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Excitons in asymmetric quantum wells

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ABSTRACT

Resonance dielectric response of excitons is studied for the high-quality InGaAs/GaAs heterostructures with wide asymmetric quantum wells (QWs). To highlight effects of the QW asymmetry, we have grown and studied several heterostructures with nominally square QWs as well as with triangle-like QWs. Several quantum confined exciton states are experimentally observed as narrow exciton resonances. A standard approach for the phenomenological analysis of the profiles is generalized by introducing different phase shifts for the light waves reflected from the QWs at different exciton resonances. Good agreement of the phenomenological fit to the experimentally observed exciton spectra for high-quality structures allowed us to reliably obtain parameters of the exciton resonances: the exciton transition energies, the radiative broadenings, and the phase shifts. A direct numerical solution of the Schrödinger equation for the heavy-hole excitons in asymmetric QWs is used for microscopic modeling of the exciton resonances. Remarkable agreement with the experiment is achieved when the effect of indium segregation is taken into account. The segregation results in a modification of the potential profile, in particular, in an asymmetry of the nominally square QWs.

1. Introduction

Excitons in quantum wells (QWs) have been extensively studied already for four decades [1–7]. Theoretical analysis of the excitons typically assumes a simplified model for the QW potential, e.g., square profiles for electrons and holes [5,8–10]. Real potential, however, is more complex due to several processes taking place during the growth of heterostructures. In the narrow QWs, the monolayer fluctuations of interfaces give rise to fluctuations of the QW width. These fluctuations result in the step-like changes of the exciton quantization energy experimentally observed as a set of exciton resonances in optical spectra [11]. The diffusion of atoms through the QW interface (segregation) during the growth process gives rise to smoothing and an asymmetry of potential profiles for carriers [12,13]. The specially designed asymmetric QWs are also extensively studied in view of their interesting properties, e.g., large electron spin-orbit splitting [14,15], enhanced optical nonlinearity [16–18] and coupling with terahertz radiation [19,20].

The exciton energy and the wave function are sensitive to the potential profile. However, the direct experimental observation of effects of the profile peculiarities on the exciton properties is difficult for several reasons. The exciton energy

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shift relative to the theoretically predicted value may be caused, apart from the modification of potential profile, by uncertainties in the QW width and in the composition of the barrier layers within the heterostructure. Various imperfections of the heterostructure like point defects, dislocations, etc., may broaden the exciton resonances and complicate the study of exciton energies. The exciton oscillator strength and the radiative decay rate, which are determined by the exciton wave function, can be studied by reflectance spectroscopy and in the time-resolved experiments [7,21,22]. However, these are the integral characteristics that does not allow one to reconstruct the potential profile when only a single exciton transition is studied.

In this paper, we experimentally study and theoretically analyze reflectance spectra of heterostructures with asymmetric InGaAs/GaAs QWs. We demonstrate that the simultaneous analysis of several exciton resonances in the spectra of relatively wide QWs allows one to obtain valuable information about the potential profile for the excitons. We have developed an approach for the direct numerical solution of the Schrödinger equation for an exciton in a QW with an arbitrary potential profile. The Coulomb electron-hole interaction in the exciton is included into the numerical approach without approximations. Calculations of the exciton energies and wave functions allowed us to accurately model the reflectance spectra using only two fitting parameters describing the maximal indium content in the QW and the characteristic length of the indium diffusion. Both these parameters cannot be controlled and measured during the growth of heterostructures with the high enough accuracy required for the modeling. The obtained agreement allowed us to model the potential profile for excitons and to determine real indium content in the heterostructures under study.

The paper has the following structure. First, we present experimental details and obtained reflectance spectra. A generalization of phenomenological theory of exciton-light coupling for the case of several exciton resonances in a QW with arbitrary potential profile is given in Section 3. Then we compare experimental results and microscopic modeling of the exciton states. Finally, we sum up major results in the Conclusion.

2. Experiment

We have experimentally studied reflectance spectra of several InGaAs/GaAs heterostructures grown by the molecular beam epitaxy (MBE). Two of the structures with the smallest inhomogeneous broadening of exciton resonances have been selected for detailed investigation. The first one (S1) contains a nominally square QW of 95-nm width with small indium content of about 2% grown between the GaAs barrier layers. The second structure, S2, is the specially designed asymmetric InGaAs/GaAs QW with one vertical potential wall and other sloping potential wall. In both structures, effects of the QW asymmetry are found in the comparative study of exciton resonances observed in reflectance spectra. The spectra have been measured using a femtosecond Ti:Sapphire laser or a halogen lamp as a light source. In the latter case, the light was focused onto a 50-μm pin-hole and then refocused onto the sample. The light was directed to the samples at small angle close to the normal incidence. The light spots on the samples were of about 100 μm in both cases. The samples were held in a vacuum chamber of a closed cycle cryostat at $T = 4$ K. The reflected light was dispersed in a 0.55 m spectrometer with the 1800 grooves/mm grating and detected by a nitrogen cooled CCD-matrix. The spectral resolution was of about 30 μeV. To obtain the absolute value of reflectivity, the reflectance coefficient was carefully measured for a single wavelength nearby an exciton resonance using a beam of a continuous wave Ti:sapphire laser focused at the same spot on the sample.

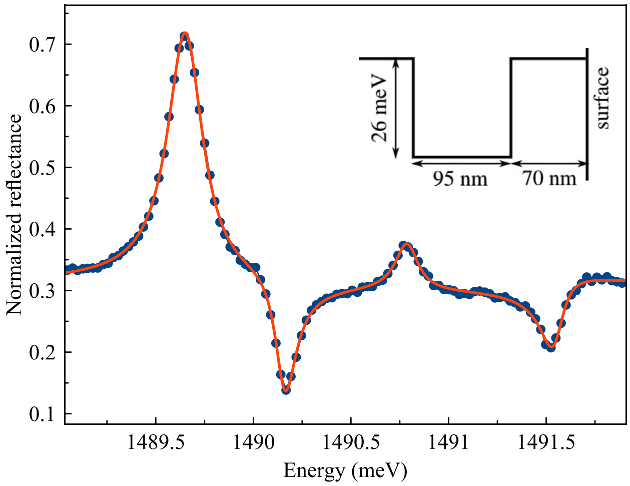

Fig. 1. Reflectance spectrum of InGaAs/GaAs heterostructure with the 95-nm square QW. The red line corresponds to the fit by a phenomenological model with the four free parameters for each resonance. Inset represents the predefined QW potential profile for excitons. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)