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Below-bandgap photoreflection spectroscopy of semiconductor laser structures

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***Abstract*. A new method of modulated light reflection – below-bandgap photoreflection, is considered. Unlike the conventional photoreflection method, the proposed method uses optical pumping by photons of energy smaller than the bandgap of any layer of a semiconductor structure under study. Such pumping allows one to obtain the modulated reflection spectrum for all layers of the structure without excitation of photoluminescence. This method is especially promising for the study of wide-gap semiconductors. The results of the study of semiconductor structures used in modern high-power multimode semiconductor lasers are presented.**

Keywords: *modulation spectroscopy, semiconductor structures, photoreflection, semiconductor lasers.*

1. Introduction

Optical spectroscopy is widely used for a detailed study of the electronic states of semiconductors. Among the methods of optical spectroscopy, the most popular are photoluminescence, modulated light reflection, and Raman and Brillouin scattering of light [1, 2]. These methods are used for measuring various parameters characterising semiconductors. Raman and Brillouin scattering are mainly applied to study the electron – phonon interaction in semiconductors. Photoluminescence is used to investigate the band structure of semiconductors, the energy distribution of free carriers in the valence and conduction bands, as well as for studying the kinetics of radiative recombination of non-equilibrium carriers.

At present, the photoluminescence method has received the widest acceptance because of its simplicity and the possibility of using this method for rapid measurements of the bandgap in semiconductors. However, unfortunately, the method allows the measurements of only a restricted set of parameters and cannot provide an adequate accuracy at room-temperature measurements.

Methods of modulation spectroscopy allow the most precise measurements of the parameters of the band structure of semiconductors, the characteristic quantum-confinement energies in low-dimension structures, and the so-called built-in electric fields. Methods of modulated light reflection play a special role in the modulation spectroscopy of semiconductors. During the last forty years the photoreflection (PR) method has become most popular among these methods [3]. Despite the obvious advantages of the PR method, the use of this method for the study of semiconductor laser structures is complicated by almost complete coincidence of the luminescence and reflection spectra [4, 5]. In addition, this method cannot be applied for studying deeply lying layers. It is also important that expensive pump sources are required for the investigation of wide-gap semiconductors [6].

In the last few years we have developed in our laboratory the new methods of modulated light reflection, devoid of these disadvantages. The method of radio-frequency modulated reflection (RMR) [7, 8] uses a high-frequency electric field (10 – 100 MHz) with a low-frequency amplitude modulation as an external perturbation. Such a field is produced in a sample placed between the plates of a flat capacitor to which an external electric voltage is applied.

The RMR method was later modified to the method of microwave modulated reflection (MMR) [9], in which an external action is produced by a microwave electric field. For this purpose, a sample is placed inside a microwave resonator, in the region with the maximal electric field strength. The optical properties of samples studied by the RMR and MMR methods are modulated due to the heating of free charge carriers by radio-frequency or microwave radiation.

An alternative method based on the heating of free carriers is the method of current reflection (CR) [10]. In this case, free carriers are heated by passing an alternating current along the layers of a semiconductor structure under study. However, it is necessary to deposit electric contacts on a sample to produce current, which makes this method, unlike the RMR and MMR methods, destructive.

Although the RMR, MMR, and CR methods have no disadvantages of the PR method, it is difficult to provide the local action of the pump on the structure under study by these methods, which is required to control the spatial distribution of the parameters of the grown structures.

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Modern semiconductor laser structures are grown in the form of wide plates (the diameter of plates grown by the method of molecular-beam or gas epitaxy achieves 10 – 15 cm), from which crystals are cut for laser chips. The quality of the grown structure should be controlled over its entire surface to find the sites suitable for fabrication of laser chips. This requires local measurements of the structural parameters at different sites of the surface.

To eliminate the drawbacks of the conventional PR method and provide the spatial localisation of optical radiation, we are developing the below-bandgap photoreflection (BPR) method [11, 12], in which pumping is performed by photons of energy smaller than the bandgap of any layers of the semiconductor structure.

2. Modulated light reflection

The periodic action of light on a structure studied by the methods of modulated light reflection produces the modulation of its electronic states, and synchronous detection is used to measure the spectrum of the relative change in the reflection coefficient $\Delta R(\omega)R^{-1}(\omega)$ of probe radiation. The permittivity of a semiconductor in a constant electric field can be written in the form $\varepsilon(\omega) = \varepsilon_1(\omega) + \mathrm{i}\varepsilon_2(\omega)$ [2]. Upon irradiation of a semiconductor, the value of $\varepsilon(\omega)$ changes most strongly if the photon energy $h\nu$ is close to the energy of critical points of its band structure. A change in $\varepsilon(\omega)$ causes a change in the reflection coefficient $R = |(\sqrt{\varepsilon} - 1)/(\sqrt{\varepsilon} + 1)|^2$. If the permittivity changes weakly ($\Delta\varepsilon(\omega) \ll 1$), the relative change in the reflection coefficient can be written in the form $\Delta R(\omega)/R(\omega) = \alpha\Delta\varepsilon_1(\omega) + \beta\times\Delta\varepsilon_2(\omega)$, where $\alpha(\varepsilon_1, \varepsilon_2)$ and $\beta(\varepsilon_1, \varepsilon_2)$ are the Seraphin coefficients [13] of the unperturbed permittivity.

The PR method uses optical radiation with the photon energy $h\nu$ exceeding the bandgap E_g of the semiconductor. The pump intensity is modulated at a low frequency $f \sim 10^2 - 10^3$ Hz. Absorption of pump radiation in the semiconductor results in the creation of nonequilibrium electron – hole pairs. The electrons and holes are separated under the action of the inner electric field, which leads to a change in this field and, hence, to a change in the semiconductor permittivity. The PR method received wide acceptance because it provides precise and noncontact measurements. However, as mentioned above, this method has a number of disadvantages.

First, the luminescence spectrum overlaps the reflection spectrum. The luminescence spectrum is broad and it can be much more intense than the reflection spectrum, which severely complicates the detection of weak variations in the reflection intensity [4, 5]. All this makes the interpretation of reflection spectra difficult. At low temperatures (77 K and lower), the separation of luminescence and reflection spectra becomes very difficult, especially in the study of low-dimensional structures.

Second, the study of semiconductors is considerably restricted by very strong absorption of pump radiation with photon energies greater than the semiconductor bandgap (the absorption coefficient is $\sim 10^4$ cm^{-1}). As a result, pumping occurs, as a rule, only within a thin surface layer of thickness ~ 1 μm, where the pump radiation is virtually completely absorbed. Layers lying deeper in the semiconductor volume make no contributions to the reflection spectrum and therefore they cannot be studied by the PR method in most cases.

Third, the use of the PR method for studying wide-gap semiconductors is complicated due to the absence of low-cost blue and UV pump sources [6].

Optical excitation in the BPR method is performed by photons with the energy $h\nu < E_g$. In the absence of two-photon absorption, such excitation cannot create electron – hole pairs in the semiconductor. Pump photons can be absorbed by free and impurity-bound charge carriers and also can be scattered by optical and acoustic phonons. These processes cause variations in $\varepsilon(\omega)$. Therefore, the BPR method allows one to study the phonon spectrum of the semiconductor. In addition, this method, retaining the advantage of noncontact measurements in the PR method, makes it possible to investigate wide-band semiconductors without the use of expensive short-wavelength pump sources.

3. Experimental setup

Figure 1 shows the scheme of the experimental setup that we developed for BPR studies. This scheme is conventional for modulated reflection methods and allows measurements to be performed both by the BPR and PR methods. Pump radiation modulated at the frequency 330 Hz is directed on a sample through multimode fibre (*3*). In the conventional PR method, pumping by a 670-nm diode laser with a fibre pigtail is used ($h\nu > E_g$), while in the BPR method, pumping is performed by a fibre laser at 1060 or 1550 nm ($h\nu < E_g$). An incandescent lamp with a broad emission spectrum was used a probe source. A wavelength range corresponding to the features of the electronic energy spectra of semiconductors under study was selected from the emission spectrum of the lamp with an optical filter.

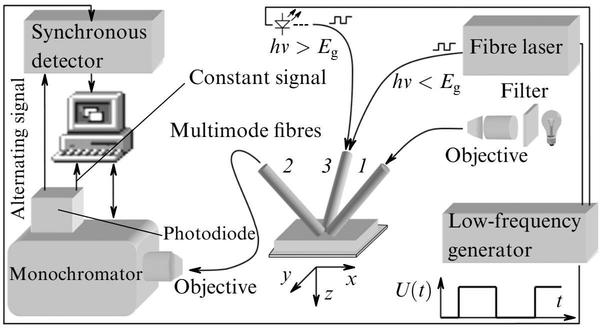

Figure 1. Scheme of the experimental setup.

Probe radiation is directed with the help of a focusing objective and multimode fibre (*1*) to the same region of a sample as pump radiation. Probe radiation reflected from the sample is collected by multimode fibre (*2*) and is directed through this fibre to a monochromator. The alternating and constant components of the spectrum of probe radiation reflected from the sample are measured with a photodiode at the monochromator exit slit. The constant component is transformed with an analog-to-digital converter (ADC) and fed to a computer. The alternating component at the modulation frequency f is selected by a synchronous detector and also is fed to the computer via the ADC. The reference signal for the synchronous detector is provided by a low-frequency generator.

In this paper, we studied a semiconductor structure used for manufacturing high-power laser diodes. The band diagram of this structure is shown in Fig. 2. This structure was grown by the method of molecular-beam epitaxy on a n^+-GaAs substrate of thickness 600 μm and consists of n- and p-AlGaAs emitters (*1*) and (*4*), gradient AlGaAs waveguide (*2*), at the centre of which InGaAs quantum well (*3*) is located, and of heavily doped p^+-GaAs layer (*5*). The composition and thickness of layers are close to those reported in [14].

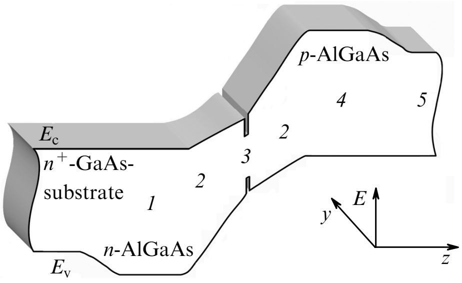

Figure 2. Band diagram of the semiconductor structure under study. (*1*, *4*) emitters; (*2*) gradient waveguide; (*3*) quantum well; (*5*) p^+-GaAs layer.

Figure 3 shows the reflection spectrum (denoted as PR + PL) of the semiconductor structure. One can see that this spectrum is the sum of the reflection and luminescence spectra, which are overlapped. Therefore, to obtain the reflection spectrum, it is necessary to subtract the luminescence spectrum from the measured spectrum, which gives rise to additional errors. Note that sometimes it is impossible to separate the reflection spectrum at all.

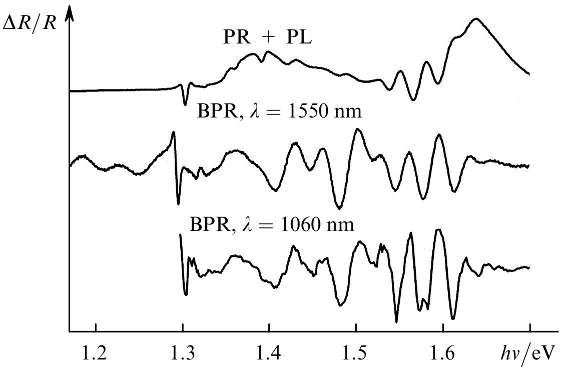

Figure 3. PR spectrum overlapped by photoluminescence spectrum and BPR spectra obtained upon pumping at 1550 and 1060 nm.

Figure 3 also shows two room-temperature BPR spectra of the semiconductor structure obtained upon pumping at 1060 and 1550 nm. Because of a rather weak absorption of pump radiation in the semiconductor structure, the radiation penetrates into all layers of the structure, interacting with them. The properties of the BPR spectra are similar to those of conventional PR spectra, but in the case of BPR, nonequilibrium electron – hole pairs are not created because of the low energy of pump photons. Pump radiation in the BPR method is absorbed by free carriers, heating them, and is also undergoes Raman and Brillouin scattering, producing nonequilibrium phonons.

Hot free carriers are redistributed in the semiconductor structure, producing changes in the electric field in waveguide layer (*2*) and in the degree of exciton screening in quantum well (*3*) (Fig. 2). The modulation of the embedded electric field in waveguide layer (*2*) produces Frantz – Keldysh oscillations in the modulated reflection spectrum in the range from 1.52 to 1.67 eV [15]. The 1.3-eV peak corresponds to the 1hh – 1e transition between the ground states in the quantum well and appears due to modulation of these states. Oscillations in the spectral range between 1.31 and 1.35 eV are caused by the modulation of excited states in the quantum well. The modulation of the ground and excited states in the quantum well occurs due to the screening of excitonic states in the well, which causes a change in the binding energy of excitonic states [16].

All the specific features of the PR spectrum are also present in the BPR spectrum. In addition, the BPR spectrum has some features at energies below 1.3 eV, which are absent in spectra measured by other methods of modulated reflection. We assume that these features are related to the generation of many nonequilibrium optical phonons during Raman scattering of pump radiation. These phonons strongly modify electronic states inside the bandgap, so that interband transitions accompanied by emission or absorption of a photon with energy smaller than the 1hh – 1e transition energy in the quantum well can occur.

4. Conclusions

The BPR method considered in the paper preserves the advantages of the conventional PR method, eliminating simultaneously a number of disadvantages of the latter. The BPR method makes it possible to study semiconductor structures which are difficult or impossible to analyse by the conventional PR method. The BPR spectrum gives additional information on the electron – phonon interaction in the structure under study, which cannot be obtained by other methods of modulated reflection. Therefore, the most comprehensive information on the parameters of semiconductor structures can be obtained by using all the family of methods of modulated light reflection, and the BPR method fits naturally into this family by expanding it.

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