The spatial and energy distribution of oxide trap responsible for 1/f noise in 4H-SiC MOSFETS

Hua Chen and Liang He

School of Advanced Materials and Nanotechnology, Xidian University, Xi’an 710126, People’s Republic of China

* Author to whom any correspondence should be addressed.

E-mail: hchen@xidian.edu.cn and Ihe@xidian.edu.cn

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Abstract

Low-frequency noise is one of the important characteristics of 4H-SiC metal-oxide-semiconductor field-effect transistors (MOSFETs) that is susceptible to oxide traps. Drain-source voltage noise models of 4H-SiC MOSFETs under low–drain–voltage and inverse condition were proposed by considering the spatial and energy non-uniform distribution of the oxide trap, based on the McWhoter model for uniform trap distribution. This study performed noise experiments on commercial 4H-SiC MOSFETs, and revealed that the non-uniform spatial and non-uniform energy distribution caused new 1/f noise phenomenon, different from that under uniform spatial and energy distribution. By combining experimental data and theoretical models, the spatial and energy distribution of oxide traps of these samples were determined.

1. Introduction

Owing to the advantages including low on-state resistance, favorable gate insulation performance and high switching speed, 4H-SiC metal-oxide-semiconductor field-effect transistors (MOSFETs) are quite promising in high-temperature, radio frequency and high-power electronic applications [1–4]. Low-frequency noise is an important property of 4H-SiC MOSFETs, which is significantly affected by the quality of the oxide layer. Low-frequency noise determines the signal lower limit of the broadband circuit and the detectivity of the optical receiver [5–13]. In fact, the low-frequency noise test offers a sensitive approach for detecting impurities and defects of the MOS structure [5–8]. In MOSFETs, NIOTs with fast interface state and/or small time constant can induce low mobility [1, 3–5], while slow traps induce low-frequency noise [5–8].

There are mainly two models to describe the origin of the carrier number dependent 1/f noise, McWhoter model and thermal activation model. Zhang et al [5, 6] used thermal activation model, the first principle simulation, and noise and threshold voltage experiments of 4H-SiC MOSFETs to conclude that low frequency noise was mainly induced by slow-speed interface traps at a temperature of below 370 K, whereas by border traps at a temperature of over 370 K, and the interface state might originated from carbon vacancy clusters and N-dopant atoms at or near the interface. However, in thermal activation model, the capture cross-section around the bottom of the conduction band of 4H-SiC MOS devices ranged from $10^{-18}$ to $10^{-20}$ cm$^2$ using AC conductance method [4]. Since the physical area of atoms is approximately $10^{-15}$ cm$^2$, these capture cross-sections are too small and make no practical sense. The McWhoter noise model now has been extensively used in BSIM model for SPICE circuit simulation [14]. As described in [3], in 4H-SiC DMOSFET, $S_l$, the noise of drain current $I_d$ was measured, and the dependence of the relative spectral noise density $S_{Is}/I_{Is}^2$ on $I_d$ (at constant drain voltage $V_d$), was qualitatively different from typical dependences for n-channel Si MOSFETs. In Si MOSFETs, in strong inversion, $S_{Is}/I_{Is}^2$ usually decreases as $\propto 1/I_d$ and tends to saturate in the subthreshold region, whereas in SiC MOSFETs under study, $S_{Is}/I_{Is}^2 \propto I_d^{-0.5}$ for the currents varying from the deep subthreshold regime to the strong inversion [7] reported that, in 4H-SiC MOSFET with NO post-oxidation annealing and epitaxial channel, the dependence of noise on gate voltage has a ‘classical’ Si-like form, and oxide traps responsible for 1/f noise, $N_I$, does not depend on $E_c - E_f$ ($E_c$ is a position of the bottom of conductivity

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band; $E_f$ is a position of the Fermi level). In this paper, we will consider the details of the distribution of oxide traps. The noise characteristics reported by [3] may be explained by the non-uniform energy distribution of traps, and the noise characteristics reported by [7] may be explained by the uniform energy distribution of traps.

In this study, the McWhoter noise model was improved for examining the effect of the spatial and energy distribution of oxide traps on noise. It should be noted that this study assumed both interface traps and border traps were included in oxide traps. Spectral noise density $S_{\omega d}$ experiments were implemented on commercial 4H-SiC MOSFETs devices. The extraction method of the spatial and energy distribution of oxide traps based on the curve of low-frequency noise was explored. The spatial and energy distribution of oxide traps responsible for $1/f$ noise in 4H-SiC MOSFETs were obtained and discussed.

2. Noise model

Under moderate to strong inversion with low drain voltage, the relative spectral noise density $S_{\omega d}/I_d^2$ can be expressed as [8, 15, 16],

$$
\frac{S_{\omega d}}{I_d^2} = \left( \frac{1}{WLn_i} \right)^2 \int_0^L S_{\Delta N}(x, f) \frac{1}{\Delta x} dx,
$$

(1)

where, $I_d$ denotes the drain current, $S_{\omega d}$ denotes the drain current noise, $\gamma$ denotes the tunneling coefficient, $W$ and $L$ denote width and length of the channel, respectively, $n_i$ denotes the number of carriers per unit area of channel, $f$ denotes frequency and $S_{\Delta N}$ denotes the power spectral density of the fluctuation of the occupied-trap number in a small neighborhood $\Delta x$ along the channel direction $x$, as shown in figure 1.

Traps are assumed to be uniformly distributed in the entire oxide layer along the channel direction and to be non-uniformly distributed in the direction perpendicular to the channel. It should be noted that this assumption is reasonable for large-size devices. Assuming that $S_{\Delta N}$ can be written as [17]:

$$
S_{\Delta N}(x, f) = 4kT W \Delta x \int_0^{T_{ox}} N_i(E_{fin}, z) \frac{\tau(z)}{1 + \omega^2 \tau^2(z)} dz,
$$

(2)

where, $N_{fin}$ is fermi energy level, $k$ is Boltzmann constant, $T$ is absolute temperature, $\tau$ is time constant and $T_{ox}$ is oxide layer thickness. In equation (2), $\omega = 2\pi f$, $\tau = \tau_0 \exp(\gamma z)$, $\gamma$ denotes the tunneling coefficient, and the typical value of $\tau_0$ is $10^{-10}$ s [8, 17].

The charge pumping measurements show that trap density in SiO$_2$ within a nanometer range may vary by nearly two or even more than two orders of magnitude [18]. Accordingly, the trap distribution is described in the following exponential form: $N_i(E_{fin}, z) = N_{i,0}(E_{fin}) e^{\gamma z}$, in which $z = 0$ denotes the interface position and $N_{i,0}$ denotes the density of traps at the interface. By substituting $N_i(E_{fin}, z) = N_{i,0}(E_{fin}) e^{\gamma z}$ into equation (1) and integrating, the following expression can be derived:

![Figure 1. Schematic of the structure of MOSFETs.](image-url)
\[ S_{\Delta N}(x, f) = 4kT \Delta x \int_{0}^{\text{Tox}} N_{t,0}(E_{fn}) \frac{e^{\frac{\tau}{1 + \omega^2 r^2}}}{1 + \omega^2 r^2} dz \]
\[ = \frac{4kT \Delta x N_{t,0}(E_{fn})}{\gamma \tau_0^{\beta / \gamma} \omega^{3 + \beta / \gamma}} \int_{\omega_0}^{\omega} \frac{(\omega \tau)^{\beta / \gamma}}{1 + \omega^2 r^2} d(\omega \tau) \]
\[ = \frac{kT \Delta x N_{t,0}(E_{fn})}{\gamma (2\pi \tau_0)^{r^{-1}} \sin \frac{\pi r}{2}} f^r. \]

\[ r = 1 + \frac{\beta}{\gamma} \text{ and the integral form } \int_{0}^{\infty} \frac{x^{r-1}}{1 + x^2} dx = \frac{\pi}{2} \frac{\omega_0}{2}, \quad r > 0 \text{ are used in the third equation of equation (3). By substituting equation (3) and } V_g - V_t = \frac{qN_t}{C_{ox}} \text{ (where } V_g \text{ is the gate voltage, } V_t \text{ is the threshold voltage, } q \text{ is the electron charge and } C_{ox} \text{ is the oxide capacitance per unit area) into equation (1), we can get } \]
\[ S_{u_d} = \frac{V_g - V_t}{kT q N_{t,0}(E_{fn}) \sin \frac{\pi r}{2}} \frac{1}{f^r}. \]

In linear region, \[ S_{u_d} / V_{d}^2 = S_{u_d} / I_d^2, \text{ in which } S_{u_d} \text{ denotes the drain-source voltage noise, } S_{u_d} \text{ can be written as: } \]
\[ S_{u_d} = \frac{V_g - V_t}{kT q N_{t,0}(E_{fn}) \sin \frac{\pi r}{2}} \frac{1}{f^r}. \]

For n-channel MOSFETs, as shown in figure 2, with the increase of \( V_g - V_t \), the conduction band of the channel surface bends down, and the oxide traps which can affect \( S_{u_d} \) are closer to the bottom of the conduction. According to equation (5), when the traps have uniform energy distribution, \( S_{u_d} \) is directly proportional to \( (V_g - V_t)^{-m} \). If the closer the traps are to the bottom of conduction band and the higher the density is, \( S_{u_d} \) is still directly proportional to \( (V_g - V_t)^{-m} \), but \( m < 2 \).

According to DC theory of MOSFETs, when \( V_g \approx 0 \), the relationship between \( V_g \), the surface potential \( V_s \) and the electron quasi Fermi level \( E_{fn} \) of n-channel MOSFETs is determined by the following two equations [19]:
\[ C_{ox}(V_g - V_t) = \sqrt{2kTN_{sub} \varepsilon_1} \left[ \sqrt{\beta \varphi_t} + (n_i/N_{sub})^2 \exp(\beta \varphi_t) - \sqrt{\beta \varphi_i} \right], \]
\[ E_{fn} - E_i = q(\varphi_i - \varphi_f), \]

where, \( \beta = q/kT \), \( N_{sub} \) denotes the substrate doping concentration, \( \varphi_t \) denotes the Fermi potential of the substrate and \( E_i \) denotes the mid-value of the forbidden band. With equation (5), \( N_t,0 \) can be obtained from the measured curve of \( S_{u_d} \), and with equations (6) and (7), \( E_{fn} - E_i \) also can be acquired.

3. Experimental details

Threshold voltage test and drain voltage noise test were performed on 4H-SiC MOSFETs, C2M0160120D, manufactured by CREE Corporation. Three samples of C2M0160120D were labeled as 120–1, 120–2 and 120–3, respectively. The MOSFETs are n-type channel with planar architecture and SiO2 gate dielectric.

Keithley 4200-SCS was used to measure the \( I_d \sim V_g \) curve and extract the threshold voltage \( V_t \). As shown in the noise test diagram of figure 3, an adaptive circuit for 4H-SiC MOSFET noise measurement was built, in which the sample could be in a setting bias condition, the fluctuation of \( V_g \) was transmitted to the pre-voltage amplifier by AC coupling, a data acquisition card collected the amplified signal and a computer processed.
time series into noise power spectral density $S_{V_d}$. The noise test was performed under room temperature. The amplifier gain was set as 5000, the measuring frequency ranged from 1 Hz $\sim$ 10 KHz.

4. Noise data and analysis

Figure 4 shows that the $I_d-V_g$ curves of these devices are normal and figure 5 shows the variations of $S_{V_d}$ with frequency in low-frequency range (1 Hz $\sim$ 1000 Hz) under linear mode. The absolute value of the spectrum slope in the log-log coordinate system reflects the frequency exponent, $r$. It can be observed that all curves of the same sample exhibit nearly similar slopes at different bias conditions. As shown in figure 5, the fitted values of $r$ approximately are 0.83 and 0.84, respectively, consistent with the general range of the $r$ of $1/f$ noise ($0.8 \leq r \leq 1.2$) [8].

When $\beta = 0$, that is $r = 1 + \beta/\gamma = 1$, the traps are uniformly distributed, and equation (5) is converted to

$$S_{V_d} = \frac{V_d^2}{(V_g - V_t)^2} \frac{kTq^2N_{t,0}}{\gamma W L f C_{ox}^2}$$

By comparing equation (5) with equation (8), the spatial non-uniformity of traps causes the deviation of $r$ from 1. The trap spatial distribution in Sample 120–1 can be expressed as $N_t(E_{tr}) = N_{t,0}(E_{tr}) e^{\beta z}$, in which $\beta = -1.1 \times 10^7 \text{ cm}^{-1}$ for Sample 120–1. A negative value of $\beta$ is indicative of decreasing oxide trap density with the distance away from SiC/SiO$_2$ interface, which is consistent with general distribution rules of traps [17].

The $S_{V_d}$ varieties of three samples with $V_d$ at $V_d = 0.1$, are measured and shown in figure 6. With the equations (5)–(7), the trap energy distribution of all samples are simulated and shown in figure 7. The oxide trap has a uniform energy distribution, and then $m = 2$, which has been reported by [20]. But the results in figure 6 are more relatively complex. For 120–type samples, we can observe $m < 2$ for all the samples. The difference of
Figure 5. $S_{Vd}$ at different bias conditions for Sample 120–1.

Figure 6. $S_{Vd}$ with $V_g - V_t$ for all samples.

Figure 7. Energy distributions of trap density for all samples.
\( m \) reflects the different trends of the trap density with energy. For Sample 120–1, the density of oxide traps decreased as the energy shifts further away from the bottom of the conduction band, and similar trend has been reported in [3]. The \( m \) value of Sample 120–2 is closest to 2, i.e. the traps in Sample 120–2 have an approximately uniform energy distribution.

With the methods described in noise model and \( N_{b,0} \) assumed as \( 1 \times 10^{15} \text{cm}^{-3} \), the trends of trap energy distribution are calculated and shown in figure 7. If the structure parameters of devices such as \( C_{ox} \) and \( W/L \) can be obtained, the horizontal and vertical coordinates of the figure can be completely determined, that is to say, the change of trap density with energy can be accurately measured. Sample 120–2 is chosen as an example to compute the trap density distribution. The measurement capacitance of 120–2 is \( 1.2 \times 10^{-9} \text{F} \), by assuming that oxide thickness is 50nm, then,

\[
W/LC_{ox} = 8.2836 \times 10^{-17} (\text{F cm})^2,
\]

and the average of \( N_{b,0} \) is \( 5.4857 \times 10^{21} / (\text{eV cm}^3) \). By multiplying \( N_{b,0} \) with the spatial distribution \( \exp(-1.15 \times 10^2 z) \), the final distribution could be obtained, which is

\[
N_t(E, z) = 5.4857 \times 10^{23} \exp(-1.15 \times 10^2 z) = N_t(z).
\]

If the sample trap has a non-uniform energy distribution, the trap density as a linear function of energy, can be gotten to use the least square method for linear fitting.

5. Conclusions

The McWhoter model for uniform trap distribution was modified, to investigate non-uniformities in spatial and energy distributions of oxide traps in 4H-SiC MOSFETs. For two kinds of sample, the characteristics of drain voltage noise with frequency and gate voltage were examined experimentally. By combining experimental data and theoretical models, the spatial and energy distribution of oxide traps in these samples were determined. The values of the parameter \( \beta \) in the trap spatial expression \( N_t = N_{t,0} \exp(-z) \) were \(-1.1 \times 10^2 \text{cm}^{-1}\) for Sample 120–1. A negative value of \( \beta \) was suggestive of the fact that the density of traps in the oxide layer further away from the SiC/SiO\(_2\) interface was lower. The exponent of \( S_{V} \) dependence on \( V_c - V_t \) was denoted as \( m. m = 2 \) was the sign of the uniform energy distribution of oxide trap, while the \( m \) value deviating from 2 meant a non-uniform energy distribution. For three 120 samples decreased slightly as the energy shifted further away from the bottom of the conduction band, and among them, the energy distribution of sample 120–2 and sample 120–3 were the closest to an uniform distribution.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

ORCID iDs

Hua Chen © https://orcid.org/0000-0002-5431-3024

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