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Low-frequency noise in 4H–silicon carbide junction field effect transistors

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Low frequency noise in 4H-silicon carbide junction field effect transistors (JFETs) has been investigated. JFETs with a buried p^+n junction gate were manufactured by CREE Research Inc. Very low noise level has been observed in the JFETs. At 300 K the value of Hooge constant α is as small as $\alpha \sim 10^{-5}$ and the α value can be decreased by an appropriate annealing to $\alpha \sim 2 \times 10^{-6}$. It has been shown that even these extremely low noise values are determined not by the volume noise sources but by the noise at the SiC–SiO_2 interface. © *1996 American Institute of Physics.* [S0003-6951(96)00919-9]

In recent years 4H–silicon carbide (4H–SiC polytype) has received much attention because of its ability to be used for high power microwave devices.[1–3] The electron mobility in 4H–SiC is about twice as high as that of 6H–silicon carbide (6H–SiC). Additionally, 4H–SiC is practically isotropic,[4] and the activation energy of the donor dopants is lower than in 6H–SiC. For microwave devices the level of low frequency noise is one of the important parameters which determines the applicability of the device for microwave communication systems. In this letter the low frequency noise in 4H–SiC field effect transistors (FETs) has been investigated.

In this research 4H–SiC FETs with a buried p^+n junction gate manufactured by Cree Research Inc. were used. The design of the devices is basically the same as that reported previously for 6H–SiC junction field effect transistors (JFETs).[5] On the p^+ gate side the channel is bounded by the space-charge region of a p^+n junction. On the opposite side the channel is bounded by an oxide layer. It will be shown that the oxide is usually negatively charged and on the oxide side the channel is also bounded by a space-charge region. Hence, the real thickness of the channel is $h = h^0 - d_{pn} - d_0$,[5] where h^0 is the geometrical thickness of the channel, d_{pn} is the thickness of the space-charge region near the gate p^+n junction, d_0 is the thickness of the space-charge region near the oxide. The gate length is $L = 5$ μm, the gate width is $W =$ 1 mm, the doping concentration is $N_d - N_a \cong 10^{17}$ cm^{-3}.

Figure 1(a) shows the temperature dependencies of the spectral density fluctuations S_I/I^2 in the temperature range 300–600 K. Unlike 6H–SiC reported previously[4] there are no pronounced maxima on S–T dependencies. For all the frequencies of the analysis the noise increases monotonically with the increase of temperature. Figure 1(b) shows the frequency dependencies of S_I/I^2. It is clear that for all temperatures the dependence $S_I/I^2 \sim 1/f^{1.5}$ is valid. This kind of frequency dependence is rather typical for GaAs, SiC, and Si FETs.[6–8]

The noise level in different materials is frequently characterized by the dimensionless Hooge parameter α:[9]

$$\alpha = \frac{S_I}{I^2} \cdot f \cdot N, \tag{1}$$

where N is the total number of conduction electrons in the sample, f is the frequency of analysis.

The real thickness of the channel at the gate voltage $V_{GS} = 0$ V estimated from the threshold voltage $V_t \cong 2.5$ V, is equal to $h \cong 0.06$ μm. Then the total number of carriers in the channel is $N = n_0 \cdot L \cdot W \cdot h \cong 3 \times 10^7$ and the value of Hooge

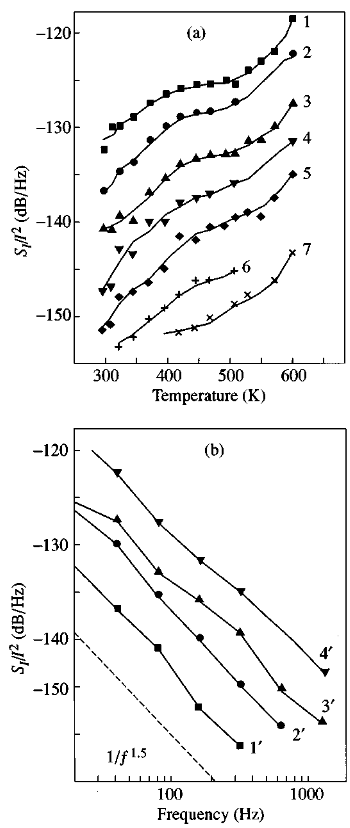

FIG. 1. The temperature (a) and the frequency (b) dependencies of spectral density fluctuations S_I/I^2. $V_{GS} = 0$ V. (a) Frequency (Hz): 1–20; 2–40; 3–80; 4–160; 5–320; 6–640; 7–1300; (b) Temperature (K): 1′–300; 2′–400; 3′–500; 4′–595.

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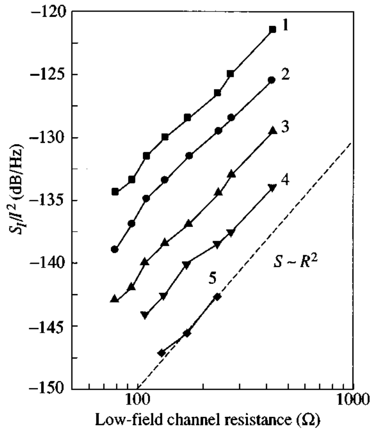

FIG. 2. The dependencies of S_I/I^2 vs low-field channel resistance R for different frequencies of analysis. T=300 K. Ohmic regime. The minimal value R=77 Ω corresponds to $V_{GS}=+2$ V. The maximal value R=414 Ω corresponds to $V_{GS}=-1.5$ V. Frequency (Hz): 1–20; 2–40; 3–80; 4–160; 5–320.

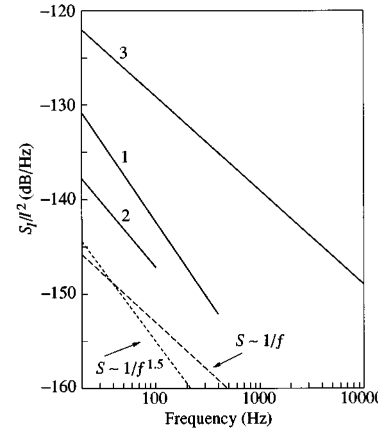

FIG. 3. Frequency dependencies of S_I/I^2 for the device before (curve 1) and after (curves 2 and 3) annealing in different regimes: T=300 K. (2) the annealing at 600 K during 2 h at $I_{DS}=0$; (3) the annealing at 600 K during 2 h in saturation regime: $V_{GS}=0$; $V_{DS}=8$ V.

parameter is $\alpha = S_I/I^2 f \cdot N$ at 300 K is equal to $\alpha \cong 3 \times 10^{-5}$ at f=20 Hz and $\alpha \cong 5 \times 10^{-6}$ at f=1300 Hz. According to the criteria established for conventional Si and GaAs FETs, such a low value of α indicates a very high degree of structural quality for the channel material and a rather small contribution of the contacts in the total noise of the device.

One can show however that even this small noise value is determined not by the volume noise sources in the 4H–SiC channel but by the fluctuations on SiC–SiO_2 interface. Figure 2 shows the dependencies of S_I/I^2 on the channel resistance R. The resistance has been controlled by the gate voltage V_{GS}. All the measurements were made in the linear (Ohmic) regime. It is seen that for all frequencies the S_I/I^2 value is proportional to R^2.

If the volume noise was dominant the dependence S_I/I^2 versus resistance value R would be $S_I/I^2 \sim R$. Indeed, in the linear regime the channel resistance R is inversely proportional to the total number of electrons in the channel N. Hence, according to Eq. (1), the relation $S_I/I^2 \sim R$ should be valid for the volume noise.

On the other hand the dependence $S_I/I^2 \sim R^2$ may be easily explained if one assumes that the volume noise of the channel is very small and that the source of the noise observed is a surface resistance $R_s \gg R$ on the channel-oxide interface.[10] In this case the source of noise can be described by an equivalent circuit in which a ''noisy'' surface resistance R_s is connected in parallel with a noise-free volume resistance R. The R_s value and the fluctuation amplitude δR_s do not depend on the gate voltage U_{GS}. Then it is easy to see that

$$\frac{(\delta I)^2}{I^2} = \frac{R^2}{R_s^2} \cdot \frac{\delta R_s^2}{R_s^2}. \tag{2}$$

From Eq. (2) it is obvious that in this case $S_I/I^2 \sim R^2$. This dependence is explained by the current redistribution between R and R_s resistances when the channel resistance R increases due to the gate voltage change. The greater the value of R, the weaker it shunts the ''noise'' resistance R_s.

The noise value and the frequency dependence of the noise may be changed considerably by appropriate annealing. The noise properties of the samples are stable up to 500 K. For T>500 K, the noise parameters depend on the regime of the annealing. The annealing of the samples at $R \sim$550–600 K for several hours in linear (Ohmic) regime or at $I_{DS}=0$ decreases the noise level to a great extent (Fig. 3, curve 2). The frequency dependence of S takes the form $S \sim 1/f$ (flicker noise). As this takes place, the Hooge α value is as small as $\alpha \cong 5 \times 10^{-6}$. This low noise level is retained for $T \leqslant 500$ K.

The annealing of the samples at $T \sim$550–600 K for several hours at saturation regime makes quite a different effect on the noise. In this case the noise level increases considerably (Fig. 3, curve 3). The frequency dependence of S again takes the form $S \sim 1/f$.

During the annealing at $T \sim$550–600 K in the saturation regime the noise level gradually increases. At the same time the current–voltage characteristic of the device $I_D(V_{DS})$ is also affected. The drain current I_D increaes monotonically at constant V_{DS} value. The measurements show that during the annealing in the saturation regime the thickness of the channel increases monotonically. At high temperature a current flow of hot electrons near the channel-oxide interface recharges the oxide. The thickness of the space-charge region d_0 decreases and the thickness of the channel h grows. As this takes place, the distance between the channel and the oxide–4H–SiC interface (which is the main source of the noise) decreases and the noise increases (Fig. 3, curve 3).

The annealing of the samples in the linear (Ohmic) regime again decreases the noise level to values comparable with the curves 1 or 2 in Fig. 3.

In summary, a very low noise level has been observed in 4H–SiC FETs. At 300 K the value of Hooge constant α is as small as $\alpha \sim 10^{-5}$ and the α value can be decreased by an appropriate annealing to $\alpha \sim 2 \times 10^{-6}$.

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