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Ramsey fringes in a single InGaAs/GaAs quantum dot

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We report the observation of Ramsey fringes in single InGaAs/GaAs quantum dots. With double pulse $\pi/2$ excitation it is possible to control the occupancy and the phase of a quantum dot. The occupancy of the quantum dot oscillates with detuning. These Ramsey fringes are caused by a voltage dependent detuning of the QD. Due to the double pulse excitation the spectral sensitivity is strongly enhanced as compared to single pulse experiments. At long delay times we are able to resolve extremely narrow spectral fringes, clearly below the homogeneous linewidth of the underlying QD two level system. Our results demonstrate precision measurements on single quantum dots with strong implications for future quantum gates and quantum measurements.

Semiconductor Quantum Dots (QD) are currently receiving a lot of attention, not only for fundamental research but also in view of possible applications. They might provide the basis for a wide range of different applications, e.g. quantum cryptography or quantum information technology [1]. Self assembled QDs are promising candidates for solid state implementations, due to their well separated energy levels (resulting from the three dimensional confinement) and their high optical quality [2]. The key on the way to possible applications is the coherent manipulation of a single quantum system. Up to now several groups demonstrated Rabi oscillations on an excitonic ground state transition in a single QD [3–10].

In the current contribution we demonstrate the coherent control of a QD two level system in a two pulse Ramsey experiment. The basic effect of the Ramsey method depends on two time delayed interactions with an incomplete inversion [11]. The final state is a result of the quantum state detuning. The resolution of the Ramsey fringes depends only on the time delay between the two laser pulses which leads to an enhanced spectral sensitivity. This effect was first described by Norman F. Ramsey [12] and it was honoured in 1989 with the Nobel Prize.

Here we report the first measurements of Ramsey fringes in a QD system. With double pulse excitation in an electric field tuneable device we are able to control the occupancy and the phase of the quantum mechanical two level system entirely via the bias voltage.

We use a MBE grown InGaAs/GaAs QD layer which is embedded in the intrinsic region of a n-i-Schottky diode. Optical isolation of a single quantum dot is achieved via a near field shadow mask. A detailed description of the sample design is given in [13]. All measurements are performed in low temperature microscope at 4.2 K. The internal electric field can be controlled via the bias voltage. At low electric fields the radiative recombination is dominant. In this regime the QD can be basically characterised by voltage dependent photoluminescence (PL) with non-resonant excitation above the band gap. At higher voltages the tunneling time decreases to values shorter than the radiative recombination time. The

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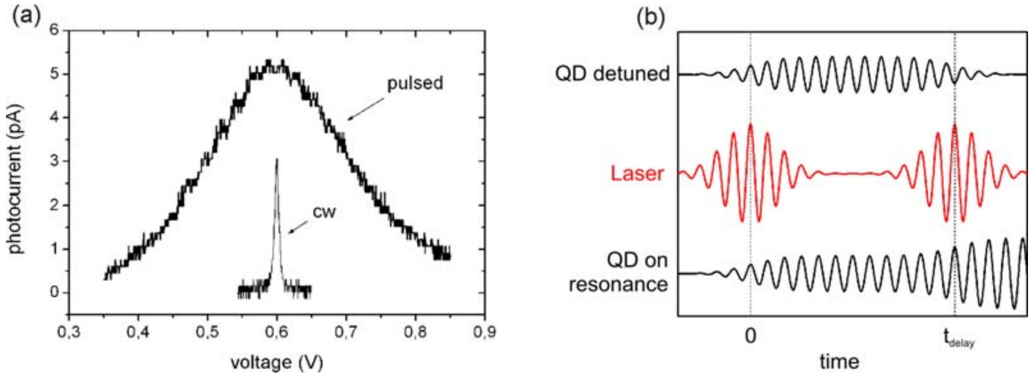

Fig. 1 (online colour at: www.pss-b.com) (a) Photocurrent spectra of the single exciton ground state comparing continuous and pulsed (π/2) excitation. (b) Schematic picture of the phase relation between the two laser pulses (central) and the two cases of detuned (upper curve) and resonanct (lower curve) QD excitation.

optical excitation then results in a photocurrent (PC). After resonant excitation of the single exciton QD ground state we are able to detect the QD occupancy in the PC.

Due to the quantum confined Stark effect the QD transition energy decreases with increasing (reverse) bias voltage. The shift in resonance energy covers the entire PL and PC regimes. Therefore we can use a quadratic fit curve for a conversion of bias voltage to energy. Furthermore it is possible to tune the QD energy precisely with respect to a fixed laser wavelength [15], which makes the realisation of defined detuning conditions easy.

Figure 1(a) displays the resonance of the exciton ground state in the PC for continuous and pulsed excitation. In the case of continuous excitation we resolve the homogeneous linewidth of the system [14]. For pulsed excitation the PC signal displays directly the power spectrum of the laser. The FWHM of 0.47 meV corresponds to the transform limit of a 2.6 ps laser pulse. In this case the QD can act as a spectrum analyser. The asymmetry of the pulsed PC spectrum is caused by the reduced tunnel efficiency in the transient region of PL and PC.

In the following experiments we want to discuss double pulse experiments under the condition of detuning. The exciton ground state of the QD represents a two level system (e.g. a qubit) if the optical excitation is restricted to this single transition [14]. The lower state $|0\rangle$ is defined by an empty dot and the upper state $|1\rangle$ by a single exciton ground state occupancy. Rotations of this qubit can be performed by short laser pulses, resulting in Rabi oscillations. A π pulse thereby results in a complete inversion of the system, e.g. a switch from $|0\rangle$ to $|1\rangle$ or vice versa.

For our current experiments we use two time delayed laser pulses with an excitation amplitude of π/2. Figure 1(b) shows schematically the phase evolution in the double pulse case. The central curve displays the two laser pulses with the frequency ω_{laser} separated by a delay time t_{delay}. The lower curve shows the case when the coherent polarisation in the QD oscillates in exact resonance ($\omega_{\text{QD}} = \omega_{\text{laser}}$) with the laser. After the first laser pulse the QD is therefore in a coherent superposition between $|0\rangle$ and $|1\rangle$. If the second laser pulse is in phase, the system will be transferred to the state $|1\rangle$. The upper curve corresponds to the same situation with a slightly detuned QD. The first laser pulse defines the QD phase again. But the time evolution happens then with a slightly lower frequency ($\omega'_{\text{QD}} = \omega_{\text{laser}} - \Delta\omega$ with $\Delta\omega \ll \omega$). When the second pulse arrives the QD can have a different phase as compared to the previous case (opposite phase in our example), resulting in the final state $|0\rangle$. Within the pulse duration the phase relation between the QD and the laser can be regarded as fixed. The final state occupancy will oscillate as a function of the detuning $\Delta\omega$ with a period of $2\pi/t_{\text{delay}}$. The frequency of the spectral fringes increases directly proportional to the delay time between the two pulses.

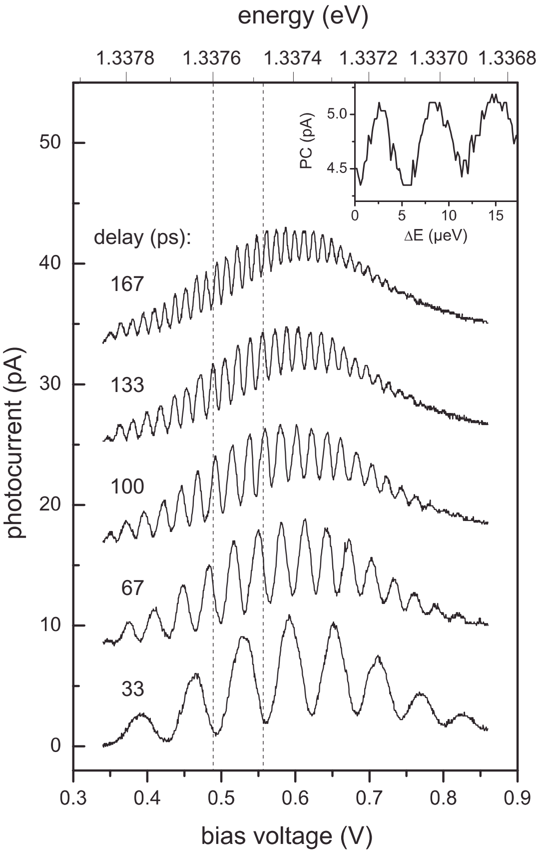

Fig. 2 Ramsey fringes measured in the photocurrent with double pulse excitation for different delays.

Figure 2 shows the measurement of the Ramsey fringes with different time delays in a range from 33 to 167 ps. The oscillation is caused by a voltage depending detuning of the QD. The oscillation frequency increases in fact directly proportional to the delay time between the two pulses. We can also observe a slight increase in the frequency of the Ramsey fringes towards higher bias voltage. This is a result of the nonlinear (quadratic) of the Stark effect. The envelope of the PC spectra corresponds to the spectrum of a single pulse with a pulse area of 1π. Towards longer delay time the interference contrast decreases due to the finite dephasing time of the system. The interference contrast decreases also with increasing voltage. This is caused by the strong voltage depending of the dephasing time [15]. The non-oscillatory 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. Then both pulses generate a PC signal of $\pi/2$ (as shown in Fig. 1(a)). If the exciton tunnels out of the QD before an interaction with the second pulse the interference will be lost.

We are able to detect Ramsey fringes at delay times even longer than the dephasing time of the QD system. This is shown in the inset of Fig. 2. This measurement is performed with resonant excitation at 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 exceeds that of any possible single pulse experiment.

In summary we have presented here 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). Furthermore any change in the environment of the QD which has an effect on the exciton transition energy will result in a notable variation of the final state occupancy at a constant bias voltage. The QD therefore might serve as a highly sensitive quantum sensor for interactions occurring in the time interval between the two laser pulses. The Ramsey setup offers a unique switch between constructive and destructive interference 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 two qubit gate operations. The first implementation of a CNOT gate on the basis of QD has been demonstrated by coupling of two excitons in a single dot, with a characteristic energy renormalization of 3.5 meV [16]. We have shown here that very small energy shifts are already sufficient for a full 1π variation of the final state rotation angle by applying the Ramsey method. Even a relatively weak coupling of states, mediated for example by dipole-dipole interaction between neighbouring 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 fit the gate operation time to any coupling strength.

In conclusion the "Ramsey-method" employing detuning at double pulse excitation opens 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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