Investigation of High-Frequency Noise Characteristics in Tensile-Strained nMOSFETs

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***Abstract*—For the first time, the high-frequency noise behavior of tensile-strained n-channel metal–oxide–semiconductor field-effect transistors, including their temperature dependency, is experimentally examined. Our experimental results show that with similar saturation voltages, the strained device is found to have larger channel noise than the control device at the same bias point. For given direct-current power consumption, however, due to enhanced transconductance, the strained device has better small-signal behaviors (higher f_t and $f_{\max}$) and noise characteristics (smaller $\mathrm{NF}_{\min}$ and R_n) than the control device.**

***Index Terms*—Metal–oxide–semiconductor field-effect transistors (MOSFETs), noise, radio frequency (RF), temperature, tensile strained, van der Ziel model.**

I. INTRODUCTION

As THE GATE length of complementary metal–oxide–semiconductor (CMOS) transistors is down-scaled to a decananometer regime, device scaling is becoming extremely difficult due to many physical and technological problems [1]. Strain engineering technology is one way to maintain scaling trends of CMOS devices. It is well known that strained-channel MOS field-effect transistors (MOSFETs) have larger carrier mobility and drain current than unstrained counterparts [2]–[6]. It is expected that improved direct-current (dc) performances can also enhance radio-frequency (RF) performances.

Recently, CMOS technologies with incorporation of high-tensile contact etch stop layer (CESL) stressors have been demonstrated for RF applications, and a very high cutoff frequency f_t has been shown [7], [8]. There have been many studies on high-frequency noise characterization and modeling of conventional MOSFET devices [9]–[17]. However, the effects of highly tensile stressors on high-frequency noise characteristics have rarely been known. In this brief, high-frequency noise characteristics of tensile-strained n-channel MOSFETs (nMOSFETs), including their temperature dependence, will be investigated and analyzed for the first time.

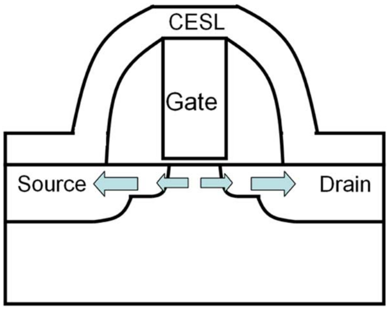

Fig. 1. Tensile stress in the channel of a high-strained nMOSFET.

II. DEVICES AND MEASUREMENTS

Multifinger CMOS transistors were fabricated using a 65-nm generation technology with a $\langle 100 \rangle$-channel orientation on a (100) wafer. For enhancing the electron mobility of the channel, an 850-Å-thick SiN_x CESL was grown as a high-tensile stressing layer. As indicated in Fig. 1, this eventually applied a lateral tensile stress of 1.5 GPa in the device's channel. In addition, for the control device, a conventional low tensile strength $(\mathrm{SiN}_x = 360\ \text{Å})$ CESL was used.

The gate length of the test devices is 60 nm, and the total gate width of the test devices is 128 μm (4 μm by 32 gate fingers). The noise parameters of the MOSFET under different temperatures were measured using Auriga noise and scattering parameter measurement system. The dummy OPEN and SHORT deembedding technique was used to eliminate parasitic contributions from probing pads and metal interconnections [12]. Finally, the intrinsic channel noise current was extracted following the approach presented in [13].

Fig. 2 compares the dc characteristics of the tensile-strained and control devices. The strained device presents larger drain current than the control one for each ambient temperature because of its enhanced carrier mobility, which can also help to boost the cutoff frequency f_t and maximum oscillation frequency $f_{\max}$, as shown in Fig. 3.

Fig. 4 compares the noise measurement results in terms of the minimum noise figure $\mathrm{NF}_{\min}$ and equivalent thermal noise resistance R_n for the strained and control devices. The strained device shows a better high-frequency noise performance than the control one. The good match between measured and

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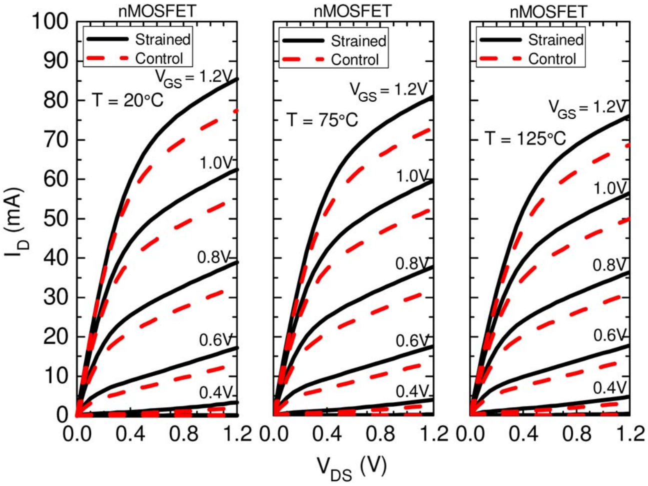

Fig. 2. I–V characteristics for the strained and control devices.

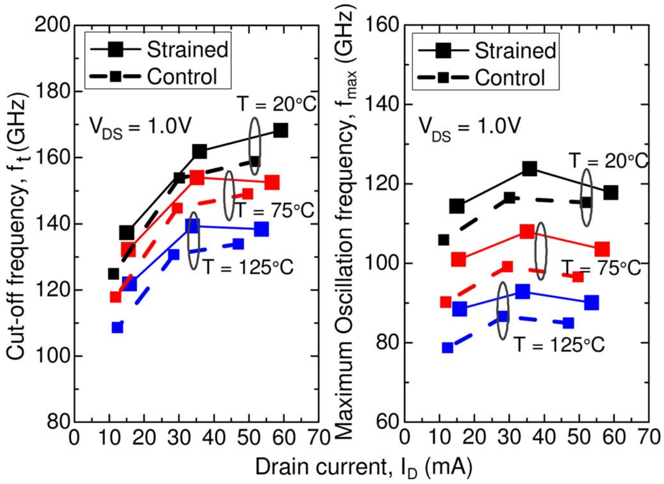

Fig. 3. f_t and $f_{\max}$ versus drain current for the strained and control devices.

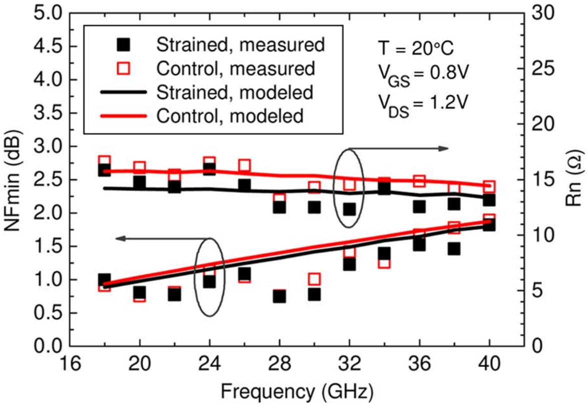

Fig. 4. Measured and modeled results for $\mathrm{NF}_{\min}$ and R_n.

modeled results based on the equivalent circuit in [14] also indicates the validity of the extracted noise parameters shown in this brief.

III. Channel Noise Characterization

The extracted power spectral density of channel noise S_{id} is shown in Fig. 5. It shows that the strained device has larger S_{id} than the control one for a given bias point. This phenomenon can be explained by the following model equation developed by Asgaran *et al.* [15]:

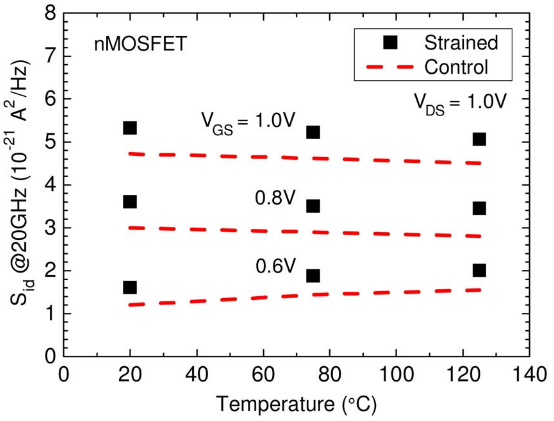

Fig. 5. Power spectrum density of channel noise S_{id} versus temperature for the strained and control devices.

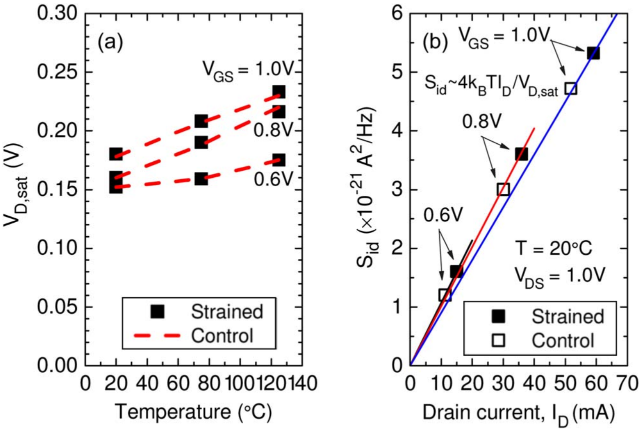

Fig. 6. (a) Similar drain saturation voltage $V_{D,\mathrm{sat}}$ for the strained and control devices at each temperature, and (b) the good match between measured S_{id} and the Asgaran model [see (1)].

$$S_{\mathrm{id}} = 4k_B T I_D \left(\frac{1}{V_{D,\mathrm{sat}}} + \frac{\alpha^2 V_{D,\mathrm{sat}}}{3V_{\mathrm{GT}}^2} \right) \approx \frac{4k_B T I_D}{V_{D,\mathrm{sat}}} \tag{1}$$

where $k_B \approx 1.38 \times 10^{-23}$ J/K is the Boltzmann's constant, T is the ambient temperature in Kelvin, $V_{D,\mathrm{sat}}$ is the drain saturation voltage, V_{GT} is the gate overdrive voltage, and α is the bulk charge coefficient.

This model indicates that in the saturation region, channel length modulation is the main mechanism responsible for excess channel noise. Since the impact of tensile strain on $V_{D,\mathrm{sat}}$ is negligible, as shown in Fig. 6(a), the larger drain current I_D present in the strained device is responsible for larger S_{id}. The validity of Asgaran model has been verified in our previous study [14] and also reconfirmed in Fig. 6(b).

On the other hand, the well-known van der Ziel model [11], which uses the white noise gamma factor to characterize S_{id}, can be written as

$$S_{\mathrm{id}} = \gamma 4 k_B T g_{d0} \tag{2}$$

where g_{d0} is the channel conductance at zero drain bias, and γ is the noise factor. For long-channel devices, γ would approach

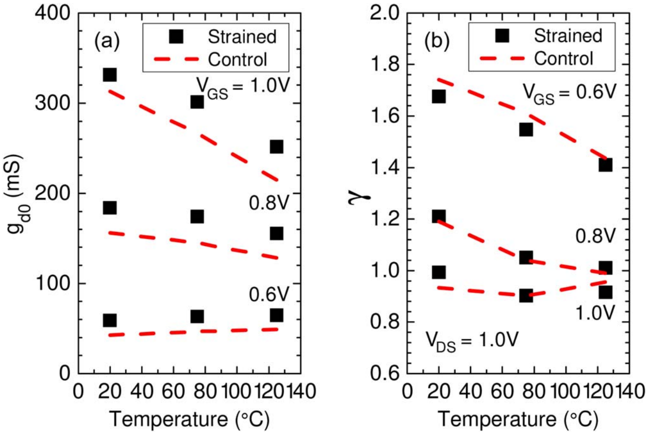

Fig. 7. (a) Channel conductance at zero drain bias g_{d0} and (b) noise factor γ versus temperature.

2/3 in the saturation region. For short-channel devices, however, it would be greater than 2/3, and can be considered as a figure of merit used to assess excess channel noise.

Fig. 7(a) shows the extracted g_{d0} value versus temperature. The larger g_{d0} value for the strained device results from its higher mobility. In addition, two different temperature dependence values can be observed. At lower V_{GS}, the lowered threshold voltage at higher temperature contributes to the positive temperature coefficient of g_{d0}. At higher V_{GS}, however, degraded carrier mobility overwhelms the threshold voltage lowering effect at higher temperature, causing g_{d0} to decrease with increasing temperature.

Fig. 7(b) shows that both the strained and control devices have nearly the same noise factor γ, which means they suffer approximately the same short-channel effect on high-frequency noise performance. In addition, since both S_{id} and I_D (or g_{d0}) scale with mobility, the results of similar γ for both the strained and control devices can be expected, as indicated in (1).

It is worth noting that for the 65-nm technology node, S_{id} tends to decrease with increasing temperature at high V_{GS} (see Fig. 5). This is consistent with the result presented in [16] for the medium-long-channel device ($L = 0.\,36\ \mu$m) for the severe decrease in g_{d0} counterbalancing the increase in temperature [see (2)]. However, the temperature dependence is not so obvious for the 65-nm device in this brief.

IV. Noise Parameter Characterization

The minimum noise figure $\mathrm{NF}_{\min}$ and equivalent thermal noise resistance R_n can be approximately expressed by the following equations [14], [17]:

$$\mathrm{NF}_{\min} \approx 1 + \frac{2}{g_m^2}\sqrt{(R_s + R_g)\frac{S_{\mathrm{id}}}{4kT_0}} \times \left\{\omega C_{gg} g_m + \omega^2 C_{gg}^2 R_g \sqrt{\frac{S_{\mathrm{id}}}{4kT_0}}\right\} \tag{3}$$

$$R_n \approx \frac{T}{T_0}(R_g + R_s) + \frac{S_{\mathrm{id}}}{4k_B T_0 g_m^2} \tag{4}$$

where $T_0 = 290$ K is the reference temperature, and $C_{gg} = C_{gs} + C_{gd}$ is the gate capacitance. Note that since the induced gate noise current has been found to be insignificant at a 65-nm node even in the millimeter-wave application [14], it has been neglected in the above derivation.

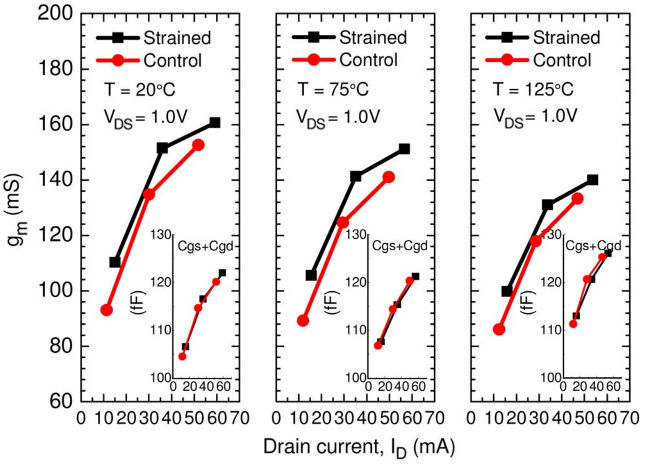

Fig. 8. Transconductance g_m versus drain current for the strained and control devices. The insets show the gate capacitance versus drain current.

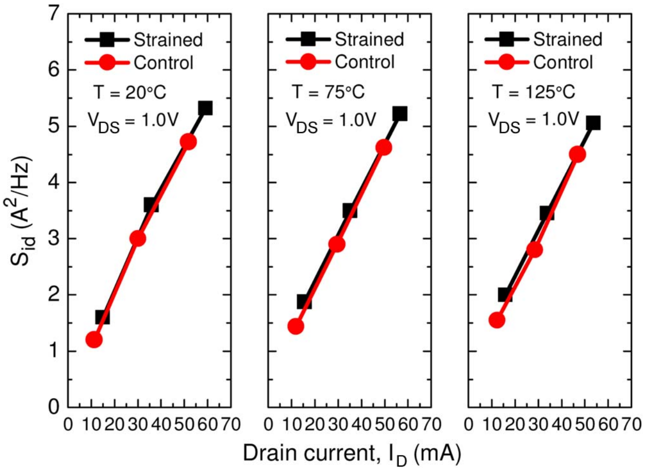

Fig. 9. S_{id} versus drain current for the strained and control devices.

For given dc power consumption, compared with the control device, since the strained device exhibits larger transconductance but comparable S_{id}, as shown in Figs. 8 and 9, respectively, (3) and (4) imply that the strained device would have smaller $\mathrm{NF}_{\min}$ and R_n, as shown in Fig. 10(a) and (b), respectively. In addition, the magnitude and phase of the optimum source reflection coefficient ($|\Gamma_{\mathrm{opt}}|$ and $\angle\Gamma_{\mathrm{opt}}$) versus drain current are respectively depicted in Fig. 10(c) and (d) for the reader's reference.

Note that the similar access resistance and gate capacitance values shown in Fig. 11 and the insets in Fig. 8, respectively, indicate the little impact of tensile strain on them for these two different fabrication processes. Therefore, they cannot be attributed to the discrepancy of the high-frequency small-signal and noise performance between these two devices.

V. Conclusion

In this brief, we have investigated the high-frequency noise behavior of the tensile-strained nMOSFET. With nearly the same saturation voltages and noise factors, the strained device

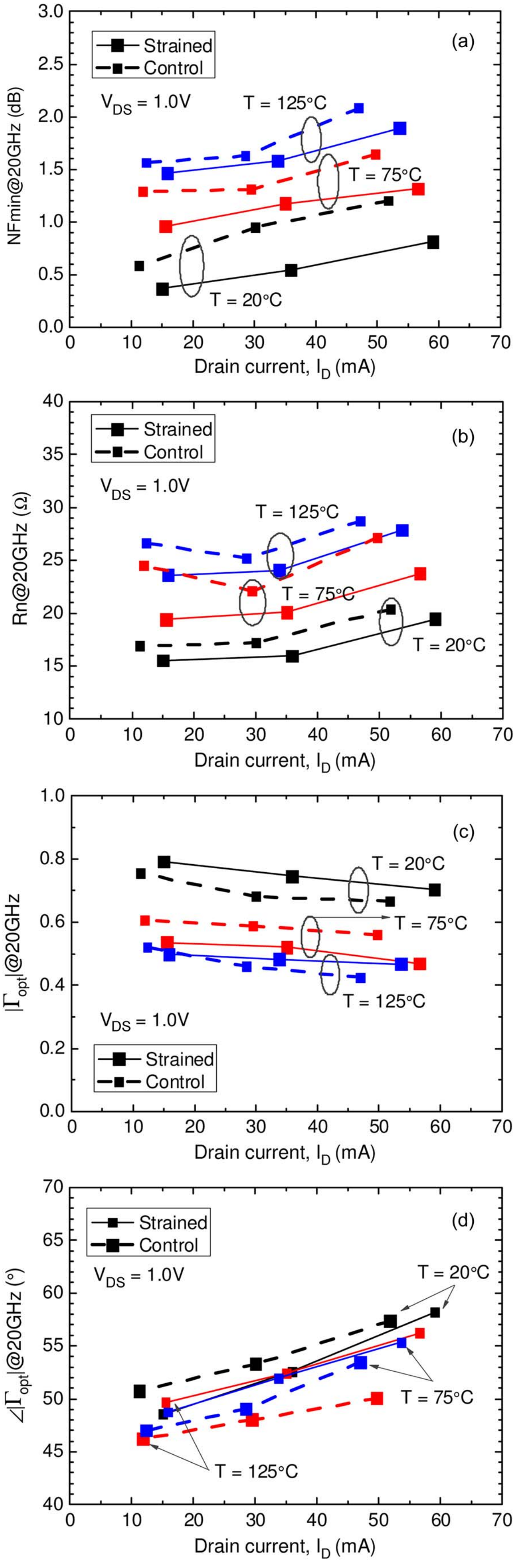

Fig. 10. (a) $\mathrm{NF}_{\min}$, (b) R_n, (c) $|\Gamma_{\rm opt}|$, and (d) $\angle\Gamma_{\rm opt}$ versus drain current for the strained and control devices.

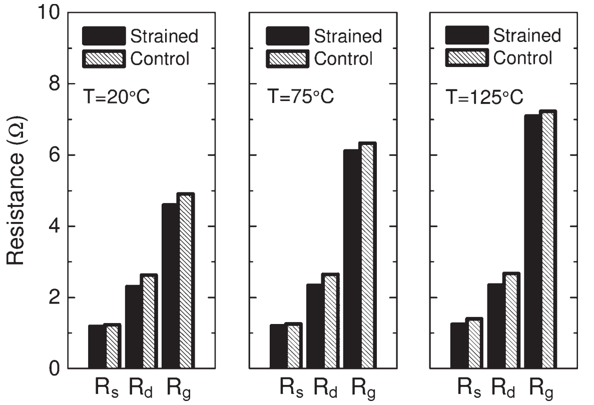

Fig. 11. Access resistance values for the strained and control devices. R_s, R_d, and R_g are access resistance values associated with the source, drain, and gate terminals, respectively.

presents larger $S_{\rm id}$ than the control device due to its enhanced mobility for a given bias point. In addition, both the strained and control devices have the same temperature dependence of $S_{\rm id}$. Finally, for a given dc power consumption, due to enhanced transconductance, our experimental results show that the strained device has better $\mathrm{NF}_{\min}$ and R_n than the control device.

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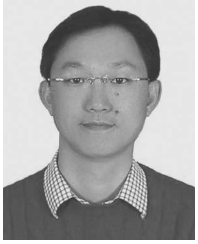

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