The Measurements of Carrier Density and Mobility in Magnetised Materials by the Help of Helicon Maser

Zigmantas Jankauskas, Vygaudas Kvedaras, Laimis Laurinavicius

Department of Electrical Engineering Vilnius Gediminas Technical University
Sauletekio av.11, LT-2040 Vilnius Lithuania
Phone: +370 684 13849; E-mail: zjan@el.vtu.lt; vk@el.vtu.lt; laurinavicius@el.vtu.lt

Abstract *A new measurement method of the carrier density and mobility in metals and semiconductors by the help of magnetoplasmic helicon waves in magnetised solid-state plasma is proposed. The helicons in this case are excited by radio frequencies f_1 (the range 100 – 600 MHz) much higher than the helicon resonator frequency f_2 (the range ~ 20 MHz). From the frequency f_2 and the resonance bandwidth the carrier density and mobility may be obtained. It is expedient to call such a device a sort of helicon maser and a high radio frequency electromagnetic field the pumping field. In full analogy with maser (o laser) the semiconductor sample plays a role of the active material and the cable line – of the resonator.*

In the experimental device the semiconductor n- InSb was used for the active material. The constant magnetic field varied within the interval 0-23 T.

1. Introduction

Radio frequency magnetoplasmic waves known as helicons will propagate in solid-state plasmas when a strong magnetic field H_0 is applied and conditions $\omega_H\tau$ is satisfied, where ω_H is the cyclotron frequency, and τ is the collision time [1]. The helicons are being used to determine carrier densities and mobility in metals and semiconductors [2].

In this paper we want to describe a new method for excitation and detection of magnetoplasmic helicon, when the excitation frequency f_1 (the range 100 – 600 MHz) is much higher than the helicon resonator frequency f_2 (the range ~ 20 MHz). From the frequency f_2 and the resonance bandwidth the carrier density and mobility may be obtained. It is expedient to call such a device a sort of helicon maser and a high frequency f_1 electromagnetic field the pumping field.

2. Subject and Methods

The block diagram of the experimental device is shown in Fig. 1. Here 1 is metal or semiconductor sample in the

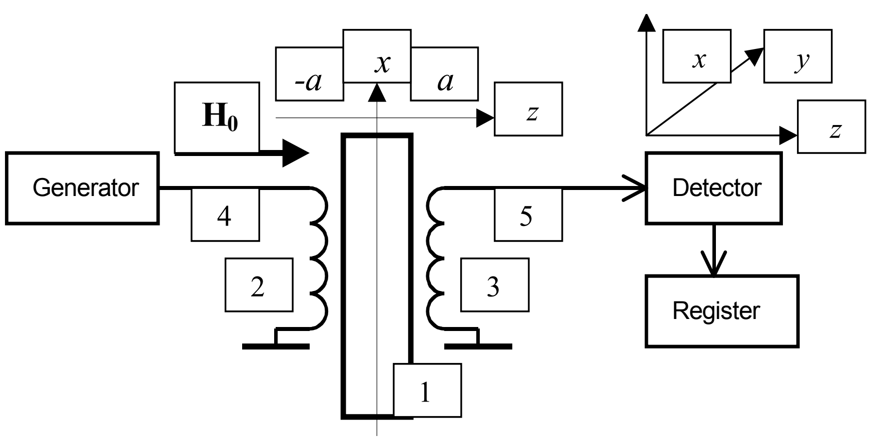

Fig. 1 The experimental device

form of plate; 2 is excitation coil; 3 is pickup coil; 4 and 5 are coaxial cable lines.

The direction of the coordinate axes *x, y, z* are also shown. The constant magnetic field $\mathbf{H_0}$ is directed along the axis *z* and is perpendicular to the sample plane *x-y*.

We shall for the sake of simplicity assume the sample plate to be infinitely large in *x-y* direction. The sample thickness is 2*a*.

When the constant magnetic field $H_0 = 0$ the oscillating magnetic field has only one component H_x along the *x* axis and electrical current has accordingly only one component j_y along the *y* axis. If the field $H_0 \neq 0$ the Hall current j_x and corresponding H_y components will appear and magnetoplasmic helicon waves may excited.

The effective magnetic permeability of the transformer's 2-1-3 core 1 on Fig. 1 is [2]

$$\mu_{eff} = \frac{tgk_{-}a}{2k_{-}a} + \frac{tgk_{+}a}{2k_{+}a}, \tag{1}$$

The propagation vectors $k_{\pm}$ may be detected from the characteristic equation

$$c^2 k_{\pm}^2 = \frac{\omega_p^2 \omega}{\pm\omega_H + i\tau^{-1}},\ \omega_p^2 = \frac{4\pi Ne^2}{m}, \qquad \omega_H = \frac{eH}{mc}. \tag{2}$$

where N, e, m and τ are the density, charge, mass and collision time of the electrons (we assume that the conductivity of the sample 1 is provided by the electrons with an isotropic mass). The item with the argument k_+ in eq. (1) is caused by the helicon waves.

In the case of strong constant magnetic field H_0 when $\omega_H\tau >> 1$ we have from (2)

$$k_+ = \sqrt{\frac{\omega_p^2 \cdot \omega}{\omega_H \cdot c^2}}\left(1 - \frac{i}{2\omega_H\tau}\right), \quad \text{or} \quad k_+ = \sqrt{\frac{4\pi Ne\omega}{H_0 c}}\left(1 - \frac{i}{2\omega_H\tau}\right). \tag{3}$$

The μ_{eff} from the (1) has the maximum in the case of resonance

$$(\mathrm{Re}\,k_+)a = \frac{n\pi}{2},\ n = 1,3,5,... \tag{4}$$

and is equal

$$\max\mu_{eff} = \frac{2i\omega_H\tau}{n^2\cdot\pi^2},\ n = 1,3,5,... \tag{5}$$

The impedance of the transformer coils 2 and 3 in the case of resonance is purely active.

The most appropriate material for the experimental verification is *InSb* semiconductor, where the $\omega_H\tau$ =1 condition may be achieved in the fields of 0,2 Tesla (at the room temperature).

The sweeping of the constant magnetic field changes the circuit voltages and currents, and virtually we have a new circuit at every step. There must be a time interval, when the device's currents and voltages are adjusting to the new magnetic field's values. The time constant at the transient period is proportional to the device's quality *Q*. The quality of the semiconductor sample (active material) $Q_1 = \omega_H\tau \leq 10$. The long cable line quality Q_2 in the resonant mode is much higher $Q_2 = 4000$. The equivalent quality of helicon maser (active sample + long line resonator) will be nearer to Q_2 and in our experiments reaches the value $Q = 300$.

If the helicon maser (HM) is connected to the pumping RF generator with the frequency f_1 = 100 MHz – 2 GHz, much higher than HM resonant frequency f_2 (in our experiment f_2 = 20 MHz), the pick-up coil (3 on Fig.1) signal during the transition time is proportional to time function [3]

$$F = \frac{1}{f_1^2 - f_2^2}\left(\frac{f_1}{f_2}\sin 2\pi f_2 t - \sin 2\pi f_1 t\right) \tag{6}$$

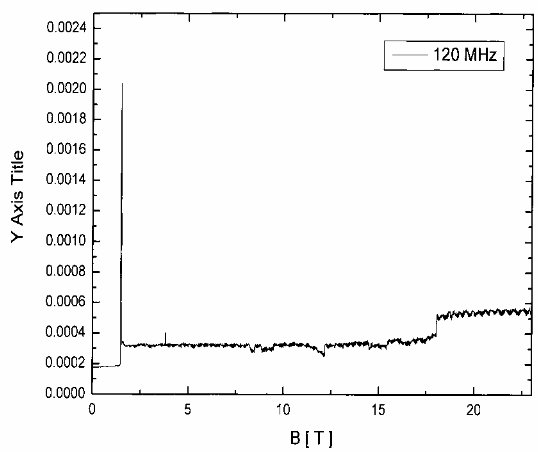

Fig. 2

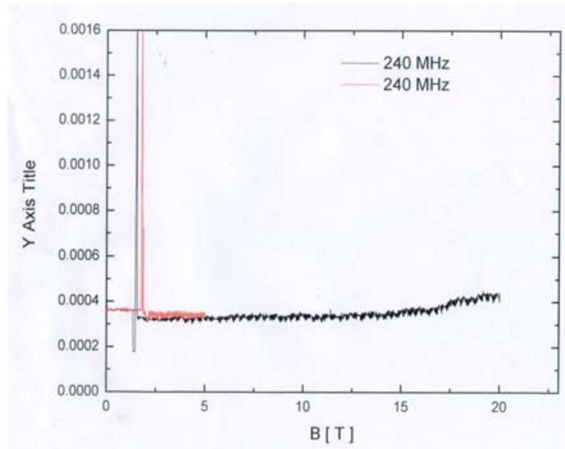

Fig. 3

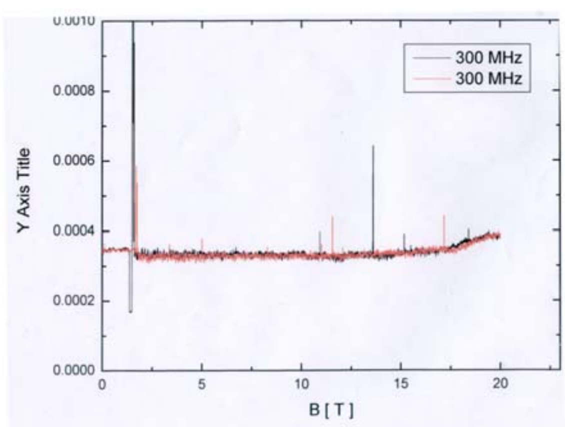

Fig. 4

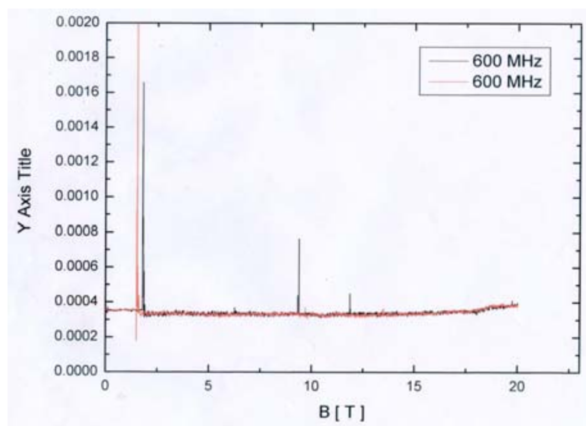

Fig. 5

with the initial condition

$$F(0) = F'(0) = 0. \tag{7}$$

During the transition time the first item (helicon maser response) is much larger than the second (the pumping signal). This maser effect is clearly visible on experimental Fig. 2-5. For the pumping field frequencies f_1 = 120; 240; 300; 600 MHz we have the same helicon generation frequency f_2 = 20 MHz in the magnetic field B = 1,55 Tesla.

3. Results

Experimental results for a sample n-InSb are shown on Fig, 2-5 (carrier density N = $1{,}5 \cdot 10^{16}$ cm^{-3}; mobility $\mu = 5 \cdot 10^4$ $cm^2\, V^{-1} s^{-1}$; sample thickness $2a$ = 0,5 cm; T = 300K). The pick-up signal in volts is plotted versus constant magnetic field induction $B = \mu_0 H$ (in Tesla; $\mu_0 = 4\pi\, 10^{-7}$ H/m). The main helicon generation peak was observed at B= 1,55 T with the helicon frequency $f_2 = \omega/2\pi$ = 20 MHz in the wide range of pumping frequencies f_1 (120; 240; 300; 600 MHz). For higher magnetic fields the higher order instabilities exist. Especially sharp peaks we have for B = 7,57 T; f_1 =600 MHz; f_2 = 100 MHz. B = 14 T; f_1 =300 MHz; f_2 = 180 MHz. For pumping frequency f_1 = 120 MHz only the first instability mode exists as far as the helicon generation is being realised only for f_1 much higher than helicon generation frequency f_2.

In all cases the carrier density may be found (by measuring the generation frequency f_2) from the eq. (3, 4), where $\omega = 2\pi f_2$; $2a$ = 0,5 cm. The carrier mobility μ may be calculated from the resonant peak bandwidth $\omega/\omega_H\tau$.

4. Conclusions

A new measurement method of the carrier density and mobility in metals and semiconductors by the help of magnetoplasmic helicon waves in magnetized solid – state plasma is proposed. The helicons are exited by the radio frequencies much higher that the helicon resonator frequency. From the resonant frequency and resonant bandwidth the carrier density and mobility may be calculated. In full analogy with the maser (or laser) device the semiconductor *InSb* sample plays a role of the active material, the long cable line – of the external resonator. The high RF electromagnetic field works as pumping field.

The measurements were performed at the Grenoble High Magnetic Field laboratory through the EEC "Access to Research Infrastructure action of the Improving Human Potential Program"

References

[1] *B. W. Maxfield.* Helicon waves in solids. American Journ. of Phys. 1969. Vol. 37. PP. 241-269.
[2] *Gayle F. Miner.* Lines and electromagnetic fields for engineers. Oxford University Press. 1996. 1008 p.
[3] *Z. Jankauskas, L. Laurinavicius.* Magnetic and Electric Excitation of Magnetoplasmic Waves. Electronics and Electrical Engineering. 2002. No 2(37). PP. 32-34.