Correction of the RTN Model considering 3D Effect of Single Trapped Charge

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Abstract— **We revisited the random telegraph noise by considering the Coulomb blockade effect and the 3D simulation. The simulation results reveal that the conventional RTN model based on the sheet charge approximation may introduce significant errors in predicting the trap position and energy. Moreover, it is shown that the device size and charge distribution are also important factors for the evaluations of the 3D single charge effect.**

Keywords- Random Telegraph Noise, Coulomb blockade effect, Trap characteristics, 3D single trapped charge, Sheet charge approximation

I. INTRODUCTION

As the MOSFET is scaled down, the low-frequency noise becomes one of the important reliability issues [1-3]. It is originated from the random process due to the carrier trapping and de-trapping by the oxide defects. In the case of the RTN, the trapping/de-trapping process results in two levels of drain current, as schematically shown in Fig. 1. In predicting the energy and position of the trap, the ratio of capture and emission time constants gives a valuable source for studying interactions between a single electron in the channel and the single trap in the oxide [4-6].

The behavior of RTN in Fig. 1 has been explained by Shockley-Read-Hall (SRH) type model [4]. However, in the nano scale regime where the gate capacitance is extremely small, it is reported that the Coulomb blockade effect should be considered to account for the free energy change in the system during the capture/emission process [7],[8]. Therefore, it

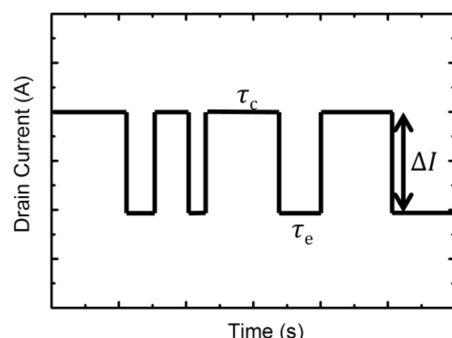

Fig. 1. Schematic of the drain current fluctuation known as RTN due to the single electron trapping and de-trapping. The capture time constant (τ_c), emission time constant (τ_e) and the current fluctuation level (ΔI) are important parameters in the RTN modeling.

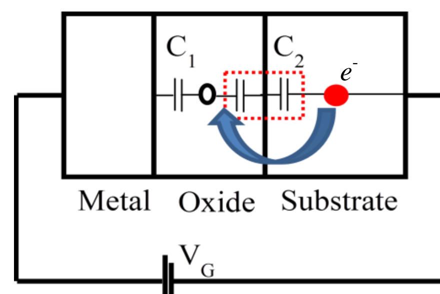

Fig. 2. Schematic of the oxide charge trapping in RTN where C_1 is total capacitance between trap and gate electrode and C_2 is total capacitance between trap and substrate.

should be included in the RTN modeling to accurately model the energy and position of the single trap [9-11]. However, the problem is that the trap charge has the 3D distribution so that the 1D sheet charge approximation for the previous studies on RTN [7-11] should be revisited. In this context, it is worthwhile to revisit the conventional Coulomb blockade model based on the 1D sheet charge approximation by considering the 3D charge distribution.

In this paper, we conduct a comparison study between the RTN model with Coulomb blockade effect using the sheet charge approximation and the model considering the actual charge distribution in the 3D space. In addition, the effect of the device size and the charge distribution on RTN is also investigated.

II. 3D EFFECT DUE TO SINGLE TRAPPED CHARGE

A. Coulomb Blockade Effect in RTN

The Coulomb blockade effect [7],[8] is caused by the free energy change in total system when the electron is captured by the oxide trap via the tunneling process as shown in Fig. 2. Hence, an additional energy which is called the Coulomb energy is required for the capture process. The Coulomb energy, which is usually very small, becomes important as the temperature becomes low and/or the capacitance becomes small. The equivalent capacitance seen from the trap site is small and the Coulomb energy as small as 250meV has been reported [7]. The ratio between the capture and emission times is modified by the Coulomb energy as,

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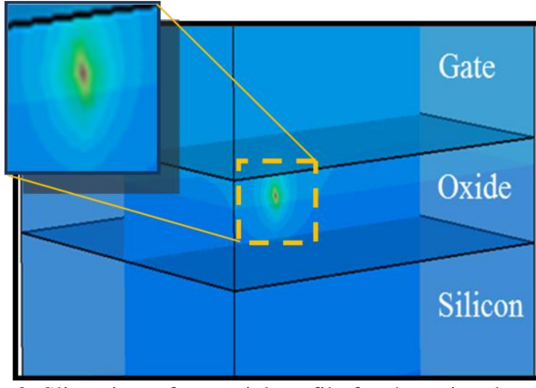

Fig. 3. Slice view of potential profile for the point charge in the oxide from the 3D DG simulation.

$$\tau_c/\tau_e = \exp[(E_f - E_T - \Delta F)/k_B T] \quad (1)$$

where E_f is the Fermi-level, E_T is the energy level of the oxide trap, and ΔF is the change in Coulomb energy due to the charge trapping. The metal-oxide-semiconductor system with a single trap site can be modeled with capacitors as shown in Fig. 2. From the equivalent circuit in Fig. 2, we can extract the total free energy (or the Coulomb energy) variation as, [7]:

$$\Delta F \approx -V_G \cdot \Delta Q_G \text{ (work done by external source)}$$
$$= V_G \cdot \frac{C_1}{C_1 + C_2} \cdot e \quad (2)$$

where V_G is the gate voltage and ΔQ_G is a gate image charge induced by the trapped charge. Since the change in the electrostatic energy is very small, the work done by the external voltage source is a dominant term in evaluating the free energy change as in (2). The free energy variation can be considered in (1) to extract the characteristics of RTN trap. In this work, we assume that the trap is acceptor-like [7],[8].

B. Extraction of the 3D capacitance

In order to obtain the capacitances in (2) considering an actual charge distribution of the point charge, we conduct a 3D simulation by using the Sentaurus tool [12]. The Density Gradient (DG) method is used to consider the quantum effect.

From the 3D-DG simulation result, we can extract the amount of the gate image charge (ΔQ_G) by the following equation [13]:

$$\Delta Q_G = e\frac{C_1}{C_1 + C_2} = e\left.\frac{\partial V_{trap}}{\partial V_G}\right|_{Q_{trap}} \quad (3)$$

where V_{trap} and Q_{trap} are the electrostatic potential and the charge concentration at the position where the trap is located, respectively. In the previous work [7],[8] using the sheet charge approximation, the gate image charge is evaluated as follows:

$$\Delta Q_G = e\frac{C_1}{C_1 + C_2} = e\frac{\varepsilon_1/t_1}{\varepsilon_1/t_1 + \varepsilon_2/t_2} \quad (4)$$

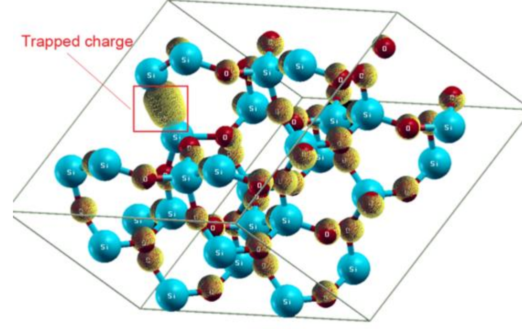

Fig. 4. Distribution of the single trapped charge in SiO_2, calculated by DFT method using the supercell with 71 atoms. The oxygen vacancy is considered as a RTN trap.

where ε_1 and ε_2 are the permittivity of the capacitance C_1 and C_2, respectively; t_1 and t_2 are the thickness of the capacitance C_1 and C_2, respectively. Note that (4) is based on the sheet charge approximation.

In the following sections, we compare the gate image charge from the 3D simulation using (3) and the 1D sheet charge model using (4). The difference in the Coulomb energy can be evaluated by the gate image charge using the eqs. (1) and (2).

C. Distribution of Trapped Charge

The actual trapped charge is not an ideal point charge but distributed in the 3D space. To decide the reasonable distribution of the trapped charge for the 3D simulation, we adopt the result from *ab-initio* calculation using the Density Functional Theory (DFT) [14],[15]. We conduct the DFT simulation for the oxygen vacancy which is regarded as a candidate for the RTN trap as shown in Fig. 4. The charge distribution (iso-surface) of the trapped charge is obtained as indicated in Fig. 4. From the result, we assume the trapped charge distribution having the uniform distribution in the cubic whose size is 3Å .

III. 3D Simulation Result

We perform the 3D device simulation to calculate the point charge effect on RTN and compare with the 1D RTN model based on the sheet charge approximation. The sample device for the simulation is same as that reported in [10] for comparison; the gate with the n^+ poly-silicon doping of $1.3\times10^{20}cm^{-3}$, channel doping of $8.0\times10^{17}cm^{-3}$, L/W of 50nm/50nm, and the gate (t_{ox}) of 1.7nm thick. Firstly, we compare the DG simulation framework with the Schrodinger equation solver to check the validity of the DG simulation in predicting the Coulomb blockade effect in 1D based on the charge sheet approximation. Secondly, we compare the results from the sheet charge approximation with that from the point charge model to check the error introduced by the sheet charge approximation. Finally, the 3D simulations under the various sizes of device and charge distributions are performed.

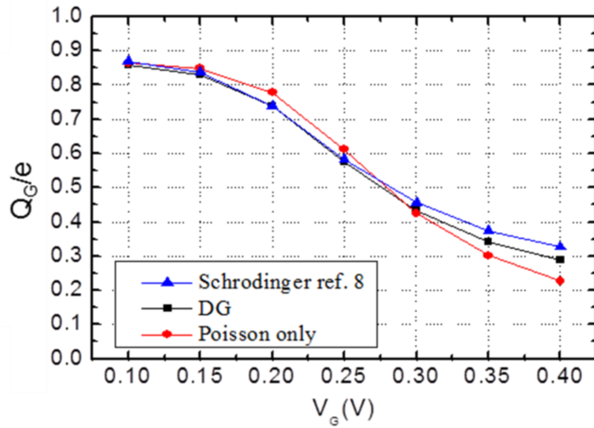

Fig. 5. Gate image charge calculated with sheet charge in Si/SiO_2 interface by using different simulation methods.

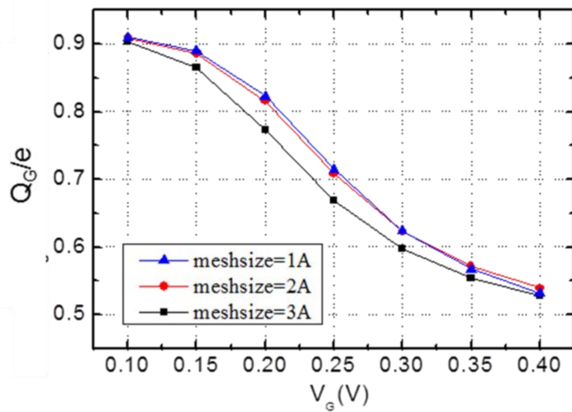

Fig. 6. Gate image charge calculated with different mesh size using 3D DG simulation.

A. Verification of our 3D DG framework

To check the validity of the DG framework, we compare our simulation result with previous one based on the Schrodinger equation [10] and the result from the Poisson solution only. The normalized gate charge which is related to the Coulomb energy is shown in Fig. 5, where the agreement between the Schrodinger equation solution and the DG model is quite reasonable.

Fig. 6 shows the mesh dependence of the gate image charge. As shown in Fig. 6, the results show that the dependence vanishes when the mesh size under 2Å . Therefore, we use the mesh size of 1Å in this work to eliminate the artifact due to the large mesh size.

B. Comparison of the sheet and point charge model

We calculate the Coulomb energy with the point and sheet charge model. As shown in Fig. 7, the sheet charge model overestimates the Coulomb energy compared with the point charge model. The reason is that the point charge model gives lower capacitance (C_1 in (2)). By fitting the RTN model to experimental results [10], the trap position and energy can be extracted as shown in Fig. 8. In Table I, the extraction result by

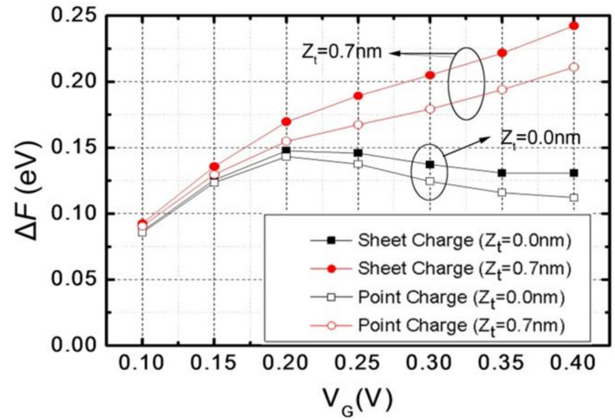

Fig. 7. Coulomb energy (ΔF) due to the point and sheet charge. The distance between trap and the interface (Z_t) are assumed to be 0.0nm and 0.7nm.

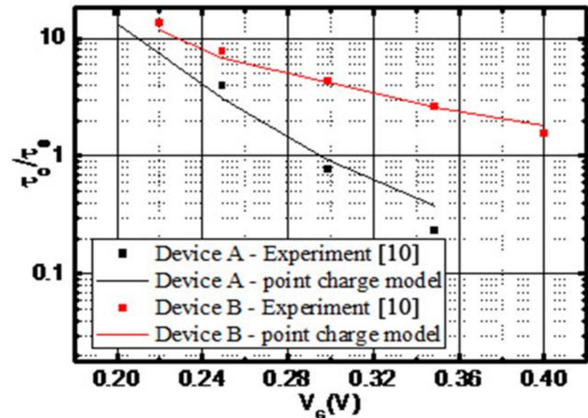

Fig. 8. Extraction of trap position (Z_t) and energy (E_t) from the point charge simulation.

	Deivce A	Device B
Sheet charge model	$Z_t = 0.7$nm $E_T = 3.3$eV	$Z_t = 0.0$nm $E_T = 3.4$eV
3D point charge model	$Z_t = 1.0$nm $E_T = 3.3$eV	$Z_t = 0.0$nm $E_T = 3.5$eV

Table I. The position and energy level of the trap extracted from the measurement result [10].

the point charge model and sheet charge approximation are summarized. From the table, it is clearly shown that the sheet charge approximation introduces non-negligible error on the trap position and energy of RTN because of the different nature of point and sheet charge.

C. Effect of Device Size and Charge Distribution

We simulate the devices with various sizes to find the size effects on the Coulomb energy, as shown in Fig. 9. The sizes of length/width are varied from 8nm/8nm to 100nm/100nm. The size dependency is negligible when the device size is over

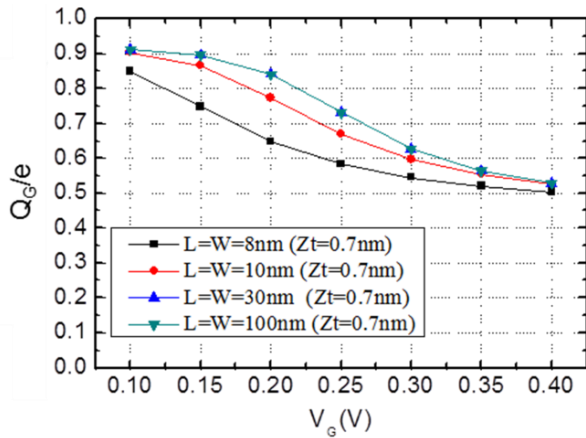

Fig. 9. Gate image charge under various device sizes when the point charge is located at Z_t of 0.7nm.

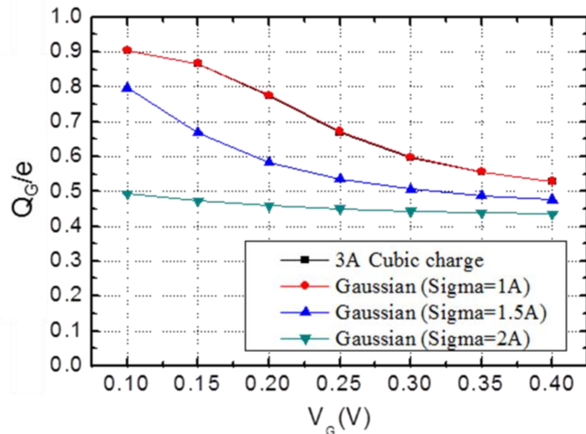

Fig. 10. Gate image charge with various charge distributions (Z_t=0.7nm).

30nm/30nm. This is because the size of the trapped charge (about 3Å) and the region affected by the trapped charge are relatively small than the channel area of the device. Note that the sheet charge approximation assumes that the charge is uniformly distributed on the entire area so that this kind of the size dependency cannot be predicted. However, when the device size is under 10nm/10nm, the device size gives a large effect on the result because the region affected by the trapped charge becomes appreciable in the channel area. The gate image charge becomes smaller as the device size decreases because the capacitance C_1 becomes smaller [13].

In Fig. 10, we simulate two types of the charge configurations: the uniform distributed charge in the cubic (3Å) and the Gaussian distributed charges. For the Gaussian distributed charges, the standard deviations of 1, 1.5 and 2Å are used. As shown in Fig. 10, the spreading of charge gives a large effect on the gate image charge, because of the change in the capacitance. Therefore, it is important to consider the realistic charge distribution in the 3D RTN model.

IV. Result and Discussion

We have studied the effect of the 3D trapped charge distribution on the RTN. It has been pointed that the sheet charge approximation gives non-negligible error in predicting the properties of the RTN trap. Moreover, we also studied the effect of device size and charge distribution on the RTN. As a result, we found that accurate modeling of the 3D trapped charge distribution becomes more important in the extremely scaled devices.

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