Semiconductor Physics, Quantum Electronics & Optoelectronics. 2004. V. 7, N 2. P. 168-170.

PACS: 78.47. +p, 78.67. Hc

"Multicoloured" superradiance in quantum heterostructures

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Abstract. The analysis of photoluminescence of heterostructures with single elastic-strained $In_{0.16}Ga_{0.84}As$ quantum wells is carried out in this work. It is shown that filling a quantum well with many quantum subbands results in appearance of multicolour superradiance.

Keywords: supperradiance, heterostructure, photoluminescence, quantum well.

Paper received 12.12.03; accepted for publication 17.06.04.

1. Introduction

The origin of Dicke superradiance is concluded to phasing closely located radiative dipoles by own electromagnetic field and macrodipole formation [1]. The phased dipoles relax simultaneously over a period of a few femtoseconds. Such a short relaxation time opens up possibilities for creation of new optical ultrashort-pulse generators.

Despite the fact that superradiance was predicted many years ago, it did not attract much attention from a practical point of view. Once the superradiance has been found in quantum heterostructure [2], interest to research this effect is rapidly growing. This stems from the fact that all conditions needed to the superradiance can be met much easier in quantum heterostructures than in gases and homogeneous solids.

For practical needs, it is very important to know how the relaxation time depends on exciting power. Recently, we have shown that [3] this dependence is controlled by the quantum well filling, and the relaxation time stabilizes when at least one quantum subband is completely filled.

In the present work, we have study a transformation of the spectral band of superradiance under high exciting power. It is shown that filling the quantum well with many quantum subbands results in appearance of multicolour superradiance.

2. Experimental details

Investigation was carried out using $In_{0.16}Ga_{0.84}As$ quantum wells embedded in GaAs matrix. The thickness of quantum wells was 8.4 nm. Structures were grown by MOCVD at the atmospheric pressure. The growth temperature was about 650 K. Pulse N_2 laser with the generation wavelength 337.1 nm and radiation power of 1.5 kW within a pulse, as well as CW He-Ne laser with the generation wavelength 632.8 nm and power about 1.7 mW were used for optical pumping. All the measurements were performed at 100 K.

Calculation of QW energy structure was performed by the method of envelope wave function in the four-band Kane model [5]. The effects of mechanical strains [6], dependence of effective mass of electrons and light holes on energy and calculations of the exciton binding energy performed in [7] were taken into account. As a result of these calculations, it was obtained that the electron quantum well contains two quasi-levels located at 33.3 and 109 meV above the well bottom. As to holes, the considered structure has a quantum well for heavy holes, which contains three quasi-levels 7.3, 28.5 meV and 58.8 meV above the well bottom. Thus, there are one ground and five excited transitions from the quantum well with the energies 1.3581, 1.3792, 1.4095, 1.4337, 1.455 and 1.485 meV, respectively.

3. Results and discussion

PL spectra obtained at different excitation power values are shown in Figs 1,*a* and 1,*b*. At low excitation power, the superradiance spectrum is generated, in general, from the ground state of excitons only (solid curve in Fig. 1,*a*). The spectrum of superradiance is determined by the formula:

$$I_{QW} = \mathrm{sech}\left\{2\pi^2\tau_N\left(E-E_{\max}\right)/h\right\} \qquad (1),$$

where τ_N is the relaxation time of superradiance, $E-E_{\max}$ is the energy detuning.

The position of the energy peak for this band agrees with the calculated one. Under further increase of the QW filling, the transitions from excited quantum subbands should be added. These transitions can be also better described by Dicke superradiance, even if the exciting power is very high (Fig. 2). In theoretical [8] and experimental [9] works, shown were that there exist a possibility to obtain two-colour superradiance in heterostructures with quantum dots. This suggests that a close energy position of these transitions leads to mutual influence of macrodipoles through own electromagnetic radiation. Therefore, we may use practically the same time of superradiance for different transitions in QWs.

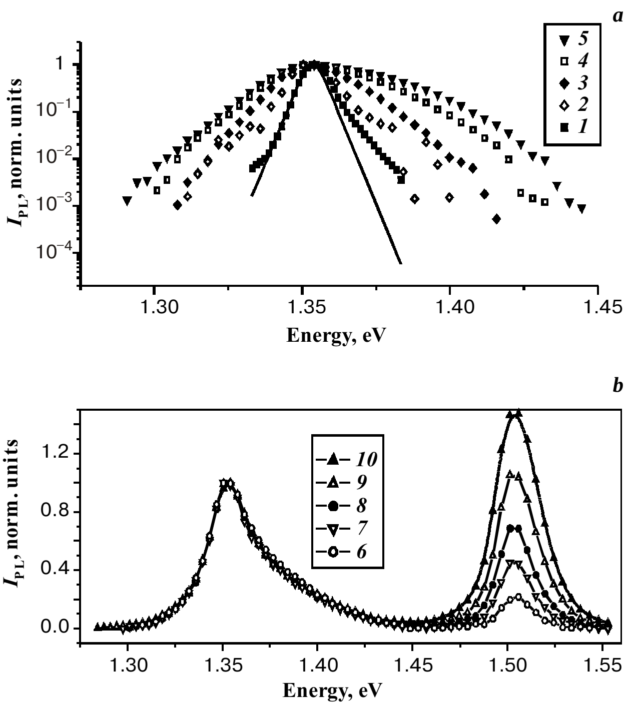

Fig. 1. Photoluminescence spectra of GaAs/In$_{0.16}$Ga$_{0.84}$As/GaAs quantum heterostructure at different excitation power densities: $P_{exc}/P_{exc}^{\max}$ = 3.3×10^{-6} (1), 3.5×10^{-4} (2), 2.8×10^{-3} (3), 5.7×10^{-3} (4), 8×10^{-3} (5), 1.8×10^{-1} (6), 3.5×10^{-1} (7), 2.5×10^{-1} (8), 7.1×10^{-1} (9), and 1 (10); here, $P_{exc}^{\max}$ = 9×10^6 W/cm^2. The solid curve in Fig. 1*a* is Dicke approximation by Eq. (1).

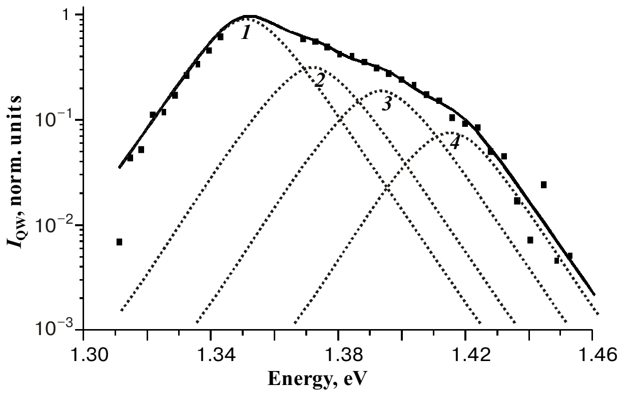

Fig. 2. Approximation of PL spectra by “multicolour” superradiance (P = 4.2×10^{-1} W/cm^2). Curves: *1* – E_{e1-hh1}=1.3504 eV, 2 – E_{e1-hh2} = 1.3728 eV, 3 – E_{e1-hh3} = 1.392 eV, 4 – E_{e2-hh1} = 1.4158 eV.

Calculation performed at the high excitation levels for the structures studied yields that characteristic times of electron (hole) – phonon interaction (τ_e, $\tau_h \le 10^{-11}$ s, respectively) exceed the *e-e* interaction time ($\tau_c \sim 10^{-14}$ s) and time of superradiance (τ_N), however, they are less than a time of spontaneous radiation (τ_i). Thus, relations between characteristic times are as follows:

$$\tau_{\mathrm{exc}} > \tau_i > \tau_e(\tau_h) > \tau_c \sim \tau_{cN},$$

where τ_{exc} is the excitation time.

Superradiance time is known to be presented as [10]:

$$1/\tau_N = (N\mu + 1)\cdot 1/\tau_i$$

where N is a number of phased dipoles in macrodipole, μ is the form-factor describing relative disposition of dipoles. The time of macrodipole formation (τ_0), i.e. phasing of single dipoles in a local part of the sample, depends on the superradiance time and characteristic times of carrier relaxation on phonons and defects [11]:

$$\tau_0 = \tau_N \ln(N\mu)\left[1 + \frac{\tau_N}{\tau_g}\cdot\sqrt{\ln(N\mu)}\right],$$

where $\dfrac{1}{\tau_g} = \dfrac{1}{\tau_e} + \dfrac{1}{\tau_h}$.

So, the phasing time is $\tau_0 \ge 10^{-12}$ s, and $\tau_0 \approx 10\cdot\tau_N$ i.e. $\tau_0 >> \tau_c$, and we can estimate the filling of quantum subbands in terms of Fermi quasi-levels. The stabilization and appearance of the additional peak, which corresponds to radiation from a substrate, have allowed us to determine the critical excitation power when quantum wells are completely filled.

The energy structure of quantum wells does not vary up to complete filling the electronic subbands. However, at the larger excitation levels, when all electronic states are already filled, the hole states continue filling with increase of excitation power, and consequently, the quantum well charges positively. To compensate this charge, the electrons will gather in the conduction band of the matrix in the vicinity of the quantum well. Consequently, at high excitation superradiance arises in the structure that possesses a transformed potential profile of the quantum well. The changes in the potential profile shift the positions of quantum subbands, and peaks of excited excitons should be shifted to low energy. Such a shift explains a small change in energy positions of peaks related to excited quantum subbands (Fig. 2) as compared with the calculated ones.

In conclusion, the model proposed allows to describe the experimental PL spectra by the best way. Moreover, in the quantum well with large (> 2) number of quantum subbands for electrons and holes at the high excitation levels, PL spectra should be considered as superposition of several superradiance bands.

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