

Drain currents and their excess noise in triple gate bulk *p*-channel FinFETs of different geometry

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ARTICLE INFO

Article history:

Received 8 December 2011

Received in revised form 17 October 2012

Accepted 17 October 2012

Available online 22 November 2012

ABSTRACT

The drain current I , spectral density of the low-frequency $1/f$ noise S_I and transconductance g_m of triple gate bulk *p*-channel field-effect transistors (FinFETs) fabricated on 200 mm diameter Cz silicon wafers have been studied in the standard (ST) and Dynamic Threshold Voltage (DT) modes of operation. For the ST regime, a sub-linear increase of the drain current I with increasing overdrive voltage $|V_{ov}|$ and practically no changes in the spectral density S_I of the noise are observed at high values of $|V_{ov}|$. The effect is attributed to a sub-linear increase of the free hole density in the channel, whereby the mobility does not change with increasing $|V_{ov}|$. An increase of the values of I , S_I and g_m normalized for the device geometry with increasing L_{eff} is found and is attributed to the decrease of the mobility degradation coefficient with increasing L_{eff} . For the DT regime of operation, the decrease of the threshold voltage $|V_{th}|$ is not accompanied by an increase of the drain current which decreases with increasing $|V_{GF}|$ due to the high leakage current passing through the forward biased drain and source junctions. However, that decrease of the drain current is not accompanied by changes in the value of S_I .

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1. Introduction

Bulk FinFETs combine the good control of the short-channel effects with the ease of manufacturing on bulk silicon substrates [1]. The technology has reached a sufficient level of maturity to enable meaningful low-frequency (LF) noise measurements. Initial results have pointed out that for triple gate (trigate) bulk FinFETs with SiO₂ or SiON gate dielectric, both $1/f$ noise and Generation–Recombination (GR) noise are present, whereby the $1/f$ noise in many cases is dominated by carrier trapping in the gate dielectric [2,3]. The GR noise was ascribed to traps both in the silicon fins and in the gate oxide, based on the gate-voltage dependence of the corner frequency f_c . It was also noted that operation of *n*-channel bulk FinFETs in the dynamic threshold mode of operation [4–6], did not affect the LF spectral density, S_I [7], while an improvement in the analog performance was observed [8]. Initial noise results on bulk *p*-MOSFETs with high-*k*/metal gate have also been reported [9].

Given the multiple gate nature of the devices, one of the obvious questions is whether the device geometry and in particular the fin width has an impact on the LF noise behavior. One should account for the fact that for narrow devices, most of the current is flowing along the (1 1 0) sidewalls, which have usually a different

orientation than for standard planar bulk transistors on (100) wafers. It turns out that for Silicon-on-Insulator (SOI) FinFETs, the device orientation has only a minor effect on the noise [10,11]. Another factor which can play a role is that in the case of narrow fins, the structure can be considered as fully depleted, i.e., the width of the fin is smaller than two times the depletion width at the sidewalls of the device.

It is the aim to report here on detailed LF noise results of narrow high-*k*/metal gate bulk *p*-FinFETs with a fin height H_{fin} of 65 nm and various channel lengths. The noise will be studied both in standard operation (ST) and in the dynamic threshold (DT) mode with the substrate contacted to the gate. The dependences of the current noise spectral density will be correlated with the DC parameters, like the hole mobility.

2. Devices and experimental

Bulk *p*-channel FinFETs with 10 fins (N_{fin}) of 65 nm height (H_{fin}) have been investigated. The devices have been processed on 200 mm Cz silicon wafers. The gate oxide consists of a 2.6 nm HfSiON-layer (40% Hf) on a 1 nm interfacial SiO₂-layer. The Equivalent Oxide Thickness $t_{EOT} = 1.5$ nm. A Selective Epitaxial Growth (SEG) in the source/drain regions is used to reduce the series resistance. Devices with a fin width $W_{eff} = 20$ nm and $W_{eff} = 35$ nm and a gate length $L_{eff} = 25$ –915 nm have been studied. The total width Z of the devices is calculated as $N_{fin}(W_{eff} + 2H_{fin})$.

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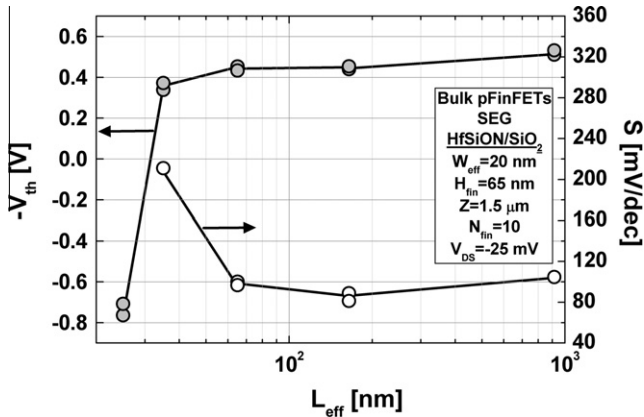


Fig. 1. Dependence of the threshold voltage and of the subthreshold slope of the curve $I(V_{GF})$ on the effective length; $W_{eff} = 20$ nm.

Fig. 1 presents the length dependence of the threshold voltage V_{th} and of the subthreshold slope S of the dependence $I(V_{GF})$ under depletion conditions where $I \sim \exp(\beta|V_{GF}|)$, I and V_{GF} are the drain current and gate voltage, respectively, β is the coefficient. It is seen that both values decrease at $L_{eff} \geq 40$ nm (short channel effects).

The drain current I and the spectral density S_I of its noise have been measured at a drain voltage $V_{DS} = -25$ mV in a wide range of gate voltages V_{GF} . The noise spectra were measured in the frequency range $f = 0.7$ Hz to 100 kHz.

The measurements have been carried out not only under standard biasing conditions (ST) but also in a Dynamic Threshold Voltage mode (DT) where the silicon substrate is short circuited with the gate.

3. Results and discussion

3.1. Drain current

Fig. 2 shows the dependences of the value of $I(L_{eff}/Z)$ on the overdrive voltage V_{ov} measured for devices of different L_{eff} . It is seen that in spite of the fact that the trivial influence of the values of Z and L_{eff} is taken into account by multiplication of I by the value of (L_{eff}/Z) , the value of $I(L_{eff}/Z)$ measured at a given value of V_{ov} , appears to depend on L_{eff} , namely: the higher L_{eff} , the higher $I(L_{eff}/Z)$.

It is also seen from Fig. 2 that the increase of $I(L_{eff}/Z)$ with increasing $|V_{ov}|$ at sufficiently high $|V_{ov}|$ appears to become sub-linear.

The dependence of $g_m(L_{eff}/Z)$ on V_{ov} for the devices of different L_{eff} where g_m is the transconductance is shown in Fig. 3a. It is seen that the normalized value of g_m increases with increasing L_{eff} . As a

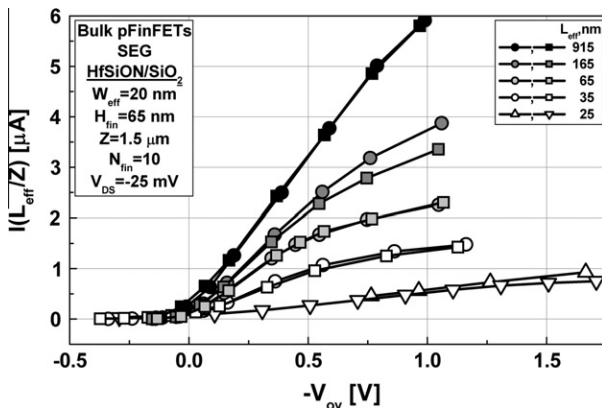


Fig. 2. Dependence of the value of $I(L_{eff}/Z)$ on the overdrive voltage for devices with different L_{eff} and $W_{eff} = 20$ nm (the dependences for two devices of each length L_{eff} are shown).

result, the value of the mobility μ_m corresponding to the maximum of the curve $g_m(V_{ov})$ also increases.

Fig. 3b presents the dependence of μ_m on L_{eff} for two different values of W_{eff} . It is seen that μ_m increases not only with increasing L_{eff} but also with decreasing W_{eff} . It should be noted that the hole mobility is expected to be higher on the (110) sidewalls compared with the (100) standard plane [11]. As the sidewall contribution becomes more pronounced for the narrower fins, a higher mobility and maximum transconductance is thus expected.

The mechanisms of both effects, namely the sub-linear increase of I with increasing $|V_{ov}|$ and the increase of μ_m with increasing L_{eff} and decreasing W_{eff} can be explained by the analysis of the drain current noise, as will be shown in the next section.

3.2. Drain current noise

The noise spectra measured for the devices studied are shown in Fig. 4. It is found that the noise spectra are $1/f^2$ -like for the whole investigated gate biases irrespective of the value of gate length L_{eff} , where γ is close to unity (see Fig. 4a and b which correspond to the devices of $L_{eff} = 915$ nm and $L_{eff} = 35$ nm, respectively). Also in the case of the devices with $L_{eff} < 165$ nm the Lorentzian components enter the noise spectra (see Fig. 4b). However in this paper we will confined to discussing the $1/f^2$ noise behavior.

The noise characteristics typical for the devices studied are presented in Fig. 5. Fig. 5a demonstrates the dependence of the normalized value of $S_I(L_{eff})^3/Z$ for the spectral density of the drain current noise S_I on V_{ov} for devices of different L_{eff} . As is seen, the value of S_I practically stops to be dependent on V_{ov} at sufficiently high $|V_{ov}|$ except for the samples of $L_{eff} = 915$ nm. It is also seen that, like in the case of the normalized drain current, the value of

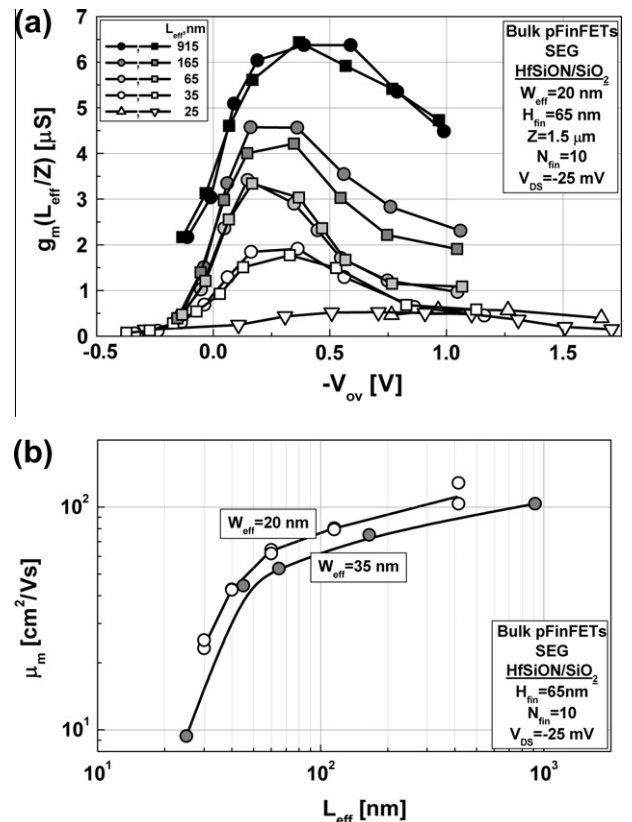


Fig. 3. Dependence of the value of $g_m(L_{eff}/Z)$ on the overdrive voltage for devices of different L_{eff} and $W_{eff} = 20$ nm (the dependences for two devices of each length L_{eff} are shown) (a) and of the mobility corresponding to the maximum in curves $g_m(V_{ov})$ on L_{eff} for devices with $W_{eff} = 20$ nm and 35 nm (b).

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