Investigation of GaAs/AlGaAs superlattice by photoreflectance method

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Abstract. The GaAs/AlGaAs superlattice grown by metal-organic chemical vapour deposition (MOCVD) was investigated by photoreflectance (PR) spectroscopy. Optical transitions over the whole band structure were measured at room temperature. Different laser pump beams (632 and 532 nm) were used to clarify the nature of the PR signal formation. Charge carriers transport over minibands was revealed by using long-wave modulation. An acceptable correlation of theoretical and experimental results was achieved for low-energy transitions. Optical transitions relating to the edges of the first and the second minibands for electrons, heavy and light holes were clearly observed experimentally.

1. Introduction
Superlattices have been an important part of micro- and nanoelectronics ever since their unique properties were discovered in [1]. Due to the strong quantum-mechanical coupling between the quantum wells, it is possible to create structures with the desired band structure parameters. Superlattices have proved to be suitable for the realization of the infrared lasers based on the quantum cascade concept [2]. GaAs/AlGaAs superlattices are also used in semiconductor lasers for mode selection. In addition, the presence of negative differential conductivity in superlattices enables creation of amplifiers, generators and detectors of the GHz and THz ranges.

Photoreflectance (PR) spectroscopy has a number of advantages over conventional diagnostic methods because of derivative spectra character, high sensitivity, as well as its contactless and non-destructive nature. The PR method can reveal optical transitions both at various critical points of the Brillouin zone, and between discrete (or quasidiscrete) energy levels. A high sensitivity is another advantage of PR: typical modulation amplitudes are about $10^{-4}$-$10^{-5}$ of the source light intensity, while the noise level can be kept below $10^{-6}$ [3]. Energy transitions from higher levels in low-dimensional structures can also be observed in room-temperature photoreflectance measurements. Additionally, such structure properties as free carrier concentration [4, 5], built-in electric fields, the Fermi level pinning at the surface [6] or interface, the degree of strain relaxation [7] can be determined by PR.

There are a number of papers describing results of investigating different semiconductor superlattices using the photoreflectance method. Authors of article [10] present the investigation the GaAs/AlGaAs superlattice at room and low temperature (10K). The influence of the growth parameters (QW and barrier widths) was obtained on GaAs/AlGaAs superlattices with Fourier transform photoreflectance by authors of paper [8]. The work [12] contains results of the room-temperature measurements on GaAs superlattices that demonstrate the influence of the build-in potential. Papers [9, 13] present the
investigating CdTe/ZnTe and GaAs/InGaAs superlattices using photoreflectance method respectively. Miniband and carrier transport properties in the GaAs superlattice structure were studied with photoreflectance, photoluminescence, and photothermal spectroscopies in work [11]. But there are no works where the nature of the PR signal formation in superlattices would be shown clearly. In this work, we used photoreflectance spectroscopy with different wavelength of modulating laser beam to investigate optical transitions in GaAs/AlGaAs superlattice.

2. Experimental setup and sample parameters
The setup employed for our photoreflectance measurements was described in [14]. The light of a 100 W tungsten-halogen lamp went through a 0.6 m monochromator and was focused on the sample as a probe beam. The modulating laser pump beam was directed into the same place on the sample. During the measurements, different pump beams were used – one was provided by a He-Ne laser (632 nm line) and the other by a Nd:YAG laser (532 nm line). The pump beam was mechanically chopped at a frequency of 36 Hz.

The reflected probe beam, which carried information about sample parameters, was focused by a collimator on the OP913WSL silicon photodetector input window. Phase sensitive detection of the modulation-induced change in reflectance was performed using a SR830 lock-in amplifier. An optical filter was employed to prevent diffused laser light from entering the detector window.

The investigated sample contains a GaAs/AlGaAs superlattice grown by metal-organic chemical vapour deposition (MOCVD). It contains 50 periods with 42 Å barrier thickness and 65 Å quantum well width and has an impurity concentration (Si) of n = 7·10^{15} cm^{-3}.

3. The possible origin of the superlattice photoreflectance signal
When the superlattice sample is irradiated with a modulating pump beam of the red laser (\(h\nu_2\)), electron-hole pairs are formed in the minibands (Fig. 1 a). They move through the minibands due to the influence of the surface built-in electric field. Approaching the surface, the holes compensate the surface states, the schematic image of which is shown in the figure. The field \(F_S\) decreases to \(F'_S\), and, consequently, the reflection of the probe beam changes. In the absence of modulating radiation, everything returns to its initial state (Fig. 1 b).

![Figure 1](image1.png)

**Figure 1.** The effect of laser radiation on the superlattice band structure.  
*\(a\) - the superlattice is pumped by a laser beam ; \(b\) – the initial state of the superlattice;
Surf. st. – surface states;

$F_S'$ < $F_S$ - the built-in electric field with laser irradiation on and off, respectively;

$w' < w$ - width of the depletion region with and without laser irradiation.

The change in the reflectance $\Delta R$ of the superlattice is based on the quantum-dimensional Stark effect. The edges of the minibands shift in energy as the field is varied, thus the dielectric function and, consequently, the reflectance $R$ changes. Therefore, the registered PR is a derivative signal.

When the modulation with the green laser takes place (the laser photon energy $h\nu_1$ is greater than the Al$_{0.45}$Ga$_{0.55}$As band gap at room temperature), the mechanism of surface electric field change can be the same as for a bulk semiconductor material. The charge carriers are separated by the field, and the holes compensate the surface states. However, there is also a probability of relaxation of photoinduced charge carriers to quantum wells of the superlattice. Then the situation becomes identical to the case described above with carrier transport in the miniband.

4. Results and discussion

Figure 2 shows the resulting $\Delta R/R$ spectra measured with the different modulating laser radiation. The red line is related to He-Ne radiation, the green one shows the signal modulated by Nd:YAG laser. Since PR is a derivative signal, the spectra were transformed with the method described in [15] to determine the energies of the interband optical transitions. The resulting transformed spectra are shown in Figure 3. Here, the energy of each peak corresponds to the energy of the optical transition.

![Figure 2](image_url)

Figure 2. Photoreflectance spectra of a GaAs/Al$_{0.45}$Ga$_{0.55}$As superlattice with $\lambda_1 = 0.53$ $\mu$m and $\lambda_2 = 0.63$ $\mu$m pump beams, measured at room temperature.
The following interband transitions were determined (they are pointed with arrows in Fig. 3 and shown on the band diagram in Fig. 4):

- the ground state transition $e_1$-$hh_1$ between the first electron miniband and the first miniband of heavy holes;
- transitions involving light holes of the first miniband ($e_1$-$lh_1$) at the $\Gamma$ and $\Pi$ critical points, corresponding to the lower and upper edges of the miniband, respectively. These transitions are located very close on the energy scale and practically merge;
- transitions of heavy holes and electrons from the second minibands: $e_2$-$hh_2$ ($\Pi$) and $e_2$-$hh_2$ ($\Gamma$);
- $e_2$-$lh_2$ ($\Pi$) and $e_2$-$lh_2$ ($\Gamma$) transitions, related to the second miniband of electrons and the second miniband of light holes.
Figure 4. A schematic image of the observed energy transitions within the superlattice band structure

The obtained experimental results were compared with the theoretical energy values of the band structure transitions calculated within the effective mass approach assuming a parabolic dispersion law for both electrons and holes. The experimental and theoretical transition energy values are summarized in Table 1.

| Energy transition | $E_{\text{theor}}$ eV | $E_{\text{at } \lambda_1}$ eV | $E_{\text{at } \lambda_2}$ eV |
|-------------------|----------------------|----------------------|----------------------|
|                   | -                    | -                    | 1.411 1.456 1.501 1.529 - 1.672 1.703 1.824 - |

As can be seen from Table 1, both experimental spectra (at $\lambda_1$ and $\lambda_2$) are in good agreement in the 1.48-1.8 eV energy range. The neodymium laser enables measurement of the spectrum over a wider wavelength range, which allows for detection of higher-energy transitions. The experimental result for the ground state transition is in good correlation with theoretical calculations. It is revealed that the first energy level in the valence band and in the conduction band is practically discrete. According to experimental data, the light hole minibands and the second electron miniband are wider due to the smaller degree of charge carriers localization in quantum wells. The difference between experiment and theory for high-energy minibands could be related to the chosen calculation model based on the parabolic assumption.
5. Conclusion
In conclusion, the GaAs/Al0.45Ga0.55As superlattice band structure has been optically investigated using photoreflectance spectroscopy. Different pump beams (632 and 532 nm) were used. As a result the energy transitions were identical for both wavelengths, so the mechanisms of PR signal formation are very close. Charge carrier transport over minibands is revealed by using long-wave modulation. When the modulation photon energy exceeds the barrier band gap, an additional mechanism of surface electric field change, analogous to a bulk material, could also take place. An acceptable agreement of theoretical and experimental results is achieved for the measurements at room temperature.

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