

# Low Flicker-Noise GaN/AlGa<sub>N</sub> Heterostructure Field-Effect Transistors for Microwave Communications

A. Balandin, S. V. Morozov, S. Cai, R. Li, K. L. Wang, *Fellow, IEEE*,  
G. Wijeratne, *Member, IEEE*, and C. R. Viswanathan, *Life Fellow, IEEE*

**Abstract**—We report a detailed investigation of flicker noise in novel GaN/AlGa<sub>N</sub> heterostructure field-effect transistors (GaN HFET). Low values of  $1/f$  noise found in these devices (i.e., the Hooge parameter is on the order of  $10^{-4}$ ) open up the possibility for applications in communication systems. We have examined the scaling of the noise spectral density with the device dimensions in order to optimize their performance. It was also found that the slope  $\gamma$  of the  $1/f^\gamma$  noise density spectrum is in the 1.0–1.3 range for all devices and decreases with the decreasing (i.e., more negative) gate bias. The results are important for low-noise electronic technologies requiring a low phase-noise level.

**Index Terms**—FET's, microwave, nitrogen compounds, noise measurement.

## I. INTRODUCTION

**L**OW-NOISE electronic technologies for mobile communications impose strict limitations on the value of phase noise in the constituent devices. Continuous down-scaling of the device feature size and increasing package densities also require high temperature (high power density) operation of these devices.

Recently, wide-bandgap compound semiconductors demonstrated potential for high-frequency and high power-density device applications. These materials offer several inherent advantages, such as higher breakdown voltage, higher thermal conductivity, comparable carrier mobility, and high saturation velocity. GaN is among those that show a great promise for microwave applications.

Development of high-performance microwave technology requires detailed knowledge of the noise behavior of the devices. It is particularly important to know the value of flicker noise, e.g.,  $1/f$  noise, since this type of noise is the limit-

ing figure for all kinds of high electron-mobility transistors (HEMT's) and MOSFET's. Especially when these devices are used as oscillators or mixers, the flicker noise limits the phase-noise characteristics and degenerates the performance of the electronic system.

Recent advances in GaN-related compound materials and heterojunction field-effect transistors (HFET's) have led to demonstration of high power-density microwave operation of these devices. However, little is known about their noise behavior. There have been reported values of the low-frequency noise varying as much as four orders of magnitude. For example, in [1] and [2], the authors reported values of the Hooge parameter higher than  $10^{-2}$ . Current authors in their preliminary investigation found that the Hooge parameter of GaN/AlGa<sub>N</sub>/sapphire HFET devices was on the order of  $10^{-5}$ – $10^{-4}$  at rather high values of the drain bias  $V_{DS} = 5$  V (subsaturation region) [3]. The values of the Hooge parameter  $\alpha_H$  of about  $(1.5\text{--}4) \times 10^{-4}$  were reported for AlGa<sub>N</sub>/GaN HEMT's grown on SiC substrates in [4]. These discrepancies seem to arise from the variations of material quality (e.g., mobility, doping, defects in the barrier layer), and device processing (e.g., contact resistance, geometry, etc.). Due to this reason, a more detailed investigation of the noise behavior of these devices is needed.

This investigation is particularly difficult since there is no universally accepted  $1/f$  noise theory even for devices based on conventional material systems such as GaAs or Si. No single model has been able to explain all the diverse results obtained under different experimental conditions and from different devices. At this time, there are two competing models that are invoked to explain noise data: the carrier density fluctuation model and the mobility fluctuation model. The former attributes noise to random trapping and detrapping of free carriers by traps that have a particular distribution of time constants. McWhorter noted that such a distribution could arise naturally at a semiconductor–oxide interface from a spatially uniform distribution of tunneling depths to the trapping sites [5]. This model seems to work well for CMOS devices.

In this paper, we report investigation of  $1/f$  flicker noise in GaN HFET's designed for microwave applications. The remainder of this paper is organized as follows. In Section II, we present device structure and measurement procedures. The results of the measurements and discussion are given in Section III. Finally, conclusions are drawn in Section IV.

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A. Balandin was with the Electrical Engineering Department, University of California at Los Angeles, Los Angeles, CA 90095-1594 USA. He is now with the Electrical Engineering Department, University of California at Riverside, Riverside, CA 92502 USA.

S. V. Morozov is with the Institute of Microelectronic Technology, Russian Academy of Sciences, Chernogolovka 142432, Russia.

S. Cai, R. Li, K. L. Wang, G. Wijeratne, and C. R. Viswanathan are with the Electrical Engineering Department, University of California at Los Angeles, Los Angeles, CA 90095-1594 USA.

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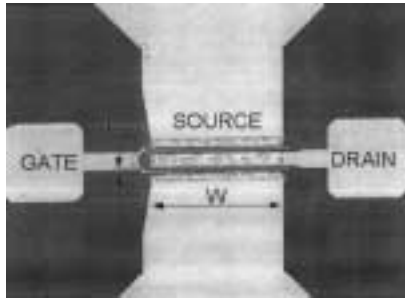


Fig. 1. Top view of the examined device shown with the notations used in the text.

## II. DEVICE STRUCTURE AND MEASUREMENTS

We have carried out a detailed investigation of the flicker noise in a GaN/Al<sub>0.15</sub>Ga<sub>0.85</sub>N-doped channel HFET (referred as a GaN HFET). The devices were made from a commercial wafer grown by the standard metal-organic chemical vapor deposition (MOCVD) technique. During the device fabrication step, we paid special attention to improvement of the ohmic contacts. The composition of various metal films and details of the rapid thermal annealing processes used for fabrication of GaN HFET's were reported earlier [6]. The top view of the GaN HFET and typical dimensions are shown in Fig. 1. The layered structure was fabricated on a sapphire substrate. A 1.0- $\mu\text{m}$ -thick i-GaN buffer layer was followed by 50-nm-thick n-GaN layer with the doping level of  $5 \times 10^{17} \text{ cm}^{-3}$ , and 3-nm-thick i-Al<sub>0.15</sub>Ga<sub>0.85</sub>N-undoped spacer layer. On top, there was 30-nm-thick n-Al<sub>0.15</sub>Ga<sub>0.85</sub>N layer with the doping level of  $2 \times 10^{18} \text{ cm}^{-3}$ . The barrier and channel doping resulted in a sheet electron concentration of about  $1.6 \times 10^{13} \text{ cm}^{-2}$ . Electron Hall mobility was determined to be  $460 \text{ cm}^2 \text{ V/s}$  at room temperature.

Devices selected for this paper had a fixed gate length  $L_G = 0.25 \mu\text{m}$ . A device with  $L_{DS} = 3 \mu\text{m}$  had the drain current  $I_{DS} = 0.55 \text{ A/mm}$  at the gate bias  $V_{GS} = -3.0 \text{ V}$ . The maximum transconductance (for negative gate biases) was  $g_m = 102 \text{ mS/mm}$  (at  $V_{GS} = -5 \text{ V}$ ). A device with  $L_{DS} = 2 \mu\text{m}$  had the maximum transconductance (for negative gate biases)  $g_m = 133 \text{ mS/mm}$  at  $V_{GS} = -3 \text{ V}$  ( $L_G = 0.25 \mu\text{m}$ ).

We have examined a large number of devices (over 20) with the gatewidth  $W = 2 \times 40 \mu\text{m}$ , and four different source-drain separation distances  $L_{SD} = 2, 3, 4$ , and  $5 \mu\text{m}$ . All examined devices were made on the same wafer. For these devices, we obtained experimental dependence of the equivalent input referred noise power spectrum on frequency, gate, and drain voltages. The measurements were carried out for both the linear region of the device operation corresponding to low drain-source voltage  $V_{DS}$  and the onset of the saturation region of operation (subsaturation) corresponding to  $V_{DS} = 5 \text{ V}$ .

Typical dc current-voltage characteristic of GaN HFET is presented in Fig. 2(a) and (b). In Fig. 2(a), the gate bias  $V_{GS}$  is used as a parameter and it changes from  $0 \text{ V}$  with the step of  $-1 \text{ V}$ . In Fig. 2(b), the drain bias  $V_{DS}$  varies from  $0 \text{ V}$  with the step of  $+1 \text{ V}$ .

The low-frequency noise measurement system consists of a low-noise amplifier (three stages), dynamic signal analyzer,

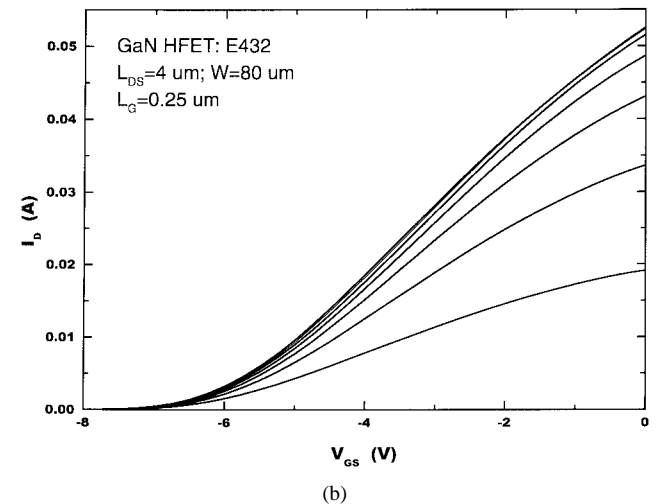
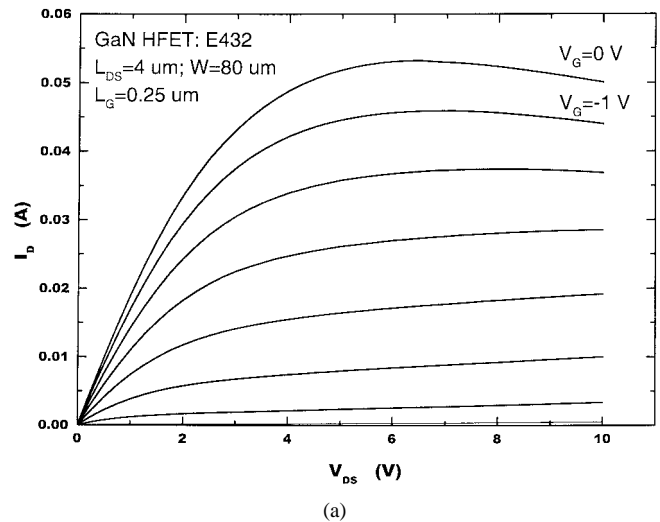


Fig. 2. DC current-voltage characteristics for GaN HFET E432. The gatewidth  $W = 80 \mu\text{m}$ , gate length  $L_G = 0.25 \mu\text{m}$ , and source-drain separation distance  $L_{DS} = 4 \mu\text{m}$ . (a) The gate bias  $V_{GS}$  is used as a parameter and it changes from  $0 \text{ V}$  (top curve) with the step of  $-1 \text{ V}$ . (b) The drain bias  $V_{DS}$  varies from  $0 \text{ V}$  (bottom curve) with the step of  $+1 \text{ V}$ .

and bias power supplies. The HP4142B modular source and monitor were used for current-voltage measurements. The amplifier is made from commercially available integrated circuit (IC) op amps and has an equivalent noise voltage on the order of  $3 \text{ nV}/\sqrt{\text{Hz}}$  and an equivalent noise current of  $2 \text{ pA}/\sqrt{\text{Hz}}$ . A detailed description of the amplifier used for these measurements can be found in [7]. The amplifier and GaN HFET's were enclosed in a shielded box during the measurements in order to prevent pick up of environmental noise.

## III. RESULTS OF NOISE MEASUREMENTS

Experimental noise spectra of two GaN HFET's for different gate bias  $V_{GS}$  and a fixed drain voltage  $V_{DS} = 5 \text{ V}$  are shown in Fig. 3(a) and (b). The threshold voltage for both devices is  $V_T = -7.5 \text{ V}$ . As one can see, the slope  $\gamma$  of the  $1/f^\gamma$  dependence in all spectra is very close to one, although varies for different devices and gate bias values. We did not observe any clear trace of the generation-recombination ( $g-r$ ) bulges in the noise spectra.

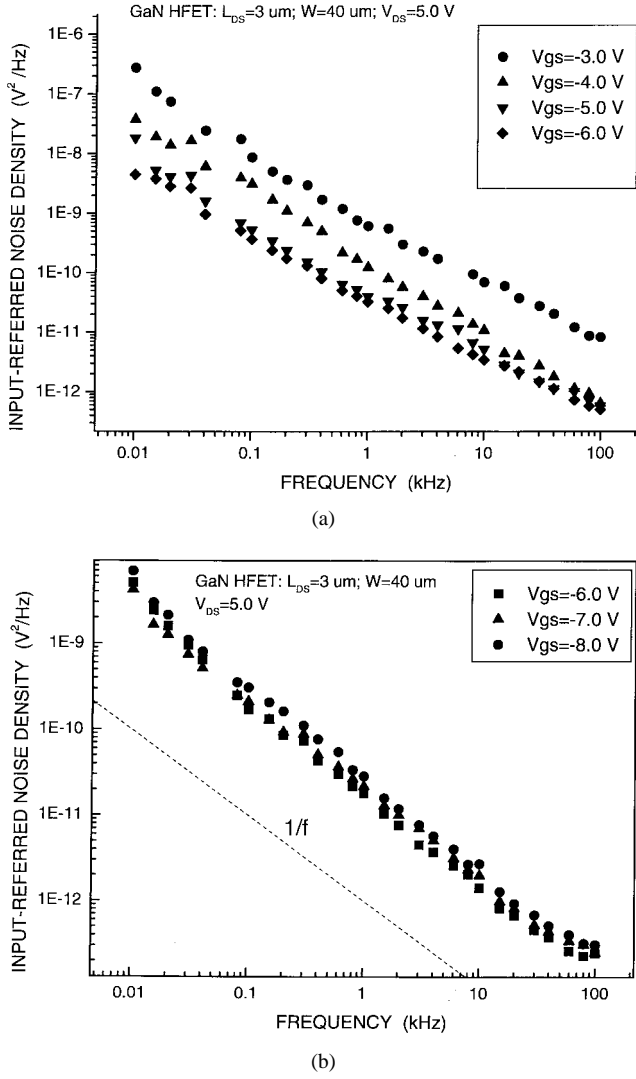


Fig. 3. Input referred noise spectra for GaN HFET E332. The drain bias  $V_{DS} = 5$  V. The gate dimensions are  $0.25$   $\mu\text{m} \times 80$   $\mu\text{m}$ , the source–drain separation distance  $L_{DS} = 4$   $\mu\text{m}$ .

The equivalent input-referred noise spectral density, shown in Fig. 2, was obtained from the drain–current noise spectral density using the regular relation

$$S_{V_{eq}} = \frac{S_{I_D}}{g_m^2} \quad (1)$$

where  $S_{V_{eq}}$  is the equivalent input-referred noise spectral density,  $S_{I_D}$  is the drain current noise spectral density, and  $g_m$  is the transconductance of the device.

One can see from Fig. 3 that at relatively small absolute values of the gate bias  $|V_{GS}|$ , the noise spectral density  $S_V$  is gate bias dependent, and decreasing with a higher negative bias. At high absolute values of the gate bias [see Fig. 3(b)] when the channel is almost pinched off, the noise density is about the same for different values of  $V_{GS}$ . This type of behavior was characteristic for all examined transistors. For comparison, it is also interesting to note how close the experimental curves to the  $1/f$  function shown in the figure.

In order to have quantitative characteristic of the overall noise in the device, we use the Hooge parameter  $\alpha_H$

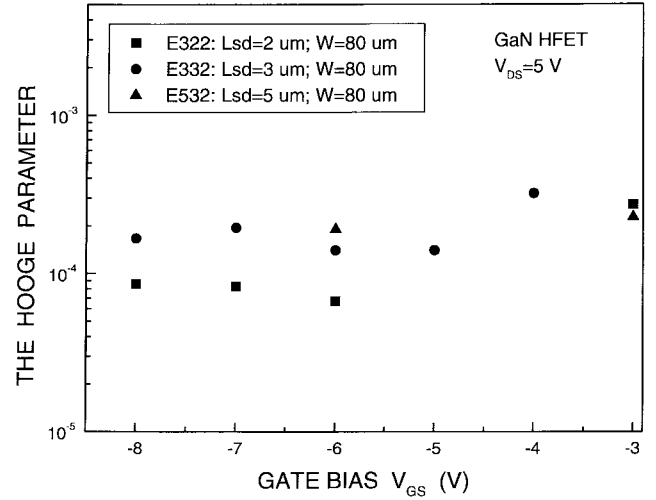


Fig. 4. Hooge parameter  $\alpha_H$  as a function of the gate bias. The results are shown for three devices biased at  $V_{DS} = 5$  V. The gate dimensions are  $0.25$   $\mu\text{m} \times 80$   $\mu\text{m}$ .

introduced via [8]

$$\frac{S_{I_D}}{I_D^2} = \frac{\alpha_H}{Nf} \quad (2)$$

where  $f$  is the frequency,  $N$  is the total number of carriers under the gate calculated from the drain–source current at which the noise was measured. The number of carriers in homogeneous samples can be expressed as

$$N = \frac{L^2}{R\mu}. \quad (3)$$

Here,  $\mu$  is the mobility in the conducting channel,  $R$  is the resistance between two device terminals, and  $L$  is the channel length. Two quantities ( $R$  and  $\mu$ ) in (3) are determined experimentally. The resistance is found at a given  $V_{DS}$  during the noise measurements, while the mobility is determined for the layered structure using the Hall measurements. The gate leakage current for the devices was small (less than 1%) and, hence, its effect on their noise performance was neglected. The values of  $N$  and  $\alpha_H$ , calculated by using (2) and (3), are approximate numbers since the conducting channel of the device is not a homogeneous one. Meanwhile, consistent use of these equations for devices similar in design and utilization of the same type of mobility measurements gives rather precise comparative characteristic of the noise level.

Finally, the Hooge parameter was calculated using (1)–(3) for different devices and bias points. The results for  $V_{DS} = 5$  V are given in Fig. 4. Despite some variations of the  $\alpha_H$  parameter values, they are all close to  $10^{-4}$ . It is also seen that  $\alpha_H$  almost does not depend on the gate bias. For all examined values of  $L_{DS}$ , the Hooge parameter was in the same range and did not show any clear trend. Based on this, we concluded that the source–distance separation does not strongly affect low-frequency noise performance of GaN HFET's.

Very low values of the Hooge parameter determined for our devices prove that GaN HFET's can be used in microwave applications. For comparison, the measured  $\alpha_H$  for the commercial GaAs MESFET NEC NE244 device is approximately  $2 \times 10^{-4}$ , and it is also not sensitive to the gate voltage [9].

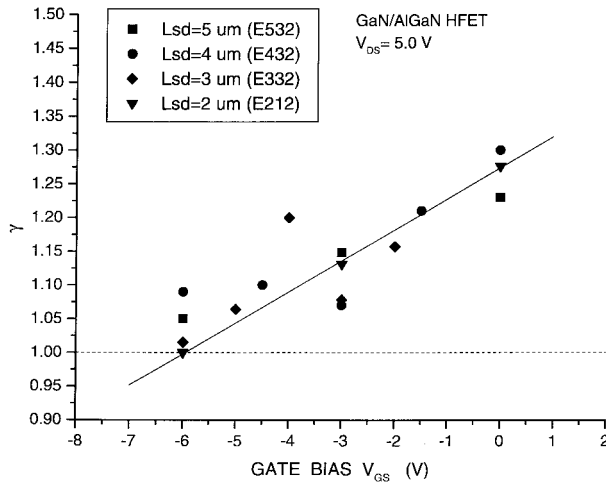


Fig. 5. Dependence of the exponent  $\gamma$  of the  $1/f^\gamma$  noise power density on the gate bias. The results are shown for four devices with different  $L_{DS}$ . All four devices are biased at  $V_{DS} = 5$  V. The exponent  $\gamma$  approaches one with more negative bias.

In AlGaAs/GaAs MODFET's ( $1 \mu m \times 300 \mu m$ ), the Hooge parameter was approximately  $7.2 \times 10^{-5}$  as reported in [9]. The value of the Hooge parameter determined for GaAs MODFET's in [10] was approximately  $2 \times 10^{-4}$ . All these numbers indicate that the overall noise level in GaN HFET's examined by us is comparable to the one in conventional GaAs FET's.

One should note that the Hooge parameter  $\alpha_H$  in our analysis was used as a figure-of-merit for the purpose of comparison with other published results and was not intended to suggest the mobility fluctuation model and not carrier density fluctuation noise model for our devices [11], [12].

In an attempt to clarify the origin of the low-frequency noise in our devices, we extracted the exponent  $\gamma$  of the  $1/f^\gamma$  noise power density for all examined devices and studied its gate bias dependence. The  $\gamma$  versus  $V_{GS}$  dependences are shown in Fig. 5 for four devices with different  $L_{DS}$ . All four devices are biased at  $V_{DS} = 5$  V. One can see that  $\gamma$  is in the range of  $1.0 < \gamma < 1.3$  and decreases with increasing (more negative) gate bias. Such a dependence of the magnitude of the  $1/f^\gamma$  noise spectral density can be most easily interpreted in terms of the modified carrier density fluctuation model [13], which is an extension of the well-established McWhorter formalism. The modified carrier-density fluctuation model explains the liner dependence of the exponent  $\gamma$  on the gate bias by the nonuniformity of the trap distribution. The argument is that trap density across the band gap varies with energy, and the band bending with increasing gate voltage will change the number of effective traps and, thus, the time constants contributing to  $1/f^\gamma$  noise. Since the quality of GaN/AlGaIn heterojunctions remains rather poor, we expect a lot of imperfections (traps) nonuniformly distributed both in energy and space. Due to this reason, the above interpretation of the pronounced  $\gamma$  dependence on the gate bias seems very realistic.

#### IV. CONCLUSION

We have carried out a detailed investigation of the low-frequency noise characteristics of GaN HFET's grown on a

sapphire substrate. Our results indicate that the average value of the Hooge parameter  $\alpha_H$  of GaN HFET's is on the order of  $10^{-4}$ . This low value of the  $1/f$  noise is comparable to the noise level in conventional GaAs FET's. The latter indicates possibility of the use of microwave GaN HFET's in communication systems, particularly those requiring high power density and high-temperature operation. The presented results also allow to model the noise response of the devices for different gate and drain biases and device geometrical dimensions.

#### REFERENCES

- [1] M. E. Levinshtein, F. Pascal, S. Contreras, W. Knap, S. L. Rumyantsev, R. Gaska, J. W. Yang, and M. S. Shur, "Low-frequency noise in GaN/GaAlN heterojunctions," *Appl. Phys. Lett.*, vol. 72, no. 23, p. 3053, 1998.
- [2] D. V. Kuksenkov, H. Temkin, R. Gaska, and J. W. Yang, "Low-frequency noise in AlGaIn/GaN heterostructure field effect transistors," *IEEE Electron Device Lett.*, vol. 19, pp. 222–224, July 1998.
- [3] A. Balandin, S. Cai, R. Li, K. L. Wang, V. R. Rao, and C. R. Viswanathan, "Flicker noise in GaN/Al<sub>0.15</sub>Ga<sub>0.85</sub>N-doped channel heterostructure field effect transistors," *IEEE Electron Device Lett.*, vol. 19, pp. 475–477, Dec. 1998.
- [4] M. E. Levinshtein, S. L. Rumyantsev, R. Gaska, J. W. Yang, and M. S. Shur, "AlGaIn/GaN high electron mobility field effect transistors with low  $1/f$  noise," *Appl. Phys. Lett.*, vol. 73, no. 8, p. 1089, 1998.
- [5] For a review on  $1/f$  noise device theory see A. Van Der Ziel, "Unified presentation of  $1/f$  noise in electronic devices: Fundamental  $1/f$  noise sources," *Proc. IEEE*, vol. 76, p. 233, Mar. 1988.
- [6] S. J. Cai, R. Li, Y. L. Chen, L. Wong, W. G. Wu, S. G. Thomas, and K. L. Wang, "High performance AlGaIn/GaN HEMT with improved Ohmic contacts," *Electron. Lett.*, vol. 34, no. 24, p. 2354, 1998.
- [7] J. Chang, A. A. Abidi, and C. R. Viswanathan, "Flicker noise in CMOS transistors from subthreshold to strong inversion at various temperatures," *IEEE Trans. Electron. Devices*, vol. 41, pp. 1965–1971, Nov. 1994.
- [8] F. N. Hooge, T. G. M. Kleinpenning, and L. K. J. Vandamme, *Rep. Prog. Phys.*, vol. 44, p. 479, 1981.
- [9] K. Duh and A. van der Ziel, "Hooge parameters for various FET structures," *IEEE Trans. Electron. Devices*, vol. ED-32, pp. 662–666, Mar. 1985.
- [10] J.-M. Peransin, P. Vignaud, D. Rigaud, and L. K. J. Vandamme, "1/f noise in MODFET's at low drain bias," *IEEE Trans. Electron. Devices*, vol. 37, pp. 2250–2253, Oct. 1990.
- [11] L. K. J. Vandamme, "Model for  $1/f$  noise in MOS transistors biased in the linear region," *Solid State Electron.*, vol. 23, p. 317, 1980.
- [12] L. K. J. Vandamme and H. M. M. de Werd, "1/f Noise model for MOST's biased in nonohmic region," *Solid State Electron.*, vol. 23, p. 325, 1980.
- [13] Z. Celik-Butler and T. Y. Hsiang, "Spectral dependence of  $1/\gamma$  noise on gate bias in N-MOSFETS," *Solid State Electron.*, vol. 30, p. 419, 1987.



**A. Balandin** was born in Nizhny Novgorod, Russia, on April 30, 1968. He received the M.S. degree (*cum laude*) in applied physics and mathematics from the Moscow Institute of Physics and Technology (PhysTech), Dolgoprudny, Russia, in 1991, and the M.S.E.E. and Ph.D. degrees in electrical engineering from the University of Notre Dame, Notre Dame, IN, in 1995 and 1996, respectively.

From 1996 to 1997, he was a Research Associate in the Quantum Device Laboratory, University of Nebraska, Lincoln. In 1997, he joined the Device Research Laboratory, Electrical Engineering Department, University of California at Los Angeles, as a Research Engineer. Since July 1999, he has been an Assistant Professor of electrical engineering at the University of California at Riverside. His research interests are in electronic materials and devices, low-dimensional phenomena, nonlinear optics, noise theory and measurements, thermoelectrics, and quantum and nanoelectronic computer architectures.

Dr. Balandin is a member of Eta Kappa Nu.



**S. V. Morozov** received the B.S. and M.S. degrees in physics from the Moscow Institute of Steel and Alloys, Moscow, Russia, in 1982 and 1984, respectively, and the Ph.D. degree from the Institute of Microelectronics Technology of the Russian Academy of Sciences, Chernogolovka, Russia, in 1992.

In 1984, he joined the Institute of Microelectronics Technology, Russian Academy of Sciences, where he is currently a Senior Scientific Staff Member in the Semiconductor Nanostructures Physics

Laboratory. His research interests focus on the investigation and development of high-speed heterostructure devices, physics of hot electrons in short channel heterostructures, resonant tunneling phenomena, and 2DEG quantum transport in high magnetic fields. In 1998, he spent three months as a Visiting Scientist at the Device Research Laboratory, University of California at Los Angeles.

**S. Cai**, photograph and biography not available at the time of publication.

**R. Li**, photograph and biography not available at the time of publication.

**K. L. Wang** (S'68–M'70–SM'78–F'92) received the M.S. and Ph.D. degrees in electrical engineering from the Massachusetts Institute of Technology (MIT), Cambridge, in 1966 and 1970, respectively.

From 1970 to 1972, he was an Assistant Professor at MIT. From 1972 to 1979, he was a Physicist and Electrical Engineer with the General Electric Corporate Research and Development Center. He also served as an Adjunct Professor in the Department of Physics, State University of New York, Albany. Since 1982, he has been a Professor of electrical engineering at the University of California at Los Angeles, where, from 1993 to 1996, he was also Chairman of the Department. He has published over 200 papers in various areas of semiconductor material and devices, including those relating to surfaces and interfaces, molecular beam epitaxy (MBE) growth, nanostructures, and devices, as well as processing technology.

Dr. Wang is a Guggenheim Fellow and received the J. H. Ahler Achievement Award (1991), SRC Invention Awards (1989–1996), and SRC Technical Excellence Award (1996).



**G. Wijeratne** (S'96–M'97) was born in Colombo, Sri Lanka. He received the B.S. and M.S. degrees in electrical engineering from the University of California at Los Angeles.

He is currently a Graduate Researcher in the Device Modeling and Characterization Laboratory, University of California at Los Angeles, where his work includes studies on deep submicrometer symmetric and asymmetric CMOS devices, GaN/AlGaIn/SiC HET's, modeling techniques involving  $1/f$  flicker noise, and hot carrier effects

in MOS devices.

**C. R. Viswanathan** (M'60–SM'78–F'81–LF'95) received the undergraduate degrees in India and the Ph.D. degree from the University of California at Los Angeles (UCLA).

He is currently a Professor of electrical engineering and has served as the Chairman of the Electrical Engineering Department and as Assistant Dean of the School of Engineering, UCLA. His research interest is in semiconductor electronics. He has spent the past few years involved with low-temperature operation of semiconductor devices, small geometry devices, and low-frequency noise.

Dr. Viswanathan has served as the director of the California MICRO Program. He has been the recipient of several teaching and research awards.