Numerical simulation of noise in quantum well infrared photodetectors

M. Ershov
University of Aizu, Aizu-Wakamatsu, 965-8580, Japan
Phone: (81-242) 37-2736, Fax: (81-242) 37-2749, E-mail: ershov@u-aizu.ac.jp

The main source of noise in quantum well infrared photodetectors (QWIPs) is generation-recombination (g-r) processes related to carrier capture to QWs and emission from QWs into continuum. Conventional theories of g-r noise assume exponential form of the current pulse $\delta I_0(t) \sim \exp(-t\tau_c)$ (τ_c is the capture time to QWs), resulting in a simple Lorentzian function for the noise power:

$$S_0(f) = 4egI/[1 + (2\pi f \tau_c)^2], \qquad (1)$$

where g is the photocurrent gain and I is the total current. Accordingly, the current autocorrelation function and distribution of carrier life-times are exponential functions with the same time constant. However, QWIP transient response is influenced by the carrier transit and injection modulation effects [1], which are not accounted for in conventional theories. This work presents the first self-consistent numerical simulation of g-r noise in QWIPs.

Total g-r noise power is a sum of contributions from QWs and contact injection:

$$S(f) = S_c(f) + \sum_{i=1}^{N} S^i_{QW}(f), \qquad (2)$$

where N is the number of QWs. Noise power generated by i-th QW is given by:

$$S^i_{QW}(f) = 2r|\delta I(\omega)|^2, \qquad (3)$$

where r is the rate of carrier capture/emission to/from QW, and $\delta I(\omega)$ is the Fourier transform of transient current in QWIP in response to extra generated carrier from the QW. The numerical procedure of noise calculation is described as follows. QWIP operation is simulated using 1D numerical model including current continuity equation (in the drift-diffusion approximation), Poisson equation, and rate equations for carrier capture/emission to/from QWs [2]. At first, self-consistent steady-state solution is calculated to obtain DC distributions of quantities of interest (electric field, capture/emission rates, etc.). Then, transient current in QWIP in response to extra charge emission from i-th QW is simulated in the time domain, and its Fourier transform is calculated. This procedure is repeated for all QWs and injecting contact, and the total noise power is calculated according to eqs. (2–3).

Figure 1 shows the transient current in response to extra charge generation in the bulk (i=16) of 32-QW device. Transient current is deviates *far* from simple exponential function. It contains fast and slow transients. Time constants of these transients differ by more than 5 orders of magnitude, which requires variation of time steps during simulation to guarantee necessary time resolution. The fast transient corresponds to decaying exponential (due to QW capture), which is cut off at a time moment equal to transit time ($\tau_{tr} \sim 5.5$ ps). Slow transient has much smaller amplitude and much longer time constant (~ 1 μs). This transient is due to enhanced electron injection from the emitter to compensate the extracted charge. Slow transient is followed by damping oscillations due to spatial waves of non-equilibrium charge in QWs.

Calculated current autocorrelation function is shown in Fig. 2. Autocorrelation function of fast transient has a characteristic triangular shape. An analytical model of fast transient results in following expression for autocorrelation function:

$$c(\tau) \sim \frac{\sinh[(\tau_{tr} - \tau_c)/\tau_c]}{\sinh[\tau_{tr}/\tau_c]}, \qquad (4)$$

which is transformed into $\exp(-\tau/\tau_c$ if $\tau_{tr} \gg \tau_c$, and into $1 - \tau/\tau_{tr})$ if $\tau_{tr} \ll \tau_c$.

Transient current can be represented as a sum of contributions of elementary current pulses with amplitude ev/L and life times distributed as $p(\tau)$: $\delta I(t) = \int_t^\infty p(\tau)\, d\tau$. Calculated distribution $p(\tau)$ is plotted in Fig. 3. It can be approximated by an exponential function for $\tau \lesssim \tau_t r$, and has a peak at $\tau = \tau_{tr}$, corresponding to carriers leaving QWIP without capture. The distribution $p(\tau)$ has a very long tail due to extra electron injection from the emitter.

Noise power spectral density (for one QW) is shown in Fig. 4. Generally, it has two flat and two fall-off regions. The first fall-off is due to the injection modulation effect, while high-frequency fall-off is due to life-time effects. Strong oscillations of noise power at high frequencies are due to transit-time resonances at $\sin(\omega\tau_{tr}/2) = 0$.

[1] M. Ershov, Appl. Phys. Lett., v. 69, no. 23, p. 3480 (1996).
[2] M. Ershov, V. Ryzhii, and C. Hamaguchi, v.67, no. 21, p. 3147 (1995).

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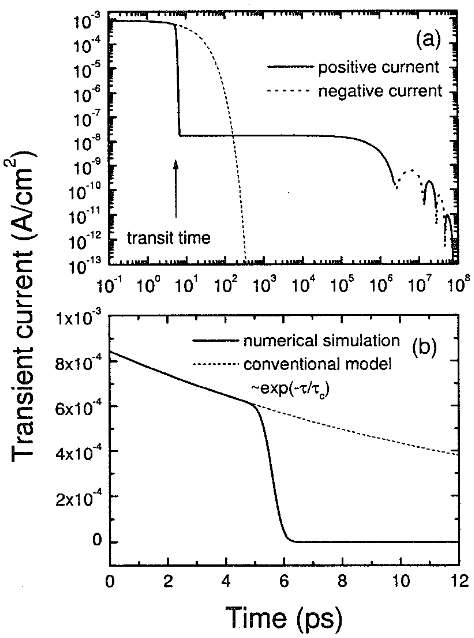

Fig. 1. Transient current pulse in response to extra charge generation (a) in log-log scale and (b) in linear scale.

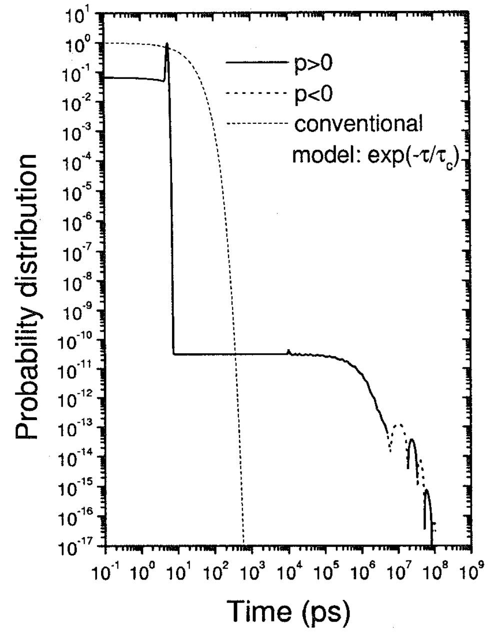

Fig. 3. Life time probability distribution of current pulses.

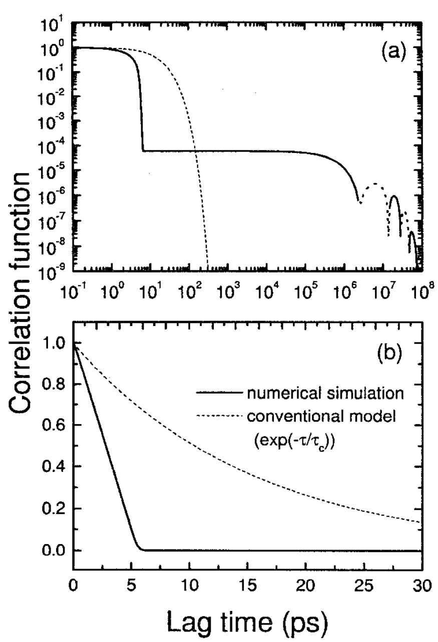

Fig. 2. Current autocorrelation function (a) in log-log scale and (b) in linear scale.

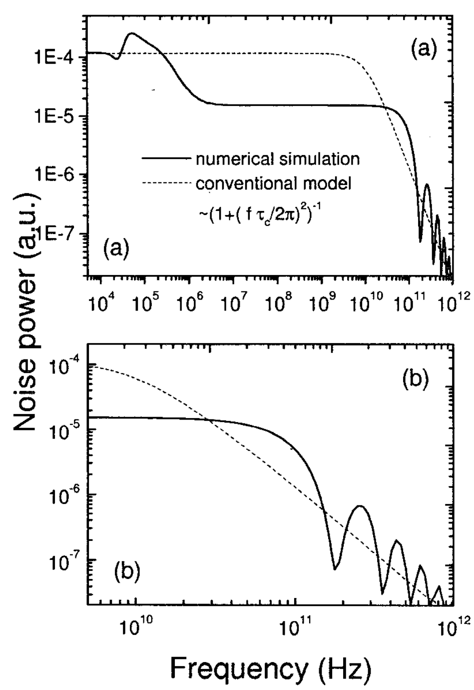

Fig. 4. Noise power spectral density due to i=16-th QW.