High-k shallow traps observed by charge pumping with varying discharging times
Szu-Han Ho, Ting-Chang Chang, Ying-Hsin Lu, Bin-Wei Wang, Wen-Hung Lo, Ching-En Chen, Jyun-Yu Tsai, Hua-Mao Chen, Kuan-Ju Liu, Tseung-Yuen Tseng, Osbert Cheng, Cheng-Tung Huang, Tsai-Fu Chen, and Xi-Xin Cao

Citation: Journal of Applied Physics 114, 174506 (2013); doi: 10.1063/1.4828719
View online: http://dx.doi.org/10.1063/1.4828719
View Table of Contents: http://scitation.aip.org/content/aip/journal/jap/114/17?ver=pdfcov
Published by the AIP Publishing

Articles you may be interested in
Temperature dependence of the resistive switching-related currents in ultra-thin high-k based MOSFETs
J. Vac. Sci. Technol. B 31, 022203 (2013); 10.1116/1.4789518

Investigation of extra traps measured by charge pumping technique in high voltage zone in p-channel metal-oxide-semiconductor field-effect transistors with HfO2/metal gate stacks
Appl. Phys. Lett. 102, 012106 (2013); 10.1063/1.4773914

Cross characterization of ultrathin interlayers in HfO2 high-k stacks by angle resolved x-ray photoelectron spectroscopy, medium energy ion scattering, and grazing incidence extreme ultraviolet reflectometry
J. Vac. Sci. Technol. A 30, 041506 (2012); 10.1116/1.4718433

Investigation on interface related charge trap and loss characteristics of high-k based trapping structures by electrostatic force microscopy

The Relation Between Crystalline Phase, Electronic Structure, and Dielectric Properties in HighK Gate Stacks
AIP Conf. Proc. 788, 92 (2005); 10.1063/1.2062944
High-k shallow traps observed by charge pumping with varying discharging times

Szu-Han Ho,1 Ting-Chang Chang,2,3,a) Ying-Hsin Lu,2 Bin-Wei Wang,4 Wen-Hung Lo,2 Ching-En Chen,1 Jyun-Yu Tsai,2 Hua-Mao Chen,5 Kuang-Ju Liu,2 Tseung-Yuen Tseng,1 Osbert Cheng,6 Cheng-Tung Huang,6 Tsai-Fu Chen,6 and Xi-Xin Cao4

1Department of Electronics Engineering, National Chiao Tung University, Hsinchu 300, Taiwan
2Department of Physics, National Sun Yat-Sen University, Kaohsiung 804, Taiwan
3Advanced Optoelectronics Technology Center, National Cheng Kung University, Tainan, Taiwan
4Department of Embedded System Engineering, Peking University, Beijing, P.R.China
5Department of Photonics and Institute of Electro-Optical Engineering, National Chiao Tung University, Hsinchu, Taiwan
6Device Department, United Microelectronics Corporation, Tainan Science Park, Taiwan

(Received 26 July 2013; accepted 17 October 2013; published online 5 November 2013)

In this paper, we investigate the influence of falling time and base level time on high-k bulk shallow traps measured by charge pumping technique in n-channel metal-oxide-semiconductor field-effect transistors with HfO2/metal gate stacks. NT-Vhigh level characteristic curves with different duty ratios indicate that the electron detrapping time dominates the value of NT for extra contribution of Icp traps. NT is the number of traps, and Icp is charge pumping current. By fitting discharge formula at different temperatures, the results show that extra contribution of Icp traps at high voltage are in fact high-k bulk shallow traps. This is also verified through a comparison of different interlayer thicknesses and different TiN1−x metal gate concentrations. Next, NT-Vhigh level characteristic curves with different falling times (tfalling time) and base level times (tbase level) show that extra contribution of Icp traps decrease with an increase in tfalling time. By fitting discharge formula for different tfalling time, the results show that electrons trapped in high-k bulk shallow traps first discharge to the channel and then to source and drain during tfalling time. This current cannot be measured by the charge pumping technique. Subsequent measurements of NT by charge pumping technique at tbase level reveal a remainder of electrons trapped in high-k bulk shallow traps. © 2013 AIP Publishing LLC.

I. INTRODUCTION

As metal-oxide semiconductor field-effect transistors (MOSFETs) continue to shrink, the scaling of SiO2 gate dielectrics is reaching its critical limit of only a few atomic layers thick. This scale causes a rise in gate current, degradation in performance, and an increase in power dissipation. Many years of research and development has shown that one valid way to solve these problems is by replacing conventional SiO2 gate dielectric with high-k dielectric, especially with HfO2 gate dielectric. HfO2 gate dielectrics have been implemented at the 32 nm technology node and smaller, and Intel has been using high-k/metal gate since their 45 nm node. Furthermore, high-k gate dielectric can be integrated with strained-silicon, silicon on insulator (SOI), and architectures to improve device characteristics. High-k dielectric can also be combined with thin-film transistor devices and memory devices. However, with the introduction of HfO2 dielectrics, many measurement techniques must be refined, especially charge pumping techniques. For instance, in conventional SiO2-based dielectrics, with a decrease in frequency, Icp decreases since carriers have enough time to discharge from interface shallow traps. Conversely, in Hf-based dielectrics a decrease in frequency leads to an increase in Icp since carriers have enough time to tunnel into high-k bulk traps. Charge pumping techniques play an important role in inspection of defects. This study mainly focuses on high-k bulk shallow traps measured by the charge pumping technique at different falling and base level times for HfO2 dielectric n-MOSFETs. To further investigate the behavior of these additional traps contributing to charge pumping current, devices with different interlayer thicknesses and different N concentrations in the TiN1−x metal gate are compared.

II. EXPERIMENTAL PROCEDURES

The HfO2/metal gate n-MOSFETs used in this study were fabricated with a gate first process flow. First, a high quality 1 nm or 3 nm thick thermal oxide was grown as an interfacial layer. Second, 3 nm of HfO2 dielectrics were sequentially deposited by atomic layer deposition. Third, 10 nm-thick TiN metal gate with varying N concentrations were deposited by radio frequency physical vapor deposition because metal gates can eliminate gate depletion and resist remote phonon scattering. Next, poly-Si was deposited as a low resistance gate electrode. Finally, the dopant activation was performed at 1025 °C. The n-MOSFETs were measured by the charge pumping technique with different duty...
ratios at different temperatures. A pulse train with low-voltage of $-0.6 \text{ V}$, high-voltage from $0 \text{ V}$ to $1.8 \text{ V}$, frequency of $200 \text{ kHz}$, and $t_{\text{rising time}} = t_{\text{falling time}} = 100 \text{ ns}$ was applied on the gate terminal. $I_{\text{g}}V_{\text{g}}$ transfer curves were measured with the source, drain, and body terminals all grounded, with $V_{\text{g}}$ ranging from $0 \text{ V}$ to $1.8 \text{ V}$. Then through body floating (BF), source/drain floating (SDF), and source-/drain/body all grounded (SDB) process, the current path and carrier polarity were confirmed. Next, the $I_{\text{g}}V_{\text{g}}$ curve was fitted by Frenkel-Poole current and tunneling current. Then devices of different interlayer thicknesses and different $\text{TixN}_{1-x}$ metal gate N concentrations were measured by charge pumping technique at $60\%$ and $98\%$ duty ratios. For devices with different interlayer thicknesses, a pulse train with low-voltage of $-0.8 \text{ V}$, high-voltage from $0 \text{ V}$ to $1.8 \text{ V}$, frequency of $200 \text{ kHz}$, and $t_{\text{rising time}} = t_{\text{falling time}} = 100 \text{ ns}$ was applied on the gate terminal. For devices with different N concentrations of $\text{TixN}_{1-x}$, a pulse train with low-voltage of $-0.8 \text{ V}$, high-voltage from $0 \text{ V}$ to $1.8 \text{ V}$, frequency of $200 \text{ kHz}$, $t_{\text{rising time}} = 100 \text{ ns}$, and $t_{\text{falling time}} = 500 \text{ ns}$ was applied on the gate terminal. Evidence showed that extra contribution of $I_{\text{cp}}$ traps are in high-k bulk. Finally, to study the influence of falling time on high-k bulk traps measured by charge pumping technique, the other n-MOSFETs were measured by the charge pumping technique with different $t_{\text{falling time}}$ and different $t_{\text{base level}}$. A pulse train with low-voltage of $-0.8 \text{ V}$, high-voltage from $0 \text{ V}$ to $1.71 \text{ V}$, $t_{\text{rising time}}$ of $100 \text{ ns}$, $t_{\text{high level}}$ of $2.5 \mu\text{s}$, $t_{\text{base level}}$ from $0 \text{ s}$ to $3 \mu\text{s}$, and $t_{\text{falling time}}$ from $20 \text{ s}$ to $5 \mu\text{s}$ was applied on the gate terminal. All experimental curves were measured using an Agilent B1500 semiconductor parameter analyzer and a Cascade M1500 probe station.

III. RESULTS AND DISCUSSION

Figure 1 shows the $N_{\text{T}}V_{\text{high level}}$ characteristic curves at different duty ratios. $N_{\text{T}}$ is the number of traps ($N_{\text{T}} = I_{\text{cp}}(qA)/I_{\text{cyc}}$) and duty ratio $= \left( t_{\text{rising time}} + t_{\text{high level}} \right)/t_{\text{cycle}}$. Clearly, $N_{\text{T}}V_{\text{high level}}$ characteristic curves remain unchanged with an increase in duty ratio when $V_{\text{high level}} < 1.2 \text{ V}$. This implies that interface traps detected by the charge pumping technique are not dependent on $t_{\text{base level}}$. This is because the time for electrons in the interface traps to recombine with holes is very short since hole density is very large in the accumulation area ($\tau = 1/p_{\sigma}V_{\text{th}}$). Hence, the numbers of interface traps measured by $I_{\text{cp}}$ are not sensitive to duty ratio. On the contrary, $N_{\text{T}}$ decreases with a rise in duty ratio when $V_{\text{high level}} > 1.2 \text{ V}$. Furthermore, $N_{\text{T}}$ measures only interface traps with a duty ratio value of $98\%$ ($t_{\text{base level}} = 0 \text{ s}$). In other words, extra contribution of $I_{\text{cp}}$, traps almost disappears. The detrapping time ($t_{\text{base level}}$) of electron dominates the value of $N_{\text{T}}$ such that $N_{\text{T}}$ becomes smaller with a decrease in detrapping time. This demonstrates that electrons need time to discharge. Thus, it is necessary to know the relationship between $N_{\text{T}}$ and the detrapping time ($t_{\text{base level}}$) for $V_{\text{high level}} > 1.2 \text{ V}$. The inset of Fig. 1 shows body current-$V_{\text{high level}}$ ($I_{\text{cp}}$) and body current-$V_{\text{g}}$ ($I_{\text{DC}}$) curves with source and drain all grounded. $I_{\text{cp}}$ and $I_{\text{DC}}$ body currents are measured when AC and DC gate voltage are applied. It can be observed that $I_{\text{DC}}$ is much smaller than $I_{\text{cp}}$. In addition, $N_{\text{T}}$ is dependent on the detrapping time. Hence, these results mean that $N_{\text{T}}$ measured by the charge pumping technique is not caused by gate leakage current, but rather high-k bulk traps that have been detected, as shown in the energy band diagram of Fig. 3. Figure 2 shows the $N_{\text{T}}V_{\text{high level}}$ characteristic curves at different $t_{\text{base level}}$. A pulse train with low-voltage of $-0.8 \text{ V}$, high-voltage from $0 \text{ V}$ to $1.7 \text{ V}$, $t_{\text{base level}}$ of $2.5 \mu\text{s}$, $t_{\text{high level}}$ of $100 \text{ ns}$, $t_{\text{falling time}}$ of $100 \text{ ns}$, and $t_{\text{base level}}$ from $0 \text{ s}$ to $3 \mu\text{s}$ was applied on the gate terminal. Obviously, $N_{\text{T}}$ measured at the body terminal by charge pumping measurement is similar to that when measured at source/drain terminal when $V_{\text{high level}} < 1.2 \text{ V}$ since this current is generated by recombination of electrons and holes in the interface traps. When $V_{\text{high level}} > 1.2 \text{ V}$, however, $N_{\text{T}}$ measured at the body terminal is much smaller than when measured at source/drain terminal. In addition, $N_{\text{T}}$ measured at source/drain terminal is independent of $t_{\text{base level}}$ because this current is gate leakage current from gate to source/drain whereas $N_{\text{T}}$ measured at the body terminal is dependent on $t_{\text{base level}}$. Thus, Figure 2 confirms that $N_{\text{T}}$ measured through the body terminal is not an artifact related to gate leakage.
where $e_p$ is the escape probability and $\tau_p$ is the average escape time. Thus, slope is indicated by $e_p$ or $1/\tau_p$ with $e_p$ not dependent on temperature. Hence, $e_p$ may be the tunneling probability in large-area device. The average value of the slope at different temperatures ($m_{\text{average}}$) is $1.53 \times 10^5$, and $\tau_{p,\text{average}}$ is $6.52 \times 10^{-7}$ s. Now the value of tunneling distance can be determined by using $\tau_{p,\text{average}}$ and can verify that the traps are actually in the high-k bulk. The relationship between tunneling time and distance can be approximated by

$$t = \tau_0 \exp \left( \frac{x_e}{s} \right),$$

where $x_e$ is an electron tunneling characteristic time, $s_e$ is electron effective mass for SiO$_2$, and $q\phi_0$ is the effective tunneling barrier height. However, because electrons are tunneling through two layers, SiO$_2$ and HfO$_2$, this equation can be described by

$$t = \tau_0 \exp \left( \frac{x_{\text{SiO}_2}}{s_{\text{SiO}_2}} + x_{\text{HfO}_2}/s_{\text{HfO}_2} \right),$$

where $x_{\text{SiO}_2} = 2(2m_e^0q\phi_{0,\text{SiO}_2}/h^2)^{0.5}$, $x_{\text{HfO}_2} = 2(2m_e^0q\phi_{0,\text{HfO}_2}/h^2)^{0.5}$, $\alpha = 2.4$ is the distance from traps to interlayer between SiO$_2$ and HfO$_2$; $m_e^0$, $q\phi_{0,\text{SiO}_2}$ and $q\phi_{0,\text{HfO}_2}$ are effective tunneling barrier heights in SiO$_2$ and HfO$_2$, respectively. Thus, only one parameter ($\phi_{0,\text{HfO}_2}$) is unknown.

The inset in Figure 4(a) shows $I_g-V_g$ characteristic curves with BF, SDF, and SDB for distinguishing gate current at 30°C. Clearly, the $I_g-V_g$ characteristic curve in BF is similar to that in SDB, and the $I_g-V_g$ characteristic curve in SDF is much smaller than either. These results indicate that electrons transfer from source/drain to the gate, rather than holes transferring from gate to body. Section A of Fig. 4(b) indicates the tunneling current detailed in Fig. 4(b), from $V_g = 0.35$ V to $V_g = 0.75$ V, while section B is Frenkel-Poole current, shown in detail in Fig. 4(c), from $V_g = 1$ V to $V_g = 1.8$ V. $\phi_B = 0.49$ eV can be obtained by fitting the Frenkel-Poole mechanism in the inset in Fig. 4(c). When $V_{\text{high level}} < 1.2$ V, $I_g$ is interface traps ($N_{it}$) only. On the contrary, when $V_{\text{high level}} > 1.2$ V, $I_g$ is both high-k bulk shallow traps ($N_{\text{hsh}}$) and $N_{it}$. A comparison of Fig. 1 with Fig. 4(a) shows that $N_T$ is only $N_{it}$ when gate current is tunneling current and Frenkel-Poole current is very small. Conversely, $N_T$ is both $N_{it}$ and $N_{\text{hsh}}$ when gate current is Frenkel-Poole current. This indicates that bulk traps charging electrons via the Frenkel-Poole mechanism and bulk traps discharging electrons at $V_{\text{base level}}$ in charge pumping measurement may be the same. In order to confirm this theory, $\phi_B = \phi_{0,\text{HfO}_2} = 0.49$ eV is substituted into formula (3), where $m_e^0$, $m_e^0$, $m_e^0$ and $0.35m_0$, $\alpha = 6.6 \times 10^{-14}$, $q\phi_{0,\text{SiO}_2}$ is 10 Å, and $q\phi_{0,\text{SiO}_2} = 1.6$ eV + $\phi_{0,\text{HfO}_2}$. Finally, it can be determined that $d_{\text{HfO}_2,\text{trap}}$ is 13 Å. This is a reasonable value. While $V_g$ transits from $V_{\text{high level}}$ to $V_{\text{base level}}$, electrons in the high-k bulk shallow traps near the gate and substrate discharge to the gate and source/drain, respectively. Hence, only traps in the middle of the high-k bulk shallow traps can be measured by the charge pumping technique. In addition, when $I_{cp}$ is measured at a duty ratio of 98%, at $t_{\text{base level}} = 0$ s, electrons in the middle of the high-k bulk shallow traps have no time to tunnel to the substrate in the accumulation area. Thus, only interface traps are measured by $I_{kp}$ at a duty ratio value of 98%.
30 Å-thick interlayer devices, where practically none exists, as shown in Fig. 5(b). This phenomenon means that electrons in the channel are not able to tunnel through the interlayer to high-k bulk shallow traps due to its thickness, leading to high-k bulk shallow traps not charging electrons at accumulation and inversion areas in the charge pumping measurement. Hence, high-k bulk traps cannot be measured for 30 Å-interlayer devices when $V_{\text{high level}} - V_t > 0.45$ V. Figure 5(c) shows the $N_T(V_{\text{high level}} - V_t)$ characteristic curves at 60% and 98% duty ratios for different of $T_i N_{1-x}$ metal gate N concentrations. Obviously, with an increase in N concentration, two things occur, i.e., interface traps increase (as indicated by the large blue arrow), and the value of $N_T$ (duty ratio = 60%)–$N_T$ (duty ratio = 98%) becomes smaller when $V_{\text{high level}} - V_t > 0.45$ V (as indicated by the blue, green, and red arrows). A previous paper shows that nitridation processes cause N to diffuse to the interlayer and Si substrate interface, causing to a rise in interface traps, a reduction in mobility and an increase in Negative-bias temperature instability (NBTI). Thus, interface traps increase due to N diffusion to the interlayer. Other previous literature has shown that N can passivate high-k bulk shallow traps, leading to a rise in effective barrier height in the Frenkel-Poole mechanism and a decrease in gate current. Gate current indeed reduces with an increase in

![Figure 4](image-url)  
**FIG. 4.** (a) $\log(I_g) - V_g$ characteristic curves with SDB. Inset shows $I_g - V_g$ characteristic curves with BF, SDF, and SDB. (b) Gate current in section A is fitted by tunneling model. (c) Gate current in section B is fitted by Frenkel-Poole model.

![Figure 5](image-url)  
**FIG. 5.** (a) $N_T(V_{\text{high level}} - V_t)$ characteristic curves with 60% and 98% duty ratio for 10 Å and 30 Å interlayer devices. (b) $I_g(V_g - V_t)$ in 10 Å and 30 Å interlayer devices. Inset shows log $I_g(V_g - V_t)$ for different $N_T(V_{\text{high level}} - V_t)$. (c) $N_T(V_{\text{high level}} - V_t)$ characteristic curves at 60% and 98% duty ratio in different N concentrations for $T_i N_{1-x}$ metal gates. (d) $I_g(V_g - V_t)$ for different N concentration $T_i N_{1-x}$ metal gate devices. Inset shows log $I_g(V_g - V_t)$ for different N concentration $T_i N_{1-x}$ metal gate devices.
N concentration of the TiN$_{1-x}$ metal gate, as shown in Fig. 5(d). Therefore, high-k bulk shallow traps are passivated by N, causing the high-k bulk traps measured by charge pumping measurement to become smaller. These above results show that extra contribution of $I_{cp}$ traps measured by $I_{cp}$ technique are actually high-k bulk shallow traps.

Next, the influence of falling time on high-k bulk traps measured by $I_{cp}$ is discussed. Figure 6(a) shows the $N_{T}$-V$_{high}$ level characteristic curves for different $t_{falling}$ time and $t_{base}$ level. $N_{T}$ is the number of traps. Obviously, three main phenomena can be observed. First, with an increase in falling time, $N_{T}$ decreases when V$_{high}$ level < 1.2 V (as indicated by the large blue arrow). In this condition, $N_{T}$ includes both $N_{t}$ and $N_{cp,gc}$ caused from the “geometrical component” of $I_{cp}$. With an increase in $t_{falling}$ time, those channel electrons have enough time to diffuse back to source and drain (S/D) rather than drift to the body in the accumulation area, leading to a decrease in $N_{T}$. Second, with fixed $t_{falling}$ time and an increase in $t_{base}$ level, $N_{T}$ increases when V$_{high}$ level > 1.2 V (as indicated by the large red arrow). This is because electrons trapped in high-k bulk shallow traps need time to tunnel to the body in the accumulation area, leading to a decrease in $N_{T}$. Next, the influence of falling time on high-k bulk traps measured by $I_{cp}$ is discussed. Figure 6(a) shows the $N_{T}$-V$_{high}$ level characteristic curves for different $t_{falling}$ time and $t_{base}$ level. $N_{T}$ is the number of traps. Obviously, three main phenomena can be observed. First, with an increase in falling time, $N_{T}$ decreases when V$_{high}$ level < 1.2 V (as indicated by the large blue arrow). In this condition, $N_{T}$ includes both $N_{t}$ and $N_{cp,gc}$ caused from the “geometrical component” of $I_{cp}$. With an increase in $t_{falling}$ time, those channel electrons have enough time to diffuse back to source and drain (S/D) rather than drift to the body in the accumulation area, leading to a decrease in $N_{T}$. Second, with fixed $t_{falling}$ time and an increase in $t_{base}$ level, $N_{T}$ increases when V$_{high}$ level > 1.2 V (as indicated by the large red arrow). This is because electrons trapped in high-k bulk shallow traps need time to tunnel to the body in the accumulation area, leading to a decrease in $N_{T}$. Third, with fixed $t_{falling}$ time and an increase in $t_{base}$ level, $N_{T}$ increases when V$_{high}$ level > 1.2 V (as indicated by the red and green arrows). This is because electrons which are still charged in the high-k bulk traps when $t_{base}$ level is the time for electrons to discharge from traps. Clearly, fitting these curves can be accomplished with straight lines even for different $t_{falling}$ time. In addition, slopes are also similar at these falling times and $V_{f}$ is the tunneling probability in the previous result. From formula (3), the distance of high-k bulk shallow traps from the interlayer boundary (HfO$_{2}$/SiO$_{2}$) can be computed. It can be obtained that $d_{HfO_{2,trap}}$ is about 15 Å for different $t_{falling}$ time. However, with an increase in $t_{falling}$ time, the slopes remain the same while the intercepts decrease, indicating that the trap distances are the same. The intercept represents $\Delta Q(t_{base level}=0\ s)$, the number of electrons which are still charged in the high-k bulk traps when $t_{base level}=0\ s$. Thus, with an increase in $t_{falling}$ time, electrons...
still charged in the high-k bulk traps decrease. The lost electrons should go to body terminals, but in fact do not. This is because electrons trapped in the high-k bulk discharge to the channel and then to S/D during tfalling time. This current cannot be measured by the charge pumping technique. Thus, at tbase level, Nhkst measured by Icp represents leftover electrons in high-k bulk. This theory is similar to the mechanism of the “geometrical component” of Icp (Ncp,gc).

Fig. 8(a) shows an NT-tbase level-tfalling time characteristic surface diagram at Vhigh level = 0.81 V while Fig. 8(b) shows a ΔNT-tbase level-tfalling time characteristic surface diagram at Vhigh level = 1.71 V. NT includes Nit and Ncp,gc. However, ΔNT represents only Nhkst (NT (tbase level) - NT (tbase level = 0 s)). Obviously, with an increase in tfalling time, NT and ΔNT both decrease due to more channel electrons and electrons trapped in high-k bulk shallow traps flowing to the S/D rather than to the body. In addition, NT is independent of tbase level since channel electrons drifting to body do so quickly. On the contrary, with an increase in tbase level, ΔNT increases since electrons trapped in high-k bulk shallow traps need time to tunnel to the body in the accumulation area. In this way, Ncp,gc and Nhkst can be easily distinguished.

Combining these results above, the energy band diagram of the model for charge pumping measurement can be determined, as shown in Fig. 9. When Vhigh level < 1.2 V, gate current is tunneling-path dominated, leading to high-k bulk shallow traps not charging electrons. Electrons are in interface traps and the channel, as shown in Fig. 9(a). Subsequently, electrons recombine with holes in the interface traps at Vbase level or drift from the channel to the body, as shown in Fig. 9(b). Thus, Icp detects Nit and Ncp,gc. On the contrary, when Vhigh level > 1.2 V, the gate current is dominated by the Frenkel-Poole mechanism, causing high-k bulk shallow traps to charge electrons. Therefore, electrons are in interface traps, high-k bulk shallow traps, and the channel, as shown in Fig. 9(c). Subsequently, three currents exist at Vbase level in Fig. 9(d). Electrons in the interface traps recombine with holes. Electrons from high-k bulk shallow traps flow to the body, as do electrons in the channel. Therefore, Icp measures Nit, Nhkst, and Nch. In addition, electrons trapped in high-k bulk shallow traps flow to the body, as do electrons in the channel. Therefore, Icp measures Nit, Nhkst, and Nch. In addition, electrons trapped in high-k bulk shallow traps first discharge to S/D at tfalling time. This current cannot be measured by Icp. Therefore, Nhkst (ΔNT) measured by Icp at tbase level is the electrons remaining in the high-k bulk.

IV. CONCLUSION

In summary, NT-Vhigh level characteristic curves are nearly the same in value for Vhigh level < 1.2 V with a rise in duty ratio. However, NT decreases with an increase in duty ratio for Vhigh level > 1.2 V. This indicates that the electron detrapping time dominates the value of NT. Comparison of Icp and IDC results show that extra contribution of Icp traps is not gate leakage current. Next, from curve fitting, the values of ep obtained by the slope of ln (NT (tbase level = 2.4 μs) - NT (tbase level)) are found to be independent of temperature. Hence, electrons discharge from high-k bulk shallow traps via the tunneling mechanism. Then, the distance of traps can be acquired by the equation t = τp exp(ϕe,SiO2 ΔSiO2 + ϕe,HfO2 ΔHfO2) with ϕ0,HfO2 = 0.49 eV and ϕ0,HfO2
This current cannot be measured by $I_{cp}$. This study shows that electrons still charged in the high-k bulk traps decrease when $t_{base}$ level decreases. Therefore, through fitting $\ln(N_T(t_{base} level))-t_{base}$ level for different falling times, $N_{cp,gc}$ and $N_{hkst}$ that indicate that the longer the $t_{falling}$ time, the less $N_{cp,gc}$ and $N_{hkst}$ that are obtained. When $V_{high}$ level $<1.2$ V, the energy band diagram of high-k/metal gate MOSFETs with charge pumping measurement (a) for $V_{high}$ level and (b) for $V_{base}$ level, When $V_{high}$ level $<1.2$ V. The energy band diagram of high-k/metal gate MOSFETs with charge pumping measurement (c) for $V_{high}$ level and (d) for $V_{base}$ level, while $V_{high}$ level $>1.2$ V.

FIG. 9. The energy band diagram of high-k/metal gate MOSFETs with charge pumping measurement (a) for $V_{high}$ level and (b) for $V_{base}$ level. When $V_{high}$ level $<1.2$ V. The energy band diagram of high-k/metal gate MOSFETs with charge pumping measurement (c) for $V_{high}$ level and (d) for $V_{base}$ level, while $V_{high}$ level $>1.2$ V.

obtained from fitting the gate current with the Frenkel-Poole mechanism. From this, $d_{HfO_2,trap}$ can be calculated to be 13 Å, a reasonable value. This result is proof that extra contribution of $I_{cp}$ traps is actually located in the high-k shallow bulk. In addition, comparison of different thickness interlayer devices and different N concentrations in the Ti$_x$N$_{1-x}$ metal gate show that extra contribution of $I_{cp}$ traps can be measured only when high-k bulk traps charge electrons in the gate current. $N_{cp,gc}$ and $N_{hkst}$ ($\Delta N_T$) decrease with an increase in $t_{falling}$ time since more channel electrons and electrons trapped in high-k bulk shallow traps flow to the S/D rather than to the body. Those currents cannot be measured by $I_{cp}$. Furthermore, through fitting $\ln(N_T(t_{base} level)$ $= 3 \mu s)-N_T(t_{base} level)$ for different falling times and comparing the trap distance by the equation $t = t_0 \exp(-\frac{\phi}{\mu E_0} + \frac{\phi_{HfO_2} d_{HfO_2,trap}}{\mu E_0})$, the results show that $d_{HfO_2,trap}$ is about 15 Å for different falling times, which means that the trap distances are the same. In addition, the intercept decreases with an increase in $t_{falling}$ time. This indicates that electrons still charged in the high-k bulk traps decrease when $t_{base} level = 0$ s since electrons trapped in high-k bulk shallow traps discharge to S/D during $t_{falling}$ time. This current cannot be measured by $I_{cp}$. This study shows that the longer the $t_{falling}$ time, the less $N_{cp,gc}$ and $N_{hkst}$ that are observed. When $t_{base} level = 0$ s, $N_{hkst}$ disappears. Thus, only $N_{cp}$ is obtained for a more correct value.

ACKNOWLEDGMENTS

Part of this work was performed at United Microelectronics Corporation, at National Science Council Core Facilities Laboratory for Nano-Science and Nanotechnology in Kaohsiung-Pingtung area, NSYSU Center for Nanoscience and Nanotechnology. The work was supported by the National Science Council of the Republic of China under Contract No. NSC-102-2120-M-110-001.


