Quantum-information processing with electron spins in "artificial molecules"

F. Troiani[1,*], U. Hohenester[2], and E. Molinari[1]
[1]INFM-S3 and Dipartimento di Fisica, Univerità di Modena e Reggio Emilia, via Campi 213/A, 41100 Modena, Italy
[2]Institut für Theoretische Physik, Karl-Franzens-Universität Graz, Universitätsplatz 5, 8010 Graz, Austria
[*]Corresponding author : Phone +39 059 2055283 Fax +39 059 367488 Email: troiani.filippo@unimore.it

Abstract. We propose the storage of the quantum information (qubit) in the spin of an excess electron in two vertically coupled quantum dots and its all-optical manipulation through ps-laser pulses. The auxiliary levels of the "artificial molecule" allow the implementation of the logical gates solely by means of stimulated Raman adiabatic passages, and the consequent suppression of the environment losses. The mapping of the spin states onto the orbital degrees of freedom results in the switch on of the dipole-dipole interaction between neighbouring qubits and thus allows the conditional dynamics (two-qubit gates) to be performed.

PACS: 73.21.La, 03.67.-a, 71.35,-y
Keywords: quantum-information, spin, coupled dots

1. Introduction

Quantum information processing (QIP) represents a new arena where intrinsic quantum mechanical systems are investigated and engineered in order to outperform "classical" devices [1]. In recent years an increasing variety of physical systems has been proposed for the realization of a first proof-of-principle quantum computer. In this prospect, semiconductor quantum dots (QDs) are among the most promising solid-state candidates: on the one hand, the reduced dimensionality suppresses the coupling to the environment (e.g., phonons), thus allowing coherent manipulation of the spin and charge degrees of freedom; on the other, the control on the carrier localization results in a wide tuneability of their mutual Coulomb interactions.

In particular, the spin of an excess (conduction - band) electron confined in a dot is known to benefit from long ($\sim$1 μs) decoherence times as compared the charge degrees of freedom, and have therefore been suggested for the storage of the quantum information (qubits). This identification, however, brings two conflicting requirements: on the one hand, the different electrons have to be spatially separated, in order for the qubits to be unambiguously defined; on the other, their spins have to efficiently interact in order for the conditional dynamics (two-qubit gates) to be performed. As a possible solution, Loss and DiVincenzo proposed to tune the interdot barrier, and thus the exchange interaction between neighbouring electrons, by means of time-dependent electric and magnetic fields [2]. Following a different strategy, Piermarocchi and coworkers suggested to let the electron spins interact via the exchange interaction with a common, photo-generated electron-hole pair, overlapping the involved, localized qubits [3]. In the present work, instead, the qubit-qubit coupling is provided by the Coulomb (dipole-dipole) interaction between the carriers. More specifically, during the gating the electron-spin states 0 and 1 are mapped onto two orbitals localized in different dots: different spin states thus result in different Coulomb potentials felt by the neighbouring electrons [4].

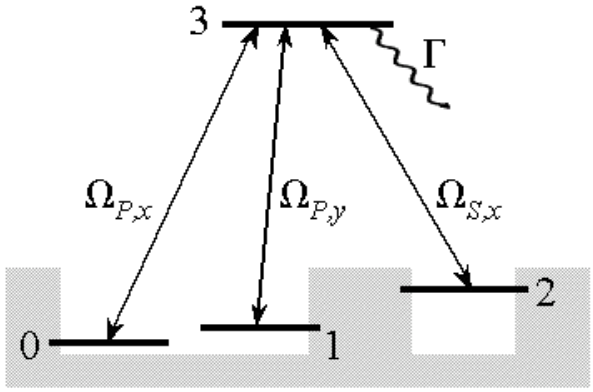

Fig. 1: Level scheme of the two vertically-coupled quantum dots: states $|1\rangle$ and $|0\rangle$ (single electron localized in the larger dot with spin $|S_x=\pm 1/2\rangle$), as well as the auxiliary state $|2\rangle$ (smaller dot, $|S_x=-1/2\rangle$), are optically coupled to a common charged exciton state $|3\rangle$. The two pump fields (P) and the Stokes one (S) are linearly polarized and in resonance with the respective transitions. The shaded area qualitatively represents the band profile of the heterostructure in the growth direction.

2. Qubit identification

Within the present proposal, we identify the qubit with the spin of an excess electron in two asymmetric vertically-coupled QDs: a simplified level scheme of such structure and its band profile in the growth direction are reported in Fig. 1. In the absence of a strong spin-orbit coupling in the conduction band and due to an in-plane magnetic field $\mathbf{B}=B\boldsymbol{x}$, the single-electron state is given by the product of the orbital and of the spin parts: $|1,0\rangle = |L\rangle\otimes|S_x=\pm 1/2\rangle$ and $|2\rangle = |S\rangle\otimes|S_x=-1/2\rangle$, where $|L\rangle$ and $|S\rangle$ are the lowest orbitals localized in the larger and in the smaller dot respectively. These states are optically coupled to a

common charged exciton $|3\rangle$ by resonant laser fields of specific linear polarizations [5]; state $|3\rangle$ undergoes spontaneous emission at a rate Γ.

The relevant features that characterize the present level scheme and the carrier localization are the following: (*i*) the existence of two, nearly degenerate ground states, sharing the charge state while differing on the spin one; (*ii*) a non-overlapping auxiliary state $|2\rangle$, which is stable on the timescale of the gating process; (*iii*) an excited state which is optically coupled to all the above single-particle ones. As discussed in more detail below, these requirements can hardly be fulfilled in a single QD.

3. All-optical adiabatic gating

As an important step within our scheme, we propose to perform both the single- and the two-qubit gates solely by means of stimulated Raman adiabatic passages (STIRAPs) [6]. A STIRAP essentially consists in a population transfer between stable states optically connected by an intermediate leaky state, whose occupation is kept negligible throughout the process (namely a "dark state"); the transfer is vehicled by an adiabatically varying "trapped state", i.e. by an eigenstate of the time-dependent Hamiltonian $H_0 + H_{int}$. In its simplest formulation (e.g., in a three-level Λ scheme) the STIRAP does not adiabatically implement a unitary transformation: in other words, the required pulse sequence depends on the initial conditions of the system. However, it was recently shown that any rotation of SU(2) on a general and unknown linear combination of two stable states can be applied by means of two STIRAPs already in the presence of a further (auxiliary) stable state [7].

The time evolution of the four-level system depicted in Fig. 1 is basically determined by the rotating-wave Hamiltonian $H_{int} = H - H_0 = \frac{1}{2}(\Omega_{P,x}(t)|0\rangle + \Omega_{P,y}(t)|1\rangle + \Omega_{S,x}(t)|2\rangle)\langle 3| + \text{H.c.}$, where all the fields are set in resonance with the respective transitions, $\Omega_{P,y}(t)/\Omega_{P,x}(t) = \text{tg}\,\chi\ e^{i\eta} = \text{cost.}$, and $H_0 = \Sigma_{i=0,2} E_i |i\rangle\langle i| + (E_3 - i\Gamma)|3\rangle\langle 3|$. H_{int} has two "trapped states" with no component along the state $|3\rangle$ and two orthogonal components in the $\{|0\rangle,|1\rangle\}$ subspace, $|S_{NC}\rangle$ and $|S_C\rangle$, depending on the pump laser parameters χ and η. As demonstrated in Ref. 7, a first STIRAP, consisting in a Stokes pulse followed by a delayed pump one, transfers the $|S_C\rangle$ component of the initial state $|\psi_i\rangle$ to $|2\rangle$; a reversed pulse sequence subsequently inverts such population transfer. The overall sequence results in the general unitary transformation $U(\delta,\chi\ \eta) \equiv |S_{NC}\rangle\langle S_{NC}| + e^{-i\delta}\ |S_C\rangle\langle S_C|$ (where δ includes the phase difference between the laser fields and a dynamical contribution, arising from the energy differences between states 1−3), which is implemented without ever occupying the state $|3\rangle$ and thus suppressing the environment loss (spontaneous emission).

For a specific set of laser parameters, namely $\chi = -\pi/2$ and $\eta = 0$, the first STIRAP maps the spin states onto the charge degrees of freedom: $|\psi_i\rangle = |L\rangle \otimes (\alpha|S_x{=}-1/2\rangle + \beta|S_x{=}+1/2\rangle) \longrightarrow |\psi'\rangle = (\alpha|L\rangle + \beta|S\rangle) \otimes (|S_x{=}-1/2\rangle \equiv U_{map}|\psi_i\rangle$. This particular transformation plays a crucial role in the implementation of the conditional dynamics. As discussed in more detail in Ref. 4, a C-NOT would essentially consist in: (*i*) a rotation U_{map} applied to the control qubit; (*ii*) a NOT gate applied to the (neighbouring) target qubit in such a way that the laser fields are in resonance with the corresponding transitions only if the control qubit is in its $|2\rangle$ state (electron in the small dot); (*iii*) a U_{map}^{-1} rotation applied to the control qubit.

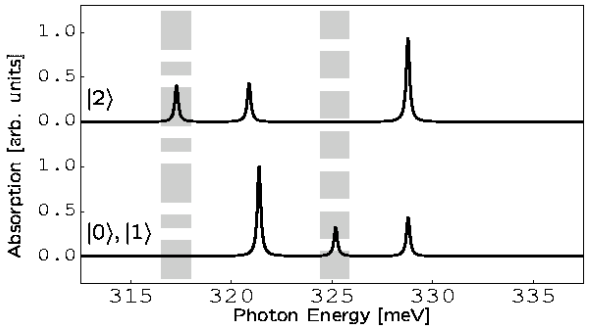

Fig. 2: Calculated absorption spectra of the two vertically-coupled QDs in three different initial states: $|0\rangle$, $|1\rangle$ (lowe line) and $|2\rangle$ (upper line); the photon zero corresponds to the semiconductor band gap. The shaded regions correspond to the energies of the Stokes (left) and pump (right) pulses. The Zeeman splitting $E_1 - E_0$ is neglected in the calculations.

4. Few-particle states

To conclude, we comment on the possibility of identifying a semiconductor heterostructure with the desired features. In particular, we shall consider a double GaAs dot embedded in an AlGaAs barrier; the heterostructure is modeled by a confining potential which is double-well like in the growth (*z*) direction and parabolic in the *xy* plane. As a first step, we diagonalize in real space the effective-mass Hamiltonian, thus computing the SP eigenvalues and eigenstates for electrons and holes. The overall Hamiltonian is given by the sum of the SP part H_0 and of the Coulomb (carrier-carrier) interaction part H_{cc}. The few-particle states are obtained by directly diagonalizing H in a truncated basis of Fock states, that are obtained by combining fixed numbers of electron and hole orbitals (for further details see, e.g., Ref. [8]). The optimization of the structural parameters finally led us to the following values: l_L=3.5 nm and l_L=3.6 nm for the well widths, d=7 nm for the interdot-barrier width, $\hbar\omega_{e,h}$=50,60 meV.

The results are shown in Fig. 2: the upper line corresponds to the absorption spectrum of the system being initially in state $|0\rangle$ or $|1\rangle$, while the upper line refers to an initial state $|2\rangle$; the peaks with the superimposed gray stripes correspond to the optical

transitions towards the charged exciton state $|3\rangle$. Two major features need to be underlined here: (*i*) the actual existence of a an exciton state connecting the three relevant SP states, with comparable oscillator strengths; (*ii*) the large (few meV) energy separations between those peaks and the neighbouring ones, associated to unwanted transitions. This last feature is relevant parameter, since the ratio $\hbar/\Delta$ (where Δ is the smallest energy separation that has to be spectrally resolved) gives a lower bound for the pulse duration: the present value of $\hbar/\Delta \sim 1$ ps thus allows optical gating of the "artificial molecules" on the ps timescale [9].

5. Conclusions

To summarize, we have proposed a novel, QD-based scheme for the implementation of QIP, based on the storage of the quantum information in the spin of excess electrons confined in "artificial molecules" and on its optical manipulation on the ps-timescale by means of stimulated Raman adiabatic passages. The resulting suppression of the environment loss (which would arise from the spontaneous decay of the involved exciton states) allows to fully profit from the combination of the long spin decoherence times and of the ultrafast manipulation of the interband degrees of freedom.

References

[1] M. A. Nielsen and I. L. Chuang, *Quantum Computation and Quantum Information* (Cambridge University Press) 2000.

[2] D. Loss and D. P. DiVincenzo, Phys. Rev. A **57**, 120 (1998).

[3] C. Piermarocchi, P. Chen, L. J. Sham, and D. G. Steel, Phys. Rev. Lett. **89**, 167402 (2002).

[4] F. Troiani, U. Hohenester, and E. Molinari, Phys. Rev. Lett. **90**, 206802 (2003).

[5] A. Imamoglu, D. D. Awschalom, G. Burkard, D. P. DiVincenzo, D. Loss, M. Sherwin, and A. Small, Phys. Rev. Lett. **83**, 4204 (1999).

[6] K. Bergmann, H. Theuer, and B. W. Shore, Rev. Mod. Phys. **70**, 1003 (1998).

[7] Z. Kis and F. Renzoni, Phys. Rev. A **65**, 32318 (2002).

[8] M. Rontani, F. Troiani, U. Hohenester, and E. Molinari, Solid State Commun.
119, 309 (2001).

[9] U. Hohenester, F. Troiani, E. Molinari, G. Panzarini, and C. Macchiavello, Appl. Phys. Lett. **77**, 1864 (2000).