Physics Department
Quantum Lab

STUDY OF THE HALL EFFECT IN A n- and p-Ge SEMICONDUCTOR

1 Objectives

1. Study and understand the Hall Effect.
2. Measure the Hall voltage as a function of the current circulating through a Germanium semiconductor of conductivity type n or p, and as a function of the magnetic field passing through it.
3. Determine the Hall coefficient.
4. Identify the sign of the charge carriers as a function of the polarity of the Hall voltage, the direction of the magnetic field, and the direction of current in the semiconductor.

2 Theoretical foundations

The *HALL* Effect was discovered by physicist Edwin Herbert Hall in 1879. This consists of the appearance of an electric field **E** perpendicular to the direction of current **I** passing through a material (conductor or semiconductor) that is within a magnetic field **B** perpendicular to that current.

2.1 Semiconductors. General.

According to the electronic properties of materials related to conductivity σ, these can be classified into three main groups: *insulators, semiconductors* and *conductors.* For a material to conduct electricity it is necessary that there must be free electrons, that is, charge carriers in the conduction band (BC), so that not all carriers are linked to the crystal (atoms and ions), as in the valence band (BV). The separation between the valence band and the conduction band is called bandgap (BP), because there can be no carriers in it. According to the band structure:

1. conductors (metals) are those in which both bands of energy overlap.
2. insulators are those in which the width of the BP is greater than or equal to 6 eV, which makes it impossible for an electron to jump at moderate temperatures ($E = kT$) between BV and BC, so there are no free carriers in BC.
3. semiconductors (SC) are those in which the width of BP is of the order of 1 eV. For example, in germanium it is 0.66 eV. In this case, the conductivity is very temperature dependent: at moderate temperatures

(T~350K) the carriers have enough energy to jump from BV to BC, thus increasing the concentration of free carriers in BC, while at low temperatures they behave as perfect insulators, as there is not enough energy to create free carriers in BC.

According to the level of impurities contained in semiconductors, they can be classified into *intrinsic,* with negligible concentrations of impurities, and generally unwanted, and extrinsic, with high levels of impurities intentionally created in the manufacturing process. Depending on the type of impurity with which it is intentionally doped, a SC can have an extrinsic conductivity by holes (semiconductor *type p,*SCp) or by electrons (semiconductor *type n,*SCn).

In the dependence of the conductivity in an extrinsic SC with temperature we can differentiate three possible regimes: at low temperatures we have extrinsic conduction (R-I, see Fig. 1)), that is, as the temperature increases, the charge carriers are ionized from the impurities, passing to the BC. At moderate temperatures (R-II) we speak of depletion of impurities, since almost all impurities have already been ionized and an increase in temperature does not lead to an increase in carriers in BC. At high temperatures (R-III) the predominant conduction is intrinsic (see Figure 3); the carriers that reach the BC come from the BV, that is, they are ionized atoms of the SC material itself, not of the impurities. In the latter regime, conductivity as a function of temperature can be expressed as:

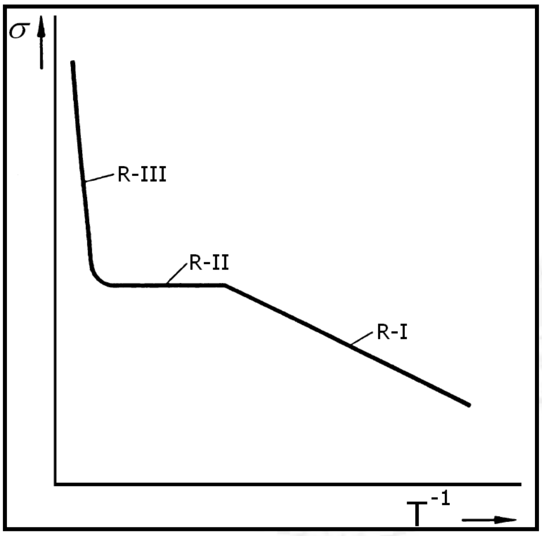

Figure 1. Dependence of conductivity with temperature in a SC.

$$\sigma = \sigma_0 \cdot e^{-\frac{\Delta E_p}{2kT}} \qquad [1]$$

where ΔEp is the energy width of the BP of the SC, k=8.625·10^{-5} eV/K is the Boltzmann constant and T the absolute temperature (in K).

Let us remember that:

1. conductivity is the inverse of resistivity ρ, and its units are $(\Omega m)^{-1}$.
2. the current density (current per unit area) is **J** =qn**v**, where n is the concentration of carriers, and according to Ohm's law: **J** = σ **E**.
3. the average velocity of the carriers is **v** = μ**E**, where μ is the mobility of the carriers.

Therefore: $\mathbf{J} = qn\mu\,\mathbf{E} = \sigma\,\mathbf{E}$ [2]

Thus $\sigma = qn\mu$ [3]

2.2 Hall effect in a semiconductor.

If a rectangular-shaped SC material with a width *h,* a thickness *d* and a length *l* through which a stationary current **I** circulates, is placed within a homogeneous magnetic field **B** as shown in Figure 2, the carriers of negative charge (electrons, q=-e) or positive charge (holes, q=e), moving with an average velocity **v,** feel the action of the magnetic or Lorentz force given by **F** = q (v x **B**). This force causes the carriers to deviate, accumulating in the upper region or lower of the SC, depending on the type of conductivity n or p of the latter (see Figure 3) and the direction of **I** and **B.**

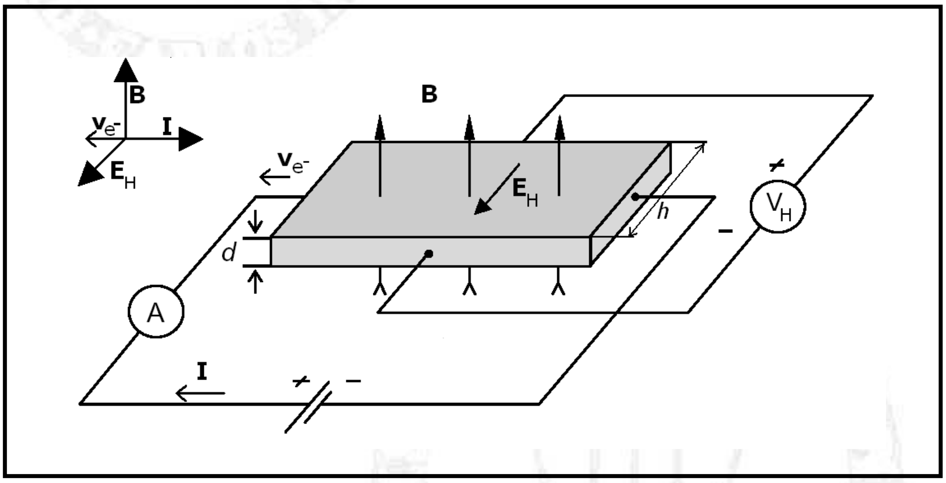

Figure 2. Hall effect on an n-type semiconductor.

The accumulation of carriers in these regions generates an electric field called *the Hall* field $\mathbf{E_H}$, which is perpendicular to **B** and **I** and which is opposed to accumulations of more carriers, reaching equilibrium for given values of **I** and **B.** Linked to $\mathbf{E_H}$ appears the Hall voltage, $V_H = \mathbf{E_H} \cdot h$, which can be measured by connecting a voltmeter as shown in Figure 2. Depending on whether the voltmeter reading is positive or negative, and knowing the direction of **B** and current **I** circulating through the circuit provided by the battery, we can deduce whether the charge carriers in the SC material are positive charges (holes) or negative charges (electrons). As can be seen in the case of Figure 2 the carriers are the electrons, as well as in Figure 3a), while in Figure 3b) the carriers are the holes.

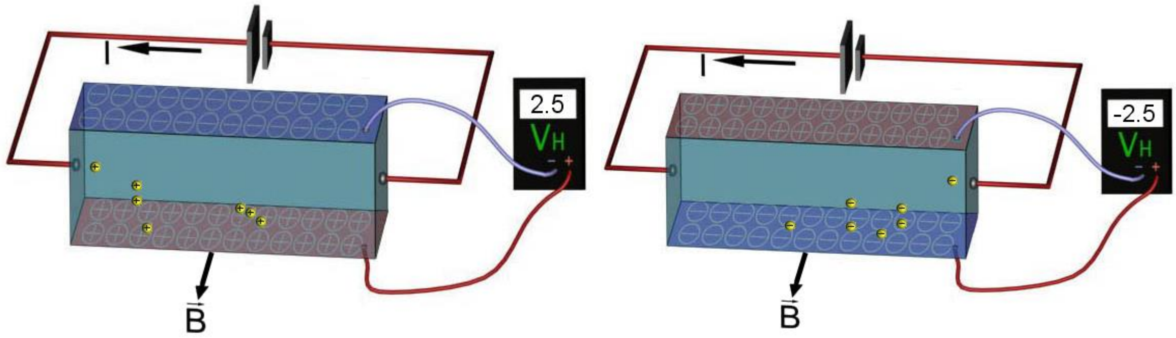

Figure 3. a) SC type n: the carriers are electrons. b) CS type p: carriers are hollow.

In equilibrium, that is, when the electric force due to the Hall field $\mathbf{F_H}$ is equal to the Lorentz force $\mathbf{F_L}$ we have:

$$|\mathbf{F_H}| = |\mathbf{F_L}| \quad \Rightarrow \quad qE_H = qvB \quad \Rightarrow \quad E_H = vB$$

since

$$\mathbf{F_H} = q\mathbf{E_H} \Rightarrow |\mathbf{F_H}| = qE_H \quad \text{and} \quad \mathbf{F_L} = q(\mathbf{v} \times \mathbf{B}) \Rightarrow |\mathbf{F_L}| = qvB, \text{ if } \quad \mathbf{v} \perp \mathbf{B}$$

As the width of the SC sample is h then the Hall voltage V_H will be:

$$V_H = E_H h = vBh$$

Knowing that the current density is:

$$\mathbf{J} = qn\mathbf{v}$$

and that in addition, J=I/A, where A is the sample transversal area (A=$d \cdot h$), then:

$$|\mathbf{J}| = J = qnv \Rightarrow v = \frac{J}{nq} = \frac{I}{nqA}$$

and we can write V_H as:

$$V_H = \frac{I}{nqdh} Bh = \frac{IB}{nqd}$$

If we denote by R_H the Hall coefficient, whose expression is given by 1/qn, and which has positive value in the case of holes and negative in the case of electrons, we finally have:

$$V_H = R_H B \frac{I}{d}$$ **[4]**

Therefore we can rewrite equation **[3]** using Hall's coefficient as

$$\sigma = \frac{\mu}{R_H}$$ **[5]**

3 *Find out more...*

- **TIPLER P.A. y MOSCA, G., "Física para la Ciencia y la Tecnología", Vol 2. 5ª edición. Ed. Reverté, Barcelona, 2005. Capítulo 26. Páginas 783-785.**
- **SERWAY, R.A y JEWETT, W. "Física", Vol 2, 3ª edición. Ed. Thomson-Paraninfo, Madrid, 2003. Capítulo 2. Páginas 843.**
- **C. KITTEL, "Introduction to Solid State Physics", 8th edition, pp.153-156**

And internet

http://hyperphysics.phy-astr.gsu.edu/hbase/hframe.html

http://www.eeel.nist.gov/812/effe.htm

http://es.wikipedia.org/wiki/Efecto_Hall

http://personales.upv.es/jquiles/prffi/magnetismo/ayuda/hlphall.htm

4 Material

1. Hall module
2. Semiconductor carrier plate (p- or n-type germanium)
   Semiconductor carrier dimensions: d=1 mm, h=10 mm and l = 20 mm
3. Electromagnet
4. Power supply
5. Teslameter
6. Digital meter
7. Probe to measure the tangential magnetic field
8. Connection cables

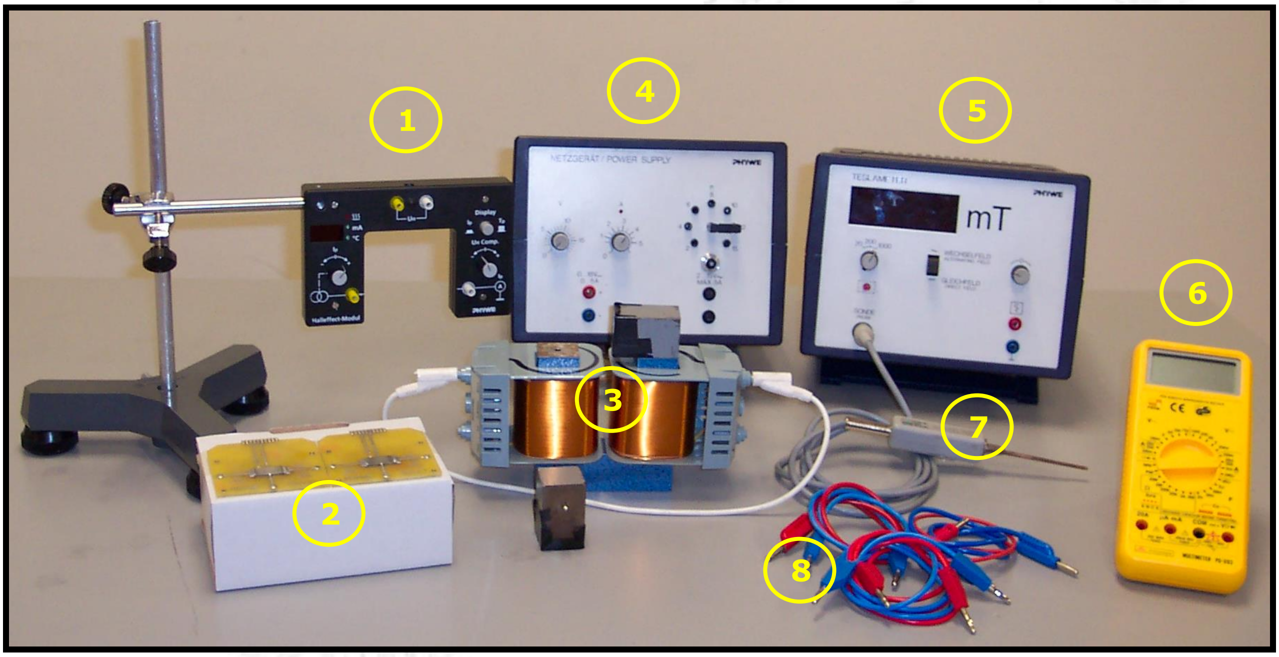

Figure 4. Workstation and Instrumentation.

5 Procedure

1. Measurement of the Hall potential V_H as a function of the intensity of the current circulating in the sample.

- With the power supply **off** (switch on the back panel of the computer) check that:
- the AC voltage output selector (bridge 1) is at the 12 V position.
- the position of the voltage (2) and current (3) controls are at a minimum.

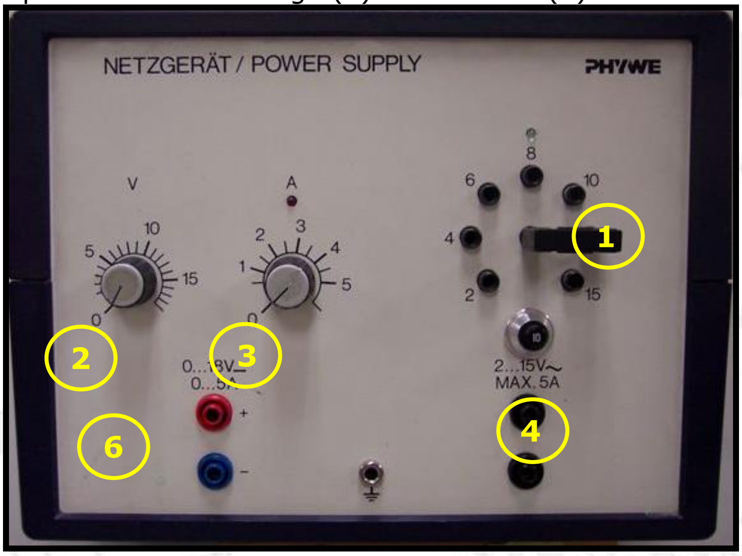

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Figure 5. Power supply in DC and AC.

2. Connect the AC voltage output of the source (4) to the input of the Hall module (5), marked with 12V~ and located on the back of it.

Figure 6. Hall module. Front and rear view.

3. Connect the DC voltage output of the source (6) to the two free ends of the electromagnet (one on each side) (7a and 7b). Keep in mind that the polarity you choose changes the direction of current in the coils of the electromagnet and with it the direction of the magnetic field.

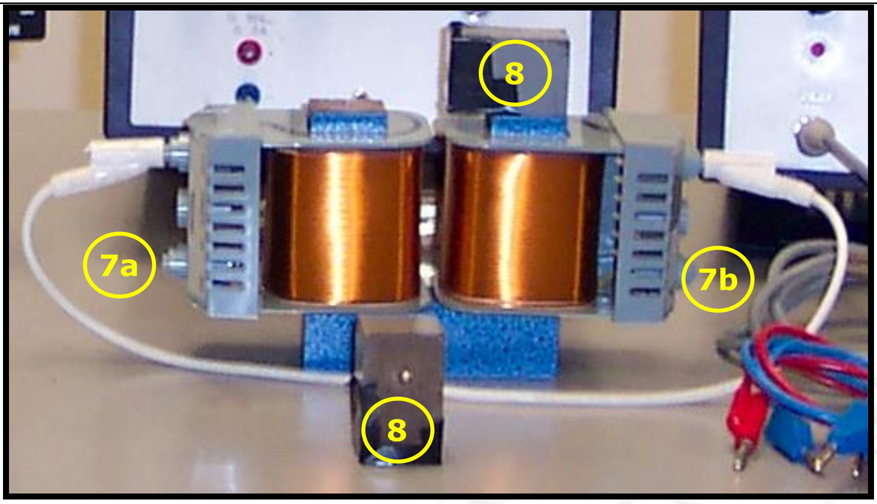


Figure 7. Electromagnet.

4. Place the top of the iron core of the electromagnet (8).

5. The teslameter calibration:

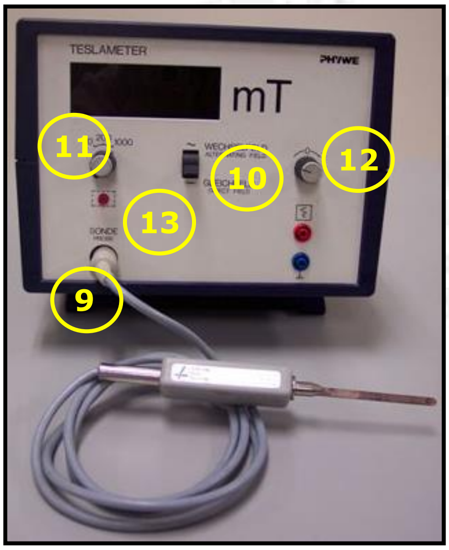


Figura 8. Teslameter.

- Connect the probe (tangential magnetic field meter) to the corresponding pin of the teslameter (9) and turn it on using the switch on the back of the equipment.
- Verify that the magnetic field selector (10) is in continuous (Direct Field).
- Move the probe away from the electromagnet as much as possible.
- Place the scale selector (11) at the scale of 1000 and adjust with the fine control (12) until the field measure is zero. Turn it down progressively (to 200 and 20) and make the same adjustment. In case you cannot adjust the reading of the field to zero, use the red button (13) located under the scale selector. Move this button delicately.

6. Remove the top of the iron core of the electromagnet in front of the semiconductor, delicately insert the probe into the hall module slot to the end, with the knob label on the observer's back, and check that the sensor tip is right in front of the semiconductor sample. Replace the electromagnet head. Attention! The probe should not be pressed against the sample.

7. Connect the meter as a voltmeter respecting the polarity at the hall voltage output (14), labeled with U_H in the Hall module, turn it on and select the 200 mV scale in CD.

8. Turn on the power supply and check that in the Hall module, the screen reading corresponds to current (led mA (15) on). Otherwise, select with the button (16) marked with Display the current measurement.

9. Set the current control (3) in the power supply to 2A; do not exceed this value. Increase V with the voltage control (2) of the power supply until the reading of the value of the magnetic field in the teslameter is 300mT. The scale selector of the teslameter must be at 1000.

10. With the current control (17) in the semiconductor sample, marked with I_p in the Hall module, adjust until the reading of the current on the module screen is 0, and with the control (18) marked with U_H comp (Hall compensating voltage), adjust until the reading of the meter, on the scale of 200 mV, is as close to zero as possible. See Figure 9.

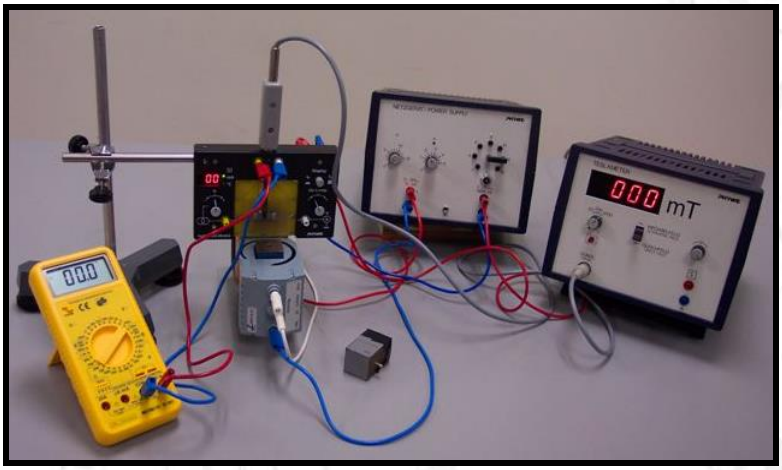
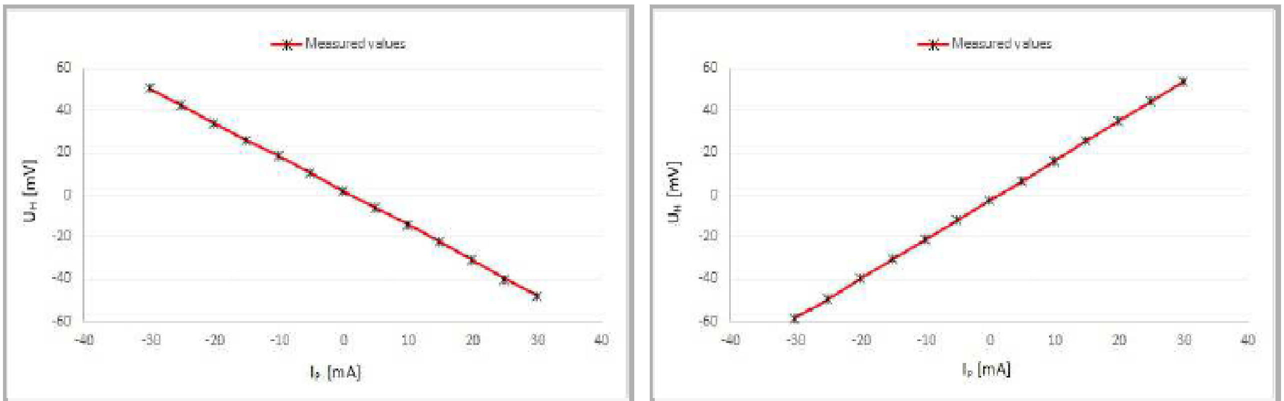


Figura 9. Montaje para la medida de V_H frente a I.

11. Vary the current in the sample using control I p(17) from – 60 mA to 60 mA in steps of 10 mA. In no case exceed these values and move the control with great delicacy. Take Hall voltage reading for each step. With these values build a table of V_H versus I.

12. Represent graphically V_H versus I. Perform a least squares adjustment.

13. Interpret the values of the adjustment parameters, using equation [4]. Say what the sign of the charge carrier is. Obtain the value of the Hall coefficient R_H and the concentration of carriers n or p from the adjustment parameters.



(a) n-Germanium

(b) p-Germanium

1. Measurement of the Hall potential V_H as a function of magnetic field strength.

2. Set the value of the current in the sample with the control I_p (17) to 20 mA.

3. With the V control of the power supply (2) increase the strength of the magnetic field in the sample up to 350 mT, in steps of 50 mT and take the reading of V_H for each step. Under no circumstances shall it exceed the value of 350 mT. See Figure 10.

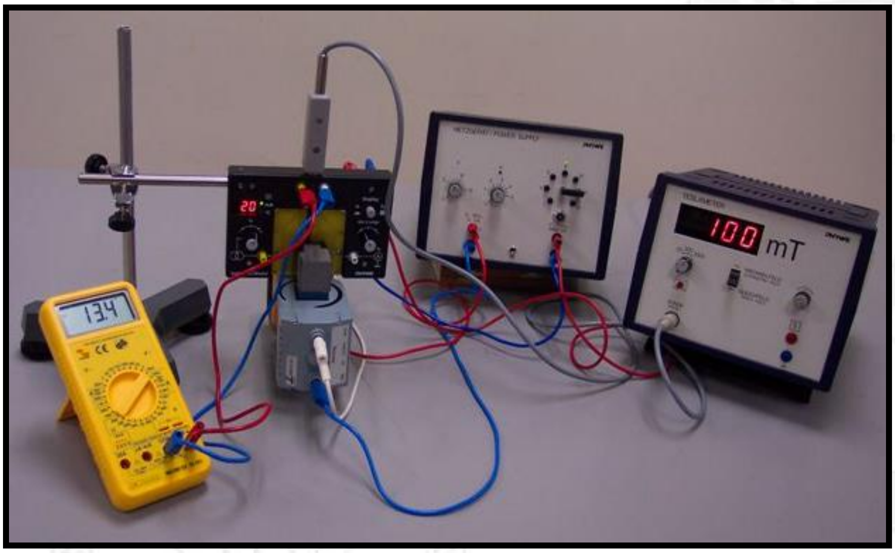


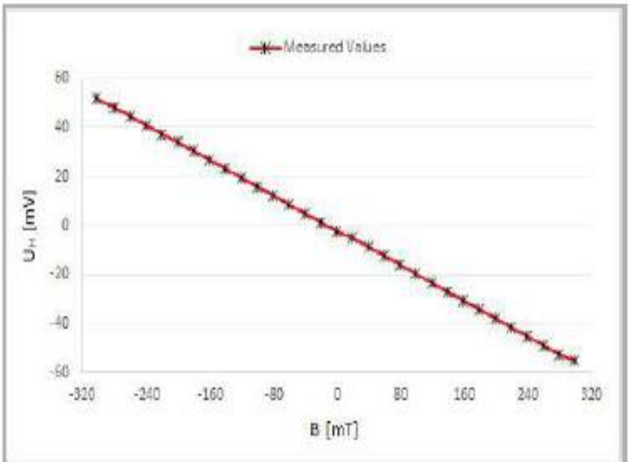
Figura 10. Montaje para la medida de V_H frente a B

4. Reverse the direction of the magnetic field in the electromagnet. To do this, swap the wires at the entrances (7a) and (7b). Check that the sign in the reading of the magnetic field in the teslameter has changed, and consequently the sign of V_H has changed. Repeat step 3. from 0 to −350 mT.

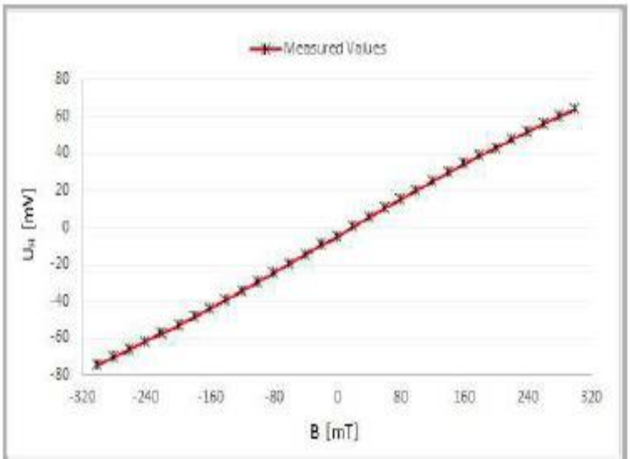
5. Build a table of V_H versus B.

6. Represent graphically V_H versus B. Perform a least squares adjustment.

7. Interpret the values of the adjustment parameters, using equation [4]. Obtain the value of the n or p carrier concentration from the adjustment parameters and compare it with that obtained in the previous section. Comment on the result.



(a) n-Germanium



(b) p-Germanium