Understanding on Surface Orientation Impacts on Random Telegraph Signal Noise Related Carriers Trapping Time Constants and Current Fluctuations

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Abstract
Random telegraph signal (RTS) noise in (110)- and (100)-oriented nMOSFETs are studied systematically, with main focuses on surface orientation impacts on carrier trapping time constants and traps induced channel current fluctuations. On the one side, single trap’s RTS noise and multiple traps’ RTS noise are all evaluated to estimate current fluctuations ($\Delta I_d/I_d$) and threshold voltage shifts ($\Delta V_o$). It is observed that $\Delta I_d/I_d$ and $\Delta V_o$ degradations are much more serious in (110) nFETs. On the other side, couplings between time constants and applied gate biases are compared. Traps in (110) nFETs illustrate much stronger couplings than in (100) nFETs, which might related to various trap positions and inversion electron distributions. Correlations between current fluctuations and couplings are also discussed for further understandings.

Introduction
Along with development of scaling-down techniques, device structures are changed from traditional flat structures to three dimensional (3D) structures. Accordingly, in order to improve device performances with higher carrier mobility and steeper sub-threshold slopes, structure optimizations have been studied systematically [1]. Simultaneously, how to suppress reliability degradation in small area devices, like worse RTS noise, is also important. Studies on RTS noise have been continued for a long time and intensively reported in last few years because its serious impacts in scaling-down devices and circuits can not be ignored anymore, such as CMOS image sensors [2] and NAND flash memories [3]. Accordingly, finding acceptable balances between performances and reliabilities by optimizing structures is believed to be critical from now on.

It was used to be reported that performances in (110) nFETs are approaching to those in (100) nFETs as scaling down [4], while experiment work on RTS noise comparison between (110) and (100) devices are still limited [5]. In this work, impacts of surface orientations on RTS noise are systematically studied in both (100) nFETs and (110) nFETs, including trap time constants and carrier trapping induced fluctuations ($\Delta I_d/I_d$, $\Delta V_o$). On the one hand, it is found that couplings between time constants and gate biases are stronger in (110) nFETs; on the other hand, $\Delta I_d/I_d$ and $\Delta V_o$ degradations are much more serious in (110) FETs. Physical mechanisms on correlations between time constant couplings and fluctuation amplitudes are also discussed for further understandings.

Experimental Results and Discussions

A. RTS noise characterization methods
RTS noise are studied and compared in (110) nFETs and (100) nFETs with identical 2nm gate oxide, by using Agilent B1530 RTS noise characterization system. Channel doping concentration ($N_a$) ranges from 2E17cm$^{-2}$ to 2E18cm$^{-2}$. Typical RTS phenomena due to one and two traps are illustrated respectively in Fig. 1(a). For single trap, detail information of time constants can be extracted, such as time to capture ($\tau_c$), time to emission ($\tau_e$), and time constant couplings on the gate bias $V_g$ ($\alpha_{\tau_c}$, $\alpha_{\tau_e}$, $\alpha_{\tau_c\tau_e}$), as shown in Fig. 1(b). For multiple traps, though time constants of each trap are difficult to be extracted, histogram graph of drain currents or time lag plot (PLT) [6] can be utilized to estimate trap numbers as well as $\Delta I_d/\bar{I}_d$. So, surface orientation impacts on trap density can be qualitatively studied.

B. RTS noise in (100) and (110) nFETs
Firstly, single trap and multiple traps are both evaluated for statistic analysis on RTS noise impacts. Here, $\Delta V_o$ is estimated by using measured $g_m$ from $I_dV_g$ sweeping together with $\Delta I_d$ from $I_d$ sampling at a fixed $V_g$, via $\Delta V_o=\Delta I_d(V_g)/g_m(V_g)$. 

Fig.1 (a) Observation of typical RTS noise, single trap induced two $I_d$ levels and two traps induced four $I_d$ levels; (b) extracted time constants from single trap RTS noise, $\tau_c$, $\tau_e$, and $\tau_c/\tau_e$.

Fig.2 Measured properties of (a) $\Delta I_d/I_d$ versus $V_g$ and (b) $\Delta V_o$ versus $V_g$, in (100) nFETs and (110) nFETs. Dotted and solid lines are used as trend lines.
Here, $V_{th}$ is defined as the applied $V_g$ at $\tau_e$ (Fig. 1(b)). Generally, single trap induced $\Delta I/I$ fluctuations should be stronger at higher $V_g$ because of stronger screening effects. However, as increasing $V_g$, traps at higher energy levels will contribute to observed $\Delta I/I_{th}$ and average $\Delta I/I_{th}$ values show weak $V_g$ dependences. Similarly, considering $\Delta n_{th}$ degradations at higher $V_g$, $\Delta V_{th}$ dependences on $V_g$ (Fig. 2(b)) could be explained. Nevertheless, as shown in Fig. 2, it is found that $\Delta I/I_{th}$ and $\Delta V_{th}$ degradations in (110) devices are much more serious than those in (100) devices. Since noise power spectrum density (PSD) is in proportion to the trap density $N_{th}$ [7], larger fluctuations in (110) nFETs can be explained by worse $N_{th}$ in SiO$_2$ on (110) surface. As shown in Fig.3, it is found that RTS trap densities in (110) nFETs are almost twice as many as those in (100) nFETs.

Therefore, $\alpha_{\Delta n_{th}}$ should be expressed as $(X_e+Z_{inv})\tau_{tr}, Z_{inv}$ is the average distance from the surface to electrons. On the one side, $\alpha_{\Delta n_{th}}$ might be related to various trap positions in SiO$_2$ on (100) and surface [11]. On the other side, it is known that $Z_{inv}$ is inversely proportional to the effective mass $m_0$ of electrons perpendicular to the surface via $Z_{inv} \propto (m_0^{-1})^{1/3}$ [10]. $m_0$ in (100) surface is 0.918$m_0$ (m$_0$: free-electron mass) for the lowest subband while that in (110) surface is 0.315$m_0$. Deeper $Z_{inv}$ goes with lighter $m_0$, which means electron distributions in (110) surface are deeper from the surface (Fig. 5(b)). In simple words, deeper $Z_{inv}$ and possible farther $X_e$ could enhance $\alpha_{\Delta n_{th}}$.

More importantly, larger $\alpha_{\Delta n_{th}}$ in devices of higher channel doping are observed in both (100) nFETs and (110) nFETs, indicating that substrate dopant fluctuations (RDF) can also strengthen couplings. These agree with 3D simulation results [12], in which it is believed that electrostatics could be largely modulated by RDF. In other words, various $\alpha_{\Delta n_{th}}$ could also partly originate from different dopant profiles in (110) and (100) substrates. Furthermore, it was used to find that $\Delta I/I_{th}$ are correlated to coupling values $(\alpha_{\Delta n_{th}}/\alpha_{\Delta n_{th}})$ [8], as what we observed in (110) nFETs. Actually, $\Delta I/I_{th}$ can be explained by modulations on carrier distributions after carriers’ trapping. Larger $\Delta I/I_{th}$ degradation is possibly triggered by larger $\Delta n_{th}$, which can also enhance $\alpha_{\Delta n_{th}}$ because $Z_{inv}$ should be replaced with $Z_{inv}+\Delta V_{th}$. It should be noted that $\Delta V_{th}$ is not only determined by traps in the dielectrics, but also by RDF in the substrate. In addition, $\Delta V_{th}$ could possibly explain why correlations between trap positions and $\Delta V_{th}$ are difficult to be experimentally observed [5, 6].

**Conclusions**

RTS noise in both (100) and (110) nFETs are characterized and compared systematically. In comparison with (100) nFETs, stronger couplings of time constant to gate biases and larger current fluctuations are observed in (110) nFETs. Whereas, various inversion electron distributions and possible farther trap distributions are considered to be important reasons for larger couplings, while worse trap densities can contribute to larger $\Delta I/I_{th}$ degradations. Correlations between $\Delta I/I_{th}$ and couplings are also discussed for further understandings.

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**Reference:**