Quantum 1/f Optimization of Resonant & Nonresonant Sensors
THE EXAMPLE OF QUANTUM WELL IR DETECTORS

Peter H. Handel, Amanda Truong & Erika Splett, Dept. of Physics and Astronomy, Univ. of Missouri, St. Louis Mo 63121 USA

Abstract: QWIPS

The Quantum Well Intersubband or Infrared Photodetector (QWIP) is a multiple quantum well (MQW) photon detector. The design of the structure allows an excited carrier within the well to escape, joining others to form what is called the dark current. This dark current is always present, even without illumination or background radiation. Fluctuations of this dark current will compete with the signal to be detected and limit the detectivity. The noise is described by the fundamental conventional quantum 1/f effect, based on decoherence, and infrared divergence. It describes the fluctuations of physical cross sections of processes that limit the current, such as scattering of the electrons, tunneling, or trapping.

Quantum Well Intersubband Detectors:

QWIPs are semiconductor photon detectors that rely on inter-subband absorption within either the conduction band (n-type) or the valence band (p-type). One requirement of these detectors is that the well material must be doped. Because the energy of an absorbed photon is less than the band gap, it cannot produce an excited photo-carrier by itself. With the addition of carriers in the well, excitation only needs to happen from the first bond state to the next. For n-type QWIPs, intersubband transitions are classified into four types depending on the first excited state of the well and the barrier layer structure.

The dark current, one of the most important aspects regarding performance optimization, refers to the current flow through the QWIP under no illumination. Fluctuations in this dark current compete with the signal for detection and limit the detector performance. See www.umsl.edu/~handel

Quantum 1/f Fluctuations in the Dark Current:

Excited carriers within the well escape with a rate Γ affected by quantum 1/f fluctuations, joining others to form what is called the dark current. The quantum fluctuations of this rate show a 1/f spectral density of fractional fluctuations given by ($\alpha=2\pi e^2/hc=1/137$):

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

Here $\Delta\mathbf{V}/c$ is the vector change in velocity of the charge carriers in the scattering process, divided by the speed of light, and N is the number of particles that defines the scattered current **j**. Thermionic emission of carriers is considered; The dark current is then composed of the number of carriers excited out of the quantum wells and the number of carriers in the continuum, or conduction band region of the device, which are swept along by the applied bias, and eventually reach the collector. Because of the independence, the squared average is also independent and contains no cross terms. The number of carriers defining the dark current depends on several factors including well volume, doping concentration, applied bias, in addition to the ionization W_i and activation W_0 energies of the donors. For each QWIP device, Handel's quantum 1/f formula shown above yields an expression for the spectral density of dark current fluctuations[1-2] based on the activation energy W_0, the expression of the number of carriers N in the dark current, and the applied bias U:

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

Comparison with Experiment:

Theoretical calculations of dark current noise are then compared with several reported experimental findings. The first comparison is with a $Ga_{0.47}$ $In_{0.53}$ As /InP quantum well QWIP fabricated and tested by J.Jiang[3]. Using the parameters of Jiang's QWIP listed below in Table 1, a reasonable approximation of the activation and ionization energies was formulated, leading to an expression for the number of carriers in the dark current. The spectral density of dark current noise fluctuations can then be calculated for increasing values of dark current and applied bias. The results of the comparison are graphically presented in Figure 1 below.

The comparisons with two more experiments are displayed below. Two samples of Jelen[4] and one sample of Thibaudeau[5]. Sample 'A' of Jelen is a $In_{0.53}Ga_{0.47}As$/InP structure and sample "B" is a $In_{0.52}Ga_{0.38}Al_{0.1}As$ /InP QWIP structure. The sample of Thibaudeau is a $GaAs/Al_{0.263}Ga_{0.737}As$ QWIP.

In each case, the theoretically calculated noise spectra are shown to agree with experimental findings, for various types of QWIP structures and molar concentrations. Sample A is larger, has also a coherent Q1/f noise part. These results prove that the quantum 1/f theory is capable of predicting low frequency noise spectra for any given QWIP device (where thermionic emission is the dominant mechanism) and can be used as valuable tool for device improvement and 1/f noise reduction for optimal signal detection.

[1]P.H. Handel, "Quantum Approach to 1/f Noise" Phys. Rev. **22A**, 745-757

[2] A.M. Truong "Quantum 1/f Noise in Infrared Photodetectors and Scanning Tunneling Microscopes", Univ. of Mo Ph.D. Thesis, (2010).

[3] J. Jiang, "Infrared focal plane array based on GaInAs/InP QWIPs", Northwestern U. Ph.D. Thesis, Evanston IL (2003).

[4] C. Jelen, S. Slivken, V. Guzman, M. Razeghi, and G. Brown, "InGaAlAs/InP Quantum Well Infrared Photodetectors for 8–20 µm Wavelengths," IEEE J. Quantum Electron., **34** No.10, p. 1873 (1998).

[5] L. Thibaudeau, P. Bois, and J. Y. Duboz, "A Self – Consistent Model for Quantum Well Infrared Photodetectors," J. Appl. Phys., **79** No.1, pp. 446 (1996).

TABLE 1: Jiang's $Ga_{0.47}$ $In_{0.53}$ As /InP quantum well structure parameters.

PARAMETER	VALUE
MQW periods	20
Quantum well thickness ($Ga_{0.47}$ $In_{0.53}$ As)	57 Å
Barrier thickness (InP)	514 Å
Well doping level	5 x 10^{17} cm^{-3}
Effective electron mass (InP)	0.077 m_o
Area of QWIP mesa	400 x 400 µm
Conduction band offset	0.251 eV

FIGURE 1: Experimental and theoretical noise current vs. dark current for the case of Jiang's $Ga_{0.47}$ $In_{0.53}$ As / InP QWIP. Open circles are experi-mental data values. Squares are theoretical values.

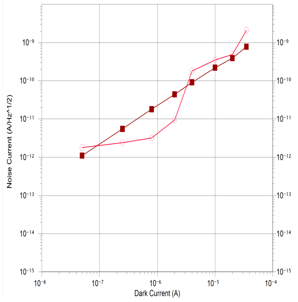

TABLE 2: $In_{0.53}Ga_{0.47}As$/InP quantum well structure parameters of Jelen's sample 'A'

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 x 10^{17} cm^{-3}
Effective electron mass (InP)	0.077 m_o
Area of QWIP mesa	400 x 400 µm
Conduction band offset	0.229 eV

FIGURE 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'. Open circles represent expe-rimental data values. Squares are theoretical values.

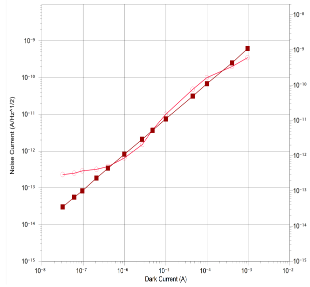

TABLE 3: $In_{0.52}Ga_{0.38}Al_{0.1}As$ /InP quantum well structure parameters of Jelen's sample 'B'.

PARAMETER	VALUE
MQW periods	20
Quantum well thickness ($In_{0.52}Ga_{0.38}Al_{0.1}As$)	59 Å
Barrier thickness (InP)	400 Å
Well doping level	8 x 10^{17} cm^{-3}
Effective electron mass (InP)	0.077 m_o
Area of QWIP mesa	400 x 400 µm
Conduction band offset	0.146 eV

FIGURE 3: Experimental and theoretical noise current vs. dark current for the case of Jelen's $In_{0.52}Ga_{0.38}Al_{0.1}As$ / InP QWIP sample 'B'. Open circles represent experimental data values. Squares are theoretical values.

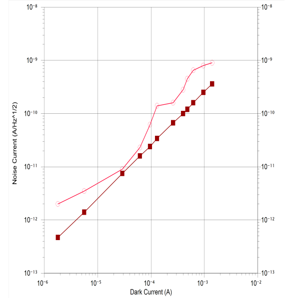

TABLE 4: $GaAs/Al_{0.263}Ga_{0.737}As$ quantum well structure parameters Thibaudeau's sample 'A'.

PARAMETER	VALUE
MQW periods	40
Quantum well thickness (GaAs)	52 Å
Barrier thickness ($Al_{0.263}Ga_{0.737}As$)	342 Å
Well doping level	4.7 x 10^{17} cm^{-3}
Effective electron mass ($Al_{0.263}Ga_{0.737}As$)	0.089 m_o
Conduction band offset	0.227 eV

FIGURE 4: Experimental and theoretical noise current density vs. dark current density for the case of Thibaudeau's $GaAs/Al_{0.263}Ga_{0.737}As$ QWIP sample 'A'. Open circles are experimen-tal data values. Squares are theoretical values.