Quantum Computing with QD Excitons

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Abstract

This paper discusses the potential application of elementary excitation in semiconductor quantum dots to quantum computation. We propose a scalable hardware design and all-optical implementation of logical gates that exploit the discrete nature of electron and hole states and their well-concentrated oscillator strength for ultrafast gate operations. We also propose a multiple-bit design based on the nearest neighbor dipole-dipole coupling. Rabi population oscillation of an excitonic two-level system in an isolated single $In_xGa_{1-x}As$ quantum dot is manifested by quantum wave function interferometry in the time domain, demonstrating a long lived coherence of zero-dimensional excitonic states and revealing the coherent population flopping under strong optical field. Phase-sensitive coherent gate operations on a single-dot exciton qubit are demonstrated.

1. Introduction

In recent years, semiconductor nanostructures have drawn a lot of attention. With the rapid progress of nano-fabrication technologies making it possible to grow zero-dimensional semiconductor systems that are not spoiled by fabrication-induced damage, quantum dots (QDs) [1], [2] are becoming attractive for quantum information science. QD applications proposed so far range from lasers to memory devices and from single-photon emitters to quantum bits for quantum computation. The potential flexibility in controlling the carrier density and/or spins is the primary reason for such a broad range of applications. The discrete density-of-states leads to an atom-like optical response and well suppressed interaction of quantized electrons and holes with environmental degree of freedom such as phonons. The localized spatial extent of a QD carrier system serves as a platform for single quanta, and the resulting enhanced carrier-carrier correlation provides greatly increased few-particle effects, which may potentially introduce new electro-photonic functions in quantum information technology. The similarity between atoms and QDs together with a sharply concentrated oscillator strength may therefore offer great opportunities for coherent manipulation of a well-defined single localized quantum system by an optical field.

The best known example of such manipulation is obviously quantum computing, which essentially exploits the phase coherence of each member belonging to an ensemble of two-level systems and the phase coherence of their quantum mechanical correlation. Each two-level system plays the role of a quantum bit (qubit) and carries logical information. An important point is that unlike the bit in classical computing, the quantum bit can represent not only zero or one but also their superposition. The qubits are manipulated according to unitary time-evolution driven by external perturbation. In this sense, such a perturbation driven time-evolution is called gate operation. The essential aspect of quantum logic is to control the quantum mechanical correlations among the ensemble of qubits that are induced by interaction among them. Because of such correlations, even a single-bit gate operation can affect the status of the other bits. The main advantage of such hardware is that it searches all possibilities represented by the bits in the superposition state. Namely, if we have a condition bit in a superposition state, a sequence of quantum mechanical gate operations executes the corresponding test algorithm according to all the conditional

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weights given in the condition bit at once. This is indeed a simultaneous super-multiplication of the computing, and it is the most essential advantage of quantum computing.

In this paper we focus on quantum computation based on optically excited electron-hole pair states in semiconductor QDs. Coherent control of single excitons according to unitary time-evolution is highlighted. The use of dipole interactions inherent to the excitation of a quantum dot electronic system is crucial for quantum computing, because one may easily turn on and off the interaction that drives unitary time-evolution. From this viewpoint, a quantum dot exciton that serves as an atom-like density-of-states and the resulting long-lived coherence are significant. First, we describe a simple quantum computation scheme that is based on an array of quantum dots as qubits and multi-color lasers as control gates. Then, we describe the implementation of a quantum mechanical coherent gate on an exciton qubit, which effectively uses Rabi oscillation of the atom-like discrete states of the exciton with large optical dipole moments. As a simple but crucial demonstration, Rabi oscillation of an isolated excitonic two-level system in an $In_xGa_{1-x}As$ quantum dot is reported: control of the population and phase of the single-dot excited excitonic state and read-out of the superposition are described. Finally, a prototype of quantum gate functionality on an exciton qubit is demonstrated.

2. Quantum computing with quantum dot excitons

Prerequisites for quantum computing [3] are: i) a well defined physical system corresponding to qubits, ii) initialization, iii) control with external perturbation that results in unitary time-evolution and acts as gate control, iii) read-out of specific qubits, and preferably iv) control of noise. In addition, the major obstacle is decoherence, which spoils the unitary time-evolution through uncontrollable coupling with the environment. The proposals for realistically establishing physical platforms for quantum information processing have mostly aimed to overcome the difficulties related to decoherence. Thus the proposals range from the use of real atoms/ions, through the use of quantum optics, to the use of nuclear or electron spin, all of which offer long-lived coherence. The pioneer proposal by Loss and DiVincenzo [4] used well-isolated electron spins in QDs and utilized their dynamics: due to the less efficient coupling with the environment they exploit the low decoherence relative to that of charge. On the other hand, practical quantum computations require a large number of quantum mechanical two-level systems as qubits. In this sense, a semiconductor-based quantum system may exploit its scalable integration and may benefit the implementation by ultrafast optoelectronics. Using atom-like density-of-states and enhanced optical dipole moments of quantum dot excitons as elementary excitations, it is possible to induce fast unitary time-evolution by coherent picosecond or femtosecond laser radiation: partial use of Rabi oscillation of an isolated excitonic state can realize coherent gate functionality. This augmentation is particularly important since the performance of the physical qubit systems is to be evaluated by a ratio: the gating time over the decoherence time, *i.e.*, the maximum number of gate operations before decoherence.

2.1 Quantum computing and the implementation of quantum gates

Our scenario is as follows: We start with a number of qubits defined by an array of QDs. We then use QD excitons, each of which is well localized within each QD, as elementary excitations representing logical binaries: logical one (zero) corresponds to the existence (nonexistence) of an exciton in a QD. We introduce a gate function by turning on coherent electromagnetic radiation. As a QD occupies the mesoscopic regime, where its extent has a range of a few exciton Bohr radii, we expect an enhanced exciton dipole moment. This corresponds to the situation where the extent of the QD confinement potential is small enough to result in quantization of the exciton center-of-mass motion that well suppresses the phonon scattering: the exciton center-of-mass motion is coherent over the QD volume interacting with electromagnetic radiation. This effectively enhances the dipole moment (mesoscopic enhancement). In the absence of the radiation, the QD system is in the ground state because the thermal excitation should overcome the energy gap, which can be chosen to be larger than 1 eV. Therefore, the initialization is straightforward. A schematic representation of a (linear) QD array and access to the qubits by optical means are shown in Fig. 1.

Since any universal quantum computations can be decomposed into a series of one-bit rotation gates and two-bit control-NOT (CNOT) gates [5], it is natural to use a one- or two-dimensional array of QDs and to establish the gate sequence acting only on two adjacent qubits at a time. Important gate functions are one-bit rotation, two-bit conditional rotation, and

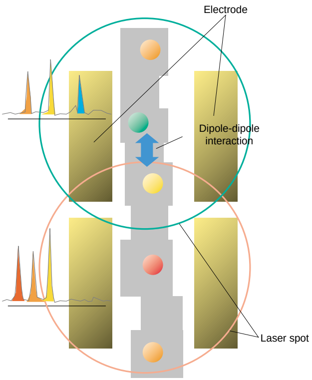

Fig. 1. Linear array of quantum dots for all-optical computation. Individual QDs are accessed and distinguished by positioning the tunable laser and probe. The statistical distribution of QD characteristics enables the identity of an exciton in a particular QD to be recognized by frequency domain discrimination.

SWAP gates. The rotation gate essentially results in the single qubit population flopping corresponding to a π-pulse according to Rabi oscillation induced by external gate radiation. The CNOT gate rotates one qubit (the target bit) only when the other bit (control bit) is in the state $|1\rangle$. The CNOT gate in general operates on a distant bit pair. The problem here is therefore how to correlate such distant pairs. Below, we show that a remote bit CNOT gate can be made even with quantum correlations only between nearest neighbor pairs. The CNOT gate for such an adjacent qubit pair is realized via quantum mechanical correlation between them. For this conditional two-bit gating, we use dipole-dipole interaction between two excitons in a nearest-neighbor QD pair. The important part of our scenario is to exploit only the nearest-neighbor exciton-exciton interaction for conditional gating operations. The effective Hamiltonian may be reduced to

$$\sum_i E_i n_i + \sum_{ij} \frac{\Delta E_{ij}}{2} n_i n_j .$$

Here, E_i denotes the energy of the ground-state exciton in dot I and ΔE_{ij} is the exciton-exciton correlation energy between dots i and j, where $n_i = 0$ and $n_i = 1$ correspond to the absence and presence of an exciton, respectively. The correlation energy ΔE_{ij} is estimated to be non-zero only for adjacent dots. The single-exciton energy E_i is altered by the presence of another exciton in the next dot j

$$E_i' = E_i + \sum_{j \neq i} \Delta E_{ij} n_j .$$

Therefore, for a given pair of QDs, namely c (control) and t (target), the transition energy of the t-dot is a function of the occupation number of the c-dot n_c, namely $E_i'(n_c) = E_t + \Delta E_{tc} n_c$. Similarly, the transition energy of the c-dot is a function of the occupation number of the t-dot. These transitions are described in Fig. 2(a), and the two possible spectra corresponding to the pathways

$$|1_c,1_t\rangle \rightarrow |0_c,1_t\rangle + \hbar\omega_c[1_t]$$
$$\rightarrow |0_c,0_t\rangle + \hbar\omega_c[1_t] + \hbar\omega_c[0_t]$$

and

$$|1_c,1_t\rangle \rightarrow |1_c,0_t\rangle + \hbar\omega_t[1_c]$$
$$\rightarrow |0_c,0_t\rangle + \hbar\omega_t[1_c] + \hbar\omega_c[0_t],$$

are shown in Fig. 2(b). Here, $\hbar\omega_i[n_j]$ represents the photon absorbed (emitted) into (from) the i -dot under the occupation n_j of the j-dot, so

$$\hbar\omega_t[0_c] = E_t, \quad \hbar\omega_t[1_c] = E_t + \Delta E_{tc},$$
$$\hbar\omega_c[0_t] = E_c, \quad \hbar\omega_c[1_t] = E_c + \Delta E_{tc}.$$

A coherent laser (π-pulse with energy $E_t'(n_c)$ results in π rotation if and only if the control qubit is in the state $|n_c\rangle$. Now we have the CNOT gate for adjacent two bits. We show successive operation of a number of CNOT gates each of which acts on a pair out of the bits in between the control and the target bits in a distance. First, we introduce the SWAP gate, which effectively swaps the contents of two qubits. This is achieved by three successive CNOT gate operations, as shown in Fig. 3(a). Although the SWAP gate in general works on a distant bit pair, a sequence of nearest neighbor SWAP gates enables a CNOT gate to act on a distant bit pair as follows: Since we have correlation only between nearest neighbors, we need to copy the control bit to the bit before the target bit. A series of SWAP gates, as shown in Fig. 3(b), is used

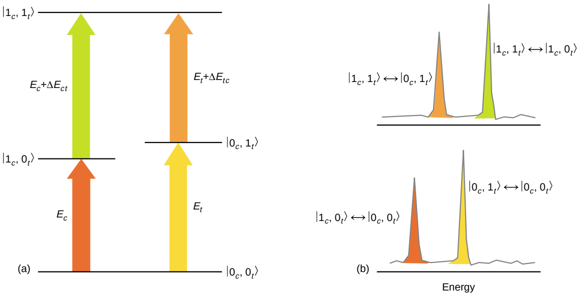

Fig. 2. Energy diagram of excitons in two adjacent QDs of different size, denoted *c* and *t*, coupled by dipole-dipole interaction (a). Because of the coupling, the energy cost to create an extra exciton in one of the two QDs differs depending on the presence or absence of an exciton in the other dot. This exciton-exciton correlation results in four possible transitions among four exciton occupations (b).

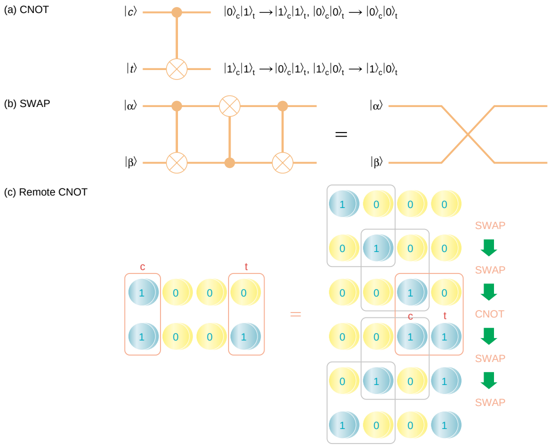

Fig. 3. Important quantum gate functions: (a) the control-NOT (CNOT) gate flips the target bit only when the control bit is one, (b) the SWAP gate swaps two qubits; it is realized by three CNOT gate operations, and (c) the CNOT gate on a distant qubit pair that is decomposed into a sequence of nearest-neighbor SWAP and CNOT gates.

for this. First of all, a nearest-neighbor SWAP gate exchanges the contents of the control bit and the bit next to it. Similar sequences are repeated until the bit before the target bit is set to the value that the original control bit holds. Now the nearest neighbor CNOT gate between this pair rotates the target bit. One then needs to restore the bits of the original control and target bits back to their original values. For this, one may repeat a similar SWAP gate sequence until all the bits except the control and target bits have had their original contents restored. These sequences in fact make possible the remote CNOT gate. We know that a single CNOT gate operation requires multiple sequences of nearest-neighbor CNOT gates, which consumes the coherence lifetime, so the total number of gate operations can never undergo an exponential increase. With these three types of coherent gate functions, we can construct a gate sequence for any quantum algorithm.

Thus far, exciton-exciton correlation for the exciton/biexciton system in a single QD has been experimentally evaluated to be as large as 5 meV [6], [7]. To exert this correlation for a conditional two-bit gate operation, the distance between two adjacent QD needs to lie within a range from 1 to 10 nm. A more sophisticated method of enhancing this dipole-dipole coupling has been proposed: Biolatti *et al*. [8] proposed an enhancement of the dipole-dipole coupling by an external static Stark field that effectively increases the relative distance between an electron-hole pair. Since the electric field is tunable, it effectively turns on and off or alters the strength of the two-qubit coupling. It is also used to shift some particular exciton transitions to prevent nearby qubits from undergoing unwanted coherent evolution.

Now we focus on access to individual qubits. Whatever we use the quantum dot system for and whatever the fabrication technology we use, there will always be a statistical distribution of QD size and composition. This statistical distribution in turn produces inhomogeneous broadening of the QD optical response such as transition frequencies: This favors the distinction of one qubit from the others since the energy-domain discrimination is facile. Access to a specific qubit is achieved by positioning the excitation/probe beam spot onto the desired location where a number of qubits with different frequencies can be accessed. Access to specific qubits can therefore be achieved by position selective addressing combined with frequency discrimination. The coherent gating and read-out are described schematically in Fig. 1. The most unintentional method for the read-out may be the use of dissipation: the QD exciton system is open to bosonic vacuum, so the spontaneous emissions of phonons and photons leading to the dissipation of the excitation is the primary cause of the decoherence. As long as the series of ultrafast coherent gates is made within the coherence lifetime, the coherent evolution of the whole system ends up with emission of the phonon and photons. Because spontaneous emissions of a given bunch of qubit excitons differ in frequency, the result of the coherent evolution of all the qubits can be read out. Extending this strategy to a large number of QDs seems straightforward, so the scalability of the computation seems to be guaranteed. Alternatively, the read-out may be done before the spontaneous decay of the whole system, and read-out by probe pulses is preferable. Experimental demonstrations have already been done, for example, by differential transmission measurements in a pump-and-probe configuration [9], [10]. Such procedures need to consume an extra time period within the coherence lifetime but they still guarantee the scalability.

At present, both measurement strategies require a number of repeated measurements. Thus they give results averaged over a huge number of measurement sequences. One problem remaining to be solved is to establish a means of achieving single-shot measurement. Another conceivable problem is that as in the case of nuclear magnetic resonance (NMR) quantum computation, an increase in the number of qubit transitions in a given frequency range can lead to technological difficulty in giving an upper bound of the number of QDs in an optical spot of typical size. This kind of constraint will be solved, for example, by improving the scheme of unitary gate operation as adopted in NMR quantum computing, for example. The details of such an approach, however, are unclear at this stage and the discussion remains open.

2.2 Quantum dot fabrication

To realize the above-mentioned QD qubits, one must establish a fabrication technology. We have been using unique self-assembled $In_xGa_{1-x}As$ QD systems grown on the (311)B face. In this self-assembling phenomenon, disk-shaped $In_xGa_{1-x}As$ QDs are spontaneously formed via unique strain-driven reorganization of a strained $In_xGa_{1-x}As/Al_yGa_{1-y}As$ heterostructure on a (311)B-GaAs substrate [2]. Typical surface secondary electron microscope images of the self-assembled dots with three different nominal compositions are shown in Fig. 4 (bottom left), and atomic force microscope images are shown for two composi-

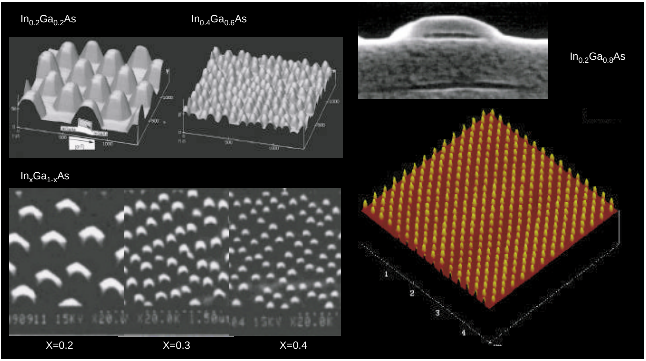

Fig. 4. InGaAs/AlGaAs self-assembling QDs: Scanning electron microscope (SEM) images of 5-nm $In_{0.2}Ga_{0.8}As/Al_{0.5}Ga_{0.5}As$, 3.5-nm $In_{0.3}Ga_{0.7}As/Al_{0.5}Ga_{0.5}As$, and 3-nm $In_{0.4}Ga_{0.6}As/Al_{0.5}Ga_{0.5}As$ sample surfaces (bottom left). Also shown are atomic-force microscope images of similar samples (top left). The cross sectional view of the SEM image of a larger dot (5 nm-$In_{0.2}Ga_{0.8}As/Al_{0.5}Ga_{0.5}As$) indicates contrast between the In-rich disk-shaped region and Al-rich surrounding (top right). The ordering is dramatically refined by an array of embedded periodically ordered large (100 to 200 nm in lateral extent) InGaAs islands used as a template for vertically stacking dots via preferential islanding on strained surface (bottom right).

tions (x=0.2 and 0.4) in Fig. 4 (top left). Unlike the well-known Stranski-Krastanow growth of QDs, our system has no wetting layer. This is because during the self-assembling process, atomic intermixing across the strained interface and extremely efficient mass transport cause In-rich disk-shaped islands to be spontaneously covered by Al-rich alloy. This spontaneous embedding of the InGaAs disk is well demonstrated in Fig. 4 (top right). It has been shown that i) the extremely dynamic atomic rearrangement enables energy lowering through the formation of strained islands that relaxes the strain and ii) atomic inter-diffusion and surface rearrangement into low-index surfaces play key roles; all of these are driven essentially by the strain within the material. The extent of the resulting disk-shaped structure is as small as 30 to 100 nm in diameter, and it is controlled by the strain, *i.e.*, by the composition x of $In_xGa_{1-x}As$. Another remarkable feature of this phenomenon is a natural ordering of the InGaAs dots. Because of this tendency, a little artificial help to control locations during self-assembling dramatically improves the QD ordering (bottom right in Fig. 4): in brief, by forming a periodically ordered array of large InGaAs islands and subsequently embedding them in AlGaAs by overgrowth and growing an $In_xGa_{1-x}As$ layer that undergoes one to three minutes of growth interruption, we have successfully obtained a remarkably well-ordered two-dimensional QD array as shown in Fig. 4 (bottom right). The large InGaAs islands act as strain anchors that help the InGaAs islanding just above through strain propagation. Details of the procedure are described elsewhere [11].

With these technologies, quantum computing based on QD excitons seems realistic. A linear array may be most simply fabricated by stacking QD layers: It is known that strained dots tend to form a vertical alignment, because strained structures prefer a lattice closer to their relaxed lattice. Another way to define a one-dimensional array may be to use quantum wires with interface fluctuation. This is because it is known that fluctuation of the heterointerface over one to two monolayers forms potential minima, which effectively trap and localize excitons, leading to quantum-dot-like exciton spectra [6], [12]. An important point is how we can manage to fabricate the array with an inter-dot distance that allows nearest-neighbor exciton-exciton correlation. A trial to fabricate such structures is under way.

3. Rabi oscillation and single qubit rotation gate

As discussed in the preceding section, the implementation of single quantum gate operation is to force a qubit to undergo coherent time-evolution either freely or under the influence of other qubits. Therefore, experimental implementation is extremely simple. For a given number of QDs, we access a particular QD through microscope-type optics with a pulse laser source resonant to the relevant transition, and we distinguish its response by frequency-domain filtering. The quantum dot sample used was 3.5-nm-thick $In_{0.4}Ga_{0.6}As/Al_{0.5}Ga_{0.5}As$ on a (311)B-GaAs substrate, as described in the preceding section. An appropriate QD was chosen for experiments.

As is well known, electromagnetic radiation induces a dipole oscillation and population change. For strong fields, the population periodically changes (Rabi oscillation) via absorption and stimulated emission. Such a Rabi oscillation can be experimentally observed in the energy domain as Rabi splitting, or it can be directly observed in the time domain. Although the coherence of the QD exciton lasts for 20 to 100 ps, much longer than in bulk or quantum well structures, the decoherence is still a primary obstacle. Decoherence and the resulting dissipation can, however, be used as a means of "measurement", as already mentioned. For this, we chose an excited exciton state X^* of a single QD as the upper state, and excited it resonantly, as shown in Fig. 5(a). Single-dot photoluminescence shown in Fig. 5(b) reflects the population of the excited state manipulated by the laser. If picosecond laser pulses are used to induce the population change, the subsequent decoherence and energy relaxations, which proceed much more slowly, simply copy the population to the exciton lowest state X_0. This subsequently emits photoluminescence, letting the system return to null excitation. The intensity of this emission varies with the coherent population change induced by the laser pulses. An interesting observation in excited state resonant excitation is that even with a continuous laser, resonant excitation with high enough intensity results in splitting of the ground state photoluminescence emission [13]. In fact, this is Rabi splitting, reflecting the splitting of the driven levels into "dressed" pairs. A spectral trace of the ground state emission under intense excitation is shown in Fig. 5(b).

We also conducted a single-dot exciton dipole interferometry [14], [15] experiment using two-pulse excitation with phase control. In this experiment, the excited state X^* given in Fig. 5 was excited resonantly by a sequence of picosecond laser pulse pairs. Single-dot photoluminescence reflecting the population change in the excited state manipulated by the two optical pulses (Fig. 5(a)) was recorded as a function of temporal pulse delay between the two pulses. The first laser pulse of the pair created an exciton polarization (coherence) oscillating at the frequency of the laser pulse. While phase coherence persisted, the second laser pulse either enhanced (constructive interference, if the two pulses were in phase) or weakened

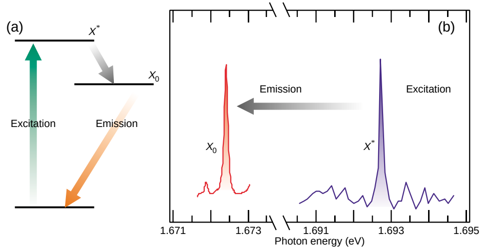

Fig. 5. (a) Energy level scheme of a single dot exciton and excitation and detection: the ground state (no excitation) and an excited state denoted X^* formed a two-level system. (b) Single dot exciton luminescence spectrum from the lowest state X_0 and photoluminescence excitation spectrum near the excited state resonance X^* of relevance.

(destructive interference, if they were out of phase) the exciton population, depending on the relative phase of the two pulses. Such quantum mechanical interference gives a fast oscillating fringe in the period of the driving frequency and its amplitude may decay due to decoherence. A schematic drawing of this in Fig. 6 explains that a phase-controlled pulse pair induces dipole interference as well as population flopping: a nearly overlapping pulse pair effectively produces a summation of the two field vectors that depends on the relative phase (Fig. 6(a)). Under low excitation, the effective fields induced only a sinusoidal population change as a function of the relative phase, thus giving a sinusoidal dipole interference fringe (Fig. 6(b)). In distinct contrast, as the electric field increased and the corresponding pulse area exceeded π, a significant distortion and complex fringe evolution were expected (Fig. 6(c)). Since the relative phase of the two laser pulses was essential in this dipole interferometry experiment, we used a phase control function based on a Mach-Zehnder interferometer whose path difference was locked by the interference of a highly coherent He-Ne laser beam. Simply passing a mode-locked Ti:sapphire laser beam through the stabilized interferometer produced a sequence of pairs of phase-locked optical pulses. The relative phase of the pulse pair was stabilized to about λ/130 (λ=633 nm). The temporal pulse correlation width was controlled to about 5 ps to enlarge the temporal overlap of the pulse pair.

The experiment revealed the above-mentioned features, as demonstrated in Fig. 7. For low excitation, the coherent dipole oscillation (Fig. 7(e)) induced by the first pulse persists for as long as 40 ps with a decaying fringe amplitude with the two-pulse time interval (Figs. 7(a) and 7(b)). The decay was primarily due to the population relaxation via acoustic phonon emission down to the exciton lowest state that dissipated the population outside the relevant two-level system. As the excitation increased by about one order of magnitude or more, the radiation induced not only dipole oscillation (precession) but also population oscillation (nutation), leading to a complex dipole interference fringe (Fig. 7(f)) as expected. Correspondingly, another oscillatory behavior appeared with a period of 10–20 ps in the fringe envelope (Figs. 7(c) and 7(d)). These observations are manifestations of the Rabi oscillation of the

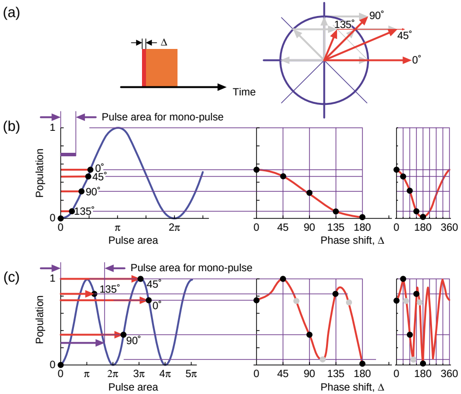

Fig. 6. Response of an exciton two-level system in two-pulse dipole interferometry: (a) A nearly overlapping pair of pulses with a phase difference sum up to an effective field depending on the phase difference. The dipole interference fringe evolves according to whether the Rabi oscillation is for (a) a low field or (b) a high field.

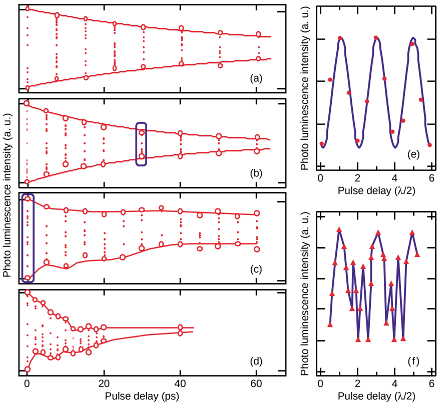

Fig. 7. Exciton interference fringes measured for PL emission intensity as functions of relative pulse delay: (a) for power density P_1 (0.067 μJ/cm^2/pulse), (b) for 2 P_1, (c) for 12 P_1 (0.8 μJ/cm^2/pulse), and (d) for 24 P_1. Each fringe is normalized to the amplitude maximum. Fast oscillation due to interference is shown in (e) for a coarse delay of 30 ps in (b) and in (f) for 0 ps in (c).

exciton two-level system. The dipole moment of the 0D exciton was estimated to be 43 Debye.

Finally, we demonstrate a simple coherent control of the population as well as the phase of the single QD exciton. It is now feasible to generate any superposition of two-level wavefunctions with controlled phase for isolated QD excitons. To demonstrate coherent control of the exciton wavefunction and phase, the same setup based on the interferometer was used. The basic implementation of coherent exciton population control is that the first pulse creates an exciton population and the second pulse either increases the population or pulls it back to null depending on the relative phase of the pulses. Figure 8 shows an experimental demonstration. The first pulse set the excitonic two-level system into a superposition state. Since the pulse areas were set to about 0.3–0.4π, the population gain due to the first pulse was about 0.3–0.4π. The second pulse, 10 ps after the first one, nearly doubled the population because it was in phase with the first one. In this case, the corresponding luminescence intensity was nearly twice that induced by the first pulse alone. When it was out of phase, it pushed the population back to null, so the luminescence vanished. Thus, a single qubit rotation gate has been established.

Since it has been reported that the coherence lifetime of the lowest exciton state in self-assembling dots can be as long as a nanosecond [16], [17], the number of coherent gate controls on the exciton qubits could reach one thousand. With this outlook, coherent manipulation of exciton qubits will pave the way for achieving quantum computing. The next targets are the control and read-out of two-qubit correlated time-evolution.

4. Conclusion

We have described a prototype of a quantum computation scheme utilizing elementary excitations in semiconductor quantum dots and logical gate implementation. It effectively creates an atom-like density-of-states and large optical dipole moments of the quantum dot excitons. The quantum mechanical control corresponding to logical gate operation employs unitary time-evolution driven by external electro-

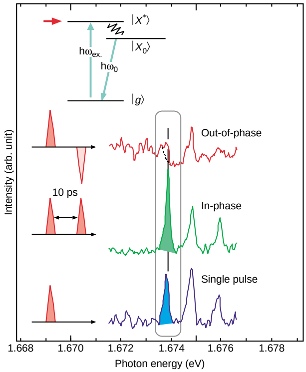

Fig. 8. Experimental demonstration of phase-controlled rotation gate on an exciton qubit: A pair of phase-locked picosecond pulses with equal pulse areas either doubled or cancelled out the population created by the first pulse.

magnetic radiation and the two-bit gate function uses exciton-exciton correlation. As the primary step along this orientation, we examined coherent time-evolution of a single dot exciton. Strong coupling between quantum states and a dynamic electric field shows the important role of coherent processes in QDs. Optical Rabi oscillation and the corresponding energy level splitting in quantum dot exciton states have been demonstrated. It is now feasible to generate the wave function of an exciton by producing the superposition of states with controlled phase. This further promises the implementation of coherent control of quantum states in solids in more sophisticated ways and may also pave the way for generating entangled states.

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