Sub-Poissonian Photon-State Generation by Stark-Effect Blockade of Emissions in a Semiconductor Diode Driven by a Constant-Voltage Source

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It is predicted that sub-Poissonian photons can be generated without recourse to pump control in a tailor-made semiconductor diode. Monte Carlo simulations reveal that both photon noise and pump noise are drastically suppressed by automodulation of bimolecule-recombination lifetime due to the quantum-confined Stark effect and recharging effects. The noise of photon fluxes is reduced to below the standard quantum limit even under constant-voltage operation. [S0031-9007(96)00090-7]

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Sub-Poissonian photon-state generation has been observed using semiconductor lasers [1] or light-emitting diodes (LEDs) [2,3] driven by high-impedance constant-current sources [4,5]. The LED-mode operation is of crucial importance for realizing robust ten-photon communication [6] because the pump current $\sim$16 nA required to generate ten photons within 100 psec is far below the fundamental lowest threshold current for the onset of lasing [7]. Unfortunately, in such low-current high-frequency regimes, a high source impedance ($\geq$1 MΩ) would be shunted by the vacuum impedance or a large stray capacitance (even when the high impedance is due to space charge effect [8]). Hence the generation of sub-Poissonian photons by pump control in such extreme regimes is very hard to realize unless individual pump events could be regulated by using, for example, Coulomb blockade and quantum confinement effects [9]. The schemes proposed in Ref. [9], however, are not easy to implement in practice because they put stringent upper limits on the device temperature ($<$1 K) and the device size aside from electrodynamic environmental effects such as stray capacitance and cross talks which are haunting single-electron devices.

This Letter proposes a *pump-control-free* scheme for the generation of sub-Poissonian photons, in marked distinction from all schemes reported so far [1–3,5,7–9] that presuppose quiet electrons. The present scheme is based on automodulation of the bimolecule-recombination lifetime due to the quantum-confined Stark effect (QCSE) [10] and recharging effects characteristic of the *constant-voltage* operation of a semiconductor *p*-*i*-*n* junction diode. The proposed scheme allows us to generate sub-Poissonian photons whose number $\sim$10 is smaller than that of electron-hole pairs $\sim$100 in the diode.

The band diagram of our *p*-*i*-*n* junction diode is shown in Fig. 1. The diode is designed in such a way that at 30 K, for instance, a forward-bias voltage supplies an injection current of 16 nA due primarily to tunneling through the potential barriers to maintain high-density stationary electron-hole pairs of 10^{12} cm^{-2} in the quantum well (QW) with area $S = N_0/10^{12} = 10^{-10}$ cm^2 and average recombination lifetime of $\tau_{r0} = 1$ nsec. Here and henceforth, the subscript 0 denotes the average values of physical quantities. The high-density polarized charges in the QW substantially screen the electric field $E_0 \sim$ 150 kV/cm with depolarization field $E_{do} \sim 80$ kV/cm. The doping concentration in the *n*- and *p*-type regions are determined to make the average electron and hole populations equal, $N_0 = P_0 \sim 100$. The radiative recombination rate R is assumed to be bimolecular, i.e., $R = BPN$, where B, P, and N denote the recombination coefficient, hole, and electron populations in the QW, respectively. The free electron-hole pair recombination presupposes the absence of excitonic states which is justified by the lack of electron-hole correlation due to complete screening of the Coulomb potential within the QW plane by the high-density electron-hole plasma [11].

Consider that the tailor-made diode described above is driven by a voltage source, V_0, through an effective series resistance R_s, which is much smaller than the differential input resistance of the diode r_d, as shown in Fig. 2(a). In the constant-voltage operation, it is essential to take into account the dynamics of the external circuit as follows. Carrier transport in the present system occurs via three stochastic processes: (i) The pump event of one electron at $t = t_i$, $\Delta N_{pi} = \theta(t - t_i)$, produces positive and negative excess charges $\pm e$ in the *n*-side depletion layer and in the QW, where $\theta(t - t_i)$ is a unit step function. This

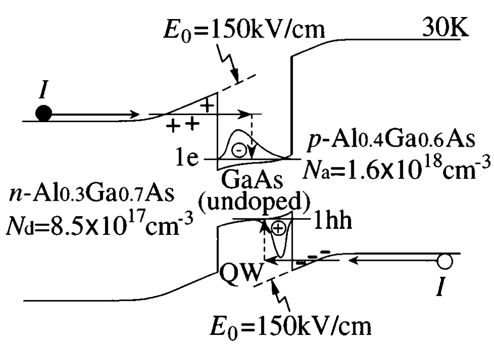

FIG. 1. Energy-band diagram of a semiconductor heterojunction diode.

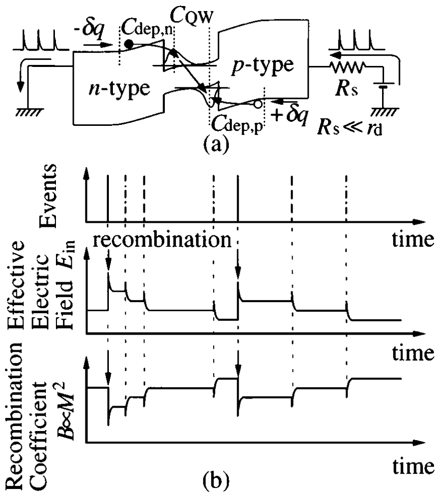

FIG. 2. (a) Diode connected to a voltage source through a very small resistance R_s; (b) schematic drawings of time evolution of recombination (solid lines) and electron-pump (dashed lines) and hole-pump (dash-dotted lines) events, where $E_{\rm in}$ is the effective electric field in the QW, and B the recombination coefficient under the constant-voltage operation.

pump-induced charge dipole increases the electric field mainly in the electron-localized regime of the QW and in the n-side depletion layer, pushing the electron wave function toward the n-side barrier. The pump-induced increase in the charging energy of the junction slightly suppresses subsequent pump events (Coulomb blockade of pump events). Similar dynamics associated with a hole-injection event at $t = t_j$, $\Delta P_{pj} = \theta(t - t_j)$, take place around the p-side barrier. (ii) When a spontaneous photon-emission event occurs at $t = t_k$, one electron-hole pair in the QW disappears, $-\Delta N_{rk} = -\theta(t - t_k)$, and, therefore, the electric field $E_{\rm in}$ around the center of the QW jumps up, as illustrated in Fig. 2(b), because the annihilation of one electron-hole pair leads to a decrease in the internal depolarization field. (iii) The electron- and hole-pump and recombination events induce current spikes in the external circuit which quickly recover the voltage drop across the diode. The diode can be viewed as involving three series capacitors: the capacitance $C_{{\rm dep},n}$ in the n-side depletion layer, the capacitance $C_{{\rm dep},p}$ in the p-side depletion layer, and the effective capacitance $C_{\rm QW}$ due to the polarized electron-hole pairs in the QW, as shown in Fig. 2(a). These capacitors can be designed to be nearly equal, $C_{{\rm dep},n} \sim C_{\rm QW} \sim C_{{\rm dep},p}$ with a real diode structure. Under these conditions, the current induced by electron-pump events is described by

$$i_e(t) = \frac{e}{R_s C_{{\rm dep},n}} \sum_i \exp\{-(t - t_i)/R_s C_t\}\theta(t - t_i), \quad (1)$$

where $1/C_t = 1/C_{{\rm dep},n} + 1/C_{\rm QW} + 1/C_{{\rm dep},p}$. Similar expressions for currents, $i_h(t)$ and $i_r(t)$, are given for hole-pump and recombination events, if we replace $C_{{\rm dep},n}$ in Eq. (1) by $C_{{\rm dep},p}$ and $C_{\rm QW}$, and t_i by t_j and t_k, respectively. Note that electric charge carried by the individual current spike, for instance, $(e/R_s C_{{\rm dep},n}) \exp\{-(t - t_i)/R_s C_t\}\theta(t - t_i)$ is a *fraction of the elementary charge*, i.e., $\delta q_e = (C_t/C_{{\rm dep},n})e$, $\delta q_h = (C_t/C_{{\rm dep},p})e$, or $\delta q_r = (C_t/C_{\rm QW})e < e$. The fractional charge transfer is caused by extremely small displacement of carriers as a whole and therefore has a physical entity. The fractional charges, $\pm\delta q_e$, $\pm\delta q_h$, and $\pm\delta q_r$, which are supplied to the outside edges of the p- and n-side barriers, cancel the charges due to the ionized impurities as shown in Fig. 2(a), and each charge transfer decreases the internal electric field $E_{\rm in}$. Hence, the field $E_{\rm in}$ is increased by pump and recombination events, while it is decreased by fractional charge transfer, as illustrated in Fig. 2(b). The field increase (or decrease) results in a decrease (or an increase) in the recombination coefficient through changes in the overlap integral between the electron and hole wave functions inside the QW ($B \propto M^2 = |\langle \phi_{1e} | \phi_{1hh} \rangle|^2$) [10] as shown in Fig. 2(b).

The recombination rate is given by $R(t) = B(t)P(t) \times N(t)$, where $N(t) = N_0 + \sum_i \Delta N_{pi}(t) - \sum_k \Delta N_{rk}(t)$, $P(t) = P_0 + \sum_j \Delta P_{pj}(t) - \sum_k \Delta N_{rk}(t)$, and

$$B(t) = B_0\Bigg(1 - c_e K_B \frac{\sum_i \Delta N_{pi}(t)}{N_0} - c_h K_B \frac{\sum_j \Delta P_{pj}(t)}{N_0} - c_r K_B \frac{\sum_k \Delta N_{rk}(t)}{N_0} + K_B \frac{\int^t [I(t')/e]\, dt'}{N_0}\Bigg), \quad (2)$$

where $I(t') = i_e(t') + i_h(t') + i_r(t')$. In Eq. (2), K_B represents the linearized response of the B coefficient to external fields in the n- and p-side barriers, $E_{{\rm ext},n}$ and $E_{{\rm ext},p}$ for the fixed carrier population, $P_0 = N_0$ and is given by $K_B = -\{(eN_0/\epsilon S)/B_0\}\{\partial B/\partial E_{{\rm ext},n} + \partial B/\partial E_{{\rm ext},p}\}$. The coefficients c_e, c_h, and c_r are all positive and given by $c_e = -\{(eN_0/\epsilon S)/B_0\}\{\partial B/\partial E_{{\rm ext},n} + (\epsilon S/e)\partial B/\partial N\}/K_B$, $c_h = -\{(eN_0/\epsilon S)/B_0\} \times \{\partial B/\partial E_{{\rm ext},p} + (\epsilon S/e)\partial B/\partial P\}/K_B$, and $c_r = (N_0/B_0) \times \{\partial B/\partial P + \partial B/\partial N\}/K_B$. Obviously, they satisfy $c_e + c_h + c_r = (\delta q_e + \delta q_h + \delta q_r)/e = 1$ which means that the reduction of the B coefficient induced by one electron- and hole-pump event and recombination event is completely compensated for by associated rechargings, δq_e, δq_h, and δq_r. The electron pump rate is described by [5]

$$R_{{\rm pump},e} = R_{p0} \exp\Bigg[- r_e \sum_i \Delta N_{pi}(t) + r_e \int^t [I(t')/e]\, dt'\Bigg]. \quad (3)$$

The pump rate is characterized by the relaxation time constant of the n-side junction τ_{te} or the inverse cutoff frequency for Coulomb blockade Ω_{ce}^{-1}, i.e., $\tau_{te} = 1/\Omega_{ce} = e/r_e I_0 = \tau_{r0}/r_e N_0$ where τ_{r0} is the average recombination lifetime, $\tau_{r0} = 1/B_0 N_0$. Also, r_e is given by $r_e = (8/3)e\sqrt{m_e^* \epsilon/N_d}/\hbar C_{\mathrm{dep},n}$, for a triangular potential barrier at low temperature (i.e., $k_B T \ll$ Fermi energy of electrons in the n-type region) [12], where m_e^* and N_d denote the electron effective mass and doping density in the n-type barrier layer. The hole pump rate is described by a similar expression characterized by r_h, namely, Ω_{ch}^{-1}. From Eq. (2), the reduction, $\Delta B = -B_0 c_r K_B/N_0$, in the B coefficient induced by an emission event is not completely recovered by the emission-induced charge transfer δq_r, $\Delta B = -(B_0/N_0)K_B(c_r - C_t/C_{\mathrm{QW}})$ if $c_r > C_t/C_{\mathrm{QW}} \sim 1/3$. The reduction in B is expected to suppress subsequent emission events until the recovery of the B coefficient is accomplished by the subsequent pump-induced charge transfers, δq_e and δq_h, as shown in Fig. 2(b) [recall $c_e + c_h + c_r = (\delta q_e + \delta q_h + \delta q_r)/e = 1$]. The regulation mechanism based on automodulation of the bimolecule-recombination coefficient through QCSE by the emission and pump events and step-wise recharging processes is the heart of the present scheme, which we wish to call *QCSE blockade of photon emissions*. On the other hand, the reduction of electron-pump rate induced by one electron-pump event, for instance, $\Delta N_{pi}(t) = 1$ in Eq. (3), is not completely recovered by the pump-induced fractional charge transfer, $\delta q_e < e$. Similar dynamics associated with a hole-pump event and fractional charge transfer $\delta q_h < e$ take place on the hole-pump rate. Therefore, the Coulomb blockade of pump events, also, survives in the constant-voltage operation of the tailor-made diode.

Let us examine the linearized fluctuation of the recombination rate to discuss more quantitatively the present regulation mechanism,

$$\Delta R = B_0 N_0 \Bigg[\Bigg(\sum_i \Delta N_{pi}(t) + \sum_j \Delta P_{pj}(t) - 2 \sum_k \Delta N_{rk}(t) \Bigg) + K_B \Bigg(\int^t [I(t')/e]\, dt' - c_e \sum_i \Delta N_{pi}(t) - c_h \sum_j \Delta P_{pj}(t) - c_r \sum_k \Delta N_{rk}(t) \Bigg) \Bigg]. \quad (4)$$

In Eq. (4), the sum of the three terms inside the first set of parentheses represents the usual self-feedback mechanism. The sum of the four terms inside the second set of parentheses represents the new regulation mechanism proposed in the present work. The pump events themselves suppress the recombination rate in the present scheme, unlike the usual mechanism. The recombination rate can be recovered by the external recharging current consisting of the event-induced current spikes ($\int [I(t')/e]\, dt' = \int \{[i_e(t') + i_h(t') + i_r(t')]/e\}\, dt'$). In this respect, the present scheme is essentially different from a previously proposed one [7] in which pump events directly recover the recombination rate and external charging processes do not affect the recombination rate at all and, as a result, pump regulation is still required for the regulation of emission events. In particular, when K_B is much larger than unity, the present mechanism dominates the ΔR and, in other words, the fluctuation of the B coefficient dominates ΔR. Therefore in such a case, $K_B \gg 1$, the QCSE blockade mentioned above effectively regulates emission events.

We are interested in the relatively large number of average electron-hole pairs, for instance, $N_0 = P_0 \sim 100$, to be free from the disadvantages of single-electron effects. Hence quantum charge fluctuations on the junctions can safely be disregarded for almost any values of source resistance R_s and tunneling resistance R_t in the barriers (~ 1 MΩ in the present case), as $R_s, R_t \gg (h/2\pi e^2)/(N_0 + 1/2) \sim 40\ \Omega$. Electrons (holes) injected into the QW are thermally equilibrated within a short time ~ 1 psec in the conduction (valence) band [11]. Therefore we can study the junction dynamics using a Monte Carlo method that stochastically simulates pump and radiative recombination processes [9]. Monte Carlo simulations can be performed by the use of Eq. (2) for $R = BPN$, Eq. (3), and the corresponding expression for hole pump rate. The coefficients relevant to the QCSE blockade are determined to be $K_B = 5$, $c_r \sim 2/3$, and $c_e \sim c_h \sim 1/6$ by self-consistently solving the Schrödinger and Poisson equations for a QW structure with thickness of 180 Å and high density of electron-hole pairs, 10^{12} cm^{-2} in the presence of an external electric field of 150 kV/cm at a temperature less than or equal to 30 K. The values for the coefficients sensitively depend on the potential profile in the QW. For instance, a larger K_B (~ 10) would be possible by properly designing the potential profile [7]. The Ω_{ce} and Ω_{ch} can be designed to be $\Omega_{ce}\tau_{r0} \sim \Omega_{ch}\tau_{r0} \equiv \Omega_c \tau_{r0} \geq 10$ with a real diode at $T \leq 30$ K.

Figure 3 shows the results of Monte Carlo simulations for noise power spectra of photon flux, those of single (electron or hole) pump events, and those of total (sum of electron and hole) pump events under constant-voltage operation ($R_s = R_t/100$). Consider first the case of no QCSE blockade ($K_B = 0$). Both single pump events and photon-emission events show 3 dB noise reduction at low frequencies because the diode forms a double barrier structure and each barrier serves as a high-impedance resistance for the other barrier. The noise reduction therefore occurs as a result of macroscopic Coulomb blockade for pump events. However, the noise reduction is effective only when a large number of photons are involved (or, equivalently, at the low-frequency regime, $\Omega \tau_{r0} < 1$). At higher frequencies, photon-emission events show noise greater than that of single pump events because of the stochastic nature of each photon emission. Only at the limit of low frequencies the noise spectra of photons and electrons (or holes) coincide as they should do in view of the conservation of the particle number.

The fact that the total pump noise for $K_B = 0$ is at the standard quantum limit (SQL) level indicates that an almost perfect correlation exists between electron-pump and hole-pump events. In fact, under constant-voltage operation an electron (or hole) pump event is most likely to be followed by a hole (or electron) pump event. The noise power spectrum of the total pump events should always be at the SQL level.

Consider next the effects of the QCSE blockade (i.e., $K_B \neq 0$). The noise power of single pump events decreases with increasing the values of K_B because for $K_B \neq 0$ electrons and holes in the QW polarize and effectively form a capacitor. Thus besides two tunnel barriers the diode forms an additional dynamical capacitor as schematically illustrated in Fig. 2(a). Consequently, further noise reduction occurs compared with the case of only two tunnel barriers (i.e., $K_B = 0$). Another important consequence of the QCSE blockade is that the noise power spectra of photon-emission events almost coincide with those of single pump events over a wider spectral range, implying that the QCSE blockade makes *both electrons and photons quiet.* In general, the frequency range in which the noise level of the photon emission events coincides with that of the single pump events extends from $\Omega\tau_{r0} < 1$ to $\Omega\tau_{r0} < 1 + K_B$ in virtue of the QCSE blockade. Thus, for $K_B = 10$, 1.2 dB noise suppression can be achieved even for only ten photons in a time interval $\tau_{r0}/(1 + K_B) \simeq 100$ psec, despite that a much greater number of electrons and holes $\sim$100 are involved in the QW. Were it not for the QCSE blockade, we could not expect noise suppression of photons whose number is less than 100. Even the regulation of individual photon emission would be possible if we reduce carrier populations to $P_0 = N_0 = 10$ by using a QW with smaller area $S = 10^{-11}$ cm^2 and with $K_B = 10$.

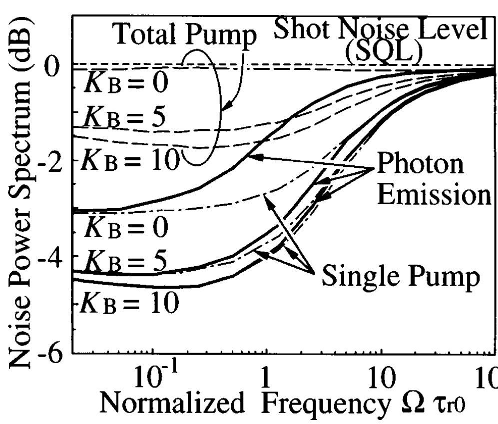

FIG. 3. Noise power spectra of photon fluxes and total (sum of electron and hole) and single (electron or hole) pump events in diodes driven by constant-voltage sources ($R_s = R_t/100$) for $K_B = 0$, 5, and 10. For $K_B = 0$, the capacitors are assumed to be $C_{\mathrm{dep},n} = C_{\mathrm{dep},p}$ and $C_{\mathrm{QW}} = \infty$, which means the absence of polarization of electron and hole wave functions in the QW. For $K_B = 5$ and 10, the three capacitors are reasonably assumed to be equal, $C_{\mathrm{dep},n} = C_{\mathrm{dep},p} = C_{\mathrm{QW}}$. The remaining parameters are commonly taken to be $P_0 = N_0 = 100$, $\Omega_{ce}\tau_{r0} = \Omega_{ch}\tau_{r0} \equiv \Omega_c\tau_{r0}(= r_eN_0 = r_hN_0) = 10, c_r = 2/3$, and $c_e = c_h = 1/6$ for all values of K_B.

If a constant-current source ($R_s \gg R_t$) is available, we can achieve further reduction in photon noise for each value of K_B. We have confirmed this by Monte Carlo simulations, although the feasibility of the constant-current operation in a low-current ($I = 16$ nA), high-frequency ($\Omega \geq 10$ GHz) regime is highly questionable.

To summarize, the scheme proposed in this Letter opens a door toward mutual quantum manipulation of electrons and photons in the generation of sub-Poissonian photons from semiconductor diodes. By Monte Carlo simulations we have demonstrated that the QCSE blockade makes both electrons and photons quiet for a constant-voltage operation without the help of presupposed pump regulation. These findings, in our opinions, merit further experimental and theoretical study.

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