Noise in single quantum well infrared photodetectors

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The spectral density of current fluctuations in single quantum well infrared photodetectors is calculated using the Langevin approach. The noise gain and photocurrent gain are expressed in terms of basic transport parameters. Fluctuations of the incident photon flux are taken into account. © *1997 American Institute of Physics.* [S0003-6951(97)01638-0]

The noise of the dark current and photocurrent is an important factor in operation of the quantum well infrared photodetectors (QWIPs).[1] For typical operating conditions, the main source of fluctuations in QWIPs is generation-recombination noise associated with the excitation of carriers from the QWs into the continuum and their capture into the QWs. For applications the study of noise in QWIPs is important in order to obtain devices with high detectivity, and it also provides additional physical insight into these systems. Fluctuations are the natural sources of transient excitation, therefore the QWIP response to this excitation provides information on internal physical processes, and thus forms the basis for noise spectroscopy.[2,3] Due to the numerous experimental and theoretical works on noise properties of QWIPs with multiple QWs (see, e.g., Refs. 1,4–9), the overall understanding of the QWIP noise characteristics is satisfactory. Some issues, however, are still controversial, such as the relation between the noise gain and the photocurrent (optical) gain, the frequency dispersion of the noise spectral density, and the role of the injecting contact.

In this letter we consider a single QW QWIP (SQWIP). SQWIP is especially attractive theoretically because its simple structure allows an accurate self-consistent calculation of the electric field, injection current, and charge accumulation in the QW, and hence a better understanding of the noise properties. In addition, SQWIPs are intrinsically fast devices promising for CO_2-laser based high-speed applications, for which noise is an important consideration.[10–12] Although SQWIPs have been studied by several research groups (see, e.g., Refs. 13–16), we are aware of only one theoretical paper[17] dealing with the noise in SQWIPs. However, the result obtained in Ref. 17 requires a number of restrictive assumptions (large photocurrent gain, absence of the electron transport from the QW to emitter, etc.).

In this letter we extend recent theoretical studies of SQWIPs[18–20] to present a noise theory for SQWIPs. The frequency-dependent spectral density of current fluctuations is expressed in terms of the basic transport and injection parameters, and is applicable for SQWIPs with different design concepts.

The SQWIP under consideration contains a single-level QW separated by undoped barriers from heavily doped contacts (Fig. 1). Our model basically follows Refs. 18 and 20; however, we do not assume any particular shape of the emitter and collector barriers, so, for example, the injection current I_e has a general dependence on the electric field E_e in the emitter barrier. An important transport parameter of the model is the efficiency β ($\beta<1$) which is the probability for an injected electron to pass from emitter directly to collector, while $(1-\beta)$ is the probability of electron capture by the QW (here the meaning of the QW capture probability is different from that in the case of drift electron transport in QWIPs with multiple QWs; see Ref. 9). The electrons emitted from the QW are collected by the collector and emitter with probabilities ζ and $(1-\zeta)$, respectively (electron transport from the QW to the emitter is especially important for SQWIPs with triangular barriers[18–20]). Electron transport across the emitter and collector barriers is assumed to be instantaneous, therefore, our analysis is limited by frequencies $\omega \ll v_T/\max(W_e,W_c)\sim 10^{12}\ \mathrm{s}^{-1}$, where v_T is a typical (thermal) velocity and W_e, W_c are the emitter and collector barrier thicknesses, respectively (the model of instantaneous jumps can be used for both thermoactivated emission and tunneling). We also neglect the electron interactions during traveling in the barrier regions, and single-electron correlations. The dynamics of the electron transport in SQWIP is described[21] by the following Langevin equations:

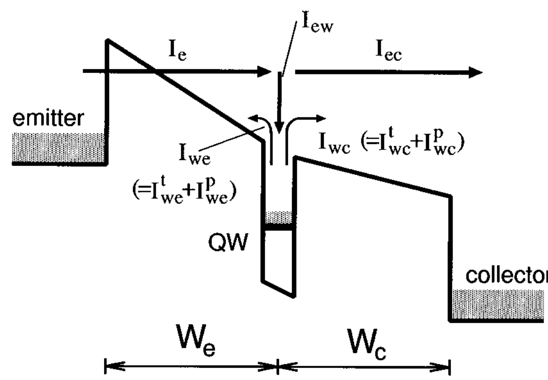

FIG. 1. Schematic diagram of the conduction band profile and currents in a SQWIP (the barrier shapes are arbitrary). SQWIPs with thermoactivated as well as tunneling transport can be described by the model used.

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$$I=\frac{W_e}{W}(I_{ew}-I^t_{we}-I^p_{we}+\xi_{ew}-\xi^t_{we}-\xi^p_{we})$$
$$+\frac{W_c}{W}(I^t_{wc}+I^p_{wc}+\xi^t_{wc}+\xi^p_{wc})+I_{ec}+\xi_{ec}, \quad (1)$$

$$\dot{Q}=I_{ew}-I^t_{we}-I^p_{we}-I^t_{wc}-I^p_{wc}$$
$$+\xi_{ew}-\xi^t_{we}-\xi^p_{we}-\xi^t_{wc}-\xi^p_{wc}. \quad (2)$$

Here I is the total current through SQWIP (which is equal to the sum of the conduction and displacement currents at any cross section), $I_{ec}=\beta I_e$ and $I_{ew}=(1-\beta)I_e$ are the currents from the emitter to the collector and the well, respectively, and $I_{wc}=\zeta I_w$ and $I_{we}=(1-\zeta)I_w$ describe the electron transport from the well to the collector and the emitter ($I_w=I^p_w+I^t_w$ where superscripts t and p denote the currents due to thermo- and photoexcitation, respectively). We neglect the current from the collector assuming sufficiently large bias voltage V. The well is assumed to be narrow, so the total structure thickness is $W=W_e+W_c$, while the finite well thickness in the first approximation can be taken into account via effective values for W_e and W_c. The current I_e depends mainly on the electric field E_e in the emitter, $E_e=E^0_e+V/W-QW_c/(\varepsilon\varepsilon_0 AW)$, while I_w depends on the electron population in the QW and electric fields in the barriers,[14,15,18] so all currents are some functions of the QW charge Q (here A is the SQWIP area, $\varepsilon\varepsilon_0$ is the dielectric constant, and E^0_e is the parameter of the SQWIP design). For simplicity we neglect the dependencies of β and ζ on the accumulated charge.

Studies of the steady-state characteristics and admittance of SQWIPs described by similar models have been reported recently.[14,15,18,20] In this letter we concentrate on the fluctuations which in Eqs. (1) and (2) are caused by random Langevin terms $\xi(t)$. All random terms (except ξ^p_{we} and ξ^p_{wc}, see below) have no mutual correlation, all of them are δ correlated in time, and the corresponding spectral densities $S(\omega)$ are given by usual Schottky formula:

$$S_{\xi_{ew}}(\omega)=2\,e\langle I_{ew}\rangle, \quad S_{\xi^t_{wc}}(\omega)=2\,e\langle I^t_{wc}\rangle, \text{ etc.} \quad (3)$$

(brackets denote time averaging). The fluctuations of the photocurrent depend on the photon source noise. Let the photon flux incident on the SQWIP have the spectral density $S_p(\omega)=2\nu[1+\alpha(\omega)]$ where ν is the average flux (photons per second) and α describes the deviation from the Schottky level. Then the noise of the photoexcitation currents from the QW is given by

$$S_{\xi^p_{wc}}(\omega)=2\,e\zeta\langle I^p_w\rangle[1+\zeta\eta\alpha(\omega)], \quad \langle I^p_w\rangle=e\eta\nu,$$
$$S_{\xi^p_{we}}(\omega)=2\,e(1-\zeta)\langle I^p_w\rangle[1+(1-\zeta)\eta\alpha(\omega)], \quad (4)$$
$$S_{\xi^p_{we}\xi^p_{wc}}(\omega)=2\,e\langle I^p_w\rangle\zeta(1-\zeta)\eta\alpha(\omega).$$

Here the last equation describes the mutual spectral density, and the absorption quantum efficiency η includes the finite probability for a photoexcited electron to escape from the QW. Equations (4) can be derived by separating the terms in the correlation functions corresponding to one and two excitation events. The first term is proportional to the probability $\xi\eta$ or $(1-\xi)\eta$ while the second term is proportional to the corresponding product of probabilities. Equations (4) show that the photoexcitation current noise has simple Schottky behavior only if the photon flux is Poissonian ($\alpha=0$) or η is small.

Equations (1)–(4) allow us to calculate the noise properties of SQWIP. Applying the standard Langevin method[2,3] to the linearized version of Eqs. (1) and (2), we first formally solve Eq. (2) in the frequency representation taking into account the dependence of currents on the accumulated charge. Substituting the result into Eq. (1) and using Eqs. (3) and (4) for Langevin sources we obtain the following spectral density of the total current:

$$S_I(\omega)=2e\langle I_{ec}\rangle+2e[\langle I_{ew}\rangle+\langle I^t_{we}\rangle+\langle I^p_{we}\rangle$$
$$\times(1+(1-\zeta)\eta\alpha(\omega))]\left|\frac{W_e}{W}-\frac{\chi}{1-i\omega\tau}\right|^2$$
$$+2e[\langle I^t_{wc}\rangle+\langle I^p_{wc}\rangle(1+\zeta\eta\alpha(\omega))]$$
$$\times\left|\frac{W_c}{W}+\frac{\chi}{1-i\omega\tau}\right|^2+4e(\langle I^p_{we}\rangle+\langle I^p_{wc}\rangle)$$
$$\times\zeta(1-\zeta)\eta\alpha(\omega)\ \mathrm{Re}\left[\left(\frac{W_e}{W}-\frac{\chi}{1-i\omega\tau}\right)\right.$$
$$\left.\times\left(\frac{W_c}{W}+\frac{\chi}{1+i\omega\tau}\right)\right], \quad (5)$$

$$\tau^{-1}=-\frac{dI_{ew}}{dQ}+\frac{dI_{we}}{dQ}+\frac{dI_{wc}}{dQ}, \quad (6)$$

$$\chi=\tau\left[-\frac{dI_{ec}}{dQ}+\frac{W_e}{W}\left(\frac{dI_{we}}{dQ}-\frac{dI_{ew}}{dQ}\right)-\frac{W_c}{W}\frac{dI_{wc}}{dQ}\right]. \quad (7)$$

Here the derivatives dI_i/dQ also take into account the dependence via the electric field modulated by Q. (Obviously $\langle I_{ew}\rangle=\langle I_{we}\rangle+\langle I_{wc}\rangle$.) One can see that in the case of $\alpha(\omega)=$const the spectral density has a Lorentzian shape (with a pedestal) with the characteristic frequency τ^{-1}. Equation (5) can be used to determine the noise gain which is traditionally defined as $g_n(\omega)\equiv S_I(\omega)/4e\langle I\rangle$.

Equations (1) and (2) without noise sources can also be used to calculate the photocurrent gain (the ratio between the variations of the total current and the photoexcitation current for small-signal harmonic infrared excitation):

$$g_p(\omega)\equiv\frac{\delta I(\omega)}{\delta I^p_w(\omega)}=\zeta-\frac{W_e}{W}+\frac{\chi}{1-i\omega\tau}. \quad (8)$$

The frequency dependence of the photocurrent gain is obviously governed by the same time constant τ of QW recharging.[20] (This time constant corresponds to the time required to establish equilibrium at the injecting contact in QWIPs with multiple QWs.[22])

To simplify the analysis further let us assume $|dI_{we}/dQ+dI_{wc}/dQ|\ll|dI_{ew}/dQ|$ (that is a typical experimental case). Then $\tau=(1-\beta)^{-1}(-dI_e/dQ)^{-1}$ and $\chi=\beta/(1-\beta)+W_e/W$. If we also assume $\alpha(\omega)I^p_w\ll I_w$ (so that we can neglect the non-Poissonian term of the photocurrent), then the noise gain is given by

$$g_n(\omega)=g_n(\infty)+\frac{g_n(0)-g_n(\infty)}{1+(\omega\tau)^2}, \quad g_n(0)=\frac{1}{2}\frac{1+\beta}{1-\beta},$$
$$g_n(\infty)=\frac{1}{2}+(1-\beta)\frac{W_e}{W}\frac{W_e/W-\zeta}{\beta+\zeta-\beta\zeta}. \tag{9}$$

Under the same assumptions the ratio between the noise gain and the photocurrent gain at small frequencies is given by the expression

$$g_n(0)/g_p(0)=(1+\beta)/[2(\beta+\zeta-\beta\zeta)] \tag{10}$$

(in conventional photoconductors this ratio is close to unity[11] while in our case unity is realized only if $\beta\rightarrow 1$ or $\zeta=1/2$), and the minimal detectable photon flux ν_{min} at low frequency is given by

$$\nu_{min}\equiv\frac{\sqrt{S_I(0)\Delta f}}{e\eta g_p(0)}=\frac{\sqrt{2eI\Delta f}}{e\eta}\frac{\sqrt{1-\beta^2}}{\beta+\zeta-\beta\zeta}, \tag{11}$$

where Δf is the bandwidth.

The time constant $\tau\simeq[(1-\beta)W_c/(\varepsilon\varepsilon_0 W)\times d(I_e/A)/dE_e]^{-1}$ for typical SQWIP structures and operating conditions[20] can be within a quite wide range ($\sim 10^{-9}-10^{-3}$ s) and depends strongly on the applied voltage, temperature, and SQWIP design. Because of strong (typically exponential) dependence of I_e on E_e, τ starts to decrease with illumination intensity when the illumination changes E_e considerably (crudely this occurs when the photocurrent becomes comparable or larger than the dark current). The dependence of τ on temperature is typically exponential,[20] $\tau\propto\exp(-kT/\varepsilon_a)$, where ε_a is the activation energy, which can be used for evaluation of the QW parameters from the measurements of the SQWIP noise or photocurrent characteristics at different frequencies and temperatures.

At high frequencies, $\omega\gg 1/\tau$, the QW recharging processes are ''frozen,'' and the spectral density of current fluctuations is determined by the shot noise of elementary currents with appropriate geometrical factors. The photocurrent is due to the electrons emitted from the QW only, i.e., the primary photocurrent.[22] It is interesting to note that in the case of $\zeta<W_e/W$ the high-frequency photocurrent gain $g_p(\infty)$ is negative.

At low frequencies, $\omega\ll 1/\tau$, the SQWIP operates in the quasistatic regime. The QW charge responds to the external excitation and modulates the injection current. In this regime the modulation effect results in a strong enhancement of both the photocurrent gain and the noise gain provided $1-\beta\ll 1$.

If all the electrons injected from the emitter are captured by the QW ($\beta=0$), then [see Eq. (9)] the low-frequency noise gain $g_n(0)=1/2$ corresponds to the usual Schottky level. This has been observed experimentally in the SQWIP with thin emitter barrier.[16]

In the special case when $\zeta=1$ and $\alpha=0$ our main result given by Eq. (5) can be compared with the result of Ref. 17. They coincide in the limit of high photocurrent gain; however, they are different for finite photocurrent gain because the result of Ref. 17 is not applicable in this case. We have checked that for $\zeta=1$, $\alpha=0$ the correct expression can also be obtained using the Fokker-Plank technique[3] (averaging $\exp(i\omega(t_m-t_n))$ where t_m and t_n are the moments of electron jumps). In the general case considered in the present letter, the Fokker-Planck technique becomes much more cumbersome than the Langevin method.

In conclusion, we have calculated noise in the SQWIP under the assumption of fast electron jumps over (or through) the barriers.

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[21] The sign convention used in this letter is most simply understood if the electron charge is considered to be positive (this obviously does not affect the final results), then the direction of the current coincides with the direction of electron transport. Alternatively, one can consider true negative electron charge, then all currents (I_e, I_w, etc.) are also negative and $e<0$.
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