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Experiment Study on Random Telegraph Signal Noise in (110) pMOSFETS with 1nm EOT

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Abstract

In this work, random telegraph signal (RTS) noise are investigated in (110)-orientated pFETs with 1nm thick SiO_2 and various channel doping concentrations, with main focus on properties of traps that locate besides the interface of SiO_2 and the substrate. Carrier trapping time constants, couplings and carrier trapping induced channel current fluctuations are systematically measured for comprehensive understandings. On the one side, although degradations of drain current fluctuations and threshold voltage shifts are observed in pFETs with stronger channel doping, this cannot be well explained by trap number differences that used to explain RTS noise in nFETs. On the other side, in pFETs with thinner SiO_2, unexpected stronger time constant couplings are observed as well as faster time constants. Possible underlying mechanisms are also discussed.

Introduction

Along with device scaling techniques, device area turns to be smaller and smaller, while this brings many challenges on reliabilities of devices and circuits. As an example, random telegraph signal (RTS) noise turns to be a big problem because one single trap can trigger larger current fluctuations in smaller devices. Considering its serious impacts on logic circuits [1] and memories [2], studies on RTS noise have been intensively reported recently. However, understandings on RTS noise related traps are still not enough due to large variations and trap diversities. Though RTS noise in devices with thick dielectrics has been investigated in previous work [3-5], it is still unclear whether we are talking about traps in the dielectric or traps just besides the interface, while this is important for our understandings on RTS noise mechanisms.

Systematical studies on RTS noise in pFETs with 1nm thick SiO_2 are done in this work, aiming at understandings on impacts and properties of traps that locate just besides the interface between the substrate and gate dielectrics. On the one hand, (110) pFETs are characterized because RTS noise in (110) pFETs is much more serious than that in (100) pFETs, and this could be a key problem for 3D device with multiple surface orientations. On the one hand, RTS traps induced current fluctuations ($\Delta I_d/I_d$) and threshold voltage shifts (ΔV_{th}) are compared in pFETs with various channel doping concentrations (N_{ch}). To understand trapping and de-trapping processes of RTS traps that locate just besides the interface, time constants and couplings to the applied gate bias (V_g) of each single trap are also summarized and discussed.

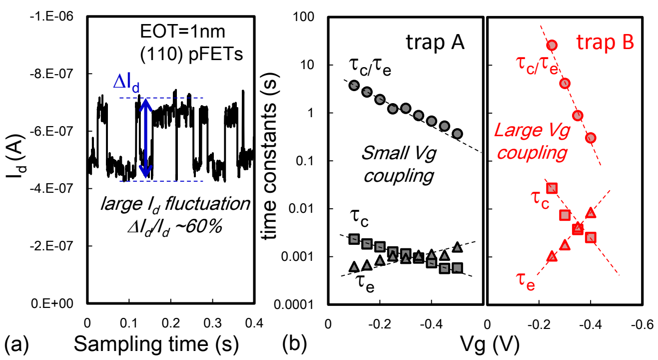


Fig.1 (a) Observation of large I_d fluctuations in pFETs with 1 nm SiO_2; (b) time constant (τ_c, τ_e, τ_c/τ_e) dependences on V_g, here two traps with large and small V_g couplings are illustrated.

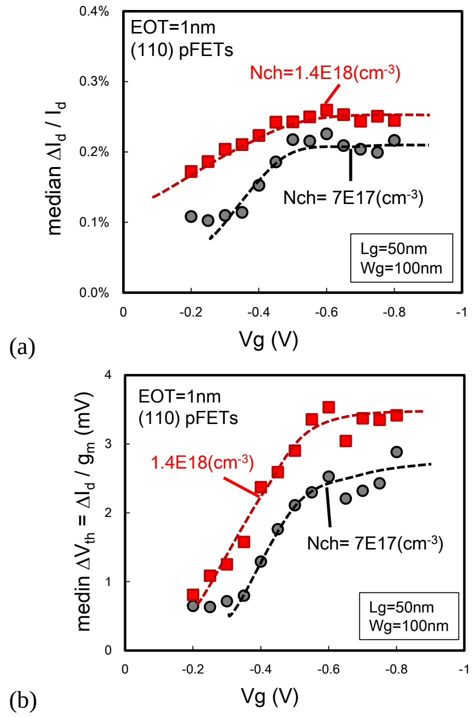


Fig.2 Measured results of (a) RTS induced $\Delta I_d/I_d$ versus V_g and (b) ΔV_{th} versus V_g, in (110) pFETs. Dotted lines are used for eye guide.

Experimental Results and Discussions

RTS noise is studied in (110) pFETs with 1nm SiO_2 gate oxide and various channel doping concentrations, ranging from 7E17cm^{-3} to 1.4E18cm^{-3}, by using Agilent B1530 RTS noise characterization system. Though SiO_2 is ultrathin, large current fluctuations $\Delta I_d/I_d$ can be clearly observed (Fig. 1(a)). In Fig. 1(b), two different traps with large V_g couplings and small V_g couplings are illustrated. For multiple traps, histogram graph of drain currents or time lag plot (PLT) [6] can be utilized to estimate trap numbers, as well as $\Delta I_d/I_d$ and ΔV_{th}. For a single trap, time constants, such as time to capture (τ_c), time to emission (τ_e), and time constant couplings on the applied gate bias V_g ($\alpha_{\tau e}$, $\alpha_{\tau c}$, $\alpha_{\tau e/\tau c}$), can be estimated.

Firstly, both single trap and multiple traps are evaluated for statistical analysis on RTS noise. Here, ΔV_{th} is estimated by using $\Delta V_{th}=\Delta I_d(V_g)/g_m(V_g)$, with measured g_m from I_d-V_g curves and ΔI_d from I_d sampling. As shown in Fig. 2, similar to our previous work in nFETs and pFETs with 2nm SiO_2 [4, 5], large degradations of both $\Delta I_d/I_d$ and ΔV_{th} can be observed in pFETs with larger N_{ch}, especially in the sub-threshold voltage region at low V_g. Interesting thing is that, as observed in [5], $\Delta I_d/I_d$ turns to be larger at higher V_g in pFETs, while it has weak dependences on V_g in nFETs. Also, ΔV_{th} saturation region at higher V_g cannot be found in nFETs [4] but can be observed in pFETs. Then, from estimated RTS trap densities shown in Fig.3, it is found that N_{ch} impacts on RTS traps observation are small. In other words, number fluctuation model that used to explain RTS noise in nFETs [4] cannot be used in pFETs, and the mobility fluctuation model could be the dominant mechanism for observed large RTS noise degradations in pFETs with heavily doped channel. With a hypothesis that $\Delta\mu_{eff}$ is identical, carrier mobility (μ_{eff}) degradations in heavily doped pFETs could result in enhanced mobility fluctuations ($\Delta\mu_{eff}/\mu_{eff}$) [8].

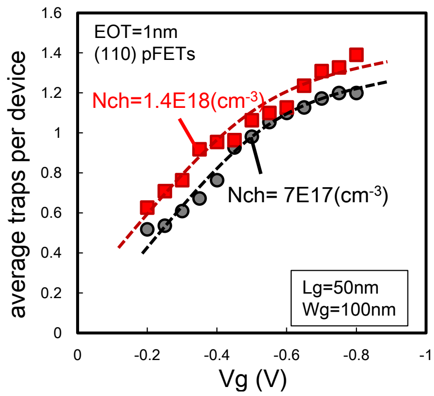
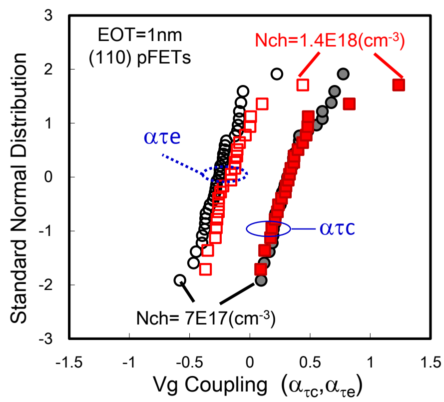
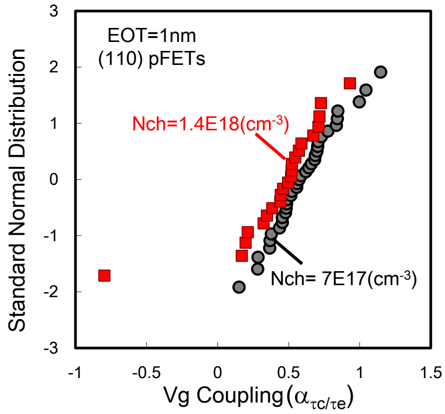


Fig.3 V_g dependences of average trap numbers per device, which are estimated from I_d fluctuation levels [5, 6].



(a)



(b)

Fig.4 Channel doping dose dependences of (a) time constant τ_0, and (b) time constant couplings to V_g, $\alpha_{\tau c}$ and $\alpha_{\tau e}$.

For understandings on mechanisms of RTS related traps, time constant couplings of $\alpha_{\tau c}$, $\alpha_{\tau e}$ and $\alpha_{\tau c/\tau e}$ are summarized in Fig.4, by measuring V_g dependence of τ_c and τ_e of each single trap. On the one side, identical distributions of $\alpha_{\tau e}(\alpha_{\tau c})$ in pFETs with various channel doping are observed, which is similar to our previous work in (110) and (100) pFETs with 2nm SiO_2 [4, 5], except enhanced $\alpha_{\tau c}$ in (100) pFETs with heavier channel doping. On the other side, it is found that $\alpha_{\tau c/\tau e}$ were not be enhanced by stronger channel doping, which is similar to 2nm SiO_2 pFETs but different from nFETs [5]. In other words, impacts of random dopant fluctuations (RDF) on $\alpha_{\tau c/\tau e}$ [9] in pFETs are kind of weak in comparison to that in nFETs. On the contrary, $\alpha_{\tau c/\tau e}$ turns to be smaller in pFETs with heavily doped channels. Actually, definitions of trap depth (X_T) and $\alpha_{\tau c/\tau e}$ are same [6], $\alpha_{\tau c/\tau e}$~X_T/T_{ox}. In the carrier transport channel, carriers in the inversion layer distribute in subbands with discrete energy levels and a distance from the interface. Supposing that z_{inv} is the average distance from the surface to electrons in the inversion layer, $\alpha_{\tau c/\tau e}$ expression should be $(X_T+z_{inv})/T_{ox}$, which can be modulated by different channel doping. Similarly, in Fig.5, faster τ_0 in heavily doped pFETs are observed, which could also come from different inversion carrier distributions if trap distributions are identical. Next, time constants and couplings in pFETs with different SiO_2 thickness are compared in Fig. 6. Faster τ_0 in thinner SiO_2 can be understood since observed traps are limited within 1nm depth from the interface. The interesting thing is that time constant couplings turn to be enhanced in thinner SiO_2. In traditional RTS noise model [6], V_g couplings should be suppressed if traps locate closer to the interface. Though further study is required to understand this, it might be related to the low trap activation energies (E_c) by taking the band-gap narrowing effects at Si/SiO_2 interface into account [7].

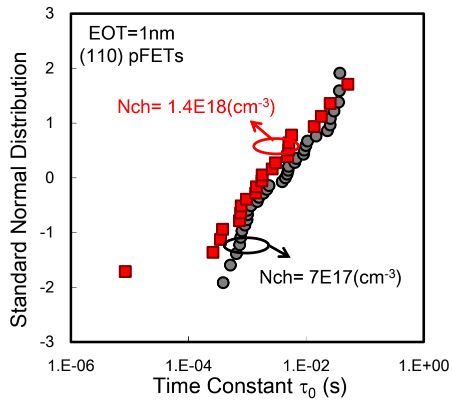


Fig.5 Distributions of time constant couplings $\alpha_{\tau c/\tau e}$, in devices with various channel doping dose N_{ch}.

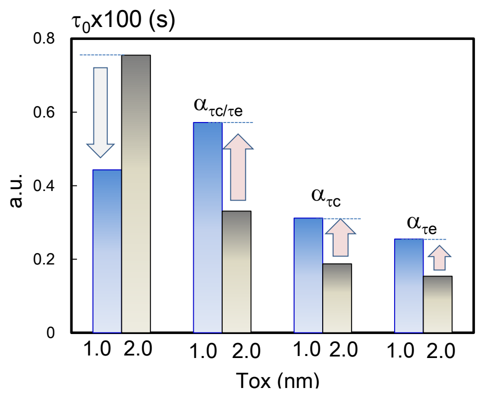


Fig.6 Comparisons between (110) pFETs of different SiO_2 thickness, a part of data in 2nm SiO_2 (110) pFETs is cited from ref. [7].

Conclusions

A systematically study on RTS noise in (110) pFETs with 1nm SiO_2 are described in this work. On the one side, it is observed that channel doping concentration does not largely affect observed RTS trap densities, time constants and couplings. On the other side, larger degradations of current fluctuations and threshold voltage shifts are still observed in heavily doped pFETs. With further discussions, it is believed that the mobility fluctuation model is adoptable in pFETs with ultrathin SiO_2. Also, in comparison to RTS noise in pFETs with thick SiO_2, unexpected stronger time constant couplings are observed together with faster time constants. Underlying mechanisms are discussed for understandings.

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Reference: [1] M. Gonthier *et al.*, IEDM 2011, p.183; [2] D. Kang *et al.*, VLSI2011, p.206; [3] H. Miki *et al.*, VLSI 2011, p.148; [4] J. Chen et al., SSDM2013, p.724; [5] J. Chen et al., VLSI2013, p.184; [6] T. Nagumo *et al.*, IEDM 2009, p.759; [7] J. Chen et al., to be presenated in VLSI2014; [8] K. K. Hung *et al.*, TED, 37(3), p.654; [9] C. M. Compagnoni *et al.* TED, 59(9), p.2459.