High Magnetic Field Sensing by the Help of Semiconductor Resonator

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Abstract. *The effects of dimensional resonance of magnetoplasmic waves in semiconductors were investigated. It was demonstrated that these effects could be used to measure the high magnetic fields. Possible ways to design contactless magnetic field sensors operating at cryogenic temperature, such as that of liquid nitrogen are discussed. It has been shown that for high field sensors a low gap semiconductor material of high carrier mobility μ is needed.*

Keywords: Semiconductors, Helicon Waves, Dimensional Resonator, Magnetic Field, Sensor

1. Introduction

Magnetic sensors can be classified according to low, medium, or high-field sensing range and operating temperatures. High field or bias field sensors detects fields that are larger than the Earth's field [1]. Conventional sensors can detect a physical property (pressure, temperature and other) directly but magnetic sensors detect changes in magnetic fields and from them derive information on physical properties. The output signal of these sensors requires some signal processing for translation into the desired parameter. Mine high-field sensors technologies are magnetoresistance, Hall and GMR (giant magnetoresistance) effects. Some of sensors, such as magnetoresistors, are capable of measuring fields up to several teslas, others, such as GMR devices, can detect fields smaller than the Earth's field [2]. Sometimes in the practice high pulsed magnetic fields with amplitudes up to 50 T can be generated at room or cryogenic temperatures. The existing magnetic field measurement methods are applicable in case of known magnetic field direction and the accuracy of such methods is low when the direction of magnetic field is not determined in advance or it is changing during experiment [3]. Possible ways to design contactless magnetic field sensors operating at room or cryogenic temperatures, such as that of liquid nitrogen will be discussed.

2. Physical background of investigation

If semiconductor specimen is placed in external magnetic field (Fig.1), microwaves can propagate in semiconductor along the direction of magnetic induction B. The propagation of magnetoplasma wave may be detected from the characteristic equation [4].

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

where k is wave vector, ω is frequency, $\varepsilon_{\pm}$ is complex permittivity, 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:

$$\omega \pm \omega_c >> \nu; \quad \omega_c >> \omega; \qquad \omega_c \tau \equiv \mu B >> 1. \qquad (2)$$

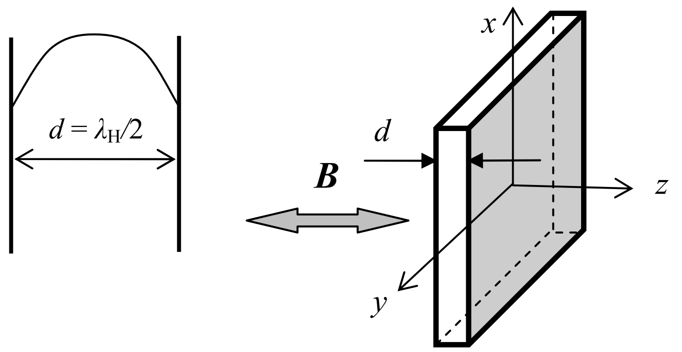

Fig.1. Semiconductor specimen is placed in external magnetic field B.

The length λ_H of helicon waves is determined by equation [5]

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

It means that it is possible to determine the density of free charge carriers N 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

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

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

Physical background of the operation of magnetic field sensor is based on the effect of the dimensional resonance of magnetoplasma waves in known semiconductor plate (charge carriers N) placed in the static magnetic field.

3. Experimental results

The technical possibility to realize the magnetic field (B) sensor by the help of high frequency Hall effect in semiconductors was proposed by author [6]. A current-carrying InSb semiconductor plate is kept in a magnetic field and has two electrodes. The Hall voltage increases with applied field to several teslas. The temperature dependence of the voltage is governed by the temperature dependence of the carrier mobility μ. Different semiconductor materials and different doping levels result in trade-offs between sensitivity and temperature dependence of sensor.

The main objective of the present paper is to show that it is possible to determine the magnetic induction B by observation of dimensional resonances of magnetoplasma microwaves in semiconductors. Thus, it is possible to create a non-contacting field sensor which design is shown in Fig. 2. A non-contacting high field sensor may be developed by applying two perpendicular coils to a semiconductor plate of finite dimensionality. Then, by satisfying the conditions of helicon origination (2) we may obtain coupling of coils of a resonant character.

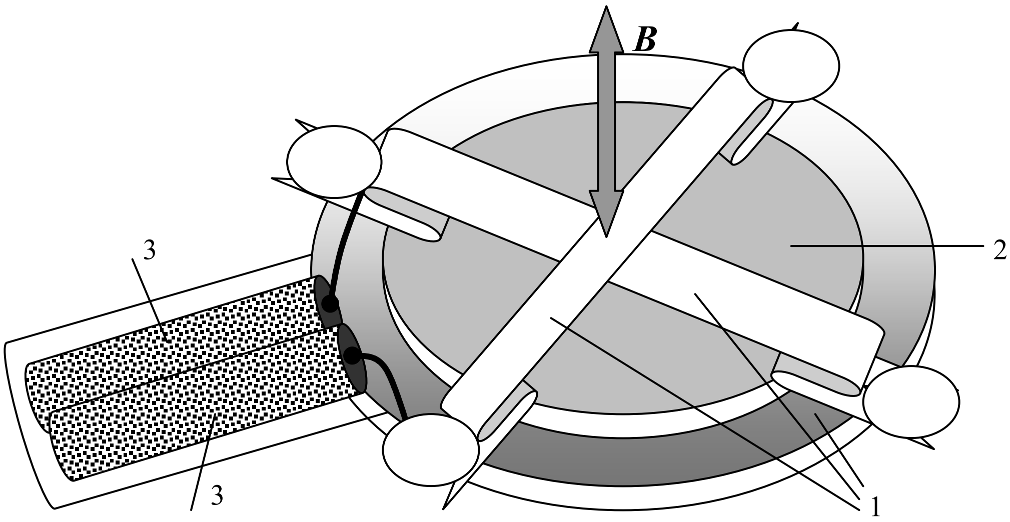

Fig. 2. A semiconductor sample (gyrotropic filling - helicon resonator) is placed into d.c. magnetic field *B* and a.c. microwawe field *b*: 1– microstrip lines; 2 – semiconductor layer; 3 – coaxial lines.

The magnetic induction *B* can be easy calculated from typical amplitude frequency response in Fig. 3:

$$B = 1{,}28 \cdot 10^{-25} N \cdot f_R \cdot d^2. \qquad (5)$$

A simplified block diagram of high magnetic field meter is shown in Fig. 4. A semiconductor plate (magnetic sensor) 1 is put in magnetic field generated by axial solenoids 2. High frequency generator 3 is connected with exciting microstrip line (coil) 4. The helicon wave is excited in local area of a semiconductor plate. Propagating across semiconductor plate helicon wave is indicated by receiving micro-strip line (coil) 5, situated perpendicular to exciting. A receiving signal is registered by recorder 6. Described magnetoplasma magnetic field meter has also a high frequency detector 7, cryogenic system and signal analyser which are not shown.

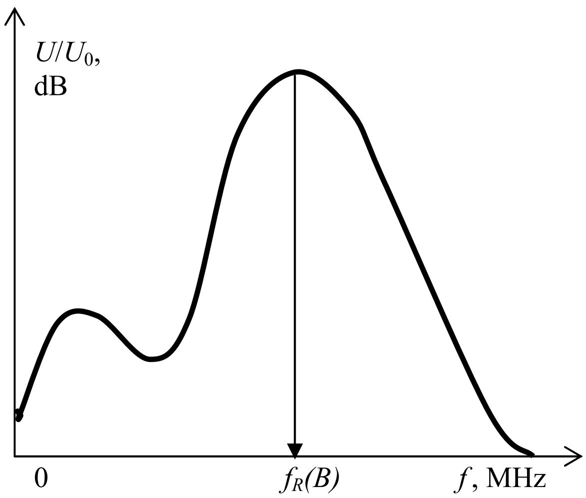

Fig. 3. A typical amplitude frequency response.

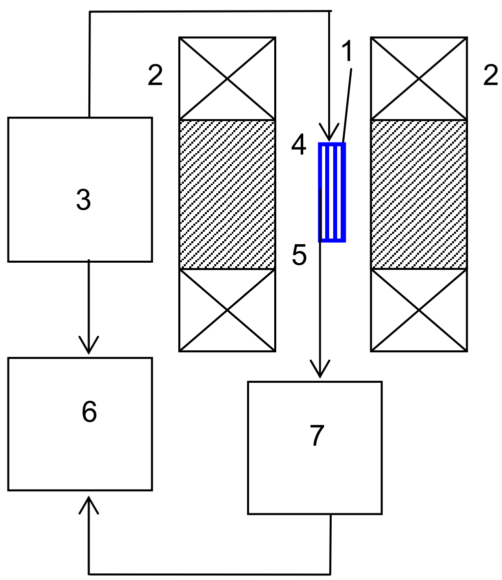

Fig. 4. Block diagram of high magnetic field meter

For the magnetic fields less than 2T, the most suitable semiconductor material is alloy $Cd_xHg_{1-x}Te$ or Te-doped *n*-InSb of high carrier mobility and high mine carrier density $N >$ 0,8 10^{23} m^{-3}. At cryogenic and at room temperatures f_R (B_R) dependence is linear (Fig. 5).

4. Conclusions

The measurements of magnetic induction by the help of helicon waves in semiconductors could be provided in contactless mode. Practically all semiconductor materials can be put into practice if the high magnetic field (~20 Tesla) is available. Magnetic field sensing by the help of semiconductor helicon resonator can be used at cryogenic temperatures as well. The measurement results are in compliance with data obtained by the use of different field sensing methods (technologies).

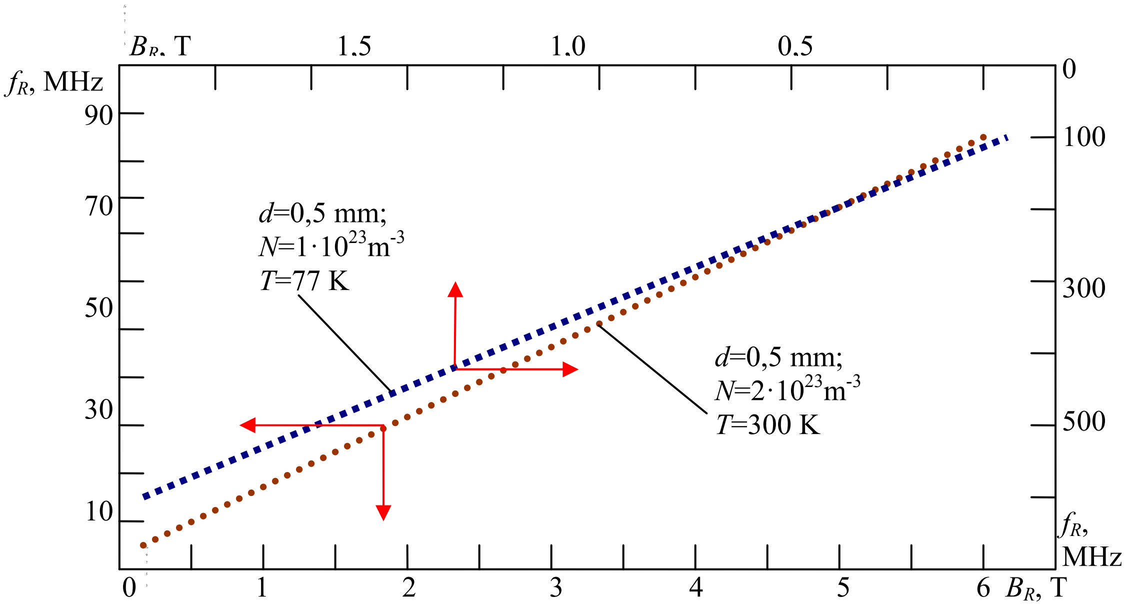

Fig. 5. High frequency f_R dependence from magnetic induction B_R at room and at liquid nitrogen temperatures.

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