PACS numbers: 42.55.Px; 42.62.Fi; 78.40.–q
DOI: 10.1070/QE2004v034n09ABEH002885

Photoreflection from a locally optically pumped semiconductor laser structure

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***Abstract*. The AlGaAs/GaAs laser heterostructure with the InGaAs quantum well is studied by the contactless photoreflection method upon local optical pumping. Unlike the conventional photoreflection method, regions on the sample surface illuminated by the probe and pump light are spatially separated. The method allows one to separate photoluminescence and photoreflection signals and to construct the three-dimensional energy band diagram of the laser structure.**

Keywords: *photoreflection, semiconductor laser, heterostructures.*

The increasing requirements on the characteristics of various semiconductor lasers stimulate the search for new efficient methods of diagnostics of semiconductor laser structures. These methods should provide the measurement of the spatial distribution of parameters of layers along the semiconductor structure. The methods of optical spectroscopy using spatial scanning upon local excitation and optical probing along the structure ensure this possibility.

Among the methods of optical modulation spectroscopy, the most popular are the methods of electroreflection (ER) (with the use of special contacts deposited on a sample) and contactless photoreflection (PR). In the classical ER method [1], two plane metal electrodes are deposited on the opposite sides of a sample, one of the electrodes being translucent. Probe light is incident on the sample through the translucent electrode. A voltage applied to electrodes, which is used as an external action, modulates the so-called built-in electric fields in the sample.

The permittivity of semiconductors in the spectral range near the fundamental absorption edge depends on the built-in electric field due to the Franz–Keldysh effect [2–4]. Therefore, by changing the built-in field, the applied voltage also changes the reflection spectrum of the probe light. In addition, the effect of the applied voltage on the permittivity of semiconductors also depends on some other factors. The permittivity depends most strongly on the binding energy and lifetime of exciton states [5].

The binding energy and lifetime of exciton states change under the action of the built-in electric field due to the Stark effect. These changes are especially strong in low-dimensional structures such as quantum wells, wires or dots [6]. The spectrum of modulated reflection of light from a semiconductor with a single quantum well contains the unique information on recombination processes proceeding in the quantum well, its temperature, and the concentration of nonequilibrium carriers. Variations in the exciton binding energy can be also caused by nonequilibrium carriers produced in the quantum well due to injection, which changes the degree of Debye screening of excitons. These nonequilibrium carriers can also affect the lifetime of exciton states due to scattering processes. Moreover, the electric field changes not only the exciton energy levels in the quantum well but also the wave functions of free electrons and holes in the well.

The main disadvantage of the classical ER method is the necessity of deposition of a metal electrode on the sample surface, which makes the method destructive and, therefore, inapplicably in fact for diagnostics. In addition, the Schottky barriers appearing in contacts of metal electrodes with a semiconductor distort built-in electric fields in the semiconductor. However, these disadvantages of the ER method can be eliminated in studies of semiconductors.

We studied earlier [7, 8] the GaAs/AlGaAs laser heterostructure with a strained InGaAs quantum well. Such structures are widely used in high-power semiconductor lasers [9, 10]. The energy band diagram of this structure is shown in Fig. 1. The structure is grown by the method of molecular-beam epitaxy on a n^+-GaAs substrate of thickness 500 μm and consists of the 0.2-μm thick *n*-GaAs buffer layer, the 0.15-μm thick *n*-$Al_{0.03-0.2}Ga_{0.97-0.8}As$ intermediate layer, 1.2-μm thick *n*- and *p*-$Al_{0.2}Ga_{0.8}As$ emitters (*1*), (*4*), gradient $Al_{0.2-0.1-0.2}Ga_{0.8-0.9-0.8}As$ waveguide (*2*) of total thickness 0.5 μm, at the centre of which $In_{0.14}Ga_{0.86}As$ quantum well (8 nm) (*3*) is located, the 0.15-μm thick *p*-$Al_{0.2-0.03}Ga_{0.8-0.97}As$ intermediate layer, and 0.15-μm p^+-GaAs surface layer (*5*). In [7], two point metal contacts A and B were made on the structure surface and its substrate (see inset in Fig. 1). As electrodes, the substrate and *n*-emitter layers were used on one side and the *p*-emitter and a heavily doped layer on the other side. The voltage applied to the contacts dropped almost completely across the waveguide layer and quantum well, resulting in the efficient modulation of their optical properties over the entire structure plane.

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Received 25 February 2004; revision received 1 July 2004
Kvantovaya Elektronika **34** (9) 875–877 (2004)
Translated by M.N. Sapozhnikov

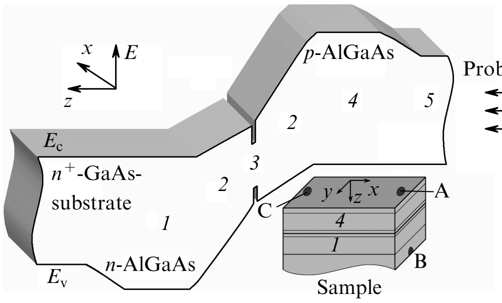

Figure 1. Band diagram of a sample (inset shows the sample geometry): (*1*, *4*) emitters; (*2*) gradient waveguide; (*3*) quantum well; (*5*) p^+-GaAs layer; A, B, C are metal contacts.

In [8], two metal contacts A and C were made on the structure surface. An electric voltage applied to the contacts caused the modulation of the built-in field in layers (*2*) and (*3*) due to the effect that is similar to a change in the transverse electric field in the channel of a filed transistor during the passage of an electric current between a drain and a source [11]. Unlike the conventional ER method, the methods used in papers [7, 8] allow the testing of grown laser structures only slightly changing the surface properties (semiconductor properties in the region of contacts). Contacts in these methods distort built-in electric fields in the substrate and *p*-emitter of the structure only at a distance of the order of the Debye screening radius. However, it would be preferable to use a contactless method for testing semiconductor laser structures.

The conventional contactless PR method [12] uses optical pumping by photons with energy $h\nu$ exceeding the bandgap E_g of the semiconductor. Electron–hole pairs produced upon such pumping are redistributed by built-in electric fields, which exists even in homogeneous semiconductors. The spatial redistribution of charge carriers at the pump modulation frequency induces internal photo-emfs, which modulate the built-in fields at this frequency. The modulation of built-in fields, as in the ER method, results in the modulation of the reflection spectrum of the probe light. Nevertheless, the PR method has its own disadvantages. The reflection spectrum can be overlapped with the photoluminescence (PL) spectrum, which is, as a rule, located at the same spectral region; and it is often very difficult to separate these spectra [13].

In this paper, we study the semiconductor laser structure (Fig. 1) by the modified PR method, which allows us to separate the PR and PL signals. The main feature of the method is that the regions on a sample surface illuminated by the probe and pump light are spatially separated. Such a modification of the PR method was earlier used for studying structures for the development of transistors with high electron mobility [14, 15].

The experimental setup is similar to that described in [16]. The 670-nm pump radiation from a semiconductor laser was modulated by current pulses at the frequency 330 Hz. The pump radiation propagated through a fibre of diameter 300 μm and was incident on a sample, providing the power density of $\sim 0.1 - 1$ W cm^{-2}. Two similar, rigidly mutually fixed fibres were used to deliver to the sample and detect the reflected probe radiation. These fibres could be moved in the plane of the sample with respect to the fibre through which pumping was performed. All measurements were carried out at room temperature.

The measured PL and PR spectra are presented in Fig. 2. When the probe and pump light illuminated the same region, the intense luminescence was observed in the same spectral range as reflection. In this case, it was necessary to subtract the luminescence signal from the alternating component ΔR of the PR signal. Note that such a procedure not always allows the separation of the PL and PR signals because the PL signal can be a few orders of magnitude greater than the PR signal. During the measurements of the PL and PR spectra, the pump radiation was strongly absorbed in layers (*4*) and (*5*) (Fig. 1).

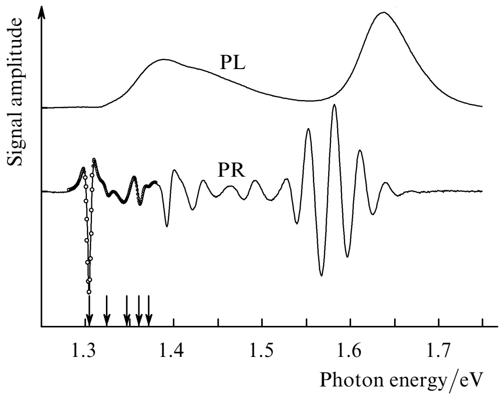

Figure 2. Experimental (solid curves) and calculated (circles) PL and PR spectra of the sample. The arrows indicate the energies of electron–hole transitions in the quantum well.

Recombination of electrons and holes produced by pump radiation in these layers gives rise to photoluminescence with the mains bands at 1.63 and 1.39 eV, respectively. Free electrons and holes generated by pump radiation in layer (*2*) are spatially separated by the built-in electric field, resulting in the modulation of this field by photo-emf in regions (*2*) and (*3*). Note that only a small fraction of pump radiation reaches region (*2*) with the built-in electric field, so that the PL signal is greater than ΔR.

The oscillations in the PR spectrum in the range between 1.52 and 1.67 eV are the Franz–Keldysh oscillations produced in layer (*2*). The built-in electric field in the waveguide region of the structure can be determined from the period of these oscillations. The main peak at 1.304 eV corresponds to the 1hh–1e electronic transition in the quantum well. The oscillations in the spectral range from 1.31 to 1.38 eV are caused by the modulation of excited electron and hole states in the quantum well due to the quantum Stark effect.

The approximation of the experimental curve by the Aspnes formula [17] gives the electronic transition energies in the well (shown by the arrows in Fig. 2). Because the quantum well has a finite depth and is located in the built-in electric field of the $p-n$ transition, the PR spectrum exhibits transitions that are forbidden in the model of an infinitely deep symmetric well, including transitions involving light holes, for which the InGaAs layer is a quantum barrier [18]. Note that such transitions are not usually observed in PL spectra.

Figure 3 shows the dependences of the amplitudes of the PL and PR signals on the distance L between the centres of regions illuminated by the probe and pump radiation. The PL signal does not appear outside the region illuminated by pump radiation. At the same time, the amplitude of the PR signal is virtually constant over a distance of one centimetre (limited by the sample size) from the region illuminated by pump radiation. This distance is four orders of magnitude greater than the diffusion length of nonequilibrium carriers in the bulk semiconductor. The distance over which the PR signal is observed achieves such a large value owing to the existence of the energy barrier of the $p-n$ junction, which prevents the recombination of electrons and holes, and due to the high conductivity of emitter layers. Electrons and holes separated by the built-in field in layer (*2*) spread over emitter *n* and *p*-layers (*1*) and (*4*), respectively.

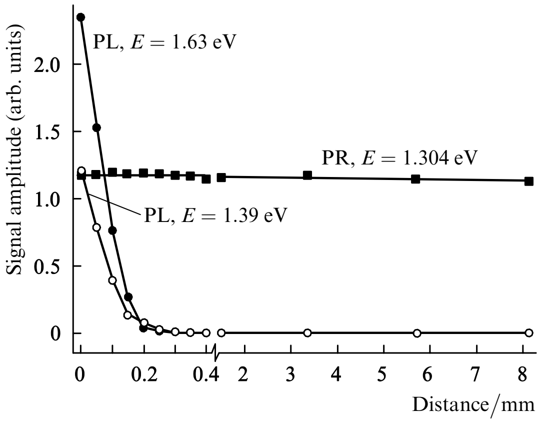

Figure 3. Spatial dependences of the PL and PR signals.

The emitter layers are in fact the capacitor plates. An alternating voltage appearing between these plates due to charges produced by pump radiation causes changes in the built-in electric fields in the waveguide layer and the quantum well over the entire plane of the structure, thereby changing the reflection spectrum of probe radiation. The shape of the PR signal did not change during scanning along the structure surface, indicating a high homogeneity of the sample. The propagation of the PR signal over the sample surface upon local photoexcitation is similar to the propagation of the ER signal [7]. However, the method used in our paper is completely contactless.

Acknowledgements. The authors thank V.P. Gapontsev for his attention and support of this study. This work was partially supported by the Russian Foundation for Basic Research (Grant No. 03-02-16942).

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