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Kandó Kálmán Electrical Engineering Faculty
Institute of Microelectronics and Technology

Micro- and nanotechnology (KMENT14TEC)

Laboratory program

Measurement guide

3. Application of Hall-sensors

a. Measurement of material parameters of the semiconductors

Theoretical background

Today's semiconductor devices and integrated circuits are made mostly of silicon in a smaller extent of compound semiconductors (e.g., GaAs, InSb, GaAsP, etc.). The latter materials are mostly used for the optoelectronics and in the microwave techniques. The current transport mechanism of the semiconductor materials (having n- and p-type charge carriers) makes possible to construct the p-n junction and using it to produce diodes, transistors and other semiconductor devices. As it is known, the semiconductor is n-type if it has surplus free electrons and is p-type if it has surplus free holes.

In the material parameters of the semiconductor are unknown, we must to measure them, e.g., the conductance type, the doping concentration (and the concentration of free charge carriers), and the mobility of the charge carrier.

At and nearby the room temperature each doping atom is giving one charge carrier (either electron or hole). If we could define the conductivity of the semiconductor, the doping concentration can be calculated.

To characterize the conductance above the concentration of the charge carrier its velocity should be known, as well. In spite of the conductance in metals the speed of charge carriers in the semiconductors has enhanced dependence on the applied electric field. Since this relation is linear the mobility of the charge carrier could be defined as the average speed of the charge carriers reached due to the applied unit electric field parallel to it.

The drift mobility is:

$$\mu = \frac{v}{\mathcal{E}} \text{ [cm}^2\text{/Vs]}$$

Where v is the average drift velocity and \mathcal{E} is the electric field.

The electrical conductance based on the differential Ohm law is:

$$\sigma = q(\mu_p p + \mu_n n),$$

Where q is the elementary charge ($q = 1.6 \times 10^{-19}$ As), μ_n and μ_p are the electron and hole mobility, while n and p stand for the carrier concentration, respectively. σ reciprocal is ρ the specific resistance, usually is given in Ωcm .

The mobility is depending on the material of the semiconductor, on the temperature, on the dopant concentration and on the type of the charge carrier. For more exact calculation databases are accessible, but a usually doped semiconductor at the room temperature has the following parameter:

Germanium	electron mobility:	$\mu_n = 3600 \text{ cm}^2\text{/Vs}$
	hole mobility:	$\mu_p = 1800 \text{ cm}^2\text{/Vs}$
Silicon	electron mobility:	$\mu_n = 1350 \text{ cm}^2\text{/Vs}$
	hole mobility:	$\mu_p = 480 \text{ cm}^2\text{/Vs}$
GaAs	electron mobility:	$\mu_n = 8500 \text{ cm}^2\text{/Vs}$
	hole mobility:	$\mu_p = 400 \text{ cm}^2\text{/Vs}$
InSb	electron mobility:	$\mu_n = 80000 \text{ cm}^2\text{/Vs}$
	hole mobility:	$\mu_p = 450 \text{ cm}^2\text{/Vs}$
CdSe	electron mobility:	$\mu_n = 600 \text{ cm}^2\text{/Vs}$
	hole mobility:	no data

The effect of the magnetic field on the semiconductors was discovered by E.F. Hall at 1879 and later it is named Hall-effect after him. The so-called Hall sensors are applying this effect. Studying the semiconductor materials it was discovered that the magnetic field is affecting the electrons moving in the semiconductor exactly the same way as it happens in the free space or in the metals. If a current is flowing in the semiconductor in the presence of a transverse magnetic field than a voltage will appear which will be perpendicular both to the current and the magnetic field direction. This voltage is called to be Hall voltage. This effect is sketched on the Fig. 1.

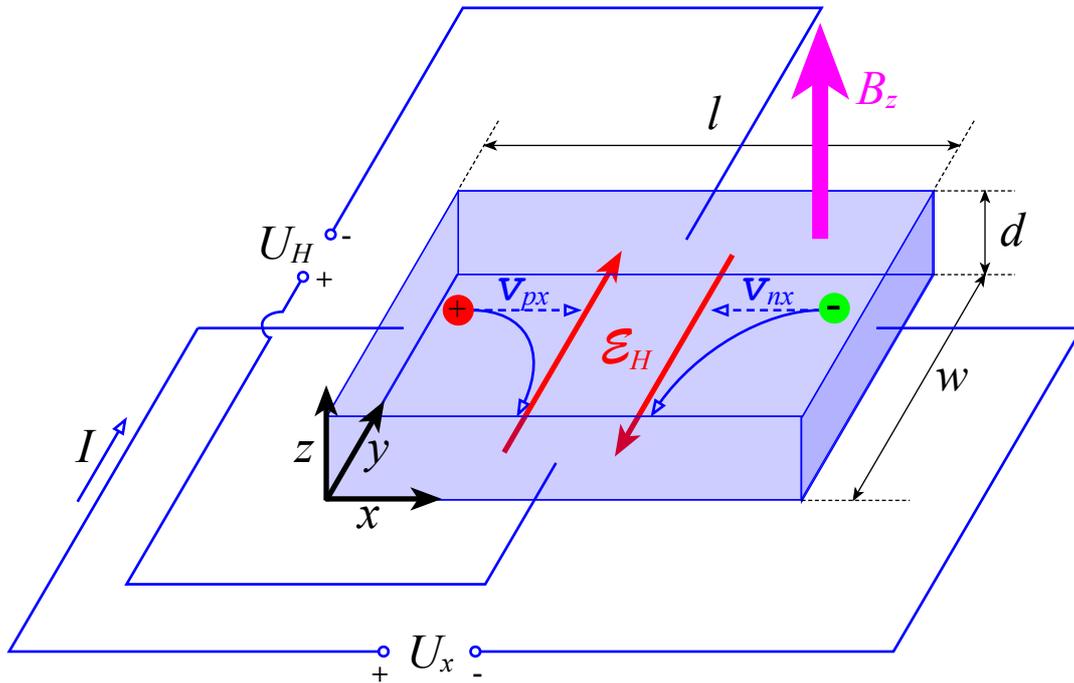


Figure 1: Hall-effect (the indices reflect the directions, U_H stands for the Hall voltage)

The voltage polarity depends on the conductivity type of the semiconductor (p- or n-type). Applying this measurement the conductivity type is obtainable. The volume of the Hall voltage is proportional to the vector multiplication of the current and the magnetic induction:

$$U_H = \mathcal{E}_H w = R_H \frac{I}{wd} B_z w = R_H \frac{I B_z}{d}$$

Where R_H - the Hall-constant ($\text{m}^3/\text{Coulomb}$),

I - the current is going through the sample (pulling current),

B - the density of magnetic induction (Tesla; Vs/m^2),

d - the thickness of the sample (m).

The R_H Hall-constant can be expressed by the free charge carrier concentration. For p- and n-type material it is:

$$R_H = \frac{1}{pq} \text{ or } R_H = -\frac{1}{nq} \text{ respectively.}$$

The polarity of the Hall voltage can be derived using the Lorenz force expression:

$$\vec{F} = Q\vec{v} \times \vec{B}$$

Where \vec{F} stands for the force vector affecting to the charge,

Q stands for the volume of the charge,

\vec{v} stands for the speed vector of the charge ,

\vec{B} stands for the magnetic induction vector

In a p-type sample the charge carriers are the holes, while in an n-type sample they are the electrons. Following the directions given in Fig. 1:

In the case of a p-type sample the direction of the current is the identical with the speed direction of the positive charges, that is why v is in x direction, Q is positive, B is along with +z axis consequently F will acts into -y direction (right hand rule). As a result the holes will accumulate at nearer xz plane in the figure, the Hall voltage (U_H) will be positive. In the case of an n-type sample Q is negative, v is in the -x direction, B is in z direction consequently the force direction is -y again. But the electrons moving -x direction mean a current which is flowing +x direction. It means a negative Hall voltage. This is the way to define the conductivity type of the sample.

Measurement tasks

The first part of the program is the determination of the specific resistance and the Hall voltage of the studied semiconductor sample. To perform this task the Hall measurement system containing the electromagnet and its current source will be used. The semiconductor Hall sample is mounted into the air gap of the magnet. The shape, sizes and wiring are sketched in Fig. 2. The basic sizes are: $w = d = 0.4 \text{ mm}$, $l = 0.308 \text{ mm}$. These data should be applied in the calculations.

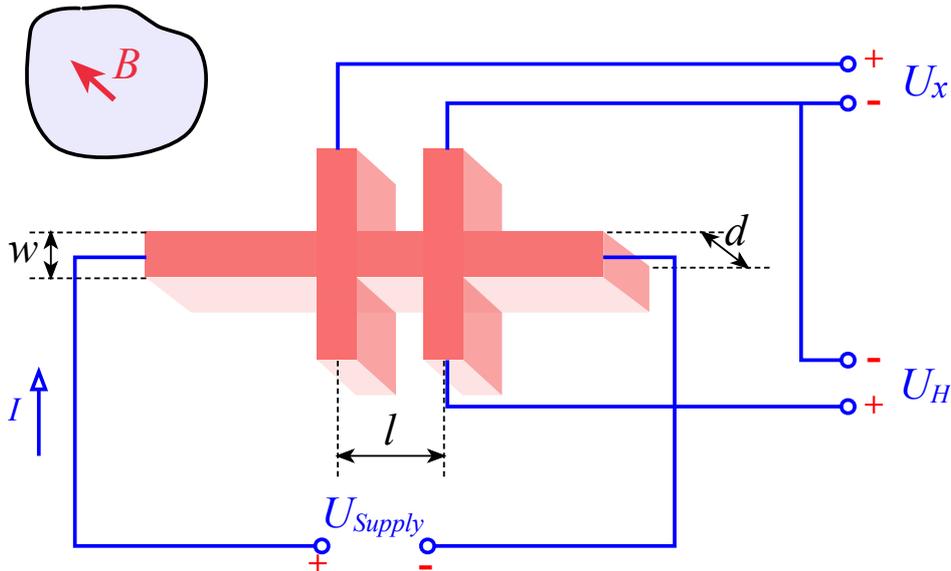


Figure 2: The dimensions and wiring of the Hall sample

Measurement of the specific resistance

The specific resistance of the sample will be measured and calculated in accordance with Ohm law:

$$U_R = U_x = IR = \rho \frac{l}{wd} I$$

Which results:

$$\rho = \frac{U_R}{I} \frac{wd}{l}$$

When measuring the specific resistance — naturally — no magnetic field is applied (don't have to use the red current generator unit yet). The supply between points marked with "U" is applied using a stabilized power supply. The DC voltmeter is connected in between the measuring point marked "U_R". The pulling current will be measured by a digital multi-meter at the points marked "I".

Measurement of the Hall voltage

After finishing the determination of the specific resistance; turn on the electromagnet by applying current from the red current generator unit to the "U_G" connection points. The induction current value and direction can be seen on the display of the current generator. The voltmeter should be connected to the "U_H" points to read out the Hall voltage.

First the conductivity type of the sample will be defined. The direction of the magnetic field is shown by the LEDs located on the display of the current generator. Knowing the direction of the current and of the magnetic field the type of the sample could be determined reading the polarity of the Hall voltage.

The relation between the B induction and I_G is shown in Fig. 3. As you can see, the curve has a hysteresis that is why special care should be taken to set the required B value. The errors of the Hall voltage measurement could be diminished if the measurement is performed using both current direction and the average of the resulted absolute values of the Hall voltage is calculated.

Let's suppose we want to measure the U_H value at I_G= 0.8 A. In this case first the current of the current generator has to be increased up to 1.5Amps, then the desired 0.8Amps can be set decreasing the current from this value. In this case the +B value is obtainable reading the magnetization curve of Fig. 3 and U_H value is shown on the voltmeter. Next the current should be decrease till -1.6 Amps and reversing from this point we could set the -0.8 Amps. Reaching the desired current, the induction value is readable from the bottom part of the magnetization curve of Fig. 3, and the Hall voltage is displayed by the voltmeter.

Performing these measurements the Hall constant, the majority carrier concentration and its mobility are obtainable.

The Hall constant is:

$$R_H = \frac{U_H d}{IB}$$

Where the measured Hall voltage (U_H), the pull current (I), the magnetic induction (B) and the thickness of the sample (d) were applied.

The carrier concentration is

p-type: $p = \frac{1}{R_H q}$

n-type: $n = \frac{1}{R_H q}$

To calculate the mobility the specific resistance is applied:

p-type: $\mu_p = \frac{1}{\rho q p}$

n-type: $\mu_n = \frac{1}{\rho q n}$

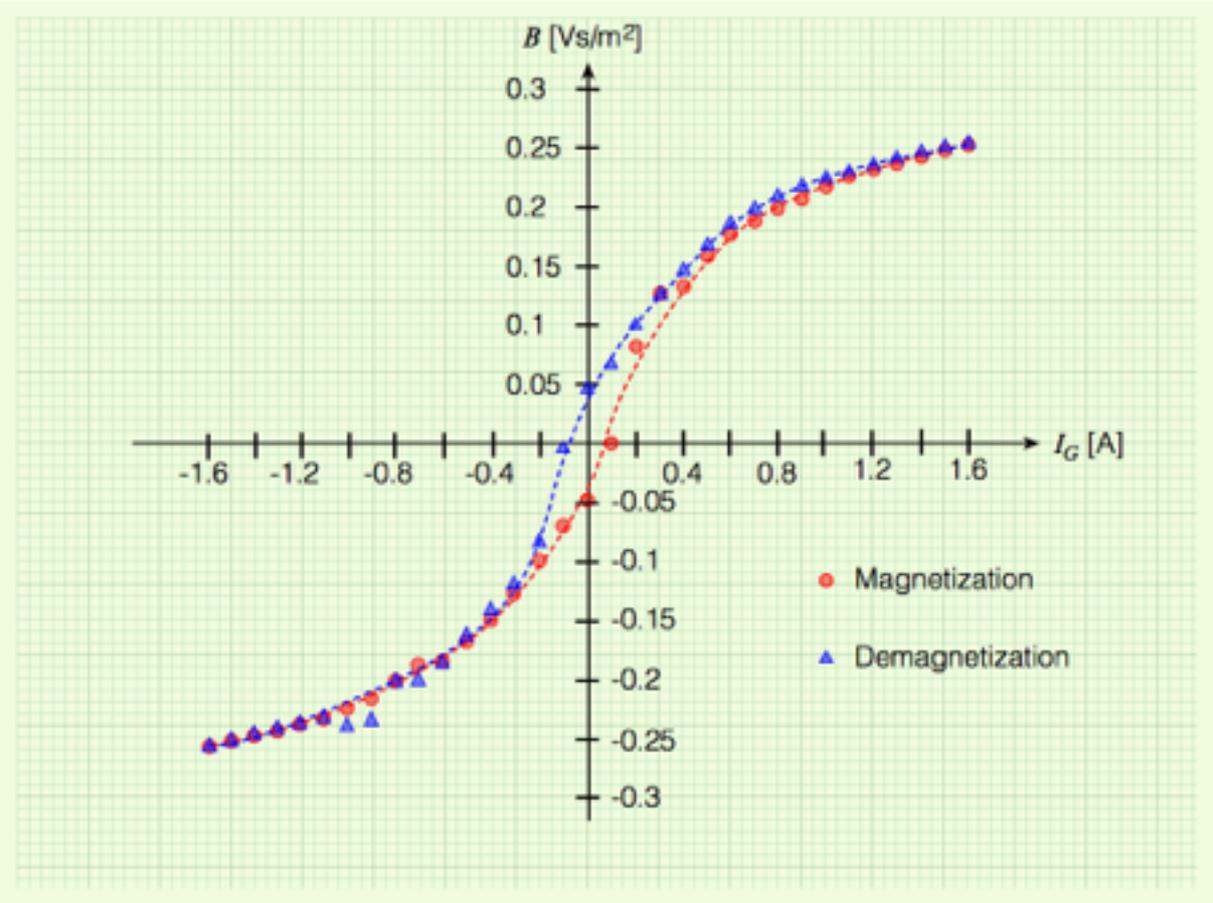


Figure 3: The magnetic induction curve of the soft ferrite

Measurement setup

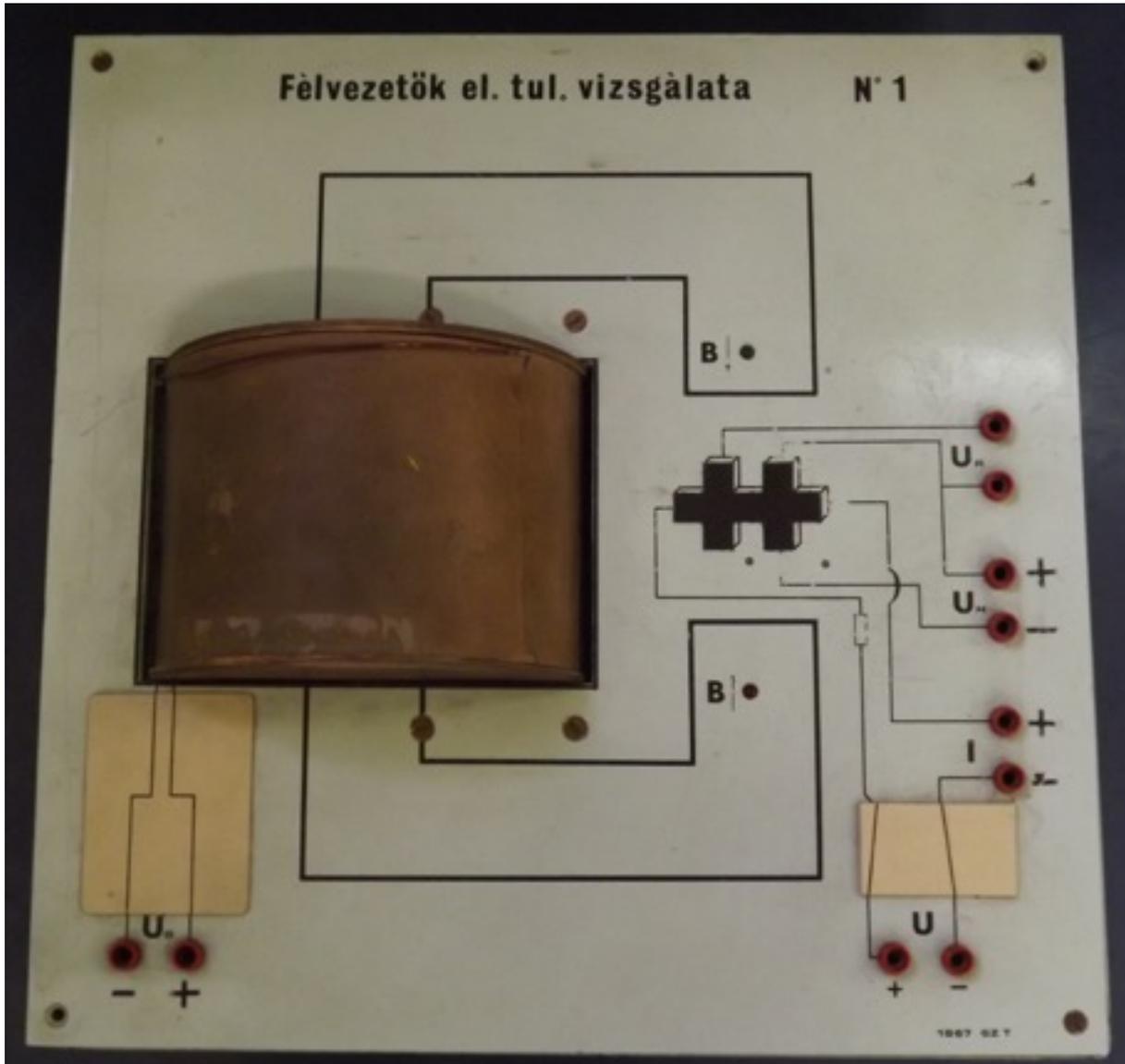


Figure 4: Test panel of the material parameters measurement

The test panel shown in Fig. 4 is used to measure the material parameters. To supply the magnet the U_G input, to supply the Hall sample the U input has to be used. To measure the pulling current the ampere meter has to be connected to the I outputs. The U_R and U_H outputs are for the resistance and Hall voltage measurement, respectively.

Measurement tasks

1. Determination of the specific resistance

Let's determine the specific resistance of the unknown sample measuring its $U_R(I)$ characteristic using at least 5 different pulling current. The applied pulling currents should be between 1 – 6 milliamps. This measurement has to be performed without any induction current. The voltage of the power supply should be controlled to reach the desired pulling current. The specific resistance has to be obtained defining the slope of the best fit line. The protocol should contain the measured $U_R(I)$ characteristic, its best fit line and the evaluated specific resistance.

2. Obtaining the hysteresis of the Hall voltage and determination of the material parameters

Let's set 3 mA pulling current! The Hall voltage has to be measured step by step decreasing the induction current (I_G) from 1.6 Amps to -1.6 Amps than increasing it backwards to 1.6 A. At least 8 measurements points has to be taken in each quadrant. To choose the proper induction current values it is advisable to take into consideration of the changing steepness of the $B(I_G)$ relation. Do the $U_H(I_G)$ and $U_H(B)$ graphs!

1. Determine the conductance type of the sample based on the polarity of the Hall voltage!
2. Calculate the Hall constant using the slope of the best fit line of the $U_H(B)$ graph! The protocol should contain the graph and the best fit line with parameters.
3. Calculate the charge carrier concentration!
4. Applying the result of the specific resistance measurement define the mobility of the majority charge carrier concentration.
5. Based on the results the possible material of the sample has to be defined.

3. Studying the pulling current dependence of the Hall voltage

Measure the Hall voltage at six different pulling current values in the 1-6mA range. The induction current should be 0.8 A. Take care the proper setting of induction and a correct read-out. Do the $U_H(I_{pull})$ graph!

The second part of the exercise is coming on the next page.

b.) Electric power measurement applying Hall sensor

Theoretical background

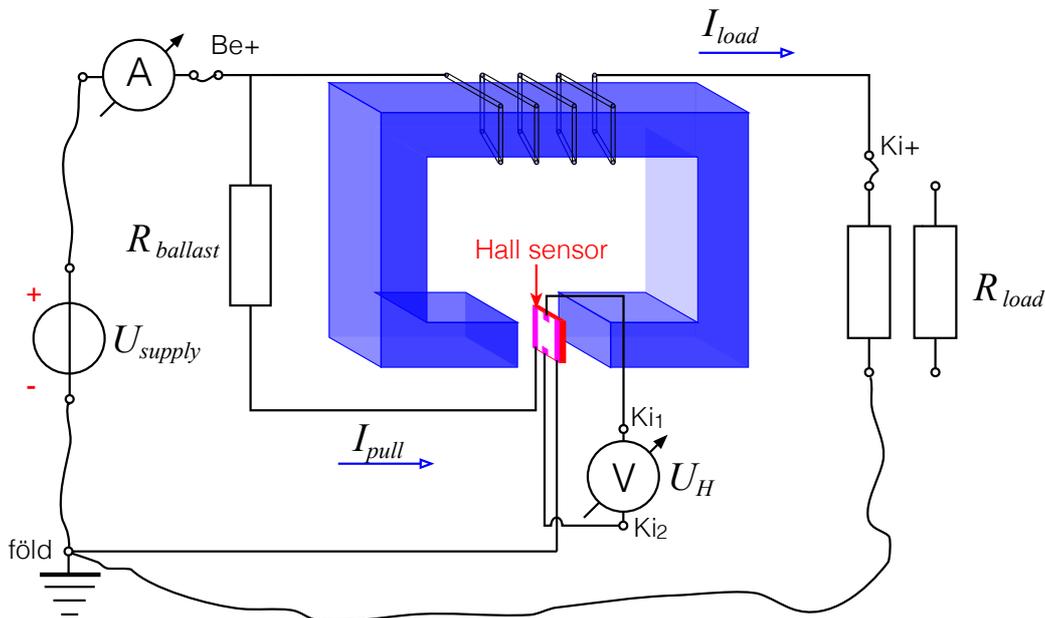


Figure 5: Measuring circuit for electric power measurement

Figure 5 is showing the basic circuitry of the power measurement performed by the Hall sensor. In the case of an alternate current, if the sensor is connected between the null and the phase line than the effective power will be measured. To understand the circuitry let's see the math:

$$U_H = kI_{pull}B$$

Where:

- U_H : Hall voltage (outgoing voltage);
- k : constant, characteristic of the sensor;
- I_{pull} : pulling current of the Hall-sensor;
- B : magnetic induction.

In the following the power measurement will be discussed using this DC version. The AC version has the same explanation.

The resistor marked R limits the Hall current, in the same time the sensitivity of the sensor could be adjusted in a certain level using it. Since the sensor has remarkable temperature dependence the compensation circuitry is necessary in the practice to have an accurate measurement (the value of the Hall current influences the self-heating of the sensor).

The sensor is put into the air gap of inductance connected in series with the load. In this way the magnetic power lines are closed mostly through the sensor. The number of turns of the inductance must be low (and the impedance must be low, as well) resulting small magnetic inductance which cannot saturate the ferrite but in this case higher sensitivity is necessary.

The electrical power is:

$$P_{load} = U_{load} I_{load} \cong U_{supply} I_{load}$$

The Hall current is linearly proportional to the supply voltage (and since the coil's resistance is negligible it is linearly proportional to the load voltage, as well) which means:

$$I_{pull} = \frac{U_{supply}}{(R_{ballast} + R_{sensor})}$$

The magnetic field in which the sensor was placed is linearly proportional to the current flowing through the coil:

$$B = \mu_0 \mu_r H = \mu_0 \mu_r N I_{load}$$

Where μ_0 stands for **magnetic permeability of the vacuum** (1.257×10^{-6} H/m),

μ_r : relative permeability of the material (1500 for the applied ferrite)

H : magnetic field

N : number of turns in the coil

L : length of each turn

I_{load} : current flowing through the coil.

$$U_H = k \frac{U_{supply}}{(R_{ballast} + R_{sensor})} \mu_0 \mu_r N I_{load} \cong \frac{k \mu_0 \mu_r N L}{(R_{ballast} + R_{sensor})} U_{load} I_{load}$$

Based on the previous equations it can be stated that Hall voltage of the Hall sensor (U_H) in Fig. 5 should be proportional with the electric power of the load. What is more, the output voltage of the sensor is independent from the frequency, that is why this solution is applied even at GHz region to measure electric power (e.g., at microwave transmitters).

In the practice the linearity is diminished by the parameter scattering of the R ballast resistance, the temperature dependence of the sensor and the nonlinearity of magnetic induction (the B - H curve is linear only at the vicinity of the origin).

Measurement setup

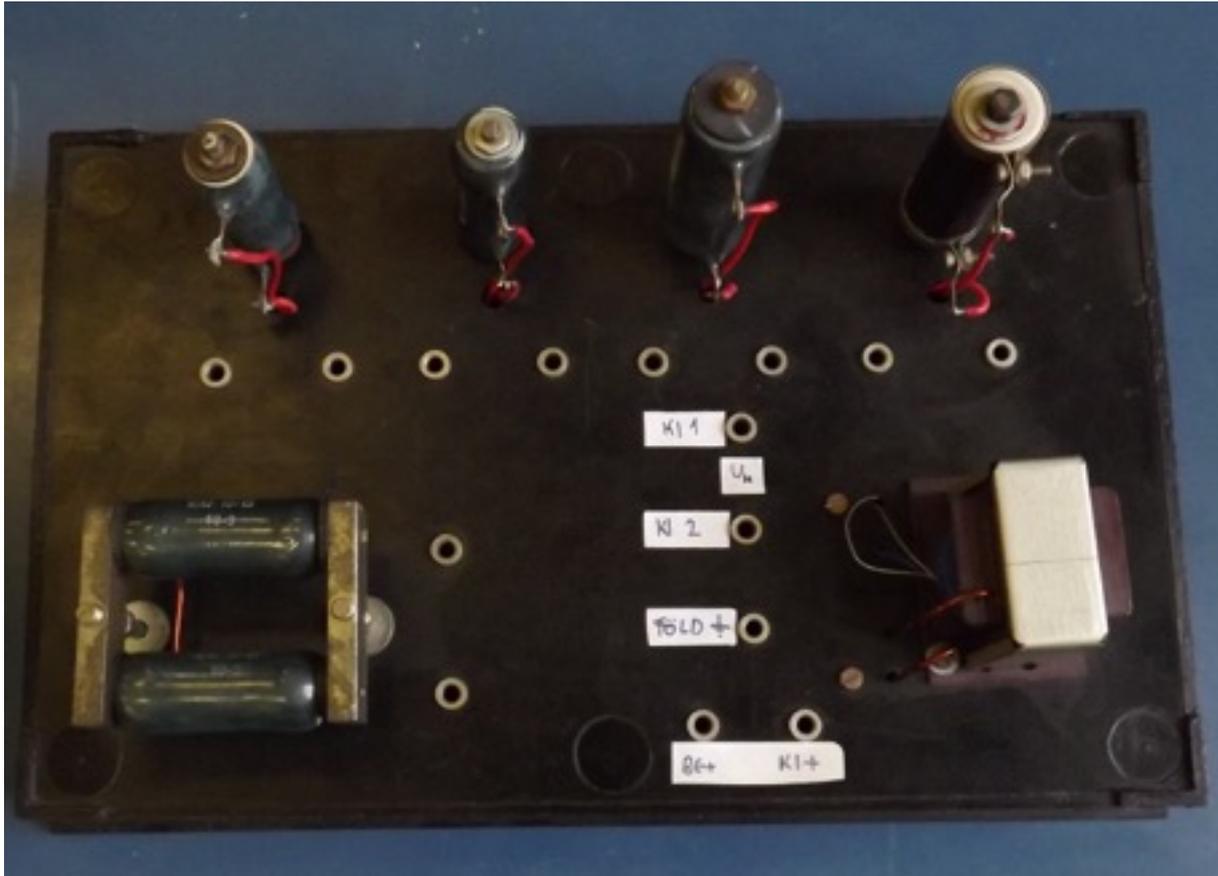


Figure 6: Test panel of the power measurement

The following measurement tasks should be performed using the test setup shown in Fig. 6. The Hall sensor is mounted into the air gap of the iron core of the coil and the ballast resistor is in place. The coil could be serially connected with different load resistors for this one of its output has to be connected to the “Ki+” the other to the common point “Föld”. The “Be+” point is going to the node of the coil and ballast resistor, this will be one connection point of the current meter, the other will be the power supply.

Measurement tasks

The measurement will be carried out in a DC circuit. To apply a down transformed line power is not expedient since it has a remarkable instability resulting changes in the Hall voltage at some mV range.

The ballast resistor $R=3.3\text{ k}\Omega$, the sensor's resistance is 1056 Ohm, the number of turns of the coil is $N=48$, the length of each turn is $L=26\text{ mm}$, the relative magnetic permeability of the ferrite core is $\mu_r = 1500$, the permeability of the vacuum is $\mu_0 = 1.257 \times 10^{-6}\text{ H/m}$.

1. Measurement of the pulling current:

Let's measure the pulling current of the Hall sensor by 5 V steps in the 0 - 40 V supply range without any load ($R_{load} = \infty$, in this case only the sensor consume the current). Do the graph! (It is expedient to perform together with task 2.)

2. Determination of the offset:

In ideal case the sensor's output voltage is 0 if there is no any load. In the reality it has a few mV output voltages even in this case. Let's measure and graph the offset voltage of the output by 5 V step in the 0 - 40 V supply range at $R_{load} = \infty$.

3. Measurement of the load characteristics:

Let's switch the digital multimeter into the ampere meter mode and put the measuring cables into the proper inputs.

Get the Hall voltage – load current (and supply voltage) graphs at $R_{load} = 50 \Omega$, 150Ω , 270Ω , $1 \text{ k}\Omega$ (at least for two of them). (The 20Ω load can be used only for a very short time!)

Determine and graph the Hall voltage — power characteristics. (It can be obtained using the previous results.)

Equipments to be used

- Adjustable current source (FETV/89)
- Digital multimeters, 2 pc (Hameg HM8012)
- Stabilized power supply (FOK-GYEM TR9175/A)
- Test panels of the Hall measurement
- Test panels of the power measurement

Review questions

- Describe the Hall effect!
- Describe the power measurement method using the Hall sensor!
- Sketch the magnetization (B-I) curve of the soft ferrite!
- What kind of effects can lead to errors in the measurements of the Hall sensor?

Measurement protocol

Each measuring group is asked to give in one protocol. The protocol should be submitted through e-mail latest after two weeks of the measurement performed.

The protocol has to contain:

1. The title of the measurement
2. The names of the colleagues performing the task
3. The date and location of the measurement
4. A declaration stating that the task is performed by the enumerated colleagues
5. The list of applied equipments with types and identification numbers
6. The tabulated list of the measured values, the calculated values, and the requested graphs
7. In the case of calculations, the applied forms
8. Short discussion of the results for each measurement task

PLEASE do not copy previous reports. Identical reports will be refused.