Carrier lifetime and Diffusion Length of Minority Carriers in Germanium by Valdes Method (T2)

The aim of the project is to investigate diffusion phenomenon in germanium crystal of n-type doping and determine diffusion length and minority carrier lifetime.

In crystalline solids electrons are located in the periodic potential. Hence, their wavefunctions have Bloch form. It allows for electrons movement, but the quasipartices described by it have unexpected properties – their masses differ from the electron mass in vacuum and their charges can be positive. Their energy dependence, E, on a wavevector $p = \hbar k$ is also different than for an electron in vaccum. The dependence $E(k)$ is called the band structure (see an example in Fig. 1). The bottom curves represent the valence band where positively charged holes can be located (i.e. they fulfill the given dispersion relation). The top curve represents the conduction band of negatively charged electrons (i.e. quasielectrons to distinguish it from an electron in vaccum). The bands are separated by the energy gap. No quasiparticle can posses an energy from the range of the bandgap. Band gap can range from 0 eV (e.g. CdHgTe) to over 5 eV (e.g. AlN, diamond).

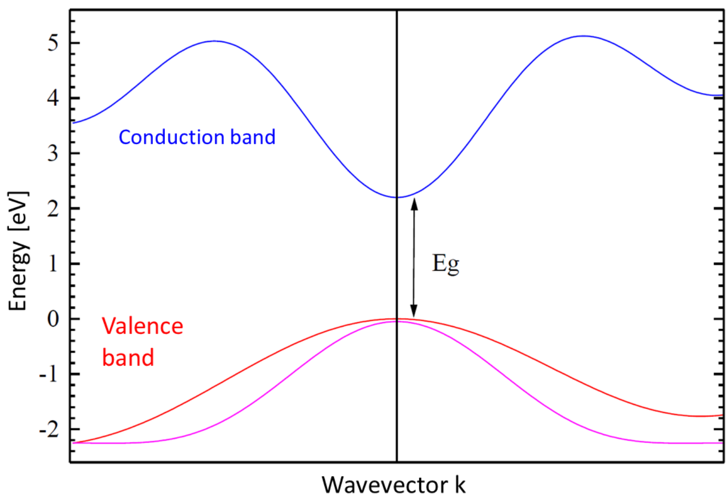

Figure 1: Exemplary band structure of a semiconductor.

Semiconductors – unlike metals – have completely filled valence band and completely empty conduction band at zero temperature (unless they are doped). There are direct and indirect bandgaps in semiconductors. When the bottom of the conduction band is placed exactly over (in the wavevector scale) the top of the valence band we call the bandgap direct. Otherwise, we deal with an indirect bandgap and any transition between the bottom of the conduction band and the top of the valence band must include not only an energy transfer but also a momentum transfer. Thus, carriers in semiconductors with indirect bandgaps have longer lifetimes.

The number of carriers in a volume is called concentration. The ability of a particle to conduct current is described by the mobility μ, that is its an average velocity per unit electric field. The carrier mobility depends on many factors, for example on the effective mass of the particle, so

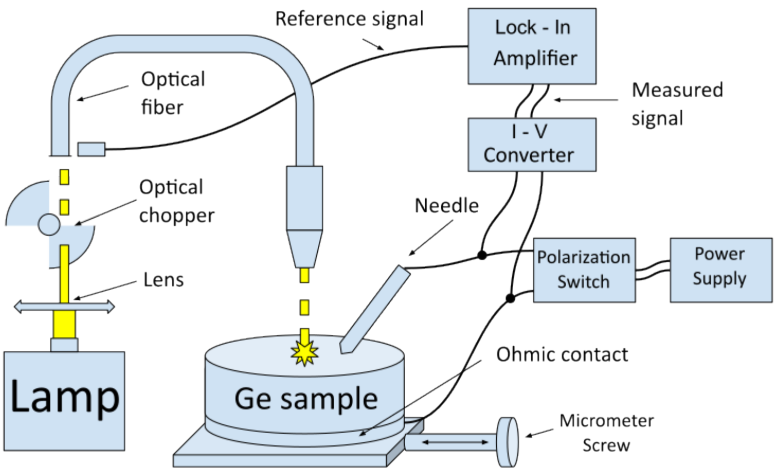

Figure 2: Scheme of experimental setup of Valdes experiment in a version realized during the project (author: Piotr Łukawski).

it differs among semiconductors. For a hole driven conductivity we can calculate conductivity $\sigma = pe\mu$, where p is hole concentration, e is an elementary charge ($1,602 \cdot 10^{-19}$ C) and μ is mobility. Resistivity equals $\rho = 1/\sigma$.
In any temperature greater than zero, carriers move continuously. If their distribution is even (equilibrium concentration) an electrical current flow cannot be observed. If an additional concentration of carriers is introduced locally (for example by light excitation), than a diffusion of carriers in all directions can be observed. A density of electrical current j_D exerted by a hole concentration (p) gradient is given by:

$$\vec{j_D} = -D_p \vec{\nabla} p, \tag{1}$$

where D_p is hole diffusion constant, which depends on mobility μ and temperature T in the following way:

$$D_p = \frac{\mu k_B T}{e}, \tag{2}$$

where $k_B = 0,0861$ meV/K is Boltzmann constant.
For a constant excitation and constant recombination rate (related to the hole lifetime τ), a stationary state occurs, that is j_D =const and $dp/dt = 0$. Hole concentration $p(\vec{r})$ will be described by the stationary diffusion equation:

$$\nabla^2 p(\vec{r}) - \frac{p(\vec{r})}{L_p^2} = 0, \tag{3}$$

where L_p is a hole diffusion length:

$$L_p = \sqrt{D_p \tau}. \tag{4}$$

Unlike in the original Valdes experiment, you will be using a point beam of light, so we can consider spherical diffusion (see Fig. 2), where only r-dependence of p will be relevant. It will be enough to solve diffusion equation in spherical coordinates:

$$\frac{\partial^2 p(r)}{\partial r^2} + \frac{2}{r}\frac{\partial p(r)}{\partial r} - \frac{p(r)}{L_p^2} = 0. \tag{5}$$

With the assumption that far away from the beam hole concentration is zero $p(\infty) = 0$, the solution has the following form:

$$p(r) = A_R \frac{\exp\left(-r/L_p\right)}{r}, \tag{6}$$

where A_R is a constant. Plotting $\ln(p(r) \cdot r)$, should yield a linear dependence.

1 What should you know before undertaking the project?

General facts related to the physics of semiconductors:

a. Band structures of solids, Bloch function, k-vector, band structure $E(k)$, electron in solid state, hole, effective mass, direct and indirect bandgaps.
b. Density of states, distribution statistics, Fermi level carrier concentration, doping types and its influence on semiconductor properties.

Specific details related to the electron transport:

c. Excitation of carriers in semiconductors with light.
d. Diffusion equation, diffusion constant, carrier lifetime.
e. Drift and diffusion current.
f. p-n junctions and metal-semiconductor junctions – band schematics, consequences of applying external voltage, current-voltage characteristics, related definitions (work function, electron affinity).
g. Lock-in Amplifier working principles.

You are expected to refer not only to this instruction but also to the literature (you will find suggested literature at the end with the first three positions as strongly recommended [1, 2, 3]).

2 Sample investigated

The sample investigated during the project is a large Ge monocrystal with n-type doping. There is an ohmic contact underneath the sample. Another electrical contact is realized from the top by touching a metallic, steel needle to the semiconductor surface (metal-semiconductor junction). The sample surface was prepared by grinding or chemical etching. The state of the surface influences the surface recombination rate. In the experiment you will be directly measuring electrical current flow. For certain conditions, a current flow through a metal-semiconductor junction may be directly proportional to the concentration of minority carriers (e.g. majority carriers flow should be suppressed) and we can call the needle the collector.

3 Experimental procedures

1. Check current-voltage characteristics of the metallic semiconductor junction for a set of needle positions. See whether there is any influence of illumination on it. Perform a fit of a theoretical curve.
2. Study diffusion effect by the Valdes method. Investigate photocurrent dependence on a distance of the needle from the light beam r (Fig. 2) for several (4-5) junction biases (both forward and reverse direction). Photocurrent measurement takes place with the

modulated light beam. Actually, you directly perform a voltage readout on the output of current-voltage converter with lock-in phase detection, which can be easily recalculated to current flow. Plotting $\Delta I(r) \cdot r$ as a function of r with the logarithmic vertical axis will allow you to determine L_p and τ.
3. Critically analyze the results. Based on the effective diffusion length dependence on the bias voltage $L_E(U_B)$ estimate the diffusion length for the lack of bias by extrapolation $L_P(U_B = 0)$. Assuming $\mu = 1700\,\mathrm{cm}^2/\mathrm{Vs}$, calculate diffusion constant and holes lifetime.

4 What should you include in the report?

The report must include the following parts:
1. Abstract - here you summarize what has been done in a concise manner.
2. Theoretical introduction - where you briefly recall fundamentals relevant to the studied effects and the material.
3. Description of the methodology - it answers the question how the experiment was done, what was the setup and the sample as if someone else wanted to reproduce it.
4. Results and analysis - where you present obtained data, determined parameters and comment on them.
5. Summary and conclusions - where you recap the most important results.

During report writing remember about enumerating all the equations and figures. When referring to sources or citing, please provide references in the bibliography at the end.

5 Appendix I - Lock-in amplifier working principles

In numerous experimental setups, we deal with the problem of noise, which is sometimes as strong as the signals measured. One of the methods to separate a weak signal from noise is its modulation. For instance, we can modulate a beam of light with a chopper. We expect that the signal triggered by the modulated light will be modulated as well. If we make a measurement at a time where the signal is expected and then, at a different time when mere noise is present, the difference between the results of these two measurements will give us a number with smaller experimental uncertainty than just a single measurement. For further improvement, measurements should be conducted multiple times and they should be averaged. Even better approach is integrate a measurement over time. An equipment capable of integration over specified periods of time is phase-sensitive voltmeter (lock-in amplifier). A modulated reference signal is provided to the lock-in amplifier together with a modulated measured signal. The lock-in amplifier averages measured signal with the plus sign when the reference is high and it averages with a minus sign when the reference is low. Additionally, an amplification of the voltmeter allows us to measure as small as μV. Low-pass and high-pass filters removes undesired noise that differs much with respect to the reference signal.

6 Appendix II - Self-check evaluation

Questions below may help you to prepare to the the entrance test.

Is the diffusion current directly measured in the experiment? What wavelength of the beam is needed for the experiment? Why conduction electrons are often suppressed from entering the metal at the semiconductor-metal interface? What is charge continuity equation

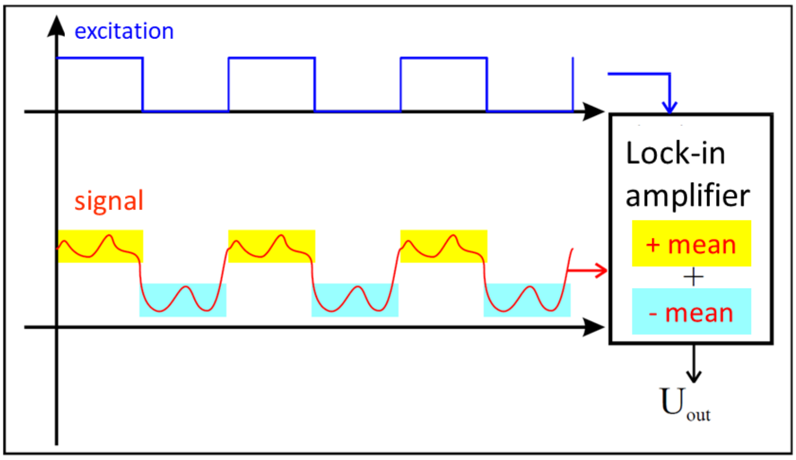

Figure 3: Signals as a function of time in lock-in amplifier. Exciting equipment provides a reference signal. Lock-in amplifier averages measured signal with plus (when the reference is high) or with minus (when the reference is low).

and Shockley equation? Can you attempt solving diffusion equation (5) in 1D Cartesian case? Is the solution similar to or different from the spherical case (and in what way)? Can you attempt to do that in cylindrical coordinates, too? What experimental configurations will these two cases correspond to?

References

[1] R. A. Smith. *Semiconductors.* Cambridge University Press, 1964. chapter: Diffusion of electrons and holes.

[2] H. Ibach and H. Lüth. *Solid-State Physics.* Springer, 2009.

[3] L. B. Valdes. Measurement of minority carrier lifetime in germanium. *Proceedings Inst. Radio Engrs*, 40:1420–1423, 1952. http://ieeexplore.ieee.org/xpl/articleDetails.jsp?partnum=4050845&searchProductType=IEEE%20Journals.

[4] C. Kittel. *Introduction to Solid State Physics.* Wiley.

[5] P. S. Kireev. *Semiconductor Physics.* Mir Publishers.