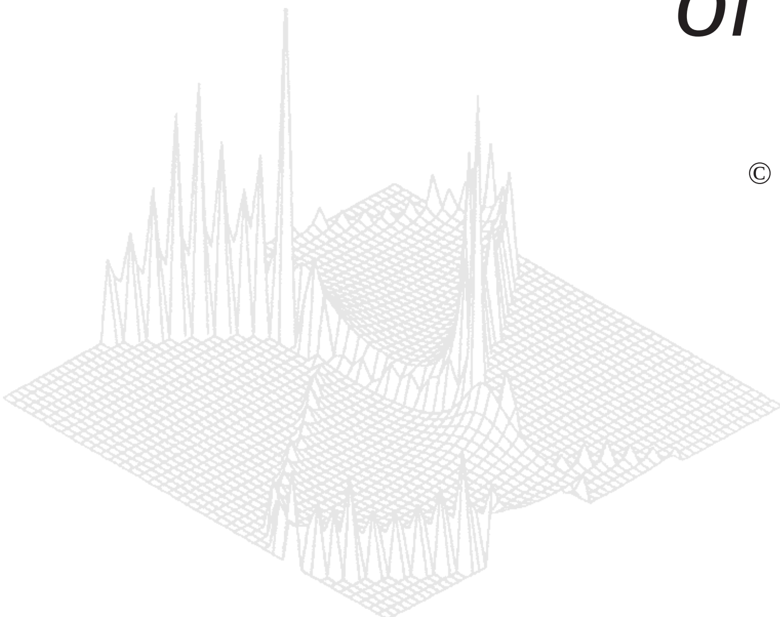
CSIRO PUBLISHING

Australian Journal of Physics

Volume 53, 2000



A journal for the publication of
original research in all branches of physics

www.publish.csiro.au/journals/ajp

All enquiries and manuscripts should be directed to
Australian Journal of Physics
CSIRO PUBLISHING
PO Box 1139 (150 Oxford St)
Collingwood
Vic. 3066
Australia

Telephone: 61 3 9662 7626
Facsimile: 61 3 9662 7611
Email: peter.robertson@publish.csiro.au

Published by **CSIRO** PUBLISHING
for CSIRO Australia and
the Australian Academy of Science

CSIRO AUSTRALIA

Academy of Science

Aust. J. Phys., 2000, **53**, 179–92

Sub-Poissonian Electronic and Photonic Noise Generation in Semiconductor Junctions*

Paul J. Edwards

Centre for Advanced Telecommunications and Quantum Electronics Research,
University of Canberra, Canberra, ACT 2601, Australia.

Abstract

This paper addresses sub-Poissonian electronic and photonic noise generation in semiconductor junctions. Recent theoretical and technical advances in the understanding and generation of quantum noise-suppressed ('quiet') light have emphasised the links between photonic and electronic shot noise. Shot-noise suppression and single electron–photon control through the operation of the collective and single-electron Coulomb blockade mechanisms are described.

1. Introduction

As new fabrication technologies are developed to provide the increased switching speed, bandwidth and information packing density required of integrated electronic circuitry, the quantum effects associated with the quantisation of electronic charge and energy have become increasingly apparent. One of the consequences of this is the occurrence of 'granularity noise' (shot noise) in optical interconnects and mesoscopic electronic circuits.

Over the last decade, the quantum (non-classical) properties of light beams have been closely investigated and photonic noise suppression techniques with potential applications in metrology, communications and computing have been developed. Similar attention is now being paid to electronic 'quantum shot noise' and its minimisation in mesoscale and nanoscale circuits. It has now become apparent that close similarities exist between photonic shot noise, ballistic electron shot noise and diffusive electron shot noise, particularly when these three phenomena are viewed as the outcomes of stochastic point processes.

The so-called 'collective Coulomb blockade' effect (Imamoglu and Yamamoto 1994) has been utilised to suppress optical shot noise fluctuations in the light emitted by macroscopic semiconductor junctions (Yamamoto and Machida 1987; Yamamoto *et al*. 1993; Tapster *et al*. 1987; Edwards 1990, 1991; Edwards and Pollard 1932; Kim and Yamamoto 1997). Such quantum noise-suppressed devices have obvious application in those optical measurement, communications and computing systems where performance is limited by photonic shot noise.

Macroscopic Coulomb space charge suppression of electronic shot noise was an essential feature of the low noise vacuum electronic devices belonging to

* Refereed paper based on a talk presented to the Workshop on Nanostructures and Quantum Confinements, held at the Australian National University, Canberra, in December 1998.

 10.1071/PH99074 0004-9506/00/010179$05.00

an earlier era (Schottky 1918). It is not generally recognised that macroscopic space charge smoothing of electronic shot noise is also an essential feature of low noise semiconductor junction diodes and transistors (Edwards *et al*. 1999), as well as of sub-Poissonian laser and light-emitting diodes (Yamamoto *et al*. 1987). New mesoscopic and reduced dimension semiconductor devices such as the high electron mobility transistor, resonant tunnelling diode and single electron transistor, employ both classical (Coulomb) and quantum (Pauli) effects to suppress electronic transport noise (Milburn and Sun 1998).

Nanoscale devices such as 'electron–photon turnstiles' have also been envisaged (Imamoglu and Yamamoto 1994) and partially realised (Kim *et al*. 1999). In these the single particle Coulomb blockade effect (Averin and Likharev 1986) potentially enables the manipulation and control of individual photons and electrons with applications in the efficient transfer and processing of information.

In what follows we present a simple semiclassical discussion of the electronic and photonic shot noise generated in semiconductor junctions. The processes of charge injection, transport, storage and recombination are represented in Fig. 1*a* for a semiconductor diode and in Fig. 1*b* for a light-emitting junction diode with the additional process of radiative recombination. Radiative recombination provides a means of directly probing the recombination process in semiconductor junctions.

This paper is organised in five sections. Section 2 introduces electronic shot noise in the form of thermionic shot noise and its suppression by Coulomb interactions. Electronic noise in ideal macroscopic semiconductor junctions is discussed in Section 3. Partition noise and the second order counting statistics of electronic and photonic streams are discussed in Section 4. Section 5 examines photonic noise from semiconductor junctions, stochastic charge injection, the collective and single electron Coulomb blockade effects and concludes with a discussion of heralded photon states in mesoscopic junctions.

2. Electronic Shot Noise

(2a) Thermionic Emission

Shot noise, the random fluctuation in electric current arising from the discrete character of electronic charge, the 'Schroteffekt', was first identified (Schottky 1918) in the thermionic current flowing in a temperature-limited vacuum thermionic diode. Electrons are, in the main, emitted randomly and independently from heated metallic cathodes and thermionic emission therefore constitutes a naturally occurring Poisson point process (Teich and Saleh 1988). Providing this description also adequately describes the charge collection process, the resulting thermionic current fluctuations will have the Markovian correlation function,

$$\langle i(t)i(t')\rangle = 2Ie\delta(t-t')\,, \tag{1}$$

and will show the full single-sided shot noise current spectral density, the Fourier transform of the correlation function, $S_i(\omega) = 2I\,e$, associated with the transport of a mean current I of independent particles, each of charge e. In general, however, the emission, transport and charge collection processes will lead to a non-zero correlation function for $|(t-t')| > 0$ and will consequently modify the white noise spectrum of this idealised process. Non-zero charge collection time will reduce the spectral density at high frequencies so that the spectrum must be written more generally to take these effects into account.

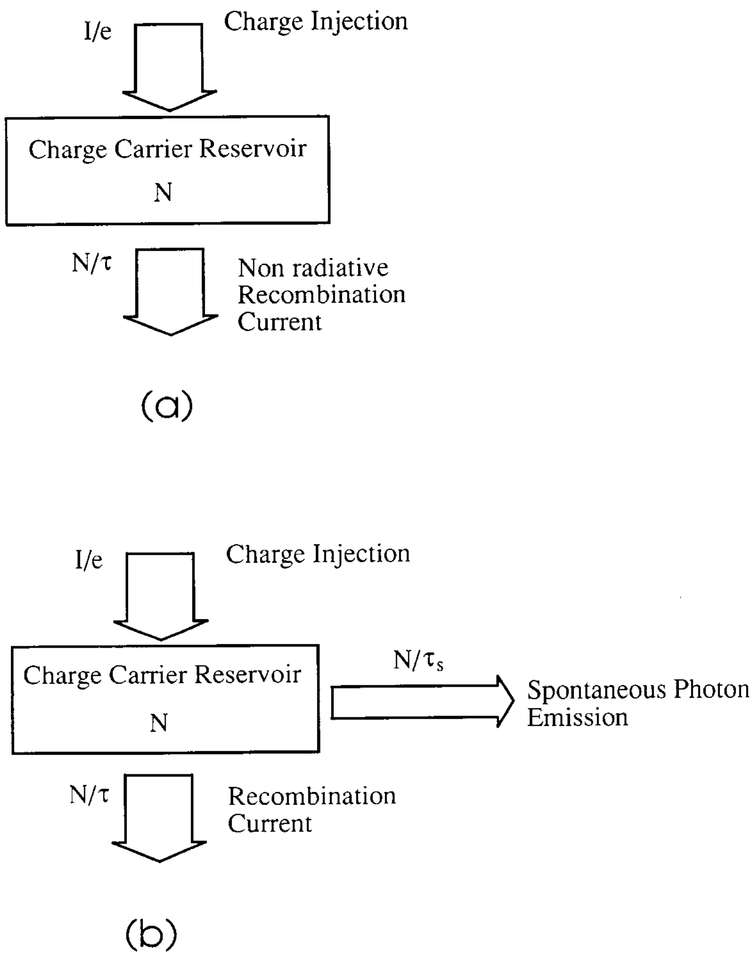


Fig. 1. Simplified models of (*a*) an ideal semiconductor junction diode showing minority charge injection, storage and subsequent recombination; (*b*) an ideal light-emitting diode showing the additional process of radiative recombination and spontaneous photon emission.

In these cases the spectral density will be reduced below the full shot noise level and the Fourier transformed autocorrelation function $\langle i(t)i(t')\rangle$, the current spectral density $S_i(\omega)$, will contain a frequency dependent Fano factor $F_i(\omega) \leq 1$, and thus,

$$S_i(\omega) = 2F_i(\omega)Ie. \tag{2}$$

Here $F_i(\omega)$ is readily measurable as the frequency dependent ratio of the spectral density of the current noise to the spectral density of the full shot noise current fluctuation.

On the other hand, the related time-domain Fano factor $F_n(\tau)$ expresses the total number counting (integrated current) variance relative to the Poissonian (full shot noise) value. It is formally defined as the variance ${\sigma_n}^2$ of the number count $n(\tau)$ in time interval τ, normalised to the Poissonian variance $\langle n(\tau)\rangle$ where

$$F_n(\tau) = \sigma_n^2(\tau)/\langle n(\tau)\rangle = [\langle n^2(\tau) - n(\tau)\rangle^2]/\langle n(\tau)\rangle\,. \tag{3}$$

Thermionically generated shot noise tends to be super-Poissonian ($F_\omega > 1$) at low frequencies, due to positively correlated emission variations on long time scales, and sub-Poissonian at higher frequencies, due to the combined effects of space charge smoothing and finite charge collection time. Similar comments apply to thermionic emission at Schottky junctions and heterostructure junctions (Imamoglu and Yamamoto 1993; Kim and Yamamoto 1997; Kobayashi *et al.* 1999).

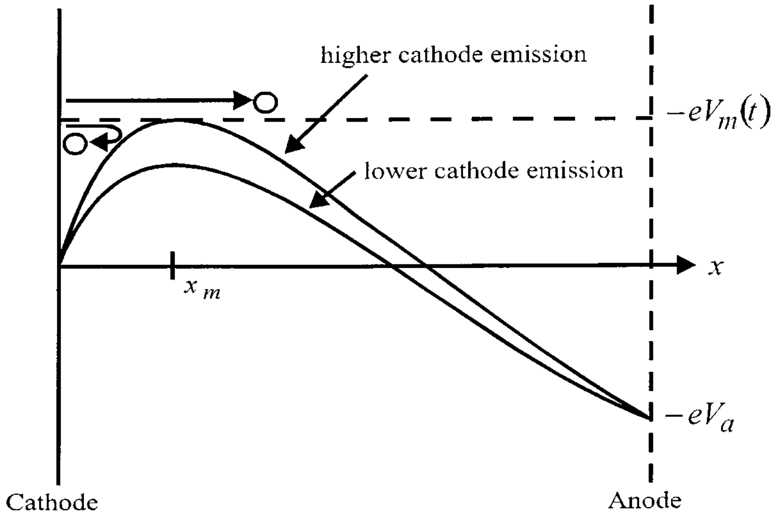


Fig. 2. Representation of space charge smoothing of thermionic vacuum electron emission: a model for the macroscopic Coulomb blockade in semiconductor junctions.

(2b) Space Charge Suppression of Shot Noise

Space charge smoothing (Rack 1938) in thermionic diodes operated in the space charge-limited regime introduces anti-correlated density fluctuations into the electron stream. Fig. 2 illustrates this concept of shot noise suppression by a fluctuating potential barrier. The height of the barrier fluctuates with the electronic space charge population which itself fluctuates in response to random variations in thermionic emission. Low frequency shot noise suppression by Coulomb-moderated negative feedback mechanisms of this type are a common feature of classical and quantum electronic systems and devices.

The space charge-limited thermionic diode provides a conceptual model for photonic shot noise suppression in macroscopic systems (Teich and Saleh 1985;

Yamamoto and Machida 1987) and in mesoscopic systems involving the ballistic transport of electrons where Pauli exclusion provides an additional noise suppression mechanism (Lesovik 1989; Buttiker 1990). Space charge-limited thermionic noise has a thermal character, reflecting its thermal origin, with Fano factor derived in the classical limit as (Teich *et al*. 1987)

$$F_n(\omega) = 8kT/eV\,, \tag{4}$$

for cathode temperature T and applied voltage V ($\gg kT/e$). A similar result applies to the external noise current in a semiconductor junction diode operated under constant current conditions. More recent discussions of shot noise suppression (e.g. Blanter and Buttiker 1999) show how shot noise suppression can be explicitly accounted for in terms of electron–electron interactions.

We shall illustrate shot noise suppression for diffusive transport associated with semiconductor junctions and discuss the transition from collective Coulomb interactions in macroscopic junctions to single electron 'Coulomb blockade' in low capacitance mesoscopic junctions.

3. Macroscopic Semiconductor Junction Noise

The first theoretical treatment of shot noise generated in semiconductor junctions was given by van der Ziel (1955, 1957), who initially attributed it to the random transport of charge carriers across the depletion layer. The results of van der Ziel's analysis were confirmed for both diodes and transistors with the measurement of the full shot noise level for diodes operated with a fixed potential difference. However, the physical basis of the analysis was challenged by Buckingham and Faulkner (1974) and Buckingham (1983) who attributed the shot noise to two independent mechanisms operating in the neutral (bulk) regions of the structure: thermal fluctuations in minority charge carrier diffusion and fluctuations in the rates of generation and recombination. Their model, unlike the van der Ziel model, is consistent with the generally accepted diffusion model of charge carrier transport in a forward biased junction.

This diffusion model was adopted by Yamamoto and Machida (1987) to describe the generation of sub-Poissonian light by semiconductor diode lasers and by Edwards (1993) to describe the generation of sub-Poissonian light in light-emitting diodes. These authors also drew attention to a long-standing confusion in the literature which had led to the erroneous conclusion that the electron–hole recombination noise in a semiconductor junction is characterised by full shot noise, contrary to their observations of suppressed photonic shot noise in the light generated by laser and light-emitting diodes when driven from high impedance constant current sources (Machida *et al*. 1987; Machida and Yamamoto 1988; Tapster *et al*. 1987; Edwards 1990).

The charge carrier number present in the vicinity of a semiconductor junction, $N(t) = N + n(t)$, is determined by the processes of charge injection, diffusion, and recombination which are taken into account in the following rate equation:

$$\delta N(t)/\delta t = I(t)/e - N(t)/\tau + f_n(t)\,. \tag{5}$$

In the first term on the right-hand side $I(t) = I+i(t)$ represents the current supplied from an external circuit. It is taken to equal the net (fluctuating) rate at which charge is injected across the space charge layer at the junction into the 'active' (recombination) region. The second term, in which τ is the mean lifetime of the diffusing carriers, comprises the mean recombination rate N/τ plus a fluctuating term $n(t)/\tau$. This latter represents the response of the reservoir population, $N(t)$, and hence of the (population number-dependent) recombination rate to external 'pump' noise, $i(t)/e$, and to the stochastic charge recombination process itself as represented by the third term, the Langevin noise term $f_n(t)$. The second and third terms together then represent the fluctuating recombination rate: a population-dependent time varying rate plus an intrinsic stochastic (Poissonian) fluctuation.

Linearisation of equation (5) yields

$$\delta n(t)/\delta t = i(t)/e - n(t)/\tau + f_n(t)\,. \tag{6}$$

If the stored electron population N is fixed, for example, by pinning the junction voltage, then $\delta n(t)/\delta t = n(t) = 0$ and the charge carriers will recombine randomly with mean lifetime τ. This constitutes a Poisson point process with correlation function $\langle f_n(t)f_n(t')\rangle = 2N\delta(t-t')/\tau$, rate N/τ, mean square value $\langle f_n^2\rangle = (N/\tau)\Delta f$, and double-sided spectral density equal to the mean recombination rate N/τ. From equation (6) the recombination current noise and the current noise in the external circuit, $i_{sn}(t) = -\ e\, f_n(t)$, are both at the full shot noise level. The single-sided mean square shot noise current spectral density is then, as expected,

$$S_i(\omega) = 2\langle f_i^2\rangle/\Delta f = 2e^2\langle f_n^2\rangle/\Delta f = 2Ie\,. \tag{7}$$

If $N(t)$ is allowed to freely fluctuate and in addition the injection current noise is suppressed, then $i(t)= 0$, and so $\delta n(t)/\delta t = -\ n(t)/\tau + f_n(t)$. Taking Laplace transforms, the recombination current noise spectrum in this case becomes

$$S_i(\omega) = 2\omega^2\tau^2\langle f_i^2\rangle/\Delta f(1+\omega^2\tau^2) = 2Ie\omega^2\tau^2/(1+\omega^2\tau^2)\,, \tag{8}$$

and has the character of single pole high-pass filtered shot noise and vanishes in the low frequency limit of $\omega\tau \ll 1$. This illustrates low frequency shot noise suppression according to the 'leaky reservoir' model (Edwards 1993). In passing we note that the electron reservoir number fluctuation spectrum has a complementary low pass character with a total mean square fluctuation of $\langle N\rangle/2$, just one-half the Poissonian value.

Writing equation (6) in the form of a state equation using the fluctuations in the junction potential $\eta_{jn}(t)$, the injected current $i(t)$, and the charge $q(t)$ stored in the so-called 'diffusion capacitance' C as state variables, gives (Edwards 1993)

$$C\delta\nu_{jn}/\delta t = i(t) - \nu_{jn}(t)/r - i_{sn}(t)\,, \tag{9}$$

and thus

$$\delta q/\delta t = i(t) - q(t)/rC - i_{sn}(t)\,. \tag{10}$$

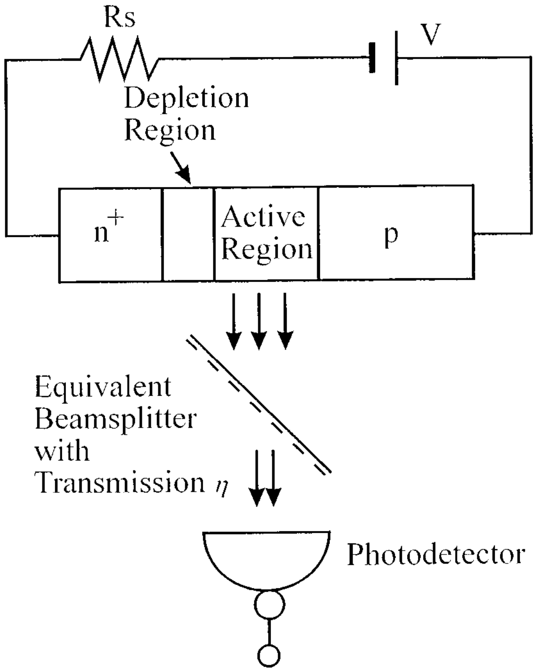


Fig. 3. Representation of the optical measurement of the recombination fluctuations in a semiconductor light-emitting junction. Non-ideal detection (η <1) is represented by a notional optical beam-splitter with transmission η.

Referring to the corresponding noise equivalent circuit of Fig. 3, in which the stored charge fluctuation $q(t) = n(t)e = Cv_{jn}(t)$ shows that in this model the junction voltage fluctuation is a direct measure of the carrier number fluctuation $n(t)$. Thus, shot noise suppression at frequencies $\omega \ll 1/\tau = 1/rC$ is evidently achieved by making the external impedance R_s much greater than r, the internal differential resistance of the junction, so that $i(t) = [\nu_s(t) - \nu_{jn}(t)]/R_s$ vanishes in that limit. The voltage source ν_s(t) in Fig. 3 represents the thermal Nyquist noise voltage associated with resistance R_s. Then the mean square injected noise current $\langle i(t)^2\rangle$ can be reduced to negligible proportions by raising the value of the resistance R_s. Noiseless charge injection into the reservoir is thus assumed for a high impedance current source. A detailed physical analysis of this noiseless injection process has been recently given (Kim and Yamamoto 1997) and refined by Kobayashi *et al.* (1999) in connection with a generalised theory of photon noise suppression in both macroscopic and mesoscopic junctions. In more detailed microscopic treatments (Buckingham and Faulkner 1974; Kim and Yamamoto 1997; Kobayashi *et al.* 1999) this current can be written to explicitly contain two stochastic Langevin terms representing forward and backward charge carrier injection noise.

The junction diode diffusion noise model above adequately describes electronic noise generation in macroscopic circuits and devices. It has also been used as the conceptual basis for models of sub-Poissonian light generation in light-emitting diodes (Edwards 1993) and diode lasers (Yamamoto and Machida 1987). These account for many of the measured characteristics of macroscopic optoelectronic devices.

4. Partition Noise

The term ‘bunching’ is used in semi-classical quantum optics (Teich and Saleh 1988) to describe departures from a Poissonian photon stream having uncorrelated density fluctuations. Reduced (sub-shot noise) photo-current fluctuations, generally at low frequencies, are associated with ‘anti-bunching’, formally defined in terms of anti-correlated photo-current fluctuations in the two components of a split light beam.

If a stream of countable particles (electrons or non-interfering photons) is subject to Bernoulli partition and randomly partitioned into two beams of equal intensity, I_1 and I_2, the normalised intensity correlation (Loudon 1980; Oliver *et al.* 1999) between the two beams is

$$\begin{aligned} G_{11}^{(2)}(0) &= \langle I_1(t) I_2(t)\rangle / \langle I_1\rangle^2 \\ &= \langle n(n-1)\rangle / \langle n\rangle^2 = 1 + (F_n - 1)/\langle n\rangle \,, \end{aligned} \tag{11}$$

where the currents $I(t) = en(t)/\Delta t$; $\langle I_1\rangle = \langle I_2\rangle = \langle I\rangle/2$ and $\langle n\rangle = \langle I\rangle \Delta t/e$. This function evidently deviates significantly from unity only in the limit of low mean count $\langle n\rangle$, that is, for weak currents and short integration times Δt. It is therefore a useful parameter in cases where small controlled numbers of electrons or photons are required. In the macroscopic case it is more useful to rewrite the covariance

$$\langle i_1(t) i_2(t)\rangle = [G_{11}^{(2)}(0) - 1]\langle I_1\rangle^2 = \tfrac{1}{4}[\langle i^2(t)\rangle - \langle i_{sn}^2\rangle] \,, \tag{12}$$

as a correlation coefficient

$$\begin{aligned} R_{12} &= \langle i_1(t) i_2(t)\rangle / [\langle i_1^2(t)\rangle \langle i_2^2(t)\rangle]^{1/2} \\ &= (\langle i^2(t)\rangle - \langle i_p^2\rangle) / [\langle i^2(t)\rangle + \langle i_p^2\rangle] \,, \end{aligned} \tag{13}$$

and to express this as a conventional (frequency dependent) correlation coefficient relating the fluctuations in the partitioned streams

$$R_{12}(\omega) = [F_n(\omega) - 1](1-T)/[T F_n(\omega) + (1-T)] \,. \tag{14}$$

The denominator in equation (14) expresses the shot noise as the sum of two independent variance terms, a transmitted noise term and an additional partition noise term. For transmission probabilities T and $(1 - T)$, the ‘partition noise’ (van der Ziel 1970) introduced into particle streams has binomial statistics with variance given by

$$\langle n^2\rangle - \langle n\rangle^2 = T(1-T)\langle n\rangle \quad \text{and} \quad \langle i_p^2\rangle = T(1-T)\langle i_{sn}^2\rangle \,. \tag{15}$$

From above, the spectral density of the total noise following random loss of particles from the beam can then be written in terms of the transmission factor T, and input and output Fano factors F_i and F_o, as

$$F_o = TF_i + (1 - T)\,. \tag{16}$$

This equation which also follows from the cascade variance formula (Burgess 1959) is well known in the quantum optics and mesoscopic literature (Teich 1988; Shimizu and Sakaki 1991). Conceptually, it illustrates the binomial statistics which arise from the operation of independent Bernoulli selection with fixed probability T. It can be generalised (Lesovik 1989; Buttiker 1990) to describe the additive partition noise generated in multiple channel mesoscopic systems. Historically, it describes the shot noise in the anode current of a multielectrode space charge-limited thermionic vacuum device (van der Ziel 1970). The thermionic current fluctuations are initially suppressed below the full shot noise level, typically to $F_i < 0{\cdot}05$, by the fluctuating space charge barrier (Fig. 2) between cathode and anode and then raised by the additional noise introduced by current partition as given by equation (16). Here T is the conditional probability of an electron being counted, given its emission at the source of the particle stream.

Partition noise is present in bipolar junction transistors, as 'quantum shot noise' in mesoscopic electron transport and as 'quantum vacuum fluctuations' in lossy photonic systems.

5. Photonic Shot Noise

Measurement of the photonic shot noise in the light emitted from a semiconductor junction is represented in Fig. 3. As mentioned in Section 2, photonic noise measurements provide a direct probe of the intrinsic fluctuations in the radiative recombination rate. These are characterised by the Fano factor F_i in Fig. 3 and equation (16) with $T = \eta$, the overall quantum transfer efficiency between radiative recombination events in the junction and their subsequent photodetection.

The partition noise is a consequence of the lack of a one to one correspondence between the individual recombination events in the junction and their subsequent photodetection in the form of electron–hole pairs generated at the detector. Providing these photon deletion losses are statistically independent Bernoulli events, they can be treated like those arising at an optical beam splitter with overall transmission probability η, as in Fig. 3.

Fig. 4 shows the equivalent circuit of an ideal light emitting diode coupled with quantum efficiency η to a photon detector as in Fig. 3. A fraction η of the recombination current appears at the detector. It therefore becomes possible in principle to measure externally the radiative recombination current in a light-emitting diode and to check the validity of the diode circuit noise model previously discussed.

When the recombination noise is completely suppressed ($F_i = 0$), the detector noise relative to the expected shot noise level is evidently $F_o = (1-\eta)$. This is an expression of the extreme fragility of sub-Poissonian 'quiet' light to attenuation of the light beam and reveals why it cannot provide any significant advantages in metrology or communications in the presence of even moderate losses.

(*5a*) *Sub-Poissonian Photonic Noise*

Fluctuations in photoelectron emission from a photocathode illuminated by a steady light source were for many years regarded as conceptually similar to thermionic emission fluctuations, being assumed to show the full shot noise due to Poissonian statistics. The direct detection of sub-Poissonian light from semiconductor lasers (Yamamoto and Machida 1987) and light-emitting diodes (Tapster *et al.* 1987; Edwards 1990) has emphasised the similarities between photonic and electronic shot noise processes. These processes have a common description when viewed as stochastic point processes (Teich and Saleh 1988). For example, Edwards *et al.* (1999) noted that the equation describing the transfer of quantum noise between a photon emitter and photo-detector is identical with that describing the transfer of electronic shot noise between the emitter and collector of a semiconductor bipolar junction transistor and the generation and propagation of 'quantum shot noise' in a mesoscopic circuit (Shimizu and Sakaki 1991).

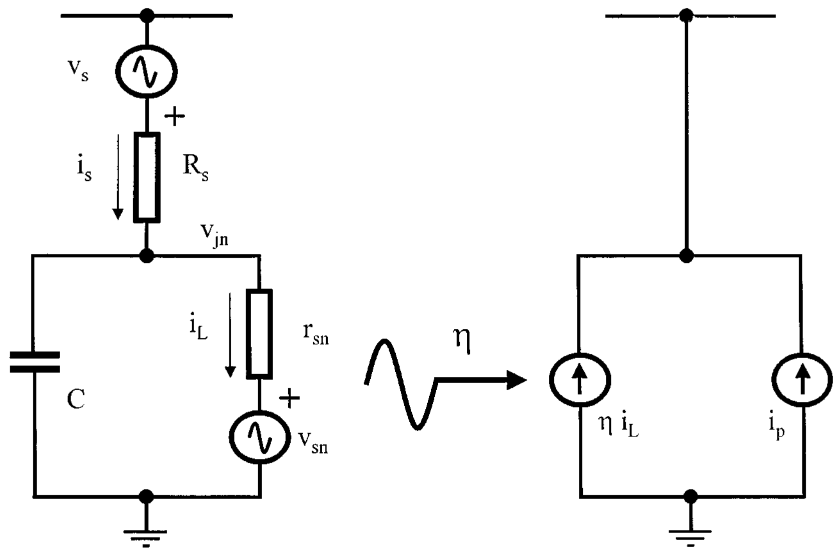


Fig. 4. Noise equivalent circuit representation of the Langevin rate equation (6) showing a light emitting junction with junction capacitance C, differential resistance r_{sn}, and equivalent shot noise voltage source ν_{sn}, driven through external resistance R_s, coupled with quantum efficiency η to a photon detector with partition noise current i_p.

The first measurements of sub shot noise light from light-emitting diodes driven from high impedance circuits were made by Tapster *et al.* (1987). These showed 4% noise reduction ($F_d = 0{\cdot}96$), below the full shot noise level. Edwards (1990, 1991, 1992) subsequently confirmed the validity of equation (16) for quantum efficiencies $\eta \leq 0{\cdot}3$ and $F_i \leq 0{\cdot}05$. The maximum, quantum efficiency-limited noise reduction reported to date of 50%, obtained by Shinozaki *et al.* (1997) is in agreement with that expected from equation (15) with complete noise suppression ($F_i = 0$) at the junction. These measurements support the shot noise suppression model based on the simple rate equations (5) and (6). In particular, the spectral dependence of the suppressed recombination noise has been measured and is evidently (Fig. 5) the same as that of the corresponding external current modulation characteristic, as expected for the leaky reservoir recombination model (Zhang *et al.* 1995). However, it is also evident from Fig. 5 that the bandwidth of the suppressed noise varies with the junction current and does not equal $B = 1/2\pi\tau = 1/2\pi rC$ as would be expected from the simple reservoir model. The model ignores the stochastic injection of minority charge carriers across the space charge region of the junction into the active region where radiative recombination takes place. This is a significant omission, particularly as the size of the junction is reduced to mesoscopic dimensions and collective Coulomb effects give way to the single electron Coulomb blockade phenomenon (Imamoglu and Yamamoto 1993).

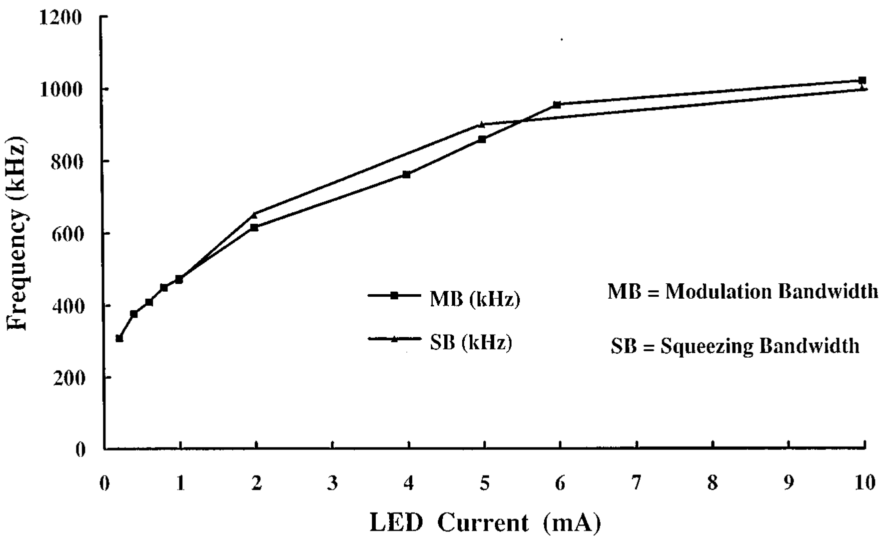


Fig. 5. Variation of the 'squeezing bandwidth' (the half-power bandwidth over which the noise is suppressed below the full shot noise level) and the current modulation bandwidth for a pump noise suppressed light-emitting junction diode with injection current showing the macroscopic Coulomb blockade effect (Zhang *et al.* 1995).

Measurements (Kim *et al.* 1995; Zhang *et al.* 1995; Kobayashi *et al.* 1999) on macroscopic and microscopic light-emitting junctions show that the bandwidth over which noise reduction occurs is more accurately predicted by a stochastic injection model in which transport across the depletion (space charge) layer and its depletion capacitance play an important part.

(*5b*) *Stochastic Injection Model of Light-emitting Junctions*

These recent measurements on light-emitting microjunctions and mesojunctions have led to a clarification of the diffusion based models of junction noise in favour of stochastic injection models. In these recent models, stochastic injection across the space charge layer into the active recombination region of the junction is accounted for. These models employ a space charge smoothing mechanism similar to that proposed by Teich and Saleh (1985) on the basis of the space charge model of a thermionic vacuum diode (Section 2*a*).

The charging energy $N_i e^2/2C_{\rm dep}$ at the junction associated with the injection of N_i electrons into the active layer raises the Coulomb barrier against subsequent charge injection. This occurs providing $N_i e^2/2C_{\rm dep} \gg kT$, the thermal energy. It results in a sub-Poissonian stream of anti-bunched electrons on a characteristic time scale $\tau_i = rC_{\text{dep}} = kTC_{\text{dep}}/eI$. As the injection current is lowered, this time scale lengthens and exceeds the recombination time. The corresponding bandwidth over which noise suppression occurs then becomes $B = eI/2\pi kTC_{\text{dep}}$. With low injection, this will be less than the recombination bandwidth as is evident from Fig. 5. In this situation the suppression is due entirely to the 'macroscopic Coulomb blockade' process (Imamoglu and Yamamoto 1993) since there can be no significant storage of diffusing charge in the reservoir. The corresponding rate equation is then equation (10) and the corresponding equivalent circuit is Fig. 4, with C replaced by C_{dep}, the depletion capacitance. In general the macroscopic junction capacitance required to correctly model the noise suppression measurements will evidently be the sum of the depletion (collective Coulomb blockade) capacitance and the diffusion (leaky reservoir) capacitance.

(*5c*) *Single Photon Generation*

The successive injection of N_i electrons (typically 10^8 or more) perturbs the junction potential by an amount $Ne/C_{\text{dep}} \gg kT/e$, the thermal voltage fluctuation, and thus introduces antibunching and consequent shot noise suppression. If the electron count or current integration time interval exceeds the characteristic time τ_i, then sub-Poissonian variance and sub shot noise current spectral densities will be observed, although the traditional measure of anti-bunching, the second order coherence function [$G_{11}^{(2)}(0)$ from equation (11)] will not be significantly different from unity since $\langle n\rangle$ is large, being of the order of N_i. Moreover, as the injection current is reduced the bandwidth of the suppressed noise will continue to contract, requiring ever longer integration times in order to maintain low noise levels. Full shot noise [$F_i(\omega) = 1$] will result if the integration time is made much shorter than τ_i.

However, if C_{dep} and T are reduced to make $e^2/kTC_{\text{dep}} \gg 1$, the potential drop due to the passage of single electrons may become sufficiently large relative to the thermal fluctuations to regulate the flow of individual electrons via the single electron Coulomb blockade effect (Averin and Likharev 1986). This requires a sub-micron sized semiconductor nanojunction with junction capacitance of order 10^{-16} F operated at liquid helium temperatures.

If, in addition, the spontaneous recombination time can be made much shorter than the electron inter-arrival time e/I (1 ns for $I = 0{\cdot}16$ nA), then control over the emission of single photons becomes possible. This is the basis of proposals for realising 'electron photon turnstiles' utilising both single electron Coulomb blockade and quantum confinement effects in mesoscopic semiconductor junctions (Imamoglu and Yamamoto 1993, 1994). Quantum control of photon emission would enable the generation of well-defined photon numbers (photon number states) at specified times. Such 'heralded' photon number states have applications in quantum communications and cryptography. For example, from equation (11), an ideal single photon state source for quantum key distribution purposes would be characterised by $\langle n\rangle = n = 1$, $F_n = 0$ and ${G_{11}}^{(2)}(0) = 0$. The inefficient weak Poissonian sources currently used in quantum cryptographic systems are typically characterised by $\langle n\rangle \approx 0{\cdot}1$, $F_n = 1$ and $G_{11}^{(2)}(0) = 1$.

Proposed single-photon and single electron devices also have applications in quantum computing, quantum communications and quantum metrology, as well as in fundamental tests of quantum mechanical theory (Kim *et al.* 1999).

6. Conclusions

Electronic and photonic shot noise remain significant impediments to the performance of optoelectronic and mesoscopic systems. However, investigations of sub-Poissonian light from macroscopic light-emitting semiconductor junctions have highlighted the close parallels between electronic and photonic shot noise, have resulted in a better understanding of the physical processes involved, and have pointed the way to new noise suppression technologies on macroscopic and mesoscopic scales.

Acknowledgments

I acknowledge with thanks the financial support of the Australian Research Council under its Large Grants Program and the encouragement and support of the late Rolf Landauer.

References

Averin, D. V., and Likharev, K. K. (1986). *J. Low Temp. Phys.* **62**, 345.
Blanter, Ya. M., and Buttiker, M. (1999). *Phys. Rev.* B **59**, 10217.
Buckingham, M. J. (1983). 'Noise in Electronic Devices and Systems' (Wiley: New York).
Buckingham, M. J., and Faulkner, E. A. (1974). *Radio Electron. Engin.* **44,** 125.
Burgess, R. E. (1959). *Faraday Soc. Disc.* **28**, 151.
Buttiker, M. (1990). *Phys. Rev. Lett.* **65**, 2901.
Edwards, P. J. (1990). Fourth Australian Conf. on II-VI Semiconductor Compounds, Handbook of Abstracts W9.
Edwards, P. J. (1991). *Int. J. Optoelectron.* **6**, 23.
Edwards, P. J. (1993). *IEEE J. Quant. Electron.* **29**, 2302.
Edwards, P. J. (1994). *In* 'Quantum Optics VI' (Eds D. F. Walls and J. D. Harvey), pp. 285–95 (Springer: Berlin).
Edwards, P. J., and Pollard, G. H. (1993). *Phys. Rev. Lett.* **69**, 1757.
Edwards, P. J., McDonald, R., and Cheung, W. N. (1999). Proc. 2nd Int. Conf. on Unsolved Problems of Noise (UpoN' 99) (Eds D. Abbott and L. B. Kiss) (AIP Press: New York), in press.
Imamoglu, A., and Yamamoto, Y. (1993). *Phys. Rev. Lett.* **70**, 3327.
Imamoglu, A., and Yamamoto, Y. (1994). *Phys. Rev. Lett.* **72**, 210.
Kim, J., and Yamamoto, Y. (1997). *Phys. Rev.* B **55**, 9949.
Kim, J., Benson, O., Kan, H., and Yamamoto, Y. (1999). *Nature*, **397**, 500.
Kim, J., Kan, H., and Yamamoto, Y. (1997). *Phys. Rev.* B **52,** 2008.
Kobayashi, M., Yamanishi, M., Sumitomo, H., and Kadoya, Y. (1999). *Phys. Rev.* B (in press).
Landauer, R. (1993). *Phys. Rev.* B **47**, 16,427.
Landauer, R. (1996). *Physica* B **227**, 156.
Lesovik, G. B. (1989). *JETP Lett.* **49**, 592.
Loudon, R. (1980). *Rep. Prog. Phys.* **43**, 914.
Machida, S., and Yamamoto, Y. (1988). *Phys. Rev. Lett.* **60**, 792.
Machida, S., Yamamoto, Y., and Itaya, Y. (1987). *Phys. Rev. Lett.* **58**, 1000.
Milburn, G., and Sun, H. (1998). *J. Contemp. Phys.* **39**, 67.
Oliver, W. D., Kim, J., Liu, R. C., and Yamamoto, Y. (1999). *Science* **284**, 299.
Rack, A. J. (1938). *Bell System Tech. J.* **17**, 592.
Schottky, W. (1918). *Ann. Phys.* (*Leipzig*) **57**, 541.
Shimizu, A., and Sakaki, H. (1991). *Phys. Rev.* B **49**, 10520.
Shinozaki, G., Hirano, T., Kuga, T., and Yamanashi, M. (1997). *Japan J. Appl. Phys.* **36**, 6350.
Tapster, P. R., *et al.* (1987). *Europhys. Lett.* **4**, 293.
Teich, M. C., and Saleh, B. E. A. (1985). *J. Opt. Soc. Am.* B **2**, 275.
Teich, M. C., and Saleh B. E. A. (1988). *In* 'Progress in Optics', Vol. 26 (Ed. E. Wolf) (North Holland: Amsterdam).

Teich, M. C., Capasso, F., and Saleh, B. E. A. (1987). *J. Opt. Soc. Am.* B **4**, 1663.
van der Ziel, A. (1955). *Proc IRE* **43**, 1639.
van der Ziel, A. (1957). *Proc. IRE* **45**, 1011.
van der Ziel, A. (1959). 'Fluctuation Phenomena in Semiconductors' (Butterworth: London).
van der Ziel, A. (1970). 'Noise: Sources, Characterisation, Measurement', Ch. 6 (Prentice–Hall: New Jersey).
Yamamoto, Y., and Machida, S. (1987). *Phys. Rev.* A **35**, 5114.
Yamamoto, Y., Inoue, S., Richardson, W., and Machida, S. (1993). *Int. J. Mod. Phys.* B **7,** 1577.
Zhang, T., Edwards, P. J., Cheung, W. N., and Sun, H. B. (1995). *CLEO Pacific Tech. Digest* 71.

Manuscript received 13 August, accepted 26 October 1999