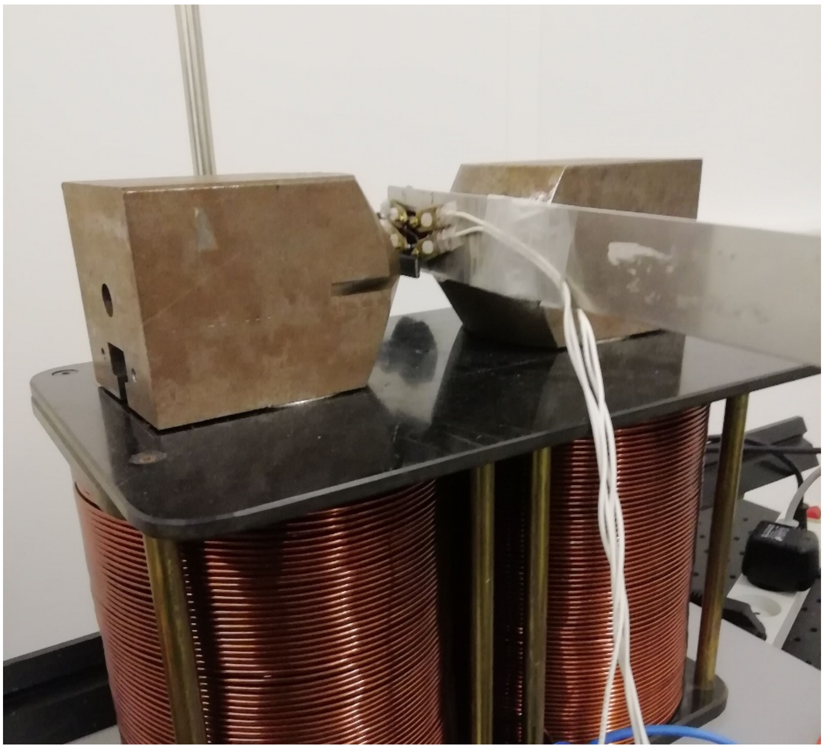
“Semiconductors: Hall effect”



Theory

We can not imagine modern industry and our daily life without electronics. Nowadays, it is mainly based on semiconductor devices. In order to construct devices with appropriate characteristics one needs to measure important electric parameters of semiconductor materials, which can be done using the Hall effect.

Before looking into this effect, one needs to start with a concept of electrons and holes. Typical elementary semiconductor, for example, silicon (Si) has four valence electrons. In a crystal, every atom makes four bonds with the neighbours. If one of electrons becomes free it leaves behind a vacant place which is called a hole and can be considered as a virtual particle with positive elementary charge. See Fig. 1.

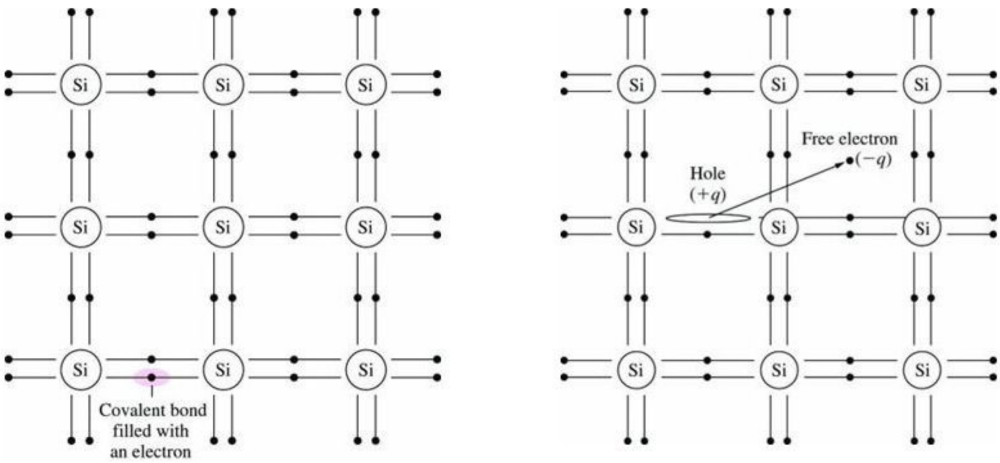


Figure 1. Si bonds in a crystal.

One can increase a number of free electrons in Si by doping it with donors, the atoms having 5 valence electrons, for example nitrogen, phosphorus etc. Then, a donor atom will substitute Si making 4 bonds with neighbours and donating one free electron. One can also increase hole concentration by doping Si with acceptors, the atoms having 3 valence electrons, for example boron, aluminium etc. Every acceptor atom substituting Si will lack one electron to make fourths bond, thus, producing excess of holes. Semiconductors doped by donors are called n-type materials, while by acceptor – p-type.

Thus, a very important parameter for any semiconductor is concentration of electrons or holes, ***n*** or ***p***, respectively as well as charge carrier mobility μ. The mobility is a physical quantity describing the velocity $\boldsymbol{v}$ of an electron or hole in a presence of electric field $\boldsymbol{E}$:

$$\mu = \frac{v}{E}. \quad (1)$$

The carrier concentration and mobility can be measured using the **Hall effect**. This phenomenon was discovered by Edwin Hall in 1879.

Idea of the experiment is based on the fact that in a magnetic field ***B*** there is a force ***F***, which is called **Lorentz force**, acting on every charge ***q*** moving with the velocity $\boldsymbol{v}$:

$$F = qv \times B,$$ (2)

where $\boldsymbol{v} \times \boldsymbol{B}$ is the vector product resulting in the force which is perpendicular to both vector quantities (see Fig. 2).

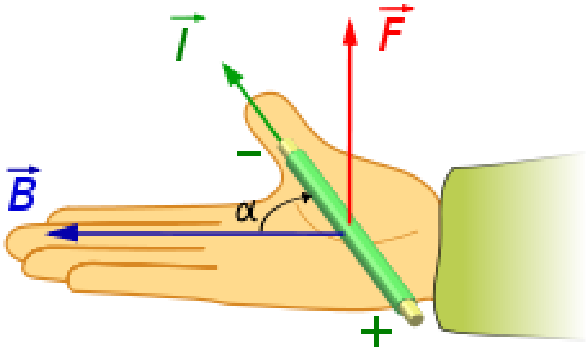


Figure 2. Right-hand rule showing direction of Lorentz force for the case of moving charges (current) in the direction of thumb and magnetic field applied along palm.

Let's consider a piece of semiconductor as shown in Fig. 3, where we apply electric field $\boldsymbol{E_x}$ (run current) along x-axis and apply magnetic field along z-axis $\boldsymbol{B_z}$. The Lorenz force will act along y-axis deflecting positive charges (holes) to one side, while the negative ones (electrons) to the other. This charge separation causes formation of additional electric field, **Hall field $\boldsymbol{E_H}$**, along y-axis. This field will balance the Lorenz force:

$$F = q[\mathrm{E} + v \times B] = 0 \qquad q\mathrm{E}_y = qv_x B_z$$ (3)

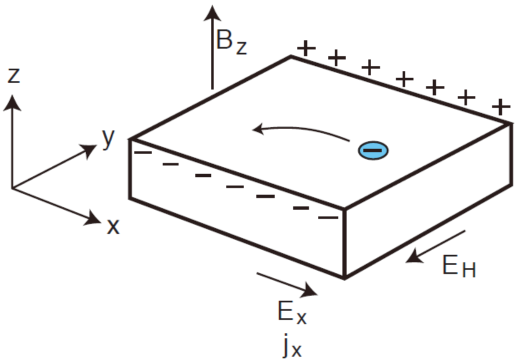


Figure 3. Rectangular piece of a semiconductor with external electric field applied along x-axis, magnetic field along z-axis and generated Hall field along y-axis.

It is found that the generated Hall field is proportional to the current density and applied magnetic field

$$E_H = J_x R_H B_z,$$ (4)

where $\boldsymbol{R_H}$ is the Hall coefficient, which is a specific characteristic of given semiconductor material inversely proportional to the carrier concentration. Thus, by measuring Hall field (Hall voltage in practice) one can directly calculate $\boldsymbol{n}$ or $\boldsymbol{p}$, from which μ can be found.

Following equations are used in practical realization of Hall measurements. You put the sample into known magnetic field, apply a certain voltage in x-direction and measure corresponding current I as well as Hall voltage V_H. Then, use equation for the carrier velocity in the sample of known geometry (sample cross-section *Wd*, see Fig. 4)

$$v_{dx} = \frac{J_x}{ep} = \frac{I_x}{(ep)(Wd)} \quad (5)$$

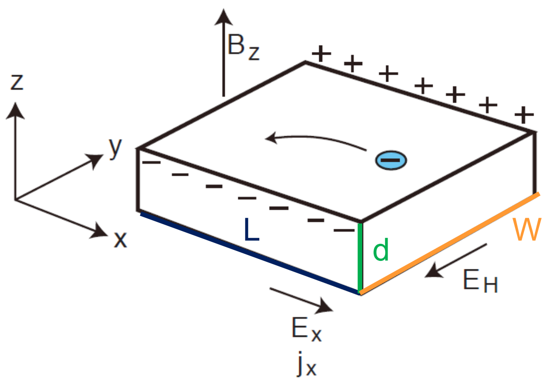


Fig. 4. Schematics of measurements

and put it into the equation for Hall voltage

$$V_H = +E_H W \qquad V_H = v_x W B_z . \quad (6)$$

obtaining

$$V_H = \frac{I_x B_z}{epd} \quad (7)$$

from which the hole concentration is calculated

$$p = \frac{I_x B_z}{edV_H} . \quad (8)$$

For calculation of mobility we use an equation for the current density

$$J_x = ep\mu_p E_x \quad (9)$$

$$\frac{I_x}{Wd} = \frac{ep\mu_p V_x}{L}$$

which gives us

$$\mu_p = \frac{I_x L}{epV_x Wd} . \quad (10)$$

Similar approach provides us with the equation for electrons:

$$n = -\frac{I_x B_z}{edV_H} \quad (11)$$

$$\mu_n = \frac{I_x L}{enV_x Wd} . \quad (12)$$

In the project, mobility and carrier concentration of several silicon samples of n- and p-type will be calculated by applying current and measuring Hall voltage in the magnetic field.