Ramsey Fringes in an Electric-Field-Tunable Quantum Dot System

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We report on Ramsey fringes measured in a single InGaAs/GaAs quantum dot two-level system. We are able to control the transition energy of the system by Stark effect tuning. In combination with double pulse excitation this allows for a voltage controlled preparation of the phase and the occupancy of the two-level system. For long pulse delay times we observe extremely narrow fringes with spectral width below the homogeneous linewidth of the system. Implications on quantum information processing are discussed.

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Semiconductor quantum dots (QDs) show strong analogies to single atoms due to their three-dimensional confinement and well separated energy levels [1]. Coherent manipulations of single QDs currently receive a lot of attention as they might provide the basis for future applications in the field of quantum information technology [2]. Several groups have recently succeeded in demonstrating Rabi oscillations on an excitonic transition in a single QD [3–10]. In this fundamental optical experiment the population of a two-level system can be coherently controlled via the amplitude of a single laser pulse.

The basic effect of (moderate) detuning in such an experiment is an incomplete inversion at π-pulse excitation and a slight modification of the Rabi frequency [11]. The spectral sensitivity of a two-level system is substantially enhanced, though, by applying two pulses separated by a fixed time delay. This effect was first described by Ramsey and is well known from atom optics [12]. Because of numerous applications of the effect in precision spectroscopy and devices, Ramsey has been awarded the 1989 Nobel Prize.

We report here on the first measurement of Ramsey fringes in a QD system. By applying the method of double pulse excitation to an electric-field-tunable device, we are able to control the occupancy and the phase of a quantum mechanical two-level system entirely via a bias voltage. Possible implications on quantum information processing are discussed in the conclusion of this Letter.

Our sample consists of MBE grown InGaAs/GaAs QDs, which are incorporated in the intrinsic region of an n-i-Schottky diode. Optical selection of a single QD is achieved via near field shadow masks. A detailed description of the sample structure is given in [13].

The internal electric field of the sample can be controlled via a bias voltage. At low electric fields excitons in the QD will mostly recombine radiatively. The QD energy levels in this regime are measured by photoluminescence (PL) using nonresonant optical excitation above the GaAs band gap. At higher electric fields the tunneling time decreases to values shorter than the radiative lifetime. Optical excitation of the QD then results in a photocurrent (PC). We thus are able to electrically detect the QD occupancy, which allows for experiments with resonant excitation of the ground state. The QD can be well approximated by a two-level system if the optical excitation is restricted to this single transition [14]. In our case the lower state $|0\rangle$ is defined by the empty dot and the upper state $|1\rangle$ is defined by the ground state single exciton.

The resonance energy of this two-level system decreases with increasing (reverse) bias voltage due to the quantum confined Stark effect. Figure 1 shows the Stark shift of the ground state exciton in the PL and PC regimes. The solid line represents a quadratic fit curve that is used for a conversion of bias voltage to energy levels. We thus are able to tune the QD energy levels very sensitively with respect to a fixed laser wavelength [15]. Figure 2(a) displays the spectral response of the system for the conditions of cw and pulsed excitation. For the cw case we observe the

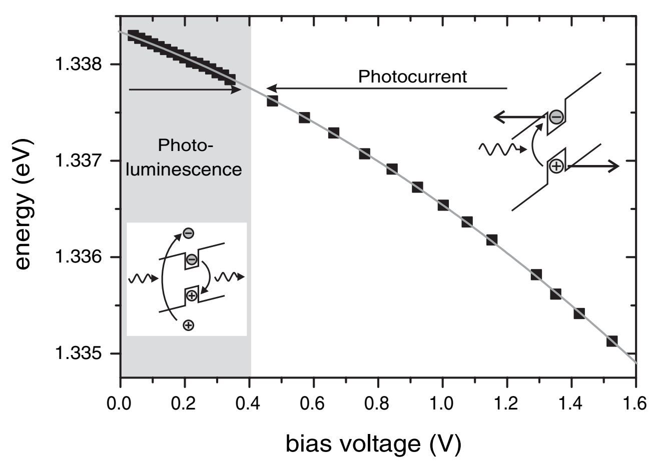

FIG. 1. Stark shift of the ground state exciton measured in the photoluminescence and photocurrent regime (squares). The solid line represents a fit curve, which is used for conversion between voltage and energy.

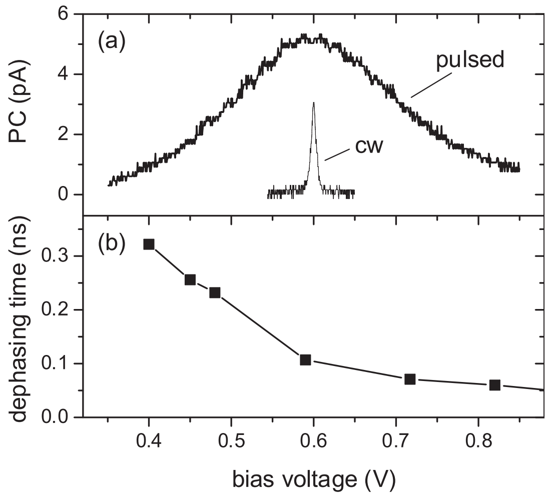

FIG. 2. (a) Photocurrent spectrum at excitation with (single) $\pi/2$ pulses. Voltage levels can be converted into energy scales via the Stark effect. The spectrum essentially represents the intensity profile of the laser pulse, a cw spectrum is included for comparison. (b) Dephasing times derived from quantum interference experiments. The coherence time decreases significantly towards high bias voltage due to faster tunneling.

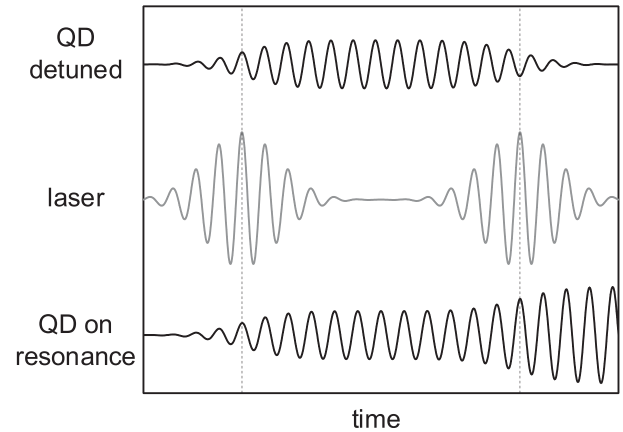

FIG. 3. Schematic picture of the phase relation between a coherent QD polarization (upper and lower curves) and two laser pulses (central curve). At arrival of the second pulse the phase of the QD in the detuned case is exactly opposite to that in the resonant case. This results in a strong variation of the final state occupancy although the detuning would be almost negligible for single pulse excitation.

homogeneous linewidth, whereas for pulsed excitation the PC signal almost directly displays the power spectrum of the laser. We obtain a spectral FWHM of 0.47 meV, which is about the transform limit for 2.6 ps laser pulses. The slight asymmetry is caused by a reduced tunneling efficiency at low bias voltage.

In the context of quantum information processing the QD two-level system is described as a qubit. Rotations of this qubit can be performed by short laser pulses, evidenced in Rabi oscillations. A π pulse thereby results in a complete inversion of the system, for example, a switching from $|0\rangle$ to $|1\rangle$ or vice versa. A $\pi/2$ pulse applied to the empty dot creates a coherent superposition of both states. In the absence of decoherence the phase of this superposition is stored in the QD and can be detected by a second $\pi/2$ pulse. Depending on whether the two pulses are of the same or opposite phase, the superposition state is turned into the pure $|1\rangle$ or $|0\rangle$ state, respectively. In previous experiments the phase of the second pulse has been controlled by varying its optical path length via a piezoelectric translation stage [4,6,8,14]. The amplitude of the quantum interference decays exponentially with increasing delay time between the two pulses. The dephasing times determined in this way are shown in Fig. 2(b). Note that in our case the dephasing time varies with the bias voltage, as it is dominantly determined by the tunneling time. A detailed description of the coherent properties of the QD two-level system can be found in [14].

We now want to examine the influence of detuning in the case of double pulse excitation. We generally consider two $\pi/2$ pulses as those can result in a pure $|1\rangle$ or $|0\rangle$ in the final state. Figure 3 schematically shows the phase evolution in a double pulse experiment. The central curve represents two laser pulses of a certain frequency ω_{laser} separated by a delay time τ_{delay}.

The lower curve displays the coherent polarization of the QD, which oscillates at exact resonance to the laser frequency ($\omega_{\text{QD}} = \omega_{\text{laser}}$). In the actual experiment we start with an initially empty QD. The phase of the QD excitation therefore is defined by the first laser pulse. In the situation displayed in Fig. 3 the second pulse is in phase with the QD polarization. The occupancy of the QD hence would go from 0 to 1/2 after the first pulse and from 1/2 to 1 at the second pulse.

The upper curve in Fig. 3 displays the same situation for a slightly detuned system. The phase of the QD excitation again is defined by the first laser pulse. The time evolution of the QD polarization then follows a slightly lower frequency than ω_{laser} ($\omega'_{\text{QD}} = \omega_{\text{laser}} - \Delta\omega$ with $\Delta\omega \ll \omega$). On arrival of the second laser pulse it has reached exactly the opposite phase with respect to the light field. As can be seen in Fig. 3, the phase relation between the QD and the laser field is fairly constant for the duration of a single pulse. For the manipulation induced by the first pulse, the effect of detuning is therefore almost negligible. The occupancy of the QD hence would again go from 0 to (almost) 1/2 after the first pulse, but then, due to the accumulated phase shift, would go back to 0 again after the second pulse. In general, the final state occupancy will oscillate as a function of the detuning $\Delta\omega$ with a period of $2\pi/\tau_{\text{delay}}$. This means that the frequency of the spectral fringes increases directly proportional to the delay time between the two pulses.

Figure 4 shows a measurement of Ramsey fringes at delay times ranging from 33 to 167 ps. The oscillation is caused by the voltage dependent detuning of the QD

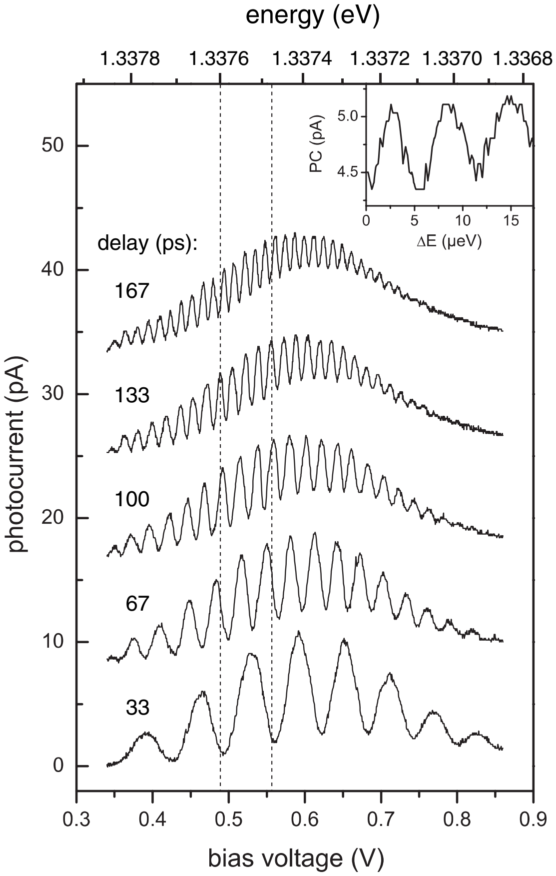

FIG. 4. Photocurrent spectra at excitation with two pulses separated by a fixed delay. The envelope of the signal corresponds to the spectrum of a single pulse, centered at 1.3374 eV. When tuning the transition energy of the quantum dot, we observe interference oscillations (Ramsey fringes). The number of fringes within a defined energy interval (dashed lines) is directly proportional to the temporal pulse separation. Inset: Fringes at excitation resonant to 0.43 V with a pulse separation of 670 ps. The interference half period is smaller than the homogeneous linewidth.

resonance with respect to a fixed laser energy (1.3374 eV), as described above. The frequency of this oscillation increases directly proportional to the delay time between the two pulses. Within a fixed energy interval of $\Delta E = 0.124\,\text{meV}$ we thus observe $n = \tau_{\text{delay}} \Delta E / h = \tau_{\text{delay}} / 33.3\,\text{ps}$ periods of the oscillation, where h is Planck's constant. Near the resonance we are able to detect Ramsey fringes even at delay times longer than the dephasing time of the QD system. The inset of Fig. 4 shows such a measurement for an excitation resonant to 0.43 V and a delay time of 670 ps. The half period of the Ramsey fringes here is only about 3 μeV, which is smaller than the homogeneous linewidth of the system (5 μeV). The spectral resolution of the double pulse experiment hence is shown to exceed that of any possible single pulse experiment (considering cw excitation as an infinitely long single pulse).

Looking very closely at the data in Fig. 4, we also observe a slight increase in the frequency of the Ramsey fringes towards higher bias voltage. This is caused by the slight nonlinearity of the Stark effect as displayed in Fig. 1. The phase of the Ramsey fringes at a certain voltage is not a well defined parameter in the present experiment, as we generally obtain a phase shift between the two laser pulses. This phase shift is constant within a single measurement but may vary arbitrarily between measurements at different delay times.

The envelope of the PC signal corresponds to the spectrum of single pulses with 1π pulse area [$2 \times \pi/2$, compare Fig. 2(a)]. The interference contrast of the Ramsey fringes decreases towards long delay times, due to finite dephasing times of the system [16]. The asymmetry in the interference contrast is caused by the voltage dependence of the dephasing times in our system [see Fig. 2(b)]. The ratio of the oscillatory part versus the total signal is therefore always highest for low bias voltages. Dephasing times derived by an analysis of the Ramsey experiment are in good agreement with those displayed in Fig. 2(b). The nonoscillatory part of the PC signal, which is dominant at long delay times and high voltage, appears if the tunneling time is shorter than the delay time between the two laser pulses. Both pulses then generate a PC signal similar to that shown in Fig. 2(a) but the interference is lost if the exciton has tunneled out of the QD before an interaction with the second pulse becomes possible.

In summary, we have presented the first measurement of Ramsey fringes in a semiconductor QD. For delay times longer than the dephasing time the spectral resolution is increased beyond the continuous excitation limit (i.e., the homogeneous linewidth). This effect is utilized in atomic systems with a fixed transition energy to increase the accuracy of frequency standards. In our system, which exhibits a tunable transition energy, we might use the effect inversely to stabilize the transition energy of the QD system with respect to the excitation laser. Furthermore, at constant bias conditions, any change in the environment of the QD that has an effect on the exciton transition energy will result in a notable variation of the final state occupancy. The QD therefore might serve as a highly sensitive quantum sensor for interactions occurring in the time interval between the two laser pulses.

In view of quantum information processing we consider the case of delay times shorter than the dephasing time. An excitation with two $\pi/2$ pulses then can be used for a full inversion of the two-level system or, in terms of quantum computing, a full 1π qubit rotation. In our system we are able to switch between constructive and destructive interference, and therefore zero or 1π rotation, simply by a small variation of the bias voltage. We thus establish a link between today's "classical" information technology, also relying on voltage based control, and the new field of coherent control on single quantum systems.

The Ramsey effect can also be applied to a quantum mechanical gate operation where target *and* control bit are based on coherent quantum states. In general, any quantum gate relies on the coupling of two or more qubits. The first implementation that has been demonstrated with QDs is based on the coupling of two excitons in a single dot, exhibiting an energy renormalization of 3.5 meV [17]. More scalable approaches are based upon vertical or lateral coupling of QDs. It has been found, though, that the coherence times in vertically aligned QD molecules decrease strongly with increasing electronic coupling of the dots [18].

We have demonstrated here that, with double pulse excitation, very small energy shifts are already sufficient for a full 1π variation of the final state rotation angle. The half period of Ramsey fringes, for example, is only $1/70$ of the above-mentioned biexciton binding energy if the two pulses are separated by 80 ps (that is $1/4$ of the measured dephasing time at 0.4 V and probably $1/10$ of the dephasing time at zero electric field). This example illustrates that even a relatively weak coupling of states, mediated, for example, by dipole-dipole interaction between neighboring dots [10], could be used for a conditional qubit rotation. The use of double pulses for the target bit rotation hence extends the range of applicable coupling mechanisms. By varying the delay time, it is possible to ideally match the gate operation time to any coupling strength.

In conclusion, ''Ramsey-like'' experiments employing detuning at double pulse excitation open up an important new degree of freedom for coherent QD manipulations. The range of applications might further be extended by including time-dependent voltage control on time scales shorter than the dephasing time.

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