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Quantum Mechanical Time-evolution of Exciton States in Semiconductor Quantum Dots: Quntum Gate Operation of Exciton Qubits

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A semiconductor quantum dot (QD) is an artificial solid-state atom. The spatial confinement of electrons and holes along all three directions leads to a discrete energy level structure, which serve as atom-like optical transitions with long coherence time. Large oscillator strength concentrating to well-defined energy levels and long-lived coherence makes QD's very attractive for electro-optic and nonlinear optical applications. More specifically, excitons in QD's are promising as shingle photon emitter [1], and are considered as key elements for implementing the coherent control of the quantum states [2], which is an essential function for quantum computation and coherent information processing [3]. Single excitonic wave function has been manipulated by controlling the optical phase of the pulse sequence through timing and polarization, and quantum mechanical interference controlled by external optical fields. In any of such approaches, Rabi oscillation is the most essential physics that coherent optical control of the quantum states relies on. In particular, as we use excitons in isolated QD's as quantum bits (qubits), and adopt absence/presence of exciton as logical 0/1, a sequence of pulsed optical excitations which use the Rabi oscillation by part, essentially correspond to single qubit rotation gates (Fig. 1). In this paper, we show the Rabi oscillations in a single-dot exciton and demonstrate intentional manipulation of the exciton wavefunction with phase control [4].

Quantum dots used in this study were disk-shaped InGaAs dots formed via unique strain-driven spontaneous reorganization of the 3.5 nm-thick $In_{0.4}Ga_{0.6}As/Al_{0.5}Ga_{0.5}As$ heterostructure on (311)B-GaAs substrate [5]. As 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 energy-domain as Rabi splitting, or it is directly observed in time-domain. Although the coherence of the QD exciton last for several ten to a hundred ps, the decoherence is still a primary obstacle. The decoherence and dissipation can, however, be used as method of "measurement". For this, we have chosen an excited exciton state as the upper state, and have excited this resonantly. Since the laser pulse induces the population change within a picosecond pulse and the decoherence and energy relaxation are much slower, the light-induced population change is copied to the exciton lowest state, that follows spontaneous emission letting the system back to the null excitation. It is this emission that gives us the coherent population change.

With this prescription, a single-dot exciton dipole interferometry [2,6] was conducted. In this experiment, the first pulse creates an exciton polarization (coherence) oscillating at the frequency of the pulse. While phase coherence persists, another optical pulse either enhances (constructive, two pulses in phase) or weakens (destructive, 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 a period of the driving frequency and its amplitude may decay due to decoherence. Schematic drawing is given in Fig. 2 explaining that a phase-controlled pulse pair induces

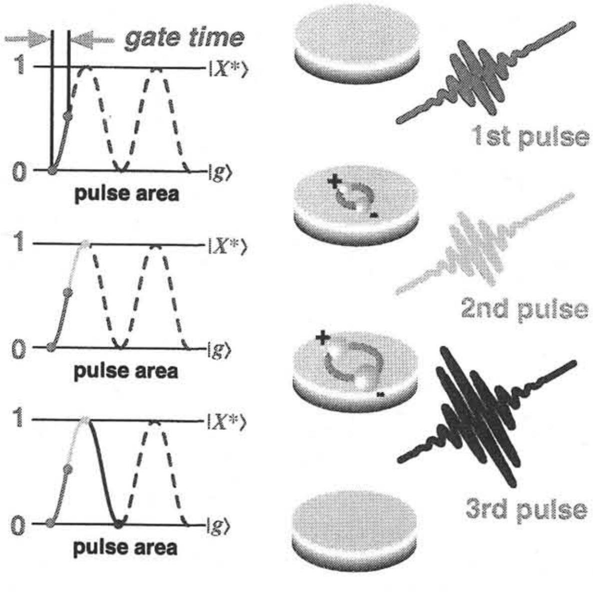

Fig. 1 Basics of coherent control of single dot exciton wavefunction, which relies on the light-induced population flopping (Rabi oscillation) and control is made of strength, duration and relative phase of sequence of light pulses.

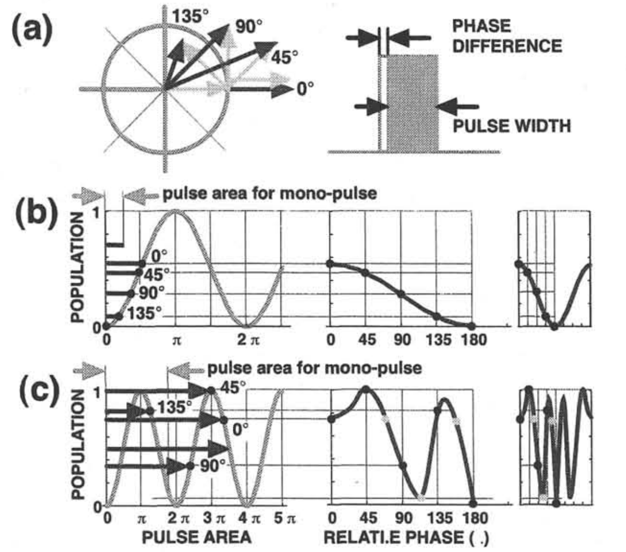

Fig. 2 Response of an exciton two-level system in two-pulse dipole interferometry: (a) Nearly overlapping pulse pair with a phase difference sum up to an effective field depending on the phase difference. Dipole interference fringe evolves according to Rabi oscillation; (a) for low field, and (b) for high field.

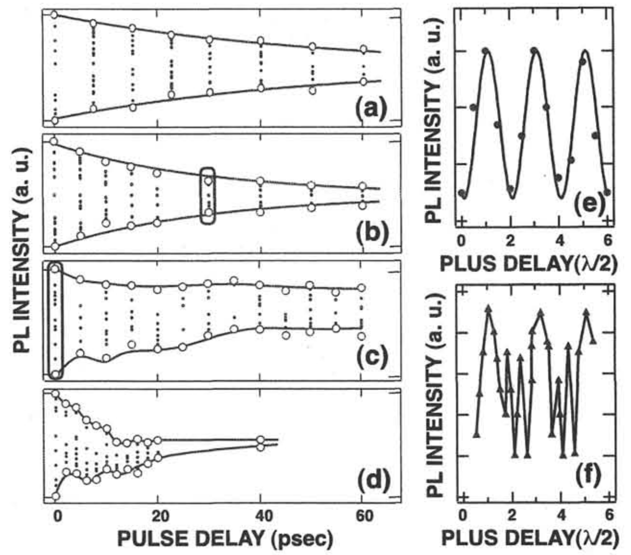

Fig. 3 Exciton interference fringes measured for PL emission intensity as functions of relative pulse delay; (a) for power density P_1 (0.067 μJ/cm^2 /pulse), (b) for 2 P_1, (c) for 12 P_1 (0.8 μJ/cm^2 /pulse), and (d) for 24 P_1. Each fringe is normalized to the amplitude maximum. Fast oscillation due to interference is shown in (e) for a coarse delay 30 ps in (e), and in (f) for 0 ps in (c).

the dipole interference as well as the population flopping: Nearly overlapping pulse pair effectively gives a summation of two field vectors that depends on the relative phase [Fig. 2(a)]. Under low excitation, the effective fields induce only a sinusoidal population change as a function of the relative phase, therefore giving a sinusoidal dipole interference fringe [Fig. 2(b)]. In distinct contrast, as electric field increases and corresponding pulse area exceeds π, a significant distortion and complex fringe evolution are expected [Fig. 2(c)]. The experiment has revealed these features as demonstrated in Fig. 3: For low excitation, the coherent dipole oscillation [Fig. 3(e)] induced by the first pulse persists as long as 40 ps with a decaying fringe amplitude with two-pulse time interval [Figs. 3(a) and 3(b)]. The decay is primarily due to the population relaxation down to the exciton lowest state that dissipates the population outside the relevant two-level system. As the excitation increased about one order of magnitude or more, the radiation induced not only the dipole oscillation (precession) but also the population oscillation (nutation), leading to a complex dipole interference fringe [Fig. 3(f).] as expected. Correspondingly, another oscillatory behavior appeared with a period of 10~20 ps in the fringe envelope [Figs. 3(c) and 3(d)] [2]. These observations manifest the Rabi oscillation of the exciton two-level system. A dipole moment of the 0D exciton was estimated to be 43 Debye.

We finally demonstrate a simple coherent control of the population as well as the phase of the single QD exciton. Since it is recently reported that the coherence time of the lowest exciton state in self-assembling dots may reaches as long as sub-ns [7-9], a thousand coherent gatings on the exciton qubits may be reachable. With this outlook, the coherent manipulation on exciton qubits will pave the way for the realization of quantum computing.

In conclusion, we have observed Rabi oscillation and corresponding energy level splitting in quantum dot exciton states. Strong coupling between quantum states and dynamic electric field manifests an important role of coherent processes in QD's: Generating a wave function of exciton by producing the superposition of states with control of phase is now feasible. It promises further an 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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