Electrically controlled rapid adiabatic passage in a single quantum dot

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We demonstrate electrically controlled robust state preparation of an exciton qubit by rapid adiabatic passage with Fourier-limited laser pulses. In our approach resonant ps laser pulses are applied to generate excitonic population in a quantum dot, whereas synchronously applied ps electric transients provide a controlled sweep of the exciton transition energy. The ps electric transients applied to the quantum dot in a diode structure results in ultrafast Stark shifts of the exciton energy on time scales below the decoherence time of the exciton. We experimentally demonstrate that tailored electric chirp of the exciton energy leads to a controlled rapid adiabatic passage, which results in a robust state preparation of the exciton. Our experimental results are confirmed by a theoretical analysis of the chirped coherent manipulation of the exciton two level system. Our approach towards optoelectronic quantum control paves the way for broader applications that require a scalable control of functional coherent systems.

Semiconductor quantum dots (QDs) are an excellent platform for the implementation of photonic quantum technologies. QD-based sources for single indistinguishable photons [1, 2] and entangled photon pairs [3, 4] of high quality have become available during the last decade. With the ablity to deterministically deliver photon streams on demand, QDs are promising sources for the implementation of photonic quantum technologies, such as measurement induced nonlinearities [5] or boson sampling [6, 7].

The advances in the field of semiconductor QDs as quntum photon sources are so far based on mainly three major achievements: Excellent material quality resulting in virtually lifetime limited exciton coherence times at low temperatures [8], the integration in high quality photonic structures [9, 10], and the coherent state preparation by optical pulses such as Rabi flopping on one- and two-photon transitions [11, 12].

Currently, coherent state preparation is accomplished by Rabi rotations, performed with resonant optical pulses. Such techniques suffer from spectral diffusion and needs precise laser intensity control. Alternative approaches using polarization tailored pulses [13] or phonon assisted excitation [14, 15, 16] have been shown to be more robust to laser intensity fluctuation. However, these methods still require high control over the QD transition energies. Another technique, based on rapid adiabatic passage (RAP), is able to achieve robust inversion using frequency chirped optical pulses [17, 18]. Deterministic single photon emission [19] and biexciton generation [20] has been demonstrated by RAP excitation. Apart from being insensitive to laser fluctuations and transition energies, this technique has been shown to avoid phonon induced population reduction for the case of positive chirp [21, 22]. However, RAP excitations requires laser pulses, tailored in specific ways by specially designed dispersive elements for each application and thus lacking dynamic control over individual pulses.

In this letter, we report the implementation of a scalable approach, where transform limited optical pulses are used in combination with ultrafast Stark tuning of the QD to perform RAP and achieve robust inversion of the QD exciton TLS. The novel coherent optoelectronic concept involves the use of optical ps laser pulses in combination with electrical ps pulses, both applied within the coherence time of the QD system. The electric control of the QD system implies the possibility to control the energy of the QD states in a high dynamic time range using the ultrafast Stark effect, the electrical pulses must be in the ps time range. This was demonstrated by us recently by coherent phase control of a QD exciton in Ramsey interference experiment [23]. Our hybrid approach has the advantage of being compatible with single photon emitting optical cavity structures, where optical bandwidth of operation limits optically chirped excitation. Electric chirp offers also dynamic control of the induced chirp by delivering different degrees or even signs of chirp for each individual optical pulse.

We use a single InGaAs QD in a n-i-Schottky diode with a low capacitance semi-transparent Schottky gate. By integrating it with an ultrafast electric pulse generator chip ultrafast electrical Stark tuning of energy levels is possible together with a quantitative measurement of the population by photocurrent spectroscopy [24].

In the photodiode the QD layer is embedded in an i-GaAs layer, 280 nm below the surface and 40 nm above n^+-GaAs layer (see Fig 1). In this configuration, the QD exhibits an excellent exciton linewidth of about 1.6 µeV measured by photocurrent spectroscopy at T=4.2 K (dephasing time of 820ps). This result is achieved for low power cw excitation and a low reverse bias condition at V_B=-0.25 V. Further details of the sample structure can be found in Ref. [23].

The ultrafast electric transient generator was designed as integrated circuit (IC) based on a 0.13 µm SiGe:C BiCMOS technology from the IHP Leibniz institute [25]. The main core of the circuit was implemented with CMOS logic (see Ref. [23]), which generates fast ps transients (<50 ps) output from

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an input trigger pulse with slow input rise time (~500 ps) while keeping the dissipative heating negligible at cryogenic temperatures. Fig. 1b shows a photograph of the IC connected to a photodiode by wire bonding. The QD photodiode is operated in a RF-grounded condition (see Fig. 2).

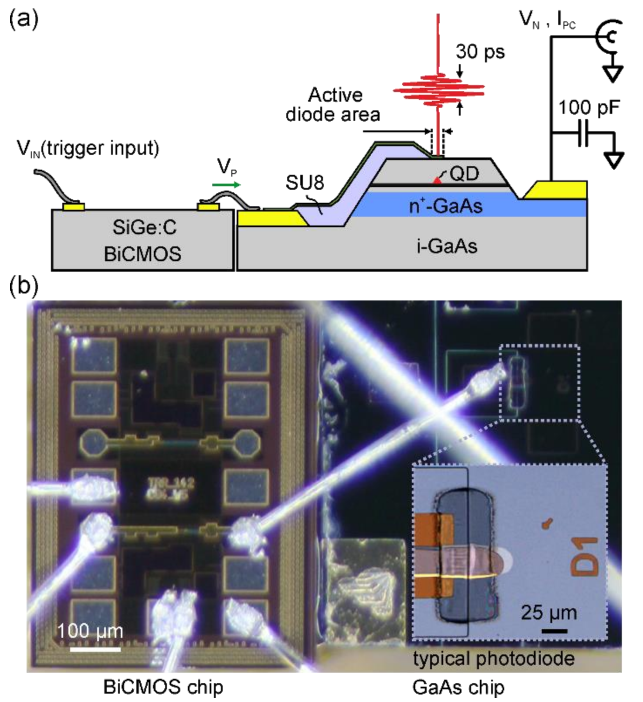

Fig. 1: System integration of an ultrafast electric BiCMOS chip and a low capacitance QD photodiode. (a) Schematic layout of the connected electrical chip and the GaAs photodiode sample in cross-sectional view. (b) Photograph of the used BiCMOS chip connected to a GaAs QD photodiode.

The RF-Signal $V_P(t)$ is generated by the IC and connected to the Schottky contact (diode anode). The n^+ layer (diode cathode) is RF-grounded by a capacitance (100 pF) and connected to a source meter, which supplies the cathode voltage V_N and performs a sensitive measurement of the photocurrent I_{PC}. The effective bias voltage of the photodiode is given by $V_B(t) = V_P(t) - V_N$, which remains negative for all conditions. A reverse photocurrent I_{PC} leads to a positive readout from the source meter. The experiments have been performed on a single QD, where the resonant excitation of the ground state exciton X^0 was obtained at V_B= -0.52 V for a laser energy of E = 1.340 eV.

For optical excitation a mode locked Ti:sapphire laser with a pulse duration of about 3 ps and a repetition rate of 80 MHz was used. The laser pulses have been transmitted through a plane-parallel Fabry-Perot interferometer (FPI), which increases the pulse duration while keeping the pulses at the Fourier-transform limit [26]. For the results shown here the pulse duration was adjusted to 30 ± 5 ps (interferometer mirror distance ~500 µm). The output of the FPI was sent through a tunable power controller and was finally focused by a low temperature microscope on the QD photodiode with attached BiCMOS chip, both being held at T = 4.2 K (see Fig. 2, Ref. [23]).

The most essential part of our experiment is the generation of chirp in the QD TLS by transient ultrafast Stark shift, which was designed to achieve controlled inversion with Fourier-limited laser pulses by RAP. This requires that the application of the ultrafast electric transient synchronized with the arrival time of the laser pulse. The electric transient results in a blue shift of the exciton transition (see Fig. 3a). The laser energy initially appears red-shifted relative to the time independent transition energy of the exciton. With increasing optoelectronic delay Δt_{OE} this red-shift is first decreased, crosses the resonance condition, and finally turns into an increasing blue-shift. This scheme corresponds to the scenario of positively chirped laser pulses acting on a TLS with constant exciton energy [16]. For the conditions of our experiment, the applied electric transient results in a total shift of the exciton energy of about 1.4 meV, which is achieved for a voltage swing of ΔV_B = -0.8 V.

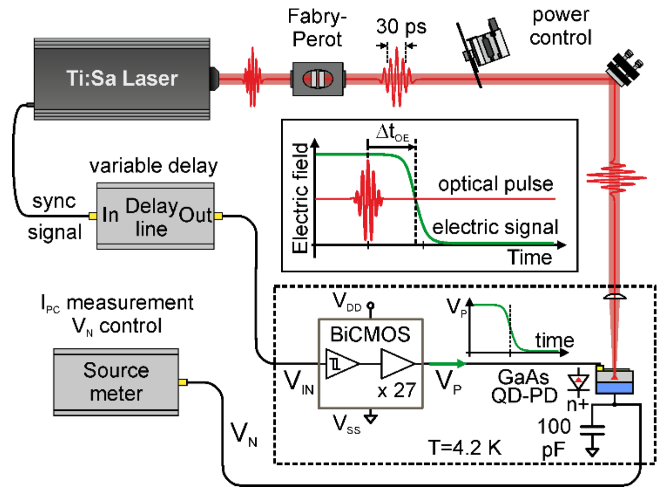

Fig. 2: Experimental set up for electric chirp experiments. The low capacitance QD photodiode and the ultrafast BiCMOS chip are cooled down to liquid helium temperature. The delay line controls the timing between the optical and electric pulses.

The electric transient is provided by the chip, which can generate a negative slope from V_P = 0.8 V to V_P = 0.0 V within about 50 ps without capacitive load. With a QD photodiode connected to the chip, this transient is slowed down by RC limitation. The electric transient determines the strength of the temporal energetic detuning of the exciton ground state. The transient profile can be determined using a sampling method based on the photocurrent measurement under simultaneous optical ps-excitation of the exciton. This allowed us to determine the following temporal evolution of the diode voltage on the falling edge of the electric pulse (see Fig. 3b). From a linear fit around the resonance condition (@ V_B= -0.52 V) we can determine an electric slope of -1.75 ± 0.09 V/ns or an energy chirp of 3.1 ± 0.2 µeV/ps.

The state control of the QD exciton has to be performed at time scales much faster than the available decoherence time. In the photocurrent detection regime, the decoherence time is controlled by the bias dependent ionization rate of the exciton, which is given by the tunneling rate of the electron [27]. During the applied electric chirp, the decoherence time is dependent on the momentary bias voltage V_B. At constant V_B the decoherence time of the investigated QD varies from ~450 ps at V_B=-0.3 V (initial state) to ~300 ps at V_B=-0.52 V (resonance condition) and finally to ~175 ps at V_B=-0.7 V (measured in Ramsey interference experiments at constant V_B). We have performed our experiment with a laser pulse width of 30 ps, which leads to conditions of coherent excitation throughout the entire bias voltage range. This value results from the timing of the electric transient and the resulting energy chirp of the TLS. The spectral width of the Fourier-limited laser pulses is about 25 µeV for 30 ps pulse duration. Within this time the TLS performs an energy sweep of about 94 μeV around the resonance condition (see Fig. 3b). The applied electric chirp leads to an almost constant energy chirp of 3.1 μeV/ps even over a time range of 50 ps, providing ideal conditions for our RAP experiment.

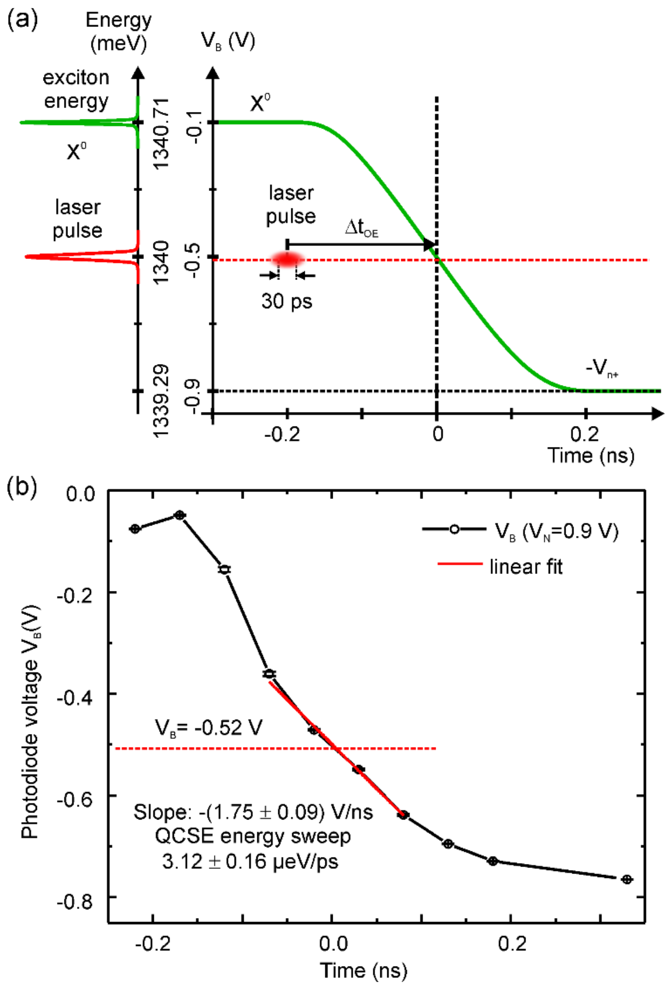

Fig. 3: Scheme of electric chirp experiment using transform limited optical pulses and ultrafast electrical transients. (a) Tuning of the exciton energy by the applied electric transient (green) with respect to the constant laser energy (red) (b) Electric transient obtained by photocurrent-based sampling of the time-dependent exciton energy as a function of the optoelectronic delay of 30 ps.

For longer laser pulses in the range of 300 ps the electric chirp would be no longer constant and the excitation would suffer increasingly from decoherence. For shorter pulses in the range of 3 ps the TLS would perform an energy sweep of only 9.4 μeV during the pulse duration which is insufficient for a RAP. Furthermore the spectral width is ~0.6 meV and already comparable to the total range of the electrically induced energy transient.

In Fig. 4a we present the experimental demonstration of an electrically induced RAP. The resulting occupancy of the QD exciton with increasing pulse area, measured via photocurrent clearly corresponds to electrically chirped RAP with fast electric field transient and in comparison to Rabi rotations without applied field transient. The black curve represents the photocurrent, when Fourier limited laser pulses were used (photodiode at constant V_B=-0.52V). The red curve shows the photocurrent for the same incident optical pulses, however applied while ps electric transients are synchronously driving the photodiode.

The black curve shows the expected Rabi oscillations with clear minima at 2π and 4π pulse area. In contrast (red curve), the photocurrent first increases with increasing pulse area and then tends to saturate near the maximum limit beyond a pulse area of 2π. This saturation behavior is the typical signature of a RAP [17, 18, 19]. The electric transient tunes the energy of the exciton TLS though the laser energy within the QD's decoherence time. In effect, the QD experiences an excitation, which is chirped in energy and performs a RAP although the optical pulse is not chirped. The QD TLS is deterministically inverted via a RAP induced by fast electric control.

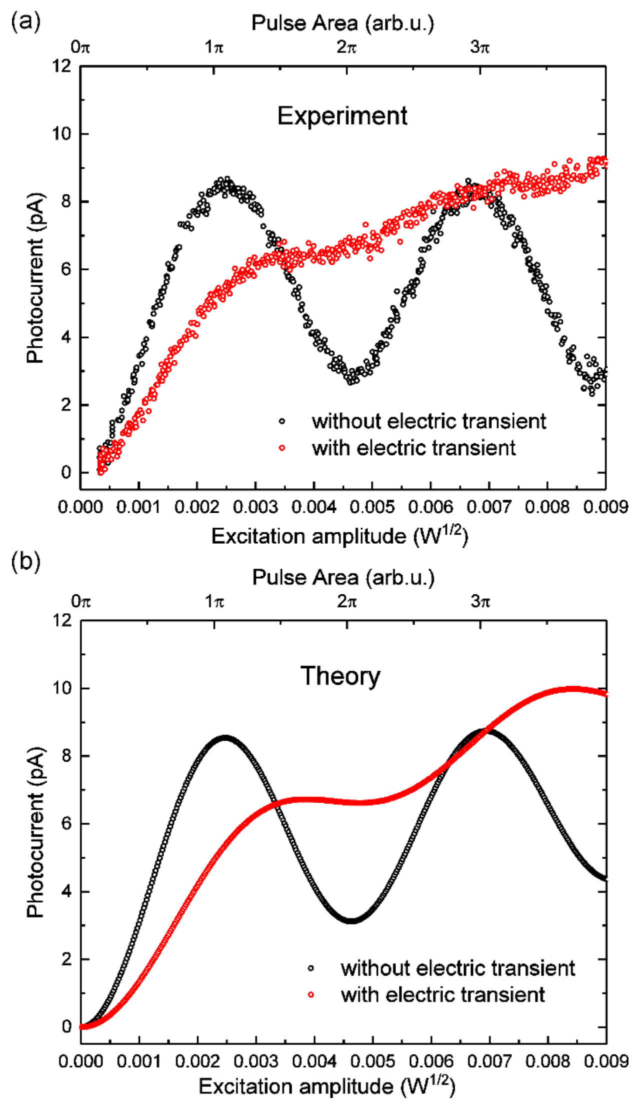

Fig. 4: Photocurrent corresponding to the occupancy of the two level system as a function of pulse area (a) Experimental data for conditions with (red) and without (black) applied electric transient. (b) Theoretical results corresponding to the experimental conditions.

The photocurrent detection technique allows quantitative measurement of the TLS occupancy. However, the exact relationship between the photocurrent and the TLS occupancy is influenced by processes such as incomplete tunneling and re-excitation of the quantum system. For this reason, only the photocurrent results have been used in our comparison between the experiment and the theory. The theoretical calculations, however, contain the complete description of all processes. For the ideal case of complete tunneling and π-pulse excitation one would expect a peak photocurrent of 12.8 pA for a laser repetition frequency of 80 MHz [24]. For V_B=-0.52 V tunneling remains however incomplete, leading in our case to a peak π-pulse photocurrent of only 8.5 pA. The raw Rabi measurement data have been also corrected by the subtracting a background signal, which increases linearly with laser power [28, 29]. The same background correction has been applied also to the raw RAP data. The residual photocurrent of about 3 pA at the Rabi minima i.e. 2π, 4π can be explained by the partial tunneling and re-excitation during the duration of the optical pulse (about 30 ps) [30, 31]. To achieve the best possible correspondence between the Rabi rotations and the RAP, we have set V_N to 0.9 V and applied a transient V_P from 0.8 V to 0 V for the RAP experiment. With these settings the resonance condition with the 30 ps laser excitation appears at V_P = 0.38 V, which corresponds to V_B = -0.52V. The transient electric field creates a positive chirp of 3.1 µeV/ps, which corresponds to a sweep rate of b=0.00237 ps^{-2} for a 30 ps laser pulse.

Fig.4b represents a theoretical calculation of the photocurrent performed by solution of extended optical Bloch equations for a TLS. In addition to the bare TLS, the model considers a heavy hole state [32]. We also apply a time dependent TLS detuning given by an exponential decay function (RC behavior). Actual experimental parameters were used as reference values and a numeric optimization tool was used to fine-tune the parameters within the error range of the experimental values [33, 34]. The closest match between theory and experiment was found for a higher chirp value of about 6.3 µeV/ps: compared to the experimentally determined value of 3.1 ± 0.2 µeV/ps. This indicates that the chirp value determined in the experiment might have a higher error range or the electrical and optical pulse interact at a slightly different optoelectronic delay (i.e. more negative delay where the electrical edge is steeper see Fig. 3b). Furthermore, at higher pulse areas (>3π) there is a deviation between the measured photocurrent data with and without electric transient. We assume that at higher pulse areas damping occurs due to the interaction with the acoustic phonons. This results in a lower coherent photocurrent for Rabi oscillations. Population resulting from positively chirped excitation is relatively immune to phonon interaction [17, 18, 19]. This is also evident for electrically induced chirp. Therefore, phononic contributions were neglected for the calculations. Finally, a slight decrease of the photocurrent can be observed in the red curve in Fig. 4b at values just slightly below 2π and 4π pulse area. This effect is due to only partially complete chirp coefficient achieved in the experiment, which leads to a partial inversion of the TLS. Theoretical simulations with higher chirp coefficients do not show such feature anymore.

With perspective to the operation of the quantum system in the regime of radiative recombination by application of the electrically induced RAP, which we presented here, the following points have to be addressed. Three time domains are crucial: the tunneling time of the charge carriers, the radiative recombination time and the time required for an electrical manipulation of the system (basically determined by the RC time constant of the system). The times should be in the following relation to each other: the radiative recombination time must be shorter compared to the tunneling time of the charge carriers. Additionally, both times have to be much longer compared to the RC time of the system. Thus, by implementing tunneling barriers the tunneling time is increased but furthermore the RC time constant still must be reduced. The time domain of radiative recombination can be further modified by means of photonic structure.

A viable concept for fabrication of electric field tunable photonic structures could be based on PIN transitions embedded in a Bragg resonator and restricted in the mode volume by implementing a micro resonator. With diameters in the range of 5 µm and lateral contacts such structures can even bring down the device capacitance by a factor of five compared to our current design, which still has a gated area of 5 µm x 25 µm.

With our work, we demonstrate the successful state preparation of an exciton qubit in a single semiconductor QD by electrically controlled RAP using just Fourier-limited laser pulses. We find good agreement between the experimental data and simulated results, especially concerning the formation of a photocurrent plateau for pulse areas of slightly more than 1π. Implementation of ps electrical control unlocks the possibility for flexible and dynamic manipulation of quantum systems down to pulse-to-pulse regime. With improved diode-design higher electric chirp coefficients should be achievable in the future. Finally, electrically controlled RAP is a viable concept to perform robust state control also on quantum systems embedded in high-Q photonic structures, where chirped laser excitation is inapplicable.

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The data that support the findings of this study are available from the corresponding author upon reasonable request.

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