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Dynamical control of quantum tunneling due to ac Stark shift in an asymmetric coupled quantum dot

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Dynamical suppression and enhancement of the quantum tunneling in an asymmetric coupled-quantum-dot structure is predicted to occur when a laser field drives a subband transition in one of the dots. The laser field induces the splitting and shift of the quasiresonant energy levels, i.e., ac Stark (or light) shift. As a result, the tunneling between the energy levels perturbed by the laser field and another level in the neighboring dot is strongly modified as the amplitude of the laser field is increased. Furthermore, it is shown that the amount of the ac Stark shift has an oscillatory behavior for large amplitudes of the laser field, which is not predicted from the conventional rotating-wave approximation for the matter-light interaction. [S0163-1829(97)08340-9]

The problem of coherent tunneling through the barrier of a double well or a superlattice in the presence of an external laser field has received a considerable amount of attention recently.[1–10] Grossmann *et al.*[2] reported on an interesting effect of a cw laser acting on an electron in a double well. If the electron is initially localized in one of the two wells, and if the laser power and frequency are chosen appropriately, the radiation field can prevent the coherent tunneling (or coherent oscillation). They called this phenomenon ''coherent destruction of tunneling.'' Bavli and Metiu[3] reported on a more complex situation. They showed that a semi-infinite laser field, which acts on a ground-state (delocalized) electron, localizes it in one of the wells and then confines it there. Tsukada *et al.*[9] reported that the localization of the electron on one of the wells is realized if the ratio of the field magnitude and the field frequency is a root of the ordinary Bessel function of order n for n-photon-assisted resonances. They also pointed out that the ''miniband collapse'' of the superlattice and the ''destruction of coherent tunneling'' is physically an identical concept.

Recently, Kilin, Berman, and Maevskaya[11] proposed a scheme to dynamically suppress the tunneling by a laser field. The system considered by them is a molecule that is placed in an appropriate host medium. The molecule is characterized by two electronic states with double-well potentials for the ground and excited states. The ground-state potential is symmetric, but the excited-state potential does not possess this symmetry. The two lowest eigenstates of the ground-state potential have symmetric and antisymmetric wave functions, while the excited-state wave function is localized in the one of the wells of the excited-state potential. A coherent (laser) field drives transitions between the ground and excited states. The interaction in this three-level system is analyzed semiclassically in the rotating-wave approximation (RWA). In effect, the laser field suppresses the tunneling by lifting the degeneracy of the ground state, provided that the Rabi frequency is greater than the energy-level separation.

In this paper, we adopt their idea to a semiconductor coupled-quantum-dot system without RWA. Figure 1 illustrates an asymmetric coupled-quantum-dot structure investigated in this paper. The large dot has two energy states $|a\rangle$ and $|c\rangle$ but the small dot has only one energy state $|b\rangle$. The states $|a\rangle$ and $|b\rangle$, and the states $|c\rangle$ and $|b\rangle$ are coupled by the tunneling through the barrier, and the states $|a\rangle$ and $|c\rangle$ are coupled by a coherent electromagnetic (laser) field $E(t)=E_{\omega}\sin(\omega t+\delta)$ having the frequency ω and the phase δ. Furthermore, a bias voltage E_0 is applied perpendicular to the barrier layer. As the bias voltage is varied, the state $|b\rangle$ in the small dot is scanned with respect to the states $|a\rangle$ and $|c\rangle$ in the large dot. Here we assume that the linear polarized laser field is applied parallel to the barrier layer. In this situation, the laser field does not change the relative potentials of the energy states in the dots. This situation just corresponds to one investigated in Ref. 11. The situation in which the direction of the electric field of the laser beam is perpendicular to the barrier layer will be a future study. Figures 1(a)–1(c) show unbias, first resonance [close alignment of both $n=1$ states ($|a\rangle$ and $|b\rangle$) of the large and the small dot], and second resonance [close alignment of the $n=2$ state ($|c\rangle$) of the large dot and $n=1$ state ($|b\rangle$) of the small dot], respectively.[12]

We consider the time evolution of the electron occupation probability in the states $|a\rangle$, $|b\rangle$, and $|c\rangle$. The time evolution of the wave function $\psi(t)$ is treated by the time-dependent Schrödinger equation

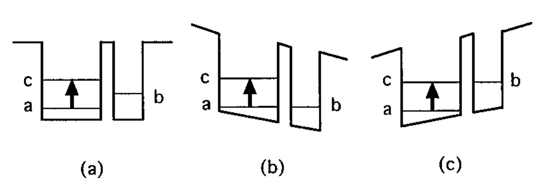

FIG. 1. Schematic potential profiles of a coupled-quantum-dot system under an external electric field at unbias (a), first resonance (b), and second resonance (c).

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$$i\hbar[\partial\psi(t)/\partial t]=H\psi(t), \tag{1}$$

with Hamiltonian

$$H=\kappa(|a\rangle\langle b|+|b\rangle\langle a|+|c\rangle\langle b|+b\rangle\langle c|) \\ +pE(t)(|a\rangle\langle c|+|c\rangle\langle a|)+eE_0d|b\rangle\langle b|+\hbar\omega_0|c\rangle\langle c|, \tag{2}$$

where κ is the tunneling matrix element, p the dipole transition moment, d the center-to-center separation of the quantum dots, and ω_0 the separation energy between the state $|a\rangle$ and the state $|c\rangle$. We express the eigenstate of an electron in the double-dot quantum structure as a linear combination of the three wave functions ψ_j ($j=a$, b, and c) of the isolated quantum dots, i.e., $\psi(t)=a(t)\psi_a+b(t)\psi_b+c(t)\psi_c$. Here the coefficients satisfy the simple normalization $|a(t)|^2+|b(t)|^2+|c(t)|^2=1$, which implies that the probability for finding the electron in a state other than ψ_a, ψ_b, or ψ_c is zero. For convenience, the energy of the state $|a\rangle$ is chosen to be zero in Eq. (2).

Substituting $\psi(t)$, H, and $E(t)$ into the Schrödinger equation (1) and we can obtain a coupled equation as follows:

$$da(t)/dt=-i\kappa_{ab}b(t)-i\Omega_\omega\sin(\omega t+\delta)c(t), \tag{3a}$$

$$db(t)/dt=-i\Delta b(t)-i\kappa_{ba}a(t)-i\kappa_{bc}c(t), \tag{3b}$$

$$dc(t)/dt--i\omega_0c(t)-i\kappa_{cb}b(t)-i\Omega_\omega\sin(\omega t+\delta)a(t), \tag{3c}$$

where $\Delta=eE_0d/\hbar$, $\Omega_\omega=p_{ac}E_\omega/\hbar$, p_{ac} is the dipole transition moment between the state $|a\rangle$ and the state $|c\rangle$ and κ_{ij} is the tunneling (coupling) coefficient between the state $|i\rangle$ and the state $|j\rangle$ due to the interdot tunneling. Ω_ω is the interaction energy frequency, or Rabi frequency, for the transition between the states $|a\rangle$ and $|c\rangle$ induced by the laser field, and ω_0 is the energy difference between the states $|a\rangle$ and $|c\rangle$.

The coupled system given by Eq. (3) is similar to the situation of the two-level atomic system driven by pump and probe laser fields,[13] in which the atomic levels perturbed by the strong pump field are monitored by the weak probe field. In the system of Eq. (3), the information of the energy states in the large dot perturbed by the laser field can be probed by varying the bias voltage, i.e., Δ in Eq. (3b) being the relative energy of the state $|b\rangle$. In other words, the state $|b\rangle$ in the small dot acts as a probe of the perturbed energy states $|a\rangle$ and $|c\rangle$ in the large dot.

If we consider that the tunneling coefficients κ_{ij}'s are very small compared with Ω_ω, κ_{ij}'s can be considered as a perturbation and, therefore, Eqs. (3a) and (3c) can be decoupled from Eq. (3b). The coupled equations obtained from Eqs. (3a) and (3c) neglecting κ_{ij}'s represent the two-level system interacting with a laser field that is familiar to the fields of laser physics and quantum optics.[14,15] The eigenenergies of the combined system of the atom and pump field are obtained in the dressed-atom approach within the RWA (Refs. 16 and 17). With strong atom-field interaction, the energy-level structure appears as an infinite set of equally spaced doublets. The splitting between two states in a doublet can be obtained from degenerate perturbation theory and is given by $\Omega=[(\omega_0-\omega)^2+\Omega_\omega^2]^{1/2}$ which is the generalized Rabi frequency. The two dressed states are symmetrically located with respect to the unperturbed levels.

In this paper, we intend to probe the dressed states of the bare states $|a\rangle$ and $|c\rangle$ in the large dot by the state $|b\rangle$ through the tunneling process between the dots. We numerically solve the coupled equations [Eqs. (3a)–(3c)] without RWA for the inter-subband coupling between the states $|a\rangle$ and $|c\rangle$ induced by the laser field. The numerical calculations are carried out by means of the "NDSOLVE" program based on the Runge-Kutta method in MATHEMATICA. We restrict our calculations within the resonant case of the subband transition ($\omega_0=\omega$) and assume $\kappa_{ij}=\kappa$ and $\delta=0$. We assume throughout this paper that the electron is initially in the state $|b\rangle$, i.e., $|b(0)|^2=1$, and $|a(0)|^2=|c(0)|^2=0$.

First we investigate the first resonance that the state $|a\rangle$ is resonant with the state $|b\rangle$, i.e., $\Delta=0$ [see Fig. 1(b)]. Figure 2 shows one of the results on the suppression behavior of the quantum tunneling by the laser field. The parameters used in the calculation are $\omega=\omega_0=20$, $\kappa=1$. The solid line shows the electron population in the state $|b\rangle$, i.e., $|b(t)|^2$, and the dotted and the thin dashed line represent the population of the state $|a\rangle$ and the state $|c\rangle$, i.e., $|a(t)|^2$, and $|c(t)|^2$, respectively. In the absence of the laser field ($\Omega_\omega=0$), the electron population initially in the state $|b\rangle$ (or in the small dot) is almost completely transferred into the state $|a\rangle$ (or into large dot), as expected from the resonant coupling of the states $|a\rangle$ and $|b\rangle$ [Fig. 2(a)]. Very small ripples of $|c(t)|^2$ are due to the off-resonant coupling between the states $|b\rangle$ and $|c\rangle$ through the tunneling κ_{bc} or κ_{cb}. As the laser field increases, the oscillation amplitude $|b(t)|^2$ gradually decreases and nearly completely suppressed at $\Omega_\omega=80$ [see Figs. 2(b)–(d)]. Note that the population $|c(t)|^2$ becomes larger than the population $|a(t)|^2$ at $\Omega_\omega=5$. This is due to the quantum interference effect between two coupling routes from the state $|b\rangle$ to the state $|c\rangle$, i.e., $b\rightarrow a\rightarrow c$ by the tunneling and the successive laser field excitation, and $b\rightarrow c$ by the tunneling.

Next, we investigate the maximum transfer rate $T_{\max}$ as a function of the detuning Δ of the probe state $|b\rangle$. $T_{\max}$ is defined by the maximum population transfer rate from the small dot (state $|b\rangle$) to the large dot (states $|a\rangle$ and $|c\rangle$), i.e. $T_{\max}$ is the maximum value of $|a(t)|^2+|c(t)|^2$. $T_{\max}$ is very useful quantity to investigate the inter dot coupling rate and probe the dressed states of the bare states $|a\rangle$ and $|c\rangle$ perturbed by the laser field. The spectra of $T_{\max}$ for various values of the laser field Ω_ω are shown in Fig. 3. In the absence of the laser field, the spectra of $T_{\max}$ have two peaks [A and B in Fig. 3(a)] as a function of the bias field Δ. They correspond to the first and the second resonance as shown in Figs. 1(b) and (c). As the spectrum is symmetric about $\Delta=10$, we do not plot the spectrum for $\Delta<-10$. The width of the resonance lines is given by the coupling coefficient κ (half-width at half-maximum corresponds to $\Delta=\kappa=1$). For the laser field $\Omega_\omega=5$, each peak (A and B) splits into doublets, i.e., $A\rightarrow A_1,A_2$ and $B\rightarrow B_1,B_2$, the splittings of which vary as a function of the laser field amplitude Ω_ω (Rabi frequency). It should be noted that many narrow lines other than A_1, A_2, B_1, and B_2 appear in the region of the large Δ. These peaks may correspond to the dressed states of the bare states $|a\rangle$ and $|c\rangle$. As expected from the dressed-atom ap-

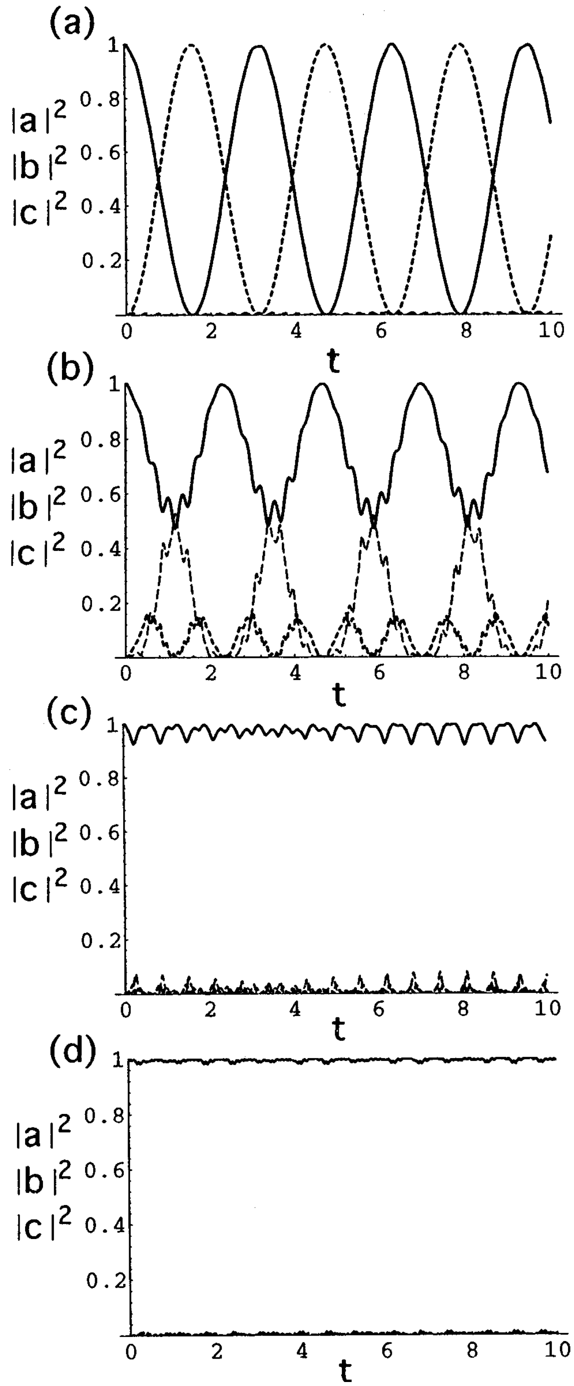

FIG. 2. Time evolution of the electron population $|a(t)|^2$ (dotted line), $|b(t)|^2$ (solid line), and $|c(t)|^2$ (thin dashed line) in the levels a, b, and c for different values of the electric field amplitude Ω_ω: (a) $\Omega_\omega=0$, (b) $\Omega_\omega=5$, (c) $\Omega_\omega=20$, and (d) $\Omega_\omega=80$.

proach, a pair of lines appear near integer multiples of the laser frequency, i.e., $\Delta=\pm n\omega$ $(n=0,1,2,3\ldots)$ and their splitting frequency, which we call "ac Stark shift Ω_s," is nearly given by the Rabi frequency $(\Omega=\Omega_\omega=5)$ expected from the dressed-atom approach. The width of the lines become narrower and narrower as n increases. It is, therefore, difficult to find the doublets expected at $n=4$ $(\Delta=80)$. For the laser field $\Omega_\omega=15$, the splitting frequency (Stark shift) increases and is still given by the dressed-atom approach $(\Omega=\Omega_\omega=15)$. As the laser field is increased further

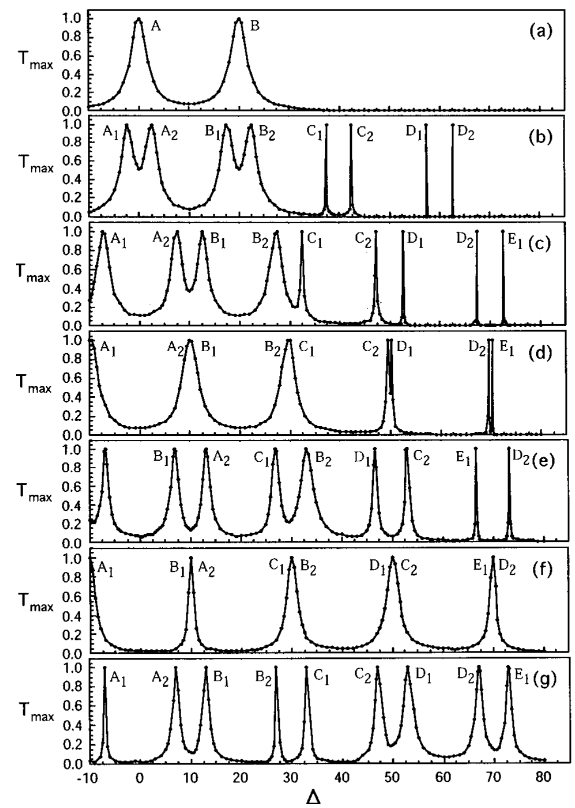

FIG. 3. Maximum transition amplitude $T_{\max}$ vs Δ, the detuning of the level b from the level a, for various values of the laser field amplitude Ω_ω: (a) $\Omega_\omega=0$, (b) $\Omega_\omega=5$, (c) $\Omega_\omega=15$, (d) $\Omega_\omega=20$, (e) $\Omega_\omega=30$, (f) $\Omega_\omega=54$, and (g) $\Omega_\omega=68$.

$(\Omega_\omega=20)$, the splitting peaks originated from different bare states $|a\rangle$ and $|c\rangle$, i.e., A_2 and B_1, converge into one line at $\Delta=10$. The splitting frequency (the Stark shift) Ω_s becomes nearly 20, but slightly less than 20, as we can see from the double-peak spectra of the higher-order peaks near $\Delta=50$ (C_2 and D_1) and 70 (D_2 and E_1). For $\Omega_\omega=30$, the Stark-shift Ω_s exceeds the subband transition frequency $\omega_0=20$ [see Fig. 3(e)]. The peaks A_2 and B_1, therefore, cross at $\Delta=10$. As the laser field is increased further, the Stark shift Ω_s becomes a maximum, and then decreases [see Figs. 3(e)–(g)]. Note that the width of the resonance lines increases and decreases in a complex manner as the laser field is increased.

A simple physical interpretation of the above results is given in terms of the dressed-state model.[16,17] As described above, for the resonant case as our calculations $(\omega=\omega_0)$, we can expect the spectrum with infinite doublets separated by an interval $\Omega=\Omega_\omega$ and with the frequency separation between two adjacent doublets being the laser frequency ω. The numerical results of the peak positions for the relatively small amplitudes of the laser field $(\Omega_\omega<20)$ [see Figs. 3(a)–(d)] exactly correspond to the spectrum which is predicted by the dressed-state approach. The spectrum for large amplitudes of the laser field $(\Omega_\omega>20)$, however, strongly deviate from those expected from the dressed-atom approach. This may be due to the neglect of the counter rotating component of the laser field or, in other words, to the neglect of multiphoton coupling processes in the dressed-atom approach within RWA.

We can also see in Fig. 3 that the suppression behavior of

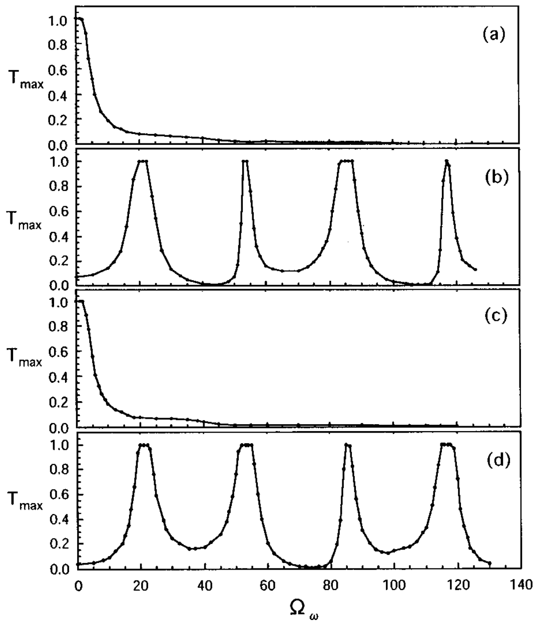

FIG. 4. Suppression and enhancement behaviors of the tunneling by the laser field: (a) $\Delta=0$, (b) $\Delta=10$, (c) $\Delta=20$, and (d) $\Delta=30$.

the coherent electron oscillation (or suppression of transfer rate $T_{\max}$ between dots) at $\Delta=0$ as shown in Fig. 2. The suppression of the maximum transfer rate $T_{\max}$ is due to the level splitting caused by the laser field, i.e., the ac Stark shift of the energy states. $T_{\max}$ gradually decreases as the laser field is increased. In contrast, we can also see in Fig. 3 that $T_{\max}$ is very small in the absence of the laser field at $\Delta=10$. When the laser field is increased, however, $T_{\max}$ gradually increases, becomes a maximum when the splitting peaks A_2 and B_1 converge into one peak, and then decreases and increases again and so on. This behavior is summarized in Figs. 4(a)–(d), which correspond to for $\Delta=0$, 10, 20, and 30, respectively. For $\Delta=0$ and 20, we can see the suppression behavior of the tunneling. On the other hand, the enhancement behavior of the tunneling against the laser field is observed for $\Delta=10$ and 30. The enhancement behavior of the tunneling against the laser field is also observed for $\Delta=50$, 70, . . . [see Figs. 3(d)–(g)].

Finally, we illustrate the normalized amount of the ac Stark splitting Ω_s/ω against the normalized amplitude of the laser field Ω_ω/ω. The linear property of the ac Stark shift is supported insofar as $\Omega_\omega/\omega \leqslant 1$. This property is expected from the dressed-atom approach within RWA (see line A). For the strong laser fields $\Omega_\omega/\omega \geqslant 1$, the ac Stark shift strongly deviates from the dressed-atom approach and shows the oscillatory behavior (line C). The central frequency of the oscillation $(\Omega/\omega=1)$ is shown by the line B as a guide to the eye. The ac Stark splitting shown in Fig. 5 is a universal property that does not depend on the parameters used in the numerical calculations whenever $\omega \gg \kappa$.

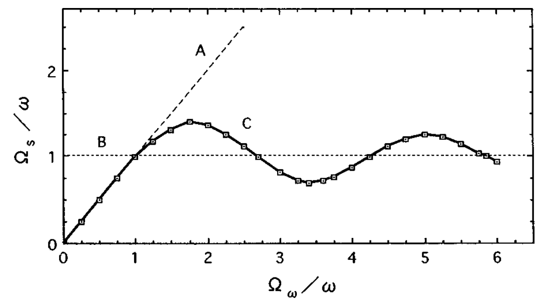

FIG. 5. Normalized ac Stark shift Ω_s/ω vs normalized laser field amplitude $\Omega_\omega/\Omega_\omega$. Line A shows the ac Stark shift obtained by the RWA. C shows the numerical result of the ac Stark shift without RWA. C oscillates around a center line B $(\Omega_\omega/\omega=1)$.

In conclusion, we have shown that the quantum tunneling for the asymmetric coupled-quantum-dot structure can be suppressed or enhanced by means of coherent electromagnetic excitation. The dynamical control of the quantum tunneling is due to the splitting into doublets of the states that are resonant or quasiresonant with the laser field, well known as the ac Stark (or light) shift. Furthermore, it was shown that the amount of the ac Stark shift has an oscillatory behavior for the large amplitudes of the laser field, which is not predicted from the conventional RWA for the matter-light interaction. The coherent tunneling between the asymmetric dots presented in this paper may present a new scheme to directly observe the dressed states, whereas the dressed states have not been directly observed and indirectly observed by fluorescent transitions or absorptive transitions in atomic and molecular systems.

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