Extended Abstracts of the 2011 International Conference on Solid State Devices and Materials, Nagoya, 2011, pp194-195

Hot Carrier Effect on RF Characteristics of High-k/Metal Gate SiGe Channel pMOSFETs

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1. INTRODUCTION

Strain engineering and new channel materials such as germanium, strained silicon-germanium, and III-V compounds have been investigated to enhance the performance of CMOS devices [1]. Especially, the SiGe material has been widely used because of its higher mobility than Si and good process compatibility with Si [2]. The reliability for the SiGe material has been intensively studied in DC region, but the study of the reliability in radio frequency (RF) is needed because RF applicability of the SiGe devices increases due to its higher mobility. In particular, the SiGe pMOSFETs increases the impact ionization at the drain edge region because of their narrow band gap energy compared with Si pMOSFETs [3]. Therefore, hot carrier injection (HCI) should be studied to provide deeper understanding for RF reliability of SiGe devices. In this paper, we report the effect of HCI on RF performance of SiGe pMOSFETs based on the analysis of RF small-signal parameters. Additionally, the role of Si capping layer on SiGe channel in hot carrier instability is also investigated, comparing with Si pMOSFETs as a control device.

2. EXPERIMENTS

The thickness of epitaxial SiGe layers and the concentration of Ge were optimized to 5 nm and 25 %, respectively. A 3 nm Si capping layer was deposited to encapsulate the SiGe channel, as shown in Fig. 1. A 3 nm HfO_2 layer was deposited by atomic layer deposition (ALD) on a 1 nm interfacial layer (IL). TiN was deposited by ALD as the gate electrode. Si pMOSFETs as a control devices were also fabricated as 2 fingers devices with a finger width of 20 μm and a gate length of 180 nm. Detailed split conditions are shown in Table I [4]. The stress condition was chosen to apply the same vertical and lateral field in both SiGe pMOSFETs and Si pMOSFETs, considering the effective gate length and EOT. The hot carrier stress was applied at $V_G = V_D = -2.5$ V for Si pMOSFETs and $V_G = -2.5$ V, $V_D = -2.3$ V for SiGe pMOSFETs. For RF characteristics, *S*-parameters were measured in the frequency range from 1 GHz to 20 GHz by using Anritsu 37397C vector network analyzer (VNA).

3. RESUTS AND DISCUSSION

As shown in Fig. 2, the SiGe pMOSFETs showed higher I_D and g_m/C_{inv} than Si pMOSFETs, which was attributed to the higher mobility. To extract the intrinsic RF small-signal parameters, the effect of the source/drain series resistance (R_{sd}) should be removed. The R_{sd} and R_s was determined by extrapolating $Re(Z_{22})$ and $Re(Z_{12})$ at high gate voltages respectively as shown in Fig. 3 [5]. After the R_{sd} correction, the C_{gs} and C_{gd} were extracted from Y-parameters of intrinsic part of the device before and after the hot carrier stress. Both C_{gs} and C_{gd} decreased after the stress and increased slightly after the relaxation as shown in Fig. 4. The degradation of C_{gs} (SiGe : 31 %, Si : 13 %) was higher than that of C_{gd} (SiGe : 4 %, Si : 2 %), which was attributed to the larger hole trapping to pre-existing defects of high-k layer at the source edge region [6]. The degradation of g_m in SiGe pMOSFETs (50 %) was higher than that of g_m in Si pMOSFETs (24 %) shown in Fig. 5.

In terms of RF performances, the C_{gg} ($C_{gg} = C_{gs} + C_{gd}$) and transconductance (g_m) are related with the current gain cutoff frequency (f_T) which is expressed as

$$f_T \cong \frac{g_m}{2\pi(C_{gs}+C_{gd})} \quad (1)$$

Even though C_{gg} decreased, f_T decreased because of more severe degradation of g_m. Due to the higher degradation of g_m in SiGe pMOSFETs than that of g_m in Si pMOSFETs, the degradation of f_T in SiGe pMOSFETs (15 %) was more serious than that of f_T in Si pMOSFETs (8 %) after the stress (Fig. 5). Because the band gap of SiGe is smaller than that of Si, the probability of impact ionization in the SiGe channel increases. Therefore, the higher degradation of f_T in SiGe pMOSFETs was attributed to the higher degradation of g_m due to the new trap generation by injected hot hole into the IL.

Additionally, in terms of carrier injection, SiGe pMOSFETs have longer distance for injection to the gate dielectric because the Si capping layer resulted in a deeper channel than Si pMOSFETs as shown in the Fig. 6. To analyze the role of Si capping layer in HCI, the stress condition ensuring the same impact ionization rate in the channel was used. As shown in Fig. 7, the stress condition could be determined by using the impact ionization ratio (I_b/I_s) as an index of the electrons generated by impact ionization. Under the stress, the degradation of f_T was similar in both devices shown in Fig. 8. Therefore, in terms of hot carrier-induced degradation, the role of Si capping layer is almost negligible.

4. CONCLUSION

In terms of RF performance, the degradation of f_T in SiGe pMOSFETs was more severe than the Si pMOSFETs because the narrow band gap of SiGe channel resulted in more severe degradation of g_m. Under the stress condition ensuring the same impact ionization ratio in both devices, the Si capping layer on SiGe channel has not considerable effect on HCI.

Acknowledgements

The authors would like to thank SEMATECH for device fabrication. This research was partially supported by BK21 program, system IC 2010 program, the National Center for Nanomaterials Technology (NCNT), and World Class University program funded by the Ministry of Education, Science and Technology through the National Research Foundation of Korea(R31-2010-000-10100-0).

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Table I. Split conditions of Si control and SiGe(Ge 25%) pMOSFETs

	Si	SiGe
Si capping layer	X	O
EOT (nm)	1.1	1.1
High-k dielectric	3nm HfO_2	3nm HfO_2
R_{sd} (Ω)	30	35
μ_{eff} (cm^2/V-sec)	43.1	68.4

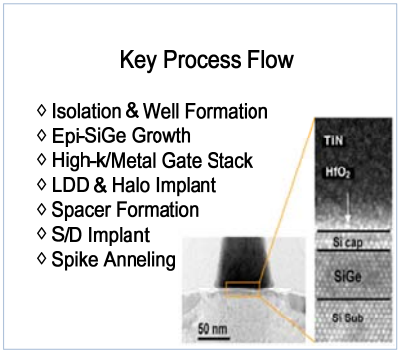

Fig. 1. Process flow and TEM image of device structure for SiGe/Si pMOSFETs with high-k/metal gate dielectric gate stack

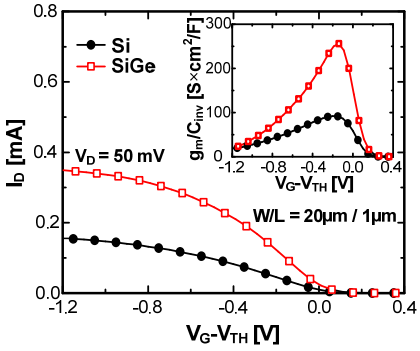

Fig. 2. Comparison of DC characteristics of SiGe pMOSFETs and Si pMOSFETs

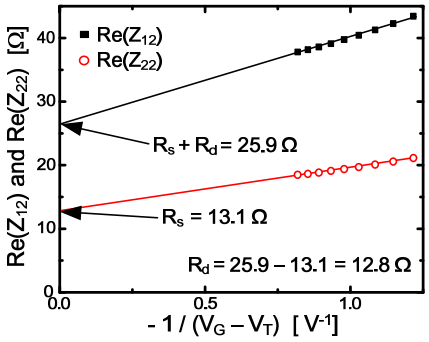

Fig. 3. Extraction of R_d and R_s from the real part of Z-parameters

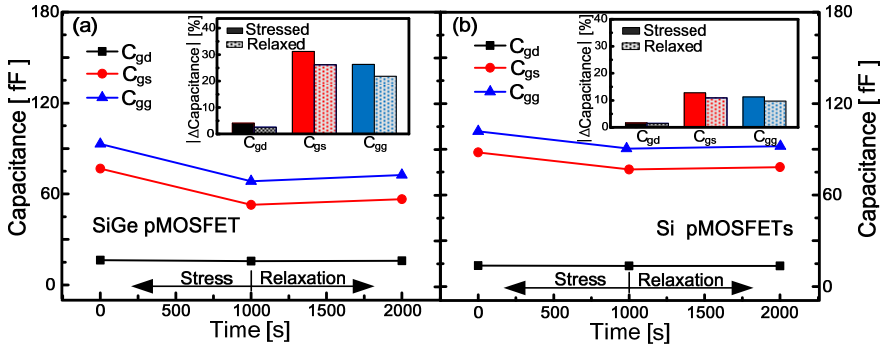

Fig. 4. The degradation of capacitance under the HCI (a) in SiGe pMOSFETs and (b) in Si pMOSFETs

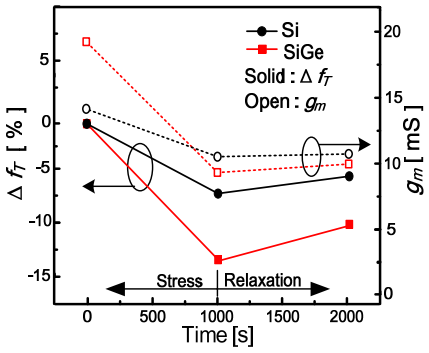

Fig. 5. Comparison of variation of f_T and g_m between SiGe pMOSFETs and Si pMOSFETs under the HCI

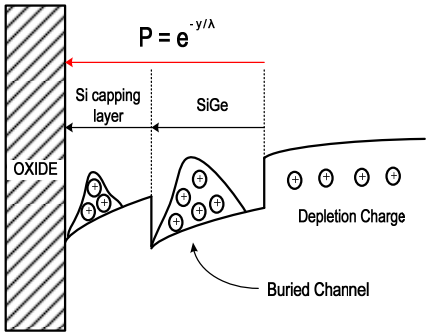

Fig. 6. The band diagram of SiGe pMOSFETs with Si capping layer

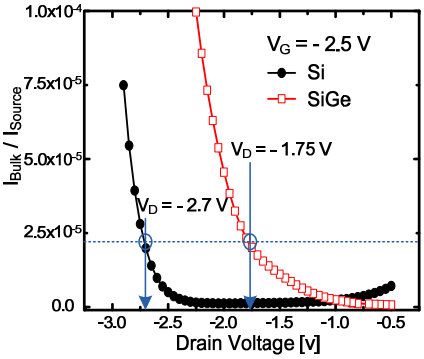

Fig. 7. The ratio of impact ionization (I_{Bulk}/I_{Source}) versus drain voltage

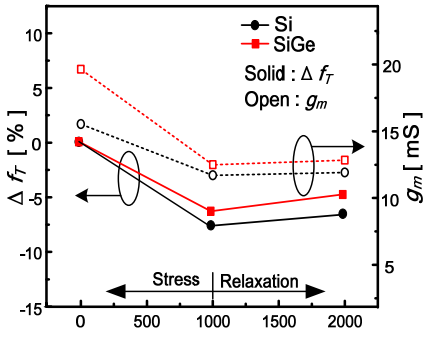

Fig. 8. Comparison of variation of f_T and g_m under the stress ensuring the same impact ionization rate