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14. ABSTRACT

The "9th International van der Ziel Symposium on Quantum 1/f 1/f Noise and Other Low Frequency Fluctuations, mainly in GaN, Quantum or Nanometric Devices" has brought substantial progress both in fundamental quantum 1/f noise theory, and in the application to GaN devices and oscillators. The new developments were obtained in the US, in Japan and in Europe, with the top specialists in this new quantum 1/f field participating from 3 continents, with their students. They have further refined and improved a unique tool for the optimization of high-tech devices and systems, based on the quantum 1/f theory. Finally, they have contributed to the education of a new generation of specialists that can optimize high-tech devices and nano-devices with the quantum 1/f formulas.

15. SUBJECT TERMS
Quantum 1/f Noise, 1/f Noise, Phase Noise, Oscillators, Resonators, Excess Noise, Noise in GaN, HFET, FET

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Final Conference Report

Contents

1. Summary of Scientific Papers Presented

The "9th International van der Ziel Symposium on Quantum 1/f 1/f Noise and Other Low Frequency Fluctuations, mainly in GaN, Quantum or Nanometric Devices" was organized by Supriyo Bandiopadhyay and myself at the Virginia Commonwealth University School of Electrical Engineering in Richmond, Virginia, on August 2-4, 2002. The Vice-President of this young, rich and thriving graduate Campus greeted the Symposium on the first day, and the Associate Dean delivered the Welcome Address. The Proceedings of the Symposium are in final stages of preparation for publication as part of a book at Springer in Heidelberg.

The first paper, "Quantum 1/f Effect in MEMS Resonators and Biochemical Sensors" by myself, presented the new quantum theory of 1/f noise in MEMS resonators, discovered in the first quarter of 2001 under AFOSR Grant. No. F49620-00-1-0306 directed by Dr. Gerald Witt. Originated from an urgent challenge from Dr. John Vig, the problem first appeared to be intractable. Indeed, MEMS are silicon microstructures, with no piezoelectric, paramagnetic or ferromagnetic properties. The MEMS resonators were excited with a wire attached to oscillating microscopic levers similar to oscillating bars fixed at one end. The wire was in a magnetic field and carried a HF current at the resonance frequency. In addition, electrostatic excitation was possible in principle. It was not clear at the beginning how either the QED-type, or the QLD-type coherent or conventional aspects of the quantum 1/f theory could be applied to this case. QED is quantum electrodynamics, and QLD is quantum lattice-dynamics, leading respectively to electrodynamic and piezoelectric quantum 1/f noise.

The solution became possible when I realized that the loss of any quantum of oscillation of a silicon MEMS resonator was accompanied by a corresponding sudden decrease in the rate of change of the magnetic moment of the circuit of the above mentioned wire attached to it. That sudden change in the rate of change of the magnetic moment caused bremsstrahlung that was easy to calculate. The latter, in turn, entailed conventional quantum 1/f noise in the rate of loss of oscillation quanta from the fundamental mode of the mechanical oscillator. A simple, practical engineering formula was derived for the 1/f frequency and $1/f^3$ phase noise caused by these 1/f dissipation fluctuations, and the problem was solved completely.

It was very gratifying to extend the solution to the case of simple electrostatic excitation of the MEMS resonator. In that case, the oscillating MEMS resonator bar would be one of the plates of a capacitor with a HV voltage applied. This time, the bremsstrahlung arises from a sudden decrease of the rate of change in the dipole moment of the capacitor, and is much larger. Therefore, another engineering formula was derived, that shows a much larger $1/f^3$ phase noise for electrostatically excited MEMS resonators, and explains why they are not used. The new formulas are useful for optimizing MEMS resonators. These can be used as microscopic biological and chemical sensors that are hard to detect.

I was the adviser of the international PhD student Sia Eng Kee from Singapore, who got his PhD in October 2003 with the thesis "The Application of Piezoelectric Quantum 1/f Noise Theory to Describe the Low frequency Noise in ELO-GaN and n-GaN". Professors S. J. Chua, Inst. of Mat. Res. & Engr., Singapore (and MIT) and H. L. Hartnagel, Institut fur Hochfrequenztechnik, Germany (Univ. Darmstadt) were supervisors. Sia Eng Kee presented the second invited paper "Coherent Piezoelectric Quantum 1/f Noise in GaN Based Materials", with the main results of his Thesis. This paper contained a detailed experimental and theoretical study of 1/f noise in GaN, on the basis of the quantum 1/f theory. It is the first practical verification in GaN of the coherent piezoelectric quantum 1/f effect, that I had first introduced in 1982-1983 under my first AFOSR Grant, supervised by Dr. Gerald Witt. It is also the first verification of the newly derived connection between the coherent and conventional piezoelectric quantum 1/f effects, in any material. This connection was for the first time presented by me as the last paper of the Symposium, "Derivation of the Connection Between Conventional and Coherent Piezoelectric Quantum 1/f Effect". It was a physical QLD derivation that follows for piezoelectric materials a path similar to the derivation of the s-parameter for vacuum in QED. The new parameter introduced into physics and engineering was called s'.

Professor Munecazu Tacano of Meisei University, Tokyo, Japan, presented the third invited paper of the Symposium, "Cross Correlational Quantum 1/f Noise Parameter of GaN and

Its Measurement", authored by himself and by his group of collaborators and students. This paper brought the results of an extensive system of numerical calculations of the Quantum 1/f Hooge parameter in GaN, based on my earlier detailed analytical calculation performed through the dedication of my Stanford University student Thomas H. Chung-Tyglon in the 80s. These new GaN calculations of conventional QED quantum 1/f noise in GaN were performed on my insistence, with my assistance, and motivated by the great importance Dr. Witt and also ONR and the "Ultra Low Phase Noise Electronics" MURI at UCSB place on GaN.

The fourth paper, presented by Sam Lin, was "1/f Noise Measurement in GaN HFETs" by myself and by my research assistant Sam Lin, provided theoretical and experimental results of our measurements performed on UCSB-CANE's GaN/AlGaN HFETs. Good agreement was obtained with the quantum 1/f HFET formula as a function of drain voltage and as function of gate bias, for 3 different substrates: HVPE GaN, sapphire and SiC.

The afternoon session started with a paper R. Krishnan and M. Cahay, Univ. of Cincinnati, titled "Transition from Sub-Poissonian to Super-Poissonian Shot Noise in Planar Cold Cathodes". It showed the way in which 1/f noise gradually changes the statistics of electronic noise to super-poissonian, when it is added to the current of electrons in increasing proportion.

C. M. Van Vliet, University of Miami, presented the paper "Theory of Multiple Trapping Generation and Recombination Noise in Homogeneous Materials and Space Charge Layers". It used the many-variate Master Equation and the Darwin-Fowler method to prove once more that the Bernamont-Surdin -McWhorter conjecture does not pan out. This shows that there are less than two decades of 1/f-like spectrum that can be obtained this way. A slight extension of this non-fundamental 1/f spectrum is possible when the bans are bent near the surface. The following year Hooge proved independently the inconsistence of the McWhorter model at ICNF'03 Prague.

I presented "Generalization of the Leeson Formula", showing that particularly in the high stability oscillators, a new term must be included into the well known, classical, Leeson formula. It is the Q^{-4} term, directly caused in the oscillation frequency by (usually Quantum 1/f) fluctuations in the dissipation rate. This analytical formula allows for the optimization of oscillators for lowest phase noise, highest operating frequency, and reduced current or gain collapse.

Svetlana Vitusevich from the Forschungzentrum Julich, Germany, presented the invited paper "1/f Noise in III-V High-Electron-Mobility Transistors and its Up-Conversion in Cryogenic Whispering_gallery Mode K-Band Oscillators" by S. Vitusevich, N. Klein and A. E.

Belyaev. This paper shows that the usual reduction of phase noise with temperature is observed also in this oscillator, since the loss tangent of sapphire is proportional to T^5. The quality factor is several millions, over the tuning range that is limited to lower than 50 MHz at 77K.

The up-conversion factor was 3MHz/V, and the phase noise 118 dBc/Hz. Although the oscillator was based on InGaAs?AlGaAs pseudomorphic HEMTs, some GaN/AlGaN HEMTs were also studied, and showed better radiation hardness than their GaAs counterparts.

The paper "Permanent Quantum 1/f Noise Increases in Irradiated Junction Type Devices", presented by me, showed the different responses of junction-type semiconductor devices and FETs to irradiation. The quantum 1/f noise derivation of the radiation caused change in 1/f noise as a function of the respective defect creating cross section and of the radiation dose is the first that has ever been done. It can be used analytically by engineers for the optimization of radiation-hardened devices.

Several papers dealt with fundamental quantum 1/f theory problem that are not immediately applicable in practice. However, Prof. Charles Surya from the Hong Kong Polytechnic Univ., Hong Kong presented "Characterization of 1/f Noise in GaN Based Thin Films and Devices", by B. H. Leung, W. K. Fong and C. Surya. It reported new investigations of low-frequency excess noise in GaN-based cross bridge structures and metal-semiconductor-metal (MSM) devices. The devices were fabricated on GaN thin films deposited by RF-plasma assisted molecular beam epitaxy (MBE) on two different types of buffer structures. The type I buffer layer consisted of a single AlN high temperature buffer layer (HTBL) of thickness about 20 nm. The type II buffer structure consisted of a unique double buffer layer (DBL) structure in which a GaN intermediate temperature buffer layer (ITBL) was deposited on top of a thin buffer layer. The thickness of the ITBL was varied between 400 nm to 1.2 μm. The low-frequency noise was studied as a function of the ITBL thickness. The optimal thickness is found to be 800 nm. The results indicated that both the polarity and the ITBL have significant impact on the low-frequency noise properties of the devices. The Hooge parameter for the Ga-faced cross bridge utilizing the AlN-HTBL/GaN-ITBL DBL system was found to be 3.8×10^{-4}. The MSM devices also exhibit over two orders of magnitude reduction in the flicker noise with the use of the DBL structure, as seen in Fig. 1. We believe that the DBL structure exhibits fundamental QED 1/f noise, because its magnitude corresponds to electrodynamic quantum 1/f effect adequate for the dimensions of the sample. The results clearly indicate significant reduction in the trap density due to the utilization of the DBL. We also performed systematic studies on the hot-electron degradation of the devices through the application of a large voltage bias (stress), as seen on Fig.2. The data demonstrate substantial improvement in the hot-electron hardness for devices fabricated on the double buffer layer structures.

I presented the paper "Coherent Quantum 1/f Effect in Cavity Resonators", that allows for the first time calculation of the quantum 1/f noise caused in the resonance frequency of a Helmholtz resonator by quantum 1/f noise in the skin depth on its metallic walls.

R. S. Duran, Florida Int. Univ. presented "Noise in GaN Based Quantum Well Structures", by R. S. Duran, C. M. Van Vliet, Univ. of Miami, G. L. Larkins, Florida Int. Univ. and H. Morkoc, Virginia Commonwealth Univ. This paper shows that noise in these GaN QW structures is dominated by traps, and that they are not yet close to their quantum limit, requiring many preliminary improvements of the material.

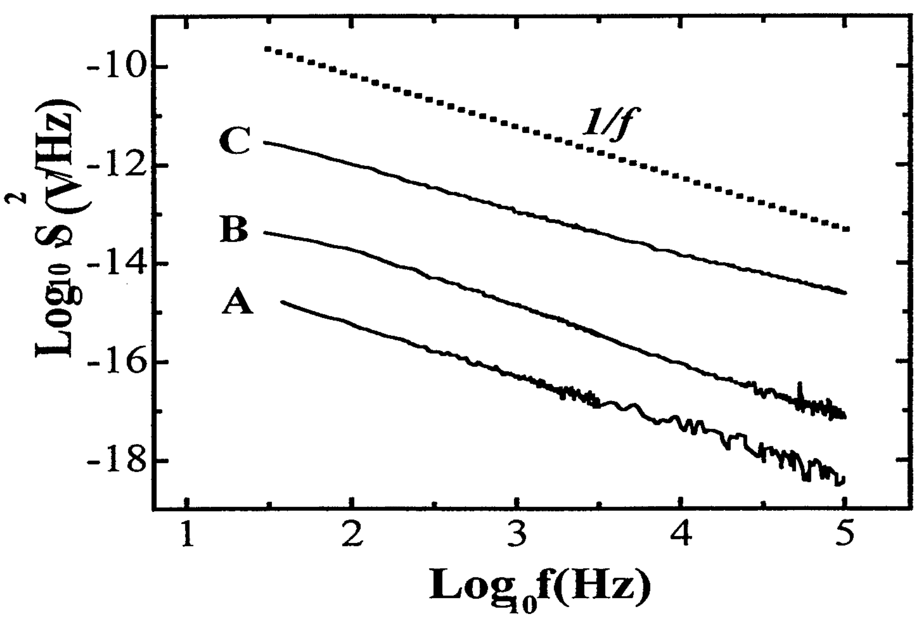

Fig. 1: Voltage noise power spectra measured from cross bridge structures: Device A (Ga-face with 800 nm ITBL); Device B (Ga-face without ITBL); and Device C (N-face without ITBL).

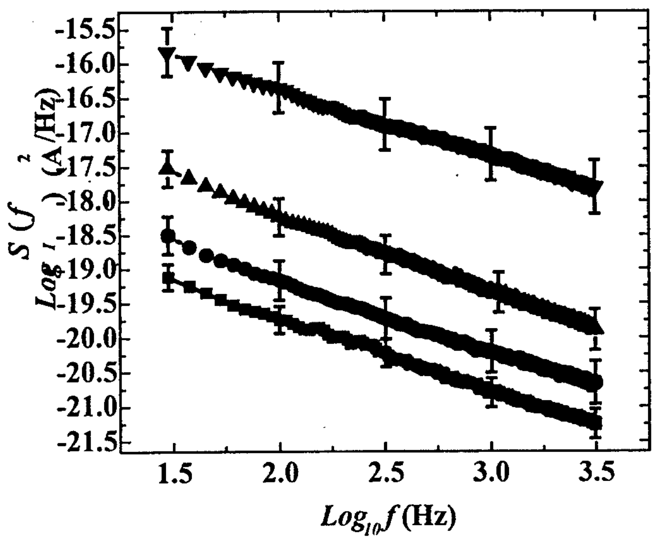

Figure 2: Room temperature current noise power spectra, $S_I(f)$, for device A before stressing (■), device B before stressing (▲), device A after stressing (●), and device B after stressing(▼).

I presented the paper P. H. Handel, Univ. of Missouri-St Louis, USA "Ultra Low Phase Noise HFET Structures", that gives practical engineering formulas for optimizing a GaN/AlGaN HFET for lowest 1/f noise. These can be used for minimizing phase noise, by also reducing at the same time the gate capacitance and the nonlinearities caused by current and gain collapse at high drain voltage.

The following paper presented by S. Bandyopadhyay, Virginia Commonwealth Univ, "What has scattering got to do with noise in nanostructures?", by Supriyo Bandyay and Alexey Swizhenko, showed that the quantum 1/f noise formulas have created a new connection between scattering and 1/f noise, that was not realized before.

Finally, I presented the paper "Derivation of the Connection Between Conventional and Coherent Piezoelectric Quantum 1/f Effect" in which the smooth transition between the coherent and conventional piezoelectric (or Quantum Lattice-Dynamical, not QED) quantum 1/f effect is bridged for the first time. This allows the calculation of 1/f noise in piezoelectric (and therefore also in ferroelectric) materials, such as GaN and AlGaN, independent of the size and polarization of the sample.

In conclusion, the "9th International van der Ziel Symposium on Quantum 1/f 1/f Noise and Other Low Frequency Fluctuations, mainly in GaN, Quantum or Nanometric Devices" has brought substantial progress both in fundamental quantum 1/f noise theory, and in the application to GaN devices and oscillators. The new developments were obtained in the US, in Japan and in Europe, with the top specialists in this new quantum 1/f field participating from 3 continents, with their students. They have further refined and improved a unique tool for the optimization of high-tech devices and systems, based on the quantum 1/f theory. Finally, they have contributed to the education of a new generation of specialists that can optimize high-tech devices and nano-devices with the quantum 1/f formulas. The necessity of a National or International "Quantum 1/f Theory and Applications Institute" was emphasized in discussions with the participants.

2. Program/List of Papers Presented

August 2, 2002 (Morning Session)

8:45-9:00 Welcome address: Bart Creggar, Assoc. Dean of Engineering

Session chair: Marc Cahay, Univ. of Cincinnati

9:00-9:40: (INVITED) P. H. Handel, Univ. of Missouri-St Louis, USA
"Quantum 1/f Effect in MEMS Resonators and Biochemical Sensors"

9:40-10:20 (INVITED) E. K. Sia, S. J. Chua, Inst. of Mat. Res. & Engr., Singapore
H. L. Hartnagel, Institut fur Hochfrequenztechnik, Germany
and P. H. Handel, Univ. of Missouri-St Louis, USA
"Coherent Piezoelectric Quantum 1/f Noise in GaN Based Materials"

10:20-10:40 Coffee Break

10:40-11:20 (INVITED) N. Tanuma, H. Tanoue, H. Tanizaki, S. Yokokura, T. Matsui and M. Tacano, Meisei University, Japan, Electrotechnical Lab, Japan and Electrocommunication Lab, Japan
"Cross correlational Quantum 1/f Noise Parameter of GaN and Its Measurement"

11:20-11:45 P. H. Handel and S. Lin, , Univ. of Missouri-St Louis, USA
"1/f Noise Measurement in GaN HFETs"

August 2, 2002 (Afternoon Session)

Session chair: E-K Sia, Inst. of Mat. Res., Singapore

1:30-2:10 (INVITED) R. Krishnan and M. Cahay, Univ. of Cincinnati, USA
"Transition from Sub-Poissonian to Super-Poissonian Shot Noise in Planar Cold Cathodes"

2:10-2:50 (INVITED) C. M. Van Vliet, University of Miami, USA
"Theory of Multiple Trapping Generation and Recombination Noise in Homogeneous Materials and Space Charge Layers"

2:50-3:15 P. H. Handel, Univ. of Missouri-St Louis, USA
"Generalization of the Leeson Formula"

3:15-3:35 Coffee Break

3:35-4:15 (INVITED) S. Vitusevich and N. Klein, Forschungzentrum Julich, Germany
A. E. Belyaev, Institute of Semiconductor Physics, Ukraine "1/f Noise in III-V High-Electron-Mobility Transistors and its Up-Conversion in Cryogenic Whispering-gallery Mode K-Band Oscillators"

4:15-4:40 P. H. Handel, Univ. of Missouri-St Louis, USA
"Permanent Quantum 1/f Noise Increases in Irradiated Junction Type Devices"

4:40-5:30 Recess

August 2, 2002 (Banquet)

7:00-9:00 Strawberry Street Café.. Casual restaurant with American classics

August 3, 2002 (Morning Session)

Session chair: S. Vitusevich, Forschungzentrum Julich

9:00-9:40 (INVITED) M. Planat, LPMO CNRS Besancon, France
S. Perrine, France Telecom, France
"Arithmetical statistical mechanics: the scene of 1/f noise"

9:40-10:20 (INVITED) P. H. Handel, Univ. of Missouri-St Louis, USA
"Gravidynamic Quantum 1/f Effect"

10:20-10:40 Coffee Break

10:40-11:20 (INVITED) B. H. Leung, W. K. Fong and C. Surya, The Hong Kong Polytechnic Univ., Hong Kong "Characterization of 1/f Noise in GaN Based Thin Films and Devices"

11:20-11:45 P. H. Handel, Univ. of Missouri-St Louis, USA
"Coherent Quantum 1/f Effect in Cavity Resonators"

August 3, 2002 (Afternoon Session)

Session chair: M. Tacano, Meisei Univ., Japan

1:30-2:10 (INVITED) H. Unlu, Istanbul Technical Univ., Turkey
"Modeling of Quantum 1/f Noise in Nanoscale III-Nitride Heterostructure Bipolar Devices"
2:10-2:50 (INVITED) R. S. Duran, Florida Int. Univ. USA
C. M. Van Vliet, Univ. of Miami, USA
G. L. Larkins, Florida Int. Univ. USA
H. Morkoc, Virginia Commonwealth Univ, USA
"Noise in GaN Based Quantum Well Structures"

2:50-3:15 P. H. Handel, Univ. of Missouri-St Louis, USA

"Ultra Low Phase Noise HFET Structures"

3:15-3:35 Coffee Break

3:35-4:15 (INVITED) S. Bandyopadhyay, Virginia Commonwealth Univ, USA
A. Svizhenko, NASA Ames Research Center, USA
"What has scattering got to do with noise in nanostructures?"

4:15-4:40 P. H. Handel, Univ. of Missouri-St Louis, USA
"Derivation of the Connection Between Conventional and Coherent Piezoelectric Quantum 1/f Effect"

August 4, 2002

9:00-10:00 P.H. Handel: Symposium Summary, Discussions, and Closing Remarks
10:00-13:00 Quantum 1/f Noise Retreat: Free Forum at the Virginia Microelectronics Center, Virginia Commonwealth University

3. List of Participants

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Virginia Commonwealth University
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August 2-4, 2002

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Belyaev, A.E.
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Cahay, M
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Duran, R.S.
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