Impact of RF Stress on the Low-Frequency Noise in nMOSFETs

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Abstract In this paper, the degradation of low-frequency (LF) noise under different RF stress conditions in nMOSFETs has been reported and compared with the conventional DC stress condition. LF noise increases after RF stress and the increment of noise under RF stress at a large $V_{gs}$ value is bigger than that caused by DC stress. The change in LF noise intensity under RF stress raised more rapidly at large $V_{gs}$ values than that at small $V_{gs}$ values, which are contradictory to LF noise performance after DC stress. The influence of the input power and frequency of stress on LF noise has also been investigated separately. As the stress input power or frequency increases, the increment of noise intensity rises as well. The $\gamma$ decreases as the growth of the stress input power or frequency, and the values of $\gamma$ are below 1 after 18 GHz RF stress. The results provide experimental verification that the interface traps generated by RF stress play a major role in the degradation of LF noise.

Keywords: RF stress, low-frequency noise, hot-carrier degradation, nMOSFETs

Classification: Electron devices, circuits, and modules (silicon, compound semiconductor, organic, and novel materials)

1. Introduction

RF technology has been widely used in many fields and served the enormous momentum of the wireless market, and the increasing demand requires devices that meet higher performance and reliability standards. At present, 0.18 μm CMOS technology is a cost-effective process for RF circuits below 6 GHz. Because of the higher withstand voltage characteristics, 0.18 μm MOSFET has been widely used in RF circuit design, especially for the on-chip high-power PA design below 6 GHz [1, 2, 3]. In RF circuits, MOSFETs are operated under a high lateral electric field and high RF drive. Under such an operation condition, the parameters of transistors degrade which negatively affect the performance and reliability of RF circuits. Thus, the study on the performance of 0.18 μm MOSFET under RF and DC conditions is crucial to the reliability of RF integrated circuits.

Many studies have considered the performance of DC and RF parameters degradation under RF stress in MOSFET [4, 5, 6]. However, few studies focus on low-frequency (LF) noise degradation under actual RF operating conditions. The LF noise of MOSFETs is a very important parameter in RF circuit applications because it gives rise to phase noise in oscillators or multiplexers [7, 8]. The LF noise performance of MOSFET under various kinds of hot-carrier DC stress has been successfully studied [9, 10, 11, 12, 13, 14, 15, 16], but MOSFET’s in real circuits are exposed to the gate terminal and drain voltage conditions. Even though there have been the degradation of LF noise under dynamic stress verified up to 10 MHz [17], RF stress applied to the transistors is only marginally mentioned in the literature.

Furthermore, many works have applied RF stress to the drain by using a load-pull setup to perform on-wafer RF stress measurements [18, 19, 20], but RF stress applied to the gate is only marginally mentioned in the literature. Even though some studies the RF stress applied in the gate through the use of load-pull, the degradation of the devices was only focused on linear drain current and S parameters [21]. Some investigated LF noise degradation under DC and AC stress to the gate terminal with a frequency up to 900 MHz [22, 23, 24], but the frequency of stress was not high enough because the operating condition in RF circuits is up to a few gigahertz. Even though it has been investigated the NBTI degradation under RF stress to the gate terminal directly through the use of VNA with the frequency from 10 MHz to 3.2 GHz [25], the degradation of LF noise has not been mentioned. Thus, it is practical to explore the LF noise performance under RF stress in MOSFETs.

In this work, we applied various RF stress on the gate terminal in nMOSFETs. It has been explored that the difference of LF noise behavior in nMOSFETs with DC stress and RF gate stress methods. The LF noise measurement results were compared under RF and DC stress at different $V_{gs}$ values and correlated with the degradation of DC parameters. Moreover, the impacts of various RF stress conditions on LF noise were compared and correlated with the stress frequency and input power. We found that the degradation of LF noise is correlated with $V_{gs}$ values. The impact of RF stress caused a worse LF degradation at a large $V_{gs}$ value. The increment of LF noise is greater as the greater value of $V_{gs}$, indicating that the dominant degradation mechanism of RF stress is
attributed to interface traps. The effect of the input power and frequency of stress on LF noise has also been investigated separately. The experimental results under different RF stress show that the increment of LF noise increases when the stress frequency rises or the input power grows. And the $γ$ of the LF noise reduces as the stress frequency or input power increases. The values of $γ$ under 18 GHz RF stress are lower than 1, which further verify the main reason for the degradation of devices is the generation of interface traps caused by RF stress.

2. Experimental details

In this paper, the nMOS transistors were fabricated by using a 0.18 μm CMOS process. The gate insulator is silicon dioxide (SiO2) with an equivalent oxide thickness (Tox) of 3.5 nm. The geometry ratio (W/L) of devices are 24 μm/0.18 μm and 60 μm/0.18 μm. The device has a common source configuration and is embedded in a Ground-Signal-Ground (GSG) RF test structure. To test both stress and LF noise characteristics, nMOSFETs with GSG contact pads for RF stress tests were used as shown in Fig. 1(a).

![Fig. 1(a)](image)

Fig. 1 (a) Photograph of RF GSG probes on nMOSFETs; (b) DC stress pattern applied to the device; (c) RF stress patterns applied to the device.

In this study, the degradation was investigated using two different kinds of stress patterns, DC and RF stress as shown in Fig. 1(b) and (c). The DC and RF stress were performed for 5000 s at room temperature. The experimental results found that the drain breakdown voltage of the device under test (DUT) is 3.4 V. Thus, the drain voltage of the DC stress is set to 3 V which is 90 % of the drain breakdown voltage to ensure the DUT can accelerate degradation. The DC stress was performed at high gate bias, which is $V_{gs, stress}=3$ V. The RF stress is applied to the gate terminal of the device as a sine wave, the waveforms are presented in Fig. 1(b). The experimental results found that DUT would be breakdown when the gate input power over 16 dBm. To accelerate the degradation of the device under a high RF drive while the device can work, the highest power of the input RF signal is 90 % of the breakdown power, which is 14 dBm. And three input power conditions were set to $P=6$ dBm (4 mW@50 ohm), 9 dBm (8 mW@50 ohm), and 14 dBm (25 mW@50 ohm) at the gate terminal. As for the input frequency of the RF signal, three stress frequency conditions were set at $f=1$ GHz, 5 GHz, and 18 GHz, which are lower than the $f_T$ of DUT. Total 9 different conditions of RF stress were applied to each size of devices, which are 6 dBm-1 GHz, 6 dBm-5 GHz, 6 dBm-18 GHz, 9 dBm-1 GHz, 9 dBm-5 GHz, 9 dBm-18 GHz, 14 dBm-1 GHz, 14 dBm-5 GHz, 14 dBm-18 GHz. Table 1 shows the comparison of previous works and this work on the RF reliability.

| References | Stress Conditions | Methods | Test Parameters |
|------------|-------------------|---------|----------------|
| [17]       | 10 MHz            | Directly to gate | LF noise       |
| [18]-[20]  | Up to 5.2 GHz     | Load pull to drain | S parameter, $\gamma$  |
| [21]       | 6 GHz, 10 GHz     | Load pull to gate | S parameter     |
| [22]-[24]  | Up to 900 MHz     | Directly to gate | LF noise       |
| [25]       | 10 MHz to 3.2 GHz | VNA to gate     | DC parameters  |

During the RF stress, DUT was with a static operating bias at $V_{gs}=0.9$ V and $V_{ds}=1.2$ V. The experimental results show that the degradation of DC parameters is lower than 0.1 % after 5000 s working under this DC bias condition. As a result, there won’t be any additional hot carrier effect caused by this DC bias during the RF stress.

A schematic of the setup to assess the influences of the RF stress method and LF noise characteristics is shown in Fig. 2. As illustrated in Fig. 2(a), RF power stress was applied to the gate of the transistor. RF voltage signal was superimposed on DC voltage by a Marki BT-0018 bias tee. RF power stress conditions have been provided by the RF signal generator SMB100A. The Keithley 4200A-SCS semiconductor parameter analyzer provided the DC stress and a static bias at the drain and gate terminals during RF stress. In Fig. 2(b), the LF noise measurement was performed using a low-noise current preamplifier (Stanford Research, SR570) and a dynamic signal analyzer (Stanford Research, SR780) [26, 27]. The SR570 also provided a voltage supply to bias the drain terminal during the LF noise measurement. The drain voltage is set at 0.1 V during the measurements to avoid generating extra hot carriers.

Each stress condition is individually applied to a new transistor. Only one stress condition is applied to each device. DC parameters and the LF noise of the devices were tested three times before and after each stress to ensure the stability of the results. Each stress condition has been reproduced on three devices and shows consistent behavior.
3. Result and discussion

In Table II, degradation of threshold voltage ($V_{th}$), the saturation drain current ($I_{dsat}$), and subthreshold swing (SS) parameters in 60 μm/0.18 μm devices are summarized and compared after DC stress and RF stress. For the RF stress, the stress condition that causes the greatest degradation to the 60 μm/0.18 μm device is selected for discussion, which is 5 GHz-6 dBm. It can be seen that the degradation of $I_{dsat}$ and SS under DC stress are both beyond 50% and the $V_{th}$ increases over 300 mV. It is observed that the worst-case degradation occurs at DC stress. The $\Delta I_{dsat}$ and $\Delta SS$ under RF stress are above 10%. However, note that $V_{th}$ under the RF stress hardly degrades while $V_{th}$ degrades significantly after DC stress. To explain this phenomenon, the shifts in the linear transfer curves after DC and RF stress are illustrated in Fig. 3. The drain voltage bias is fixed at 0.1 V when the $I_{ds}$-$V_{gs}$ curve is being measured.

Table II Comparison of degradation of DC parameters under DC and RF stress in 60 μm/0.18 μm devices.

| Stress Conditions | $\Delta V_{th}$ (mV) | $\Delta I_{dsat}/I_{dsat}$ | $\Delta SS/SS$ |
|------------------|---------------------|---------------------------|-----------------|
| DC stress        | 339.1               | 57.1%                      | 53.6%           |
| $V_{gs}=V_{ds}=3$ V |                     |                           |                 |
| RF stress        | 6 dBm-5 GHz         | 4.1                       | 16.1%           |
|                  |                     |                           | 13.9%           |

Fig. 3 Normalized $S_{id}/I_{d}^2$ measurements after DC and RF stress conditions at different $V_{gs}$ values; (a) $V_{gs}$=0.7 V, (b) $V_{gs}$=1.5 V.

Fig. 4 Linear $I_{ds}$-$V_{gs}$ curves characteristics of nMOSFET after DC and RF stress ($V_{gs}$ = 0.1 V).

As shown in Fig. 3, it can be seen that the worse degradation of $I_{ds}$ below 1.3 V occurs at DC stress. However, when the $V_{gs}$ values over 1.3 V, the RF stress 5 GHz-6 dBm causes the worse degradation of $I_{ds}$. It is also observed that the RF stress causes $I_{ds}$ degradation mainly near the saturation region, but the degradation is relatively small at low $V_{gs}$ values especially at the sub-threshold region. The degradation characteristics after DC stress is for the opposite case. This phenomenon explains the reason that $V_{th}$ degradation caused by RF stress is so small. $\Delta V_{th}$ is extracted at $I_{d} = 100$ nA × ($W/L$) in linear $I_{ds}$-$V_{gs}$ curves at the sub-threshold region. The $I_{ds}$ degradation due to RF stress can be neglected at the sub-threshold, indicating that RF stress hardly induces the degradation of $V_{th}$.

Fig. 4 shows the averaged data of measured normalized drain-current noise spectral density ($S_{id}/I_{d}^2$) at $V_{ds}$=0.1 V for different stress conditions and $V_{gs}$ values. It can be seen in Fig. 4(a) that LF noise dramatically increases when the device is subjected to DC stress at $V_{gs}$=0.7 V, but the increments are smaller under 5 GHz-6 dBm RF stress. However, the characteristic of LF noise degradation is opposite at $V_{gs}$=1.5 V in Fig. 4(b). The more apparent increment is caused by the RF stress 5 GHz-6 dBm, but the LF noise degradation caused by DC stress is trivial at $V_{gs}$=1.5 V.

Since the degradation of LF noise is highly dependent on the stress condition and has a notable difference at various $V_{gs}$ values, the percentage of $S_{id}$ degradation at $f$=100 Hz is depicted in Fig. 5 as a function of $V_{gs}$ for the two stress cases. Each measured point is an average of three measurements. The same characteristics as seen in Fig. 5 are also observed for other frequencies. Fig. 5 shows that the RF stress-induced $\Delta S_{id}$ increases with $V_{gs}$ values and the DC stress-induced $\Delta S_{id}$ decreases with $V_{gs}$ values. The noise intensity increases strongly for large $V_{gs}$ values under RF stress conditions, whereas the increase is much smaller for small $V_{gs}$ values. And the $\Delta S_{id}$ at $V_{gs}$=1.5 V is nearly 25 times larger than that at $V_{gs}$=0.5 V. However, the characteristic of $\Delta S_{id}$ under DC stress is entirely on the contrary. A further observed specific feature is that $\Delta S_{id}$ due to RF stress is larger than...
that induced by DC stress at $V_{gs}=1.5$ V. This is a similar result as observed for the shifts in the linear $I_{ds}$-$V_{gs}$ curves in Fig. 3. The same degradation phenomenon of DC parameters and LF noise can be observed in the 24 μm/0.18 μm devices.

In the view of Fig. 5, LF noise and the $\Delta S_{id}/S_{id}$ under RF stress rise as the $V_{gs}$ value rises. On the contrary, the LF degradation under DC stress is smallest at $V_{gs}=1.5$ V and the reduction of $\Delta S_{id}$ under DC stress as the growth of $V_{gs}$ values. It is known that the noise intensity at different $V_{gs}$ values is related to the types of traps. The existence of deep-level trap states, known as gate oxide electron trap $\Delta N_{ot}$, is responsible for $\Delta S_{id}$ at small $V_{gs}$. [28]. Thus, the degradation mechanism of a high gate bias ($V_{gs, stress}=V_{ds, stress}=3$ V) stress is $\Delta N_{ot}$ due to the higher increment of LF noise at small $V_{gs}$ than at large $V_{gs}$. It is further proved by the obvious degradation of DC characteristics $\Delta S$ and $\Delta I_{dat}$ in Table I, which are mainly due to the $\Delta N_{ot}$.

The shallow trap states, known as interface traps $\Delta D_{it}$, are much more sensitive to the LF noise characteristics of large $V_{gs}$ [28, 29]. As for the RF stress, it can be deduced that the dominant degradation mechanism of RF stress is attributed to $\Delta D_{it}$ because of the higher increment of LF noise at large $V_{gs}$. And the degradation of $I_{dat}$ and $S_{id}$ under RF stress further proves the conclusion, which is smaller by almost four times than those under DC stress.

Fig. 6 shows noise spectral density ($S_{id}/I_{d}^{2}$) under three RF stress conditions $f=1$ GHz, 5 GHz, and 18 GHz at $P=14$ dBm in 24 μm/0.18 μm devices. The threshold voltage of the DUT is 545 mV, LF noise was measured at $V_{gs}=0.7$ V in the linear range. As can be seen from Fig. 6, the measured LF noise increase after all three RF stresses. The increment of the noise is more visible as the frequency of RF stress rises. The most apparent increment is caused by the stress condition of 18 GHz-14 dBm, followed by 5 GHz-14 dBm, and the smallest stress frequency causes the smallest increment.

As illustrated in Fig. 6, the measured LF noise follows a $1/f^{\gamma}$, especially between 100 Hz and 1000 Hz, the value of $\gamma$ within 100 Hz to 1000 Hz is closest to 1. To eliminate the effect of the system noise and white noise, the values of $\gamma$ are extracted mainly in the range of 100 Hz to 1000 Hz. The typical value of $\gamma$ is 1. However, the value of $\gamma$ varies around 1 in practice, and the normal interval is 0.8–1.2. In this interval, the device has good reliability.

Fig. 7 presents the value of $\gamma$ which is estimated within 100 Hz to 1000 Hz in Fig. 6 and the percentage change of $\gamma$ $(|\Delta \gamma|/\gamma)$ at $V_{gs}=0.7$ V. It can be seen that the values of preset stress $\gamma$ is 1.19 and $\gamma$ reduce after the RF stress. The value of $\gamma$ under 1 GHz RF stress reduces by a factor of 3.86 %, but for 5 GHz RF stress is almost 4 times of 1 GHz RF stress. The biggest reduction of $\gamma$ occurs at 18 GHz RF stress which is beyond 40 % and the value of $\gamma$ is lower than 1. The experimental results indicate that the larger frequency of RF stress has a deeper influence on devices. The same degradation characteristics of noise as the stress frequency grows in Fig. 7 also can be seen under the stress $P=6$ dBm and 9 dBm.

Fig. 8 shows the percentage changer of $S_{id}/I_{d}^{2}$ ($\Delta S_{id}$)
versus the input power of RF stress at \( f = 100 \) Hz for stress frequency \( f = 1 \) GHz, 5 GHz, and 18 GHz in 24 μm/0.18 μm devices. It can be seen that RF stress-induced \( \Delta S_{\text{id}} \) increases with the input power. The input power of 14 dBm at \( f = 18 \) GHz causes the biggest increment, almost five times larger than the increment under 6 dBm. But for 1 GHz and 5 GHz, the difference between the noise increment after different input power of stress is not obvious. The same characteristics as seen in Fig. 8 are also observed for other frequencies.

![Graph](image1)

**Fig. 8** The values of \( \gamma \) and fractional changes in the values of \( |\Delta \gamma|/\gamma \) under different input power of RF stress conditions at the stress frequency of 18 GHz for \( V_{gs} = 0.7 \) V.

The experimental results of the influence of stress frequency and the input power on LF noise, the worst case of RF stress condition is 18 GHz-14 dBm for 24 μm/0.18 μm devices. The phenomenon that the increment of noise under RF stress rises as the input power and stress frequency grows only can be seen in device 24 μm/0.18 μm. For 60 μm/0.18 μm devices, the worst-case RF stress is 5 GHz-6 dBm.

In the view of Fig. 7 and 9, the values of \( \gamma \) reduce under RF stress and the \( \gamma \) is below 1 after the worst-case RF stress. It is known that the frequency exponent deviates from 1 if the trap density is not uniform in-depth. And a trap distribution that is skewed toward the interface leads to \( \gamma < 1 \), and \( \gamma > 1 \) for the opposite case [30]. Thus, the \( \gamma < 1 \) after the worst-case RF stress implies that the traps generated by RF stress mainly distribute close to the interface.

Combined the experimental results of DC parameters and LF noise, it can be believed that the main degradation mechanism of RF stress is attributed to the generation of interface traps. This is probably because the RF stress is input to the gate as a sinusoidal signal wave. Compared with the DC stress of a high steady gate bias \( (V_{gs} = V_{ds}) \), it has a smaller possibility for hot carriers to gain enough energy to enter into the deeper gate oxide to generate deep-level traps. As a result, hot carriers caused by RF stress are more possible to lie at the Si/SiO₂ interface and create more interface traps. It is proved by the obvious increment of LF noise at large \( V_{gs} \) and the visible shifts of \( I_{ds} \) at the saturation region in \( I_{ds} \) \( V_{gs} \) curves. And the degradation of \( \gamma \) and \( \gamma < 1 \) under RF stress further proves this conclusion.

**4. Conclusion**

We have investigated the performance of LF noise under RF stress and DC stress. Besides, the dependence of the increment of LF noise on the input power and frequency of stress has been further explored. The degradation of LF noise is strongly dependent on the values of \( V_{gs} \). The LF noise increases under both RF and DC stress conditions. The LF noise after RF stress rises more rapidly at a large \( V_{gs} \) value, while the DC stress causes more degradation at a small \( V_{gs} \) value. The increment of LF noise \( \Delta S_{\text{id}} \) raises as the growth of \( V_{gs} \) while the \( \Delta S_{\text{id}} \) reduces under DC stress for the opposite case. For \( W/L = 24 \) μm/0.18 μm devices, the noise under RF stress rises more apparently as the input power and stress frequency grows, whereas the value of \( \gamma \) decreases.

Thus, the worst-case of RF stress conditions is the input power of 14 dBm at \( f = 18 \) GHz in 24 μm/0.18 μm devices. And the values of \( \gamma \) are all below 1 after 18 GHz RF stress which indicates the generation of traps close to the interface is the main reason for the increment of noise. The experimental LF noise results suggest that the
dominant degradation mechanism of RF stress is the generation of the interface traps \( D_h \) at the Si/SiO\(_2\) interface. The experimental degradation results of DC parameters \( \Delta \) and \( \Delta S \) further verify this conclusion.

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