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Controlling two-dimensional electron localization via phase-controlled absorption and gain in the three-coupled quantum wells

Tao Shui, Zhiping Wang *, Benli Yu

Laboratory of Opto-Electronic Information Acquisition and Manipulation of Ministry of Education, Anhui University, Hefei 230601, China

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ABSTRACT

We investigate two-dimensional (2D) electron localization via phase-controlled absorption and gain of a weak probe field in an asymmetric semiconductor three-coupled quantum well (TCQW) with a closed loop under the action of two orthogonal standing-wave fields. It is found that we can achieve high-precision and high-resolution 2D electron localization via properly varying the parameters of the system. The influences of direct one-photon transition and indirect three-photon transition on the precision of probe absorption–gain spectra are also discussed in details. Thus, the proposed scheme shows the underlying probability for the formation of the 2D electron localization in a solid.

1. Introduction

In the past few decades, high-precision spatial position measurement of a moving atom passing through the standing-wave field has attracted much attention and has been extensively researched because of its potential wide applications in laser cooling and trapping neutral atoms [1], Bose–Einstein condensation [2], atom lithography [3], measurement of the center-of-mass wave function of moving atom [4], and coherent patterning of matter waves [5]. Based on atomic coherence, many schemes [6–22] have been proposed for one- and two-dimensional (2D) atom localization. Studies show that atom localization can been controlled via the measurement of the atomic population, double-dark resonances, the probe absorption or gain spectrum, spontaneous emission and so on.

Among these schemes, some researchers used the collective phase of applied fields to investigate the behavior of atom localization due to the phase sensitive property of an atomic system with a closed-loop structure. By tuning the collective phase, the periodicity of the position probability distribution can be greatly reduced to sub-half-wavelength domain. For 1D atom localization, Sahrai et al. proposed a scheme for subwavelength atom localization via amplitude and phase control of the absorption spectrum. And two localization peaks in either of the two half-wavelength regions along the cavity axis were observed by appropriate choice of the system parameters [15]. Then they showed the position of the atom is restricted to one-half of each wavelength in a V-type three-level atom by only adjusting the phase difference between applied fields [16]. For 2D atom localization, Ding and his coworkers achieved 100% probability of finding the atom at an expected position by using phase dependent absorption [20] and spontaneous emission [25], when two orthogonal standing-wave fields coupled the same atomic transition. Recently, a scheme for two-dimensional atom localization based on the phase control of absorption and gain of a weak probe field in a four-level double-Λ system was proposed by Wan et al. [21], they found that the probability of finding the atom at a particular position can be 100% when a photon with certain frequency was absorbed or amplified.

In recent years, great attentions have been paid to semiconductor quantum wells (QWs), which can be viewed as the 2D electron gas, due to their inherent advantages such as high nonlinear optical coefficient and large electric dipole moments of intersubband transitions. Furthermore, the transition energies, dipole moment and symmetries can be flexibly engineered as desired by choosing the materials and structure dimensions in device design. The implementation of quantum coherence and interference effects in QWs is much more practical than its atomic counterpart in quantum information and quantum networking. Several quantum coherence and interference effects have been studied in recent year, such as gain without inversion [26,27], electromagnetically induced transparency [28,29], optical bistability [30–32], optical soliton [33,34], Kerr nonlinearity [35], slow light [36], and other phenomena [37–40]. Lately, Wang et al. [41–43] investigated the 2D probe absorption spectrum in semiconductor quantum wells driven by two orthogonal standing-wave lasers, which showed the underlying probability for the formation of the 2D localization effect in solids.

* Corresponding author. Tel.: +86 055 163861753.
E-mail address: zhipwang@126.com (Z. Wang).

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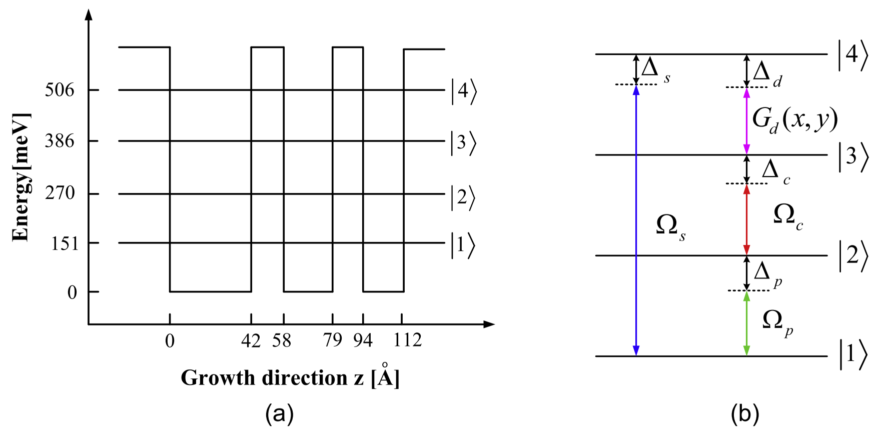

Fig. 1. (a) Schematic energy-band diagram of a single period of the asymmetric AlInAs/GaInAs TCQW structure. The layer thicknesses in the QW regions are 42 Å (GaInAs well), 16 Å (AlInAs barrier), 20 Å (GaInAs well), 16 Å (AlInAs barrier), and 18 Å (GaInAs well). (b) The energy arrangement we study. Each field drives only one transition.

In this Letter, we investigate the two-dimensional (2D) electron localization in an asymmetric semiconductor three-coupled quantum well with a closed loop under the action of two orthogonal standing-wave fields. Due to the phase sensitive property of the closed-loop structure, the high-precision and high-resolution 2D electron localization can be achieved. Our work is mainly based on the [19–25,41–43], however, which is drastically different from those works. The major differences are obtained as follows. First, we are interested in showing the 2D electron localization in an asymmetric semiconductor three-coupled quantum well. Second, due to the spatial-dependent quantum interference effect, the probe gain–absorption spectrum can be controlled at a particular position and the 2D localization effect is indeed achieved efficiently. Third, the scheme proposed in this paper shows the underlying probability for the formation of the 2D electron localization in a solid, which may provide some important applications for electron propagation and dissociation in semiconductors.

The outline of this paper is organized as follows. In Section 2, the theoretical model under consideration is introduced and the expression of position-dependent absorption and gain is given by deriving the equations of motion for the probability amplitude in the TCQW system. In Section 3, we give a detailed analysis and explanation for 2D probe absorption–gain spectra in the form of graphs. Finally, the main conclusions are summarized in Section 4.

2. Model and basic equations

We consider an asymmetric TCQW structure consisting of a wide well and two narrow wells as shown in Fig. 1, where all possible transitions are dipole allowed. A weak probe field with Rabi frequency Ω_p (amplitude E_p and central frequency ω_p, which is called as probe and denoted by ‘p’) is applied to the intersubband transition $|1\rangle \rightarrow |2\rangle$ of frequency ω_{21}. The transition $|2\rangle \rightarrow |3\rangle$ of frequency ω_{32} is coupled by a strong traveling-wave driven field with Rabi frequency Ω_c (amplitude E_c and central frequency ω_c, which is called as couple and denoted as ‘c’). The transition $|3\rangle \rightarrow |4\rangle$ of frequency ω_{43} is driven simultaneously by the composition of two orthogonal standing-wave fields with position-dependent Rabi frequency $G_d(x, y)$ (amplitude $E_d[\sin(kx) + \sin(ky)]$ and central frequency ω_d, which is called as driving and denoted ‘d’). To establish a closed-loop configuration, we apply a weak signal field with Rabi frequency Ω_s (amplitude E_s and central frequency ω_s, which is called as signal and denoted by ‘s’). Under the rotating-wave approximation (RWA) and the electro-dipole approximation (EDA), via choosing the proper free Hamiltonian, in the Schrödinger picture, the free and the interaction Hamiltonian in our system can be written as [38] (with the assumption of $\hbar = 1$)

$$H_0 = \omega_p|2\rangle\langle 2| + (\omega_p + \omega_c)|3\rangle\langle 3| + (\omega_p + \omega_c + \omega_d)|4\rangle\langle 4| \quad (1a)$$

$$\begin{aligned} H^S_{\text{int}} = &-\Omega_p e^{-i(\omega_p t-\varphi_p)}|2\rangle\langle 1| - \Omega_c e^{-i(\omega_c t-\varphi_c)}|3\rangle\langle 2| \\ &- G_d(x, y)e^{-i(\omega_d t-\varphi_d)}|4\rangle\langle 3| - \Omega_s e^{-i(\omega_s t-\varphi_s)}|4\rangle\langle 1| \\ &+ h.c. \end{aligned} \quad (1b)$$

Here, $h.c.$ means Hermitian conjugation. The parameters φ_p, φ_c, φ_d and φ_s are the initial phases of applied fields. In the interaction picture, when the carrier frequencies fulfill the relationship $\omega_p + \omega_c + \omega_d = \omega_s$, the resulting interaction Hamiltonian can be rewritten as

$$\begin{aligned} H^I_{\text{int}} = &\Delta_p|2\rangle\langle 2| + (\Delta_p + \Delta_c)|3\rangle\langle 3| + (\Delta_p + \Delta_c + \Delta_d)|4\rangle\langle 4| \\ &- \big(\Omega_p e^{i\varphi_p}|2\rangle\langle 1| + \Omega_c e^{i\varphi_c}|3\rangle\langle 2| + G_d(x, y)e^{i\varphi_d}|4\rangle\langle 3| \\ &+ \Omega_s e^{i\varphi_s}|4\rangle\langle 1| + h.c.\big) \end{aligned} \quad (2)$$

where $\Delta_p = \omega_{21} - \omega_p$, $\Delta_c = \omega_{32} - \omega_c$, $\Delta_d = \omega_{43} - \omega_d$ and $\Delta_s = \omega_{41} - \omega_s$ stand for the detuning of applied laser fields from the corresponding transition. Ω_p, Ω_c, $G_d(x, y)$ and Ω_s denote one-half Rabi frequencies for the relevant driven transition, i.e., $\Omega_p = \mu_{21}E_p/2\hbar$, $\Omega_c = \mu_{32}E_c/2\hbar$, $G_d(x, y) = \Omega_d[\sin(kx) + \sin(ky)]$ ($k = 2\pi/\lambda_d$ is the wave vector of the standing-wave field) with $\Omega_d = \mu_{43}E_d/2\hbar$, and $\Omega_s = \mu_{41}E_s/2\hbar$. Here, μ_{ij} denotes the relevant intersubband dipole moment for the transition between $|i\rangle$ and $|j\rangle$. The relationship $\omega_p + \omega_c + \omega_d = \omega_s$ is reduced to $\Delta_p + \Delta_c + \Delta_d = \Delta_s$ in such a closed system.

The electronic energy state of the system is defined as

$$\begin{aligned} \big|\psi(t)\big\rangle = &b_1(t)|1\rangle + b_2(t)e^{i\varphi_p}|2\rangle + b_3(t)e^{i(\varphi_p+\varphi_c)}|3\rangle \\ &+ b_4(t)e^{i(\varphi_p+\varphi_c+\varphi_d)}|4\rangle \end{aligned} \quad (3)$$

where b_j ($j = 1$–4) is the probability amplitude of level $|j\rangle$. By utilizing the Schrödinger equation, we can obtain the equations of motion of the probability amplitudes

$$\frac{\partial b_1}{\partial t} = i\Omega_p b_2 + i\Omega_s b_4, \quad (4a)$$

$$\frac{\partial b_2}{\partial t} = i(-\Delta_p + i\gamma_2)b_2 + i\Omega_p b_1 + i\Omega_c b_3, \quad (4b)$$

$$\frac{\partial b_3}{\partial t} = i\big[-(\Delta_p + \Delta_c) + i\gamma_3\big]b_3 + i\Omega_c b_2 + iG_d(x, y)b_4 e^{-i\varphi}, \quad (4c)$$

$$\begin{aligned} \frac{\partial b_4}{\partial t} = &i\big[-(\Delta_p + \Delta_c + \Delta_d) + i\gamma_4\big]b_4 + i\Omega_s b_1 \\ &+ iG_d(x, y)b_3 e^{i\varphi}, \end{aligned} \quad (4d)$$