Quantum state preparation in semiconductor dots by adiabatic rapid passage

Yanwen Wu, 1 I.M. Piper, 1 M. Ediger, 1 P. Brereton, 1 E. R. Schmidgall, 1
P. R. Eastham, 2 M. Hugues, 3 M. Hopkinson, 3 and R. T. Phillips 1

1 Cavendish Laboratory, University of Cambridge, J.J. Thomson Avenue, Cambridge CB3 0HE, United Kingdom
2 School of Physics, Trinity College, Dublin 2, Ireland.
3 Department of Electronic and Electrical Engineering, University of Sheffield, Mappin Street, Sheffield S1 3JD, United Kingdom

(Dated: June 10, 2010)

Preparation of a specific quantum state is a required step for a variety of proposed practical uses of quantum dynamics. We report an experimental demonstration of optical quantum state preparation in a semiconductor quantum dot with electrical readout, which contrasts with earlier work based on Rabi flopping in that the method is robust with respect to variation in the optical coupling. We use adiabatic rapid passage, which is capable of inverting single dots to a specified upper level. We demonstrate that when the pulse power exceeds a threshold for inversion, the final state is independent of power. This provides a new tool for preparing quantum states in semiconductor dots and has a wide range of potential uses.

Preparation of a specific quantum state in a semiconductor quantum system is a required step for quantum computation, generation of single photons and entangled photon pairs, and studies of Bose-Einstein condensation. A two-level quantum system, such as that of an exciton in a single quantum dot, can be driven into a specified state by use of a coherent interaction between the system and a tuned optical field. Previously, the interaction used to invert a two-level system in semiconductor quantum dots has driven the system with a resonant transform-limited light field. In this case, in the Bloch sphere representation the Bloch vector precesses about a field vector which lies in the equatorial plane, and so the optical pulse rotates the Bloch vector from its initial position at the south pole (ground state) through an angle \( \theta = \pi \) to the north pole (inversion). The angle \( \theta = \int \frac{\mu \cdot E}{\hbar} dt \) is defined as the pulse area in a Rabi rotation where \( \mu \) is the dipole moment describing the two-level system and \( E(t) \) is the envelope of the optical field.

Coherent resonant interaction has been shown to be capable of generating several such Rabi cycles, and permits readout of the state of the system optically or electrically by ionisation of the optical excitation and extraction of a current. The Rabi approach requires precise control over the integrated pulse area (determined by the temporal field profile and the dipole coupling strength) to achieve an inversion angle of \( \pi \) as shown schematically in Fig. 1a.

Here we show experimentally that state preparation is also possible by adiabatic rapid passage (ARP), which has the advantage that it is largely unaffected by variation in the dipole coupling, which is a normal feature of dot systems, and likewise insensitive to variation in the optical field which typically arises from laser fluctuation or positional variation in arrays of dots. Several theoretical proposals have recognized the potential of ARP excitation to create entanglement between locally separated electron spins for robust two-qubit quantum operation, exert quantum control between two-subband quantum wells, and generate novel Bose-Einstein condensates in semiconductors. ARP is a form of coherent interaction which effectively produces an anticrossing of the two quantum levels involved. At an anticrossing the wavefunction weight associated with a particular energy eigenvalue always switches from one state to the other as the anticrossing is traversed, and ARP uses this to switch the system from the ground state to the excited state as shown in Fig. 1b.
For ARP to operate, the quantum dynamics during the interaction with the field must not be interrupted by random events leading to dephasing of the coherent superposition of the ground and excited states. The quantisation of electronic states in a semiconductor quantum dot leads to an electronic level structure discrete in energy. This significantly reduces dephasing and non-radiative recombination which proceed through phonon scattering, since the phonons retain most features of the bulk material. Cross-gap electronic excitation remains primarily excitonic in character, and the quantum confinement potential of the dot enhances the stability of the multi-exciton and charged exciton species with respect to their counterparts in quantum wells or bulk material. This leads to a complication which can be exploited as the ARP approach can be designed to invert the quantum system to a specific final state of one of these other forms of excitation if a suitable optical pulse is constructed.

In order to detect the quantum state in which the system is left by the ARP interaction we have adopted the approach introduced by Zrenner et al., who recognised that it is possible to exploit the separation of timescales between excitation and dephasing to read out a quantum state electronically. In the ground state, $|0\rangle$, there is no exciton, but the excited state, $|X\rangle$, corresponds to an electron in the conduction band and a hole in the valence band, bound by the mutual Coulomb interaction as an exciton. The resonant optical excitation takes the system from the ground state to an arbitrary coherent superposition with the upper state: $c_0|0\rangle + c_X|X\rangle$. The dot is embedded in a biased Schottky diode structure (Fig. 2), and the applied electric field leads to ionisation of the excited state on a timescale longer on average than the excitation time. Clearly, the probability of charge flow depends on the relative amplitude in state $|X\rangle$; when the system is entirely inverted and $|c_X|^2 = 1$, the current flow in the external circuit is one electron per excitation cycle. For a repetition of the incident laser pulse at a rate $f = 76$ MHz, the peak current expected in this simple picture is just $e$ where $e$ is the electron charge; in our experiment $ef = 12.2$ pA.

We have selected a single InGaAs dot formed by Stranski-Krastanow growth, observed through a 200 nm diameter aperture fabricated in a Ti/Au Schottky contact by electron-beam lithography, as illustrated schematically in Fig. 2. Within the structure the dot layer is separated from the heavily n-doped back layer by 40nm of GaAs which acts as a tunnelling barrier. The position of the dots with respect to the Fermi level can be changed by varying the bias applied to the top Schottky contact. The aperture is illuminated by a confocal system and light collected for spectroscopy. Illumination is at a photon energy higher than the gap for excitation of photoluminescence (PL) or by pulses from a mode-locked Ti:Sapphire laser for the resonant pulse experiments. The selection of the laser wavelength for the pulsed experiments is made by first conducting photoluminescence mapping of the transitions corresponding to this dot, as shown in Fig. 3a.

Note that the dot can be switched from the negatively-charged exciton ($X^-$, at about 1.338 eV) to the neutral exciton ($X$, at about 1.3435 eV) and to the positively-charged exciton ($X^+$, at about 1.3445 eV) by varying the bias on the device, demonstrating the charge injection by tunnelling. Also present is the recombination of the first exciton pair in the biexciton state ($BX$) which is emitted at about 1.341 eV corresponding to a biexciton binding energy of around 3 meV. In order to read the quantum state of the dot by means of the ionisation current the bias has to be chosen to suppress photoluminescence as the main recombination channel. We have chosen to operate the device at a bias of -1 V, which suppresses the PL signal but does not produce too short a tunnelling time. Fig. 3b shows the photocurrent at that bias as a function of tunable continuous-wave laser wavelength incident on the structure; the photocurrent peak at 1.343 eV corresponds to resonant excitation of $X$, with the transition energy modified slightly by the applied field.

Under pulsed excitation with a transform-limited pulse with zero temporal chirp ($\alpha = 0$ ps$^{-2}$; see definition below) of 2 ps full width at half maximum (FWHM) (Fig. 4a), tuned to coincide with the photocurrent peak, the system clearly exhibits Rabi oscillation as the pulse area...
The dipole coupling is specified by $\mu_X$ and the optical field by $E(t)$. Under a unitary transformation

$$U(t) = \exp \left[ 0 \langle 0 | \langle 0 | + \omega(t) I | X \rangle \langle X | \right] \] (2)$$

this yields a picture appropriate to interaction driven by an applied field whose frequency varies in time as $\omega(t)$. The simplest variation is linear in time, with $\omega(t) = \omega_0 + \alpha \dot{\omega}$, where $\alpha$ is the linear temporal chirp. This is the form of optical field produced by the grating pair in our setup shown in Fig. 2. The Hamiltonian in the rotating frame of the central frequency of the laser, $\omega_0$, is

$$H_{\text{eff}} = \left( \begin{array}{cc} 0 & -\frac{1}{2} \mu_X E_0(t) \\ -\frac{1}{2} \mu_X E_0(t) & \Delta_X - 2 h \omega(t) \end{array} \right) \] (3)$$

where the detuning of $\omega_0$ from the transition frequency of the exciton is $\Delta_X$. In the experiment, $\Delta_X$ is zero. In this picture, the condition for adiabatic transfer (extensively explored previously) is that the effective Rabi frequency $\Omega(t) = \sqrt{\|E_0(t)\|^2 + \delta(t)^2}$ satisfies $\frac{\delta(t)}{\Omega(t)} \ll 1 $, and $\Delta \ll 1$, where $h\delta = \Delta_X - \hbar \omega(t)$ and $\Omega_0(t) = \mu_X E_0(t)/\hbar$. In this adiabatic regime, the Bloch vector follows the field vector as it rotates at a rate of $\delta$ from one polar extreme to another during the pulse while precessing rapidly at $\Delta$ around the field vector within a small solid angle.

To calculate the current drawn from the dot in the presence of both dephasing and ionisation of the exciton, the Hamiltonian model of the individual system is
used to evaluate the time evolution of the density matrix; the current is calculated from the scattering term corresponding to taking state |X⟩ to state |0⟩ by ionisation, using the Lindblad form of the scattering terms as described by Schmidgall et al. This term is integrated throughout the pulse interaction. Note that this model does not incorporate terms intended to explain the reduction in contrast of the Rabi oscillation usually observed for high values of pulse area in Rabi flopping. For realistic values of dephasing and tunnelling parameters, the model generates the curves shown in Fig. 4d, which confirm that the measured signals correspond to ARP.

Our results demonstrate the possibility of quantum state inversion in a system measured by electrical readout, robust with respect to variation in the details of the strength of the optical interaction. This opens the possibility of using adiabatic rapid passage in a range of contexts, including inversion of systems with level structures which can lead to deterministic single photon emission, or entangled photon pair emission. Adiabatic rapid passage requires only a chirp of the relative frequency offset of the optical field and transition frequency, so can be driven by a suitably rapid electrical pulse sweeping the transition. The insensitivity to the details of the interaction can be expected to provide access for the first time to physics associated with injection of tailored inversion profiles, such as complex microcavity electrodynamics.

Acknowledgments

This work is supported by EPSRC grant EP/F040075/1. YW is grateful for a Herchel Smith Fellowship. We would like to thank Prof. Dr. Artur Zrenner for his valuable advice on the fabrication of a low-leakage current Schottky device for electrical readout, Dr. Paul Eastham for helpful discussions and Dr. Geb Jones and Jonathan Griffiths for invaluable assistance with electron beam lithography.

1. D.P. DiVincenzo, Quantum Computation, Science 270 255 (1995)
2. E. Farhi, et al., A quantum adiabatic evolution algorithm applied to random instances of an NP-complete problem, Science 292 472 (2001)
3. P. Michler, et al., A quantum dot single-photonturnstile device, Science 290 2282 (2000)
4. R. M. Stevenson, et al., A semiconductor source of triggered entangled photon pairs, Nature 439 179 (2006)
5. P. R. Eastham, R. T. Phillips, Quantum condensation from a tailored exciton population in a microcavity, Phys. Rev. B 79 165303 (2009)
6. T. H. Stievater, et al., Rabi oscillations of excitons in single quantum dots, Phys. Rev. Lett. 87 133603 (2001)
7. H. Kamada, H. Gotoh, J. Temmyo, T. Takagahara, H. Ando, Exciton Rabi Oscillation in a Single Quantum Dot, Phys. Rev. Lett. 87, 246401 (2001)
8. H. Htoon, et al., Interplay of Rabi Oscillations and Quantum Interference in Semiconductor Quantum Dots, Phys. Rev. Lett. 88, 087401 (2002)
9. A. Zrenner, et al., Coherent properties of a two-level system based on a quantum-dot photodiode, Nature 418 612 (2002)
10. E. R. Schmidgall, P. R. Eastham, R. T. Phillips, Population inversion in quantum dot ensembles via adiabatic rapid passage, Phys Rev B 81 195306 (2010)
11. U. Hohenester, J. Fabian, F. Troiani, Adiabatic passage schemes in coupled semiconductor nanostructures, Optics Communications 264 426 (2006)
12. S. K. Saikin, C. Emary, D. G. Steel, L. J. Sham, Adiabatic optical entanglement between electron spins in separate quantum dots, Phys Rev B 78 235314 (2008)
13. A. A. Batista, D. S. Citrin, Quantum control with linear chirp in two-subband n-type doped quantum wells, Phys. Rev. B 74 195318 (2006)
14. A. A. Batista, Pulse-driven interwell carrier transfer in n-type doped asymmetric double quantum wells, Phys. Rev. B 73 075305 (2006)
15. V. S. Malinovsky, J. L. Krause, General theory of population transfer by adiabatic rapid passage with intense, chirped laser pulses, Eur. Phys. J. D14 147 (2001)
16. J. M. Villas-Bôas, Sergio E. Ulloa, A. O. Govorov, Decoherence of Rabi Oscillations in a Single Quantum Dot, Phys. Rev. Lett. 94 057404 (2005)
17. A. J. Ramsay, et al., Damping of Exciton Rabi Rotations by Acoustic Phonons in Optically Excited InGaAs/GaAs Quantum Dots, Phys. Rev. Lett. 104, 017402 (2010)
18. J.M. Villas-Boas, Sergio E. Ulloa, Alexander O. Govorov, Photocurrent oscillations in a quantum dot photodiode, Solid State Communications 134 33 (2005)
19. H. Y. Hui, R. B. Liu, Proposal for geometric generation of a biexciton in a quantum dot using a chirped pulse, Phys. Rev. B 78 155315 (2008)
20. F. Findeis, M. Baier, E. Beham, A. Zrenner, G. Abstreiter, Photocurrent and photoluminescence of a single self-assembled quantum dot in electric fields, Appl Physics Letters 78 2958 (2001)
21. Svetlana A. Malinovskaya, Optimal coherence via adiabatic following, Optics Communications 282 3527 (2009)
22. G. Lindblad, On the Generators of Quantum Dynamical Semigroups, Commun. Math. Phys. 48, 119 (1976)
23. H.S. Brandl, A. Latgé, Z. Barticevic, L.E. Oliveira, Rabi oscillations in two-level semiconductor systems, Solid State Communications 135 386-389 (2005)
24. A. Vagov, M. D. Croitoru, V. M. Axt, T. Kuhn, F. M. Peeters, Nonmonotonic Field Dependence of Damping and Reappearance of Rabi Oscillations in Quantum Dots, Phys. Rev. Lett. 98 227403 (2007)
25. Q. Q. Wang, et al., Decoherence processes during optical manipulation of excitonic qubits in semiconductor quantum dots, Phys. Rev. B 72, 035306 (2005)