Physical Aspects of Microwave and Radar Applications

Microwave Radar for Non-Destructive Express Testing of Electrical Properties of Semiconductor Materials

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Microwave radar for non-destructive express testing of electrical properties of semiconductor materials which consists of pulsed magnet, transmitting and receiving antennas, high frequency generator, pulsed modulator and digital oscilloscope is described. In semiconductor specimen placed in pulsed magnetic field a magnetoplasmic wave is excited and propagated through the specimen. Delay time and attenuation of transmitted and reference signals are measured to find a value of concentration and mobility of free charge carriers in semiconductors. Experimental data of testing of InSb, n-InSb specimens are presented and acceptable for express testing correspondence of results was achieved.

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1. Introduction

Modern technologies allow producing various semiconductor materials with unique parameters and their electrical properties should be constantly tested to provide high quality of electronic devices. Therefore testing of electrical properties of semiconductor materials is very topical subject due to practical importance and it was developed in the same pace as electronics to guarantee technical support of fundamental investigations in semiconductor physics and technology. Main electrical properties of semiconductor materials can be characterized by values of concentration and mobility of free charge carriers. In variety of measuring methods non-destructive methods have evident advantage because provide high productivity and do not require additional contacts or surface processing of tested specimens [1].

When magnetoplasmic waves were discovered it has become natural to use them for measurements of electrical properties of semiconductors because differently to ordinary electromagnetic waves magnetoplasmic waves can propagate inside of the conductive area placed in external magnetic field and wave dispersion depends on its electrical properties [2].

There are two common methods mainly used for microwave magnetoplasmic investigations in semiconductors. One of them is based on magnetoreflection and another one is based on magnetotransmission phenomena. In case of finite thickness of the specimen the dependence of magnetoreflection and magnetotransmission on magnetic field has a resonant character. Measuring oscillation of the Fabry–Perot resonance of magnetoplasmic wave a concentration of free charge carriers can be specified [3]. In case of magnetotransmission Rayleigh interferometer can be used successfully [4]. Such facility consists of the reference signal arm and the sample arm. A phase shifter and an attenuator are used to change the phase and amplitude of reference signal. Semiconductor specimen is placed in the sample arm between the special dielectric waveguide sensors put in external magnet. A special design of sensors provides the local excitation and indication of magnetoplasmic wave in 24–37 GHz range. Values of concentration and mobility of free charge carriers in semiconductors can be calculated measuring periods and amplitudes of oscillations because the phase and amplitude of magnetoplasmic wave depend on electrical properties of tested specimen [5]. In case of testing electrical properties of semiconductor alloys and doped semiconductors with high more than 10^{22} m^{-3} concentration of free charge carriers it is more preferable to carry out measurements in high frequency range up to 3 GHz because damping of magnetoplasmic waves is proportional to frequency [6].

Main conditions of magnetoplasmic wave propagation used in microwave range are valid in radio frequency range, too. General distinctions appear in device design and the measurement technology. But in any case magnetic flux density is the most limited factor in all magnetoplasmic methods. The higher magnetic field is experimentally available the wider measurement ranges of concentration and mobility of free charge carriers of semiconductors can be achieved. Therefore high frequency methods combined with the application of pulsed magnetic fields prove to be very useful, because they provide non-destructive testing of electrical properties of

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semiconductor materials over the wide range of measurements [7].

The experimental infrastructure of Vilnius Magnetic Field Centre includes a variety of compact pulsed magnetic field generators equipped with low temperature liquid nitrogen vessels and nanosecond duration high voltage electrical pulse generators, high frequency generators and real time measurement systems [8]. Recently physical properties of semiconductors, polycrystalline manganites, single crystals and thin films are investigated intensively [9]. Electrical and magnetic properties of thin films have become a special interest due to their potential application in the development of spin-electronics devices, nanostructured devices and magnetic field sensors [10].

In present article pulsed power facilities for investigation of electrical properties of semiconductor materials are described. The principle of operation of microwave radar is based on pulsed magnetoplasmic waves excitation technique in semiconductors placed in pulsed magnetic field [11].

2. Principle of operation

If a semiconductor specimen is placed in external magnetic field, high frequency circularly polarized plane magnetoplasmic waves can be excited and propagate in semiconductor area along the direction of magnetic flux.

In general case the propagation of magnetoplasmic wave in semiconductor can be characterized by dispersion equation [12]:

$$\frac{k^2c^2}{\omega^2} = \varepsilon'_\pm + \mathrm{i}\varepsilon''_\pm = \varepsilon_1\left(1 - \frac{\omega_\mathrm{p}^2}{\omega\left[(\omega \pm \omega_\mathrm{c}) + \mathrm{i}v\right]}\right). \quad (1)$$

Here k is propagation constant, c is light velocity in vacuum, $\varepsilon'_\pm, \varepsilon''_\pm$ are the real and imaginary parts of the complex relative dielectric constant in the medium respectively, ω is exciting frequency, $\omega_\mathrm{c} = eB/m^*$ is frequency of cyclotron resonance, $v = 1/\tau$ is frequency of carriers collisions, $\omega_\mathrm{p} = \sqrt{en^2/m^*\varepsilon_0\varepsilon_1}$ is plasma frequency, B is magnetic flux density, ε_0 is dielectric constant, ε_1 is lattice constant, m^* and n are effective mass and concentration of free charge carriers, respectively. The subscripts (+) and (−) refer to the ordinary and extraordinary waves. A wave is called extraordinary if the direction of field circularly polarization coincides with cyclotron rotation of free charge carriers. In our case extraordinary waves only are of interest for further technological applications.

For extraordinary wave equations of real and imaginary parts of complex relative dielectric constant look as follows:

$$\varepsilon' = \varepsilon_1\left(1 - \frac{\omega_\mathrm{p}^2(\omega - \omega_\mathrm{c})}{\omega\left(v^2 + (\omega - \omega_\mathrm{c})^2\right)}\right),$$

$$\varepsilon'' = \varepsilon_1\left(\frac{\omega_\mathrm{p}^2 v}{\omega\left(v^2 + (\omega - \omega_\mathrm{c})^2\right)}\right). \quad (2)$$

Magnetoplasmic waves can propagate in semiconductor if lossless conditions are carried out [2]:

$$\omega \pm \omega_\mathrm{c} \gg v\,, \quad \omega_\mathrm{c} \gg \omega\,, \quad \omega_\mathrm{c}\tau \equiv \mu B \gg 1\,. \quad (3)$$

If a semiconductor has n-type conductivity and enough high mobility $\mu$of electrons, an isotropic effective mass m^*, constant relaxation time τ equations of real and imaginary parts of the complex relative dielectric constant for extraordinary wave can be simplified as:

$$\varepsilon' = \varepsilon_1\left(1 + \frac{\omega_\mathrm{p}^2}{\omega_\mathrm{c}\omega}\right) = \varepsilon_1\left(1 + \frac{en}{\varepsilon_0\varepsilon_1\omega B}\right),$$

$$\varepsilon'' = \frac{\varepsilon_1 v\omega_\mathrm{p}^2}{\omega\omega_\mathrm{c}^2} = \frac{en}{\varepsilon_0\omega\mu B^2}\,. \quad (4)$$

Obtained real and imaginary parts of the complex relative dielectric constant in medium allow us to find main parameters characterising magnetoplasmic wave propagation in semiconductor specimen placed in external magnetic field with constant magnetic flux density B.

Wavelength of magnetoplasmic wave depends on concentration of electrons and can be expressed as

$$\lambda = \frac{c}{\omega}\frac{2\pi}{\sqrt{\varepsilon'}} = 2\pi\frac{c}{\omega}\sqrt{\frac{\varepsilon_0\omega B}{en}}\,. \quad (5)$$

Amplitude of propagated wave at opposite surface of specimen with thickness of d is

$$A_\mathrm{t} = A_0\exp\left(-k''d\right). \quad (6)$$

Here $k'' = \omega\varepsilon''/2c\sqrt{\varepsilon'}$ is an imaginary part of wave propagating constant or wave damping factor, which depends on mobility of free charge carriers in semiconductor. Therefore measuring the damping of magnetoplasmic wave it is possible to evaluate mobility of electrons in magnetized semiconductor specimen.

A wave packet or rectangular-shaped pulse modulated sinusoidal signal propagating in dispersive medium can be defined with spectrum of superposition of different harmonically related sine waves using the Fourier analysis [13]:

$$\phi(z,t) = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{+\infty}\mathrm{d}\omega A(\omega) \times \exp\left(\mathrm{i}\left(\frac{N(\omega)\omega}{c}z - \omega t\right)\right). \quad (7)$$

Here $\phi(z,t)$ is a wave packet, $A(\omega)$ is the Fourier component, $N(\omega)$ is index of refraction.

The spectrum of a rectangular-shaped pulse modulated sinusoidal signal with carrier frequency ω_0 and pulse width τ_0 is centred at frequency ω_0 and amplitudes of spectral lines are varied according to $\sin(\omega\tau_0/2)(\omega\tau_0/2)^{-1}$. As longer pulse is modulated as narrower distribution of spectral lines close to central spectral line at ω_0 can be achieved. Every sine component with frequency ω will propagate with phase velocity $v_\mathrm{p} = \omega/k$ and pulse propagation as a superposition of different harmonically related sine waves can be characterised with group velocity $v_\mathrm{g} = \mathrm{d}\omega/\mathrm{d}k$.

A group velocity of pulse modulated sinusoidal signal can also be expressed as

$$v_\mathrm{g} = v_\mathrm{p}\left(1 - \frac{k}{N}\frac{\mathrm{d}N}{\mathrm{d}k}\right) = v_\mathrm{p} - \lambda\frac{\mathrm{d}v_\mathrm{p}}{\mathrm{d}\lambda}\,. \tag{8}$$

Here N is real part of the index of refraction, λ is wavelength.

In case $\tau_0 \gg 1/\omega_0$ a spectrum of pulse modulated sinusoidal signal can be simplified to monochromatic wave spectrum due to negligible frequency difference $\mathrm{d}\omega$ in spectrum and in lossless and non-resonant magnetoplasma a pulse will propagate with group velocity close to phase one. Therefore for first estimation the velocity of pulse modulated magnetoplasmic wave can be expressed as

$$v \cong c\sqrt{\frac{\varepsilon_0\omega B}{en}}\,. \tag{9}$$

In semiconductor alloys and doped semiconductors with high more than 10^{22} m^{-3} concentration of electrons velocity of magnetoplasmic wave is much smaller than velocity in free space. Therefore such materials are being tested with pulsed technique in nanosecond range. Measuring delay of microwave signal propagating through a magnetized semiconductor specimen with thickness d and a reference one the value of concentration n of free charge carriers in semiconductors can be found as

$$n \cong \frac{\varepsilon_0\omega Bc^2}{ed^2}\Delta t^2 = C_n\Delta t^2. \tag{10}$$

In case of constant thickness d of investigated specimens, magnetic flux density B and frequency ω of excited magnetoplasmic wave it is enough to control a signal delay Δt only. Such express measurements can be very useful to sort out specimen lot with different parameters.

Mobility of free charge carriers in semiconductor can be specified from Eqs. (4) and (6) as

$$\mu \cong \sqrt{\frac{en\omega d^2}{4\varepsilon_0 c^2 B^3}}\left(\ln\frac{A_0}{A}\right)^{-1} = C_\mu\left(\ln\frac{A_0}{A_\mathrm{t}}\right)^{-1}. \tag{11}$$

Here $A_0 = (1/\tau_0)\int p_0(t)\,\mathrm{d}t$ and $A_\mathrm{t} = (1/\tau_0)\int p_\mathrm{t}(t)\,\mathrm{d}t$ are amplitudes of referenced $p_0(t)$ and transmitted $p_\mathrm{t}(t)$ envelope of modulated pulse. Values of constants C_n and C_μ depend on experimental conditions, technical parameters of pulsed and microwave facilities and can be determined using calibrated semiconductor specimens with known concentration and mobility of electrons. But in case of strong dispersion a shape, amplitude and pulse width is changed significantly and it becomes enough difficult to evaluate damping factor of propagated wave. Therefore additional correction coefficients [14] and spectrum analysis [15] should be introduced.

3. Structure of microwave radar

The structure of microwave radar for non-destructive express testing of electrical properties of semiconductor materials is presented in Fig. 1.

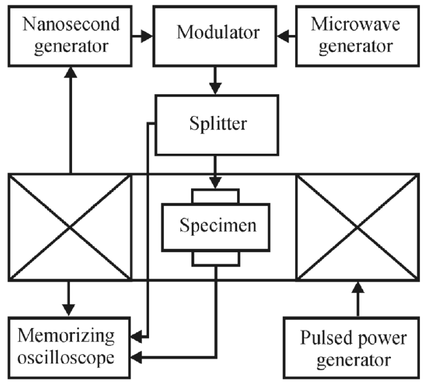

Fig. 1. Structure of microwave radar for non-destructive express testing of electrical properties of semiconductor materials.

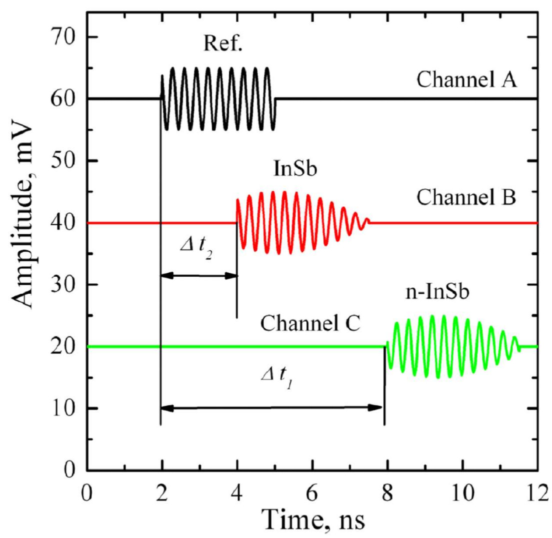

Fig. 2. Schematic view of propagating through InSb and n-InSb specimens signals and reference one.

Tested semiconductor specimen is placed in the centre of a pulsed coil which is connected to 80 kJ pulsed power generator. It consists of 4 kV high voltage power supply, 10 mF capacitor bank, optically (600 nm) controlled by remote unit 50 kA thyristor switch. Discharging the capacitor bank through the pulsed coil a sinusoid shape pulse of magnetic field up to 40 T and 1–10 ms duration can be generated [16]. An amplitude and shape of generated magnetic field pulse is controlled with magnetic field sensor (for simplicity not shown) [17]. For excitation of magnetoplasmic waves 3–30 GHz generators can be used. A microwave signal from generator is modulated with a modulator controlled by pulse generator.

For these purposes a mercury switch to discharge a coaxial transmission line is used. A pulse with 1 ns rise time and 10–100 ns in duration (duration is twice the time delay of the transmission line) is obtained. The modulator via splitter is connected to exciting antenna placed on one surface of tested specimen. Modulated microwave pulse excites magnetoplasmic wave in tested semiconductor specimen placed in external pulsed magnetic field. Propagating through the specimen magnetoplasmic wave is received by the antenna placed directly on another surface of the specimen. Loop antennas of 2 mm in diameter placed on the end of coaxial lines are applied with 3 GHz generator [18]. Receiving signal, reference signal and magnetic pulse are registered by digital memorizing oscilloscope. The operation of all electronic devices is synchronized to insure exact measurements at maximum of magnetic pulse. Receiving signal is recorded and compared with reference one to find delay and attenuation of propagating microwave wave. A view of recorded signals is shown in Fig. 2.

4. Experimental results

The operation of offered microwave radar has been demonstrated by testing of electrical properties of InSb, n-InSb semiconductors. The goal of offered experimental facilities was to demonstrate the possibility to realize described method in principle. As to accuracy of measurements due to strongly simplified model, experimental conditions and signal processing it was not forecasted. Chosen specimens had a thickness of 4–12 mm and were tested in pulsed 10 T magnetic fields. A delay time and attenuation of propagated signal was evaluated to calculate concentration and mobility of free charge carriers in semiconductors. Depending on concentration of free charge carriers and thickness of tested specimens delay time of 1–4 ns was measured.

Some data of concentration and mobility of electrons in tested semiconductor specimens can be found in Table.

All specimens were tested in 10 T magnetic field and at 293 K temperature. High frequency 3 GHz signal was modulated with the pulse of 30 ns in duration and 1 ns rise time. Non-homogeneity of pulsed magnetic field was not taken into account because millisecond magnetic pulse for nanosecond process can be described as a constant one if measurements are synchronized and executed at the moment close to maximum of generated magnetic field. Every measurement was repeated few times to achieve reproducible results. Many factors as signals interference, position of antennas, geometrical sizes, exciting condition, holding of specimens strongly influenced the results. In experiments it was difficult enough to specify delay and attenuation of strongly distorted real pulses with different rise time and shape. As the shorter delay should be registered, higher indetermination of obtained results took place. But in any case obtained results were enough reproducible especially with highly doped semiconductor specimens.

TABLE

Measured and reference values of concentration and mobility of electrons in tested semiconductor specimens.

Specimen	Thickness [10^{-3} m]	Delay [10^{-9} s]	Concentration [10^{22} m^{-3}]		Mobility [m^2 V^{-1} s^{-1}]	
	measured		measured	reference	measured	reference
InSb	8.0	1.1	1.8	1.6	5.2	6.8
InSb	12.0	1.6	1.7	1.6	5.6	6.8
n-InSb	6.2	2.2	13	12	3.4	4.2
n-InSb	4.2	1.6	16	14	3.3	3.9
n-InSb	9.8	3.8	15	14	3.6	3.9

5. Conclusions

Offered conception of microwave radar for non--destructive express testing of electrical properties of semiconductor materials with pulsed magnetic field source can be used for investigation of various semiconductor materials if lossless conditions for magnetoplasmic wave are carried out. A delay time and attenuation of propagated signal was evaluated to calculate concentration and mobility of free charge carriers in semiconductors. A case of magnetoplasmic circularly polarized plane wave dispersion in isotropic medium has been analyzed. Non-homogeneity, anisotropy, impact of different types of free charge carriers and other factor influencing on wave propagation were not evaluated.

Experiments with InSb and n-InSb specimens were done at room temperature and 10 T pulsed magnetic field. Obtained results of tested semiconductor specimens were enough reproductible. A mismatch of obtained results and reference one took place due to the simplification of dispersion equations and imperfection of microwave signal registration experimental facilities.

Further analysis of magnetoplasmic wave dispersion and improvements of experimental facilities should be done to carry out better correspondence of specified electrical parameters of semiconductors.

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