Investigating Hot-Carrier Degradation in MOSFETs using Constant and Switched Biased Low-Frequency Noise measurements

J.S. Kolhatkar, E. Hoekstra, A.J. Hof, C. Salm, J. Schmitz, and H. Wallinga
MESA$^+$ Research Institute, Semiconductor Components Group, University of Twente, The Netherlands
`j.s.kolhatkar@utwente.nl`

Abstract- **Periodically switching the MOSFET 'off' (switched biasing), is known to reduce the low-frequency (LF) noise power spectrum. In this work, the constant and switched biased LF noise has been measured on devices before and after hot-carrier stress. The switched biased LF noise is more sensitive to hot-carrier degradation than the constant biased LF noise. The anomalous noise reduction, due to switched biasing, observed for fresh devices, gradually disappears as the devices are subjected to hot-carrier stress. Devices with a deuterium passivated SiO_2/Si interface degrade significantly slower, as seen from our LF noise measurements.**

*Keywords—***Hot-carrier degradation, MOSFETs, Low-frequencyNoise, Switched biasing, Deuterium/Hydrogen post-metal anneal.**

1. INTRODUCTION

With shrinking dimensions, the reliability of the oxide and its interface gains importance. Trapped charge and defects or traps both in the oxide and at the Si-$Si0_2$ interface play an important role in the gradual degradation of oxide characteristics. Hot-carrier stressing is used to degrade transistors in a time-accelerated way, by changing the density and the distribution of the trapped oxide charge and the trapped interface charge. Hot carriers have more kinetic energy than the average carrier, when the transistor is biased in the saturation regime with a high drain-to-source voltage. At the drain side of the channel, the electrons gain enough energy to be injected into the gate-oxide and cause damage to the interface. The substrate current is considered as a reliable and convenient monitor for the amount of hot carrier degradation in MOSFETs. The damage caused by the hot-carrier injection is clearly visible in the reduction of the maximum transconductance (g_{mmax}) and an increase in the threshold voltage (V_t) of the device [1].

The low-frequency (LF) noise has often been used to characterize the hot-carrier degradation in MOSFETs [2-4]. The two principal theories that explain the low-frequency noise behaviour in MOSFETs are based on the mobility fluctuation model described by the Hooge parameter and the number fluctuation model based on the theory of trapping and de-trapping of the charge carriers in the traps located in the oxide or at the interface [5,6]. In addition, it has been reported in literature that the LF noise is more sensitive to hot-carrier degradation than the static device parameters (g_{mmax} and V_t) [4], and has been used as an analysis tool in hot-carrier degradation studies. The LF noise decreases anomalously, when the gate bias is periodically alternated (switched biasing) between an 'on' state where the device is in strong inversion and saturation and an 'off' state where the V_{GS} (gate-to-source voltage) is well below the threshold voltage of the device [7-9].

It is commonly accepted that interface traps arise from dangling bonds at the Si-SiO_2 interface. This is also supported with the fact that most of the interface traps created during processing are passivated by a low temperature anneal, in which atoms of an annealing gas, like hydrogen, is bonded with the dangling bonds. When a transistor is subjected to hot carrier injection (HCI) some of the hydrogen will desorb, resulting in device degradation. It has been reported in literature that, replacing H_2 with D_2, results in a reduction of transistor parameter degradation due to hot carrier stress [10].

In this paper, we investigate the hot-carrier degradation of MOSFETs using the LF noise measurements under constant and switched biased conditions. The noise measurements are carried out on devices, which used H_2/N_2 or D_2/N_2 ambient during the post metal anneal. These noise measurements are then compared with each other.

2. MEASUREMENT SETUP

A. LF noise measurements

The devices under test (DUT) are n-MOSFETS, fabricated in a standard 0.18 µm CMOS process. The devices used in this study have a gate length of 0.5 µm and a width of 2 µm. The DUT used H_2/N_2 gas, or D_2/N_2 gas during the post metal anneal. The oxide thickness of the DUT is about 7nm, as calculated from quasi-static capacitance voltage measurements.

The measurement setup used for the noise measurements is described in [11]. The advantage of using a differential setup is the rejection of common mode noise, arising from the function generator or from other sources, is rejected. The noise measurements are performed in the saturation regime on a matched pair of transistors. Both the transistors have their own drain contacts and they have a common gate, source and well contacts. The constant biased LF noise measurements are performed under a fixed drain current of 10 µA, making a reliable comparison between the noise measured before and after stress possible. This is made possible by increasing V_{GS} to compensate for the increase in V_t, due to hot-carrier injection. Under ‘switched biased’ conditions the DUT are periodically switched ‘off’, by applying a square wave of 10 kHz, with a 50% duty cycle at the gate of the device. When switching, the ‘on’ voltage of the gate signal is kept the same as in the constant bias case, and the ‘off’ voltage of switching signal is kept at a fixed level of -0.5 V. The ‘off’ value corresponds to the maximum noise reduction that can be obtained due to switched biasing [11]. Decreasing the ‘off’ voltage of switching further, does not affect the LF noise. The noise is calculated as the average noise power during the ‘on’ state between 1 and 5 Hz.

B. Hot-Carrier Stressing

The hot-carrier stressing in our measurements is carried out at V_{DS} = 4.5 V, and V_{GS} = 2.1 V, with the source and well grounded. The V_{DS} value is chosen below the breakdown value of the device. These conditions correspond to a maximum substrate current. The before and after stressing DC device parameters, V_t and g_{mmax}, are derived in the standard way from the input characteristics at V_{DS} = 0.1 V, using an Agilent 4156C Parameter Analyzer. As the hot-carriers induce damage on the drain side, all the DC characteristics and the LF noise in a post-stressed device are measured in the reverse mode, i.e., with the source and drain interchanged, so that the degraded region forms a part of the channel [2-4]. The stressing times for our measurements are 200, 1000 and 4000 seconds. The hot-carrier stressing is performed on both transistors of the matched pair at the same time.

3. NOISE MEASUREMENT RESULTS

The setup measures the drain current noise power spectral density (PSD dB V^2/Hz) of device under test.

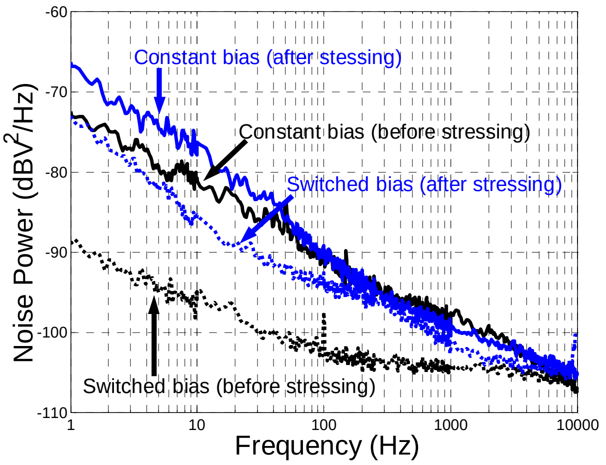

Figure 1. Sample noise power spectral density of DUT under constant and switched biased conditions before and after hot-carrier stress.

Figure 1 shows a sample noise PSD of the DUT under constant and switched biased conditions. The switched biased noise is observed to be well below the constant biased noise PSD. The noise increase for the switched biased condition is much more pronounced than that for the constant biased case.

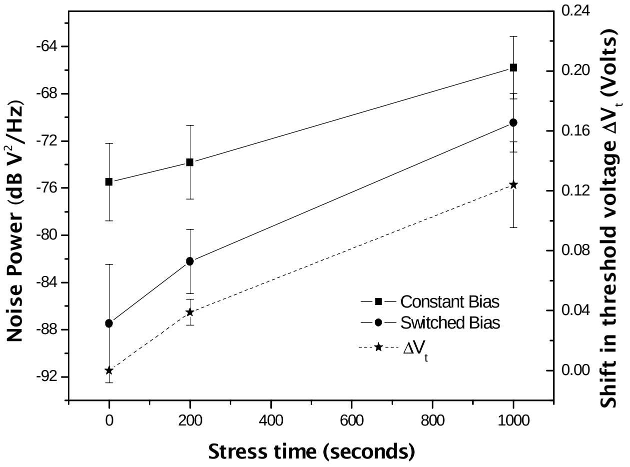

Figure 2. Constant and switched biased LF noise measurements on devices with a H_2/N_2 ambient during post-metal anneal, before and after hot-carrier stressing. Also shown is the shift in the threshold voltage of the DUT before and after stress.

The hot-carrier stressing leads to a change in the DC static parameters of the DUT. Figure 2 shows the change in the constant and switched biased LF noise after different stressing times. Also shown is the shift in the threshold voltage of the DUT. Prolonging the applied hot-carrier stress, increases the threshold voltage of the DUT. Each marker represents an average value over twelve devices. The bars indicate the standard deviation in the measurement points. From Fig. 2, it can be seen that the switched biased noise increases more rapidly as compared to the constant bias noise, when stressed. This indicates that the noise reduction (difference between constant and switched biased noise PSD) is diminishing as the devices are stressed for longer time. Hence the benefit of noise reduction by periodically switching the transistors ‘off’ gradually disappears in time when the transistor ages.

Figure 3 shows the same data plotted as a function of the shift in the threshold voltage of the DUT. It clearly shows that the stronger effect of stressing on switched biased noise power than on constant biased noise power, for the same threshold voltage shift.

The hot-carrier stress and LF noise measurements are also performed on devices with a D_2/N_2 ambient post metal anneal. The results of the comparison of the two different post metal anneal conditions (H_2/N_2 and D_2/N_2) are shown in Fig. 4. Figure 4 shows the constant and switched biased LF noise as a function of stress time. The constant and switched biased LF noise levels for fresh devices using H_2/N_2 and D_2/N_2, is approximately the same. It confirms the better resistance against hot-carrier stress of D_2/N_2 annealing above H_2/N_2 annealing [10, 12]. To obtain a similar change in the observed LF noise (i.e. device degradation), devices with a deuterium passivated interface should be subjected to over four times longer hot-carrier stress.

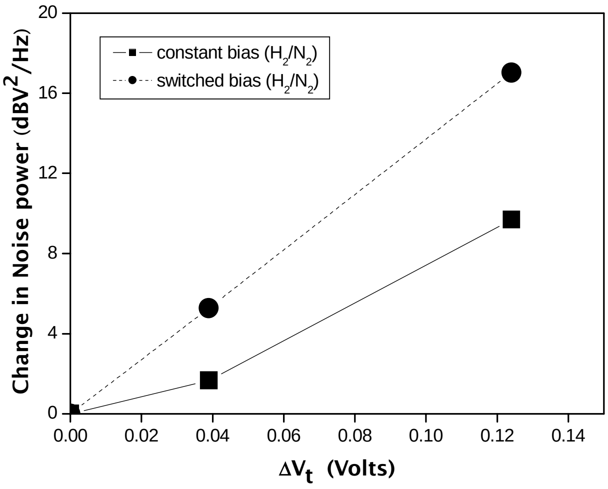

Figure 3. The change in constant and switched bias LF noise against the corresponding shift in the threshold voltage for the same DUT under hot-carrier stressing conditions.

Figure 5 shows the change in the g_{mmax} after application of hot-carrier stress for the DUT. From Fig. 5, it is observed that a similar change in g_{mmax}, devices with a deuterium passivated interface requires four times longer hot-carrier stress.

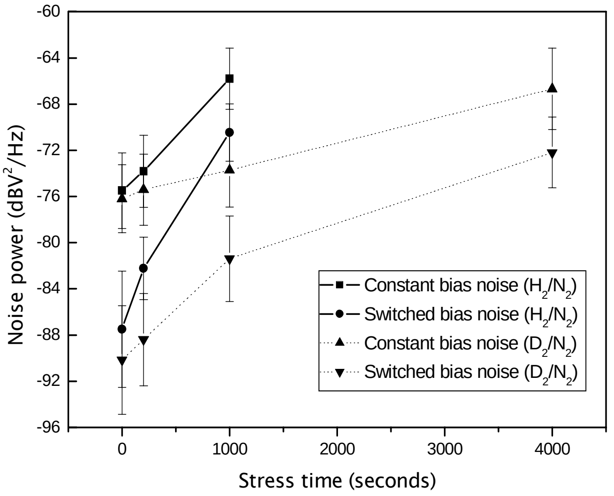

Figure 4. Comparison of constant and switched biased LF noise measurements on devices with D_2/N_2 and H_2/N_2 gas during post-metal anneal, before and after hot-carrier stressing.

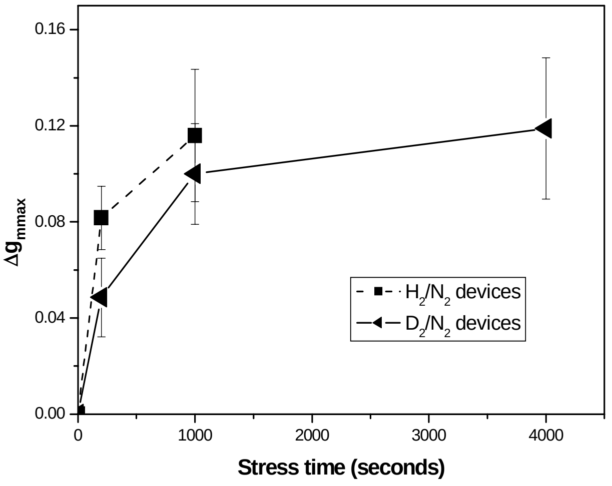

Figure 5. The change in the maximum transconductance (g_{mmax}), before and after hot-carrier stress, for devices with D_2/N_2 and H_2/N_2 gas during post-metal anneal.

Figure 6 is similar to Fig. 3, with the addition of LF noise measurement data on devices with deuterium passivation. It can be seen from Fig. 6, that for a corresponding shift in V_t, the resulting change in the constant and switched biased LF noise is the same for devices with deuterium and hydrogen passivation. Thus it can be inferred that the mechanism which leads to the shift in V_t and change in constant and switched biased LF noise due to hot-carrier stress for both devices, is the same.

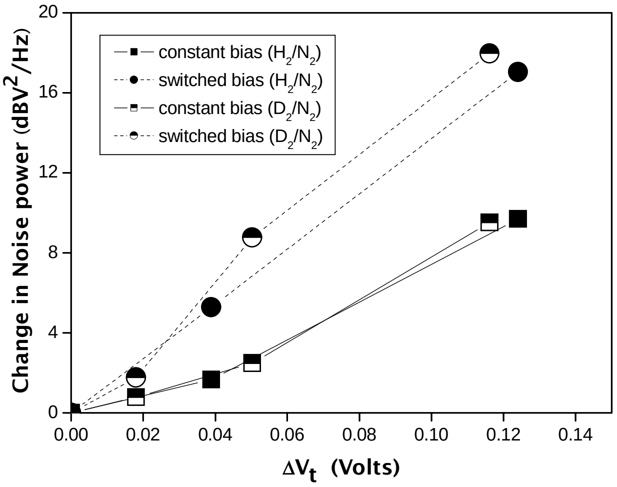

Figure 6. The change in constant and switched bias LF noise against the corresponding shift in the threshold voltage for DUT (H_2 and D_2 passivated) under hot-carrier stress.

4. DISCUSSIONS

The creation of interface traps due to hot-carrier injection is considerably slower for samples that have received a D_2/N_2 post metal anneal as compared to a H_2/N_2 post metal anneal. This is often attributed to the fact that it is more difficult to break the Si-D bond due to a better coupling between the Si-D bending mode and the Si substrate as compared to the Si-H bending mode and Si substrate [12].

One of the theories, which explain the LF noise under constant bias, is the capture and release of charge carriers in traps located at the interface or in the oxide. For fresh devices, the LF noise observed in samples passivated with H and D is approximately equal. The observed constant biased LF noise increases after hot-carrier stress, due to the creation of traps. The rapid increase in the LF noise in H_2 passivated devices is due to the faster breaking of the Si-H bond as compared to the Si-D bond for the D_2 passivated devices.

We observe a faster increase in the switched biased LF noise as compared to the constant biased LF noise in both H_2/N_2 and D_2/N_2 ambient post metal annealed devices after hot-carrier stress. This implies that the useful noise reduction is diminishing as the devices age.

5. CONCLUSIONS

We have conducted LF noise characterization of hot-carrier degraded devices with H_2/N_2 and D_2/N_2 ambient during the post metal anneal. The switched biased noise increases more rapidly due to hot-carrier degradation as compared to the constant biased noise. The useful noise reduction, due to switched biasing under non-stressed conditions, diminishes, as the devices are subjected to hot-carrier stress. Devices with D_2/N_2 ambient during post metal anneal show better resistance against hot-carrier injection than those with H_2/N_2 ambient during post metal anneal.

ACKNOWLEDGMENTS

The authors would like to thank Philips Research (Leuven) for supplying the wafers used in this study. This work is supported by the Dutch Technology Foundation (STW), applied science division of NWO, and the technology program of the ministry of Economic Affairs.

REFERENCES

[1] E. Takeda, ‘Hot-carrier effects in scaled MOS devices’, Microelectron. Reliab., vol. 33, pp. 1687-1711, 1993.

[2] M. Stegherr, ‘Flicker Noise in hot electron degraded short channel MOSFETs’, Solid-State. Electron. , vol. 27, pp. 1055-1056, 1984.

[3] P. Vasina, E. Simoen, C.Claeys, and J. Sikula, ‘A low-frequency noise study of hot-carrier stressing effects in submicron Si p-MOSFETs’, Microelectron. Reliab., vol. 38, pp. 23-27, 1998.

[4] L.K.J. Vandamme and X. Li, ‘Change in DC and 1/f noise characteristics of n-submicron MOSFETs due to Hot-Carrier degradation,’ Microelectron. Reliab., vol. 38, pp. 29-35, 1998.

[5] L.K.J. Vandamme, X. Li, and D. Rigaud, ‘1/f Noise in MOS devices, mobility or number fluctuations?’, IEEE Trans. Electron Devices, vol. 41, pp. 1936-1944, Nov. 1994.

[6] M.J. Uren, D.J. Day, and M.J. Kirton, ‘1/f and Random telegraph noise in silicon metal oxide semiconductor field effect transistor’, Appl. Phys. Lett., vol. 47, pp. 1195, 1985.

[7] I. Bloom and Y. Nemirovsky, ‘1/f Noise Reduction of Metal Oxide Semiconductor Transistors by Cycling from Inversion to Accumulation’, Appl. Phys. Lett., vol. 58(15), pp. 1664-1666, April 1991.

[8] B. Dierickx and E. Simoen, ‘The Decrease of Random Telegraph Signal Noise in Metal-Oxide-Semicondutor Field-Effect Transistors when Cycled from Inversion to Accumulation’, J. Appl. Phys., vol. 71 no. 4, pp. 2028-2029, Feb. 1992.

[9] A.P. van der Wel, E.A.M. Klumperink, B. Nauta, ‘Switched Biasing affects 1/f Noise and Random Telegraph Signals in Deep-Submicron MOSFETs,’ Electron. Lett., vol. 37, Iss. 1, pp. 56-57, Jan. 2001.

[10] J.W. Lyding, K. Hess, and I.C. Kizilyalli, ‘Reduction of hot electron degradation in metal oxide semiconductor transistors by deuterium processing’, Appl. Phys. Lett., vol. 68, pp. 2526-2528, April 1996.

[11] J.S. Kolhatkar, C. Salm, M.J. Knitel, and H. Wallinga, ‘Constant and Switched Bias Low-Frequency Noise in p-MOSFETs with Varying Gate-Oxide Thickness,’ Proceedings of 32nd ESSDERC, pp. 83-86, Sept. 2002.

[12] C.G. Van de Walle and B. Jackson, ‘Comment on: Reduction of hot electron degradation in metal oxide semiconductor transistors by deuterium processing (APL. 68, 2526, 1996),’ Appl. Phys. Lett., vol. 69, p. 2441, Oct. 1996.