QUANTUM 1/F NOISE IN SPECTRAL SENSORS, DETECTORS, MIXERS AND OSCILLATORS

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ABSTRACT

The development of spectral-based early warning sensor capabilities is critically dependent [1] on ultra-low noise sensors, detectors and UHF electronic components, e.g., Schottky diode rectifiers, multipliers, mixers, and heterodyne receivers. Schottky barrier diodes are classical room temperature detectors that respond directly with a DC current or voltage, proportional to the square of the a.c. input voltage amplitude. They are particularly useful in the THz frequency domain, but can be extended into the infrared region. They consist of a rectifying metal contact on a semiconductor sample, or of a semimetal-semiconductor heterojunction, as recently demonstrated [2]. On the other hand, a new understanding of the fundamental 1/f noise has emerged from the quantum 1/f theory, providing analytical expressions, and optimization methods for all sensors, detectors, amplifiers, resonators, and oscillators. The present contribution is applying these new methods to various Schottky diodes, for a more complete, first principles, derivation of their Noise Equivalent Power (NEP), which naturally includes a 1/f noise caused part. They are also applied here to other sensor methodologies, technologies and instrumentation that are vital for the most challenging bio-chemical and radiation agent detection and identification systems.

Schottky barrier diodes have a characteristic $I=I_o[\exp(eV/AkT)-1]$, which yields a response and NEP

$$I_d=P_a[d^2I/dV^2][2dI/dV]^{-1};\ \ NEP=[2dI/dV][d^2I/dV^2]^{-1}[S_I(f)\,\Delta f]^{1/2}=(2AkT/e)\,[S_I(f)\,\Delta f]^{1/2} \quad (1)$$

where P_a is the available power of the signal source or antenna assumed to be matched to the detector, $R=2kT/e$ is the responsivity, $1<A<2$ the ideality, and $S_I(f)$ is the power spectral density of noise

$$S_I(f)= 2eI_d +(e^3\alpha_H I_o/3kTf)[v_r v_d/(v_r+v_d)][2N_d(V_{dif}-V)/e\varepsilon]^{1/2}. \quad (2)$$

This expression takes into account the image force and is valid both in the diffusion-limited ($v_r>>v_d$) and thermionic-limited ($v_d>>v_r$) limiting regimes. Here $V_{dif}-V$ is the Schottky barrier height, Δf the bandwidth, N_d the concentration of donors, e the elementary charge, α_H the Hooge constant, and ε the permittivity of the semiconductor. For a small, heavily doped semiconductor, our conventional collisional quantum 1/f expression of α_H is

$$\alpha_H=(4\alpha/3\pi)(6kT/m^*c^2)=10^{-9}Tm/(4m^*100K), \quad (3)$$

with $v_r=(kT/2\pi m^*)^{1/2}$, $v_d=\mu[2eN_d(V_{dif}-V)/\varepsilon]^{1/2}$. For larger semiconductor contacts the capacitance of the diode increases, and a coherent quantum 1/f contribution, shown e.g. in Eq, (2.30) of [3], may yield a much larger α_H. Here α is the fine structure constant 1/137, m the electron's mass and m* its effective mass. Quantum 1/f noise is a property of physical cross sections, a new aspect of quantum mechanics.

As a THz wave mixer, with g_o=dI/dV, this diode would have quantum 1/f phase noise [3] and available matched gain

$$G_{av}=(P_{av})_{out}/P_a=R_aV_p[d^2I/dV^2]^2[4dI/dV]^{-1}\{[1+g_i(R_a+r)]^2+\omega^2C^2(R_a+r)]^2\}^{-1} \quad , \qquad (4)$$

and an equivalent available noise power per unit bandwidth at the antenna

$$(P_{eq})_a=(n_o+F_2-1)(kT/G_{av}), \qquad (5)$$

with an addition due to the phase noise from the mixer. Here R_a is the source (or antenna) resistance, V_p the pump voltage amplitude, r is the series resistance of the bulk region of the diode, C and g_i the capacity and conductance in parallel characterizing the space charge region, F_2 the noise figure of the IF amplifier, $n_o=eI_d/2kTg_o$, and ω the THz source frequency.

For lower THz frequencies, resonant tunneling diode oscillators (RTD) can be used as generators and detectors. Resonant tunneling diodes consist of two potential barriers enclosing a quantum well. If the electron energy is close to the energy level in the well, resonance occurs, and a peak I_P of the current occurs, for the voltage V_P. If the voltage increases further, only a negligibly small non-resonant current trickle remains at the voltage $V=V_V$. 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 $G=-(I_P-I_V)/(V_V-V_P)$ on the I/V curve, that is used to generate oscillations. The 1/f noise in I_V is given by the conventional quantum 1/f effect [4] with $(\Delta\mathbf{v}/c)^2=2eV_V/m$. This yields $I_V^{-2}S_{I_v}(f)=2\alpha A/f\,N$. Here N is given by $N=\tau I_V/e$, where τ is the life time of the carriers. The quantum 1/f frequency fluctuations can be obtained from the formula $S_{\delta\omega/\omega}=(1/4Q^4)S_{\delta G/G}$, which was derived in 1978 [5]. This yields

$$S_{\delta\omega/\omega}=(1/4Q^4)[I_V/(I_P-I_V)]^2(4\alpha/3\pi)(2eV_V/mc^2) \qquad (6)$$

for the fractional frequency fluctuation spectrum exhibited by the RTD, if included in an RF circuit of quality factor Q. For $Q=10^3$ and f=1Hz, we get $S_{\delta\omega/\omega}=5\cdot10^{-28}$/Hz. At $\nu=10^{11}$Hz, the RTD oscillator would have the $1/\omega^3$ phase noise $S_{\Delta\phi}(1Hz)=2\cdot10^{-4}$/Hz, or $\mathcal{L}(1kHz)=-130$dBc/Hz.

This paper will contain more examples of application of the quantum 1/f noise and phase noise theory to THz spectral-based sensing and imaging hardware.

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