

Research of resonant light reflection by a periodic system of GaAs/AlGaAs quantum wells.

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Abstract. Measurements of the optical reflection spectra from periodic structures with two quantum wells in the elementary cell have been done. The dependencies of the light reflection on the angle of the light incidence, polarization and temperature were studied. An analysis of the experimental data showed that the pattern with 60 cells is a good Bragg reflector with reflectivity more than 90% in the maximum of the spectral band.

1. Introduction

Structure with dielectric function that periodically varies in space is very interesting from both fundamental research and applied physics standpoint. These structures are called photonic crystals. The periodicity can be created in one, two or three dimensions. One-dimensional photonic crystals are often referred to as distributed Bragg reflectors. They found many applications in such devices as vertically emitting lasers, band filters, etc [1].

Resonant Bragg structures (RBS) are a type of photonic crystals [2,3]. In these structures a periodic change of the dielectric function is caused by exciton states in quantum wells. Optical properties of resonant Bragg structures have been discussed in several theoretical works [3,4,5]. In such structures exciton-polariton resonance mode arises when the Bragg reflection frequency coincides with the exciton frequency in the quantum wells. The oscillator strength of this mode is proportional to the number of quantum wells, so it is super-radiant.

Effect of external electric field on optical reflection from RBS is especially interesting for application in active photonic devices. The energies and oscillator strength of the quantum well excitons depend on the voltage applied. As a result the resonant optical response of the RBS can be detuned or modified [6,7].

Creating RBS is a quite difficult task. A system with a large number of quantum wells is required to obtain a strong super-radiant mode. The creation of such structures is complicated due to significant growth time and large thickness. The structures must be uniform with low homogeneous and inhomogeneous broadening of the excitonic states in quantum wells. The best growth technology currently available for such purpose is molecular-beam epitaxy of GaAs with AlGaAs barriers. There are several studies dedicated to RBS in this system [6-11].



In this work we study optical reflection from GaAs/AlGaAs RBS as a function of temperature, polarization and angle of the light incidence. We also studied changes in the optical reflection when an external bias is applied to the RBS.

2. Samples and experimental details

The structures were grown by molecular beam epitaxy on conductive 2-inch GaAs substrates with (001) orientation. The design of structure is shown in Figure 1. Structure consists of 60 periodically repeating elementary supercells. Each supercell contains two GaAs quantum wells separated by a thin AlAs barrier. The thicknesses of the GaAs quantum wells and AlAs barriers are 7.8 nm and 4.8 nm, respectively. A thick (97.3 nm) AlGaAs barriers with the aluminum content of 20% separate the pairs of quantum wells. The top of the structure is covered with anti-reflective conductive ITO layer.

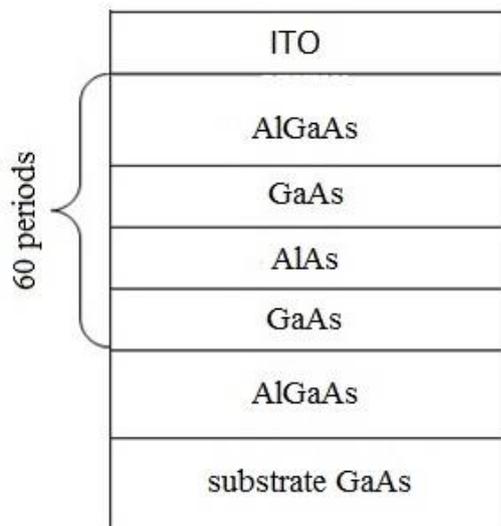


Figure 1. Structure of sample.

The optical reflection spectra with *s* and *p* polarizations for various angles of the light incidence were measured in the temperature range from 10K to 270K. An Ocean Optics LS-1 lamp was used as light source. A Glan prism was used as a light polarizer. The light was transmitted from the source to the sample and from sample to the detector by fiber optic cables. An Ocean Optics HR4000 spectrometer was used to register the reflected optical signal, which allowed us to measure in the range from 190 to 1100 nm. The spectra were recorded from unbiased sample, as well as with applied voltage of +4V and -4V. The electric current did not exceed 3 μ A.

3. Results of experiment

Figure 2 shows experimental optical reflection spectra recorded with s-polarized light for the incident angles of 23°, 45° and 67° at the temperature of 10K. Characteristic features of spectra are marked with arrows. Marker 1 indicates the band gap of the AlGaAs barrier, which is 1.78 eV at 10K and does not depend on the angle of light incidence. Marker 2 indicates the exciton resonant energy in the quantum wells, which is 1.58 eV and also do not depend on the angle of light incidence. Arrows 3 in the spectra point out to the positions of Bragg peaks. The position of these peaks is associated with periodic changes of the refractive index in the structure. With increasing the angle of incidence the Bragg peak shifts to higher energies in accord to the Bragg's Law. The amplitude of Bragg peak is 25%, 54% and 70% at the angles of 23°, 45° and 67°, respectively. Small smooth peaks over a wide range of the spectra are Bragg satellites. ITO layer provides low non-resonant reflection in the spectral range of interest at small angles of the light incidence.

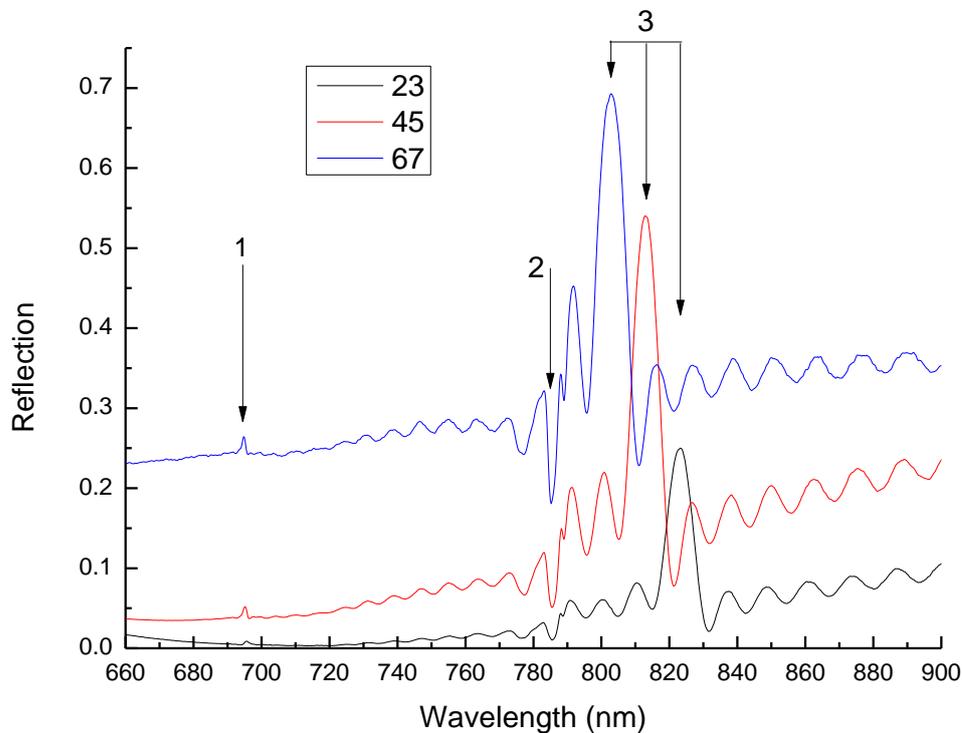


Figure 2. Optical reflection spectra recorded at 10K for s-polarized light incident at angles of 23°, 45° and 67°. Arrows show the characteristic features the spectrum.

Figure 3 shows optical reflection spectra recorded at different temperatures, namely 10K, 130K, 200K and 270K. The light has *p*-polarization and its angle of incidence is 23°. The peak positions of quantum well exciton are signed by arrows. The labelled exciton energies are derived from our theoretical calculation. It is obvious that the quantum well exciton peak shifts towards lower energy with increasing temperature, which is a result of shrinking of the band gap. At low temperature (10 and 130 K) the arrows clearly indicate features in the experimental reflection spectra. When the temperature is elevated to 200 and father to 270K, these excitonic features become hardly visible.

The major reflection peak at any temperature originates from Bragg reflection. The amplitudes of Bragg peaks are 25%, 29%, 49%, and 92% for temperatures of 10K, 130K, 200K and 270K, respectively. The width of this peak is 16.6 ± 0.6 meV and it apparently does not depend on temperature.

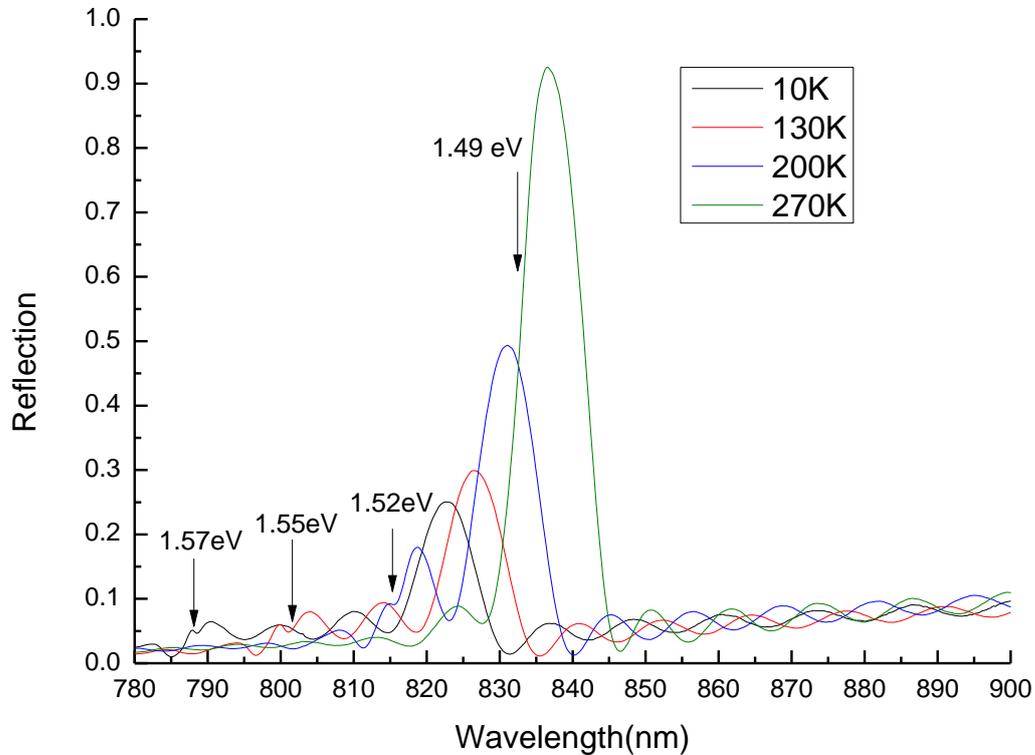


Figure 3. Optical reflection spectra from GaAs/AlGaAs RBS at 10K, 130K, 200K and 270K. The light is *p*-polarized and the angle of incidence is 23°.

The optical reflection spectra were also measured with a DC voltage applied between the substrate and ITO cap layer. In order to precisely reveal the impact of the external electric field we calculated differential spectra by subtracting the spectra without bias from biased ones recorded under the same conditions. Next, we calculated the ratio of these differential spectra to the spectrum recorded unbiased. Figure 4 shows thus obtained normalized differential spectra $\Delta R/R$, which corresponds to the temperature of 170K and light incidence angle of 23°. Noise ($\sim 1\%$) is visible in the spectrum. Arrow 1 matches with the energy gap in the AlGaAs barrier, which is 1.74 eV at 170K. Arrow 2 indicates a sharp feature with amplitude of $\sim 9\%$ for voltage of $-4V$ and $\sim 4\%$ for $+4V$. This feature occurs at the energy of the quantum well excitons, which is 1.537 eV. The full width of the peak is 7.2 meV. Third arrow corresponds to the change in the Bragg reflection. It is centered at 1.496 eV. The apparent width is in between 13 and 23 meV.

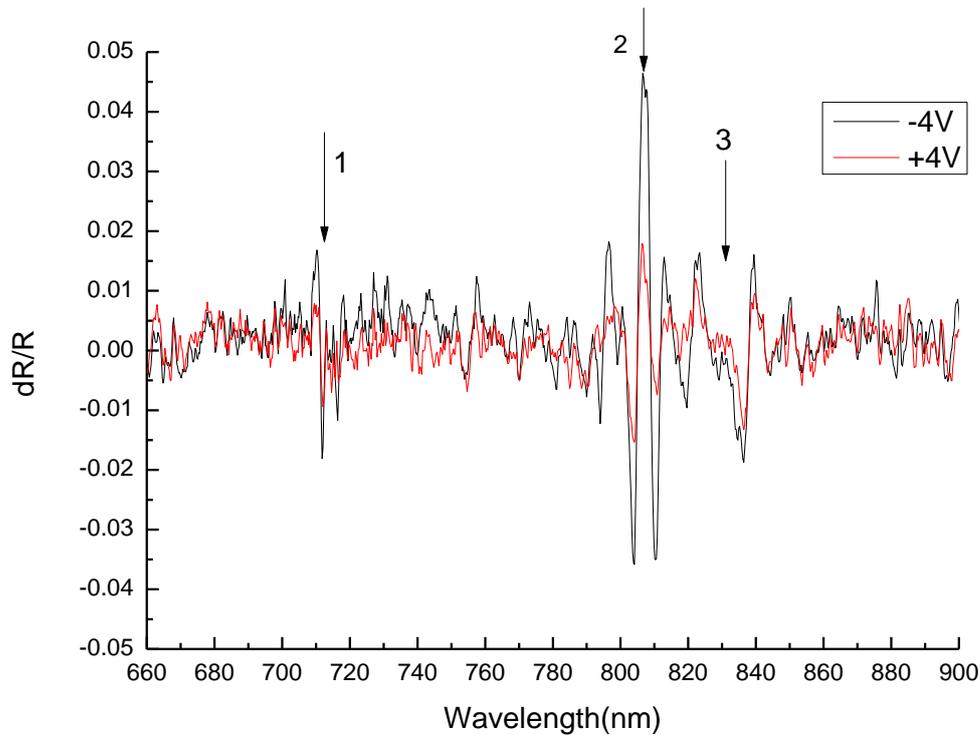


Figure 4. Dependence of a relative change in the reflection with a voltage of -4V and +4V. Temperature is 170K. Angle of incidence is 23° . Arrows indicate barrier band gap (1), quantum-well excitons (2) and Bragg band (3) features.

4. Discussion and conclusions

In this work we studied optical reflection from RBS structure consisting of 60 pairs of GaAs quantum wells separated by AlGaAs barriers. The condition of the formation of the collective exciton-polariton mode in RBS is the coincidence of the Bragg and exciton resonances. There are two ways to achieve the double resonance conditions. One of them is changing the angle of the light incidence at a constant temperature. In this case, the position of main Bragg peak is shifted. The other one is changing the temperature with a fixed angle of the light incidence, which results in a shift of the resonant frequency of the quantum well excitons.

The first way is illustrated in Figure 2 where the spectra were recorded at a constant temperature for various angles of the light incidence. In all the represented spectra the exciton and Bragg resonances are detuned from each other, so that the resonance condition is not reached. It is evident, however, that the magnitudes of both resonances increase when the Bragg and exciton peak approach each other. It is a result of interaction of the exciton-polariton and lattice-polariton modes.

In order to achieve the double resonance conditions we used the second way, i.e. variation of the temperature. One can see in Figure 3 that both exciton and Bragg peaks shift toward longer wavelength when temperature is elevated. Since the exciton shifts stronger, the two resonances can be gradually tuned to each other. Similarly to tuning by the incident angle, the tuning by temperature results in a growth of the Bragg peak amplitude as it approaches the exciton resonance. However, the exciton peak disappears from the spectrum above certain temperature. In order to follow its position we performed quantum-mechanical calculations taking into account temperature dependence of the band gap of GaAs quantum wells and AlGaAs barriers. The calculated energies of excitonic transitions are shown in the Figure 3. The arrows mark corresponding wavelengths. One can see the

features under the arrows in the low-temperature experimental spectra. The calculations show that at a temperature of 270 the exciton and the Bragg peak are just slightly detuned. As a result, the amplitude of the optical reflection becomes as high as 92% with the band width as large as 16 meV. This result is well consistent with previous observations [12].

External electric field affects the optical reflection as shown in Figure 4. The first sharp peak at 1.74 eV in the spectrum indicates the band gap of the AlGaAs barrier. It is evident in Figure 2 that the optical reflection as low as 0.8% at this wavelength. Taking into account relatively small variation $\Delta R/R \sim 3\%$ we can consider this modulation of the optical reflection to be not significant. The second sharp peak at 1.537 eV in Figure 4 corresponds to electro-reflection by excitons in quantum wells. The signal is substantially asymmetric in respect to positive and negative bias. It seems to be a result of the existence of some built-in electric field. Amplitude of the relative modulation of excitonic reflectivity is 9%, when the absolute optical reflection is 9% at this wavelength. So, the electro-modulation of the optical reflection is enhanced for the quantum well excitons compared to the bulk excitons in AlGaAs barriers.

A weak electric field should not affect the Bragg reflection, which originates from some contrast in the refraction indices of GaAs and AlGaAs. In the Figure 4 one can see that the signal is almost absent near the middle of the Bragg band indicated by arrow 3. The signal appears at the edges of the band, being opposite in sign. Such signal can be produced by a small shift of the Bragg band, which may become possible due to interplay of the lattice-polaritons and exciton-polaritons [11].

Thus, we studied optical properties of GaAs/AlGaAs RBS with 60 periods of supercell containing two quantum wells. Our study showed that a periodic system of the quantum well excitons can be arranged as a good Bragg reflector with reflectivity of 92% and bandwidth of 16 meV near room temperature. A change in the optical reflection with an applied electric field was observed for both the excitonic resonance and Bragg band.

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References

- [1] Hjelm D R, Bjerkan L, Neegard S, Rambech J S, and Aarsnes J V 1997 Application of Bragg grating sensors in the characterization of scaled marine vehicle models *Appl. Opt.* **36**, 328-336
- [2] Ivchenko E L, Poddubnyi A N 2006 Resonant Three-Dimensional Photonic Crystals *Physics of the Solid State* **48** 581–588
- [3] Ivchenko E L, Nesvizhskii A I, Jorda S 1994 Bragg reflection of light from quantum-well structures *Physics of the Solid State* **36** 1156-1161
- [4] Voronov M M, Ivchenko E L, Poddubnyi A N, Chaldyshev V V 2006 Special frequencies in the optical reflectance spectra of resonant Bragg structures *Physics of the Solid State* **48** 1814–1819
- [5] Voronov M M, Ivchenko E L, Kosobukin V A, Poddubnyi A N 2007 Specific features in reflectance and absorbance spectra of one-dimensional resonant photonic crystals *Physics of the Solid State* **49** 1792–1802
- [6] Chaldyshev V V, Kundelev E V, Yuechao Chen, Poddubny A N, Vasil'ev A P, Zhiheng Liu 2012 Resonant optical reflection by periodic systems of the GaAs/AlGaAs quantum well excitons, *Phys. Status Solidi C* **9** 1557-1559
- [7] Chaldyshev V V, Sholohov D E, Vasil'ev A P 2010 An (AlGaAs/GaAs/AlGaAs)₆₀ resonant Bragg structure based on the second quantum-confinement level of heavy-hole excitons in quantum wells *Semiconductors* **44** 1222–1226
- [8] Chaldyshev V V, Shkolnik A S, Evtikhiev V P and Holden T 2006 Optical reflection and contactless electroreflection from GaAlAs layers with periodically arranged GaAs quantum wells

Semiconductors **40** 1710

[9] Chaldyshev V V, Shkolnik A S, Evtikhiev V P and Holden T 2007 Modulation optical spectroscopy of excitons in structures with GaAs multiple quantum wells separated by tunneling-nontransparent barriers *Semiconductors* **41** 1455

[10] Chaldyshev V V, Shkolnik A S, Evtikhiev V P and Holden T 2008 Optical spectroscopy of a semi-insulating GaAs/AlGaAs multiple quantum well system near double excitons-polariton and Bragg resonance. *J.Mater.Sci.: Materials in Electronics* **19** 699.

[11] Goldberg D, Deych L I, Lisyansky A A, Shi Z, Menon V M, Tokranov V, Yakimov M and Oktyabrsky S 2009 *Nature Photonics* **3** 662

[12] Chaldyshev V V, Kundelev E V, Nikitina E V, Egorov A Yu, Gorbatsevich A A 2012 Resonance Reflection of Light by a Periodic System of Excitons in GaAs/AlGaAs Quantum Wells *Semiconductors* **46** 1016–1019