INFLUENCE OF ACCUMULATION BACK-GATE VOLTAGE ON THE NOISE SPECTRA OF DEEP SUBMICRON SOI MOSFET'S IN A WIDE RANGE OF DRAIN VOLTAGES

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The influence of an accumulation back-gate voltage on the Lorentzian component observed in the noise spectra of deep submicron partially depleted metal-oxide-semiconductor field-effect transistors (MOSFETs) at sufficiently high drain voltages has been studied. That component is associated with impact ionization near the drain $p-n$ junction. Such an accumulation back-gate voltage has been demonstrated to substantially affect the magnitude of the Lorentzian time constant and the level of the Lorentzian plateau, and to reduce the drain current. Those effects can be explained in the framework of the model proposed earlier, where the accumulation back-gate voltage is considered as that increasing the conductance of the body-source $p-n$ junction. In addition, the so-called back-gate-induced (BGI) Lorentzians, which originate from the Nyquist fluctuations of that conductance, have been detected at low drain voltages in the noise spectra.

1. Introduction

In partially depleted (PD) MOSFETs, which have been fabricated following the silicon-on-insulator (SOI) technology, the effects caused by the availability of the floating body are observed. One of them is the emergence of the excess Lorentzian noise which accompanies the so-called kink effects. Such effects involve nonlinear and linear ones (NKE and LKE, respectively). The former takes place at high enough drain voltages V_{DS} (when the impact ionization near the drain $p-n$ junction becomes possible) [1]. The latter is observed at high enough front-gate voltages $V_{\mathrm{GF}} > 1$ V (when electrons start tunneling from the valence band through an ultrathin front-gate oxide layer) and a drain voltage V_{DS}, which corresponds to the linear regime of the transistor [2]. It should be noted that the nonlinear kink effect is observed as an extra maximum in the dependence of the differential conductance of the channel g_d on V_{DS}, while the linear one – as an extra maximum in the dependence of the transistor transconductance g_m on V_{GF}.

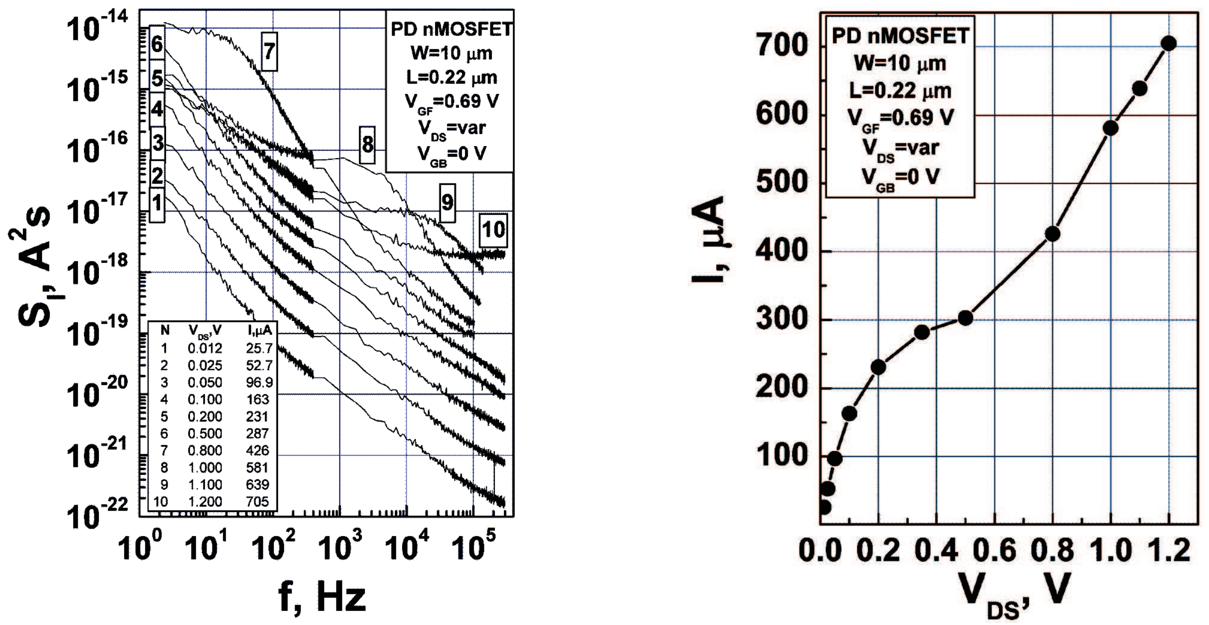
It has been demonstrated earlier that the application of an accumulation voltage to the back gate substantially affects the parameters of LKE-Lorentzians as well as the intensity of the linear kink effect [2, 3].

In this work, we study the influence of the accumulation back-gate voltage on the noise Lorentzians, which accompany the nonlinear kink-effect. We demonstrate that such a voltage considerably influences not only the time constant and the level of the noise plateau of NKE-Lorentzians but the drain current as well. We also demonstrate that the effects observed can be explained in the framework of the model [3], according to which the accumulation on the back interface gives rise to the growth of the conductance of the body-source junction. The Nyquist noise of this conductance reveals itself as the so-called back-gate-induced (BGI) Lorentzians observed in the noise spectra at low drain voltages [4, 5].

2. Experimental

Partially depleted n-channel MOSFETs fabricated by the 0.1-μm SOI technology, with a 2.5-nm nitrided front gate oxide and a 150-nm polysilicon gate were studied. The devices were fabricated on UNIBOND wafers 200 mm in diameter. The final thickness of the Si film was 100 nm. A high-dose halo implantation (3×10^{13} cm^{-2}) was applied to weaken the short-channel effects. The width and the length of the channel were $W = 10$ μm and $L = 0.22$ μm, respectively.

The current noise spectra were measured in the frequency range $f = 2$ Hz $\div$ 100 kHz, at a fixed front-gate voltage $V_{\mathrm{GF}} = 0.69$ V, and the back-gate voltages $V_{\mathrm{GB}} = 0$ and -46 V (the latter corresponds to the



a b

Fig. 1. Noise spectra (a) and current-voltage characteristic (b) measured at $V_{\mathrm{GF}} = 0.69$ V and $V_{\mathrm{GB}} = 0$ V ($V_{\mathrm{DS}} = 12$ mV $\div$ 1.2 V)

regime of accumulation on the back interface). The drain voltage V_{DS} was varied from 12 mV to 1.2 V. In addition, the dependences of the drain current I on the drain voltage V_{DS} were measured.

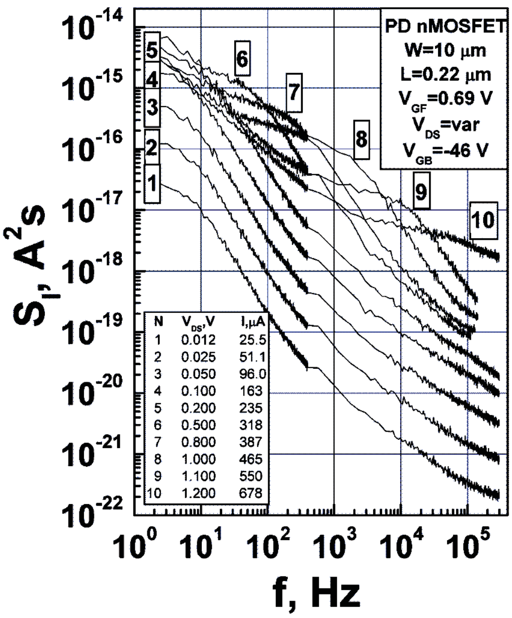
3. Results

The family of the noise spectra and the current-voltage characteristic measured in the drain-voltage interval $V_{\mathrm{DS}} = 12$ mV $\div$ 1.2 V and at $V_{\mathrm{GB}} = 0$ V are shown in Fig. 1,a and Fig. 1,b, respectively. From Fig. 1,a, one can see that the spectral density of the drain current noise $S_I(f)$ is characterized by a $1/f$-behavior in the range of low drain voltages $V_{\mathrm{DS}} = 12 \div 200$ mV (curves *1* to *5*). However, the further growth of V_{DS} brings about the appearance of a component in the spectra, which has a Lorentzian shape (curves *7* to *10*), namely, $S_I(f) = S_I(0)/[1 + (f/f_0)^2]$, where $S_I(0)$ is the noise plateau level, and f_0 is the characteristic frequency connected with the Lorentzian time constant τ by the relation $\tau = (2\pi f_0)^{-1}$. From Fig. 1,a, it is also evident that the growth of V_{DS} results in a reduction of $S_I(0)$, an increase of f_0, and, therefore, in a reduction of τ.

Figure 1,b demonstrates that the dependence $I(V_{\mathrm{DS}})$ in the voltage interval $V_{\mathrm{DS}} \leq 500$ mV is characterized by a behavior typical of field-effect transistors; namely, as V_{DS} grows, the drain current I first linearly increases and then saturates. However, the further increase of the drain voltage V_{DS} is accompanied by a drastic growth of the current I. Such a behavior of the dependence $I(V_{\mathrm{DS}})$ is typical of the SOI transistors and is referred to as a nonlinear kink-effect.

The comparison of Figs. 1,a and b demonstrates that the emergence of Lorentzian components in the noise spectra corresponds with the NKE portion of the curve $I(V_{\mathrm{DS}})$. This means that those Lorentzians are the NKE-ones. For the latter, according to the results of work [6], the growth of V_{DS} leads to a reduction of $S_I(0)$ and an increase of f_0, which is really observed in Fig. 1,a (curves *7* to *10*).

In Fig. 2, the family of noise spectra (Fig. 2,a) and the current-voltage characteristic (Fig. 2,b, curve *2*) measured at the accumulation back-gate voltage $V_{\mathrm{GB}} = V_{\mathrm{acc}} = -46$ V are shown in the same interval of drain voltages as in Fig. 1. The comparison between Figs. 2,a and 1,a demonstrates that, in the frequency range $f >$ 400 Hz, the accumulation voltage does not change the noise spectra measured at $V_{\mathrm{DS}} = 12 \div 200$ mV (curves *1* to *5* in Figs. 1,a and 2,a). However, at $f <$ 400 Hz, an essential difference between those spectra appears; namely, at $V_{\mathrm{acc}} = -46$ V, there appear BGI-Lorentzians (Fig. 2,a) [4, 5], the characteristic frequency of which does not depend on V_{DS} and is equal to $f_0 = 6.5$ Hz, which corresponds to $\tau_{\mathrm{BGI}} = 24.5$ ms. It is also seen from Fig. 2,a that the NKE-Lorentzians, for which the



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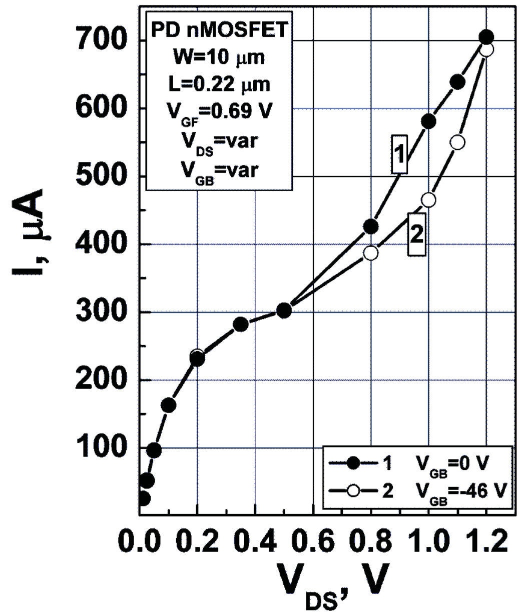

b

Fig. 2. Noise spectra measured at $V_{\mathrm{GF}} = 0.69$ V and $V_{\mathrm{GB}} = -46$ V (*a*) and current-voltage characteristics measured at $V_{\mathrm{GF}} = 0.69$ V for $V_{\mathrm{GB}} = 0$ (*1*) and -46 V (*2*) (*b*) ($V_{\mathrm{DS}} = 12$ mV $\div$ 1.2 V)

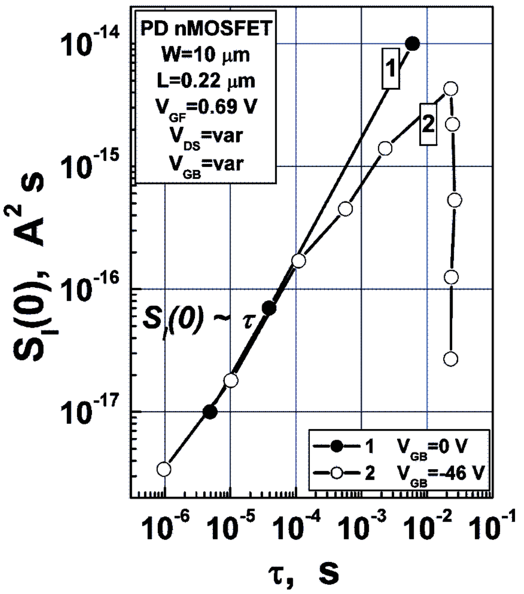

Fig. 3. Dependences of $S_I(0)$ on τ at $V_{\mathrm{GF}} = 0.69$ V for $V_{\mathrm{GB}} = 0$ V ($V_{\mathrm{DS}} = (0.8\div1.1)$ V) (*1*) and $V_{\mathrm{GB}} = -46$ V ($V_{\mathrm{DS}} = 12$ mV$\div$1.2 V) (*2*)

growth of the drain voltage V_{DS} leads to a decrease of $S_I(0)$ and an increase of f_0, reveal themselves in the noise spectra at $V_{\mathrm{acc}} = -46$ V and $V_{\mathrm{DS}} \geq 500$ mV (Fig. 2,*a*, curves *6* to *10*). The comparison of these Lorentzians with those observed at $V_{\mathrm{GB}} = 0$ V (Fig. 1,*a*, curves *7* to *10*) shows that the accumulation back-gate voltage brings about significant variations of the noise plateau level $S_I(0)$, the characteristic frequency f_0, and, as a consequence, the time constant τ.

Figure 2,*b* also demonstrates that, under nonlinear-kink-effect conditions, the accumulation back-gate voltage V_{acc} affects the channel current I itself. In particular, although curves *1* and *2* coincide in the range of drain voltages $V_{\mathrm{DS}} \leq 500$ mV, a considerable variation of the current I is observed at $V_{\mathrm{DS}} > 500$ mV (i.e. under the conditions which correspond to the NKE); namely, provided an identical drain voltage V_{DS}, the accumulation voltage V_{acc} decreases the values of I.

In Fig. 3, the dependences of the noise plateau level $S_I(0)$ on the time constant τ at $V_{\mathrm{GB}} = 0$ V (curve *1*) and $V_{\mathrm{GB}} = V_{\mathrm{acc}} = -46$ V (curve *2*) are shown. One can see that, if $V_{\mathrm{GB}} = 0$ V, the dependence of $S_I(0)$ on τ looks like $S_I(0) \sim \tau$. At the same time, in the case where $V_{\mathrm{GB}} = -46$ V, the following three portions can be distinguished in this dependence: 1) the portion that corresponds to BGI-Lorentzians, for which $\tau = 24.5$ ms $\neq \tau(V_{\mathrm{DS}})$, whereas $S_I(0) \sim (g_m)^2 \sim (V_{\mathrm{DS}})^2$ [4, 5]; 2) the portion that corresponds to the NKE-Lorentzians and is observed at $\tau < 0.1$ ms; and 3) the transition portion that is observed at 0.1 ms $< \tau <$ 24.5 ms. It follows from Fig. 3 that curves *1* and *2*

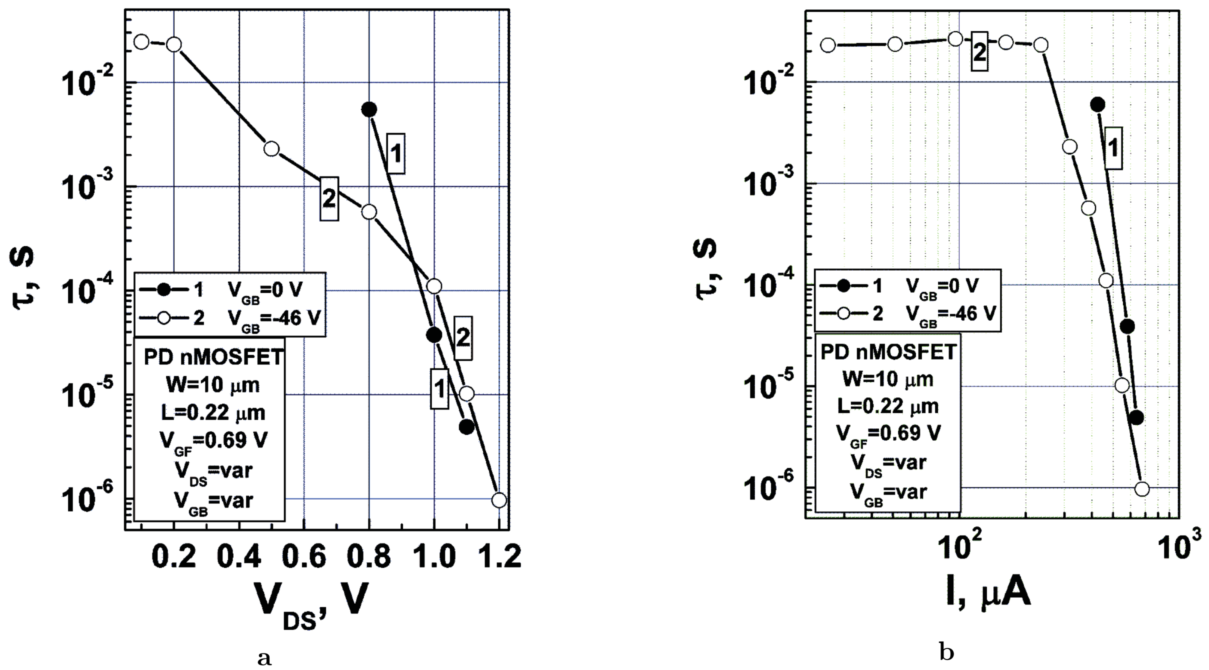

Fig. 4. Dependences of the time constant τ on the drain voltage $V_{\rm DS}$ (*a*) and on the drain current I (*b*), measured at $V_{\rm GF} = 0.69$ V for $V_{\rm GB} = 0$ (*1*) and -46 V (*2*)

coincide, if $\tau < 0.1$ ms. This means that the accumulation back-gate voltage does not influence the ratio $[S_I(0)/\tau]_{\rm NKE}$.

Figures 4,*a* and *b* demonstrate the behavior of the Lorentzian time constant with $V_{\rm DS}$ and I, respectively. It follows from Fig. 4,*a* that, at a given value of $V_{\rm DS}$, the accumulation back-gate voltage can either increase or diminish the value of τ, and the "sign" of this effect depends on the magnitude of $V_{\rm DS}$-magnitude. At the same time, it is evident from Fig. 4,*b* that, provided the value of I is fixed, the accumulation back-gate voltage always decreases the value of τ.

4. Discussion

The mechanism of a the nonlinear kink-effect is known to be as follows [1]. Stimulated by impact ionization which occurs near the drain $p-n$ junction at high enough values of $V_{\rm DS}$, the current of the majority charge carriers I_{ii} runs into the transistor body. Since the body of SOI transistors is floating, this process gives rise to the accumulation of majority charge carriers in the body and to the growth of its potential $V_{\rm BS}$. The latter means that the forward bias across the body-source $p-n$ junction increases, and, hence, the forward current I_F running through this junction increases as well. Such a growth of I_F continues until I_F becomes equal to I_{ii}, i.e. until the stationary state has been achieved, for which

$$I_F = I_{ii} = I_0\left[\exp\left(\frac{qV_{\rm BS}}{nkT}\right) - 1\right], \tag{1}$$

where q is the elementary charge; n and I_0 are the ideality factor and the saturation current of the source $p-n$ junction, respectively; k is the Boltzmann constant; and T is the temperature. Thus, for a magnitude of the body potential $V_{\rm BS}$ which corresponds to stationary conditions, the equation

$$V_{\rm BS} = \left(\frac{nkT}{q}\right)\left[\ln\left(\frac{I_{ii}}{I_0}\right) + 1\right] \tag{2}$$

holds true. The nonlinear kink-effect is associated with the fact that the availability of such a voltage on the body reduces the threshold voltage of the transistor $V_{\rm th}$. In turn, this leads to the growth of the channel current I, which can be determined as follows: $I = \beta g_m V_{\rm BS}$, where $\beta = (\partial V_{\rm th}/\partial V_{\rm BS})$ and $g_m = (\partial I/\partial V_{\rm th})$.

Concerning the nature of the noise NKE-Lorentzians, their existence stems from shot fluctuations of the currents I_F and I_{ii}, the spectral densities of which – $2qI_F$ and $2qI_{ii}$, respectively – do not depend on the frequency. However, not only the equivalent resistance $r_{\rm eq} = (\partial I_F/\partial V_{\rm BS})^{-1} = (nkT/qI_{ii})$ but also the equivalent capacity $C_{\rm eq} = C_{bb}+C_{js}+C_{jd}$ between the floating body and the grounded source are in parallel to the generator of current noise $(2qI_F + 2qI_{ii}) = 4qI_{ii}$, , where C_{bb} is the capacity of the depleted layer, and C_{js} and C_{jd} are the capacities of the body-source and body-drain junctions, respectively. As a result, the spectrum of the body potential noise, which is caused by the presence of the above noise generator, has the Lorentzian shape. The parameters of such NKE-Lorentzians are determined as follows: $S_{\rm VBS}(0) = 4qI_{ii}(r_{\rm eq})^2$ and $\tau = C_{\rm eq}r_{\rm eq}$; whence, for the spectral density of the channel current noise, we obtain

$$S_I(0)_{\rm NKE} = \beta^2 g_m^2 S_{\rm VBS}(0) =$$

$$= 4nkT\tau_{\rm NKE}\beta^2 g_m^2/C_{\rm eq} \sim \tau_{\rm NKE}, \tag{3}$$

$$\tau_{\rm NKE} = C_{\rm eq}r_{\rm eq} = C_{\rm eq}nkT/qI_{ii} \sim I_{ii}^{-1}, \tag{4}$$

$$[S_I(0)/\tau]_{\rm NKE} = 4nkT\beta^2 g_m^2/C_{\rm eq}. \tag{5}$$

Thus, the experimentally observed reduction of $\tau_{\rm NKE}$ and $S_I(0)_{\rm NKE}$ with increasing $V_{\rm DS}$ (see Fig. 1,*a*) are caused by the increase of I_{ii}.

It turned out that the behavior of the NKE-Lorentzians, observed at the accumulation back-gate voltage, can be explained in the framework of the model [3], where the accumulation voltage increases the conductance of the source $p-n$ junction. For instance, the reduction of the drain current I, which is observed in the range of drain voltages $V_{\rm DS}$ that corresponds to the NKE at $V_{\rm GB} = V_{\rm acc}$ (see Fig. 2,*b*), can be explained as follows. The accumulation back-gate voltage leads to the growth of the saturation current I_0 through the body-source junction and, hence, to the decrease of the body potential $V_{\rm BS}$ (see Eq. 2). Since $I = \beta g_m V_{\rm BS}$, this results in a reduction of the channel current I.

Consider now the behavior of the parameters of noise NKE-Lorentzians in the case where the accumulation voltage $V_{\rm acc}$ is applied to the back gate. In the framework of the model mentioned above [3], we have

$$[I_F]_{\rm acc} = [I_{ii}]_{\rm acc} = [I_0]_{\rm acc}[\exp(\gamma_{\rm acc}V_{\rm BS}) - 1], \tag{6}$$

where the subscript acc corresponds to the condition $V_{\rm GB} = V_{\rm acc}$, and $\gamma_{\rm acc}$ is the coefficient, which characterizes the growth of $I_{\rm F}$ with increasing $V_{\rm BS}$ under the condition where $V_{\rm GB} = V_{\rm acc}$. Note that $\gamma_{\rm acc} \geq (q/nkT)$ and $[I_0]_{\rm acc} > I_0$. In this case, one has

$$\tau_{\rm acc} = C_{\rm eq}[r_{\rm eq}]_{\rm acc} = C_{\rm eq}/\left(\gamma_{\rm acc}[I_{ii}]_{\rm acc} + G_0\right), \tag{7}$$

where $G_0 = \gamma_{\rm acc}[I_0]_{\rm acc}$ is the differential conductance of the body–source junction at $V_{\rm BS} = 0$ V.

In the case of high enough $V_{\rm DS}$, when $\gamma_{\rm acc}[I_{ii}]_{\rm acc} \gg G_0$, it follows from Eq. (7) and Eq. (3) for the NKE-Lorentzians

$$[\tau_{\rm NKE}]_{\rm acc} = C_{\rm eq}[r_{\rm eq}]_{\rm acc} = C_{\rm eq}/\gamma_{\rm acc}[I_{ii}]_{\rm acc} \sim [I_{ii}]_{\rm acc}^{-1}, \tag{8}$$

$$[S_I(0)_{\rm NKE}]_{\rm acc} = 4q[\tau_{\rm NKE}]_{\rm acc}\beta^2 g_m^2/\gamma_{\rm acc}C_{\rm eq} \sim [\tau_{\rm NKE}]_{\rm acc}, \tag{9}$$

$$\{[S_I(0)/\tau]_{\rm NKE}\}_{\rm acc} = 4q\beta^2 g_m^2/\gamma_{\rm acc}C_{\rm eq}. \tag{10}$$

According to our experimental results, the accumulation voltage does not influence the value of the ratio $[S_I(0)/\tau]_{\rm NKE}$ (see Fig. 3), i.e. the equality $[S_I(0)/\tau]_{\rm NKE} = \{[S_I(0)/\tau]_{\rm NKE}\}_{\rm acc}$ takes place. Then, from Eqs. (5) and (10), we obtain

$$\gamma_{\rm acc} = q/nkT. \tag{11}$$

Therefore, one has from Eq. (7)

$$[\tau_{\rm NKE}]_{\rm acc} = C_{\rm eq}[r_{\rm eq}]_{\rm acc} = C_{\rm eq}/\left(q[I_{ii}]_{\rm acc}/nkT + G_0\right) \tag{12}$$

and, from Eqs. (4) and (12),

$$\frac{[\tau_{\rm NKE}]_{\rm acc}}{\tau_{\rm NKE}} = \frac{qI_{ii}/nkT}{q[I_{ii}]_{\rm acc}/nkT + G_0}. \tag{13}$$

In the case where $V_{\rm DS} = \text{const}$, the inequality $I_{\rm NKE} > [I_{\rm NKE}]_{\rm acc}$ has been observed for the drain current in the presence of a nonlinear kink-effect (see Fig. 2,*b*). This allows us to conclude that the inequality $I_{ii} > [I_{ii}]_{\rm acc}$ is valid for our devices. Therefore, in the case of high enough $V_{\rm DS}$, where $G_0 < q[I_{ii}]_{\rm acc}/nkT < qI_{ii}/nkT$, we obtain from Eq. (13) that $[\tau_{\rm NKE}]_{\rm acc}/\tau_{\rm NKE} > 1$. However, in the case of lower $V_{\rm DS}$, where $G_0 \geq qI_{ii}/nkT > q[I_{ii}]_{\rm acc}/nkT$, it follows from Eq. (13) that $[\tau_{\rm NKE}]_{\rm acc}/\tau_{\rm NKE} \leq 1$. This explains the results depicted in Fig. 4,*a*.

At the same time for $I = \text{const}$, we have $V_{\rm DS} < [V_{\rm DS}]_{\rm acc}$ (see Fig. 2,*b*) and, respectively, $I_{ii} < [I_{ii}]_{\rm acc}$. Then, according to Eq. (13), the relation $[\tau_{\rm NKE}]_{\rm acc}/\tau_{\rm NKE} < 1$ should be valid at any value of I. In other words, in this regime, the accumulation back-gate voltage always leads to the reduction of $\tau_{\rm NKE}$. Such a behavior of $\tau_{\rm NKE}$ agrees completely with the experimental results presented in Fig. 4,*b*.

Note that, for the lowest values of $V_{\rm DS}$ when $G_0 \gg \gamma_{\rm acc}[I_{ii}]_{\rm acc}$, Eq. (7) yields

$$\tau_{\rm acc} = C_{\rm eq}/G_0, \tag{14}$$

which corresponds to BGI-Lorentzians, for which [4]

$$[S_I(0)]_{BGI} = 4kT\tau_{\rm acc}\beta^2 g_m^2/C_{\rm eq}. \tag{15}$$

5. Conclusions

The accumulation voltage at the back gate of n-channel SOI MOSFETs
(i) changes the parameters of the noise NKE-Lorentzians ($\tau_{\rm NKE}$ and $S_I(0)_{\rm NKE}$), and the character of such changes depends on the operation mode of a transistor ($V_{\rm DS}$ = const or I = const);
(ii) reduces the drain current I under conditions where the nonlinear kink-effect occurs;
(iii) gives rise to the occurrence of BGI-Lorentzians in the noise spectra measured at relatively low drain voltages $V_{\rm DS}$.

The listed effects can be explained in the framework of the model, according to which the accumulation back-gate voltage increases the conductance of the body-source junction.

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ВПЛИВ АКУМУЛЮЮЧОЇ НАПРУГИ НА НИЖНЬОМУ ЗАТВОРІ НА ШУМОВІ СПЕКТРИ СУБМІКРОННИХ КНІ МОН-ТРАНЗИСТОРІВ У ШИРОКОМУ ІНТЕРВАЛІ СТОКОВИХ НАПРУГ

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Р е з ю м е

Виявлено і досліджено вплив акумулюючої напруги на нижньому затворі субмікронних частково збіднених КНІ МОН-транзисторів на лоренціанівський компонент струмового шуму, що виникає у шумових спектрах таких приладів при достатньо високих напругах на стоковому електроді і зумовлений ударною іонізацією біля стокового p–n-переходу. Показано, що така акумулююча напруга суттєво впливає на величину постійної часу і рівень шумового плато цих лоренціанів, а також приводить до зменшення канального струму. Ці явища пояснено на основі раніше запропонованої моделі, згідно з якою акумулююча напруга на нижньому затворі збільшує провідність p–n-переходу база–витік. У спектрах шуму, що спостерігаються за нижчих стокових напруг, виявлено індуковані нижнім затвором так звані ІНЗ-лоренціани, зумовлені найквістовими флуктуаціями цієї провідності.