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Understandings 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)-orientated 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 (ΔV_{th}). It is observed that $\Delta I_d/I_d$ and ΔV_{th} 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

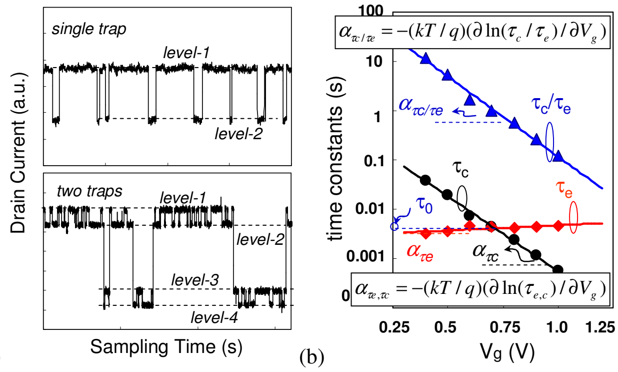
Along with development of scaling-down techniques, device structures are changed from traditional flat structures to three dimensional (3D) structures. Accordingly, in order to improve device performances with higher carrier mobility and steeper sub-threshold slopes, structure optimizations have been 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 ($\Delta I_d/I_d$, ΔV_{th}). 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 ΔV_{th} 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

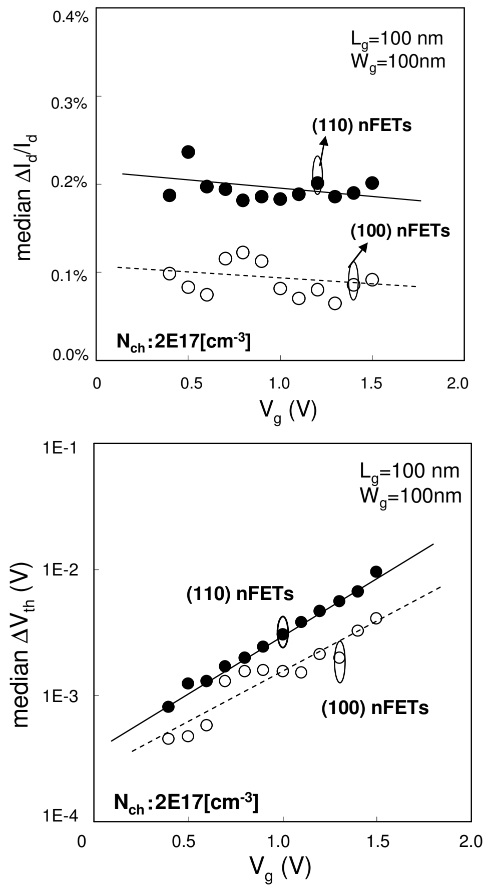
A. RTS noise characterization methods

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_{ch}) ranges from 2E17cm^{-3} to 2E18cm^{-3}. 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 (τ_c), time to emission (τ_e), and time constant couplings on the gate bias V_g ($\alpha_{\tau e}$, $\alpha_{\tau c}$, $\alpha_{\tau e/\tau c}$), 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 $\Delta I_d/I_d$. So, surface orientation impacts on trap density can be qualitatively studied.



(a) (b)

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, τ_c, τ_e and τ_c/τ_e.



(a) (b)

Fig.2 Measured properties of (a) $\Delta I_d/I_d$ versus V_g, and (b) ΔV_{th} versus V_g, in (100) nFETs and (110) nFETs. Dotted and solid lines are used as trend lines.

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, ΔV_{th} is estimated by using measured g_m from I_d-V_g sweeping together with ΔI_d from I_d sampling at a fixed V_{g0}, via $\Delta V_{th}=\Delta I_d(V_{g0})/g_m(V_{g0})$.

Here, V_{g0} is defined as the applied V_g at τ_0 (Fig. 1(b)). Generally, single trap induced $\Delta I_d/I_d$ fluctuations should be suppressed at higher V_g because of stronger screening effects. However, as increasing V_g, traps at higher energy levels will contribute to observed $\Delta I_d/I_d$, and average $\Delta I_d/I_d$ values show weak V_g dependences. Similarly, considering g_m degradations at higher V_g, ΔV_{th} dependences on V_g (Fig. 2(b)) could be explained. Nevertheless, as shown in Fig. 2, it is found that $\Delta I_d/I_d$ and ΔV_{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_{it} [7], larger fluctuations in (110) nFETs can be explained by worse N_{it} 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.

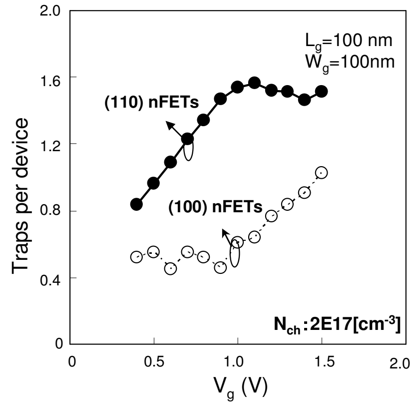


Fig.3 V_g dependences of average trap numbers per device, which are estimated from I_d fluctuation levels [5, 6].

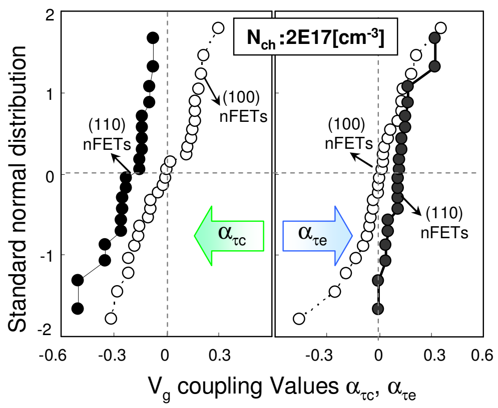
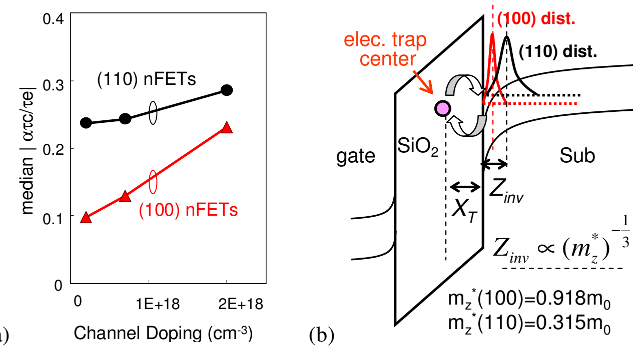


Fig.4 Channel doping dose dependences on time constant couplings to V_g, $\alpha_{\tau c}$ and $\alpha_{\tau e}$. In comparison to (100) nFETs, traps in (110) nFETs illustrates stronger couplings of τ_c and τ_e.

For more information, couplings of $\alpha_{\tau c}$ and $\alpha_{\tau e}$ are estimated and plotted in Fig.4. Similar to previous work in [8], positive $\alpha_{\tau c}$ are difficult to be observed in most cases, except in low channel doping (100) nFETs. Since positive $\alpha_{\tau c}$ likely belongs to traps that are closer to the upper interface and they trap/de-trap carriers from/into gate side [9], traps with positive $\alpha_{\tau c}$ might be easily screened by traps that locate closer to the lower interface of SiO_2/Si-sub. Nevertheless, in comparison to traps in (100) nFETs, traps in (110) nFETs show stronger couplings ($\alpha_{\tau e}$, $\alpha_{\tau c}$). Then, $\alpha_{\tau c/\tau e}$ in (110) nFETs and (100) nFETs are compared in Fig.5 (a). It is interesting to find that, $\alpha_{\tau c/\tau e}$ in (110) nFETs are obviously larger than that in (100) nFETs. In the classical model [6], trap position (X_T) and coupling are identical, $\alpha_{\tau c/\tau e}$~X_T/T_{ox}, by supposing carriers locate just at the surface. In fact, inversion carriers should be treated quantum-mechanically with discrete energy levels and distribute with a distance from the surface.

Therefore, $\alpha_{\tau c/\tau e}$ should be expressed as $(X_T+z_{inv})/T_{ox}$, z_{inv} is the average distance from the surface to electrons. On the one side, $\alpha_{\tau c/\tau e}$ might be related to various trap positions in SiO_2 on (100) and (110) surface [11]. On the other side, it is known that z_{inv} is inversely proportional to the effective mass m_z^* of electrons perpendicular to the surface via $z_{inv} \propto (m_z^*)^{-1/3}$ [10]. m_z^* in (100) surface is $0.918m_0$ (m_0: free-electron mass) for the lowest subband while that in (110) surface is $0.315m_0$. Deeper z_{inv} goes with lighter m_z^*, 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_T could enhance $\alpha_{\tau c/\tau e}$.

More importantly, larger $\alpha_{\tau c/\tau e}$ in devices of higher channel doping are observed in both (100) nFETs and (110) nFETs, indicating that substrate dopant fluctuations (RDF) can also strength 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 $\alpha_{\tau e/\tau c}$ could also partly originate from different dopant profiles in (110) and (100) substrates. Furthermore, it was used to find that $\Delta I_d/I_d$ are correlated to coupling values ($\alpha_{\tau e/\tau c}$) [8], as what we observed in (110) nFETs. Actually, $\Delta I_d/I_d$ can be explained by modulations on carrier distributions after carriers' trapping. Larger $\Delta I_d/I_d$ degradation is possibly triggered by larger Δz_{inv}, which can also enhance $\alpha_{\tau e/\tau c}$ because z_{inv} should be replaced with $z_{inv}+\Delta z_{inv}$. It should be noted that Δz_{inv} is not only determined by traps in the dielectrics, but also by RDF in the substrate. In addition, Δz_{inv} could possibly explain why correlations between trap positions and ΔV_{th} are difficult to be experimentally observed [5, 6].



(a) (b)

Fig.5 (a) Channel doping dose dependences on $\alpha_{\tau c/\tau e}$. In comparison to (100) nFETs, (110) nFETs show larger $\alpha_{\tau c/\tau e}$, which possibly originate from (b) z_{inv} differences between (110) nFETs and (100) nFETs.

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. Wherein, 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 $\Delta I_d/I_d$ degradations. Correlations between $\Delta I_d/I_d$ and couplings are also discussed for further understandings.

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Reference:

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