Accurate extraction of trap depth responsible for RTS noise in nano-MOSFETs

Ma Zhong-Fa(马中发)†, Zhang Peng(张 鹏), Wu Yong(吴 勇),
Li Wei-Hua(李伟华), Zhuang Yi-Qi(庄奕琪), and Du Lei(杜 磊)

School of Microelectronics, Xidian University, Xi'an 710071, *China*

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This paper presents an accurate analytical model of the random telegraph signal (RTS) noise time-constant ratio ($\bar{\tau}_c/\bar{\tau}_e$) for RTS noise in nano-MOSFETs, in which the Coulomb-blockade effect on trapping and detrapping processes was taken into account. Based on this new model, the depth of the trap responsible for RTS noise in a sample n-type nano-MOSFET is extracted. The results show that large errors will be introduced to the calculated trap depth when the Coulomb-blockade effect is neglected.

Keywords: trap, RTS noise, nano-MOSFETs
PACC: 7200J, 6740X, 7270, 0540

1. Introduction

The random telegraph signal (RTS) noise observed in the drain current of MOSFETs with channel areas smaller than 1 μm^2 was taken as a viable way of extracting the parameters of active traps in the gate oxide,[1–4] such as energy level E_T, depth into the oxide x_T with respect to the Si/SiO$_2$ interface and transverse location along channel length y_T, because the ratio of mean capture and emission time-constants (τ_c/τ_e) bears information on the trap energy level and changes with the bias conditons of the device. Figure 1 shows the energy diagram of an nMOSFET. Based on Shockley–Read–Hall (SRH) statistics,[2–4] the dependence of (τ_c/τ_e) on both the parameters of the trap and the bias conditions and device geometry can be expressed as

$$\ln\frac{\bar{\tau}_c}{\bar{\tau}_e} = -\frac{1}{kT}\Bigg[(E_{C_{ox}} - E_T) - (E_C - E_F) - \phi_0 + q\psi_s + q\frac{x_T}{T_{ox}}(V_{GS} - V_{FB} - \psi_s - \psi_p)\Bigg], \quad (1)$$

where $E_{C_{ox}}$ is the conduction band edge of the gate oxide, E_C is the conduction band edge of the silicon substrate, E_F is the Fermi level of the substrate, ϕ_0 is the difference between the electron affinities of Si and SiO$_2$, ψ_s is the surface potential of the channel, V_{FB} is the flat-band voltage, ψ_p is the band bending of gate poly-silicon due to depletion, T_{ox} is the oxide thickness, V_{GS} is the gate-source voltage, and q is the prime electron charge. From Eq. (1), we can obtain[3]

$$x_T = \frac{T_{ox}\left(\dfrac{kT}{q}\dfrac{\mathrm{d}\ln(\tau_c/\tau_e)}{\mathrm{d}V_{GS}} + \dfrac{\mathrm{d}\psi_s}{\mathrm{d}V_{GS}}\right)}{\left(\dfrac{\mathrm{d}\psi_p}{\mathrm{d}V_{GS}} + \dfrac{\mathrm{d}\psi_s}{\mathrm{d}V_{GS}} - 1\right)}, \quad (2)$$

where ($\bar{\tau}_c/\bar{\tau}_e$) is the ratio of mean capture and emission time of RTS noise at different gate biases.

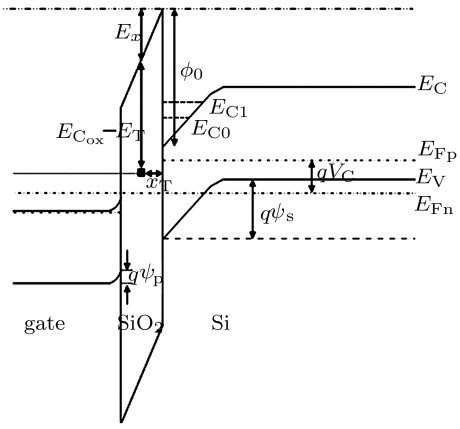


Fig. 1. A schematic energy band diagram of an nMOSFET perpendicular to the Si–SiO$_2$ interface.

Equation (2) shows good accuracy for submicron MOSFETs with thick gate oxide.[2–4] In nano-MOSFETs, because of the quantization effect, the effective band-gap of the inversion channel increases and the inversion carrier centroid shifts into deeper substrate; the Coulomb-blockade effect becomes more significant during the trapping and detrapping processes,

†Corresponding author. E-mail: mazhongfa@yahoo.com
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which leads to a severe deviation in the dependence of $\ln(\bar{\tau}_{\rm c}/\bar{\tau}_{\rm e})$ versus $V_{\rm GS}$ described by the conventional SRH model,[5−7] in which $\tau_{\rm c}$ is expected to increase linearly with $1/I_{\rm ds}$.[6]

In this work, an accurate model for $\ln(\bar{\tau}_{\rm c}/\bar{\tau}_{\rm e})$ of RTS noise in nano-MOSFETs is presented, in which the Coulomb-blockade effect during an inversion electron trapped by a neutral oxide trap is taken into account. Using this new model, the depth of the trap responsible for RTS noise in nano-MOSFETs is extracted.

2. $(\bar{\tau}_{\rm c}/\bar{\tau}_{\rm e})$ Model

Once the Coulomb-blockade effect was considered, the ratio of mean capture and emission time-constants can be written as[4,8,9]

$$\ln\frac{\bar{\tau}_{\rm c}}{\bar{\tau}_{\rm e}} = -\frac{1}{kT}\Big[(E_{\rm C_{ox}}-E_{\rm T})-(E_{\rm C0}-E_{\rm F})-\phi_0+q\psi_{\rm s} +q\frac{x_{\rm T}}{T_{\rm ox}}(V_{\rm GS}-V_{\rm FB}-\psi_{\rm s}-\psi_{\rm p})-\Delta E\Big], \quad (3)$$

where $E_{\rm C0}$ is the lowest subband in the conduction band of the inversion layer according to the quantization effect, Coulomb-energy ΔE is the energy needed to create image charges on both the gate electrode and the inversion layer of the substrate during charging of a neutral oxide trap, which plays a more and more significant role in the capture kinetics of nano-MOSFETs, especially with ultra-thin gate oxide. In nano-MOSFETs ΔE can be expressed as,[9,10]

$$\Delta E \approx Q_{\rm G}V_{\rm GS} = q\frac{x_{\rm T}(C_{\rm inv}+C_{\rm dep})+C_{\rm ox}T_{\rm ox}}{T_{\rm ox}(C_{\rm ox}+C_{\rm inv}+C_{\rm dep})}V_{\rm GS}, \quad (4)$$

where $Q_{\rm G}$ is the normalised image charges induced on the gate, $C_{\rm ox}$, $C_{\rm inv}$ and $C_{\rm dep}$ are the capacitance of the oxide, inversion and depletion layers, respectively. From Eq. (4) we can see that the value of ΔE, which is usually several hundreds of milli-eV, is decided by the trap position, oxide thickness and device bias conditions. From Eq. (3) $x_{\rm T}$ can be deduced as

$$x_{\rm T} = \frac{T_{\rm ox}\left(\dfrac{kT}{q}\dfrac{{\rm d}\ln(\tau_{\rm c}/\tau_{\rm e})}{{\rm d}V_{\rm GS}}+\dfrac{{\rm d}\psi_{\rm s}}{{\rm d}V_{\rm GS}}-\dfrac{{\rm d}(\Delta E)}{{\rm d}V_{\rm GS}}\right)}{\left(\dfrac{{\rm d}\psi_{\rm p}}{{\rm d}V_{\rm GS}}+\dfrac{{\rm d}\psi_{\rm s}}{{\rm d}V_{\rm GS}}-1\right)}. \quad (5)$$

From the device-physics of MOSFETs, we have

$$\psi_{\rm s} = \psi_{\rm B}+\frac{2kT}{q}\ln\frac{C_{\rm ox}(V_{\rm GS}-V_{\rm FB}-2\psi_{\rm B})}{\sqrt{2\varepsilon_{\rm Si}kTN_{\rm A}}}, \quad (6)$$

$$\frac{{\rm d}\psi_{\rm p}}{{\rm d}V_{\rm GS}} = \left(1-\frac{{\rm d}\psi_{\rm s}}{{\rm d}V_{\rm GS}}\right)\times\left\{1-\left[1+\frac{2}{\alpha_\upsilon}(V_{\rm GS}-V_{\rm FB}-\psi_{\rm s})\right]^{-\frac{1}{2}}\right\}, \quad (7)$$

$$\frac{{\rm d}\psi_{\rm s}}{{\rm d}V_{\rm GS}} = \frac{2kT}{q}\frac{1}{V_1}, \quad (8)$$

where $C_{\rm ox}=\varepsilon_{\rm ox}/T_{\rm ox}$, $\alpha_\upsilon = q\varepsilon_{\rm Si}N_{\rm p}/C_{\rm ox}^2$, and $V_1 = V_{\rm GS}-V_{\rm FB}-2\psi_{\rm B}$.

We can separate the expression of $x_{\rm T}$ in Eq. (5) into two parts

$$x_{\rm T} = x_{\rm T}^0 - x_{\rm T}^{\rm C}, \quad (9)$$

where $x_{\rm T}^0$ is the calculated trap depth when the Coulomb-energy is ignored, which is the trap depth value we get from the traditional model,[4] and $x_{\rm T}^{\rm C}$ is the error of the traditional model when the Coulomb-blockade effect is taken into account. Combining Eqs. (5) and (9), we have

$$x_{\rm T}^0 = \frac{T_{\rm ox}\left(\dfrac{kT}{q}\dfrac{{\rm d}\ln(\tau_{\rm c}/\tau_{\rm e})}{{\rm d}V_{\rm GS}}+\dfrac{{\rm d}\psi_{\rm s}}{{\rm d}V_{\rm GS}}\right)}{\left(\dfrac{{\rm d}\psi_{\rm p}}{{\rm d}V_{\rm GS}}+\dfrac{{\rm d}\psi_{\rm s}}{{\rm d}V_{\rm GS}}-1\right)} = \frac{T_{\rm ox}\dfrac{kT}{q}\left[\dfrac{{\rm d}\ln(\bar{\tau}_{\rm c}/\bar{\tau}_{\rm c})}{{\rm d}V_{\rm GS}}+\dfrac{2}{V_1}\right]\sqrt{1+\dfrac{2C_{\rm ox}^2}{q\varepsilon_{\rm Si}N_{\rm p}}\left(V_1-\dfrac{2kT}{q}\ln\dfrac{C_{\rm ox}V_1}{\sqrt{2\varepsilon_{\rm Si}kTN_{\rm A}}}\right)}}{\dfrac{2kT}{qV_1}-1}, \quad (10)$$

$$x_{\rm T}^{\rm C} = \frac{T_{\rm ox}\left(\dfrac{{\rm d}(\Delta E)}{{\rm d}V_{\rm GS}}\right)}{\left(\dfrac{{\rm d}\psi_{\rm p}}{{\rm d}V_{\rm GS}}+\dfrac{{\rm d}\psi_{\rm s}}{{\rm d}V_{\rm GS}}-1\right)} \approx \frac{\left[qx_{\rm T}+\dfrac{q(T_{\rm ox}-x_{\rm T})}{\dfrac{\varepsilon_{\rm ox}}{T_{\rm ox}}-\dfrac{qN_{\rm A}}{\sqrt{2\varepsilon_{\rm Si}/kT}}}\right]\sqrt{1+\dfrac{2C_{\rm ox}^2}{q\varepsilon_{\rm Si}N_{\rm p}}\left(V_1-\dfrac{2kT}{q}\ln\dfrac{C_{\rm ox}V_1}{\sqrt{2\varepsilon_{\rm Si}kTN_{\rm A}}}\right)}}{\dfrac{2kT}{qV_1}-1}. \quad (11)$$

Using the new model described by Eqs. (10) and (11), the accurate value of trap depth in nano-MOSFETs responsible for RTS noise can be extracted.

3. Experiment and analysis

The nMOSFETs used were fabricated with 45 nm CMOS technology, with $W \times L = 45 \times 250$ nm^2, n^+ poly-silicon gate doping concentration $N_{\rm p} = 1 \times 10^{20}$ cm^{-3}, p-type channel doping concentration $N_{\rm A} = 1 \times 10^{18}$ cm^{-3}, gate oxide thickness $T_{\rm ox} = 2$ nm. The operating conditions at room temperature were $V_{\rm DS} = 10$ mV, and $V_{\rm GS}$ ranging from 0 to 0.6 V. Figure 2 shows the RTS noise time trace in drain current $I_{\rm DS}$, in which the capture time $\tau_{\rm c}$ is associated with the lower level of RTS current and the emission time $\tau_{\rm e}$ is associated with the upper current level. The dependence of $(\bar{\tau}_{\rm c}/\bar{\tau}_{\rm e})$ of the RTS noise for a sample device on gate voltage $V_{\rm GS}$ is given in Fig. 3, which apparently behaves nonlinearly.

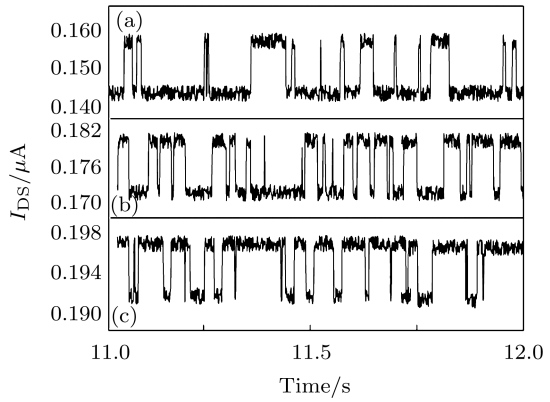


Fig. 2. The RTS noise in $I_{\rm DS}$ with $V_{\rm DS} = 10$ mV and $V_{\rm GS}$ (a) = 200 , (b) = 400 and (c) = 600 mV, respectively.

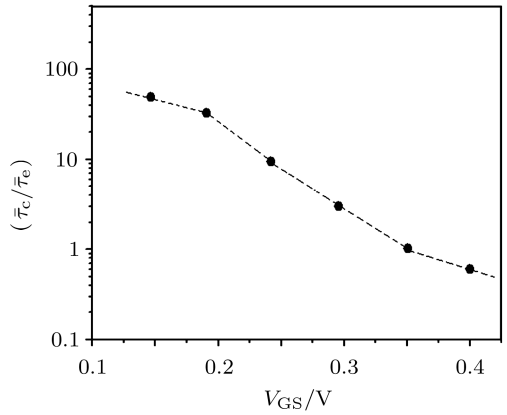


Fig. 3. Measured $(\bar{\tau}_{\rm c}/\bar{\tau}_{\rm e})$ versus gate voltage $V_{\rm GS}$ for two identical sample devices.

Figure 4 presents the calculated value of Coulumb-energy ΔE versus gate voltage $V_{\rm GS}$, in which the Coulomb-energy of an electron trapped by a neutral trap increases rapidly in the smaller gate voltage range and tends to saturate at larger gate biases. The value of Coulomb-energy varies between 130 meV to 280 meV when the gate voltage changes from 0.15 V to 0.6 V, which are relatively large values in comparison with the energy difference between the trap energy level and the first sub-conduction-level of the substrate; as a result, it can have a vital impact on the trapping and detrapping events.

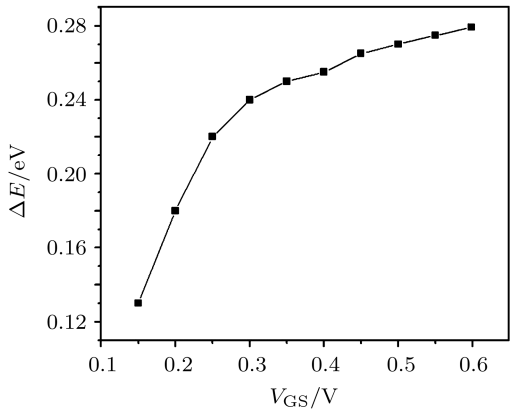


Fig. 4. Calculated ΔE versus $V_{\rm GS}$.

Figure 5 shows the extracted values of $x_{\rm T}$, $x_{\rm T}^0$ and $x_{\rm T}^{\rm C}$ obtained by Eq. (9), (10) and (11) based on the dependence of $(\bar{\tau}_{\rm c}/\bar{\tau}_{\rm e})$ versus $V_{\rm GS}$ shown in Fig. 3. Clearly, the extracted value of trap depth according to the traditional theory $x_{\rm T}^0$ is not a constant, but changes with the gate voltages from 0.8 nm to 0.6 nm, and the errors of the traditional model $x_{\rm T}^{\rm C}$ induced by Coulomb-blockade effect also change with gate biases from 0.2 nm to 0.01 nm as well. The accurate value of trap depth $x_{\rm T}$ obtained by the new model of Eq. (10) remains constant when gate voltage $V_{\rm GS}$ increases. From the results shown in Fig. 5 we can conclude that the Coulomb-blockade energy does have a significant influence on the time-constants of RTS noise in nano-MOSFETs. If it was omitted, larger errors would be induced to the trap's parameters extracted based on the RTS noise measurement technique, such as trap depth $x_{\rm T}$. In our case a relative error $(x_{\rm T}^{\rm C}/x_{\rm T})$ of about 33% was induced in low gate voltage ranges when the traditional model was used, in which no Coulomb-blockade effect was considered.

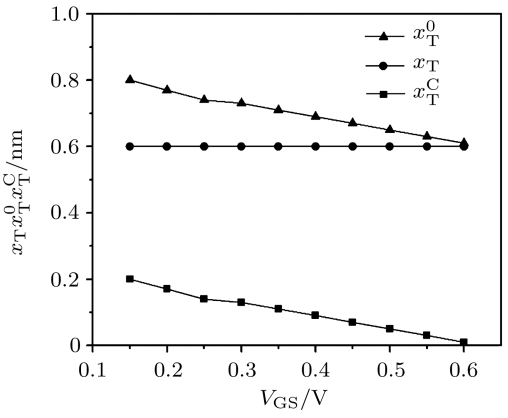


Fig. 5. Extracted $x_{\rm T}^0$, $x_{\rm T}^{\rm C}$ and $x_{\rm T}$ for different $V_{\rm GS}$.

4. Conclusion

The Coulomb-blockade effect has an important impact on the trapping and detrapping processes of channel electrons by oxide traps, which leads to a large deviation in the time-constant ratio of RTS noise from traditonal SRH theory.[4−7] Based on the mechanism of nano-MOSFETs and the expression of Coulomb energy ΔE, a new model for the time-constant ratio $(\bar{\tau}_{\rm c}/\bar{\tau}_{\rm e})$ was developed, based on which the accurate value of $x_{\rm T}$ was extracted from an experimental $\ln(\bar{\tau}_{\rm c}/\bar{\tau}_{\rm e})$ versus $V_{\rm GS}$ dependence. From the results we can see that, if Coulomb-blockade effect was omitted, large errors will be introduced, especially for nano-MOSFETs with ultra-thin gate oxide.

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