Turnstile Device for Heralded Single Photons: Coulomb Blockade of Electron and Hole Tunneling in Quantum Confined *p-i-n* Heterojunctions

A. Imamoḡlu
Institute for Theoretical Atomic and Molecular Physics, Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, MS 14, Cambridge, Massachusetts 02138

Y. Yamamoto
E. L. Ginzton Laboratory, Stanford University, Stanford, California 94305 and NTT Basic Research Laboratories, 3-9-11 Midori-cho, Musashino-shi, Tokyo 180, Japan

(Received 1 June 1993)

We show that if a double-barrier mesoscopic *p-i-n* heterojunction is driven by an alternating voltage source, then Coulomb blockade and quantum confinement effects together can suppress the quantum fluctuations usually associated with electron and hole injection processes in semiconductors. It is therefore possible to generate heralded single-photon states without the need for a high-impedance current source. Since the frequency of the alternating voltage source determines the repetition rate of the single-photon states and the magnitude of the junction current, the present scheme promises high precision photon-flux and current standards.

PACS numbers: 42.50.Dv, 03.65.Bz, 73.40.Kp, 79.40.+z

It is well known that the photon pairs (signal and idler) generated by a parametric down-conversion process have strong quantum correlations in their emission times, momenta, and energies [1]. These entangled states of light have been applied to various nonlocal quantum interference (EPR) experiments [2] and quantum cryptography [3]. If an idler photon is detected at a certain time and position, we know that a signal photon exists at a conjugate position [1]: This is considered as *single-photon state* generation. However, the generation timing of the photon pairs (and therefore the single photon state) in parametric down-conversion is completely random. Absence of information about the photon generation times imposes certain limitations to the range of applications of the photon pairs. The ultimate quantum control of the photon generation process could only be achieved when a well-defined number ($n \geq 1$) of photons are generated at arbitrarily short time intervals, with a deterministic dwell time between the successive (n) photon generation events. For $n = 1$, the result would be heralded single-photon states with complete information about the generation times of individual photons. Such a nonclassical optical source could open up a new field of *single photonics*, where the electrical-to-optical information transfer takes place at the lowest possible energy limit.

In this Letter, we propose a method to generate heralded single-photon states with a well-defined generation timing (clock), using a mesoscopic *p-i-n* heterojunction driven by an alternating (ac) voltage source. We have previously shown that a regulated single-photon stream could be generated using a mesoscopic heterojunction driven by a high-impedance constant-current source [4,5]. Constant-current operation in mesoscopic systems [6] however, is very hard to demonstrate in practice, as the electromagnetic environment puts a stringent upper limit on the real part of the source impedance [given by $R_s(f) > R_Q = h/2e^2$ for frequencies $f < e^2/2\hbar C$, where C is the capacitance of the junction] [7]. From an experimental point of view, it is therefore essential that the requirement of a high source impedance is removed.

The single-photon turnstile device analyzed here does not require a high-impedance constant-current source: Using an ac-voltage source together with a dc bias, we can control and separate (in time) the electron and hole resonant tunneling events into the undoped *i*-GaAs quantum well (dot) so that a single electron-hole pair is injected in a given cycle. Both Coulomb blockade and quantum confinement effects are essential for proper operation. The radiative recombination of the injected electron-hole pair is assumed to take place in a short time scale. Provided that the junction is embedded in a single-mode microcavity structure, a regulated single-photon stream (i.e., heralded single-photon states) with a repetition rate equal to the frequency of the applied ac voltage $f_{\rm ac}$, and a time jitter (ultimately) given by the spontaneous emission time $\tau_{\rm rad}$ can be generated. Extension to the generation of heralded multi ($n > 1$) photon states can simply be achieved by using n identical junctions in parallel. By modulating the ac drive, the proposed device can be used to reliably encode information at the single-photon level. Because of the deterministic transport and recombination of a single electron-hole pair per cycle, the analyzed scheme could also provide an alternative to the previous current standard proposals [8–10].

The energy-band diagram of the mesoscopic p-i_p-i-i_n-n AlGaAs-GaAs heterojunction that we analyze is illustrated in Fig. 1. If the junction voltage $V_j(t)$ is well below the built-in potential $V_{\rm bi}$ [$V_{\rm bi} - V_j(t) \gg kT$], the carrier transport in such a structure takes place by resonant tunneling of electrons and holes through the undoped i_p and i_n-AlGaAs *barrier* layers, respectively. The injected electron-hole pairs then recombine radiatively in the *i*-GaAs layer. We assume that the width of the *i*-GaAs

0031-9007/94/72(2)/210(4)$06.00

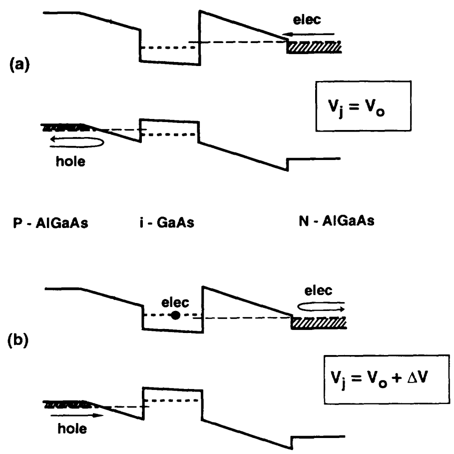

FIG. 1. The energy-band diagram of the p-i_p-i-i_n-n AlGaAs-GaAs heterojunction, with (a) and without (b) the applied voltage pulse. For $V_j = V_0$ ($V_j = V_0 + \Delta V$), the Fermi energy of the N- (P-) type AlGaAs layer is at least $e^2/2C_{ni}$ ($e^2/2C_{pi}$) higher (lower) than the energy of the quantum-well electron (hole) subband.

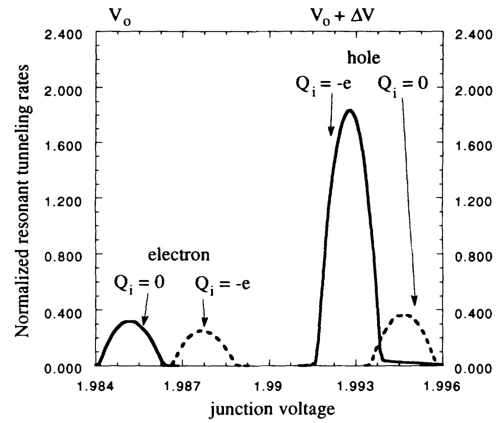

FIG. 2. The electron ($\Gamma_{\mathrm{tunn},e}$) and hole ($\Gamma_{\mathrm{tunn},h}$) tunneling rates as a function of the applied junction voltage, before and after electron and hole tunneling events. The tunneling rates are normalized to Γ_{rad}. Q_i denotes the charge of the i-GaAs Coulomb island.

quantum well is small enough that the energy separation of the quantized subbands well exceeds the single electron (hole) charging energy of the GaAs *Coulomb island* and that resonant tunneling into a single conduction (valence) subband need to be considered. The resonant tunneling of an electron or a hole is allowed only when the junction voltage is such that

$$E_{fn} - e^2/2C_{ni} \geq E_{\mathrm{res},e} \geq E_{nc} - e^2/2C_{ni} \quad \text{(electrons)} \tag{1a}$$

and

$$E_{fp} + e^2/2C_{pi} \leq E_{\mathrm{res},h} \leq E_{pv} + e^2/2C_{pi} \quad \text{(holes)}\ . \tag{1b}$$

Here, $E_{\mathrm{res},e}$ ($E_{\mathrm{res},h}$) is the energy of the electron (hole) resonant subband of the i-GaAs quantum well (or dot); E_{nc} and E_{pv} are the energies of the conduction and valence bands in the n- and p-type layers, respectively, and E_{fn} and E_{fp} are the Fermi energies in the corresponding layers. C_{ni} and C_{pi} are the capacitances of the n-i_n-i and p-i_p-i regions, respectively. The energies in Eq. (1) are determined by the applied junction voltage $V_j(t) = V_0 + v(t)$, where $v(t) = 0$ ($0 \leq t < T_{\mathrm{ac}}/2$); and $v(t) = \Delta V$ ($T_{\mathrm{ac}}/2 \leq t < T_{\mathrm{ac}} = f_{\mathrm{ac}}^{-1}$). The impurity concentrations on both n and p sides should be small enough that $E_{fn} - E_{nc} \simeq e^2/C_{ni}$ and $E_{pv} - E_{fp} \simeq e^2/C_{pi}$, since we want to be able to turn the tunneling of a particular carrier on and off by applying a voltage pulse whose magnitude is on the order of (but larger than) the single-charge charging energy. Finally, we assume that the Al concentrations in the two barrier regions are chosen independently so as to guarantee that peak electron and hole resonant tunneling occurs at (significantly) different values of the applied junction voltage.

We choose the dc-bias voltage (V_0) so that the electron tunneling is resonantly enhanced when $v(t) = 0$. The applied square voltage pulses [$v(t) = \Delta V$] enable the resonant hole tunneling, while blocking electron tunneling due to the second inequality in Eq. (1a), i.e., by quantum confinement. A second tunneling event of the same carrier during the time interval where the junction voltage remains unchanged is blocked by Coulomb blockade. Therefore, only one electron and one hole can tunnel into the i-GaAs layer within a single cycle of the applied ac voltage. Assuming that the radiative recombination occurs in a time scale short compared to the period of the ac voltage, a single photon is generated in each cycle with a probability approaching unity. If, in addition, the heterostructure is embedded in a micropost cavity [11] or photonic band-gap structure [12], then the photons are spontaneously emitted into a single mode of the radiation field.

If the fastest resonant tunneling rate is chosen on the order of the radiative recombination rate, then the smallest tunneling resistance will be determined by the inequality $\tau_{\mathrm{tunn}} = R_t C_d \simeq \tau_{\mathrm{rad}} \geq 10$ psec. For a junction capacitance of $C_d = 10^{-16}$ F, this inequality gives $R_t \geq 10^5\,\Omega$. These simple orders of magnitude imply that the quantum charge fluctuations on the junction can be safely neglected, as $R_t \gg R_Q$ [13]. We can therefore treat the charging of the *junctions* classically, and simulate the junction dynamics using a semiclassical Monte Carlo method that incorporates the resonant tunneling and radiative recombination processes as random *quantum jump* events. This method has been detailed previously [4]. The calculation of the quantum mechanical resonant tunneling rates uses the procedure described in Refs. [5] and [14].

Figure 2 shows the electron and hole tunneling rates before and after an electron tunneling event, for the chosen layer widths of $L_{in} = 470$ Å, $L_{ip} = 580$ Å, and

$L_i = 50$ Å of the i_n, i_p, and i layers, respectively. At a junction voltage of 1.985 V ($V_{bi} = 2.0$ V) and temperature $T = 0.1$ K, the electron tunneling is resonantly enhanced and takes place in an average waiting time of $\Gamma_{\text{tunn},e}^{-1} \simeq 3.0\Gamma_{\text{rad}}^{-1} (= 3.0\tau_{\text{rad}})$. Following a single electron tunneling, the junction voltage is quickly restored to its initial value of 1.985 V, and at this value, a second electron tunneling event is forbidden by Coulomb blockade, since the energy of the Coulomb island is increased by the injected electron. The hole tunneling remains negligible, irrespective of the electron tunneling events.

We assume that the applied ac voltage $v(t)$ has a period $T_{\text{ac}} = 30\Gamma_{\text{rad}}^{-1}$. The square pulses within a given cycle last for $15\Gamma_{\text{rad}}^{-1}$, with a peak voltage of $\Delta V = 0.007$ V. We see from Fig. 2 that a hole tunneling is resonantly enhanced in the presence of the square pulse ($V_j = 1.992$ V), when $Q_i = -e$. After the hole tunneling which takes place in approximately $\Gamma_{\text{tunn},h}^{-1} = 0.6\Gamma_{\text{rad}}^{-1}$, the Coulomb island becomes neutral ($Q_i = 0$) and the hole tunneling is forbidden by Coulomb blockade. As a second electron tunneling is enabled during the rising edge of the square pulse, the average electron resonant tunneling time has to be long compared to the turn-on time of the voltage pulse.

Figure 3 shows the result of our simulation of the junction dynamics using the Monte Carlo method. We choose the period of the ac voltage such that both the electron and hole tunneling occur with very high probability during the time intervals in which they are allowed. The photon emission events follow the hole tunneling in a very short time interval. We can consider the ratio of the period of the photoemission events to the jitter in the single-photon generation time as a *quality factor* $\mathcal{Q}$ for the generated single-photon stream. For a source with a time-independent generation rate, this ratio is unity (Poisson limit). In the proposed device, the quality factor is given by the ratio of T_{ac} to τ_{rad}, provided that the peak hole tunneling rate satisfies $\Gamma_{\text{tunn},h} > \Gamma_{\text{rad}}$. For the parameters of Fig. 3, $\mathcal{Q} = 30$. If the temperature is kept low enough to avoid secondary tunneling events in a single cycle, we can increase the quality factor arbitrarily by increasing T_{ac}. Finally, we note that as long as $\Gamma_{\text{tunn},e}T_{\text{ac}} \gg 1$, the electron tunneling rate has no effect on the device performance (i.e., on the $\mathcal{Q}$ factor).

The spectrum of the generated photon stream, which is shown in Fig. 4, exhibits a squeezed background noise extending to $\min[\Gamma_{\text{tunn},h}, \Gamma_{\text{rad}}]/2\pi$, together with nonstochastic peaks at integer multiples of f_{ac}, indicating regulation with the *clock* of the ac-voltage source. Prior to this work, the squeezed background noise was predicted and demonstrated only for p-n junctions driven by a high-impedance constant-current source [15]. The second-order correlation function of the photon stream obtained by inverse Fourier transforming the spectrum of Fig. 4 exhibits peaks at integer multiples of T_{ac} with negligible amplitude in between the peaks [5]. Physically, this indicates that following a photon emission event at $\tau = 0$, the probability of emitting others at the integer multiples of T_{ac} is enhanced, whereas in between, it is strongly suppressed. The generated light field has accurate information on the photon emission times: In contrast, each photoemission time is almost completely random for a photon-number or number-phase squeezed state [16].

The idea utilized in this proposal is in many ways similar to the frequency locked turnstile device proposed and demonstrated in Ref. [8]: By controlling the electron tunneling processes in a normal-tunnel junction system, Geerlings *et al.* were able to demonstrate experimentally that the generated current is to a high degree determined by the frequency (f) of the applied source, through the relation $I = ef$, as each cycle contributes to one and only

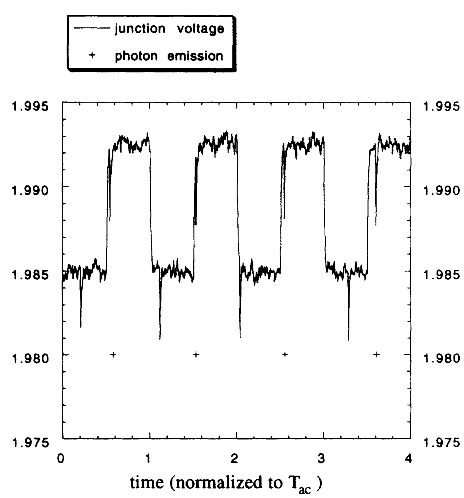

FIG. 3. The junction voltage as a function of time shown together with the accompanying photon emission events. The *voltage spikes* correspond to electron or hole tunneling events.

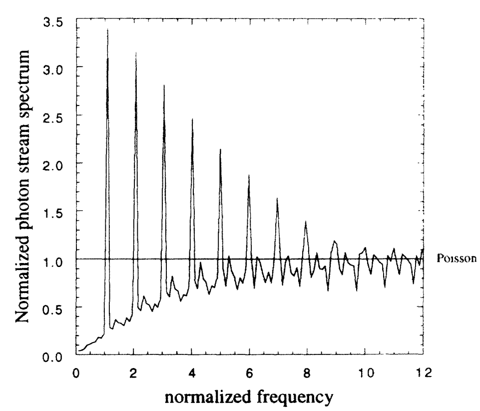

FIG. 4. The spectrum of the generated heralded single-photon states. The nonstochastic peaks in the spectrum indicate regulation of the photon generation process. The squeezing of the background noise extends to $\min[\Gamma_{\text{tunn},h}, \Gamma_{\text{rad}}]/2\pi$.

one electron transfer through the turnstile device. By utilizing the presence of two different types of carriers (electrons and holes) and quantum confinement properties, we were able to simplify the geometry considerably for our application (as compared to Ref. [8]). The single-photon turnstile device proposed here can also be used as a current standard, with properties and limitations similar to those of [8,9], for a junction with similar capacitances. The fluctuations in the current are primarily caused by the missing tunneling events, for the ideal square-pulse operation that we used in our simulations. Additional charge tunneling, whether it is caused by finite turn-on time of the ac-voltage pulse or the thermal fluctuations, will also be important in practice. Finally, we note that the accuracy of a current standard based on the analyzed scheme can be made arbitrarily high by choosing an appropriate T_{ac} that would in average cancel out the contributions from the additional and missing tunneling events.

The large penetration depth of the carrier wave functions in semiconductor heterostructures should make it possible to use wider barrier layers and therefore achieve smaller capacitances for a given junction size, as compared to metal-insulator-metal junctions used in Ref. [8]. For the effective junction diameter $2a = 300$ nm used in the simulation, the capacitance is approximately given by 4×10^{-17} F: This value is more than an order of magnitude smaller than the value predicted by Ref. [8] for a junction of similar size, implying that a higher operating temperature and ac-drive frequency should be possible. Based on the predicted junction parameters, we estimate an accuracy of about 10^{-2} at an operating frequency of 1 GHz, for a voltage-pulse turn-on time of 5 psec and $\Gamma_{\text{tunn},e}^{-1} = 100$ psec. By reducing the junction size, the operating temperature can be increased to 3 K, without considerably sacrificing the accuracy. The upper value of the ac-drive frequency f_{ac} is determined by $f_{ac} \ll \Gamma_{rad} \ll 1/R_Q C$, and can therefore be increased by decreasing the radiative recombination time. This can be achieved by utilizing the vacuum-field enhancement in a microcavity structure [11].

Even though we have considered perfect square pulses in our analysis, the proper operation of the proposed turnstile device only requires that the turn-on time of the applied voltage pulses be short compared to the peak electron resonant tunneling time ($\Gamma_{\text{tunn},e}^{-1}$). An alternative approach would be to apply short Gaussian pulses, with a pulse width τ_{pulse} that satisfies $\Gamma_{\text{tunn},h}\tau_{\text{pulse}} > 1$ and $\tau_{\text{pulse}} \ll \Gamma_{\text{tunn},e}^{-1} < T_{ac}$. It is also important to note that the regulation of the tunneling events in the analyzed device does not require quantum confinement in the transverse directions.

In summary, we proposed a method to generate a highly nonclassical photon state, without the need for a high-impedance constant-current source. The analyzed scheme relies on both the Coulomb blockade and the existence of quantized conduction (and valence) subbands. This voltage-biased single-photon turnstile device also promises high precision photon-flux and current standards.

The work of A. Imamoḡlu was supported by the National Science Foundation through a grant for the Institute for Theoretical Atomic and Molecular Physics at Harvard University and Smithsonian Astrophysical Observatory.

[1] D. C. Burnham and D. L. Weinberg, Phys. Rev. Lett. **25**, 84 (1970).
[2] J. D. Franson, Phys. Rev. Lett. **62**, 2205 (1989); P. G. Kwiat, W. A. Vareka, C. K. Hong, H. Nathel, and R. Y. Chiao, Phys. Rev. A **41**, 2910 (1990); Z. Y. Ou, X. Y. Zou, L. J. Wang, and L. Mandel, Phys. Rev. Lett. **65**, 321 (1990).
[3] C. H. Bennett, F. Bessette, G. Brassard, L. Salvail, and J. Smolin, J. Cryptology **5**, 3 (1992); A. K. Ekert, J. G. Rarity, P. R. Tapster, and G. M. Palma, Phys. Rev. Lett. **69**, 1293 (1992).
[4] A. Imamoḡlu, Y. Yamamoto, and P. Solomon, Phys. Rev. B **46**, 9555 (1992).
[5] A. Imamoḡlu and Y. Yamamoto, Phys. Rev. B **46**, 15 982 (1992); A. Imamoḡlu and Y. Yamamoto, Int. J. Mod. Phys. B **7**, 2065 (1993).
[6] D. V. Averin and K. K. Likharev, J. Low Temp. Phys. **62**, 345 (1986).
[7] M. H. Devoret, D. Esteve, H. Grabert, G. -L. Ingold, H. Pothier, and C. Urbina, Phys. Rev. Lett. **64**, 1824 (1990).
[8] L. J. Geerlings, V. F. Anderegg, P. A. M. Holweg, J. E. Mooij, H. Pothier, D. Esteve, C. Urbina, and M. H. Devoret, Phys. Rev. Lett. **64**, 2691 (1990).
[9] L. P. Kouwenhoven, A. T. Johnson, N. C. van der Vaart, C. J. P. M. Harmans, and C. T. Foxon, Phys. Rev. Lett. **67**, 1626 (1991).
[10] L. P. Kouwenhoven, Europhys. Lett. **18**, 607 (1992); J. M. Jacobson, Y. Yamamoto, and A. Imamoḡlu (unpublished).
[11] G. Bjork, S. Machida, Y. Yamamoto, and K. Igeta, Phys. Rev. A **44**, 669 (1991).
[12] E. Yablonovitch, J. Opt. Soc. Am. B **10**, 283 (1993).
[13] L. J. Geerlings, V. F. Anderegg, C. A. van der Jeugd, J. Romijn, and J. E. Mooij, Europhys. Lett. **10**, 79 (1989).
[14] C. Weisbuch and B. Vinter, *Quantum Semiconductor Structures* (Academic Press, San Diego, 1991).
[15] A. Imamoḡlu and Y. Yamamoto, Phys. Rev. Lett. **70**, 3327 (1993).
[16] Y. Yamamoto, S. Machida, and W. H. Richardson, Science **255**, 1219 (1992).