Analysis and modeling for MOSFET degradation under RF stress

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Abstract The degradation of NMOSFETs due to hot-carrier effects under DC and RF stress was studied experimentally. The experimental results indicate that DC stress leads to more serious performance degradation than RF stress. It has also been found that channel length and width can change the worst DC stress condition. Moreover, RF performance degradation can be explained by DC performance degradation. A new model is proposed to predict the degradation characteristics of devices under RF stress by the degradation under DC stress. By using knowledge-based neural network (KBNN), the model shows good accuracy. It can also reduce test data set and simplify testing process.

Keywords: hot-carrier degradation, knowledge-based neural network (KBNN), RF stress, NMOSFETs
Classification: Electron devices, circuits and modules (silicon, compound semiconductor, organic and novel materials)

1. Introduction

With the development of CMOS technology, the size of MOS devices is scaling down to increase the integration of circuits and reduce the cost. Nowadays, the channel lengths of MOSFETs are in the nanometer range, leading to serious reliability problems. For short channel devices, the influence of hot-carrier effects can not be ignored [1, 2, 3]. Because the operating voltage is not reduced in the same proportion with size, carriers gain energy from high electric field. After impact ionization, some of them may cross the Si/SiO₂ barrier and damage the gate oxide or generate interface state, and then cause degradation of device performance. In more serious cases, it will even affect the entire integrated circuit. Therefore, it is essential to study the hot-carrier reliability of MOS devices, especially NMOSFETs [4]. The majority carriers of PMOSFETs are holes. Holes have lower impact ionization rate. It is also harder for holes to get through the SiO₂ interface. As a consequence, hot carriers have less influence on PMOSFETs than NMOSFETs.

Reducing the size of devices can also increase the operating frequency to gigahertz, and they can be used in many RF integrated circuits, such as voltage-controlled oscillators (VCO), low-noise amplifiers (LNA), the mixers [2, 3, 5]. With the increasing of the circuit operating frequency, the effect of RF stress on the reliability of devices needs to be investigated. Until now, most of the research on hot-carrier effects of MOS devices focused on the influence of DC stress or low frequency AC stress [6, 7, 8, 9, 10, 11]. And there is no uniform conclusion on which of RF stress and DC stress causes the greater hot-carrier degradation. So both DC stress and RF stress were applied to devices in this experiment. In addition, the lifetime of MOS device is a key parameter to evaluate the hot-carrier degradation of device characteristics. Since the lifetime of device is different when applying different bias voltages, we usually study it under the worst stress condition, and then use the extrapolation method to obtain the lifetime under normal operating conditions. Therefore, finding the worst stress condition is the focus of studying hot-carrier effects. For DC stress, the worst stress condition of device usually occurs when \( V_g = 0.5V_D \) [12, 13]. However, in this experiment, it is found that the channel length and width of devices will change the worst stress condition. Furthermore, in order to analyze and predict the performance of devices easily and accurately, we need to establish hot-carrier degradation model. Most of the hot-carrier degradation models proposed previously are physical models or formula models [14, 15, 16, 17, 18, 19]. Physical models need to take complex microscopic mechanisms into account. Formula models need complicated derivation and calculations. Most important of all, few of them can relate degradation of device parameters caused by DC stress and RF stress.

In this letter, we describe the hot-carrier degradation of NMOSFETs performance under DC stress and RF stress first. Through the hot-carrier degradation experiment, it is observed that DC stress can lead to more serious degradation than RF stress, and RF performance degradation can be explained by DC performance degradation. In addition, channel length can change the worst DC stress condition. Finally, a new model is proposed by using knowledge-based neural network (KBNN) to predict the degradation characteristics of devices under RF stress by the degradation of devices under DC stress.

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Fig. 1 The setup of the NMOSFETs hot-carrier stress measurement.
2. Hot-carrier degradation experiment

The NMOS transistors used in this work were fabricated in 0.18 μm CMOS process. The source and bulk were connected to ground. The devices under test (DUT) are multi-finger with a finger width of Wu = 6 μm. There are three types of devices. Transistor M1 has the number of fingers n = 10 and channel length L = 0.42 μm. Transistor M2 has the number of fingers n = 10 and channel length L = 0.18 μm. Transistor M3 has the number of fingers n = 14 and channel length L = 0.18 μm.

The setup of the hot-carrier stress measurement is shown in Fig. 1. The die was tested on-chip in a Probe Station using ground-signal-ground probes. The Rohde & Schwarz SMA100B signal generator can provide RF stress up to 18 GHz. The Keithley Agilent 4200A-SCS Semiconductor Parameter Analyzer was used to supply DC stress and measure current-voltage (I–V) characteristics. The Rohde & Schwarz ZVA24 Network Analyzer was used to measure $S$-parameters. The “Open,” “short,” “match,” and “through” structures were used for on-chip parasitic de-embedding.

When applying RF stress or when measuring $S$-parameters, two bias tees were added on the drain and gate. In DC stress degradation experiment, the DC voltages were applied to the drain and gate. We studied hot-carrier reliability based on the accelerated stress test. After a voltage ramp test (VRT), it is found that the oxide breakdown voltage of device is about 3.3V. So the DC stress for drain was set at 3 V, while three gate stresses were performed at 3 V, 1.5 V and 1.2 V. In RF stress degradation experiment, a 14 dBm RF signal with different frequency was applied to the gate [20]. The frequency was set to 1 GHz, 5 GHz, 18 GHz. The gate bias voltage was set at 0.9 V and the drain bias voltage was set at 1.2 V. The stress was interrupted at a regular time when we test the parameters of devices. All devices were tested under the same bias condition. The total stress time was 5000 s.

3. Results and discussion

The DC parameters degradation of M1 and M2 is shown in Fig. 2. M3 has the similar degradation trend with M1. The drain saturation current, the maximum transconductance and the threshold voltage all degenerated with stress time. It is because hot-carrier effects lead to the formation of interfacial states and gate oxide defects, and then confine electrons to the gate oxide surface. So there are fewer electrons in the channel. Also, the degradation of $S$-parameters after 5000 s stress is shown in Fig. 3. When testing $S$-parameters, the gate bias voltage was set to 0.9 V and the drain voltage was 1.2 V. Fig. 2 and Fig. 3 illustrate the $S$-parameter degradation caused by hot-carrier stress is much larger than DC characteristics. Furthermore, RF performance degradation
can be explained by DC performance degradation. Taking $S_{21}$ as an example, the main reason of its decrease is the drop of $g_{ma}$ as shown in Fig. 2(b) and (e).

Comparing with DC stress, RF stress causes less degradation. For $M_1$, the drain saturation current decreased by $10.190\%$, $22.242\%$ and $61.601\%$ when $V_g = V_d$, $V_g = 0.5V_d$ and $V_g < 0.5V_d$ after 5000 s DC stress, while it decreased by $0.526\%$ when frequency is set to $18$ GHz after RF stress. The maximum transconductance decreased by $6.513\%$, $13.003\%$ and $32.167\%$ after DC stress while $0.814\%$ after RF stress. The threshold voltage increased by $6.336\%$, $7.231\%$ and $28.373\%$ after DC stress while $0.017\%$ after RF stress. $S_{21}$ decreased by $0.557\,\text{dB}$, $2.260\,\text{dB}$ and $3.947\,\text{dB}$ after DC stress while $0.084\,\text{dB}$ after RF stress at $5$ GHz scanning frequency. It is because trapped charges are concentrated at the interface and can easily get out of the trap under RF stress [21]. As a result, hot-carrier degradation will be less severe.

The size of devices also affects the hot-carrier degradation. In Fig. 3, the worst DC stress condition was $V_g < 0.5V_d$ for $M_1$, but it was $V_g = 0.5V_d$ for $M_2$. In other words, the worst gate stress is smaller with the increase of channel length. As listed in Table I, the worst DC stress condition was $V_g < 0.5V_d$ for $M_1$, so the worst gate stress is smaller with the increase of channel width. This is because channel length and width can influence the position of the peak electric field, and then change the worst DC stress condition. Moreover, $M_1$ has larger channel length than $M_2$ and less degradation, $M_3$ has larger channel width with $M_2$, and less degradation. It shows that when the scale of device is larger, the device is more stable and less affected by hot-carrier effects. This further proves that the research of hot-carrier effect is of great significance for short channel devices.

### 4. Modeling for hot-carrier degradation

The degradation characteristics of devices under RF stress are often difficult to achieve. On the one hand, it is step tedious and time-consuming. We need to do a lot of calibrations to remove the effect of disturbing factors. On the other hand, the test condition is greatly limited by the frequency band of the test instruments. In this work, the degradation characteristics of devices under RF stress can be established based on the degradation of devices under DC stress which is easier to obtain. Knowledge-based neural network (KBNN) is used firstly for hot-carrier degradation modeling of MOS devices [22, 23, 24, 25]. Compared with other modeling methods, neural network can describe more complex relationships with high speed and accuracy.

The flow-chart in Fig. 4 shows the modeling process in this work. The model is built, trained and tested in NeuroModeler software [26]. All data are obtained from the accelerated degradation experiment. The specific composition of data is shown in Table II. At the beginning, we should preprocess all the experimental data. After zero-mean normalization, the comparability between different inputs can be improved [27]. Then we start to build a knowledge-based neural network (KBNN) model. The first step is to create a multilayer perceptron (MLP) module [28, 29]. This part of model is to fit the relationship between $S$-parameter degradation and DC performance degradation when devices are under RF stress. The next step is to create a data module. The experimental data under DC stress is imported to the module as prior knowledge. This part of model can learn the relationship between DC performance degradation and $S$-parameter degradation when devices are under DC stress. The process of training model is actually the process of adjusting the weights of neural network. Prior knowledge can simplify the parameter adjustment process and decrease the cost of training [30, 31]. Then the train error should be evaluated. If it does not achieve our desired accuracy, we can change the number of hidden layer neurons in multilayer perceptron (MLP) to improve the accuracy. Otherwise, we can test the model. The test error is evaluated by comparing the fitted outputs with actual outputs. It indicates the accuracy of the whole model.

The diagram of model structure is presented in Fig. 5. The model has nine inputs (channel width, channel length, drain stress voltage, gate stress voltage, stress frequency, scanning frequency and the degradation of three DC parameters under RF stress) and eight outputs (the amplitude and angle degradation of $S$-parameter under RF stress). The degradation of these parameters under DC stress act as prior knowledge to help establish connections between DC and RF parameters. Distribution of the numbers of data is shown in Table III. The number of hidden layer neurons in multilayer perceptron (MLP) of the final model is 12. After training and testing, the model shows good accuracy with the average test error of 8.48%. It is visual to have compared the error between...
model outputs and experimental data in Fig. 6. The data on this graph are all standardized. The result indicates that this model can predict the degradation characteristics of devices under RF stress by the degradation under DC stress within the error allowed. The model is also applicable to the other devices which are not mentioned in the letter. When we evaluate other devices, DC stress is needed to apply to ensure accuracy. We don’t need to apply RF stress to the other new devices. It shows the usefulness of prior knowledge. As a result, the model can reduce the test data set and further simplify the testing steps. After testing, the model shows good accuracy.

5. Conclusion

The degradation of NMOSFETs under hot-carrier stress are studied. The experimental results show that RF stress causes less performance degradation than DC stress and the degradation of S-parameter caused by hot-carrier stress is much larger than DC characteristics. For DC stress, it has been found that the worst stress condition does not always appear when the gate stress $V_g = 0.5V_d$. When channel length and width increase, the coefficient will decrease slightly. Finally, a model is built by using knowledge-based neural network (KBNN) to predict the degradation characteristics of devices under RF stress by the degradation under DC stress. The model can reduce the test data set and simplify the testing process. After testing, the model shows good accuracy.

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