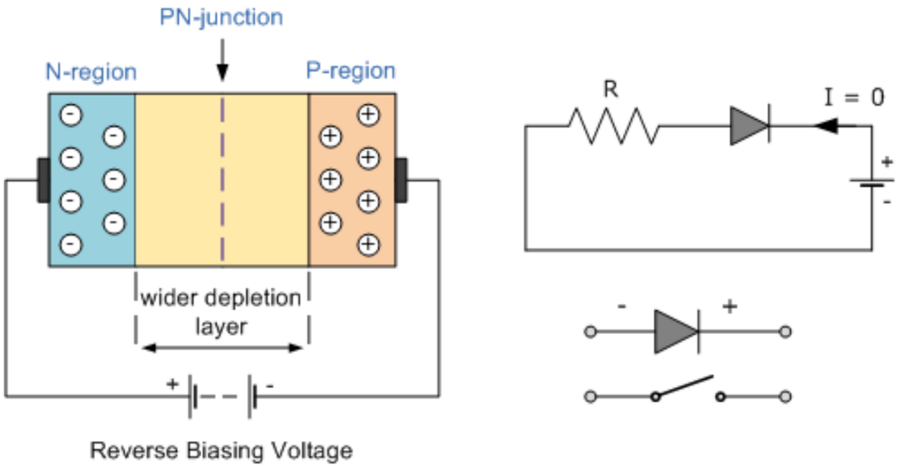


Figure 5.2: Reverse Biased Junction

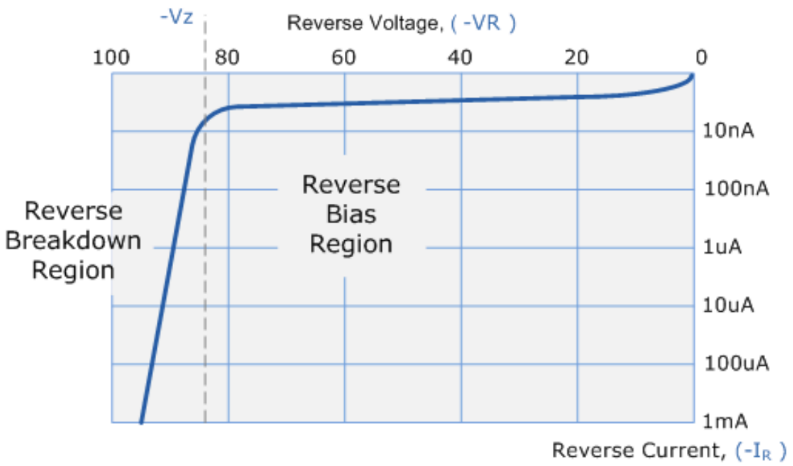


Figure 5.3: Reverse Characteristics Curve for a Diode

Forward Bias

In Forward Bias, the positive terminal of the voltage source is connected to the P-type material and the negative terminal to the N-type material. This pushes electrons and holes toward the junction, narrowing the depletion region and lowering the potential barrier.

When the applied voltage exceeds the **knee voltage** (about 0.7 V for silicon and 0.3 V for germanium), the barrier is overcome, allowing current to flow easily across the junction. The resulting current–voltage relationship is nonlinear: current remains very low until the knee voltage, then rises rapidly with increasing voltage.

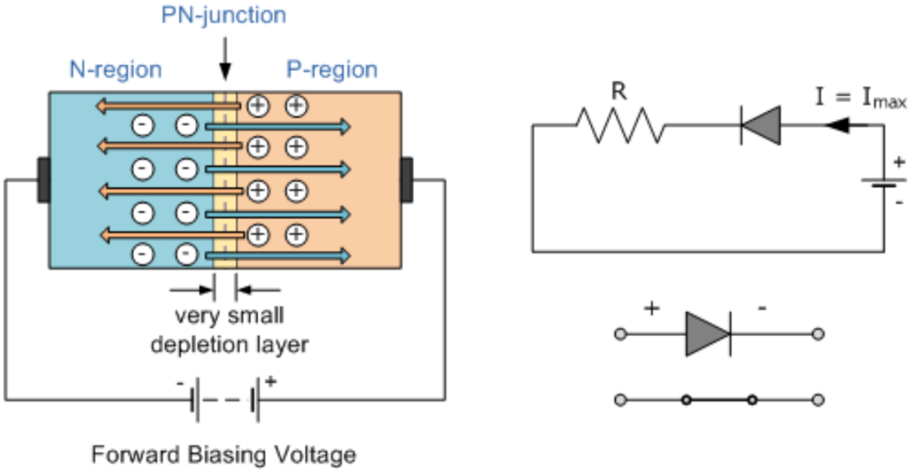


Figure 5.4: Forward Biased Junction

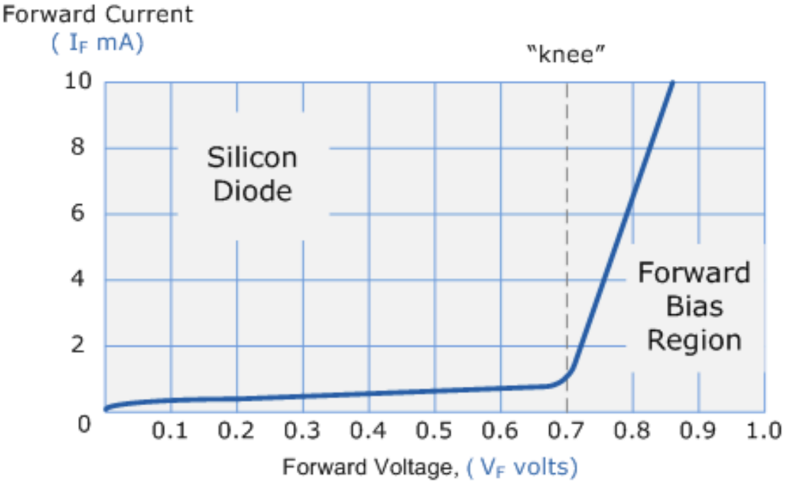


Figure 5.5: Forward Characteristics Curve for a Diode

References

- National Instruments, LabVIEW Bookshelf
- `http://matse1.matse.illinois.edu`
- `http://www.ustudy.in/node/2944`

Equipments

Function Generator, Diode, Resistors, multimeter

Instructions and Questions

1. Plot the voltage (horizontal axis) vs. the current (vertical axis) from the resistor and diode data.

2. What is the shape of the graph of the data for the resistor?

3. What is the shape of the graph of the data for the diode?

4. According to Ohm's Law, V/I represents what measurable quantity?

5. For the graph that is nonlinear, how did the values of V/I vary as the values of V increased?

6. Which device conducts electricity both directions?

7. Which device conducts electricity only in one direction?

8. Name the 2 types of charge carriers. In a metal, what conducts electricity (carries charge)? In a semiconductor, what carries charge?

9. In a resistor, increased voltage has what effect on the charge carriers?

10. In a diode, what changes to allow more current to flow as the voltage is increased?

Experiment 10

HALL EFFECT IN N- AND P-GERMANIUM

Purpose

This experiment investigates the electrical properties of n-doped and p-doped germanium by measuring the resistivity and Hall voltage as functions of magnetic field and temperature. These measurements allow determination of key semiconductor parameters, including the band gap E_g, the specific conductivity σ, the Hall constant R_H, carrier type, carrier mobility μ, and carrier concentration n (for electrons) or p (for holes). The results provide insight into charge transport in semiconductors and form the basis for understanding the operation of electronic devices.

Theory

When an electric current I flows through a thin rectangular conducting strip, and a magnetic field $\vec{B}$ is applied perpendicular to the current direction, a voltage appears across the strip in the direction transverse to both the current and the magnetic field. This transverse voltage is known as the *Hall voltage*.

The origin of the Hall effect lies in the Lorentz force. Any moving charge carrier (such as an electron or hole) with velocity $\vec{v}$ in a magnetic field experiences a force given by

$$\vec{F} = q\,(\vec{v} \times \vec{B}),$$

where q is the charge of the carrier. The cross product means that the force is always perpendicular to both $\vec{v}$ and $\vec{B}$.

Because of this deflection, charge carriers accumulate on one side of the strip, creating an electric potential difference between the two sides. The sign of this voltage depends on whether the charge carriers are positive (holes) or negative (electrons).

Thus, by measuring the polarity of the Hall voltage, and knowing the directions of the current and the magnetic field, one can determine the type of charge carrier that dominates conduction in the sample:

- A negative Hall voltage indicates conduction primarily by electrons.
- A positive Hall voltage indicates conduction primarily by holes.

This makes the Hall effect a fundamental experimental tool to probe the nature of charge transport in materials.

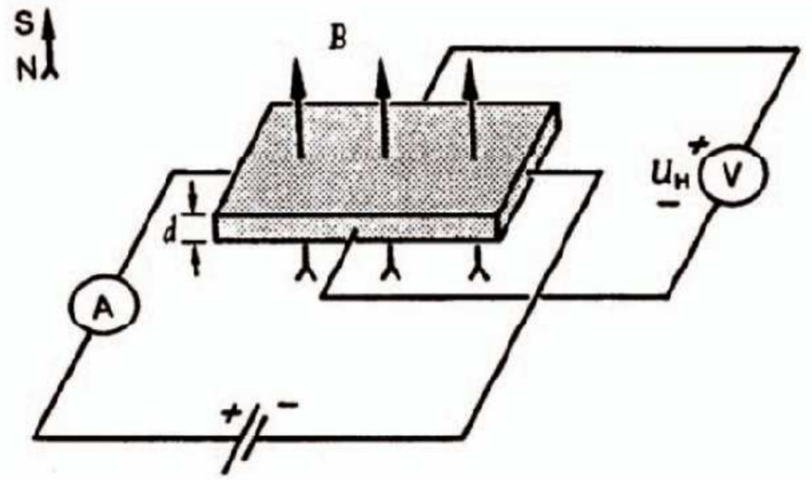


Figure 5.1: Hall effect on a rectangular specimen. The polarity of the Hall voltage indicated is for negative charge carriers.

Equipment

1. PHYWE Hall-effect unit HU 2 (11801-01)
2. Software `measureLAB`
3. Hall-effect carrier boards (n-Ge, p-Ge)
4. Coils, iron core, pole pieces, Hall probe
5. Power supply, tripod, support rod, clamps, connecting cords

Experimental Setup

The experimental setup is shown in Fig. 5.2. The test specimen is inserted into the Hall-effect module using the guide groove. The module is connected to the power unit through the AC input located on the back side of the module.

When positioning the sample, carefully bring the plate close to the magnet. Avoid applying force or bending the plate, as this may damage the crystal. The sample must be aligned at the center between the pole pieces of the magnet.

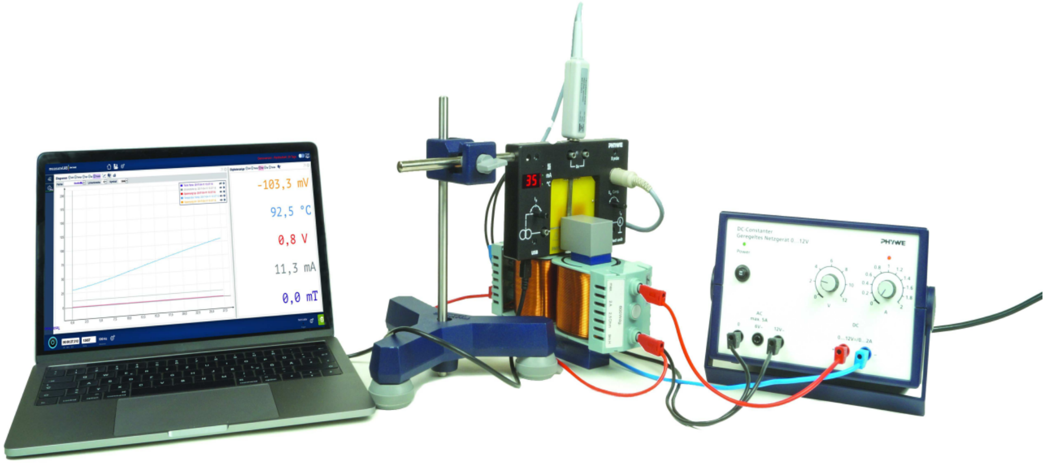


Figure 5.2: Experimental setup.

The module is connected to the computer via the USB port located on its underside. Use a standard USB cable to establish the connection. All measurements are controlled by the software *measureLAB*.

The magnetic field is measured using a Hall probe. The probe connects to the module via the port on the front side. It can be directly inserted into the groove on top of the module, ensuring that the magnetic flux is measured precisely at the position of the test specimen.

To begin measurements, launch the software *measureLAB* and select the “Quick start” option from the main menu. A start screen will appear, prompting you to choose which parameters should be recorded and displayed. For example, you may select the sample voltage as a function of temperature. Confirm your selection by clicking *OK*.

After this step, the measurement screen will appear. Start the measurement by clicking the blue button located in the lower-right corner of the screen. The results will be displayed in two ways: graphically in the “Diagram” window and numerically in the “Digital display” window.

Task 1

The Hall voltage U_H is measured at room temperature and constant magnetic field as a function of the control current I_p.

Choose the Hall voltage U_H, the current I_p and the magnetic field ”Tesla” as measurement parameters from the start screen, and click ”Ok”. Set the current I_p and the magnetic field to zero and calibrate the Hall voltage U_H to zero. Now, set the magnetic field to a value of 250 mT by changing the voltage and current on the power supply. Determine the Hall voltage U_H as a function of the current I_p from -30 mA to 30 mA in steps of 5 mA. You will receive a typical measurement like in Fig. 5.3 (a) and (b) for n- and p-Germanium, respectively.

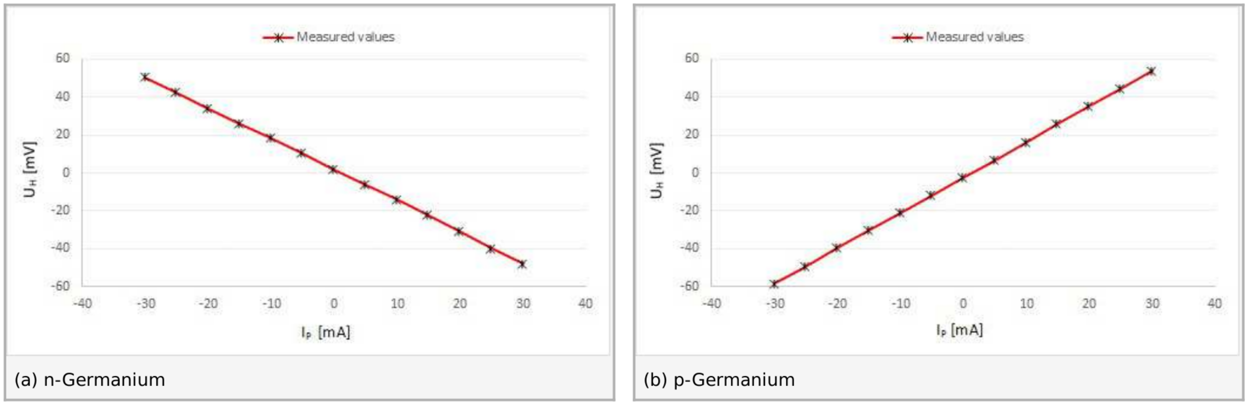
Evaluation

Fig. 5.3 shows that, for both n-Germanium and p-Germanium, there is a linear relationship between the Hall voltage U_H and the control current I:

$$U_H \propto kI,$$

where k is the proportionality factor.

Since the charge carriers in n- and p-Germanium are different, the trend of the linear relationship between U_H and I is reversed, as shown in Fig. 5.3 (a) and (b).



(a) n-Germanium

(b) p-Germanium

Figure 5.3: Hall voltage U_H as a function of the current I with B and T. (a) n-Germanium (b) p-Germanium.

Task 2

The voltage across the sample U_p is measured at room temperature and constant control current as a function of the magnetic induction B.

Choose the sample voltage U_p, the current I_p and the magnetic field ”Tesla” as measurement parameters from the start screen, and click ”Ok”. Set the control current I_p to 30 mA. Determine the sample voltage U_p as a function of the positive magnetic induction B up to 300 mT. Calculate the change in resistance of the specimens from the measurements and plot the results on graphs as shown in Fig. 5.4.

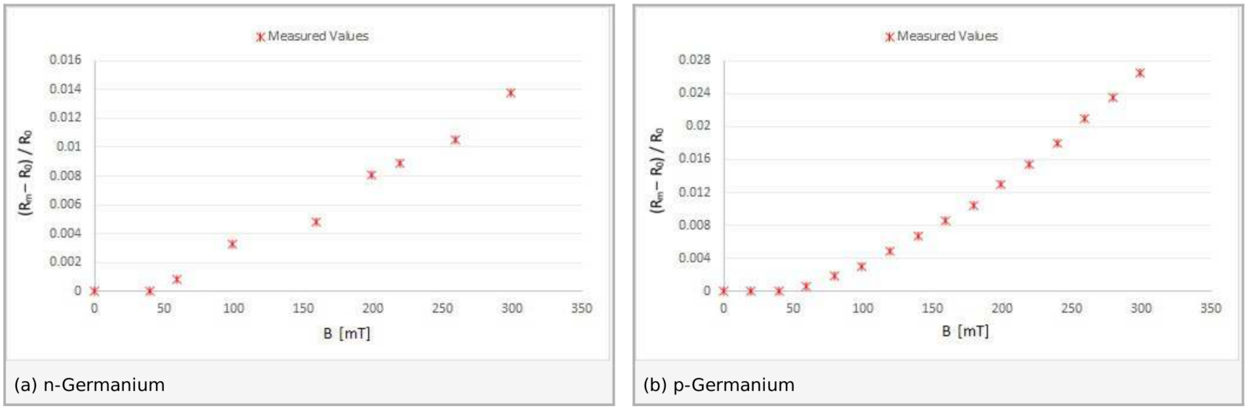
Evaluation

The change in resistance of the sample due to the magnetic field B is associated with a reduction in the mean free path of the charge carriers. Since the current I_p is constant during the measurement, the change of resistance is calculated as

$$\frac{R_m - R_0}{R_0} = \frac{U_m - U_0}{U_0},$$

where R_m and U_m are resistance and voltage of the sample with the existence of a magnetic field and R_0 and U_0 are the resistance and voltage of the sample when the magnetic field $B = 0$.

Fig. 5.4 (a) and (b) show the non-linear change in resistance as the field strength increases for n- and p-Germanium, respectively.



(a) n-Germanium

(b) p-Germanium

Figure 5.4: Change of resistance as a function of the magnetic flux B with I and T. (a) n-Germanium (b) p-Germanium.

Task 3

The voltage across the sample U_p is measured at constant control current as a function of the temperature T. The band spacing of p- and n-germanium is calculated from the measurements.

Choose the sample voltage U_p, the current I_p and the temperature "Temp" as measurement parameters from the start screen, and click "Ok". At the beginning, set the current I_p to a value of 30 mA. The magnetic field is off. The current I_p remains nearly constant during the measurement, but the voltage U_p changes according to a change in temperature T. Start the measurement by activating the heating coil with the "on/off"-knob on the backside of the module. The specimen will be heated to a maximum temperature of around 145 – 150 °C and the module will stop the heating automatically. Determine the cooling curve of the change in voltage U_p depending on the change in temperature T for a temperature range from 140 °C to room temperature. You will get typical curves as shown in Fig. 5.5.

Evaluation

In the region of intrinsic conductivity, we have

$$\sigma = \sigma_0 \exp\left(-\frac{E_g}{2k_B T}\right), \tag{5.1}$$

where σ is conductivity, E_g is energy of bandgap, k_B is Boltzmann constant, and T is absolute temperature.

By taking the logarithm of both sides of the above equation, we get

$$\ln\sigma = \ln\sigma_0 - \frac{E_g}{2k_B}\cdot\frac{1}{T}.$$

If the logarithm of the conductivity $\ln\sigma$ is plotted against the reciprocal of the temperature $1/T$, a linear relationship is obtained with a slope $E_g/(2k_B)$ from which E_g can be determined. From the measured values shown in Fig. 5.5, the slopes of the regression lines are

$b = -\frac{E_g}{2k_B} = -2.87 \times 10^3$ K with a standard deviation $s_b = \pm 0.3 \times 10^3$ K for n-Germanium, and

$b = -\frac{E_g}{2k_B} = -4.18 \times 10^3$ K with a standard deviation $s_b = \pm 0.07 \times 10^3$ K for p-Germanium.

Since $k_B = 8.625 \times 10^{-5}$ eV/K, we get

$E_g = b \cdot 2k_B = 0.50 \pm 0.04$ eV for n-Germanium, and

$E_g = b \cdot 2k_B = 0.72 \pm 0.03$ eV for p-Germanium.

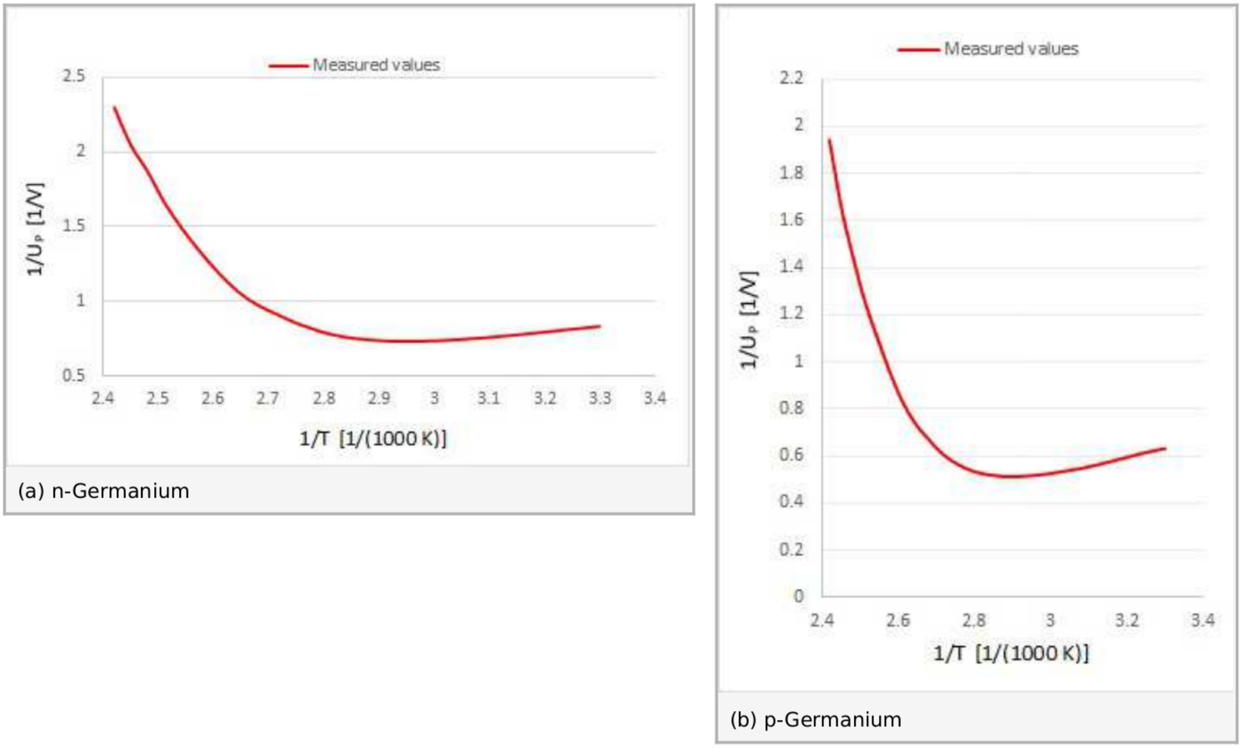


Figure 5.5: Reciprocal sample voltage $1/U$ plotted as a function of reciprocal absolute temperature $1/T$ with I and no magnetic flux. (a) n-Germanium (b) p-Germanium.

Task 4

The Hall voltage U_H is measured as a function of the magnetic induction B, at room temperature. The sign of the charge carriers and the Hall constant R_H together with the Hall mobility μ_H and the carrier concentration p are calculated from the measurements.

Choose the Hall voltage U_H, the current I_p and the magnetic field ”Tesla” as measurement parameters from the start screen, and click ”Ok”. Set the current I_p and the magnetic field to values of zero and calibrate the Hall voltage U_H to zero. Now, set the current to a value of 30 mA. Determine the Hall voltage U_H as a function of the magnetic induction B. Start with -300 mT by changing the polarity of the coil-current on the power supply and increase the magnetic induction in steps of nearly 20 mT. At zero point, you have to change the polarity again. A typical measurement is shown in Fig. 5.6.

Evaluation

With the directions of control current and magnetic field shown in Fig. 5.1, the charge carriers giving rise to the current in the sample are deflected towards the front edge of the sample. Therefore, if (in an n-doped probe) electrons are the predominant charge carriers, the front edge will become negative, and, with hole conduction in a p-doped sample, positive.

The conductivity σ_0, the charge-carrier mobility μ_H, and the charge carrier concentration p are related through the Hall constant R_H:

$$R_H = \frac{U_H}{B} \cdot \frac{d}{I} \qquad \mu_H = R_H \cdot \sigma_0, \qquad p = \frac{1}{e} \cdot R_H,$$

Fig. 5.6 shows a linear connection between Hall voltage U_H and magnetic field B. With the values used in Fig. 5.6, the regression line with the formula

$$U_H = U_0 + b \cdot B$$

has a slope $b = 0.144$ VT^{-1} with a standard deviation $s_b = \pm 0.004$ VT^{-1} for p-Germanium, and $b = 0.125$ VT^{-1} with a standard deviation $s_b = \pm 0.003$ VT^{-1} for p-Germanium.

The Hall constant R_H thus becomes, according to

$$R_H = \frac{U_H}{B} \cdot \frac{d}{I} = b \cdot \frac{d}{I},$$

where the sample thickness $d = 10^{-3}$ m and $I = 0.030$ A,

$$R_H = 4.8 \cdot 10^{-3} \frac{\mathrm{m}^3}{\mathrm{As}},$$

with the standard deviation $S_{R_H} = 0.2 \cdot 10^{-3} \frac{\mathrm{m}^3}{\mathrm{As}}$ for n-Germanium, and

$$R_H = 4.17 \cdot 10^{-3} \frac{\mathrm{m}^3}{\mathrm{As}},$$

with the standard deviation $S_{R_H} = 0.08 \cdot 10^{-3} \frac{\mathrm{m}^3}{\mathrm{As}}$ for p-Germanium.

The conductivity at room temperature is calculated from the sample length l, the sample cross-section A and the sample resistance R as follows:

$$\sigma = \frac{l}{AR}.$$

With the measured values $l = 0.02$ m, $R = 37.3\ \Omega$ for n-Ge, $R = 35.5\ \Omega$ for p-Ge, $A = 10^{-5}$ m^2, we have $\sigma_0 = 53.6\ \Omega^{-1} \cdot \mathrm{m}^{-1}$ for n-Germanium, and $\sigma_0 = 57.14\ \Omega^{-1} \cdot \mathrm{m}^{-1}$ for p-Germanium.

The Hall mobility μ_H of the charge carriers can now be determined from

$$\mu_H = R_H \cdot \sigma.$$

Using the measurements given above, we get $\mu_H = 0.257 \pm 0.005$ m^2/Vs for n-Germanium, and $\mu_H = 0.238 \pm 0.005$ m^2/Vs for p-Germanium.

The hole concentration p of p-doped sample is calculated from

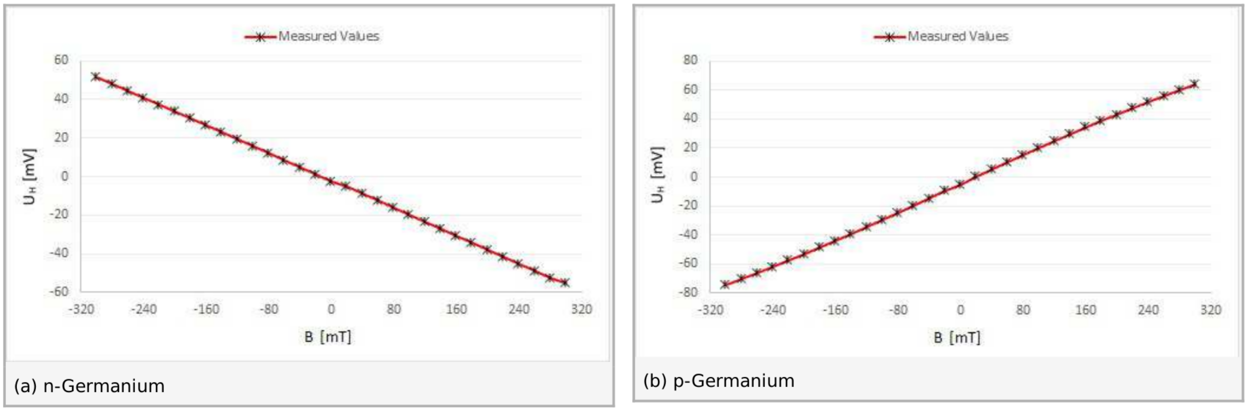
$$p = \frac{1}{eR_H}.$$

Using the value of the elementary charge $e = 1.602 \times 10^{-19}\,\mathrm{As}$ we obtain $p = 14.9 \cdot 10^{20}\,\mathrm{m}^{-3}$.

The electron concentration n of n-doped specimen is given by

$$n = \frac{1}{eR_H}.$$

Taking $e = 1.602 \times 10^{-19}\,\mathrm{As}$, we obtain $n = 13.0 \cdot 10^{20}\,\mathrm{m}^{-3}$.



(a) n-Germanium

(b) p-Germanium

Figure 5.6: Hall voltage U_H as a function of magnetic flux B with I and T. (a) n-Germanium (b) p-Germanium.

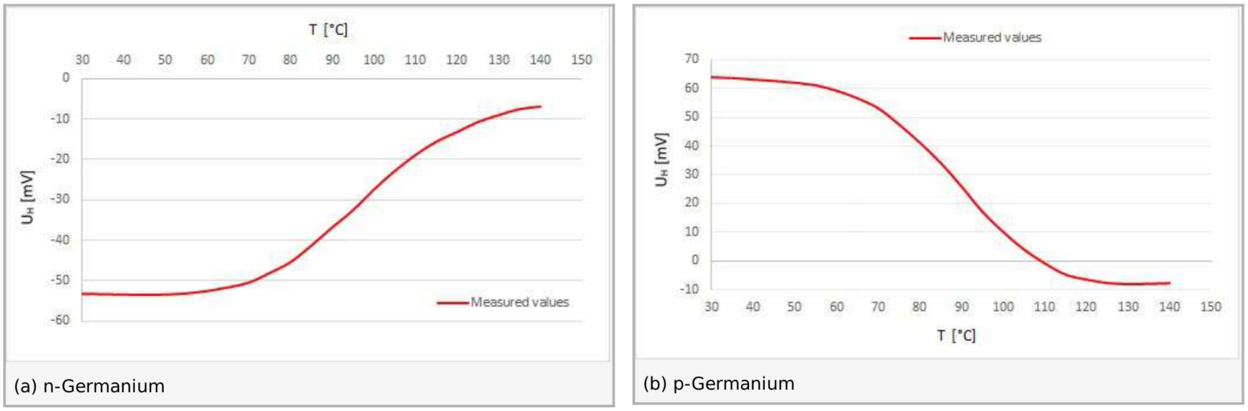
Task 5

The Hall voltage U_H is measured as a function of temperature T at constant magnetic induction.

Choose the Hall voltage U_H, the current I_p, the temperature "Temp" and the magnetic field "Tesla" as measurement parameters from the start screen, and click "Ok". Set the current I_p to 30 mA and the magnetic induction B to 300 mT. Following the same procedure in task 3 above, determine the Hall voltage U_H as a function of the temperature T. You will receive curves like those in Fig. 5.7.

Evaluation

Fig. 5.7 shows that the Hall voltage decreases with increasing temperature for both n- and p-Germanium. Since the experiment was performed with a constant current, it can be assumed that the increase of charge carriers (transition from extrinsic to intrinsic conduction) with the associated reduction of the drift velocity v is responsible for this. (The same current for a higher number of charge carriers means a lower drift velocity). The drift velocity is in turn related to the Hall voltage by the Lorentz force.



(a) n-Germanium

(b) p-Germanium

Figure 5.7: Hall voltage U_H as a function of the temperature T with I and B. (a) n-Germanium (b) p-Germanium.

Acknowledgment

This document has been prepared using information from the PHYWE student sheet (P2530116), with certain sections either directly quoted or modified for clarity.