PHYSICAL PRINCIPLES OF THE MICROWAVE FIELD DETECTION IN THE SEMICONDUCTOR STRUCTURES BY OPTICAL RADIATION.

M.A.Chernikov[(1)], **O.A.Ryabushkin**[(2)]

(1)IRE-Polus Co., Vvedensky sq.1, Fryazino, Moscow Region, 141190, Russia
e-mail: roa228@ire216.msk.su

(2)Institute of Radio Engineering and Electronics, Russian Academy of Sciences,
Vvedensky sq.1, Fryazino, Moscow Region, 141190, Russia
e-mail: roa228@ire216.msk.su

ABSTRACT

A contactless optical method for the microwave field detection in semiconductor structures is proposed in this work. The method is based on the free carriers influence on optical spectrum of the excitonic states in the semiconductor quantum wells. Contactless heating of the electron gas in quantum well by a microwave field results in the change of transmittance and reflectance of light with quantum energy near the character features of the excitonic states. The basic principles of this technique were demonstrated in resent experiments with homogeneous GaAs film.

INTRODUCTION

The semiconductor structures are used for a long time as the microwave field detectors. The microwave field detection by means of the semiconductor bolometers [1] is based on the change of the low-frequency semiconductor conductance under the heating microwave field influence. This conductance change is measured using electrical contacts. Depending on the ratios between the times of momentum and energy relaxations, the period of oscillations and duration of the microwave field impulse, the change of the low-frequency conductance can be determined mainly by the electron or lattice heating. On conditions that the impact ionization of impurities by free carriers can be neglected, the heating of the electrons leads to the change of their mobility, whereas the lattice heating can leads to the change of the free carriers mobility as well as their concentration. The bolometer operating speed restricted mainly by time of the electron energy relaxation in case of electron heating and by speed of the energy exchange between the crystal lattice and the environment in case of lattice heating. The semiconductor diodes in contrast to the usual bolometers are doped spatially inhomogeneous, they have the built-in field. The microwave field detection by the semiconductor diodes [2] is based on the spatial redistribution of the free carriers heated by this field. The free carriers spatial redistribution results in the modification of the built-in fields in the diode, EMF arises. In first approximation, under the microwave field influence, the EMF proportional to the microwave intensity is induced on the diode. This EMF is also measured using electrical contacts. The metal contacts can strongly distort the spatial distribution of the microwave field in the registration region.

The contactless optical spectral methods allow realization of the microwave field detection in the absence of any electrical contacts and closed electrical circuits in the registration region. In principle, it's possible to control the free carriers and the lattice temperatures changes (ΔT_e and ΔT_l correspondingly) in the bolometers under microwave field influence by photoluminescence spectra. A semiconductor sample under the photoluminescence spectrum measurements [3] is illuminated by pump light with quantum energy E_p higher enough than the fundamental absorption edge E_g of the sample. The pump light is absorbed in the sample and creates the electron-holes pairs with kinetic energies higher than thermal motion energy. The electrons and holes fast give excess of their kinetic energy to phonons and are thermalized to conduction band bottom and valence band top correspondingly. The thermalized electrons and holes are recombined with luminescence of light with quantum energy near E_g. The spectra of this luminescence contain information about electron and lattice temperatures. There are many technical methods to determine ΔT_e and ΔT_l from the spectra and thereby to detect microwave field. The changes in the built-in field of the diodes under microwave field influence are also possible to control by optical method. This control can be based on Franz-Keldysh effect [4]. In the presence of an electric field, the electrons of the valence zone can penetrate into the forbidden zone. Then the electrons of valence band can absorb light with quantum energy lower than E_g and transit to conduction band that leads to reduction of the fundamental absorption edge. The other event of Franz-Keldysh effect is the appearance of oscillations in the absorption and reflection spectra for quantum energy larger than E_g. The period of these oscillations unambiguously related with electric field value.

There are also other optical effects in the semiconductors, which can be used for microwave field detection. The many semiconductors possess by electrooptical properties [5]. These properties are due peculiarities of their crystalline structure, they don't depend from free carriers concentration. The microwave electric field leads to change in the optical refractive index of the semiconductor. These changes can be registered for instance by insertion of the semiconductor sample into the one of the shoulders of the Mach-Zehnder interferometer, or by measurements of the polarization changes for the light reflected from the sample. The microwave electric field acts on the bounded electron (excitons and impurities) states in semiconductors due to Stark effect that leads to change in the character energies of the bounded electron states and to ionization by field of these states [6]. These changes are exhibited in the light reflectance and transmittance spectra of the semiconductor.

EXPERIMENT

The microwave electric field acts most effectively on the free carriers. On the other hand, the excitonic states are exhibited most dramatically in the optical spectra of semiconductors and they are sensitive to free carriers temperature and concentration. These phenomena can be used for microwave field detection. The basic principles of the proposing optical method were demonstrated in the recent experiments with homogeneous semiconductor film [7]. The GaAs film with a thickness 3 µm was grown by MOCVD on a 500-µm-thick semiinsulating GaAs substrate. The experiments were performed at T=77K. The free carriers concentration was $\sim 10^{15}\mathrm{cm}^{-3}$ and the carrier mobility was $\sim 10^{4}\ \mathrm{cm}^{2}/(\mathrm{V{\cdot}s})$. The GaAs sample was mounted on a quartz rod, placed into a microwave cavity (3-cm region) and adjusted at the maximum electric field strength. (fig.1). The electric component of the microwave field in the cavity was ~50 V/cm. The sample plane was parallel to the electric field vector. The microwave field intensity in the cavity was modulated at a frequency of *f* = 330 Hz. The probing light beam from an incandescent lamp was passed through a monochromator and transmitted to the sample via an optical fiber F1. The probing light intensity on the sample surface was $\sim 1\ \mathrm{mW/cm}^{2}$. The reflected light was collected and transmitted via optical fiber F2 to photodiode. The microwave modulated reflectance MMR spectrum i.e. relative alteration ΔR/R in the sample reflectance under microwave field influence was measured at the frequency *f* by a lock-in technique. The optical fibers were introduced into the cavity via a slit in the narrow sidewall. This geometry reduces to minimum the possible microwave field distortions in the cavity. For the additional control, we have also measured the photoreflectance PR spectra. The pumping He-Ne laser radiation (quantum energy, E_p = 1.96 eV) with the intensity modulated at the same frequency (330 Hz) was transmitted to the sample via optical fiber F3. The pumping light intensity on the sample surface was $\sim 100\ \mathrm{mW/cm}^{2}$. The nonequilibrium charge carriers generated by the pumping light are redistributed by the built-in electric field. The charge carrier redistribution at the frequency of modulation of the pumping light leads to modulation of the built-in field at the same frequency by the induced internal photo-emf. The guides F1-F3 represented multimode optical fibers with a diameter of 300 µm.

The PR spectrum of the GaAs sample used (Fig. 2B) exhibits a classical shape [8]. For the probing quantum energies exceeding the bandgap of GaAs (E_g = 1.51 eV), the Franz-Keldysh oscillations in the PR spectrum are related to the pumping-induced modulation of the built-in electric field in a depleted subsurface region of the sample film estimated from the model spectrum, the strength of this field amounted to ~3kV/cm. The absence of the Franz-Keldysh

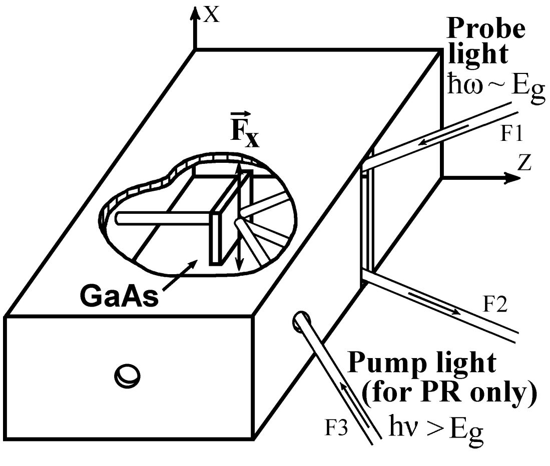

Fig.1: GaAs sample in a microwave cavity. **F$_X$** is a microwave electric field in cavity.

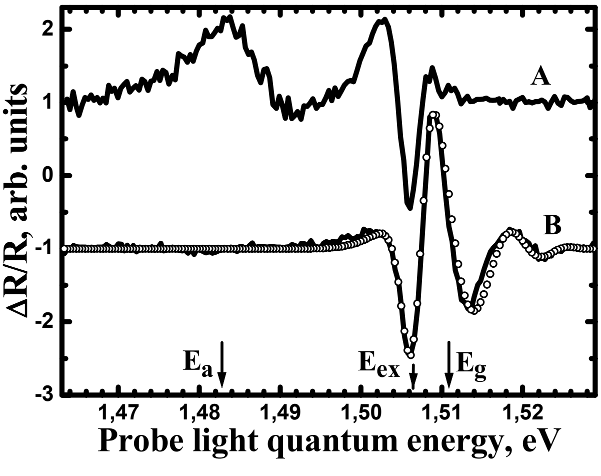

Fig.2: Experimental (solid curves) and theoretical (open circles) MMR (A) and PR (B) spectra of GaAs.

oscillations in the MMR spectrum (Fig. 2A) shows that the longitudinal microwave field does not modify the transverse built-in electric field in the depleted region of the sample. This fact is indicative of a small level of the microwave-induced thermo-emf of hot electrons. The excitonic states (E_{ex} = 1.507 eV) sensitive to various external factors are manifested in both photoreflectance and MMR spectra. In the MMR, excitons can be modulated in the bulk region of film due to interaction with the microwave-heated conduction band electrons or due to changes in the fluctuating potential created by charged impurities under the screening influence of the heated electrons. The microwave electric field strength used in the experiment is not large enough to effectively modulate exitonic states directly. The exitonic states also cannot be modulated by changes in the built-in field because of absence of built-in field modulation in MMR. The MMR spectrum displays also a feature (E_a=1.483eV) in the energy region corresponding to electron transitions from the acceptor levels to the conduction band. The n-GaAs sample film studied represented a compensated semiconductor, in which all acceptors are negatively charged in the absence of external perturbations. The conduction band electrons heated by the microwave field modify the fluctuation potential created by the charged impurities. This leads to a change in the probability of electron excitation from the acceptor levels to the conduction band by the probing light, that is, to a change in the absorption and reflection coefficients.

FUTURE PROSPECT

Modern semiconductor technology allows growing the structures with high-quality quantum wells. Excitonic effects are much stronger in such structures than in the bulk semiconductors because of quantum confinement [9]. Excitons in quantum wells give sharp absorption resonance even at room temperature and their contribution in transmittance and reflectance spectra can be easily measured. Modulation doping of such structures allows spatially separate electrons and impurities. Free electrons in modulation-doped quantum wells move without impurity scattering that leads to higher electron mobility and to more effective electron heating by microwave field. Furthermore the excitons don't experience additional line broadening due to interaction with impurities. It's possible to measure the microwave electric field strength by measurement of changes in the intensity of the monochromatic probe light transmitted or reflected from the modulation doped quantum wells, with quantum energy close to that of the excitonic states creation. Semiconductor structures as a matter of fact can have different conductivities in various layers and directions (along and across to layers) and spectral features manifested at different wavelengths for different layers. MW fields with various spatial configurations allow produce nonhomogeneous electron heating and act on separate submicron layers of the structure, thereby evolve their response in reflectance and transmittance spectra [10]. Therefore it's also possible to measure the polarization of the microwave field by measurements in the spectra of the probe light.

ACKNOWLEDGEMENTS

The authors are grateful to V.P.Gapontsev (IPG-group) for his attention and support of this work.

REFERENCES

[1] Hewlett-Packard Co., "Fundamentals of RF and microwave power measurements," *Applicat. Note* AN64-1, June 1978.
[2] A.M.Cowley and H.O.Sorensen, "Quantitative comparison of solid-state microwave detectors," *IEEE Trans. on Microwave Theory and Techniques,* vol. MTT-14, pp. 588-602, December 1966.
[3] E. Wagner and W.Bludau, "Lineshape analysis of free-electron to bound-hole transitions in electric field," *Sol. State Comm.*, vol.17, pp.709-711, 1975.
[4] H.Shen and M.Dutta, " Franz-Keldysh oscillations in modulation spectroscopy," *J. Appl. Phys.*, vol. 78, pp.2151-2177, August 1995.
[5] B.H.Kolner, D.M.Bloom, "Electrooptic sampling in GaAs integrated circuits," *IEEE J. Quantum Electron.*, vol.22, pp. 79-93, January 1986.
[6] D.A.B.Miller, et.al., "Electric field dependence of optical absorption near the band gap of quantum-well structures," *Phys. Rev.B.*, vol. 32, pp.1043-1060, July 1985.
[7] M.A.Chernikov and O.A.Ryabushkin, "Microwave modulated light reflection in semiconductors," *Techn. Phys. Lett.*, vol.27, pp. 1038-1040, January 2001.
[8] J.P.Estrera, W.M.Duncan and R.Glosser, "Complex Airy analysis of photoreflectance spectra for III-V semiconductors," *Phys. Rev. B*, vol. 49, pp. 7281-7294, March 1994.
[9] S. Schmitt-Rink, D.S.Chemla and D.A.B.Miller, "Linear and nonlinear optical properties of semiconductor quantum wells," *Adv. in Phys.* Vol. 38, No. 2, pp.89-188, 1989.
[10] A.O.Volkov, O.A.Ryabushkin, and M.S.Povolotskyi, "The light reflection from semiconductor heterostructures modulated by a double polarized radiofrequency field," *Techn. Phys. Lett.*, vol.27, pp.758-760, September 2001.