1/f Noise and Phase Noise in RTD Oscillators

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Resonant tunneling diodes (RTDs) have been proposed as generators of THz oscillations and radiation. They were not very successful, because they were utilized in an extrinsic, i.e., external charge exchange, manner [1]. They consist of two potential barriers enclosing a quantum well. In a previous paper [2], the current-voltage characteristic for AlGaSb/InAs/AlGaSb double-barrier tunneling diodes was calculated in the framework of the six-band Kane model. Our application of the multi-band model yielded results that were in excellent agreement with existing experimental measurements on staggered-bandgap structures, when well known material parameters are utilized. In our earlier paper [1], self-consistent, time-dependent Wigner-Poisson simulations demonstrated the existence of sustained THz-frequency current-oscillations in a DBQWS that arise without the benefit of external charging processes.

In the present communication, we apply the quantum theory of 1/f noise [3]-[5] to evaluate the 1/f noise of RTDs, and to also find the phase noise of RTD-based high frequency oscillators. Electrons penetrating the potential barriers by tunneling are controlled by the quasistationary energy levels defined by the penetrating the potential barriers by tunneling are controlled by the quasistationary energy levels defined by the potential well. If their energy is close to the first energy level in the well, resonance occurs, and a peak I_P of the current through the diode occurs. This corresponds to an applied bias voltage V_P. If, however, the applied voltage increases further, only a negligibly small non-resonant current trickle remains at the voltage $V=V_V$ and a broad valley is observed in the I/V characteristic. Scattering processes that reduce the energy of the carriers to a value close to eV_P will always be present, generating a finite current minimum I_V at V_V.

Between V_P and V_V there is a negative differential conductance

$$G= - (I_P-I_V)/(V_V-V_P) \qquad (1)$$

on the I/V curve, that is used to generate oscillations. If the RTD is small in cross section perpendicular to the flow of the current, the 1/f noise in I_V is given by Handel's conventional quantum 1/f equation [3]-[4]

$$S_{\delta\sigma/\sigma}(f) = I_V^{-2} S_{I_V}(f) = 4\alpha(\Delta\mathbf{v}/c)^2/3\pi f N, \qquad (2)$$

with

$$(\Delta\mathbf{v}/c)^2=2eV_V/m. \qquad (3)$$

Taking for instance $V_P=0.4$ V, $I_P=2.5\cdot10^8$ A/m^2, $V_V=0.6$ V, $I_V=4\cdot10^7$ A/m^2, we obtain with $m_{eff}=0.068\ m_o$,

$$N I_V^{-2} S_{I_V}(f) = 2\alpha A/f = 7.4/0.068\cdot10^{-9} = 1.3\cdot10^{-7} \qquad (4)$$

N is given by

$$N = \tau I_V/e, \qquad (5)$$

where τ is the life time of the carriers. With a cross-sectional area of 10^{-6} cm^2 and $\tau=10^{-10}$s, we obtain N= $2.5\cdot10^6$, and $\mathbf{S}_{\delta Iv/Iv}= 5\cdot10^{-14}$/Hz.

Finally, the quantum 1/f frequency fluctuations can be obtained from the formula

$$S_{\delta\omega/\omega}=(1/4Q^4)S_{\delta G/G} =(1/4Q^4)\ [I_V/(I_P-I_V)]^{\mathbf{2}}S_{\delta Iv/Iv} \qquad (6)$$

which is derived below. This finally yields with Eq. (4), both for $S_{\delta\omega/\omega}$ and for the spectral density $S_{\delta\varphi/\varphi}$ of phase fluctuations,

$$S_{\delta\omega/\omega}=(1/4Q^4)[I_V/(I_P-I_V)]^{\mathbf{2}}(4\alpha/3\pi)(2eV_V/mc^2) \qquad (7)$$

for the fractional frequency fluctuation spectrum exhibited by the RTD if included in an RF circuit of quality factor Q. For $Q=10^{\mathbf{3}}$ and f=1Hz, we get $S_{\delta\omega/\omega}=5\cdot10^{\mathbf{-28}}$/Hz. At $\nu=10^{\mathbf{10}}$Hz, the RTD oscillator would have $S_{\Delta\varphi}(1Hz) = 2\cdot 10^{-6}/Hz$, or $\mathcal{L}(1kHz) = -150dBc/Hz$.

To explain the physical meaning of Eq. (5), we follow the derivation first published in 1979. In general, RF resonant systems can be described as a harmonic oscillator with losses

$$dx/dt + \gamma dx/dt + \omega_0^2 x = F(t). \qquad (8)$$

The quantum 1/f fluctuations are present in the loss coefficient γ. They are given by an expression of the form

$$S_{\delta\gamma/\gamma}(f) = \Lambda/f, \qquad (9)$$

where Λ is a quantum 1/f coefficient characterizing the elementary loss process.
The resonance frequency is given by

$$\omega_r^2 = \omega_0^2 + \gamma^2. \qquad (10)$$

The quantum 1/f fluctuations in the resonance frequency are given by $\omega_r \delta\omega_r = -2\gamma\delta\gamma$ or

$$\delta\omega_r/\omega_r = -2(\gamma/\omega_r)^2 \delta\gamma/\gamma = -(1/2Q^2)(\delta\gamma/\gamma), \qquad (11)$$

where $Q = \omega_r/2\gamma$ is the quality factor. Squaring, averaging and particularizing Eq. (25) for the unit frequency interval, we obtain the Q^{-4} law

$$S_y(f) = \langle(\delta\omega_r/\omega_r)^2\rangle_f = (1/4Q^4)\langle(\delta\gamma/\gamma)^2\rangle_f$$
$$= \Lambda/4fQ^4, \qquad (12)$$

where y is the fractional frequency fluctuation $\delta\omega_r/\omega_r$. This law was first applied by Handel to quartz resonators [5], then to other resonant systems, and also to generalize the Leeson expression for phase noise.

References

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