Hall effect in n- and p-germanium (Teslameter)

Physics | Modern Physics | Solid state physics

Difficulty level	Group size	Preparation time	Execution time
hard	2	45+ minutes	45+ minutes

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http://localhost:1337/c/600a904a6080870003ab8afb

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General information

Application

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Fig. 1: Experimental set-up

The Hall effect is widely used everywhere where magnetic fields appear in solid matter. One especially importent application is its use in semiconductor detectors.

This experiment offers the opportunity to gain a first understanding about the Hall effect.

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Other information (1/3)

Prior knowledge

The prior knowledge for this experiment is found in the Theory section.

Main principle

The resistivity and Hall voltage of a rectangular germanium sample are measured as a function of temperature and magnetic field. The band spacing, the specific conductivity, the type of charge carrier and the mobility of the charge carriers are determined from the measurements.

Other information (2/3)

Learning objective

The goal of this experiment is to investigate the Hall effect in n- and p-germanium.

Tasks

The following tasks are performed with n-doped and p-doped specimens.

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

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Other information (3/3)

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Tasks

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

Theory (1/2)

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If a current I fows through a conducting strip of rectangular section and if the strip is traversed by a magnetic field at right angles to the direction of the current, a voltage – the so-called Hall voltage – is produced between two superposed points on opposite sides of the strip.

This phenomenon arises from the Lorentz force: the charge carriers giving rise to the current flowing through the sample are deflected in the magnetic field B as a function of their sign and their velocity v:

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

where F is the force acting on charge carriers and e is elementary charge.

Since negative and positive charge carriers in semiconductors move in opposite directions, they are deflected also in opposite directions.

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Theory (2/2)

The type of charge carrier causing the flow of current can, therefore, be determined from the polarity of the Hall voltage, knowing the direction of the current and that of the magnetic field. That means: if the direction of the current and magnetic field are known, the polarity of the Hall voltage tells us, whether the current is predominantly due to the drift of negative chrgers or to the drift of positive chargers.

$Z=R+i(\omega L-1\omega C)$

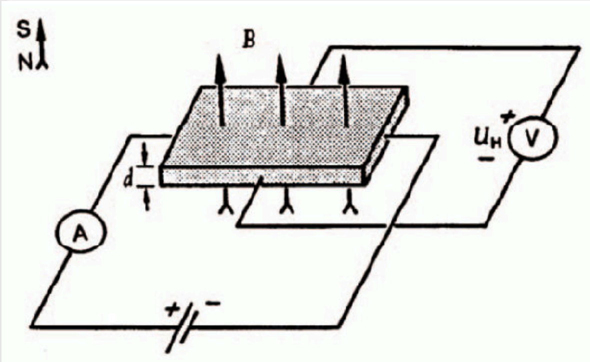

Fig. 2: Hall effect on a rectangular specimen. The polarity of the Hall voltage indicated is for negative charge carriers.

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Equipment

Position	Material	Item No.	Quantity
1	PHYWE Hall-effect unit HU 2	11801-01	1
2	Hall effect, p-Ge, carrier board	11805-01	1
3	Hall effect, n-Ge, carrier board	11802-01	1
4	PHYWE Teslameter, digital	13610-93	1
5	Hall probe, tangential, protection cap	13610-02	1
6	PHYWE Power supply, 230 V, DC: 0...12 V, 2 A / AC: 6 V, 12 V, 5 A	13506-93	1
7	Digital multimeter, 600V AC/DC, 10A AC/DC, 20 MΩ, 200 µF, 20 kHz, −20°C… 760°C	07122-00	1
8	Coil, 600 turns	06514-01	2
9	Iron core, U-shaped, laminated	06501-00	1
10	Pair of pole pieces, plane, 30 x 30 x 48 mm	06489-00	1
11	Tripod base PHYWE	02002-55	1
12	Right angle clamp expert	02054-00	1
13	Support rod, stainless steel, l = 250 mm, d = 10 mm	02031-00	1
14	Connecting cord, 32 A, 500 mm, red	07361-01	3
15	Connecting cord, 32 A, 500 mm, blue	07361-04	2
16	Connecting cord, 32 A, 750 mm, black	07362-05	2

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Setup and Procedure

Setup

The experimental set-up is shown in Fig.1. The test specimen has to be put into the hall-effect-module via the guide-groove. The module is directly connected with the 12 V ~ output of the power unit over the ac-input on the backside of the module.

The plate has to be brought up to the magnet very carefully, so as not to damage the crystal in particular, avoid bending the plate. It has to be in the centre between the pole pieces.

The Hall voltage and the voltage across the sample are measured with a multimeter. Therefore, the sockets on the front-side of the module are used. The current and temperature can be easily read on the integrated display of the module.

The magnetic field has to be measured with the teslameter via a Hall probe, which can be directly put into the groove in the module as shown in Fig. 1. So, you can be sure that the magnetic flux is measured directly on the Ge-sample.

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Procedure (1/3)

- Connect the multimeter to the sockets of the Hall voltage U_H on the front-side of the module. Set the display on the module into the "current-mode". Set the current I_P to zero and calibrate the Hall voltage U_H. 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. 3 (a) and (b) for n- and p-Germanium, respectively.
- Connect the multimeter to the sockets of the sample voltage U_P on the front-side of the module. 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. 4.

Procedure (2/3)

- 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 changes U_P according to a change in temperature T. Set the display in the temperature mode and be sure, that the display works in the temperature mode during the measurement. 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 $145-150\ ^\circ$Cand 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. plot the results as $\frac{1}{U_p}\ [\frac{1}{\mathrm{V}}]$ vs. $\frac{1000}{T+273}\ [\frac{1}{1000\,\mathrm{K}}]$ and you will get typical curves as shown in Fig. 5.

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Procedure (3/3)

- Connect the multimeter to the sockets of the Hall voltage U_H on the front-side of the module. Set the current I_P to a value of zero and calibrate the Hall voltage U_H .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. 6.
- Set the current I_P to 30 mA and the magnetic induction B to 300 mT. Set the display in the temperature mode and be sure, that the display works in the temperature mode during the measurement. 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. 7.

Evaluation

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Task 1 (1/2)

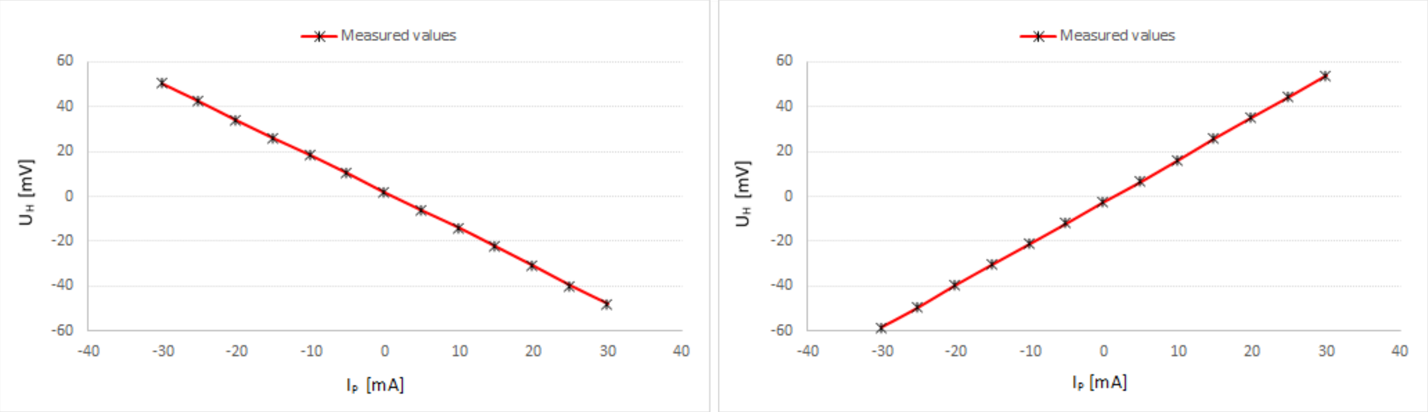
Fig. 3 shows that, for both n-Germanium and p-Germanium, there is a linear relationship between the Hall voltage U_H and the control current I_P:

$$U_H = \alpha \cdot I_p$$

where α 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_P is reversed, as shown in Fig. 3 (a) and (b).

Task 1 (2/2)



(a) n-Germanium (b) p-Germanium

Fig. 3: Hall voltage U_H as a function of the current I_P with B = 250 mT and T = 300 K.

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Task 2 (1/2)

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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, U_m are resistance and voltage of the sample with the existence of a magentic field and R_0, U_0 are the resistance and voltage of the sample when the magnetic filed B = 0.

Figs. 4 (a) and (b) show the non-linear change in resistance as the field strength increases for n- and p-Germanium, respectively.

Task 2 (2/2)

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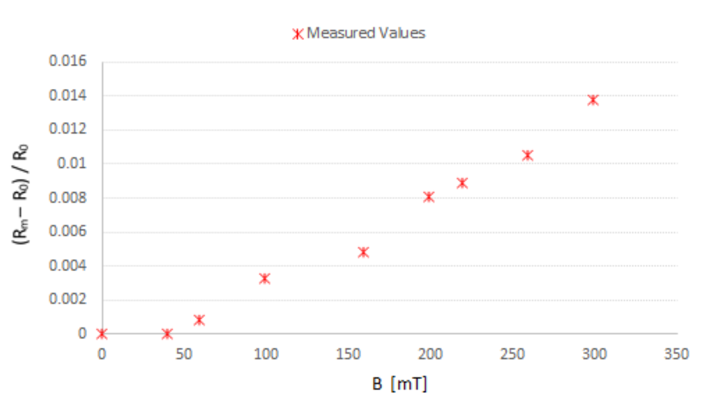
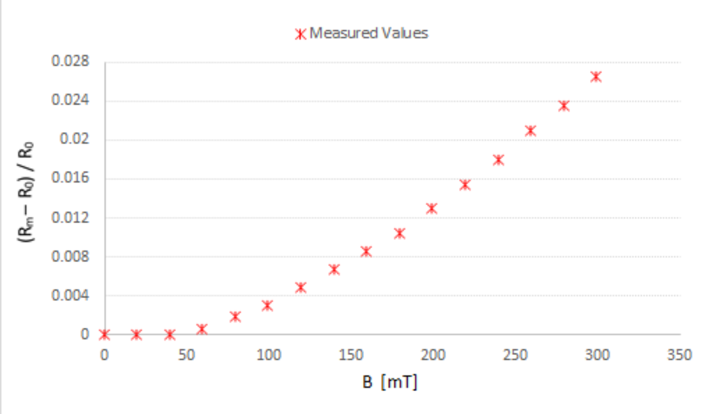


(a) n-Germanium



(b) p-Germanium

Fig. 4: Change of resistance as a function of the magnetic flux B with I_P = 30 mA and T = 300 K.

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Task 3 (1/3)

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In the region of intrinsic conductivity, we have

$$\sigma = \sigma_0 \cdot \exp\left(\frac{E_g}{2kT}\right)$$

where σ = conductivity, E_g = energy of bandgap, k = Boltzmann constant, T = absolute temperature. By taking the logarithm of both sides of the above equation, we get

$$\ln \sigma = \ln \sigma_0 + \frac{E_g}{2k} \cdot T^{-1}$$

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 from which E_g can be determined.

Task 3 (2/3)

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From the measured values shown in Fig. 5, the slopes of the regression lines are

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

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

Since

$k = 8.625 \cdot 10^{-5}\ \frac{\mathrm{eV}}{\mathrm{K}}$, we get $E_g = b \cdot 2k = (0.50 \pm 0.04)\ \mathrm{eV}$ for n-Germanium, and

$E_g = b \cdot 2k = (0.72 \pm 0.03)\ \mathrm{eV}.$ for p-Germanium.

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Task 3 (3/3)

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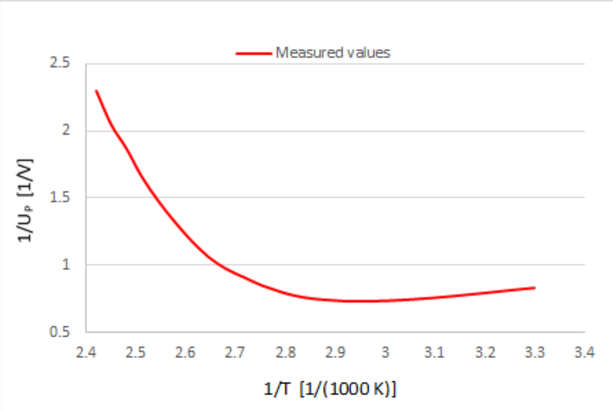

(a) n-Germanium

(b) p-Germanium

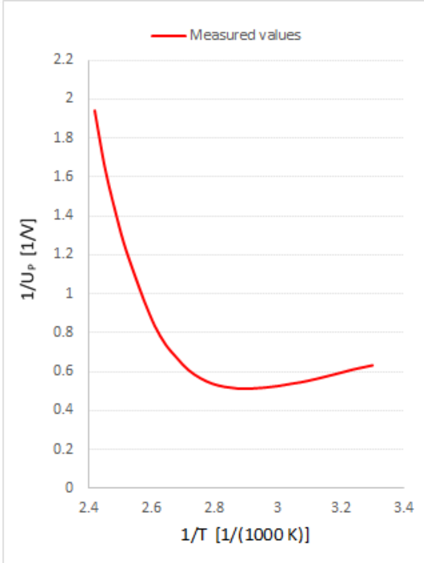

Fig. 5: Reciprocal sample voltage $1/U_P$ plotted as a function of reciprocal absolute temperature 1/T with I_P = 30 mA and no magnetic flux.

Task 4 (1/5)

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With the directions of control current and magnetic field shown in Fig. 2, 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 chargecarrier mobility μ_H, and the charge carrier concentration p are related through the Hall constantR_H:

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

$$\mu_H = R_H \cdot \sigma_0$$

$$p = \frac{1}{e} \cdot R_H$$

Fig. 6 shows a linear connection between Hall voltage U_H and magnetic field B. With the values used in Fig. 6, the regression line with the formula

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Task 4 (2/5)

$U_H = U_0 + b \cdot B$

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

The Hall constant RH thus becomes, according to

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

where the sample thickness $d = 1 \cdot 10^{-3}\,\mathrm{m}$ and I = 30 mA.

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

with the standard deviation

$S_{RH} = 0.2 \cdot 10^{-3}\,\frac{\mathrm{m}^3}{\mathrm{As}}$ for n-Germanium, and

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

with the standard deviation

$S_{RH} = 0.08 \cdot 10^{-3}\,\frac{\mathrm{m}^3}{\mathrm{As}}$ for p-Germanium

Task 4 (3/5)

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

$\sigma_0 = \frac{l}{R \cdot A}$

With the measured values

$l = 0.02\,\mathrm{m}$, $R = 37.3\,\Omega$for n-Ge, $R = 35.5\,\Omega$for p-Ge, $A = 1 \cdot 10^{-5}\mathrm{m}^2$

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

$\mu_H = R_H \cdot \sigma_0$

Using the measurements given above, we get

$\mu_H = 0.257 \pm 0.005\mathrm{m}^2/\mathrm{Vs}$for n-Germanium, and

$\mu_H = 0.238 \pm 0.005\mathrm{m}^2/\mathrm{Vs}$for p-Germanium

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Task 4 (3/5)

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Task 4 (4/5)

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

$p = \frac{1}{e} \cdot R_H$

Using the value of the elementary charge $e = 1.602 \cdot 10^{-19}\ As$

we obtain $p = 14.9 \cdot 10^{20}\ m^{-3}$.

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

$n = \frac{1}{\mathrm{e} \cdot R_H}$

Taking the elementary charge $e = 1.602 \cdot 10^{-19}\ As$we obtain $n = 13.0 \cdot 10^{20}$ m^{-3}

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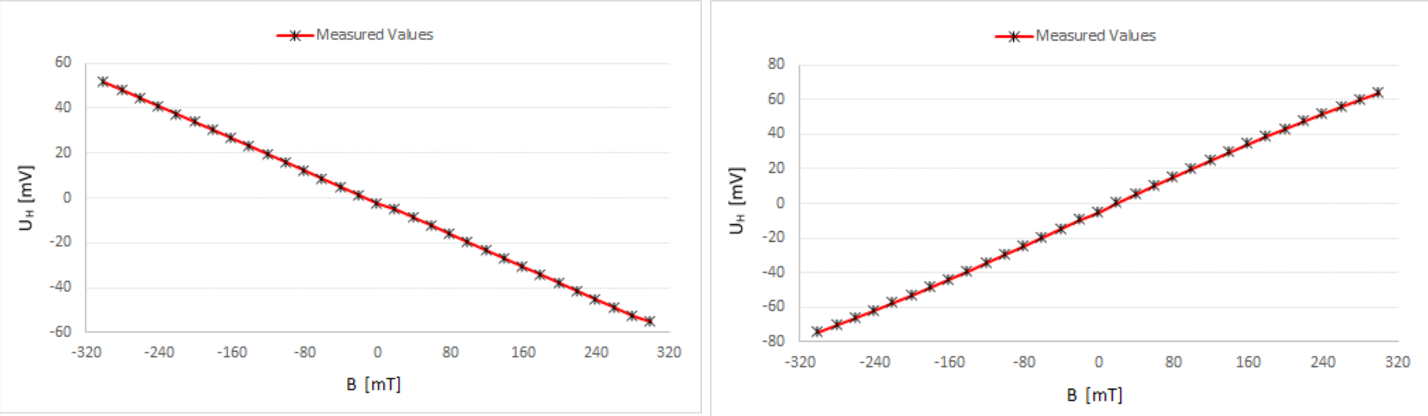
Task 4 (5/5)



(a) n-Germanium (b) p-Germanium

Fig. 6: Hall voltage U_H as a function of magnetic flux B with I_P = 30 mA and T = 300 K.

Task 5 (1/2)

Fig. 7 shows that the Hall voltage decreases with increasing temperatue for both n- and p-Germanium. Since the experment 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.

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