Temperature-Dependent Low-Frequency Noise Analysis of ZnO Nanowire Field-Effect Transistors

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***Abstract*—Low-frequency noise characteristics of ZnO nanowire field-effect transistors (FETs) are presented at temperatures down to 10 K. The carrier number fluctuation (CNF) model and Hooge's model are used to analyze the low-frequency noise in the studied devices. From 293 down to 200 K, the normalized noise power spectrum density (PSD) is proportional to $(g_m/I_d)^2$ due to CNF caused by the trapping and detrapping process between the channel carriers and oxide traps near the semiconductor and the dielectrics interface. In this case, the low-frequency noise is induced by flat-band voltage fluctuation. The density of the traps in the gate dielectrics near the Fermi level ranges from 9.4×10^{10} to 3.8×10^{10} cm^{-2} eV^{-1} from 293 and 200 K. At lower temperatures, from 150 down to 100 K, the noise mechanism is mobility fluctuation, attributed to electron and space-charge scattering due to the hoping process and slow motions of electrons. The extracted Hooge's parameter in this temperature ranges in the order of 10^{-3} to 10^{-2}. In the temperature range from 30 down to 10 K, the low-frequency noise is dominated by both CNF and mobility fluctuation caused by Coulomb scattering between oxide traps and electrons.**

***Index Terms*—Low-frequency noise, low temperature, trap density, ZnO nanowire field-effect transistors (NW FETs).**

I. INTRODUCTION

1/*f* NOISE, also called flicker noise, is the dominate noise in the low-frequency range in semiconductor devices. It is a critical method to study the electrical current fluctuation in semiconductor devices, due to either carrier number fluctuation (CNF), such as the trapping/detrapping process between the channel carriers and oxide traps, or carrier mobility fluctuation resulting from various scattering mechanisms, or the combination of both [1]–[4]. This is particularly important for low-dimensional semiconductor devices such as nanowire field-effect transistors (NW FETs) due to their high surface volume ratio. NW devices are promising candidates for nanoelectronics and optoelectronics applications in the future [5]. However, there is an issue existing in NW devices. The surface of the NW is highly defective due to the surface reconstruction in the synthesizing process, which makes the surface states have a strong impact on device performance [6]–[9]. Previous studies have shown that the low-frequency noise in ZnO NW FETs is dependent on the ambience [10]. It has been shown that the low-frequency noise of ZnO NW FETs at room temperature in vacuum agrees to Hooge's model, and Hooge's parameters are in the order of 10^{-3}, while the noise mechanism in dry oxygen is found to be CNF. With a self-assembled nanodielectric and SiO_2 gate insulator, Ju *et al.* [11] found that the low-frequency noise of ZnO NW transistors is due to mobility fluctuations in a linear regime. Some temperature dependence studies on low-frequency noise of ZnO NW FETs have also been reported [12]. It is found that at 4.2 K, the noise in ZnO NW FETs is no longer dominant by 1/*f* noise, but in the Lorentzian shape, a sign of generation and recombination noise is observed. However, so far a comprehensive and systematic investigation on temperature dependence (e.g., from room temperature to 10 K) of low-frequency noise in ZnO NW FETs is still lacking.

In this work, we show the low-frequency noise characteristics of ZnO NW FETs at both room temperature and low temperatures down to 10 K. The low-frequency noise in studied devices is dominated by the 1/*f* noise in the linear regime up to 1 kHz. We show that the noise mechanism of ZnO NW FETs varies with temperatures. The CNF induces the low-frequency noise from 293 down to 200 K. From 150 down to 100 K, mobility fluctuations due to electron and space-charge scattering become dominant. At low temperature from 30 down to 10 K, the low-frequency noise due to mobility fluctuation becomes comparable to CNF. Furthermore, the density of oxide traps located near the semiconductor and dielectrics interface is extracted.

II. EXPERIMENT

A. Fabrication of ZnO NW FETs

The structure of ZnO NW FETs is shown in Fig. 1. The ZnO NWs with a radius of 50–60 nm were grown using the

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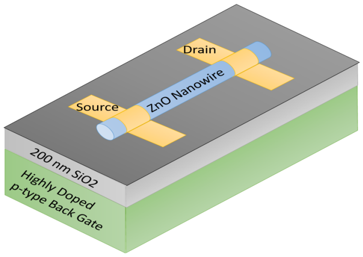

Fig. 1. Structure of ZnO NW FETs. The source and drain contacts are formed by Ti/Au (20/200 nm). p-type Si is used as the back gate. The gate dielectrics is 200-nm thick SiO_2.

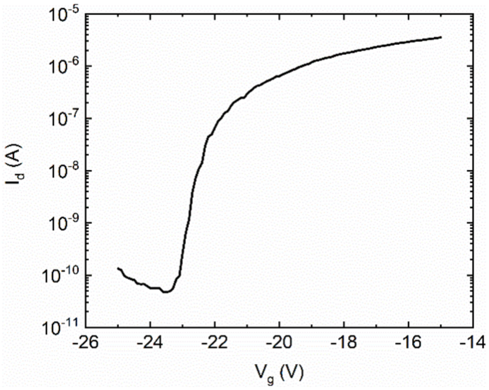

Fig. 2. I_d–V_g characteristics of ZnO NW FETs. V_d is 5 V. V_g is from −25 to −15 V.

vapor–liquid–solid method by chemical vapor deposition. A highly doped p-type silicon substrate is used as the back gate. The thickness of the SiO_2 gate oxide is 200 nm. ZnO NWs were placed on the gate oxide by spin coating. Ti/Au was deposited as source–drain ohmic contact by electron beam deposition. The source/drain spacing or the gate length is 3 μm. The details of device fabrication and transport study have been reported in [13].

B. Noise Measurement Setup

An Agilent E4440A spectrum analyzer and a Stanford Research SR570 low-noise current preamplifier were used to measure the noise spectra. At low temperatures, the low-frequency noise measurement was carried out in a Lake Shore Model TTP4 Cryogenic Station. The temperature of the station is precisely controlled by the Lakeshore Model 332 Temperature Controller. Low-frequency noise measurement was carried out after the temperature of the chamber became stable.

III. RESULTS AND DISCUSSION

A. DC Characteristics of ZnO NW FETs

The transfer I–V curves (Fig. 2) of the ZnO NW FETs were measured by Agilent 4142b at room temperature. Here, V_d is 5 V and V_g is from −25 to 15 V. The threshold voltage V_{th} is −20.8 V and the gate current level is 10^{-9} A. The devices exhibited an excellent pinchoff performance with an OFF-state current of 7×10^{-10} A and an ON/OFF ratio of 10^5. The subthreshold slope is 260 mV/dec.

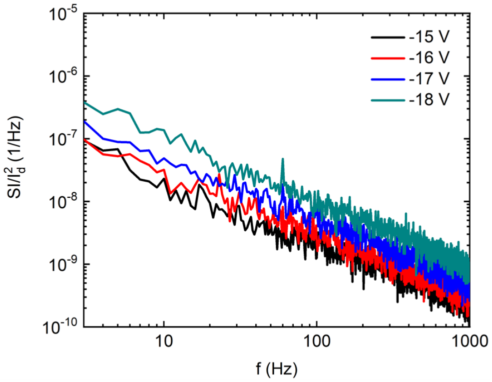

Fig. 3. Normalized noise PSD of ZnO NW FETs at room temperature at $V_d = 5$ V. The gate is biased from −18 to −15 V with a step of 1 V.

B. Low-Frequency Noise of ZnO NW FETs at Room Temperature

Fig. 3 shows the normalized power spectrum density (PSD) of the ZnO NW FETs under different gate biases at room temperature. The drain bias is set to 5 V for all noise measurements. The noise PSD in room temperature shows a $1/f^{\beta}$ shape, with β value ranging from 1.1 to 1.2. No generation and recombination noise is observed in our devices up to 1 kHz. The noise PSD level decreases with the gate bias increasing from −18 to −15 V.

C. Temperature-Dependent Low-Frequency Noise Measurements of ZnO NW FETs

Generally speaking, the trapping/detrapping process between the oxide traps and channel carriers and the bulk mobility fluctuations [1] is the mechanism for electrical current fluctuation in MOS transistors, both of which are temperature-dependent. Next, we study the mechanisms of low-frequency noise in ZnO NW FETs dependences of temperature.

The low temperature noise measurement was carried out in a cryogenic station from 293 down to 10 K. Here, we only plot the normalized PSD at three temperatures (293, 150, and 10 K) at $V_g = -15$ V. According to the noise PSD shown in Fig. 4(a), $1/f$ noise is still dominant in the low temperature range in our devices. To show the evolution of the threshold voltage of ZnO NW FETs, the transfer I–V characteristics at 293, 150, and 10 K are shown in Fig. 4(b). The V_{th} is extracted to be −20.8 V for 293 K, −19 V for 150 K, and −16.2 V for 10 K from linear extrapolations.

The normalized PSD spectra shown in Fig. 4(a) suggest that the low-frequency noise follows the $1/f$ dependence in the entire temperature we have measured, but no other clear trend is observed. To better understand the noise mechanism at different temperatures, the normalized noise PSD is plotted as a function of drain current I_d from room temperature 293 down to 10 K. As shown in Fig. 5, the normalized PSDs at 293, 200, 150, and 100 K have a linear relationship with I_d, while at 30 and 10 K, no clear relationship between the normalized PSD and I_d is observed. Besides, the slope of the linear fittings at 150 and 100 K is close to −1, which

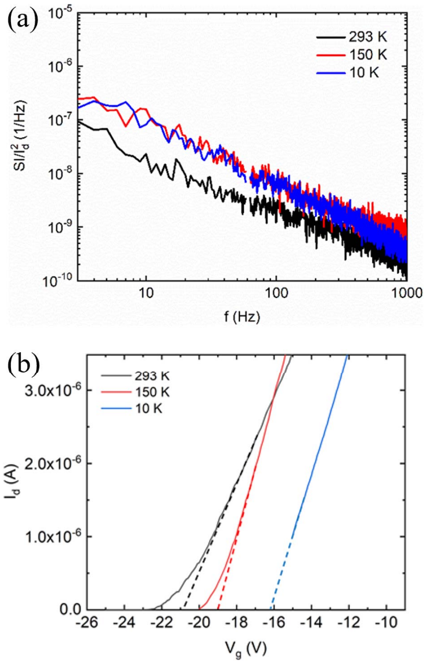

Fig. 4. (a) Normalized noise PSD of ZnO NW FETs at gate biasing condition of −15 V and $V_d = 5$ V at 293, 150, and 10 K. (b) Transfer *I–V* characteristics of ZnO NW FETs at 293, 150, and 10 K.

means in these cases that SI/I_d^2 is proportional to I_d^{-1}. The slope of linear fittings at 293 and 200 K is close to −2. These initial observations suggest that the dominant mechanisms in these temperature ranges may be different and more than one model is needed to study the observed low-frequency noise at different temperatures.

D. Low-Frequency Noise Modeling of ZnO NW FETs

In general, the current fluctuation in semiconductor devices is decided by two factors, carrier number and carrier mobility fluctuations. In MOS transistors, the CNF is due to the trapping and detrapping process between oxide traps near the interface and channel carriers [2]. The mobility fluctuation is generally attributed to the fluctuations on phonon scattering [14]. These two mechanisms are considered responsible for two widely used models in low-frequency noise, the CNF model and Hooge's model. In the CNF model, the normalized PSD approximately changes with $(g_m/I_d)^2$ in the linear regime if not considering the mobility fluctuations [4]

$$\frac{\mathrm{SI}}{I_d^2} = S_{\mathrm{vfb}} \times \left(\frac{g_m}{I_d}\right)^2 \tag{1}$$

where S_{vfb} is the noise PSD at flat-band voltage. In Hooge's model, the low-frequency noise is attributed to the mobility fluctuation of carriers in the channel. The normalized PSD can be written as the well-known Hooge's relation

$$\frac{\mathrm{SI}}{I_d^2} = \frac{\alpha}{N_{\mathrm{tot}} \cdot f} \tag{2}$$

where α is Hooge's parameter. N_{tot} is the total carrier number in the channel. Since N_{tot} is proportional to I_d in the linear regime, the normalized PSD should be proportional to I_d^{-1} for the mobility fluctuation case.

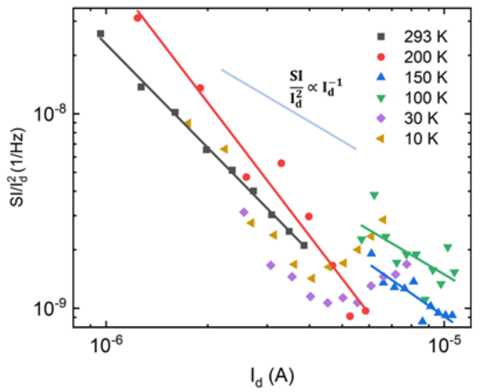

Fig. 5. Normalized noise PSD at 100 Hz versus I_d at $T = 293$, 200, 150, 100, 30, and 10 K. The normalized PSD at 293, 200, 150, and 100 K are plotted with linear fittings.

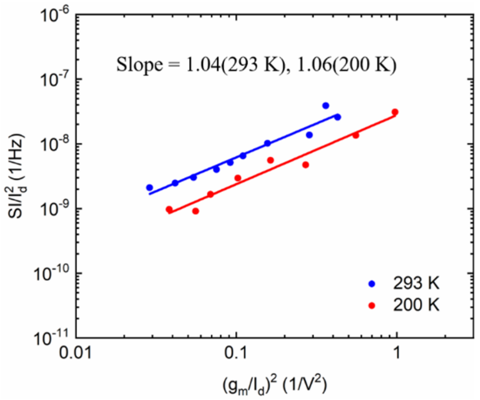

Fig. 6. Normalized noise PSD at 100 Hz versus $(g_m/I_d)^2$ at $T = 293$ and 200 K with fittings to the CNF model.

At room temperature, the measured normalized noise PSD versus $(g_m/I_d)^2$ is shown in Fig. 6. Note that the low-frequency noise of ZnO NW FETs was measured with the device linear regime. The linear relationship between the normalized PSD and $(g_m/I_d)^2$ indicates that the noise in our device at room temperature is dominated by CNF. This is also in agreement with the result reported before in ZnO NW phototransistors [11]. In other words, in a higher gate bias condition, when the device is operated at linear or saturation regime, the noise is dominated by CNF. We find that the low-frequency noise in our devices can still be fitted into the CNF model down to 200 K. As shown in Fig. 6, the noise level at 200 K is smaller than the room temperature with a linear dependence of $(g_m/I_d)^2$. This is likely because the trapping/detrapping process between the traps and carriers slows down at lower temperatures. There are less traps and carriers involved in this process. Hence, the noise level becomes smaller at low temperatures.

At temperatures below 200 K, the noise data cannot be fitted into the CNF model anymore. We plot the normalized noise PSD versus I_d instead. As shown in Fig. 7(a), the fitting result shows that the normalized noise PSD is proportional to I_d with a slope of −1.21 for 150 K and −1.03 for 100 K, which

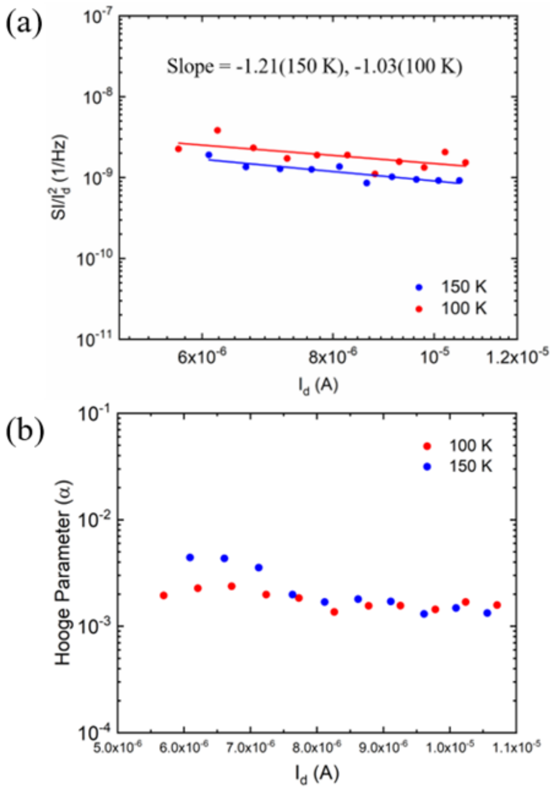

Fig. 7. (a) Normalized noise PSD versus drain current I_d at 100 and 150 K and fittings to Hooge's model. (b) Extracted Hooge parameter versus gate bias at 100 and 150 K.

follows Hooge's relation mentioned in (2). The result shows a very good linear fitting at both temperatures, which is a strong sign of mobility fluctuation, according to Hooge's model. Previous work has suggested that the transport mechanism in ZnO NW FETs is dominated by phonon scattering at temperatures higher than 167 K [13]. It has been suggested that the electron and space-charge scattering become dominant due to the electron hopping process and slow electron motion at temperatures below 167 K. Therefore, it is believed that the transition of transport mechanism in this temperature range induced larger fluctuations on carrier mobility. This explains why the low-frequency noise due to the mobility fluctuation is dominant from 150 down to 100 K. As shown in Fig. 7(b), Hooge's parameter extracted at 100 and 150 K are in the order of 10^{-2} to 10^{-3}. These values are in good agreement with the previously reported results on ZnO NW FETs [10], [12], [13].

In the extremely low temperature range from 30 down to 10 K, the noise data can be well fitted to another model, the CNF correlated with mobility fluctuation model. In this model, the low-frequency noise is still attributed to the trapping/detrapping process between the oxide traps and channel carriers. This process not only induces the CNF, but also induces the carrier mobility fluctuation through the Coulomb scattering between the oxide traps and carriers. According to this model [4]

$$\frac{S_{Id}}{I_d^2} = \left(1+\gamma\cdot\mu_0\cdot C_{\rm ox}\cdot\frac{I_d}{g_m}\right)^2\times S_{\rm Vfb}\times\left(\frac{g_m}{I_d}\right)^2 \qquad (3)$$

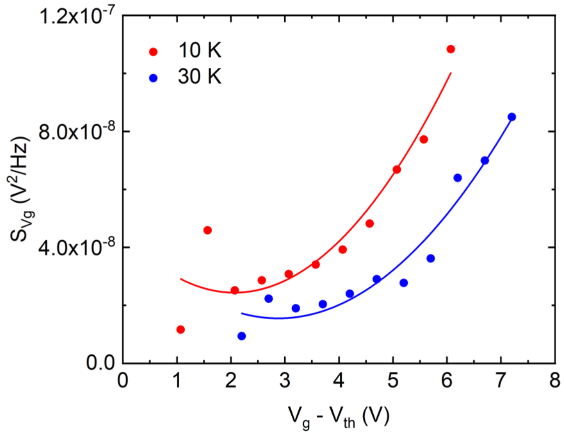

Fig. 8. Normalized noise PSD of gate voltage versus gate bias at 10 and 30 K and fittings to CNF correlated with mobility fluctuation model.

where γ is the Coulomb scattering parameter, μ_0 is the effective mobility, and $C_{\rm ox}$ is the oxide capacitance per unit area. It can be rewritten as

$$S_{Vg} = \frac{S_{Id}}{g_m^2} = \left\{\left(1+\gamma\cdot\mu_0\cdot C_{\rm ox}\cdot\left(V_g - V_{\rm th}\right)\right)\right\}^2\times S_{\rm Vfb}. \qquad (4)$$

We show $S\upsilon_g$ versus $(V_g - V_{\rm th})$ in Fig. 8 at 30 and 10 K. The result shows a good polynomial relationship between $S\upsilon_g$ and $(V_g - V_{\rm th})$. The good fitting to the CNF correlated mobility fluctuation model reveals that at low temperatures, the Coulomb scattering between oxide traps and carriers is the dominant reason for mobility fluctuation. In this case, the noise induced by mobility fluctuation is significant and comparable to the CNF.

In the CNF model, the oxide trap density near the ZnO/SiO$_2$ interface can be extracted from the noise PSD of flat-band voltage $S_{\rm vfb}$. The trap density we extracted here is the oxide traps located near the Fermi level that are involved in the trapping/detrapping process with channel carriers. In MOSFETs, the noise PSD of flat-band voltage can be expressed as [4]

$$S_{V_{\rm fb}} = \frac{S_{Q_{\rm ox}}}{C_{\rm ox}^2} = \frac{q^2kTN_t\lambda}{fWlC_{\rm ox}^2} \qquad (5)$$

where l is the channel length, W is channel width, and $C_{\rm ox}$ is oxide capacitance per unit area. λ is the tunneling distance, which can be expressed as

$$\lambda = \left[\frac{4\pi}{h}\sqrt{2m^*\varphi_B}\right]^{-1} \qquad (6)$$

where m^* is the effective mass of electrons in gate oxide, φ_B is the tunneling barrier at the ZnO/SiO$_2$ interface, and h is the Planck's constant. In this work, as shown in Fig. 1, the NW channel in our devices is placed on top of the Si back gate. Equation (5) can be expressed as

$$S_{V_{\rm fb}} = \frac{S_{Q_{\rm ox}}}{C_{\rm ox}^2} = \frac{q^2kTN_t'\lambda}{flC_{\rm ox}'^2}. \qquad (7)$$

Here, $C_{\rm ox}'$ is the gate capacitance per unit length which can be calculated as [13]

$$C_{\rm ox}' = \frac{2\pi\varepsilon\varepsilon_0}{\cosh^{-1}\left(1+\frac{t_g}{r_{\rm nw}}\right)} \qquad (8)$$

where t_g is the thickness of the gate oxide and r_{nw} is the radius of the NW. The electron affinity of ZnO we used here is 4.3 eV [16]. $S_{V_{\mathrm{fb}}}$ can be calculated from the measured noise PSD of drain current S_{Id}. The extracted values of the oxide trap density per unit area N_t' at 293 and 200 K are 9.4×10^{10} cm^{-2} eV^{-1} and 3.8×10^{10} cm^{-2} eV^{-1}, respectively.

IV. CONCLUSION

In conclusion, we investigated the low-frequency noise characteristics of ZnO NW FETs at different temperature from 293 down to 10 K. We found that $1/f$ noise is always dominant in our devices up to 1000 Hz in this temperature range. According to our analysis, three noise mechanisms are identified responsible for the low-frequency noise. From 293 down to 200 K, CNF dominates the low-frequency noise. This fluctuation is induced by the trapping/detrapping process between the oxide traps and channel carriers based on the CNF model. The activated oxide trap density according to the CNF model ranges from 9.4×10^{10} to 3.8×10^{10} cm^{-2} eV^{-1} from 293 and 200 K. From 150 down to 100 K, the low-frequency noise becomes mobility fluctuation dominant. At this temperature range, the mobility fluctuation induced by electron and space-charge scattering dominated the low-frequency noise. At extremely low temperature from 30 down to 10 K, the noise is dominated by both CNF and mobility fluctuation, which is induced by the Coulomb scattering between oxide traps and channel carriers. This work provides a comprehensive study on temperature dependence of low-frequency noise in ZnO NW FETs.

REFERENCES

[1] F. N. Hooge, T. G. M. Kleinpenning, and L. K. J. Vandamme, "Experimental studies on 1/f noise," *Rep. Prog. Phys.*, vol. 44, no. 5, pp. 479–532, 1981.

[2] A. L. McWorther, *Semiconductor Surface Physics*. Philadelphia, PA, USA: Univ. Pennsylvania Press, 1957.

[3] S. Christensson, I. Lundstrom, and C. Svensson, "Low frequency noise in MOS transistors-I theory," *Solid-State Electron.*, vol. 11, no. 9, pp. 797–812, Sep. 1968.

[4] G. Ghibaudo, O. Roux, C. Nguyen-Duc, F. Balestra, and J. Brini, "Improved analysis of low frequency noise in field-effect MOS transistors," *Phys. Status Solidi (A)*, vol. 124, no. 2, pp. 571–581, 1991.

[5] M. Law, J. Goldberger, and P. D. Yang, "Semiconductor nanowires and nanotubes," *Annu. Rev. Mater. Res.*, vol. 34, pp. 83–122, Aug. 2004.

[6] P. A. Alekseev *et al.*, "Nitride surface passivation of GaAs nanowires: Impact on surface state density," *Nano Lett.*, vol. 15, no. 1, pp. 63–68, Jan. 2015.

[7] R. Rurali and N. Lorente, "On the properties of surface reconstructed silicon nanowires," *Nanotechnology*, vol. 16, no. 5, pp. S250–S253, May 2005.

[8] H. Xu, A. L. Rosa, T. Frauenheim, R. Q. Zhang, and S. T. Lee, "Density-functional theory calculations of bare and passivated triangular-shaped ZnO nanowires," *Appl. Phys. Lett.*, vol. 91, no. 3, Jul. 2007, Art. no. 031914.

[9] Y. Shao, J. Yoon, H. Kim, T. Lee, and W. Lu, "Analysis of surface states in ZnO nanowire field effect transistors," *Appl. Surf. Sci.*, vol. 301, pp. 2–8, May 2014.

[10] W. Wang *et al.*, "Low frequency noise characterizations of ZnO nanowire field effect transistors," *J. Appl. Phys.*, vol. 101, no. 4, Feb. 2007, Art. no. 044313.

[11] S. Ju *et al.*, "Interface studies of ZnO nanowire transistors using low-frequency noise and temperature-dependent I-V measurements," *Appl. Phys. Lett.*, vol. 92, no. 2, Jan. 2008, Art. no. 022104.

[12] H. D. Xiong *et al.*, "Random telegraph signals in n-type ZnO nanowire field effect transistors at low temperature," *Appl. Phys. Lett.*, vol. 91, no. 5, Jul. 2007, Art. no. 053107.

[13] Y. Shao, J. Yoon, H. Kim, T. Lee, and W. Lu, "Temperature dependence of electron transport in ZnO nanowire field effect transistors," *IEEE Trans. Electron Devices*, vol. 61, no. 2, pp. 625–630, Feb. 2014.

[14] F. N. Hooge and J. K. J. Vandamme, "Lattice scattering causes 1/f noise," *Phys. Lett. A*, vol. 66, no. 4, pp. 315–316, 1978.

[15] M. Haartman and M. Östling, *Low-Frequency Noise in Advanced MOS Devices*, 1st ed. Dordrecht, The Netherlands: Springer, 2007.

[16] S. P. Kumar, A. Vishnu, V. Shruti, and M. Shaibal, "Blue electroluminescence from Sb-ZnO/Cd-ZnO/Ga-ZnO heterojunction diode fabricated by dual ion beam sputtering," *Opt. Exp.*, vol. 22, no. 25, pp. 30983–30991, 2014.