Regulated and Entangled Photons from a Single Quantum Dot

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We propose a new method of generating nonclassical optical field states. The method uses a semiconductor device, which consists of a single quantum dot as active medium embedded in a p-i-n junction and surrounded by a microcavity. Resonant tunneling of electrons and holes into the quantum dot ground states, together with the Pauli exclusion principle, produce regulated single photons or regulated pairs of photons. We propose that this device also has the unique potential to generate pairs of entangled photons at a well-defined repetition rate.

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If the radiative recombination of electrons and holes in a semiconductor material is a fast and efficient process, the generated photons follow the statistical properties of the carriers. In semiconductor lasers and light-emitting diodes, a regular injection of carriers leads to subshot noise intensity fluctuations of the laser light [1–3]. On a mesoscopic scale, the strong Coulomb interaction between confined carriers in heteronanostructures can be used to control the injection of individual electrons and holes in an active region. This led to the proposal of a single photon turnstile device [4], which emits regulated single photons. A first experimental demonstration was reported using a micropost quantum well structure [5].

Semiconductor quantum dots (QD's) are very attractive for possible applications in electro-optic devices due to their atomlike properties and the strong confinement of electrons and holes. The Coulomb blockade effect [6], the quantum confined Stark effect [7], and electromagnetically induced transparency [8] have been studied with the aim of realizing single electron transistors that operate at room temperature [9], ultrafast electro-optical modulators [10], and novel lasers [11].

A fundamental nonlinear effect in a QD is the saturation of a single energy level by two electrons (or holes) of opposite spin due to the Pauli exclusion principle. In this Letter, we will show how this effect can be used in a realistic device to produce nonclassical field states. We propose a device that produces regulated photons as well as pairs of entangled photons.

Figure 1(a) illustrates a scheme for the device, which consists of a single InAs QD as the active medium embedded in a GaAs p-i-n junction. Electrical contacts are made from a top metal contact and via the n^+-doped substrate. The GaAs substrate is transparent for the ground state emission from the InAs QD's, and photons can be collected through the back side. It has been demonstrated that single QD's can be isolated from an ensemble of self-assembled QD's by etching small mesa or poststructures [12], as sketched in the figure. The structure is surrounded by an optical microcavity, which modifies the spatial emission pattern and increases the spontaneous emission rate into resonant cavity modes [13]. A very large fraction β of photons is thus spontaneously emitted into a single mode of the cavity, and the outcoupling efficiency from the high refractive index material is improved as well. For the present state of the art, β values as high as 0.9 should be possible [14].

An energy-band diagram of the structure is shown in Fig. 1(b) for doping levels of 10^{18} cm^{-3} on the n side and 10^{19} cm^{-3} on the p side. The QD layer is separated from

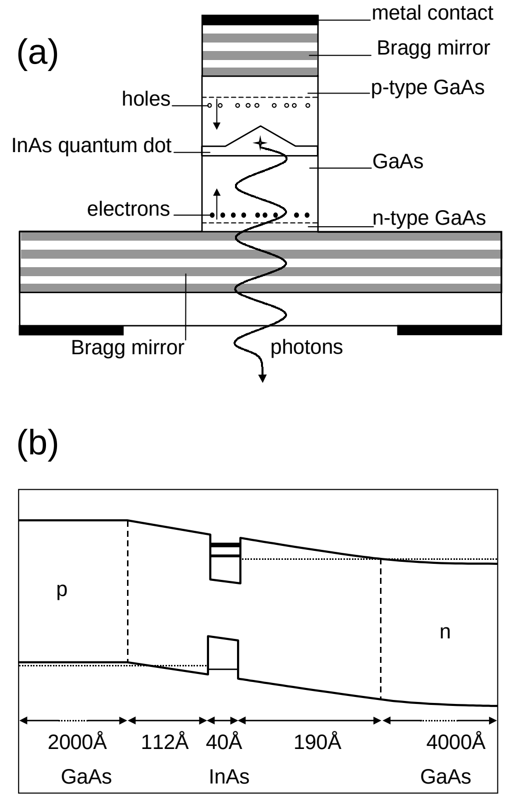

FIG. 1. (a) Proposed device structure. A single InAs QD (isolated on an etched micropost) is embedded in a GaAs p-i-n junction and surrounded by a microcavity. Metal contacts are made from the top and at the bottom substrate. Photons can be detected through the substrate. (b) Energy-band diagram of the structure. Doping levels are 10^{18} cm^{-3} on the n side and 10^{19} cm^{-3} on the p side.

the n (p) side by 190 Å (112 Å) wide GaAs intrinsic layers, which act as tunnel barriers. We assumed a typical dot diameter of 20 nm and height of 4 nm. For a qualitative discussion of the device operation, the Coulomb blockade energy can be estimated in a single particle picture [15,16] for simplicity, with strain and piezoelectric effects [17] neglected. We assumed that the one and two electron ground state energy levels are 210 meV and 190 meV below the conduction band edge of GaAs, respectively, and that the one and two hole ground state energy levels are 100 meV and 80 meV above the valence band edge of GaAs, respectively. The first excited electron (p-like) state is about 70 meV above the ground state [18,19]. These values are consistent with experimental observations [15,18] and calculations [20,21]. If the junction voltage V_j is well below the built-in potential, the carrier transport takes place by resonant tunneling of electrons and holes.

Figure 2 shows the calculated resonant tunneling rates for electrons and holes *versus* the applied bias voltage. The calculation uses the WKB approximation with an effective electron and hole mass of $0.067m_0$ and $0.082m_0$, respectively, and a temperature of 4 K. The different lines correspond to the following (from left to right): Electron tunneling into the dot containing zero or one electron (solid lines) and hole tunneling into the dot containing two electrons and zero or one hole (dashed lines). Tunneling into the first excited electron state is indicated by dotted lines, where the three lines correspond to two electrons and two, one, or zero holes. The difference in the widths of electron and hole tunneling resonances is due to the asymmetric tunnel barriers and different doping levels. We chose the position of the QD within the GaAs layer in order to have the first hole resonant tunneling condition fulfilled at a junction voltage above the second electron tunneling resonance. In this situation, we can switch on and off hole

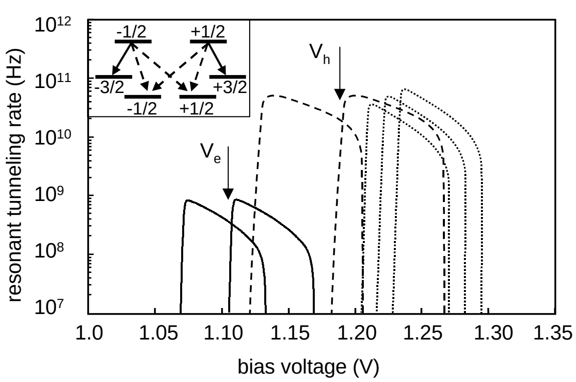

FIG. 2. Calculated resonant tunneling rates at 4 K into the QD ground state for electrons (solid lines) and holes (dashed lines) versus the applied bias voltage. Tunneling into the first excited electron state is indicated by dotted lines. In turnstile operation, the bias voltage is modulated between V_e and V_h. The inset illustrates optical transitions in a cubic lattice. The numbers indicate the projection of the total angular momentum J_z for the electrons and holes.

and electron tunneling by switching between different bias voltages.

Two-photon turnstile operation is achieved as follows: At a low bias voltage V_e (indicated in Fig. 2), two electrons can tunnel into the initially empty QD. Further electron tunneling is now completely suppressed due to the Pauli exclusion principle, since the ground state is filled and the next available electron state, the first excited state, is far off of resonance. Then, we switch up to a higher voltage V_h (indicated in Fig. 2), where two holes tunnel. Again, further hole tunneling is suppressed due to the Pauli exclusion principle since the hole ground state is filled and the first excited hole state (not shown) is off resonance. The first excited electron state shifts by typically 7 mV [18] to lower voltages when a hole tunnels. This is indicated by the three dotted lines in Fig. 2. However, even after two holes have tunneled into the QD, electron tunneling is inhibited. Once the holes have tunneled, radiative recombination annihilates two holes and produces exactly two photons. Thus, modulating the bias voltage between V_e and V_h produces a regulated stream of photons, where two photons are emitted per modulation cycle.

The two photons arise from the decay of the biexcitonic ground state of the QD, where the correlated electrons and holes have opposite spins. If this anticorrelation translates into an anticorrelation in polarization of the emitted photons, it is easy to realize a single photon turnstile operation by selecting out only one photon per modulation cycle with the help of a polarizer. For quantum wells in direct-gap materials with a cubic lattice, any photons emitted are circularly polarized, because the $J_z = \pm 1/2$ electron recombines with the $J_z = \pm 3/2$ heavy hole [22]. This is illustrated in the inset in Fig. 2, where solid arrows indicate the σ^+ and σ^- ground state transitions. In the case of a QD, the strong confinement introduces level mixing and the hole ground state may have contributions from the $J_z = \pm 1/2$ hole states. Possible transitions to the $J_z = \pm 1/2$ states are indicated by dashed arrows in Fig. 2. Accordingly, when a $J_z = +1/2$ electron radiatively recombines with a hole in a QD, the emitted light is predominately σ^+ polarized, but may also have a σ^- component. Thus, the two photons that arise from the decay of the biexcitonic ground state are not necessarily perfectly anticorrelated with respect to σ^+ and σ^- polarization. An asymmetric dot shape, strain, and piezoelectric effects [23] further reduce the anticorrelation. However, there is experimental evidence from polarized photoluminescence [24] and two photon absorption measurements [25] that the anticorrelation in σ^+ and σ^- polarization is preserved in QD's. An exact calculation of the energy levels and oscillator strength including spin for the system discussed here would be desirable (so far optical and electronic properties of self-assembled InAs QD's have been calculated neglecting spin [23]).

We point out that a previous single photon turnstile device relies on the relatively small Coulomb splitting [5]. This limits the operation of this device to very low temperatures (40 mK) in order to guarantee that thermal energy fluctuations are negligible. In the proposed device, the turnstile operation is maintained up to much higher temperatures due to the very large splitting between the electron and hole ground and excited states. Electron and hole tunneling could be controlled merely by the Pauli exclusion principle, even if the Coulomb blockade effect were absent. For the parameters we assumed here, an operation at above 20 K should be possible. At higher temperatures, the electron and hole tunneling curves are broadened, mainly due to the thermal energy distribution of the electrons and holes in the n- and p-doped layers. The broadening leads to a significant hole (electron) tunneling rate at lower (higher) bias voltage V_e (V_h), and photon emission can no longer be controlled. With a smaller QD and a larger splitting between ground and excited states, a larger broadening could be tolerated and thus a higher temperature operation is possible. We calculated that, up to a temperature of 50 K, thermionic emission can be neglected in the proposed structure.

We now focus on a unique property of the proposed device, which is the production of pairs of entangled photons at well-defined time intervals. Starting from the biexcitonic ground state of the QD, a first electron can recombine with a hole and emit a σ^+ or a σ^- photon. Then, the second electron of opposite spin recombines with a hole, and a photon of opposite polarization is emitted. This situation is very similar to a two-photon cascade decay in an atom [26]. The two-photon state has the same form in any basis and is a maximally entangled (Bell) state: $|\psi\rangle = \frac{1}{\sqrt{2}}(|\sigma^+\rangle_1|\sigma^-\rangle_2 + |\sigma^-\rangle_1|\sigma^+\rangle_2)$. Because of additional binding energy, the biexcitonic ground state has a smaller energy than twice the excitonic ground state [25,27]. Therefore, the first emitted photon 1 and the second emitted photon 2 have different energies (by approximately 4 meV).

The advantage of the proposed structure compared to other sources of entangled photons, such as two-photon cascade decay in atoms or parametric down-conversion in nonlinear crystals, is that entangled photon pairs are provided one by one with a tunable repetition rate of up to 1 GHz by a compact semiconductor device. The source is electrically pumped and the photons are emitted in resonant modes of an optical resonator, which greatly improves, e.g., the efficiency of subsequent fiber coupling.

The inset in Fig. 3 sketches the setup of a possible experiment, where the nonlocal quantum correlation between photons 1 and 2 leads to a violation of Bell's inequality. The two photons are separated with the help of a dichroic mirror (DM) and analyzed by a combination of quarter-wave plates (Q1, Q2), polarizing beam splitters (P1, P2), and detectors (D1, D2). Bell's inequality in the version of Ref. [28] is

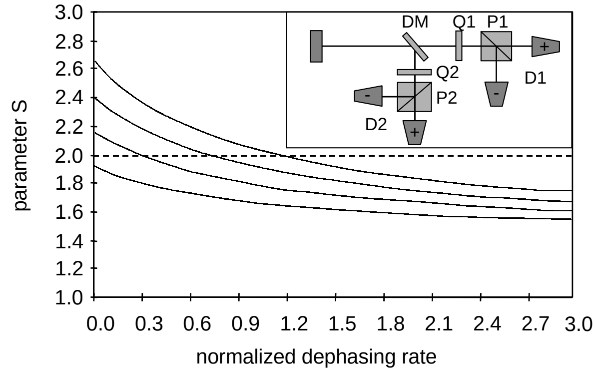

FIG. 3. The inset shows the setup for a proposed experiment. Photons are separated with a dichroic mirror (DM) and analyzed with the combination of quarter-wave plates (Q), polarizing beam splitters (P), and detectors (D). The figure shows the calculated left side of Eq. (1) (parameter S) versus the dephasing rate R_d. R_d is normalized to the radiative recombination rate R_p and $R_h = 10R_p$. Values above 2 (dashed line) are a violation of Bell's inequality. From top to bottom $\Delta_{\text{corr}} = 1$, 0.9, 0.8, and 0.7.

$$S = |E(\alpha,\beta) - E(\alpha',\beta)| + |E(\alpha',\beta) + E(\alpha',\beta')| \leq 2\,, \tag{1}$$

where

$$E(\alpha,\beta) = C_{++}(\alpha,\beta) + C_{--}(\alpha,\beta) - C_{+-}(\alpha,\beta) - C_{-+}(\alpha,\beta)\,. \tag{2}$$

Each photon is subject to a measurement of linear polarization along an arbitrary angle α or β with two-channel polarizers whose outputs are $+$ and $-$. Then, e.g., $C_{++}(\alpha,\beta)$ is the number of coincidences between the $+$ output of the polarization measurement of photon 1 along α and $+$ output of the polarization measurement of photon 2 along β. Maximal violation of Bell's inequality is observed for a particular set of angles of the two polarizers: $\alpha = 0$, $\alpha' = -\pi/4$, $\beta = 3\pi/4$, $\beta' = \pi/8$. For this set, quantum mechanics predicts $S = 2\sqrt{2}$, although the local hidden-variables theory is constrained by 2.

In the proposed device, several processes may degrade the entanglement and cause an evolution of the pure state into a statistical mixture of anticorrelated photons. For example, the QD initially contains two electrons, and then the bias voltage is changed to allow hole tunneling. It is possible that a first photon is emitted right after the first hole has tunneled, before the biexcitonic ground state has formed. A second photon can be emitted after the second hole has tunneled, but the final state is then a statistical mixture. Alternatively, even if the QD is in the biexcitonic ground state, spin dephasing may occur between the photon emission events. If the dephasing rate R_d is much larger than the radiative recombination rate R_p, then the final photon state is again a statistical mixture.

In order to demonstrate that it is possible to measure a violation of Bell's inequality we performed a numerical calculation. A rate-equation model of the tunneling and radiative recombination processes in the QD, similar to that presented in Ref. [29], is used. In order to account for the above mentioned problem of imperfect correlation, we define the degree of anticorrelation Δ_{corr} in the following way:

$$\Delta_{\text{corr}} = \frac{R_p^+}{R_p^+ + R_p^-}. \tag{3}$$

In this equation R_p^+ (R_p^-) denotes the radiative recombination rate of a $J_z = +1/2$ electron with a hole in the biexcitonic ground state of the QD through to the emission of σ^+ (σ^-) photons. In this notation, $\Delta_{\text{corr}} = 0.5$ corresponds to no anticorrelation and $\Delta_{\text{corr}} = 1$ to perfect anticorrelation.

Figure 3 shows the left side of Eq. (1) *versus* the dephasing rate R_d for a hole tunneling rate of 10 times the radiative recombination rate, in agreement with the calculated hole tunneling rate of 10 Ghz and radiative recombination rate greater than 1 Ghz in the proposed device. Values above 2 (dashed line) are a violation of Bell's inequality. The different curves correspond to different values of the degree of anticorrelation Δ_{corr}; from top to bottom, $\Delta_{\text{corr}} = 1, 0.9, 0.8,$ and 0.7. Clearly, a violation of Bell's inequality can be measured even with imperfect anticorrelation if the dephasing rate is small enough. Recent experiments in QD's indicate that the spin dephasing rate of conduction band electrons is much lower than 0.3 GHz [30], and thus much lower than the radiative recombination rate and tunneling rates.

In summary, we propose a semiconductor device which acts as a turnstile for single photons or pairs of photons. The device utilizes Pauli-exclusion principle and takes advantage of the large energy separation of the QD energy levels. A higher temperature operation than with previous device structures is possible. We show how this device could produce pairs of entangled photons at well-defined time intervals. We demonstrate that it is possible to measure a violation of Bell's inequality using the proposed device as a source of entangled photon pairs.

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