Twin Photons from Small Quantum Dots

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Due to the large energy splitting of the single-electron levels in a small quantum dot, only one single electron level and one single hole level can be made resonant with the levels in the conduction band and valence band. This results in a closed system with nine distinct levels, which are split by the Coulomb interactions. We show that flat and tall cylindrically symmetric dots have level schemes with different selection rules. In both cases entangled photon pairs can be efficiently produced.

Introduction

A quantum dot that emits single photons controlled by the switching of a voltage is called a single-photon turnstile [1]. In such a system, the quantum dot is allowed to contain at most one single electron-hole pair, so that one photon is created at a time. In order to realize this, one makes use of the Coulomb blockade effect to suppress tunneling of a second electron or hole onto the dot. This implies that the system must be cooled to temperatures with $k_{\mathrm{B}}T$ smaller than the Coulomb splittings. In a two-photon turnstile, two electron-hole pairs are created, before two successive photons are emitted. Recently, a two-photon turnstile has been proposed [2] as a device to generate entangled photon pairs, which makes these systems very interesting. Because the Pauli principle allows occupation of an electronic level by at most two electrons, a two-photon turnstile can be realized without Coulomb blockade effects, provided that the thermal energy is smaller than the splitting of the single-particle levels so that tunneling of more than two electron-hole pairs is avoided. In a small quantum dot, this splitting can be much larger then the Coulomb splittings, so that a two photon turnstile does not require cooling in the milliKelvin regime for proper operation.

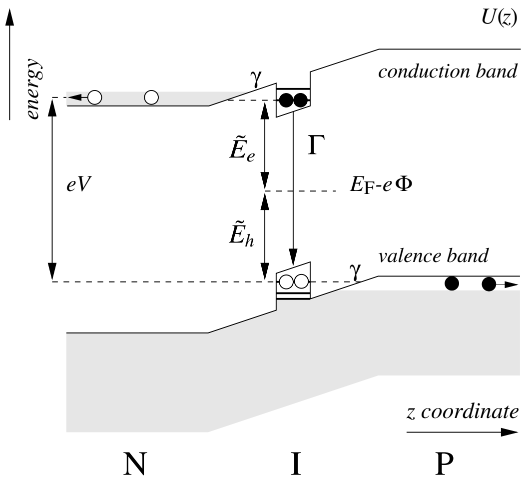

Figure 1: Energy-band structure of the PIN junction, for a cross section through the quantum dot along the z axis. The quantum dot is a small cylindrical structure located in the I layer between N and P semiconductors. With the gate potential Φ, the electron and hole energies can be shifted. A bias voltage V over the junction allows electrons (black) and holes (white) to tunnel across the barriers with rate γ and Γ is the photon emission rate, as indicated.

Cylindrically Symmetric Quantum Dots

A diagram of the semiconductor structure that we have in mind is shown in Figure 1. The quantum dot is located between P doped and N doped material. By means of a bias voltage V over the junction and a gate voltage Φ of an electrode near the dot, the electron level of the dot is made resonant with the bottom of the conduction band of the N type material and the hole level of the dot with the top of the valence band of the P type material. The quasi-particle energies $\tilde{E}_e$ and $\tilde{E}_h$ are well defined as the energy of the dot with one excess electron, respectively hole, with respect to the neutral state. The bias voltage V separates the energy levels between the N and P sides by eV and the gate voltage shifts the electron and hole levels by $-e\Phi$ and $e\Phi$. The resonance condition for a cental dot is then

$$\tilde{E}_e - e\Phi = eV/2, \;\; \tilde{E}_h + e\Phi = eV/2. \tag{1}$$

It is energetically favorable that electrons tunnel into the dot when $eV/2 > \tilde{E}_e - e\Phi$ and out of the dot when $eV/2 < \tilde{E}_e - e\Phi$. When one switches the gate voltage Φ or the bias voltage V, during a short time interval, first to a higher value and immediately thereafter to a lower value, then one promotes the tunneling of electrons from the N type material into the upper level of the dot, immediately followed by tunneling of holes from the P type material [3].

We consider the Coulomb interaction between electrons and holes as a perturbation on interaction-free levels. This approximation is well known in the context of quantum dots without holes in the electronic distribution, which are in (near) equilibrium [4]. For semiconductor quantum dots with holes, however, localized exciton states are formed from electron-hole pairs. Only if the dot is smaller than the exciton size the single particle levels are well defined and the Coulomb interaction can be treated as a perturbation [4, 5]. This is the condition that we suppose to be fulfilled in the following. Since we consider systems in absence of magnetic fields, the single-electron levels are twofold degenerate due to time-reversal symmetry. Let the two degenerate single-particle states for the electron and hole level be described by

$$\begin{aligned} |e\rangle &= \int d\vec{r}\,|\vec{r}\rangle\Big(|\uparrow\rangle\psi_1(\vec{r}) + |\downarrow\rangle\psi_2^*(\vec{r})\Big), \;\; |\bar{e}\rangle = \int d\vec{r}\,|\vec{r}\rangle\Big(|\uparrow\rangle\psi_2(\vec{r}) - |\downarrow\rangle\psi_1^*(\vec{r})\Big), \\ |h\rangle &= \int d\vec{r}\,|\vec{r}\rangle\Big(|\uparrow\rangle\chi_1(\vec{r}) + |\downarrow\rangle\chi_2^*(\vec{r})\Big), \;\; |\bar{h}\rangle = \int d\vec{r}\,|\vec{r}\rangle\Big(|\uparrow\rangle\chi_2(\vec{r}) - |\downarrow\rangle\chi_1^*(\vec{r})\Big), \end{aligned} \tag{2}$$

in terms of the wave functions $\psi_j(\vec{r})$ and $\chi_j(\vec{r})$ for the spinor components. Due to spin-orbit coupling these single particle states are not spin eigenstates in general. The dot states that form the basis of the configuration space are then described by the occupation of the four basis states (2). The number of electrons within this space thus ranges from zero up to four. The ground state has the hole level occupied with electrons and therefore is an effective quasi-particle vacuum, denoted with $|\tilde{0}\rangle$. Excited states of the dot are formed by means of creation of electrons in the higher level, and/or by creation of holes, i.e. by removing electrons, from the lower level. This gives, in addition to $|\tilde{0}\rangle$ and $|e\rangle$, $|\bar{e}\rangle$, $|h\rangle$, $|\bar{h}\rangle$, the further dot states

$$|e\bar{e}\rangle, \;\; |h\bar{h}\rangle, \;\; |eh\rangle \;\; |\bar{e}\bar{h}\rangle, \;\; |e\bar{h}\rangle, \;\; |\bar{e}h\rangle, \;\; |e\bar{e}h\rangle, \;\; |e\bar{e}\bar{h}\rangle, \;\; |eh\bar{h}\rangle, \;\; |\bar{e}h\bar{h}\rangle, \;\; |e\bar{e}h\bar{h}\rangle.$$

The resulting level schemes have sixteen basis states (see Fig. 2), part of which are charged due to the presence of one or two excess electrons or holes. In these schemes,

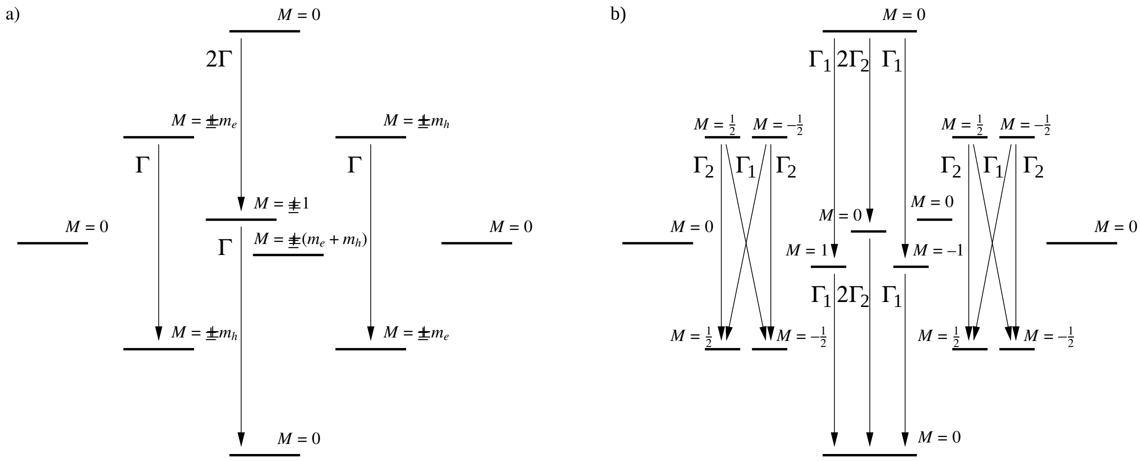

Figure 2: Two different schemes for cylindrical dots. a) In the case $|m_e - m_h| = 1$, the exciton multiplet consists of a bright and a dark doublet. b) For the case $m_e = m_h = \frac{1}{2}$, the exciton level is split into a doublet and two singlets. One singlet is a dark state. This results in six optical emission frequencies.

the state with highest energy is the bi-exciton state, with two electrons in the upper level and two holes in the lower level. The optical properties are determined by exciton and biexciton states [6, 7]. It is in the cascade decay from the biexciton to the ground state via a state of the one-exciton multiplet that an entangled photon pair may be generated.
In an axially symmetric quantum dot, the electron and hole states are characterized by well defined magnetic quantum numbers. In the most commonly used semiconductor materials the conduction band corresponds to $s\frac{1}{2}$, while the valence band is a $p\frac{3}{2}$ hole band. Hence the first unoccupied level in the dot is an $s\frac{1}{2}$ state, while the highest occupied level will be a $p\frac{3}{2}$ state. If we restrict ourselves to cylindrical dots, the confinement potential U is axially symmetric and the single-particle states have good total angular momentum quantum numbers m_e and m_h. These are found by angular momentum addition of the global motion described with the envelope wavefunction and the magnetic quantum numbers of the energy bands for the electron and the hole. These single-particle states are denoted as

$$|e\rangle = |m_e\rangle, \ |\bar{e}\rangle = |-m_e\rangle, \ |h\rangle = |m_h\rangle, \ |\bar{h}\rangle = |-m_h\rangle.$$

From the sixteen basis states of the level scheme Fig. 2, the states with an even number of electrons and of holes have total magnetic quantum number $M = 0$. Pairs of opposite M in the one-exciton multiplet, like for example $|eh\rangle$ and $|\bar{e}\bar{h}\rangle$, are degenerate. Since electric dipole transitions occur only if $|m_e - m_h| \leq 1$, we distinguish two cases: $|m_e - m_h| = 1$, diagram 2a), and $m_e = m_h$, diagram 2b). The case $|m_e - m_h| = 1$ is realized in the (lens-shaped) In(Ga)As/(Ar)GaAs quantum dots that have been extensively studied in ref. [6]. There it was found that for zero external magnetic field the exciton states with $|M| = m_e + m_h = 2$, which are formed by a $m = \frac{3}{2}$ heavy-hole state and a $m = \frac{1}{2}$ electron state, are to good approximation dark and lie below the $|M| = 1$ bright exciton states. This is a favorable situation for the creation of entangled photons, since the two exciton states with $|M| = 1$ are degenerate, due to time-reversal symmetry, and the decay paths of the biexciton via the $M = +1$ and via the $M = -1$ exciton state are therefore indistinguishable, as required for entanglement.

We now consider the situations sketched in diagram 2b), which represent the case $m_e = m_h = \frac{1}{2}$. In diagram 2b) there is a doublet of bright states, which may allow for entanglement of photons that are polarized in the horizontal plane. Note that the $m_h = \frac{1}{2}$ state is a superposition of $m_l = -1,0,1,2$ states in the $p\frac{3}{2}$ hole level, while the $m_h = \frac{3}{2}$ state is a superposition of $m_l = 0,1,2,3$ states. In dots elongated in the z direction, called 'tall' dots, the $m_f = \frac{1}{2}$ is expected to ly below the $m_f = \frac{3}{2}$ state. The relevant level in a $p\frac{3}{2}$ hole band may therefore consist of the $m_h = \pm\frac{1}{2}$ states for tall cylindrical dots. In diagram 2b) there are two degenerate exciton states, with $M = +1$ and $M = -1$, which are appropriate for the production of entangled photon pairs. Then one of the $M = 0$ exciton states is dark, the other is bright. The energy of the $M = 0$ states differs in general from that of the $M = 1$ states and therefore in total six frequencies appear in the optical spectrum.

Conclusions

We considered realizations of a two-photon turnstile based on small quantum dots. In the regime of tight confinement, the single-particle states are well separated and the Coulomb interaction can be treated perturbatively. We showed how this results in a closed level scheme with sixteen base states. The system seems ideal for generation of entangled photons on the cascade from the biexciton via the excitonic multiplet to the ground state. The biexciton can be prepared without Coulomb blockade so that low temperatures are not needed. There are two distict cases, flat and tall-shaped quantum dots, with different level schemes, shown in Fig. 2a) and 2b). Both cases can be realized experimentally and lead to generation of entangled photons. The polarization correlation and entanglement of formation in the photon pair may be corrupted by the following two effects; firstly here will be a minimal residual tunneling rate into and out of the intermediate one exciton level, which can effectively flip the spin of the exciton. Secondly, the Coulomb interaction gives rise to an exchange splitting of the exciton multiplet in dots without perfect axial symmetry, which causes different polarization states to dephase. We have studied the effect of electron tunneling and of a resonant cavity in a future publication [8].

References

[1] A. Imamoğlu, Y. Yamamoto, Phys. Rev. Lett. **72**, 210 (1994).

[2] O. Benson, C. Santori, M. Pelton, Y. Yamamoto, Phys. Rev. Lett. **84**, 2513 (2000); G.S. Solomon, M. Pelton, Y. Yamamoto, Phys. Rev. Lett. **86**, 3903 (2001); C. Santori, D. Fattal, M. Pelton, G.S. Solomon, Y. Yamamoto, Phys. Rev. B **66**, 045308 (2002).

[3] O. Benson, Y. Yamamoto, Phys. Rev. A **59**, 4756 (1999).

[4] Y.Z. Hu. Gießen, N. Peyghambarian, S.W. Koch, Phys. Rev. B **53**, 4814 (1996).

[5] A. Franceschetti. A. Zunger Phys. Rev. Lett. **78**, 915 (1997).

[6] M. Bayer, T.L. Reinecke, F. Weidner, A. Larionov, A. McDonald, A. Forchel, Phys. Rev. Lett. **86**, 3168 (2001); M. Bayer, G. Orter, O. Stern, A. Kuther, A.A. Gorbunov, A. Forchel, P. Hawrylak, S. Fafard, K. Hinzer, T.L. Reinecke, S.N. Walck, J.P. Reithmaier, F. Klopf, F. Schäfer, Phys. Rev. B **65**, 195315 (2002).

[7] E. Moreau, I. Robert, L. Manin, V. Thierry-Mieg, J.G. Gérard, I. Abram, Phys. Rev. Lett. **87**, 183601 (2001).

[8] P.M. Visser, K. Allaart, D. Lenstra, *Entangled Photons from Small Quantum Dots*, subm. to Phys. Rev. A.