AC Floating Body Effects in Partially Depleted Floating Body SOI nMOS Operated at Elevated Temperature: An Analog Circuit Prospective

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***Abstract*—AC floating body effects in PD SOI nMOSFETs operated at high temperature are investigated. Both source/body and drain/body junction diode characteristics are greatly influenced by temperature, significantly impacting the ac kink effect as well as low-frequency (LF) noise characteristics. This is especially true for the pre-dc kink operation at high temperature. The increase of junction thermal generation current becomes an important body charging source and induces the LF Lorentzian-like excess noise.**

***Index Terms*—Low-frequency noise, silicon-on-insulator technology.**

I. Introduction

THE higher density integration of CMOS on a single chip and the higher system operating frequency continue to increase the power dissipation density. These result in an increased operating temperature and raise the concern for heat management [1]. In addition, there is increasing demand for using CMOS integrated circuit technologies for high-temperature electronics. However, the severe junction leakage current significantly deteriorates the correct operation of both high-temperature digital and analog integrated circuits, preventing bulk CMOS technology from operating beyond 200 °C [2]. The reduced junction area in SOI MOSFET technology provides a much lower leakage current and a larger noise margin, suggesting that SOI digital circuits can be operated at temperatures up to 400 °C [2]. Only a few papers address the influence of high temperature on SOI analog applications [3], [4]. At room temperature, ac floating body effects have significantly impacted SOI analog circuit performance, such as degraded linearity due to the kink on output conductance $(G_{\rm DS})$ [5] and higher phase noise due to low-frequency (LF) noise overshoot [6]. This is especially true for partially-depleted (PD) SOI MOSFETs. In this study, ac floating body effects are explored in a wide temperature range.

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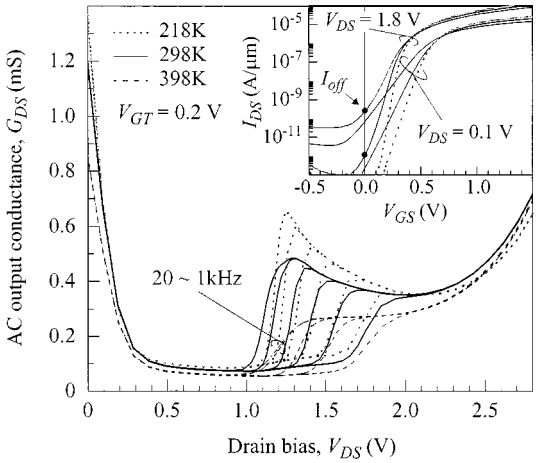

Fig. 1. AC output conductance of a 0.45 μm PD floating body SOI nMOS as a function of temperature (From left to right, the measured frequencies are 20, 100, 1 k, 10 k, 100 k, and 1 MHz). Arc indicates the convergence of $G_{\rm DS}$ ($T = 398$ K) in the low frequency range. The inset shows the subthreshold characteristics.

II. Device and Experimental Result

A 0.45-μm surface channel partially depleted SOI MOSFET process was used in this study [7]. Gate oxide, silicon film, and buried oxide thicknesses are 10.5 nm, 100 nm, and 360 nm, respectively. The temperature characterization was performed using a Lakeshore Modular Test Dewar System where the temperature was precisely controlled within 0.1 K. The temperature dependence of ac floating body effects was characterized by both ac output conductance and low-frequency (LF) noise measurements, as described in [8]. Pre- and post-kink operations are defined as the devices with drain biases lower and higher than dc kink onset voltage.

As operation temperature increases, the subthreshold slope (at $V_{\rm DS} = 0.1$ V) degrades. The dc subthreshold kink still exists in the moderate inversion region with a weak temperature dependence, as shown in the inset of Fig. 1. However, the increase of off-state current is dominated by junction thermal generation current, instead of subthreshold kink current, at high temperature operation with an optimized $V_{\rm TH}$ design. With advantages of smaller source/drain junction areas, free of a well junction, and a finite neutral body region, thin-film SOI MOSFETs provide a much smaller leakage current, while eliminating thermally activated latchup, which is suitable for high-temperature

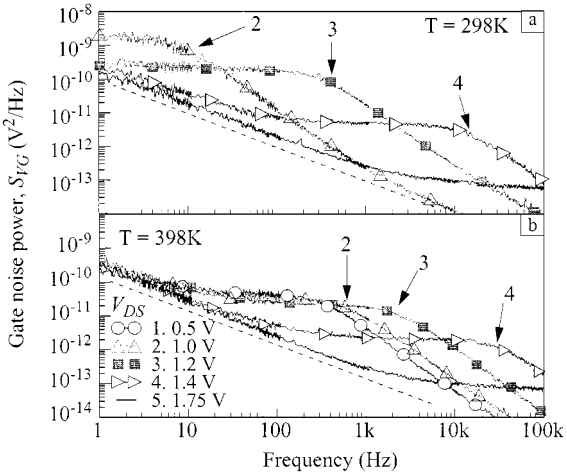

Fig. 2. Low-frequency noise characteristics of a 0.45 μm PD floating body SOI nMOS biased at $V_{\rm GT} = 0.2$ V as a function of drain bias for (a) $T = 298$ K and (b) $T = 398$ K. Arrows indicate the corner frequency f_0 at different drain biases and the dashed line represents an ideal $1/f$ noise spectrum.

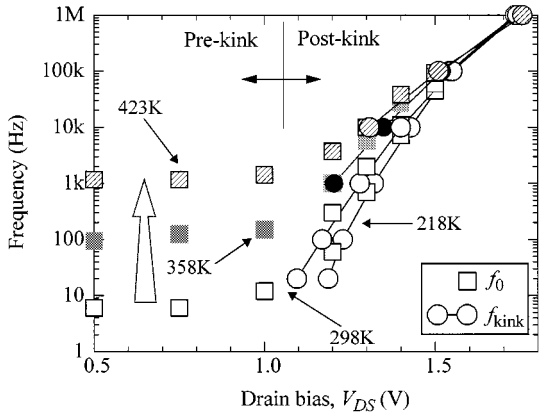

Fig. 3. Temperature dependence of the LF noise overshoot (f_0) and ac kink effects (kink on $G_{\rm DS}$ shifts toward higher drain bias as frequency increases, where $f_{\rm kink}$ can be extracted from the peak of $dG_{\rm DS}/dV_{\rm DS}$) as the devices are biased in the pre- and post-dc kink region at $V_{\rm GT} = 0.2$ V. (Gray symbols: 218 K, opaque symbols: 298 K, filled symbols: 358 K, and meshed symbols: 423 K).

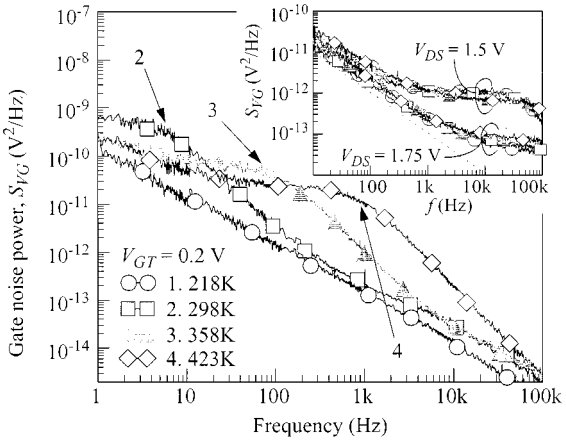

Fig. 4. Pre-kink excess noise of a PD floating body SOI nMOS biased at $V_{\rm DS} = 0.75$ V and $V_{\rm GT} = 0.2$ V as a function of temperature. The inset shows the weak temperature dependence of post-kink excess noise at higher drain biases ($V_{\rm DS} = 1.5$ V and 1.75 V).

digital circuits. While the power dissipation is the primary concern in digital SOI device design, it is important to investigate ac small signal behavior for analog applications, especially the ac output conductance ($G_{\rm DS}$). As shown in Fig. 1, both the onset of the kink (spike) in $G_{\rm DS}(f)$ at low frequency shifts toward a lower drain bias and the magnitude of the kink is reduced as the operating temperature increases from 218 K to room temperature (RT). The former shows a reverse trend as temperature continues to increase higher than 373 K and the $G_{\rm DS}$ curves converge at the lower frequency <1 kHz at $T = 398$ K.

Low-frequency (LF) noise is an important figure-of-merit for RF analog circuits. PD floating body SOI nMOS exhibits a kink-related Lorentzian-like noise overshoot (characterized by a flat plateau followed by a $1/f^2$ roll-off at the corner frequency, f_0) superimposed on the pure $1/f$ noise [8]. At RT, f_0 shifts from Hz to above 100 kHz as the drain bias increases away from dc kink onset voltage (0.95 V at $V_{\rm GT} = 0.2$ V), as shown in Fig. 2(a). As operating temperature increases (e.g., $T = 398$ K), the noise overshoot at higher drain bias (e.g., $V_{\rm DS} = 1.5$ V and 1.75 V) remains at a similar magnitude, as shown in the inset of Fig. 4. It is important to note that as the drain biases near the dc kink onset voltage, the LF noise overshoot characteristics are a strong function of temperature for both the corner frequency (f_0) and overshoot magnitude, as shown in Fig. 2(b).

III. Discussion

AC kink effect has been attributed to the frequency dependence of the body voltage due to the source/body (S/B) junction ac characteristics [9], especially for S/B junction diode saturation current, I_R. S/B junction diode current can be described as

$$\begin{aligned} I_{\rm SB} &= Aq\frac{n_i^2 D_n}{L_n N_a}\cdot(e^{V_{\rm SB}/V_T}-1) \\ &\quad + Aq\frac{n_i W}{2\tau_r}\cdot(e^{V_{\rm SB}/2V_T}-1) \\ &= I_R\cdot(e^{V_{\rm SB}/nV_T}-1). \end{aligned} \tag{1}$$

where $n_i = 38\,700\cdot T^{1.5}\cdot\exp(-7000/T)$ and the other parameters are listed in [12]. As temperature increases, the onset of impact ionization shifts toward lower drain bias. Therefore, at the same drain bias, close to the dc kink onset voltage, the increase of impact ionization current ($I_{\rm ii}$) at higher temperature shifts the ac kink effect on $G_{\rm DS}$ toward lower drain bias [11]. But I_R also increases as operating temperature increases, resulting in a reduced kink magnitude in $G_{\rm DS}$ and the convergence of lower frequency $G_{\rm DS}$ curves. This phenomenon is similar to fully-depleted SOI nMOS measurements at room temperature [5] where I_R increases as the S/B junction barrier drastically decreases.

The temperature dependence of S/B junction characteristics also affects LF Lorentzian-like noise overshoot in floating body SOI MOSFETs. Based on the correlation between post-dc kink noise overshoot and ac kink effects at room temperature [8], operating at 398 K, the convergence of ac $G_{\rm DS}$ curves up to 1 kHz results in LF noise overshoot suppression below 1 kHz. This has been confirmed by noise measurement data presented in Fig. 2 and the correlation of post-dc kink behaviors mentioned above exists for a wide temperature range (Fig. 3). In addition,

Fig. 4 shows the temperature dependence of the pre-kink (e.g., $V_{\rm DS} = 0.75$ V) excess noise behavior. f_0 shifts from 6 Hz at $T = 298$ K to 1 kHz at $T = 423$ K and the pure $1/f$ noise is observed at lower temperature operation ($T = 218$ K). While the impact ionization current is negligible at lower drain bias, the data suggests that drain/body (D/B) reverse junction thermal generation current (I_G) is also an important charging source [12]. Therefore, the low-frequency excess noise model [13] as well as ac floating body effect have to take into account both S/B and D/B junction characteristics, as follows:

$$S_{\rm VG,excess} = 4q(nV_T)^2 \frac{1}{1+(f/f_0)^2} \cdot \frac{I_G + I_{\rm ii}}{(I_R + I_G + I_{\rm ii})^2} \cdot \beta^2 \qquad (2)$$

where $I_G = qAn_iW/\tau_G$ [10] and $f_0 = f_{\rm kink} = (2\pi r_{\rm SB} C_{\rm BB})^{-1} \propto I_R + I_G + I_{\rm ii}$ where $f_{\rm kink}$ is the -3 dB frequency of body voltage. At lower drain biases, because of the increases of I_R and I_G at higher tempertaure, f_0 and $f_{\rm kink}$ can not occur at lower frequencies. Therefore, no ac floating body effects occur at low frequencies. At higher $V_{\rm DS} - V_{\rm dsat}$, impact ionization current $(I_{\rm ii})$ overwhelms I_R and I_G resulting in weak temperature dependent noise overshoot magnitude and corner frequency, as shown in Figs. 2 and 3. As temperature increases, I_R and I_G drastically increase, suppressing LF noise overshoot at the drain bias close to dc kink $(I_G + I_R \gg I_{\rm ii})$, as expected in (2). In the pre-kink region, reduced n_i (by cooling down the device) suppresses pre-kink excess noise. The increase in I_G, by increasing the operating temperature, charges the body causing body voltage instability and further shifts the drain-bias independent f_0 of excess noise toward higher frequencies, as shown in Fig. 3.

IV. Conclusion

In this study, we show that not only S/B junction characteristics influence ac floating body effects, but D/B junction features also affect the device characteristics especially at higher operating temperatures. Junction thermal generation current (I_G) becomes an important body charging source at low drain bias at high temperature operation, especially for its impact on LF noise characteristics. The increase of I_R, by reducing S/B junction barrier using fully-depleted (FD) operation, can suppress ac floating body effects [6]. The reduced depletion width as temperature increases makes it difficult to realize the FD mode operating at high temperatures. Therefore, body contacts can be an option for high temperature low noise SOI analog applications.

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