Low-frequency noise in GaN nanowire transistors

S. L. Rumyantsev[a] and M. S. Shur
Department of Electrical, Computer, and Systems Engineering, CII 9017, Rensselaer Polytechnic Institute, Troy, New York 12180-3590, USA

M. E. Levinshtein
Ioffe Institute of Russian Academy of Sciences, St. Petersburg 194021, Russia

A. Motayed and A. V. Davydov
National Institute of Standards and Technology, Gaithersburg, Maryland 20899, USA

(Received 4 December 2007; accepted 7 January 2008; published online 17 March 2008)

Noise in nanostructures is one of the key problems impeding their applications in electronic devices. We show that the level of $1/f$ and recombination-generation noise in GaN nanowire field effect transistors can be suppressed by ultraviolet radiation by up to an order of magnitude. This strong suppression of the noise is explained by the illumination changing the occupancy of traps responsible for noise. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2895398]

INTRODUCTION

Semiconductor nanowires are attractive candidates for applications in tiny diodes and transistors,[1–8] light emitting diodes,[9] gas sensors,[10,11] and power sources.[12] They are also finding applications in field-emission devices,[13] as elements of flexible electronics[14] and for enhancement of light emitting diodes performance.[15] However, a high noise level limits applications of one-dimensional structures in electronics and photonics. While noise in carbon nanotubes has been studied extensively (see Ref. 16 and references therein), noise studies of semiconductor nanowires are limited to a few publications.[17,18]

This paper reports on the low-frequency noise in GaN nanowire transistors and its suppression by UV light.

EXPERIMENTAL DETAILS

Gallium nitride nanowires with the lengths up to $L = 200\ \mu$m were grown by chemical vapor deposition (CVD) utilizing reaction of gallium vapor with ammonia at 850–900 °C in a horizontal furnace. Figure 1 shows field-emission scanning electron microscope (FESEM) image of GaN nanowires attached to the growth matrix. The growth matrix consisted of GaN microplatelets and nanowires, which often originated at the edges of microplatelets (see inset in Fig. 1). More growth details are given elsewhere.[19] Typical nanowires used for electrical measurements (such as the one encircled in the figure by a dash line for eye guidance) were 20–40 μm in length and 50–250 nm in diameter.

Transmission electron microscopy and electron-backscattered diffraction techniques confirmed that the growth direction of these nanowires was along the a axis of the wurtzite structure.[20] A suspension of nanowires in isopropanol formed by sonicating the growth matrix was dispersed on a SiO_2/Si substrate (p type, $\rho = 0.02\ \Omega$ cm) with predefined Ti (60 nm) metal pads. The silicon dioxide was thermally grown and had thickness of $h = 600$ nm. The nanowire alignment was obtained by applying 10 V peak-to-peak sinusoidal voltage at 1 kHz between the metal pads.[21] After the alignment, a 50 nm SiO_2 passivation layer was deposited on the sample using plasma enhanced chemical vapor deposition (PECVD). The oxide was removed over the metal-nanowire contact area using photolithography and wet etching, and a second metal layer (Ti/Al/Ti/Au, 30/100/30/30 nm) was deposited. The structures obtained by this method represented field effect transistors (FETs) with the common gate (Si substrate) and symmetrically designed drain and source contacts (see inset in Fig. 2).

The current-voltage characteristics and low-frequency noise in the frequency range from 1 Hz to 50 kHz were measured on wafer using the probe station with the tungsten probes. The voltage fluctuations S_V from the load resistor $R_L = 1–10\ \mathrm{k}\Omega$ connected in series with the drain were analyzed by a network analyzer.

The commercially available light emitting diodes

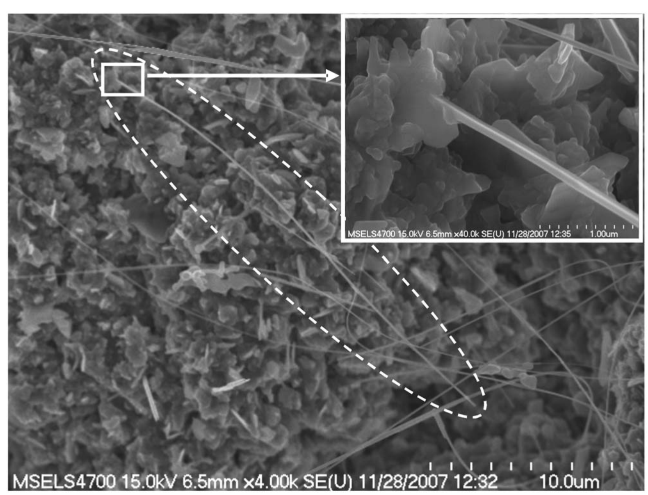

FIG. 1. FESEM images of GaN nanowires on the growth matrix. The inset shows the higher magnification image of the GaN nanowire originated at the edge of microplatelet.

[a]On leave from Ioffe Institute of Russian Academy of Sciences, 194021 St-Petersburg, Russia. Electronic mail: roumis2@rpi.edu.

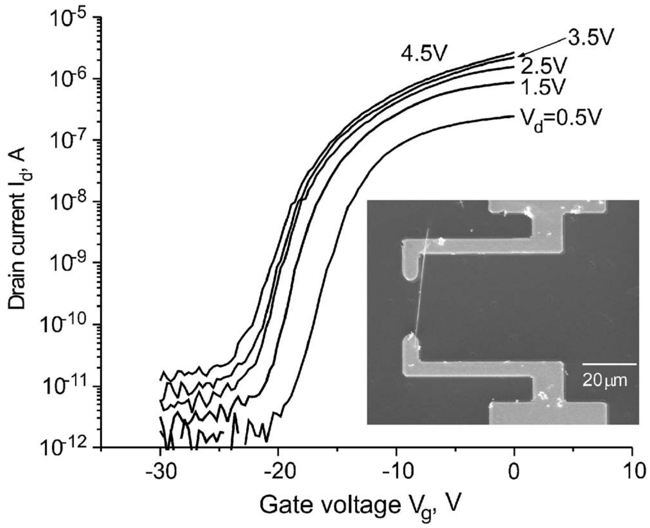

FIG. 2. Transfer current-voltage characteristics of the GaN nanowire transistor. The inset shows FESEM image of a complete GaN nanowire device with source and drain metal electrodes.

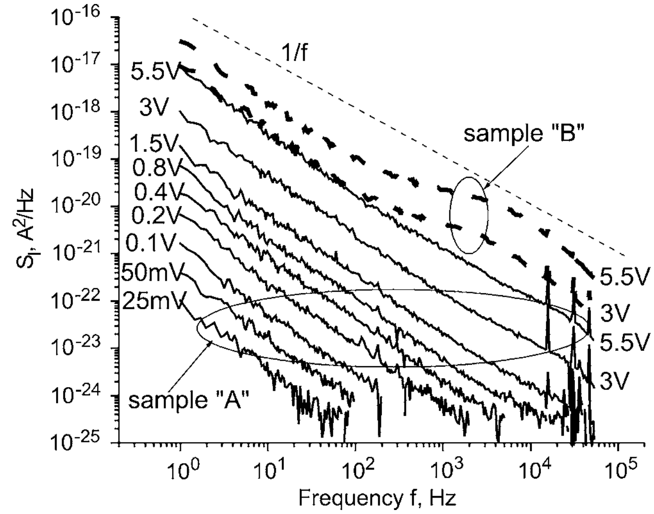

FIG. 3. Noise spectra of short circuit current fluctuations at different drain voltages for two samples, $V_g=0$.

(LEDs) of different wavelengths from 265 to 620 nm were used to study the effect of light on current and noise. The ultraviolet LEDs for this study were supplied by Sensor Electronic Technology, Inc.[22]

RESULTS AND DISCUSSION

The current-voltage characteristics at zero gate voltage and at small drain voltage below 1 V were linear and symmetrical. When the gate voltage was applied, a GaN nanowire behaved as an *n*-channel depletion mode FET.

Figure 2 shows the transfer current-voltage characteristics for different drain voltages. As seen, the current modulation was approximately five orders of magnitude. The threshold voltage determined from transfer current-voltage characteristics at small drain voltage $V_d < 2$ V was $V_{\text{th}} \approx -15$ V.

When the gate voltage was kept constant, the drain current increased slowly to steady state value during the time of several tens of minutes. This steady value of the current was approximately 30%–50% higher than the initial value. We also found the hysteresis of the transfer current-voltage characteristics when the gate voltage was first decreased and then increased. This kind of the memory effects was reported earlier[5] and might relate to the slow localized states in the PECVD silicon dioxide.

The noise spectra of the current fluctuations were close to the $1/f^{\gamma}$ noise at low voltages $V_d < 1-2$ V. The exponent γ varied from the device to device within the range of $\gamma = 1.0-1.25$. At higher voltages, the contribution of the generation-recombination (GR) noise was found for all devices. The amplitude and characteristic frequency of the GR noise differed from device to device. Figure 3 shows a few examples of the noise spectra for two nanowires at zero gate voltage and at different drain voltages. The contribution of the GR noise is seen as characteristic bulges on the smooth $1/f$-like spectra.

While at low currents the spectral noise density of the short circuit current fluctuations S_I was always proportional to the current squared, the deviation from this law was seen for many devices at higher currents $I_d > 0.2-0.7$ μA ($V_d > 0.5-1$ V).

A decrease of the gate voltage led to an increase of the noise S_I. The dependence of noise on the gate voltage in FETs might reveal the noise mechanism and the location of the noise sources. However, a slow drift of the drain current at a constant gate voltage prevented such analysis.

The level of the $1/f$ noise is often characterized based on empirical Hooge relation:[23]

$$\frac{S_I}{I^2} = \frac{\alpha}{fN}, \tag{1}$$

where S_I/I^2 is the relative spectral density of the $1/f$ noise, N is the total number of the carriers in the sample, f is the frequency, and α is the Hooge parameter, which varies for different semiconductor objects within the range $10^{-7}-10^{-1}$. The value of the Hooge parameter α for GaN films ranges from $(5-7)\times 10^{-3}$ to 2×10^{-3} (see review[24] for the references and analysis). In nanowires, one can expect the dominance of the surface noise because of a high surface to volume ratio. Therefore, the Hooge parameter, which is always calculated assuming the bulk origin of noise, should be high. However, in the recent study of the $1/f$ noise in ZnO nanowire FETs the Hooge parameter was found to be relatively small: $\alpha = 5\times 10^{-3}$ and $\alpha = 4\times 10^{-2}$ for the devices measured in vacuum and in dry oxygen environment, respectively.[18] Very small Hooge parameters $\alpha = 1.1\times 10^{-5}-7.5\times 10^{-6}$ were reported for Si nanowires.[17]

The Hooge parameter for GaN nanowire transistors was estimated as

$$\alpha = \frac{S_I}{I^2}\frac{fC|V_{\text{th}}|}{q}, \tag{2}$$

where

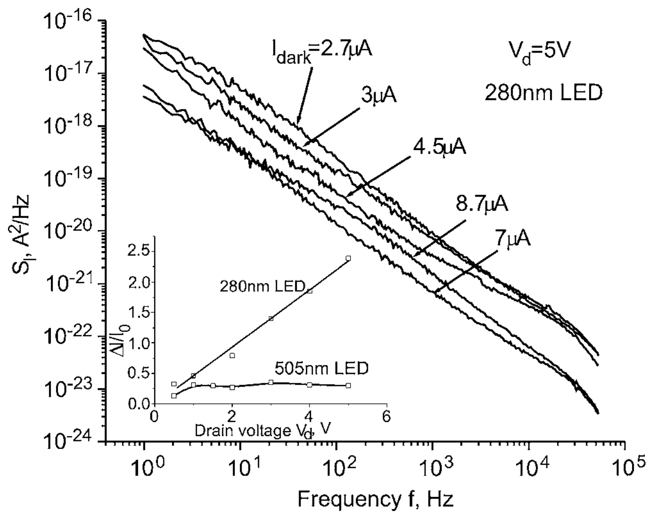

FIG. 4. Noise spectra in dark and under illumination by light of different intensity from 280 nm LED. Drain voltage V_d=5 V. The arrows indicate the current at V_d=5 V in the dark and under illumination of different intensity. The inset shows normalized photocurrent as a function of the drain voltage for the excitation with 280 and 505 nm LEDs.

$$C = \frac{2\pi\varepsilon_0\varepsilon L}{\ln(4h/d)}$$

is the capacitance between the nanowire and silicon gate, ε_0 is the permittivity of free space, ε is the permittivity of SiO_2, h is the thickness of SiO_2, and d is the nanowire diameter. We found $\alpha \geqslant = 2\times 10^{-2}$ (calculated for f=10 Hz) which is of the same order of magnitude as for ZnO nanowires measured in the oxygen environment[17] and only one order of magnitude higher than the smallest value reported for GaN films.[24] This small value of Hooge parameter allows us to assume that, in spite of the large surface to volume ratio, the noise is still of the bulk origin.

In order to determine the nature of the $1/f$ noise, the noise and dc characteristics were measured under illumination by the light of different wavelengths. This method was used before to study the $1/f$ noise in Si and GaAs.[25]

The photoconductivity excited with the long wavelength LEDs (λ > 365 nm) was small and did not depend on the drain voltage, like for a typical photoresistor. Possibly, the photoconductivity excited with long wavelengths is due to the light absorption on the GaN/SiO_2 interface. In contrast, the photoconductivity excited with short wavelength LEDs (λ < 365 nm) was considerably higher and increased with the increase of the drain voltage (see inset in Fig. 4).

The theory explaining the influence of light on the $1/f$ noise was developed in Ref. 26. This model assumed that the $1/f$ noise originated from the fluctuations in number of carriers due to the fluctuations of the occupancy of trap levels forming the density of states tails near band gap edges. Generally, the band-to-band illumination creates minority carriers which are captured by the trap levels responsible for noise. As a result, the occupancy of traps responsible for noise changes.

The spectral noise density of the GR noise in homogenous semiconductors is given by

$$S_I = \frac{4N_t q^2 \mu^2 V_d^2 A}{L^3} \frac{\tau_c F^2(1-F)}{1+\omega^2\tau_c^2 F^2}, \quad (3)$$

where N_t is the trap concentration, q is the elemental charge, μ is the electron mobility, A is sample cross section, L is the sample length, F is the occupancy of the level, $\tau_c = (\sigma n v)^{-1}$ is the capture time, σ is the capture cross section, v is the thermal velocity, and n is the carrier concentration (electrons in our case). As seen from the Eq. (3) noise S_I depends nonmonotonically on the occupancy function F and therefore on the intensity of light.

Since concentration of the traps responsible for noise is usually considerably smaller than the equilibrium carrier concentration, the effect of light on noise can be observed even for a very small photoconductivity. That was the case in the experiments on noise under the band-to-band illumination in GaAs and Si (see review[25] for the brief description of the theory and experimental results).

The effect of light on noise in GaN was studied earlier in Refs. 27 and 28. Even though band-to-band illumination modified the noise spectra, the suppression of noise with light at 300 K was not observed.

Figure 4 shows the noise spectra measured at V_d=5 V in dark and under illumination by light of different intensity from 280 nm LED. The arrows indicate the current for every measurements in the dark and under illumination at V_d =5 V. As seen, light suppressed the noise up to one order of magnitude and changed the shape of the noise spectra.

Contrary to the previous study of noise under illumination in Si and GaAs,[25] the suppression of the noise by light was found under condition of a very high photoconductivity, when the current under illumination increased several times in comparison with the dark current. Therefore, an increase of the electron concentration and decrease of the capture time τ_c might have contributed to the noise suppression by light. Note, however, that the suppression of noise cannot be explained by the reduction of the τ_c alone. While the current (concentration) increased 3.2 times under the highest light intensity (see Fig. 4), the reduction of noise is about one order of magnitude. Hence, the reduction of the occupancy function of traps responsible for noise still plays an important role in the noise suppression. This is confirmed also by the nonmonotonic dependence of the noise amplitude on the light intensity (compare spectra for I=4.5, 7.0, 8.7 μA in Fig. 4) and change of the spectra shapes under illumination, as predicted by the theory.[26]

The influence of the long wavelength light on noise (λ > 365 nm) was weak. Depending on the sample, this long wavelength light either slightly increased or decreased the noise. This confirms an important role of the minority carriers created by short wavelength light in the noise reduction mechanism. The importance of the minority carriers in the noise reduction and small value of the Hooge parameter in the dark are arguments for the favor of the bulk origin of noise in GaN nanowires.

CONCLUSIONS

Noise characteristics of the GaN nanowire transistors were studied in the dark and under illumination with the light from LEDs of different wavelengths. The nanowire transistors had the threshold voltage of $V_{th} \approx -15$ V and exhibited the on-to-off current ratio of approximately five orders of magnitude.

The noise spectra of the current fluctuations were a superposition of the $1/f$-like noise and GR noise. Hooge parameter for the $1/f$-like noise was estimated to be $\alpha \approx 2 \times 10^{-2}$. This value is only one order of magnitude higher than the smallest value reported for GaN films.

Exposing transistors to the long wavelength light had little effect on the noise spectra but the light with the wavelength <365 nm suppressed the noise up to an order of magnitude and changed the shape of the noise spectra.

This strong suppression of the noise by light is explained by changing the occupancy of traps responsible for noise under illumination and by the reduction of their characteristic capture time. Since only short wavelength light had an effect on the noise, we conclude that the minority carriers (holes) play an important role in suppression of noise by light.

ACKNOWLEDGMENTS

The nanowire devices were fabricated at the Nanofab clean room of the NIST Center for Nanoscale Science and Technology. At Ioffe Physico-Technical Institute, this work was supported by Russian Foundation for Basic Research. The work at RPI was partially supported by ONR (Project Monitor Dr. Colin Wood) and by the National Science Foundation under the auspices of the I/UCRC "Connection One." The UV LEDs for this study were supplied by Sensor Electronic Technology, Inc.

The identification of any commercial product or trade name does not imply endorsement or recommendation by the national Institute of Standards and Technology.

[1]X. Duan, Y. Huang, Y. Cui, J. Wang, and C. M. Lieber, Nature (London) **409**, 66 (2001).
[2]H. Yu, D. Xiangfeng, C. Yi, and C. M. Lieber, Nano Lett. **2**, 101 (2002).
[3]J.-R. Kim, H. M. So, J. W. Park, J.-J. Kim, J. Kim, C. J. Lee, and S. C. Lyu, Appl. Phys. Lett. **80**, 3548 (2002).
[4]E. Stern, G. Cheng, E. Cimpoiasu, R. Klie, S. Guthrie, J. Klemic, I. Kretzschmar, E. Steinlauf, D. T.-Evans, E. Broomfield, J. Hyland, R. Koudelka, T. Boone, M. Young, A. Sanders, R. Munden, T. Lee, D. Routenberg, and M. A. Reed, Nanotechnology **16**, 2941 (2005).
[5]H.-Y. Cha, H. Wu, M. Chandrashekhar, Y. C. Choi, S. Chae, G. Koley, and M. G. Spencer, Nanotechnology **17**, 1264 (2006).
[6]C. Y. Nam, D. Tham, and J. E. Fischer, Nano Lett. **5**, 2029 (2005).
[7]A. Motayed, M. Vaudin, A. V. Davydov, J. Melngailis, M. He, and S. N. Mohammad, Appl. Phys. Lett. **90**, 043104 (2007).
[8]Y. Li, J. Xiang, F. Qian, S. Gradecak, Y. Wu, H. Yan, D. A. Blom, and C. M. Lieber, Nano Lett. **6**, 1468 (2006).
[9]M. A. Zimmler, B. Jiming, I. Shalish, Yi Wei, J. Yoon, V. Narayanamurti, and F. Capasso, Nanotechnology **18**, 235205 (2007).
[10]L. M. Li, C. C. Li, J. Zhang, Z. F. Du, B. S. Zou, H. C. Yu, Y. G. Wang, and T. H. Wang, Nanotechnology **18**, 225504 (2007).
[11]C. S. Rout, G. U. Kulkarni, and C. N. R. Rao, J. Phys. D **40**, 2777 (2007).
[12]Z. L. Wang, Compound Semicond. **13**, 16 (2007).
[13]B. Ha, S. H. Seo, J. H. Cho, C. S. Yoon, J. Yoo, G.-C. Yi, C. Y. Park, and C. J. Lee, J. Phys. Chem. B **109**, 11095 (2005).
[14]E. Y. S. Menard, J. A. Rogers, H.-S. Kim, S. Kim, G. Chen, I. Adesida, R. Dettmer, R. Cortez, and A. Tewksbury, Appl. Phys. Lett. **88**, 183509 (2006).
[15]J. Zhong, H. Chen, G. Saraf, Y. Lu, C. K. Choi, J. J. Song, D. M. Mackie, and H. Shen, Appl. Phys. Lett. **90**, 203515 (2007).
[16]A. Vijayaraghavan, S. Kar, S. Rumyantsev, A. Khanna, C. Soldano, N. Pala, R. Vajtai, K. Kanzaki, Y. Kobayashi, O. Nalamasu, M. S. Shur, and P. M. Ajayan, J. Appl. Phys. **100**, 024315 (2006).
[17]S. Reza, G. Bosman, M. Saif Islam, T. I. Kamins, S. Sharma, and R. S. Williams, IEEE Trans. Nanotechnol. **5**, 523 (2006).
[18]W. Wang, H. D. Xiong, M. D. Edelstein, D. Gundlach, J. S. Suehle, and C. A. Richter, J. Appl. Phys. **101**, 044313 (2007).
[19]S. N. Mohammad, J. Chem. Phys. **125**, 094705 (2006).
[20]A. Motayed, A. V. Davydov, M. D. Vaudin, I. Levin, J. Melngailis, and S. N. Mohammad, J. Appl. Phys. **100**, 024306 (2006).
[21]A. Motayed, M. He, A. V. Davydov, J. Melngailis, and S. N. Mohammad, J. Appl. Phys. **100**, 114310 (2006).
[22]See www.s-et.com
[23]F. N. Hooge, T. G. M. Kleinpenning, and L. K. J. Vandamme, Rep. Prog. Phys. **44**, 479 (1981).
[24]M. E. Levinshtein, A. A. Balandin, S. L. Rumyantsev, and M. S. Shur, in *Noise and Fluctuations Control in Electronic Devices*, edited by A. A. Balandin (American Scientific, 2002).
[25]N. V. D'yakonova, M. E. Levinshtein, and S. L. Rumyantsev, Sov. Phys. Semicond. **25**, 1241 (1991).
[26]N. V. D'yakonova and M. E. Levinshtein, Sov. Phys. Semicond. **23**, 175 (1989).
[27]M. E. Levinshtein, F. Pascal, S. Contreras, W. Knap, S. L. Rumyantsev, R. Gaska, J. W. Yang, and M. S. Shur, Appl. Phys. Lett. **72**, 3053 (1998).
[28]N. V. D'yakonova, M. E. Levinshtein, S. Contreras, W. Knap, B. Beaumont, and P. Gibart, Semiconductors **32**, 257 (1998).