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Tunneling mechanism of the 1/*f* noise in GaN/AlGaN heterojunction field-effect transistors

A. P. Dmitriev and M. E. Levinshtein
Solid State Electronics Division, The Ioffe Physical-Technical Institute of Russian Academy of Sciences, 194021, St. Petersburg, Russia

S. L. Rumyantsev[a)]
Department of Electrical, Computer, and Systems Engineering, CII 9017, Rensselaer Polytechnic Institute, Troy, New York 12180-3590 and Ioffe Institute of Russian Academy of Sciences, 194021 St-Petersburg, Russia

M. S. Shur
Department of Electrical, Computer, and Systems Engineering, CII 9017, Rensselaer Polytechnic Institute, Troy, New York 12180-3590

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We propose a model of the $1/f$ noise in GaN/AlGaN heterojunction field-effect transistors that links the $1/f$ noise to the tunneling from the two-dimensional electron gas in the device channel into the tail states near the conduction band of the GaN layer. The model predicts a fairly weak temperature dependence of the $1/f$ noise in the temperature interval from 50 to 600 K with the value of the Hooge parameter α within the range of 10^{-3}–10^{-5}. Both these predictions are in agreement with experimental data. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1931033]

I. INTRODUCTION

GaN/AlGaN heterostructure field-effect transistors (HFETs) have emerged as attractive candidates for high-power and high-frequency applications. Low-frequency noise is one of the major factors determining the phase noise characteristics of these devices. In addition, low-frequency noise measurements are powerful tools to study impurity and defects in semiconductor structures[1,2] and to diagnose the quality and reliability of semiconductor devices.[3]

In spite of many efforts, the mechanism of the $1/f$ noise in GaN/AlGaN HFETs has not yet been established. Previous attempts to explain the nature of the $1/f$ noise in AlGaN/GaN HFETs involve three different mechanisms. The first mechanism links the $1/f$ noise to the occupancy fluctuations of the tail states near the band edges.[4–6] The second mechanism involves fluctuations in the space-charge regions surrounding dislocations. These fluctuations (which might be either mobility fluctuations or fluctuations of the width of the depletion regions surrounding the dislocations) modulate the resistance of the channel causing the $1/f$ noise.[7,8] The third mechanism explains the $1/f$ noise by electron tunneling from the two-dimensional (2D) gas into the traps in the adjacent GaN layers.[9–12]

The electron tunneling from the channel into the single Si level in the GaN buffer layer was discussed in Ref. 10. Since electrons can tunnel the different distances in order to be captured by this level, the model yields a $1/f$-like spectrum just like the well-known McWhorter model.[13] The predicted noise temperature dependence of noise had a maximum at the temperature at which the Fermi level coincided with the Si level.[10]

However, experiments show that the $1/f$ noise in such GaN/AlGaN HFETs is often characterized by the weak temperature dependence from cryogenic temperatures to 500–600 K (see Review[4] and references therein). In this paper, we discuss the model of the $1/f$ noise related to the electron tunneling from the 2D channel into the tail states in the GaN buffer and show that this model is in agreement with the experimental results. We also account for tunneling into a donor level, which makes this model applicable to devices with doped, compensated, or undoped channels.

II. THEORY

Figure 1(a) shows a simplified band diagram of the GaN/$Al_xGa_{1-x}N$ heterostructure. Numerical values in Fig. 1 correspond to the typical-doped HFET structure with the Al molar fraction $x=0.3$ in the wide-band-gap barrier layer and with the GaN buffer doped by shallow donors (Si) with the activation energy of $\varepsilon_c-\varepsilon_d=0.02$ eV. The two-dimensional electron concentration at the GaN/AlGaN interface is $n_0=1.3\times10^{13}$ cm^{-2}.[14–16] The density of the tail states in GaN layer, $\rho(\varepsilon)$, decreases exponentially as

$$\rho(\varepsilon)=\rho_0\exp\left(-\frac{\varepsilon_c-\varepsilon}{\varepsilon_0}\right), \tag{1}$$

where $\rho_0=\rho(\varepsilon_c)$ is the density of the tail states at the bottom of the conduction band.

The 2D electrons in the channel can tunnel into the GaN, where they are captured by the tail states.

The characteristic capture time τ_c of an electron by a level in the GaN layer could be expressed as

[a)]Electronic mail: roumis2@rpi.edu

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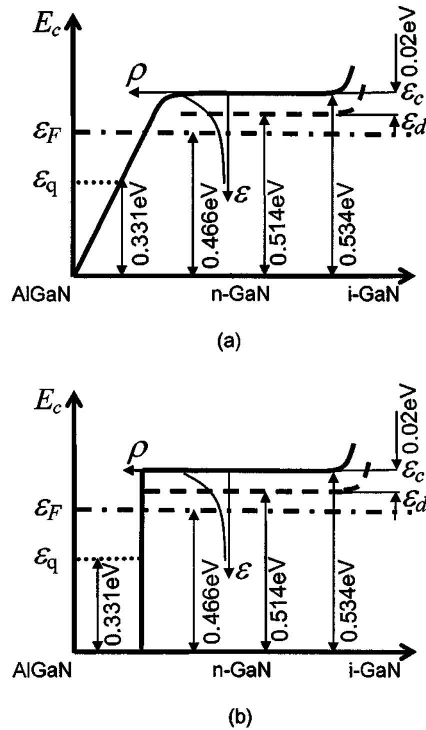

FIG. 1. Simplified band diagram of the GaN/AlGaN quantum well (a) and rectangular potential well (b) used in calculations. Parameters are calculated for GaN/$Al_{0.3}Ga_{0.7}N$ heterojunction with doping level of GaN layer 2×10^{17} cm^{-3}. T=300 K and n_0=1.3×10^{13} cm^{-2}.

$$\frac{1}{\tau_c}=\int\sigma\frac{p}{m}f_e\frac{2d^2p}{(2\pi\hbar)^2}A, \qquad (2)$$

where σ is the capture cross section, m is electron effective mass, p is longitudinal moment of electrons, f_e is the Fermi function for the electrons in the quantum well.

$$f_e=\frac{1}{1+e^{\frac{\varepsilon-\varepsilon_F}{kT}}}, \qquad (3)$$

where ε is the energy of electron, and ε_F is the Fermi energy.

A is the coefficient that depends on the quantum well shape and has a dimension of m^{-1}. As seen in Fig. 1(a), the electrons first tunnel under the bottom of the triangle quantum well and then under the flat part of the conduction-band edge. The electric field at the heterointerface is very high, such that the voltage drop across the Bohr radius is comparable or larger than the Bohr energy. The simplest model to capture the qualitative feature of electron tunneling in such a system is that of a rectangular potential well [see Fig. 1(b)] that we are using in our calculations below.

The coefficient A in Eq. (2) for a rectangular quantum well of the width a is given by.

$$A=\frac{2}{a}\left(\frac{\pi}{\chi a}\right)^2, \qquad (4)$$

where

$$\chi=\frac{[2m(\varepsilon_c-\varepsilon_q)]^{1/2}}{\hbar}, \qquad (5)$$

and $(\varepsilon_c-\varepsilon_q)$ is the energy gap between the bottom of the conduction band and the lowest quantum level in the well (Fig. 1).

The capture cross section σ is proportional to the exponential function, describing the probability for an electron to tunnel from the quantum well to the position x in the GaN layer:

$$\sigma=\sigma'\exp\left(-\frac{x}{x_0}\right), \qquad (6)$$

where

$$x_0=\frac{\hbar}{2[2m(\varepsilon_c-\varepsilon_q)]^{1/2}}. \qquad (7)$$

The electron tunneling can be phonon assisted. In this case, electrons within a certain energy interval around the energy level ε' can be captured by the level in GaN. The probability to be captured is the largest for the electrons with the energy equal to ε' and exponentially decreases with either increase or decrease of the electron energy:

$$\varepsilon>\varepsilon', \quad \sigma'=\sigma_0 e^{-(\varepsilon-\varepsilon')/\varepsilon_1}$$

$$\varepsilon<\varepsilon', \quad \sigma'=\sigma_0 e^{-(\varepsilon'-\varepsilon)/\varepsilon_2}. \qquad (8)$$

The expression for the noise density of the number of carrier fluctuations $(S_n/n_0^2)_{\rm sl}$ caused by the capture of electrons tunneling on the single level with energy ε' for a triangle quantum well was obtained in Ref. 10. For a rectangular quantum well it has the form.

$$\left(\frac{S_n}{n_0^2}\right)_{\rm sl}=\frac{4\tau_0N_e}{WLn_0^2}\int_0^\infty dx\left[\exp(x/x_0)f(\varepsilon')[1-f(\varepsilon')]\frac{1}{1+\omega^2\tau_0^2\exp 2(x/x_0)}\right], \qquad (9)$$

where N_e is the concentration of the level with energy ε', n_0 is the sheet electron concentration in the channel, W is the gate width, L is source-drain distance, $\omega=2\pi f$,

$$\tau_0=\left[A\frac{\sqrt{2m}}{\pi\hbar^2}\sigma_0\sqrt{\varepsilon'}(\varepsilon_1+\varepsilon_2)\right]^{-1}\frac{1+\exp[(\varepsilon'-\varepsilon_F)/kT]}{1+g\exp[(\varepsilon'-\varepsilon_F)/kT]} \qquad (10)$$

$$f(\varepsilon')=\frac{1}{1+ge^{(\varepsilon'-\varepsilon_F)/kT}}, \qquad (11)$$

is the level occupancy, and g is the level degeneracy factor.

The expression for the noise spectra caused by tunneling on continuous levels of the tail states can be obtained by integration of Eq. (9) over tail states [see Eq. (1)]:

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$$\frac{S_n}{n_0^2} = \frac{2\pi\rho_0 x_0}{WLn_0^2\omega}\int_{-\infty}^{\varepsilon_c}\{e^{(\varepsilon-\varepsilon_c)/\varepsilon_0}f(\varepsilon)[1-f(\varepsilon)]\}d\varepsilon$$

$$= \frac{2\pi\rho_0 x_0}{WLn_0^2\omega}\int_{-\infty}^{\varepsilon_c} e^{(\varepsilon-\varepsilon_c)/\varepsilon_0}\frac{ge^{(\varepsilon-\varepsilon_F)/kT}}{(1+ge^{(\varepsilon-\varepsilon_F)/kT})^2}d\varepsilon. \quad (12)$$

Note that Eq. (12) does not include time constant τ_0 and, consequently coefficient A.

For $kT \ll \varepsilon_0$, the main contribution to the integral in Eq. (12) comes from the levels with the energy $\varepsilon \approx \varepsilon_F$. For this case, the approximate expression for the relative spectral noise density has the form.

$$\frac{S_n}{n_0^2} \approx \frac{2\pi\rho_0 x_0}{WLn_0^2\omega}kTe^{(\varepsilon_F-\varepsilon_c)/\varepsilon_0}\frac{ge^{(\varepsilon_c-\varepsilon_F)/kT}}{1+ge^{(\varepsilon_c-\varepsilon_F)/kT}}. \quad (13)$$

In the opposite limiting case $kT \gg \varepsilon_0$, the main contribution to the integral in Eq. (12) comes from the levels with $\varepsilon = \varepsilon_c$, and the expression for the relative noise spectral density becomes.

$$\frac{S_n}{n_0^2} = \frac{2\pi\rho_0 x_0}{WLn_0^2\omega}\frac{1}{ge^{(\varepsilon_c-\varepsilon_F)/kT}}. \quad (14)$$

III. ESTIMATES AND DISCUSSION

As seen from Eqs. (12)–(14), this theory predicts the $1/f$ noise spectrum. The level of $1/f$ noise in different semiconductor materials and structures is usually characterized by the dimensionless Hooge parameter, α:[17]

$$\alpha = \frac{S_n}{n_0^2}fN. \quad (15)$$

Here $N = n_0 WL$ is the total number of the conduction electrons in the sample, f is the frequency of the analysis, and S_n/n_0^2 is the relative spectral density of noise. From Eqs. (12) and (15) we obtain

$$\alpha = \frac{N_t x_0}{n_0\varepsilon_0}\int_{-\infty}^{\varepsilon_c} d\varepsilon\{e^{(\varepsilon-\varepsilon_c)/\varepsilon_0}\times f(\varepsilon)[1-f(\varepsilon)]\}. \quad (16)$$

At $kT \ll \varepsilon_0$

$$\alpha_l \approx \frac{N_t x_0}{n_0}\frac{kT}{\varepsilon_0}e^{(\varepsilon_F-\varepsilon_c)/\varepsilon_0}\frac{ge^{(\varepsilon_c-\varepsilon_F)/kT}}{1+ge^{(\varepsilon_c-\varepsilon_F)/kT}}, \quad (17)$$

and $kT \gg \varepsilon_0$

$$\alpha_h \approx \frac{N_t x_0}{n_0}\frac{1}{ge^{(\varepsilon_c-\varepsilon_F)/kT}}, \quad (18)$$

where

$$N_t = \int_{-\infty}^{\varepsilon_c}\rho_0 e^{-\varepsilon/\varepsilon_0} = \varepsilon_0\rho_0 \quad (19)$$

is the total trap concentration in the tail states.

To estimate the Hooge parameter, we need to know the values of N_t, n_0, ε_0, and the temperature dependence of the Fermi level, $\varepsilon_F(T)$.

The N_t and ε_0 values were estimated for Si and GaAs in Refs. 18 and 19 (see Review[20] for details). For both semiconductors ε_0 was found to be close to 0.03 eV. The characteristic energy ε_0 should be higher in semiconductors with larger band gap and higher crystal imperfection. Absorption coefficient measurements near the band-gap edge[21] yield $\varepsilon_0 \approx 0.1$ eV for GaN. A reasonable estimate for the total concentration of traps in the tail states is one to two orders of magnitude smaller than the total doping level $N_d + N_a$, where N_d is the shallow donors concentration and $N_a < N_d$ is the concentration of compensating acceptors.[22]

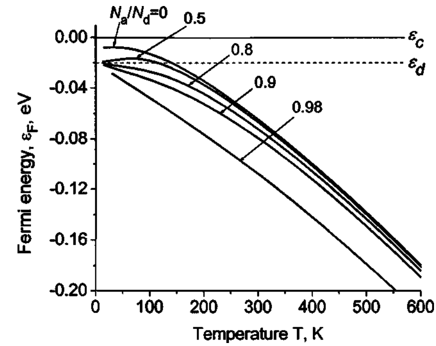

FIG. 2. Temperature dependencies of the Fermi level calculated using Eq. (20) for different compensation levels, N_a/N_d, for GaN layer with $g=2$ and $N_d = 2\times 10^{17}$ cm^{-3}.

The temperature dependence of the Fermi level has to be found from the neutrality condition: (see, for example, Ref. 23):

$$N_d - N_a - \frac{N_d}{1+ge^{(\varepsilon_d-\varepsilon_F)/kT}} = N_c e^{(\varepsilon_F-\varepsilon_c)/kT} = n, \quad (20)$$

where N_c is the conduction-band density of states. Figure 2 shows the temperature dependence of the Fermi level for $N_d - N_a = 2\times 10^{17}$ cm^{-3}, $g=2$, and for different degrees of compensation, N_a/N_d.

The solid lines in Figs. 3(a) and 3(b) show the temperature dependencies of α, calculated from Eq. (16) for $n_0 = 1.3\times 10^{13}$ cm^{-2}, $\varepsilon_0 = 0.1$ eV, $N_d - N_a = 2\times 10^{17}$ cm^{-3}, $N_t = 0.2(N_d + N_a)$, and different compensation levels N_a/N_d. As seen, the Hooge parameter α depends only weakly on temperature in the range from 50 to 600 K. As expected, the level of the $1/f$ noise increases monotonically with compensation growth while the temperature dependencies of noise are identical for all compensation levels. The parameter α ranges from $\sim 10^{-5}$ to $\sim 10^{-3}$ that agrees well with experimental data.[5,6] The dotted line 4″ in Fig. 3(a) shows the dependence calculated using Eq. (17) for $N_a/N_d = 0.5$. As seen, the results of analytical calculation agree well with the numerical one in a temperature interval from 15 to 600 K. Detailed analysis showed that Eq. (17) gives good approximation of Eq. (16) for $kT < 0.8\varepsilon_0$ at any compensation levels and ε_0 values. Equation (18) gives a good approximation of Eq. (16) only at $kT \geq 3\varepsilon_0$.

The dashed lines in Figs. 3(a) and 3(b) show the temperature dependencies of the Hooge parameter α for the noise caused by electron tunneling from 2D channel to Si doping level ε_d (see Fig. 1). Calculations were made for the same compensation levels as for the tunneling to the density-of-states tail. As seen, at low compensation levels $N_a/N_d \leq 0.5$, the $1/f$ noise from single Si level predominates across

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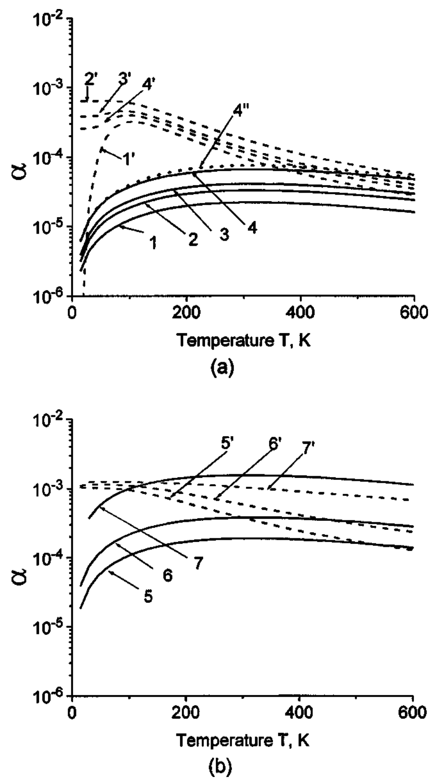

FIG. 3. Temperature dependencies of Hooge parameter α for different compensation levels N_a/N_d. Solid lines calculated using Eq. (16) correspond to the noise caused by tunneling on the tail states. The dashed lines represent the noise caused by tunneling on the doping Si level. N_a/N_d: 1,1′–0; 2,2′–0.2; 3,3′–0.3; 4,4′–0.5; 5,5′–0.8; 6,6′–0.9; 7,7′–0.98; The dotted line 4″ in Fig. 3(a) has been calculated according to Eq. (17) for N_a/N_d =0.5

the whole temperature range. For example, at $T=100$ K and at $N_a/N_d=0$, noise from the local level is two orders of magnitude higher than that for the density-of-states tail.

With the increase of the compensation, the difference between noise amplitude originating from these two noise sources becomes smaller. At $N_a/N_d=0.8$, the noise originating from the tunneling to the tail states predominates at $T \geq 400$ K [curves 5, 5′ in Fig. 3(b)] while at $N_a/N_d=0.98$, noise from the density-of-states tail is higher than noise from the Si level at $T > 100$ K [curves 7, 7′ in Fig. 3(b)].

Note the different temperature dependencies of noise for local Si level and for the density-of-states tail. At relatively low temperatures $T < 80$ K, noise from the density-of-states tail linearly depends on temperature as expected from Eq. (17). Temperature dependence of noise for the local level has a pronounced maximum at low compensation levels, which becomes smaller and disappears at higher compensation levels. At very high compensation levels, this noise only weakly depends on temperature and does not tend to zero at $T \rightarrow 0$.

IV. CONCLUSION

The model of the $1/f$ noise in GaN/AlGaN HFETs based on the phonon-assisted tunneling of the 2D electrons to the tail states in the GaN buffer layer has been proposed. This model predicts a weak temperature dependence of noise and an increase of noise with compensation growth. An estimated values of the Hooge parameter $\alpha=10^{-5}$–4×10^{-4} are in agreement with numerous experiments.[5,6]

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