Optical studies of InAs/GaAs monolayer Bragg superlattices

K A Ivanov¹,², A R Gubaidullin¹, G Pozina³, E V Nikitina²,⁴, M A Kaliteevski²
¹ITMO University, St. Petersburg, 197101, Russia
²St. Petersburg Academic University, St. Petersburg 194021, Russia
³Department of Physics, Chemistry and Biology (IFM), Linkoping University, Linkoping, Sweden
⁴Ioffe Institute, St. Petersburg 194021, Russia

Abstract. Periodic sequences of InAs monolayer in GaAs have been grown by molecular beam epitaxy. The properties of the structure have been modelled by transfer matrix calculation and experimentally studied by time-resolved photoluminescence. The structure obtained provides good localisation of excitons in quantum wells and opens possibilities for various optical effects. Coupling of excitons in quantum wells with electromagnetic field confined by a Bragg arrangement of layers produces a peculiar emission mode – a superradiant mode. Measurements and calculations show that for specific values of frequency of light and angle of emission, enhancement of spontaneous emission rate occurs.

1. Introduction

The topic of resonance Bragg quantum structures wells (BQWs) attracted attention spurred by a pioneering theoretical work [1]. In BQW structures with period \(d\), if an angle of light propagation \(\theta\) and its frequency \(\omega\) satisfy Bragg condition

\[ \hbar \omega = \frac{\pi \hbar c}{d \sqrt{n^2 - \sin^2 \theta}} \]  

(1)

giant reflection coefficient has been observed [2]. Half a century ago it has been proposed, that quantum emitter can interact through electromagnetic field forming collective radiative modes, that lead to variety of fascinating effects. One of the effects is superradiance [3], a manifestation of a collective mode of tightly bound light emitters coupled by electromagnetic field. Numerous effects suggesting coupling in Bragg structures have been recently observed [2,4-6]. Recently, similar behaviour has been observed in BQW structures with ML InAs quantum well confined in GaAs matrix [7,8]. It has been suggested that such ML structures can be used in various optical devices for different applications, including proposed Bloch oscillators or any device utilizing ultra-fast optical switching [9].

In this paper we present the results of the study of a high-quality Bragg superlattice grown by MBE and containing InAs MLs in GaAs matrix. This paper also studies further the phenomenon of superradiance in ML structures with respect to more peculiar properties of this mode.

2. Growth, measurements and calculations

Experimental sample shown in fig. 1(a) was fabricated by MBE in Riber 49 chamber on rotating (100) GaAs substrate. The process was controlled by the means of high energy electron diffraction. The sample consists of 60 periods of triple InAs-monolayer QWs separated by bulk GaAs, with the thickness about 100 nm (see [7] for additional details of the fabrication process). Each triplet of QWs consists of three monolayers of InAs embedded in GaAs matrix. The spacing between adjacent MLs was chosen to be 10 nm.
The sample was studied as to its photoluminescence spectrum and afterwards the time-resolved spectroscopy measurements were conducted. The general scheme of an experimental setup is shown in fig. 1(b).

**Figure 1(a,b).** The scheme of (a) the structure; (b) experimental setup.

The study of the PL spectrum revealed that the structure incorporates four exciton states, as is evident in fig. 2. The highest energy belongs to a bulk GaAs exciton, whereas the triplet of lower-energy states is generated by ML QWs. The splitting of the level is the result of a close disposition of the monolayers, which leads to the holes’ wavefunctions being overlapped.

We have then measured the time-resolved spectra of emission at different angles and from various positions of the structure, see next section for details. Overall quality of the results suggests good localization of excitons in ML QWs, which is a main demand for any device aiming at the utilization of quantum properties of semiconductor structures.

**Figure 2.** Measured (blue) and calculated (red) reflection spectra. Excitons’ peaks are denoted by arrows.
3. Results
The measurement PL spectrum was useful in a sense that it provided us with data to tune a model for later modelling. Indeed, an exciton in a QW can be described by a certain reflection coefficient and a transfer matrix. The parameters of an exciton are its resonance energy, radiative decay rate $\Gamma_0$ and non-radiative decay rate $\gamma$. The bulk GaAs is of course also easily modelled using the transfer matrix method. This leads us to a procedure of tuning the exciton model, when we can obtain the abovementioned parameters by varying them to match the calculated reflection spectrum and the measured one. The result of this procedure is shown in fig. 2, and the parameters obtained are shown in Table 1.

|     | Resonance energy, eV | Radiative decay $\Gamma_0$, meV | Non-radiative decay $\gamma$, meV |
|-----|----------------------|-------------------------------|----------------------------------|
| X1  | 1.4712               | 0.36                          | 7.0                              |
| X2  | 1.4820               | 0.18                          | 7.0                              |
| X3  | 1.4910               | 0.14                          | 0.6                              |

The reflection spectrum of the structure was then calculated by the transfer matrix method for the whole range of angles using the obtained exciton parameters, and the results are shown in fig. 3(a). Three monolayer QWs produce three horizontal lines of reduced reflection. One can also see, that there are areas of increased and reduced reflection coefficient for angles and frequencies of light in the vicinity of Bragg condition (1).

We have also calculated the dependence of the probability density of spontaneous emission rate on the angle of emission and frequency of light using S-quantization formalism (see [10] for details). Fig. 3(b) shows the dependence of modal Purcell factor (ratio of densities spontaneous emission rates for the emitters placed into the structure and into free space, respectively [10]). It can be seen, that pattern of modal Purcell factor shows peaks for the angles and frequencies satisfying Bragg condition (1). Surprisingly, the pattern of modal Purcell factor does not demonstrate enhanced emission for all the angles and frequencies coupled by Bragg condition which was already pointed out in [1].

![Figure 3(a,b)](image_url)

Figure 3(a,b). Modelling of (a) the reflection coefficient; (b) the modal Purcell factor. The dashed line corresponds to the Bragg condition (1).
We have also measured time-resolved spectra from the surface of the sample $F_s(\omega, t)$ (where emission is affected by the Bragg arrangement of monolayer quantum wells, fig. 4(a)) for different emission angles and from the edge of the sample $F_e(\omega, t)$ as shown in fig. 4(b).

A quick look at experimental results satisfies that for the low pumping intensity, there is only one emission line corresponding to ground state exciton for both measurements from the edge and from the surface. For the high pumping intensity additional line appears only for the emission spectrum taken from the surface of the sample (in fact, this line is a superposition of several lines). The picture shown in fig. 3(a) (on the right) corresponds to the emission angle 55 degrees when additional mode has maximal power.

4. Conclusions
We have grown a high-quality ML Bragg structure. The results of the optical study speak for its high quality including uniformity of the periods and high exciton localization. We have modelled and measured time resolved emission pattern from the edge and the surface of InAs monolayer quantum well Bragg structure. The patterns of the emission show that the superradiant mode is only possible when the QWs are excited at once and are coupled. The amplification of the emission shows a vague agreement with the line of Bragg condition, but additional conditions apply.

Acknowledgments
The work was partially supported by the RFBR grant No. 18-32-00801 and by the grant of Minobrnauka № 16.9789.2017/BCh.
References
[1] Ivchenko E L, Nesvizhskii A I and Jorda S 1994 Superlattices Microstruct 16(1) 17.
[2] Chaldyshev V V et al. 2011 Appl. Phys. Lett. 98 073112.
[3] Dicke R H 1954 Processes Phys. Rev. American Physical Society 93(1) 99.
[4] Chaldyshev V V et al. 2011 Appl. Phys. Lett. 99 251103
[5] Askitopoulos A et al. 2011 Phys. Rev. Lett. 106 076401.
[6] Goldberg D et al. 2009 Nature Photon. 3 662.
[7] Pozina G et al. 2015 Sci. Rep. 5 14911.
[8] Pozina G et al. 2017 physica status solidi (b) 254(4) 1600402.
[9] Schaarschmidt M et al. 2004 Phys. Rev. B 70 233302.
[10] Kaliteevski M A, Mazlin V A, Ivanov K A, Gubaidullin A R 2015 Optics and Spectroscopy 119(5) 832.