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Amplification and passing through the barrier of the exciton condensed phase pulse in double quantum wells

O.I. Dmytruk [a], V.I. Sugakov [b,*]

[a] Taras Shevchenko National University of Kyiv, 2, Prosp. Academician Glushkov, Kyiv 03022, Ukraine
[b] Institute for Nuclear Research, National Academy of Sciences of Ukraine, 47, Prosp. Nauky, Kyiv 03680, Ukraine

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ABSTRACT

The peculiarities and the possibility of a control of exciton condensed pulse movement in semiconductor double quantum wells under the slot in the metal electrode are studied. The condensed phase has been considered phenomenologically with the free energy in Landau–Ginzburg form taking into account the finite value of the exciton lifetime. It was shown that the exciton condensed phase pulse moves along the slot driven by an external linear potential. If the exciton density is high enough for the formation of the condensed phase then the pulse moves maintaining a constant value of a maximum density during exciton lifetime, while the exciton gas phase pulse diffuses. The penetration of the exciton condensed phase pulse through a barrier and its stopping by the barrier have been studied. Additionally, it was shown that the exciton pulse in the condensed phase can be amplified and recovered after damping by an additional laser pulse. Solutions for the system of excitons in double quantum wells under the slot in the electrode under steady irradiation in the form of bright and dark autosolitons were found.

1. Introduction

In recent years, much attention has been paid to both experimental and theoretical study of indirect excitons in semiconductor double quantum wells at low temperatures. An indirect exciton is a bound pair of an electron and a hole which are separated by an electric field to different quantum wells [1]. Consequently, the recombination of the electron and the hole is inhibited, that causes the lifetime of indirect excitons to be several orders of magnitude higher than the direct exciton lifetime. The study of indirect excitons is promising in terms of fundamental science, because a high density of excitons can be created and many-exciton effects can be studied. Additionally, the system of indirect excitons can be promising for applications, since they can travel over large distances carrying energy and information and may be used in the double quantum well based semiconductor devices. Therefore, a great number of experimental and theoretical works have been devoted to the study of the indirect excitons' properties. The experimental studies on the AlGaAS-based quantum wells revealed [2–5] new nontrivial effects such as formation of spatially inhomogeneous structures (sometimes periodical) in the distribution of exciton density. Various spatial nonhomogeneous distributions of the exciton density were observed in the emission of the indirect excitons at the pumping greater than a certain critical value. Thus, in the paper [2] the authors observed a break-down of the emitting ring outside the laser spot into separate fragments periodically localized along the ring. In the papers [3,4], in which the excitation of the quantum well was carried out through a window in a metallic electrode, the authors found a periodical structure of the luminescent islands situated along the ring under the perimeter of the window. Recently Timofeev and coauthors [5] presented examples of the emitting structures, obtained through differently shaped windows in the electrodes: a rectangle, a triangle, two circles, two triangles etc. The appearance of the structures in the exciton density distribution was observed for a periodical potential applied to excitons [6]. Besides the periodical structure imposed by external conditions, the partition of the emission into fragments existed in the direction, in which the potential was almost uniform.

The phenomenon of the break-down of the homogeneity and the emergence of emitting structures in systems of indirect excitons stimulated a number of theoretical investigations. Several different theoretical models of the formation of spatial patterns were proposed [7–14]. The authors of the work [7] considered the instability, which arises in the kinetics of the level occupation by particles with the Bose–Einstein statistics. Namely, the growth of the occupation of the level with zero momentum should stimulate the transitions of excitons to this level. But the required density of excitons was found to be greater, and the required temperature was found to be lower than the corresponding experimental values. Some authors explain the appearance of the periodicity

* Corresponding author. Tel.: +380 445254810; fax: +380 445254463.
E-mail addresses: olesia.dmytruk@gmail.com (O.I. Dmytruk), sugakov@kinr.kiev.ua, v.sugakov@ukr.net (V.I. Sugakov).

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by the Bose condensation of excitons [8,9]. There is a suggestion to describe the system by a nonlinear Schrödinger equation [10]. The appearance of islands observed in Ref. [2] was explained in the paper [12] on the ground of a classical model of the diffusion with Coulomb interaction between the particles, but without taking into account the screening of the charges at macroscopic distances. The emergence of periodicity in the exciton system was investigated in Ref. [13] using Bogolyubov's equations with some approximations of inter-exciton interaction. Also a possibility of a Mott transition in considered systems has been studied [14]. In the listed works the main efforts were applied for the ascertainment of the principal possibility of the appearance of the periodicity in the exciton density distribution. A specific application of the results for the explanation of numerous experiments with different setups, at different pumping, temperature, different type of external fields was not employed.

In the papers [15–19] we suggested a model which explained the experimentally observed spatial structures in the exciton density distribution. The theoretical approaches of the works [15–19] are based on the following assumptions:

1. There exists an exciton condensed phase caused by an attractive interaction between excitons.
   The assumption is supported by the existence of bound states of two indirect excitons, obtained in the calculations by several groups [20–22], and a new phase in the multiexciton system [23]. The attractive exchange and van der Waals interactions may exceed the repulsive long-range dipole–dipole interactions between excitons if the distance between the quantum wells in a double well setup, and, correspondingly, dipole moments of indirect excitons, are not too large. Note, that from the analysis of the shape of the exciton emission band, the authors of the work [24] came to the conclusion that the interaction between indirect excitons is exclusively repulsive. In the paper [25] an alternative explanation of the experimental result obtained in Ref. [24] was given, which does not contradict the assumption of an attractive interaction. It was shown that the important contribution to the formation of the exciton emission bandshape at low densities comes from the traps, levels of which are localized under the exciton band. These traps become saturated at increased pumping and, thus, the emission, coming from the band proper, shifts to a higher frequency.
2. The finite value of the exciton lifetime plays an important role in the formation of the exciton condensed phase.
   Usually the exciton lifetime is much greater than the time of establishment of the local equilibrium in a system. But taking into account the finiteness of the exciton lifetime is necessary in the study of the spatial distribution of phases in two-phase systems, because the exciton lifetime is less than the time of the establishment of the equilibrium between different phases. The latter is determined by slow diffusion processes and is large. The finite exciton lifetime restricts the maximal size of the condensed phase domain and causes the existence of a correlation in positions of separate regions of the condensed phase.

The suggested model [15–19] has succeeded in explaining the spatial structures observed in the luminescence of indirect excitons. Particularly, this model has allowed us to describe the spatial distribution of the excitons on the ring outside the laser spot, observed in Ref. [2], the spatial structure of the luminescence under the window in the metal electrode, observed in Refs. [3,4]. The involvement of Bose–Einstein condensation for excitons was not required for the explanation of the experiments. The Bose–Einstein nature of excitons contributes to the values of the phenomenological coefficients, which may be obtained in microscopic theory. But the condensation occurs in a real space due to the interaction between excitons. The application of the presented model of the exciton condensation in the model of nucleation [15,17] is similar to a study of creation of electron–hole drops in semiconductors [26–28]. In this case, the islands of the exciton condensed phase are a two dimensional analog of the electron–hole drops. But, compared to the works [26–28], we took into account the correlation of the mutual positions of the islands, because they draw excitons from the same environment. This correlation allows us to explain the emergence of the periodicity in the distribution of the islands, which is observed in experiments.

The possibility of using the system of indirect excitons in the optoelectronics is studied in several works [29–33]. The experimental possibility of building an exciton optoelectronic transistor [29], an excitonic integrated circuit [30] and an excitonic conveyor [31] was demonstrated recently. Therefore, the theoretical study of the propagation of the interacting system of indirect excitons in external fields is important.

In this work we study the formation, amplification and passing through the barrier of the exciton condensed phase pulse in the semiconductor double quantum well in the setup, in which one of the electrodes has a slot, through which the excitons are created. We consider this problem using our model [15–19], approbated by the analysis of experimental results. The formation of the exciton condensed phase in the double quantum well under the slot excited by a steady uniform irradiation was studied in Ref. [19]. Unlike the work [19] this paper investigates the excitation of the exciton condensed phase by a pulse irradiation. This excitation creates an exciton condensed phase pulse, the movement and control of which are analyzed. The possibility of the amplification of a pulse by an additional laser pulse in the one-dimensional system was investigated in Ref. [34]. Compared to Ref. [34], in the presented paper, the processes of passing of the exciton pulse through a barrier and the possibility of stopping of the pulse by the barrier are investigated. Also we consider the real physical two-dimensional system (a slot in the electrode) and estimate the effect of exciton–exciton annihilation on the traveling pulse. The analysis of the difference in the movement of the pulses built from the excitons in a gas phase and the excitons in a condensed phase is presented.

2. Model of the system

We consider the semiconductor structure with the double quantum well sandwiched between two metal electrodes. There is the slot in the upper electrode (Fig. 1). The width of the slot is $2b$. Let us choose the OX axis along the slot, the axis OY in the transverse direction and the OZ axis along the normal to the electrode. Let the plane of the quantum well has a coordinate z ($z<0$). The presence of the slot forms an inhomogeneous electric field that is additional to the homogeneous field of the solid electrode and gives an additional potential energy for excitons in quantum wells.

The distribution of the exciton density in the double quantum well was determined [19] for the uniform steady-state excitation of the well through the slot. It was shown that a chain of periodically situated islands arises in the well below the center of the slot if the pumping exceeds some critical value. If the width of the slot is large, two chains of exciton condensed phase islands, located along the edges of the slot, appear. Additionally, the possibility of a movement of the chains along the slot was shown in Ref. [19] if driven by an external potential.

In the considered system presented in Fig. 1, there are additional elements in comparison to the system investigated in the work [19]. We shall see, that these elements allow controlling the propagation of the exciton pulse.