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A percolation study of RTS noise in deep sub-micron MOSFET by Monte Carlo simulation*

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Based on percolation theory and random telegraph signal (RTS) noise generation mechanism, a numerical model for RTS in deep submicron metal-oxide-semiconductor field-effect transistor (MOSFET) was presented, with which the dependence of τ_c/τ_e (where τ_c=capture time, τ_e=emission period) on energy levels and trap depth with respect to the interface of traps can be simulated. Compared with experimental results, the simulated ones showed a good qualitative agreement.

Keywords: MOSFET, RTS noise, τ_c/τ_e, percolation, model
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1. Introduction

In a sub-micron MOSFET, the channel area is less than $1\mu m^2$, and the number of active traps above the channel becomes smaller. As a result, $1/f$ noise is degraded to random telegraph signal (RTS) noise.[1] Figure 1 shows a schematic diagram of the RTS noise in a submicron n-MOSFET.

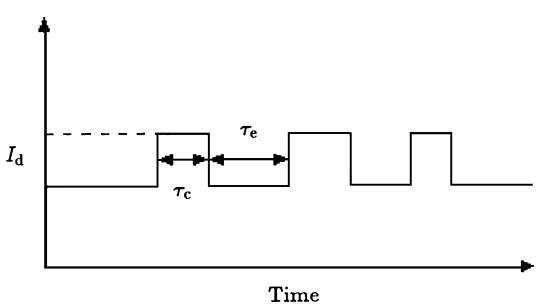


Fig.1. Schematic diagram of the RTS noise in a submicron n-MOSFET. During The capture timeτ_c, the interface trap is in a more positive charge state than during the emission period τ_e.

For RTS noise, there are two important parameters, i.e. RTS amplitude and τ_c/τ_e, where τ_c is the capture time, τ_e the emission period. The magnitude of τ_c/τ_e is closely related to the trapping and detrapping probabilities of current carriers by the trap located near the Si–SiO_2 interface, which are influenced by both the bias conditions of the devices and the energy levels, depths and locations of the traps.[2] As we know, most of the reported models are analytical, and the result obtained is statistical;[3−5] as a typical random process, the randomicity of RTS noise cannot be effectively depicted.

Based on the generation mechanism of RTS noise and percolation theory, a numerical model for RTS noise in sub-micron MOSFETs is presented. Furthermore, by using a program written with MATLAB language, the dependences of τ_c/τ_e on the energy levels and depth of the traps are simulated. The simulated results are analysed and compared with the experimental data.

2. Mechanism of RTS noise generation

In a sub-micron MOSFET, RTS noise is derived from the interactions between traps near the interface of Si–SiO_2 and the current carriers in the chan-

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nel. These interactions can lead to two effects: the number and the mobility fluctuations of the channel carriers.[2] Both effects can result in an fluctuation in drain current $I_{\rm d}$.

There are two different mechanisms for trapping and detrapping of channel carriers: one is due to the tunnel effect, the other due to the thermal activation effect. Both of these effects arise from trapping and detrapping of the carriers, so they are correlated with each other.[5] Due to the different importance of the two effects in different devices, usually only the vital one are considered in a special case.

The channel carriers are different from the traps both in energies and locations, so we take the trapping process as a composite one, which includes both thermal activation and tunnelling processes. Therefore, when computing the probabilities of trapping and detrapping, both processes must be taken into account. As a result, the probability of trapping an electron becomes[6]

$$p_{\rm c} = n_0 v_{\rm e} \sigma_0^* \exp[-(E_{\rm a}/kT + \theta x)], \tag{1}$$

where n_0 is the density of electrons in the channel, $v_{\rm e}$ is the thermal movement velocity of electrons, σ_0^* is a constant for one type of traps, $E_{\rm a}$ is the activation energy for the trapping processes which is defined as the energy consumed by emitted phonons, with a typical value between 0.19–0.65eV, k is the Boltzmann constant, T is absolute temperature, θ is the penetrating coefficient, and x is the depth of the trap with respect to the interface of Si–SiO_2. The trapped electron may be released back to the channel after

$$\tau_{\rm e} = \tau_0 \exp[(E_{\rm a}/kT + \theta x)], \tag{2}$$

where τ_0 is a constant.

Once an electron is trapped, a charged centre will form, which modulates the conducting carriers' mobility by Coulombic scattering[5] in the channel. The Coulombic potential is

$$V(r) = \frac{q}{4\pi\varepsilon_{\rm S} r}, \tag{3}$$

where r is the distance from the charged centre, and $\varepsilon_{\rm S}$ is the permittivity of silicon. The effective range of Coulombic scattering is a disc with a radius of[7]

$$r_{\rm t} = \sqrt{r^2 - x^2}; \tag{4}$$

that's to say, the deeper the charged centre is, the smaller the $r_{\rm t}$ will be. Based on Eq.(4), the induced fluctuation of the channel resistance is

$$\frac{\Delta R}{R} = \frac{2r_{\rm t}}{L}\alpha_\sigma, \tag{5}$$

where R is the total resistance of the channel, ΔR is the resistance change modulated by Coulombic scattering, L is the channel length, and α_σ is the relative change in resistance induced by charge trapping.

3. Percolation model

According to the percolation theory, the channel of a MOSFET can be divided into a network of $L \times W$, as shown in Fig.2. So in this network the total number of small areas is $2 \times L \times W$, and each small area in the network can be modelled as a resistor with a resistance r_0. According to the geometrical connectivity of these resistors, the above network can be modelled to a random resistors network. Either interface or oxide defect may have a coordination as $C_{\rm t}$ $(l, m, z, E_{\rm t})$, in which l is the coordination along channel length, m the width, and $E_{\rm t}$ the energy level of defects.

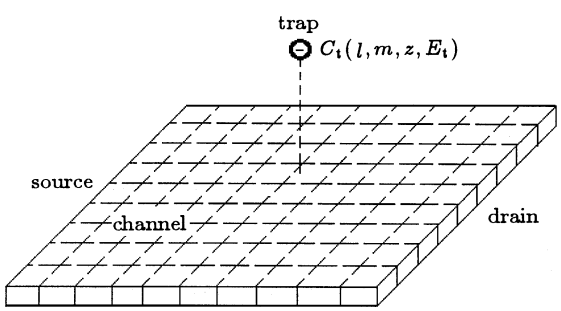


Fig.2. MOSFET channel divided into a network.

The trapping and detrapping of an electron by a trap can be modelled as the trapping and detrapping of a normal unit resistor by a trap. According to the number fluctuation theory, once a normal unit resistor is trapped with a probability $P_{\rm c}$, its resistance may increase to R_0. The relative magnitude of R_0 with respect to r_0 is determined by both the operational condition of the channel and the dimensions of the network. At the same time, the trapped electron may be emitted back to the channel after $\tau_{\rm e}$. The resistance of the trapped unit resistor will kept at R_0 until $\tau_{\rm c}$ is out. Then its resistance drop to r_0. During $\tau_{\rm c}$ the trapped charge may modulate the channel resistance through Coulombic scattering. The modulated area in the channel is a disc, with a centre of the projection of the trap in the channel, and a radius of $r_{\rm t}$. So, all the unit resistors in this area may be affected during $\tau_{\rm c}$. Their resistances increase to R_1, while after $\tau_{\rm c}$, go back to r_0. Thus, along with the trapping and

detrapping of channel electrons, Coulombic scattering may appear or disappear. As a result, the channel resistance fluctuates.

4. Monte Carlo simulation

By using a Monte Carol simulation method, the trapping, detrapping and Coulombic scattering process of the channel electron is simulated. Firstly, the total resistance of the random resistor network is computed by a transfer-matrix approach.[8] Secondly, if the trap is empty, then after every τ_0, it may trap electron with the probability of p_c. Once a normal unit resistor is trapped, its resistance becomes R_0. At the same time, Coulombic scattering effect may occur, and the resistances of the influenced resistors will not go back to r_0 until $(\tau_c + \tau_0)$ is out. Then, the trapped unit resistors are emitted and everything returns to its starting point. The total resistance of the channel is computed for every τ_0. After many times of repetition, a series of τ_c and τ_e can be obtained. So the dependences of τ_c/τ_e of RTS noise on the energy, depth of the trap and the channel area of the device can be simulated.

Some of the parameters used in simulation are $L \times W$=100×100, r_0 =1Ω, R_0=1.0001Ω, R_1=1.005Ω, $\tau_0 = 10^{-10}$s, and E_t=0.26eV.

The simulated dependence of $\bar{\tau}_c/\bar{\tau}_e$ on activation energy of trap is shown in Fig.3. During simulation, the depth of the trap and the size of the network keep unchanged, and the magnitude of $\bar{\tau}_c/\bar{\tau}_e$ increases with the activation energy of the trap exponentially.

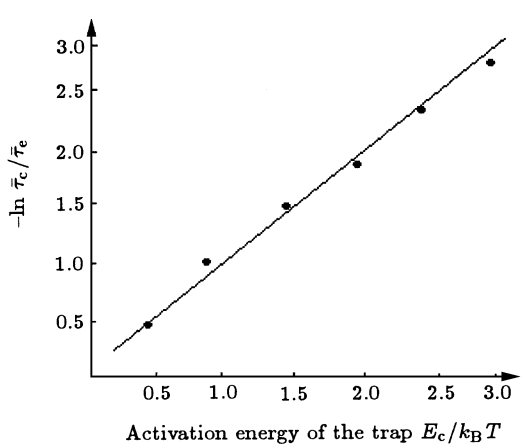


Fig.3. The simulated dependence of τ_c/τ_e on activation energy of the trap.

The simulated dependence of $\bar{\tau}_c/\bar{\tau}_e$ on the depth of the trap is shown in Fig.4. During simulation, the energy of the trap and the size of the network keep unchanged, and the magnitudes of $\bar{\tau}_c/\bar{\tau}_e$ have a negative exponential relation with the depth of the trap.

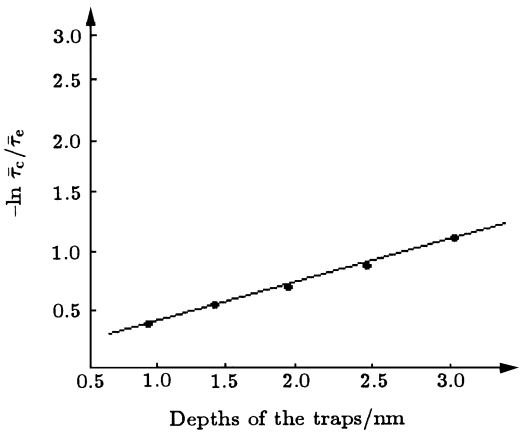


Fig.4. The simulated dependence of τ_c/τ_e on the depths of the trap.

5. Discussion and conclusions

In our experimental work, RTS is used to extract information about the trap. And based on experimental results, there is a putative relation between $\bar{\tau}_c/\bar{\tau}_e$ and all the other factors related to the trap and bias conditions[3]

$$\ln\frac{\bar{\tau}_c}{\bar{\tau}_e} = -\frac{1}{kT}\Big[(E_{Cox} - E_T) - (E_C - E_F) - \phi_0 + q\psi_s + q\frac{x_T}{T_{ox}}(V_{gs} - V_{FB} - \psi_s)\Big], \quad (6)$$

where E_T is the energy level of the trap, E_F is the energy level of current carriers in the channel, E_{Cox} is the band edge energy of the conduction band of oxide layer, E_C is the band edge energy of the conduction band of silicon underlayer, ϕ_0 is the work function difference between Si and SiO_2, ψ_s is the bending of the energy band, V_{FB} is the flat-band energy, x_T is the depth of trap with respect to the interface of Si-SiO_2, T_{ox} is the thickness of oxide layer, and V_{gs} is the voltage across the gate and source. According to Eq.(6), we can deduce the differential coefficients of $\ln\frac{\bar{\tau}_c}{\bar{\tau}_e}$ to E_T and x_T,

$$\frac{d(\ln\bar{\tau}_c/\bar{\tau}_e)}{dE_T} = \frac{1}{kT}, \quad (7)$$

$$\frac{d(\ln\bar{\tau}_c/\bar{\tau}_e)}{dx_T} = -\frac{q}{kT}\frac{(V_{gs} - V_{FB} - \psi_s)}{T_{ox}}. \quad (8)$$

So, it is obviously that there is an exponential dependence of $\bar{\tau}_c/\bar{\tau}_e$ of RTS noise on the energy levels of traps, which is consistent with the simulated results shown in Fig.3. On the other hand, $\bar{\tau}_c/\bar{\tau}_e$of RTS noise decreases exponentially with trap depth, also consistent with the simulated results shown in Fig.4.

However, neither the electric field distribution along the channel length nor the screening effect of Coulombic scattering is taken into account, so the relations between RTS noise and biased conditions of devices and trap's location with respect to the drain and source cannot be simulated.

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