Non-contact Measurement of Carrier Density and Mobility of Magnetized Materials

L. Laurinavičius

Department of Electrical Engineering, Vilnius Gediminas Technical University
Sauletekio av.11, LT-2040 Vilnius Lithuania
Email: laurinavicius@el.vtu.lt; lagnel4@gmail.com

Abstract. *The microwave density and mobility meter with constant magnetic field source and its measurement possibilities are described. It is shown that method magnetoabsorbsion of magnetoplasmic waves can be used for measurement thin films of magnetic materials. The accuracy of concentration and mobility measurements free charge carriers depends on magnetic induction relative errors. Also it was determined that solid state plasma specimen affects on measurement accuracy.*

Keywords: magnetic field, carrier density, mobility

1. Introduction

Main electrical properties of semiconductors are determined by values of concentration and mobility of free charge carriers in semiconductors. Microwave magnetoplasma methods are successfully used for investigations of semiconductors and semimetals due to their universality [1]. One of well known methods is Rayleigh interferometry when transmitted via investigated specimen microwave signal is compared with reference signal. The reference signal has a constant phase and amplitude. The amplitude and wave length of transmitted wave depend on electrical properties of a semiconductor. Therefore observing dimensional resonance of magnetoplasma waves in a semiconductor specimen, placed in pulsed magnets, which can generate a strong magnetic field it is possible to determine the concentration and mobility of free charge carriers of semiconductors. But such as it is measurement equipment is complicated and there are problems to measure thin specimen, because transmitted signal is weak. The accuracy of measurement can't be so high, because there are so many measured parameters: amplitudes of oscillations, magnetic induction and geometrical size of specimen.

In present article the author offer method to measure concentration and mobility of free charge carriers of semiconductors based on magnetoplasma phenomenon to absorb the HF signal. HF resonator lumped elements is proposed.

2. Physical background of investigation

If semiconductor specimen is placed in external magnetic field, radio microwaves can propagate in semiconductor along the direction of magnetic induction B. The propagation of magnetoplasma wave is determined by dispersion equation [2]

$$c^2 \frac{k^2}{\omega^2} = \varepsilon_{\pm}' + i\varepsilon_{\pm}'' = \varepsilon_L \left(1 - \frac{\omega_p}{\omega\left[(\omega \pm \omega_c) + i\nu\right]} \right), \tag{1}$$

where k is wave vector, ω is frequency, ε_L is lattice constant of semiconductor, $\omega_c = eB/m^{\otimes}$ is cyclotron frequency, $\omega_p = \left(\frac{e^2 n}{m^{\otimes} \varepsilon_0 \varepsilon_L} \right)^{1/2}$ is plasmas frequency, $\nu = 1/\tau$ is frequency of carrier's collisions.

The conditions when magnetoplasma helicon waves can propagate in magnetic material are as followings:

$$\omega \pm \omega_c >> \nu; \qquad \omega_c >> \omega; \qquad \omega_c \tau \equiv \mu B >> 1. \tag{2}$$

The length λ of helicon waves is determined by equation [3]

$$\lambda / 2 = \pi / k' = \frac{c}{\omega}\frac{1}{\sqrt{\varepsilon'}} = \frac{c}{\omega}\left(\frac{\varepsilon_0 \omega B}{eN}\right)^{1/2}. \tag{3}$$

It means that it is possible to determine the density of free charge carriers by observation of dimensional resonances of magnetoplasma microwaves in magnetic materials.

When mine (half – length) resonance is observed, the value of density N is determined by simple equation

$$N = \frac{A \cdot B}{d^2 \cdot f_R}, \tag{4}$$

where B is magnetic induction, f_R is exciting frequency ($d = \lambda_H/2$), d is thickness of the specimen, λ_H is wavelength of helicon and A = const.

When exciting frequencies $f << f_R$, we have non-resonance conditions in the specimen. In this case values of concentration N and mobility μ it is possible to determine by analysing tensor of specimen conductivity $|\sigma|$. Tensor of conductivity $|\sigma|$ looks as following [4]:

$$|\sigma| = \begin{Vmatrix} \sigma_{xx} & \sigma_{xy} & 0 \\ \sigma_{yx} & \sigma_{yy} & 0 \\ 0 & 0 & \sigma_{zz} \end{Vmatrix} = \begin{Vmatrix} \frac{\sigma_{zz}}{1+\omega_c^2\tau^2} & \frac{\omega_c\tau\sigma_{zz}}{1+\omega_c^2\tau^2} & 0 \\ \frac{\omega_c\tau\sigma_{zz}}{1+\omega_c^2\tau^2} & \frac{\sigma_{zz}}{1+\omega_c^2\tau^2} & 0 \\ 0 & 0 & \sigma_{zz} \end{Vmatrix}. \tag{5}$$

3. Realization of non – contact HF meter and experiment

Experimentally curves of magnetoplasma wave responses can be observed with high frequency meter whose simplified block diagram is shown in Fig. 1

A semiconductor specimen 1 is put in pulsed magnetic field generated by two axial solenoids of electromagnet 2. High frequency generator 3 is connected with coil 4 of LC resonator. The magnetoplasma wave is excited in local area of a semiconductor plate put in a constant magnetic field. Propagating across semiconductor plate magnetoplasma wave is indicated by the same coil 4. A receiving signal is indicated by memorized oscilloscope 5. Magnetic field control system 6 is connected to the oscilloscope 5. Described magnetoplasma meter has also a pulsed current source, magnetic field sensor and a scanning mechanism which are not shown.

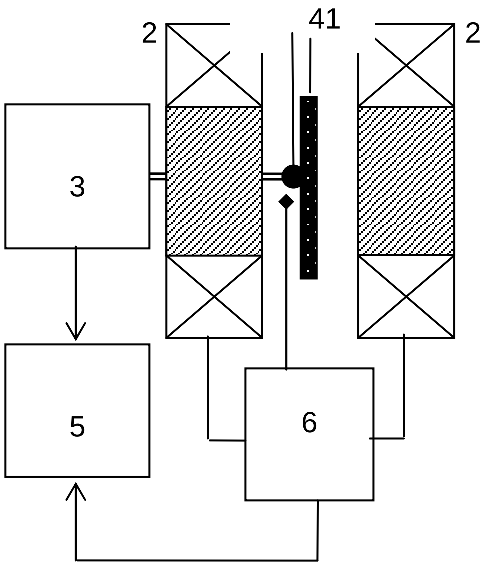

Fig. 1. Block diagram of magnetoplasma meter.

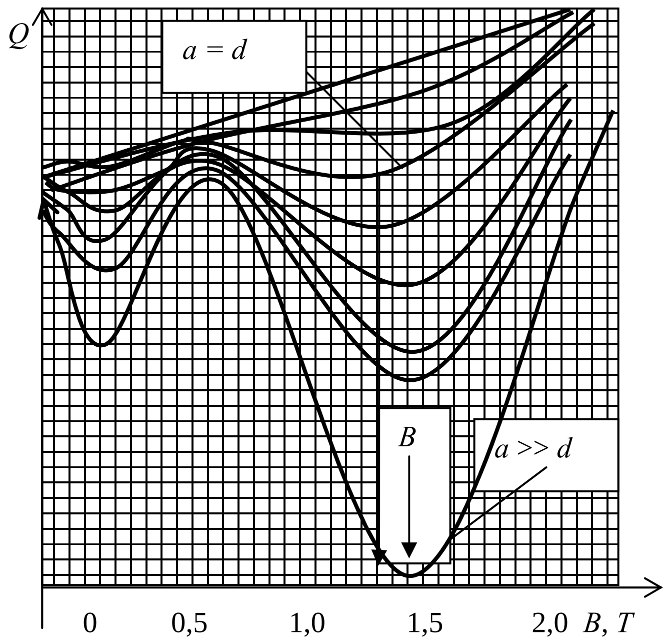

Fig. 2. Measurement of density. High frequency signal (quality of resonator Q) dependence from magnetic induction B.

Quality of induction coil (LC – resonator) placed on the surface of semiconductor in magnetic fields, when frequency of generator is $\omega_R \cong \omega$ is very low, because $Q = \frac{\sqrt{L/C}}{R}$ resistance losses R is high (mine dimensional resonance of helicon waves). The value of density N is determined (see Fig. 2) by equation (4).

When exciting frequencies $f << f_R$, we have non-resonance conditions in the specimen and dependence $Q = f(B)$ is measured.

Quality of LC – resonator Q is described by equation:

$$Q \equiv \sigma_{xx} = \frac{\sigma_{zz}}{1+\mu^2 B^2} = \frac{e \cdot N \cdot \mu}{1+\mu^2 B^2}, \tag{6}$$

where e, N, μ are mobility, density and charge of electrons respectively.
Mobility of electrons can be calculated very simply

$$\mu = \frac{1}{B_{1/2}}, \tag{7}$$

And quality $Q_{1/2} = (Q_B - Q_0)/2$.

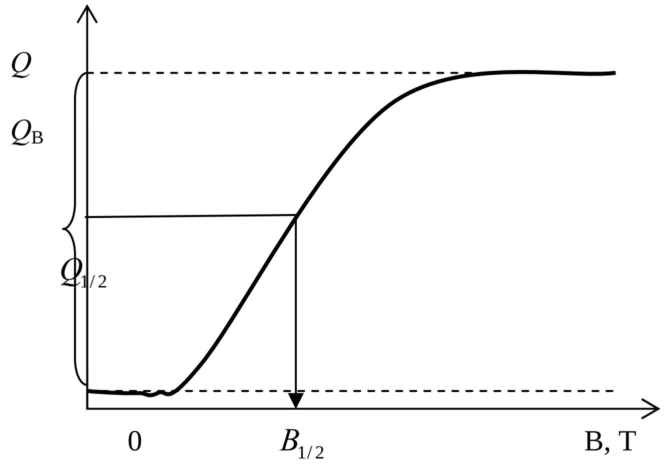

Fig. 3. Measurement of mobility. High frequency signal dependence from magnetic induction B.

4. Accuracy evaluation

The relative error of concentration can be determined by formula

$$\left(\frac{\Delta n}{n}\right)=\sqrt{\left(A_f\left(\frac{\Delta f}{f}\right)\right)^2+\left(A_d\left(\frac{\Delta d}{d}\right)\right)^2+\left(A_B\left(\frac{\Delta B}{B}\right)\right)^2}\ , \tag{8}$$

where $\frac{\Delta f}{f}$, $\frac{\Delta d}{d}$, $\frac{\Delta B}{B}$ are relative errors of frequency, sample thickness, magnetic induction respectively. A_f, A_d, A_B are influence coefficients proportional to partial derivatives of output signal. Determined values of these coefficients are A_f = -1, A_d = - 2, A_B = - 1.

A relative error of frequency determination of modern generators is less then ± 1 %. The thickness of the specimen can be measured with relative error less then ± 1 %. Magnetic field induction is controlled by memorized oscilloscopes. So magnetic field can be determined with relative error no more than $\pm$ 5 %.

Taking $\frac{\Delta f}{f} = \pm 1\%$, $\frac{\Delta d}{d} = \pm 1$ %, $\frac{\Delta B}{B} = \pm 5\%$ it was cleared that the relative error of concentration is determined in general and one does not exceed ± 5 %.

The relative error of mobility depends only of relative error of magnetic induction $\frac{\Delta B}{B}$. It was calculated, the relative error of mobility does not exceed ± 10 %.

Solid state plasma specimen size have influenced on measurement accuracy of density. If the geometrical size *a* of measurement aperture (coil) is less than *d*, the curve extreme is moving to the side of less induction. If the size of aperture is equal to *d* (*a* = *d*) relative error of magnetic induction are increasing.

5. Conclusion

Measurements of density and mobility of free charge carriers were executed in monocristalic specimens of n-Insb, n-GaAs, CdHgTe. We used magnetic field with induction B = 2 T. Good coincidence with technical specification of specimens was confirmed. Proposed method for measurement mobility of free carrier can be used in express measurement of thin films of magnetized materials.

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