Quantum Theory of 1/f Noise in Quantum Well Photodetectors

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***Abstract*—The quantum theory of 1/f noise describes the infrared-divergent conventional 1/f fluctuations of quantum mechanical cross sections and process rates by simple, universal, formulas. We calculate the ones that affect the dark current in quantum wells, and compare with known experimental results.**

***Keywords*—Quantum well photodetectors; 1/f noise; QWIPS; conventional quantum 1/f noise; infrared divergence phenomena))**

I. Introduction

The dark current of Quantum Well Inter-subband or Infrared Photodetectors (QWIPS) is known to be affected by 1/f noise. This limits the detectivity. This paper compares various experimental 1/f noise measurements in QWIPs with the prediction of the conventional quantum 1/f noise expression[1-2] for GaN/AlGaN QWIPs. The elementary process causing the dark current is the transfer of an electron out of one well. This happens under the influence of the applied electric field, and has in general both thermally activated and tunneling components. The larger the applied electric field, the larger is the squared velocity change of the carriers, and the larger is the obtained conventional quantum 1/f effect. The detectivity of the devices is calculated on this basis. The results are compared with measurements of 1/f noise in QWIPs by C. Jelen[3], and the agreement is good.

II. Analytical Calculation

As described by the conventional quantum 1/f theory[1-2], a physical scattering cross section σ (and in general, the rate Γ of any other quantum process, such as a scattering event) exhibits fundamental quantum fluctuations with a 1/f spectral density of fractional fluctuations given by

$$S_{\delta j/j}(f) = j^{-2} S_j(f) = \frac{4\alpha}{3\pi f N}\left(\frac{\Delta v}{c}\right)^2 = S_{\delta\sigma/\sigma}(f) = S_{\delta\Gamma/\Gamma}(f)$$

where $\alpha = e^2/\hbar c = 1/137$ is Sommerfield's fine structure constant, $|q| = e$ is the elementary charge of the electron, $\hbar = h/2\pi$, h is Planck's constant, c the speed of light in a vacuum, N is the number of particles used to define the current j, cross section σ or process rate Γ, and Δv is their velocity change due to such elementary physical processes. With all other factors being constant, all that remains is to formulate suitable expressions for the number of particles, N, and their velocity vector changes, $\Delta \boldsymbol{v}$.

Quantum well devices designed to detect longer wavelengths, e.g. THz, are especially susceptible to increased dark current due to both thermionic emission and thermally assisted tunneling events. In general, the total number of particles defining the dark current consists of the number of carriers that escape out of the quantum wells and the number of these ejected charge carriers, which actually reach the collector of the device. The number of carriers defining the dark current depends on several factors, including donor concentration ρ_{dope}, applied bias U, and the amount of energy W_o required for the carrier to escape the well. Considering these factors, based on the empirical form of the observed dark current, we formulate an expression for the total number of charged carriers N that define the scattered current as:

$$N = N_0 \left(1 + \frac{eU}{W_0}\right) = \rho_{dope} V e^{-W_0/kT} \left\{1 + \frac{eU}{W_0}\right\}$$

where V is the volume of the device, e is the elementary charge, U is the applied bias, and W_0 is the energy required for the donor to escape the well. The above expression gives an approximation for the total number of carriers composing the dark current of the QWIP.

Next, in order to apply the conventional quantum 1/f effect, we must formulate an expression for the momentum change of the carriers. In order to escape the quantum well, the energy required is W_0 , the activation energy, and the energy from the applied voltage U. Together they produce momentum changes, evident when the carriers pass over the next well. The first equation above thus yields the final result, shown in Figs. 1 & 2 in comparison with experiment

$$S_{\delta I_d}(f) = \left\langle (\delta I_d)^2 \right\rangle = \frac{4\alpha}{3\pi f N} \; \frac{2W_0 + 2eU}{m^* c^2} \cdot I_d^2$$

N is the number of particles used to define the current I_d described above, c the speed of light in a vacuum, m^* is the effective mass of the carriers.

III. Comparison with Known Experiments

This first principles result of the conventional quantum theory of 1/f noise was compared with several experimental results published in the literature. We present here as an example, the two samples used in the experiments of Jelen.

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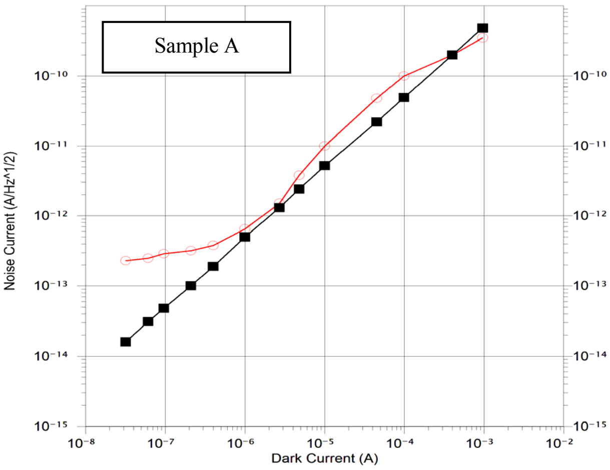

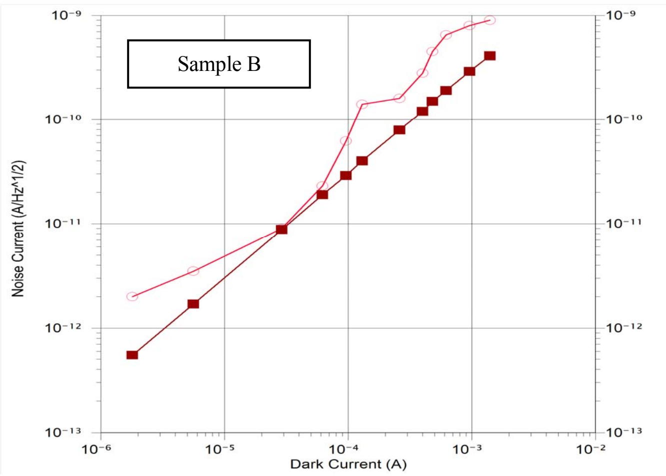

FIGURE 1 and 2. Experimental and theoretical noise current vs. dark current for the case of Jelen's $In_{0.53}Ga_{0.47}As/InP$ QWIP sample 'A' and 'B'. Open circles represent experimental data values. Squares represent theoretical values.

TABLE1. $In_{0.53}Ga_{0.47}As/InP$ quantum well structure parameters of Jelen's Sample 'A'.

PARAMETER	VALUE
MQW periods	20
Quantum well thickness ($In_{0.53}Ga_{0.47}As$)	56 Å
Barrier thickness (InP)	400 Å
Well doping level	8×10^{17} cm^{-3}
Effective electron mass in $In_{0.53}Ga_{0.47}As$	0.042 m_o
Area of QWIP mesa	400 x 400 µm
Conduction band offset	0.229 eV

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TABLE 2. Dark current measured as a function of bias voltage for Jelen's $In_{0.53}Ga_{0.47}As/InP$ QWIP sample 'A'.

BIAS (Volts)	DARK CURRENT (Amps)
0.01	3.2×10^{-8}
0.10	6.1×10^{-8}
0.20	9.6×10^{-8}
0.45	2.1×10^{-7}
0.80	4.0×10^{-7}
1.20	1.0×10^{-6}
1.70	4.8×10^{-6}
2.00	1.0×10^{-5}
2.50	4.5×10^{-5}
2.90	9.9×10^{-5}
3.50	4.0×10^{-4}
4.00	9.6×10^{-4}

TABLE 3. Experimental and theoretical noise current as a function of bias voltage for Jelen's $In_{0.53}Ga_{0.47}As/InP$ QWIP sample 'A'.

Bias (Volts)	**Dark Current (Amps)**	**Experimental Noise Current (A / $Hz^{1/2}$)**	**Theoretical Noise Current (A / $Hz^{1/2}$)**
0.01	3.2×10^{-8}	2.3×10^{-13}	1.6×10^{-14}
0.10	6.1×10^{-8}	2.5×10^{-13}	3.1×10^{-14}
0.20	9.6×10^{-8}	2.9×10^{-13}	4.8×10^{-14}
0.45	2.1×10^{-7}	3.2×10^{-13}	1.0×10^{-13}
0.80	4.0×10^{-7}	3.8×10^{-13}	1.9×10^{-13}
1.20	1.0×10^{-6}	6.5×10^{-13}	5.0×10^{-13}
1.50	2.7×10^{-6}	1.5×10^{-12}	1.3×10^{-12}
1.70	4.8×10^{-6}	3.8×10^{-12}	2.4×10^{-12}
2.00	1.0×10^{-5}	1.0×10^{-11}	5.2×10^{-12}
2.50	4.5×10^{-5}	4.8×10^{-11}	2.2×10^{-11}
2.90	9.9×10^{-5}	1.0×10^{-10}	4.9×10^{-11}
3.50	4.0×10^{-4}	2.0×10^{-10}	2.0×10^{-10}
4.00	9.6×10^{-4}	3.5×10^{-10}	4.8×10^{-10}

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