HALL-EFFECT IN SEMICONDUCTORS

EXPERIMENT PROCEDURE

- **Demonstrating the Hall effect in doped germanium.**
- **Measuring the Hall voltage as a function of the current and magnetic field at room temperature.**
- **Determining the sign, density and mobility of charge carriers at room temperature.**
- **Measuring the Hall voltage as a function of sample temperature.**
- **Determining the inversion temperature; differentiating between extrinsic and intrinsic conduction in the case of p-doped germanium.**

NOTE

The temperature dependence of the electrical conductivity of the employed germanium crystals is investigated in experiment UE6020100.

OBJECTIVE

Investigating electrical conduction mechanisms in doped germanium with the Hall effect.

SUMMARY

The Hall effect occurs in electrically conductive materials located in a magnetic field *B*. The Hall voltage's sign changes depending on whether the same current *I* is borne by positive or negative charge carriers. Its value depends on the charge carrier density. The Hall effect is consequently an important means of determining the mechanisms of charge transport in doped semiconductors. In this experiment, doped germanium crystals are examined at temperatures between 300 K and 450 K to ascertain the differences between electrical conduction enabled by doping, and intrinsic conduction enabled by thermal activation of electrons causing their transfer from the valence band into the conduction band.

REQUIRED APPARATUS

Quantity	Product	Number	
1	Hall Effect Basic Apparatus	1009934	
1	N-Doped Germanium on Printed Circuit Board	1009760	
1	P-Doped Germanium on Printed Circuit Board	1009810	
1	Magnetic Field Sensor ±2000 mT	1009941	
1	Coil D with 600 Taps	1000988	
1	U Core	1000979	
1	Pair of Pole Shoes and Clamping Brackets for Hall Effect	1009935	
1	Transformer with Rectifier 3/ 6/ 9/ 12 V, 3 A (230 V, 50/60 Hz)	1003316	or
	Transformer with Rectifier 3/ 6/ 9/ 12 V, 3 A (115 V, 50/60 Hz)	1003315	
1	DC Power Supply 0 – 20 V, 0 – 5 A (230 V, 50/60 Hz)	1003312	or
	DC Power Supply 0 – 20 V, 0 – 5 A (115 V, 50/60 Hz)	1003311	
1	Digital Multimeter P3340	1002785	
1	3B NET*log*™ (230 V, 50/60 Hz)	1000540	or
	3B NET*log*™ (115 V, 50/60 Hz)	1000539	
1	Set of 15 Safety Experiment Leads, 75 cm	1002843	
Additionally recommended			
1	3B NET*lab*™	1000544	

BASIC PRINCIPLES

The Hall effect occurs in electrically conductive materials located in a magnetic field *B*. This effect is attributable to the Lorentz force which deflects the charge carriers producing an electric current *I* through a material sample perpendicularly with respect to the magnetic field and the current's direction. Charge separation results in an electric field E_H which is perpendicular to the current's direction and compensates the Lorentz force, while generating a Hall voltage U_H between the sample's edges. The Hall voltage's sign changes depending on whether the same current *I* is borne by positive or negative charge carriers. Its value depends on the charge carrier density. The Hall effect is consequently an important means of determining the mechanisms of charge transport in conductive materials, and used often to study doped semiconductors.

This experiment examines doped germanium crystals at temperatures between 300 K and 450 K. The crystals are present in the form of flat samples which have a length *a*, width *b* and thickness *d*, and which longitudinally conduct a current *I*. The magnetic field *B* pervades each sample perpendicularly with respect to the current. The resultant Hall voltage is:

(1)
$$U_H = R_H \cdot \frac{B \cdot I}{d}.$$

The Hall coefficient is:

(2)
$$R_H = \frac{1}{e} \cdot \frac{n_p \cdot \mu_p^2 - n_n \cdot \mu_n^2}{\left(n_p \cdot \mu_p + n_n \cdot \mu_n\right)^2}$$

e = 1.602 10-19 ampere-second (elementary charge)

The densities n_n and n_p respectively of the electrons in the conduction band and electron holes in the valence band, as well as the mobilities μ_n and μ_p respectively of the electrons and corresponding holes are material quantities which depend on the sample temperature *T*.

Measured besides the Hall voltage in the experiment is the longitudinal voltage drop *U* in the sample in order to determine the electrical conductivity:

(3)
$$\sigma = e \cdot \left(n_n \cdot \mu_n + n_p \cdot \mu_p\right)$$

Also determined in this process is the Hall mobility:

(4)
$$\mu_H = R_H \cdot \sigma = \frac{n_p \cdot \mu_p^2 - n_n \cdot \mu_n^2}{n_p \cdot \mu_p + n_n \cdot \mu_n}.$$

The charge carrier densities n_n and n_p are influenced by the doping, i.e. inclusion of foreign atoms in the crystal. In the case of p-doping, acceptor atoms bind electrons from the valence band and thereby produce electron holes in that band. In the case of n-doping, donor atoms each supply one electron to the conduction band.

The doped crystals are electrically neutral, i.e. their negative and positive charges cancel each other out. Accordingly:

(5)
$$n_n + n_A = n_p + n_D$$

n_A: Concentration of acceptors

n_D: Concentration of donors

Furthermore, n_n and n_p are coupled by a mass action law, the number of electron-hole pairs which form and recombine per unit of time being equal during temperature-dependent equilibrium. The following applies:

(6)
$$n_n \cdot n_p = n_i^2$$

n_i is the charge carrier density in the case of purely intrinsic conduction (see experiment UE6020100)

In general, therefore:

(7)
$$n_n = \sqrt{n_i^2 + \frac{\left(n_A - n_D\right)^2}{4}} + \frac{n_D - n_A}{2},$$

(8)
$$n_p = \sqrt{n_i^2 + \frac{\left(n_A - n_D\right)^2}{4}} + \frac{n_A - n_D}{2}.$$

At room temperature, the concentrations n_A and n_D are significantly higher than the charge carrier density in the case of purely intrinsic conduction n_i. Consequently:

(9)
$$R_H = -\frac{1}{n_D \cdot e}, \ \mu_H = -\mu_n$$

with n-doping at 300 K

(10)
$$R_H = \frac{1}{n_A \cdot e}, \ \mu_H = \mu_p$$

with p-doping at 300 K.

The charge carriers' sign and density can therefore be read directly from the Hall coefficient. The charge carriers' mobility is equivalent to the Hall mobility.

EVALUATION

As more carriers become available for conducting electricity with increasing temperature, the Hall voltage decreases until it attains a value of zero.

In the case of p-doped germanium, the Hall voltage's sign changes because increasing intrinsic conduction leads to a dominant influence of the electrons whose mobility μ_n is higher. Electrical conduction enabled by doping dominates below the inversion temperature, while intrinsic conduction dominates above the inversion temperature.

At high temperatures, the n-doped and p-doped crystals are no longer distinguishable because:

$$n_n = n_p = \mathrm{ni}, \ R_H = -\frac{1}{n_i \cdot e} \cdot \frac{\mu_n - \mu_p}{\mu_n + \mu_p}, \ \mu_H = -\left(\mu_n - \mu_p\right)$$

The temperature dependence of the mobilities μ_n and μ_p is not evident in the Hall coefficient, because in both cases:

$$\mu \sim T^{-\frac{3}{2}}$$ (also see experiment UE6020100)

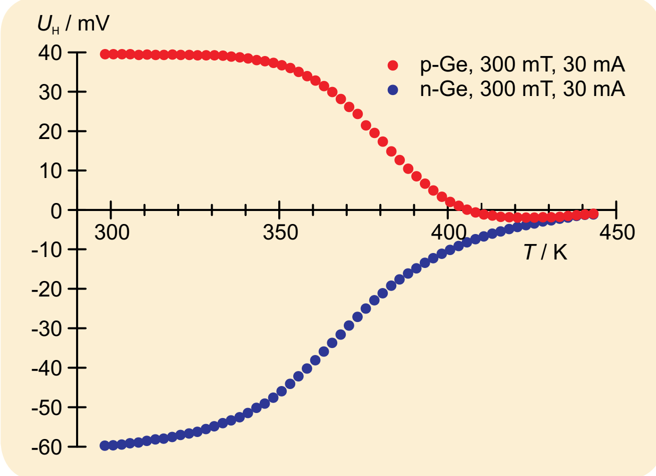

Fig. 1: Hall voltage in *p*- and n-doped germanium as a function of the temperature *T*.