2-3

Modeling Statistical Distribution of Random Telegraph Noise Magnitude

Ken’ichiro Sonoda, Motoaki Tanizawa, Kiyoshi Ishikawa, and Yasuo Inoue
Renesas Electronics Corporation, Mizuhara 4-1, Itami, Hyogo 664-0005, Japan
Email: kenichiro.sonoda.xc@renesas.com

***Abstract*—Random telegraph noise (RTN) magnitude of MOSFETs is analyzed using three-dimensional device simulation taking random discrete dopant into account. The maximum RTN magnitude is inversely proportional to the RTN region area in which the surface potential is in the vicinity of its saddle point. The inverse of the maximum RTN magnitude exhibits a normal distribution.**

I. INTRODUCTION

Random telegraph noise (RTN) has been a serious concern in scaled CMOS technology[1], as its effects are becoming comparable to traditional sources of threshold voltage fluctuation such as random dopant fluctuation. The large variation of the RTN magnitude is attributed to random discrete dopant[2]. Although the statistical distribution has been successfully expressed by exponential distribution[3] or log-normal distribution[4], physical origin of these distributions has not been clarified yet.

In this paper, RTN magnitude is analyzed using three-dimensional device simulation taking random discrete dopant into account.

II. MODELING

The RTN magnitude ΔV_{th} is defined as a threshold voltage shift caused by a trap in this paper. The threshold voltage is defined as a gate voltage at which the drain current divided by $W_{\mathrm{g}}/L_{\mathrm{g}}$ is $0.1\,\mu\mathrm{A}$. The observation time period is assumed to be much longer than the time constants of RTN. Drain current fluctuation caused by an interface trap is converted to the threshold voltage shift by dividing by transconductance. The transconductance is calculated using small-signal AC analysis.

The impedance field method[5] is used to simulate current fluctuation. The current fluctuation is calculated as the product of elementary charge and a Green’s function, which is defined as current fluctuation at a terminal caused by electric charge density fluctuation. Perturbation to Poisson equation is included in the Green’s function because electric charge explicitly appears only in the Poisson equation.

The advantage of the impedance field method is its efficiency to derive a contour plot of RTN magnitude as a function of trap position. A large number of simulation runs are required to obtain the same contour plot if a conventional method in which a single charge is located at a trap position is used. The maximum RTN magnitude $\Delta V_{\mathrm{thmax}}$ is obtained from the contour plot. Simulated RTN magnitude using the impedance field method is compared to that using the conventional method in Fig. 1. The impedance field method and the conventional method give the same results, which proves that the linear response of the terminal current to local fluctuation assumed in the Green’s function is applicable to RTN simulation.

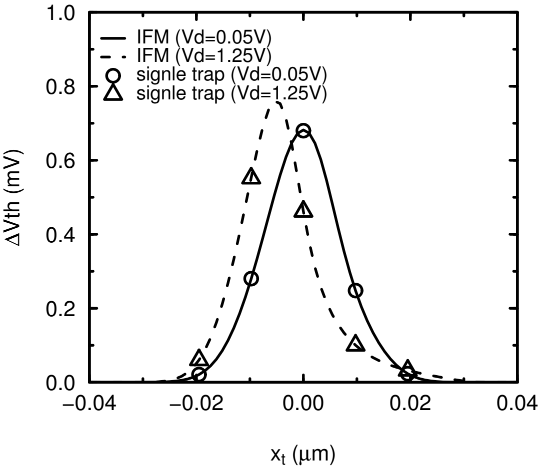


Fig. 1. Simulated RTN magnitude as a function of the trap location x_{t} along the Si/oxide interface from the source to the drain using the impedance field method (IMF) and a conventional method with a single trap. The gate length is 65 nm and the gate width is $1\,\mu\mathrm{m}$.

The random discrete dopant is assigned using the nearest grid point method. The number of dopant atoms is assumed to exhibit Poisson distribution. A statistical sample of 100 devices is simulated to obtain statistical distribution of the RTN magnitude.

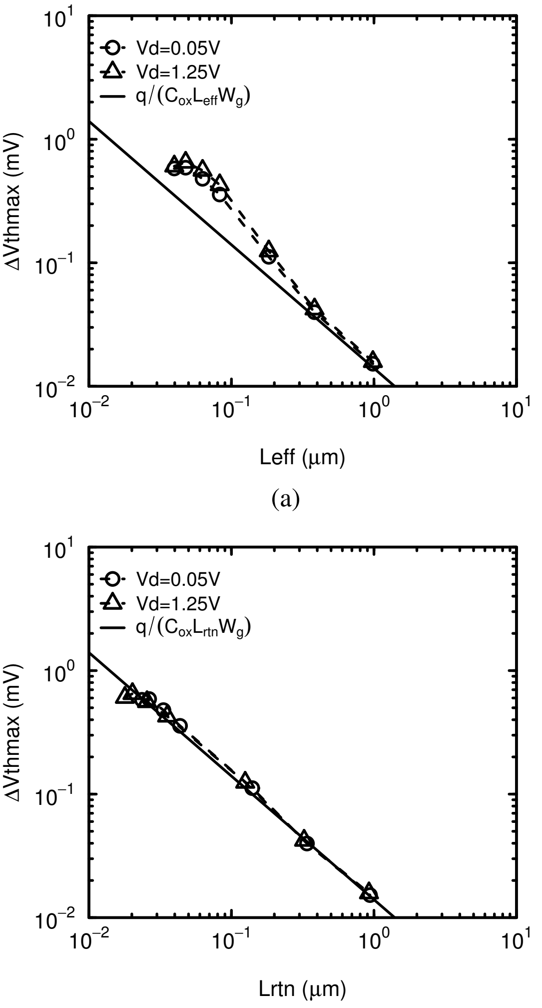
III. RESULTS AND DISCUSSION

Simulated n-channel MOSFETs have a substrate with a constant impurity profile and source and drain diffusion layers with Gaussian impurity profiles. The substrate impurity concentration is $2\times10^{18}\,\mathrm{cm}^{-3}$. The junction depth is $0.1\,\mu\mathrm{m}$. Halo implantation is not included. The equivalent oxide thickness is $2.5\,\mathrm{nm}$.

As the channel length shrinks, the maximum RTN magnitude $\Delta V_{\mathrm{thmax}}$ is larger than the value predicted by a conventional formula $q/(C_{\mathrm{ox}}L_{\mathrm{eff}}W_{\mathrm{g}})$[6] even if the random discrete dopant is not taken into account as shown in Fig. 2 (a). The discrepancy is reduced by introducing an RTN region in which the surface potential $-q\psi$ is within the kT-range

978-1-61284-418-3/11/$26.00 © 2011 IEEE

from its maximum point as shown in Fig. 3. The surface potential outside the RTN region is less sensitive to the trapped charge because of a large inversion layer capacitance $C_{\mathrm{inv}} \equiv \partial Q_{\mathrm{inv}}/\partial\psi$ associated with large inversion charge density Q_{inv}. The average surface potential fluctuation caused by a trap in the RTN region is $q/(C_{\mathrm{ox}}L_{\mathrm{rtn}}W_{\mathrm{g}})$ using the RTN region length L_{rtn}. The formula successfully expresses the simulated magnitude as shown in Fig. 2 (b).



(a)

(b)

Fig. 2. Maximum RTN magnitude with continuous doping distribution as a function of (a) the effective channel length, and (b) the RTN region length. The effective channel length L_{eff} is extracted from channel resistance as a function of gate length and gate voltage[7]. The RTN region length is defined in Fig. 3. The gate width $W_{\mathrm{g}} = 1\,\mu\mathrm{m}$.

The concept of the RTN region is extended to the non-uniform surface potential caused by random discrete dopant[2]. An interface trap at the point where the surface potential has its saddle point has the largest influence on the threshold voltage as shown in Figs. 5, 6. The saddle point of the surface potential is used to define RTN region instead of a maximum point because the potential at the saddle point is the highest on the current path from the source to the drain. An RTN region area A_{rtn} is defined by $A_{kT} - A_{\mathrm{ineff}}$, where A_{kT} is the area in which the surface potential is in the kT-range from the saddle point and A_{ineff} is the sub-area of A_{kT} which does not contribute to the drain current. As the sub-area A_{ineff} consists of narrow or isolated areas as shown in Fig. 5 (b), it is assumed to be proportional to the gate width W_{g} and expressed by $2L_{\mathrm{ineff}}W_{\mathrm{g}}$ with a fitting parameter L_{ineff}.

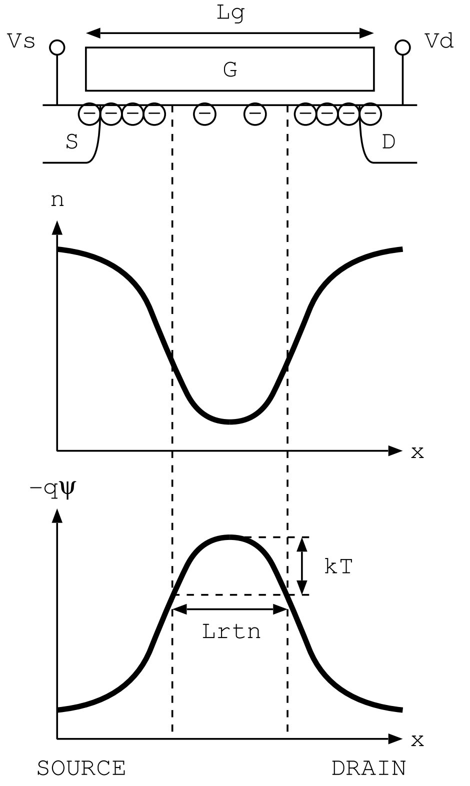


Fig. 3. Schematic picture of the surface potential $-q\psi$, carrier concentration n, and the RTN region length L_{rtn}.

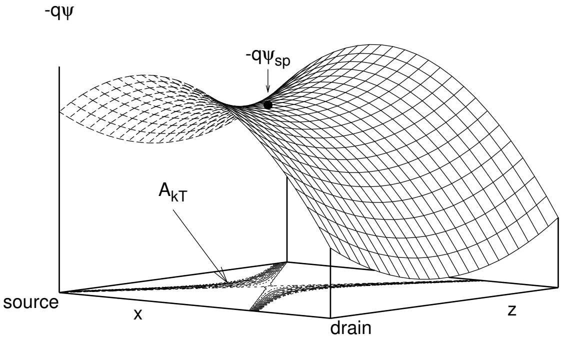
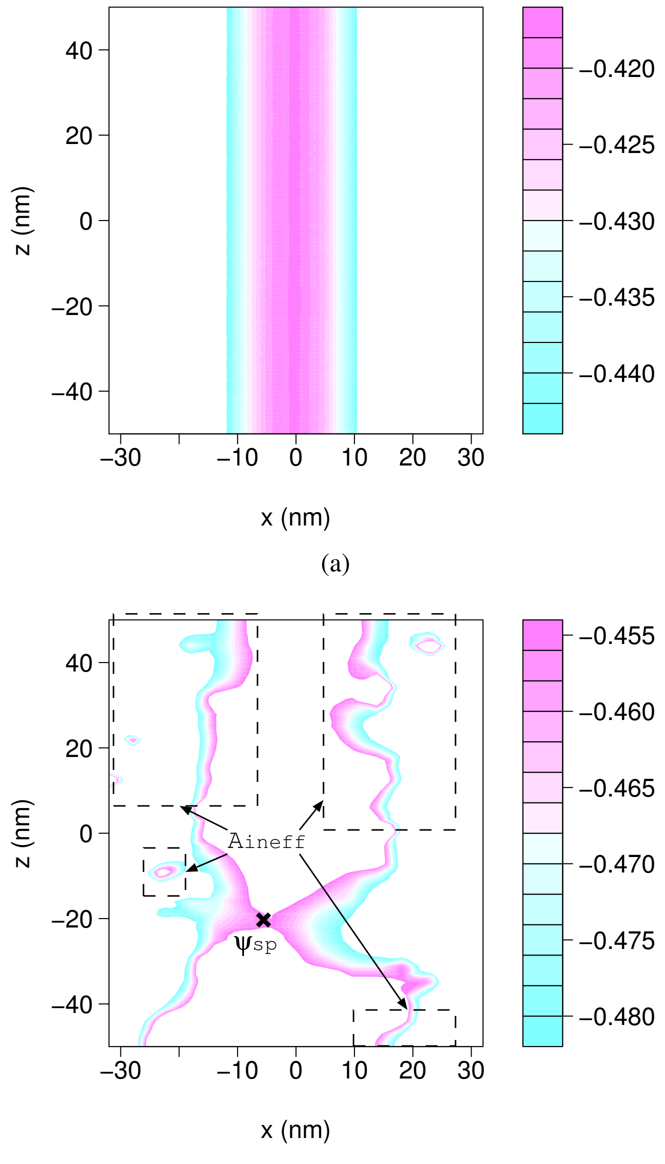


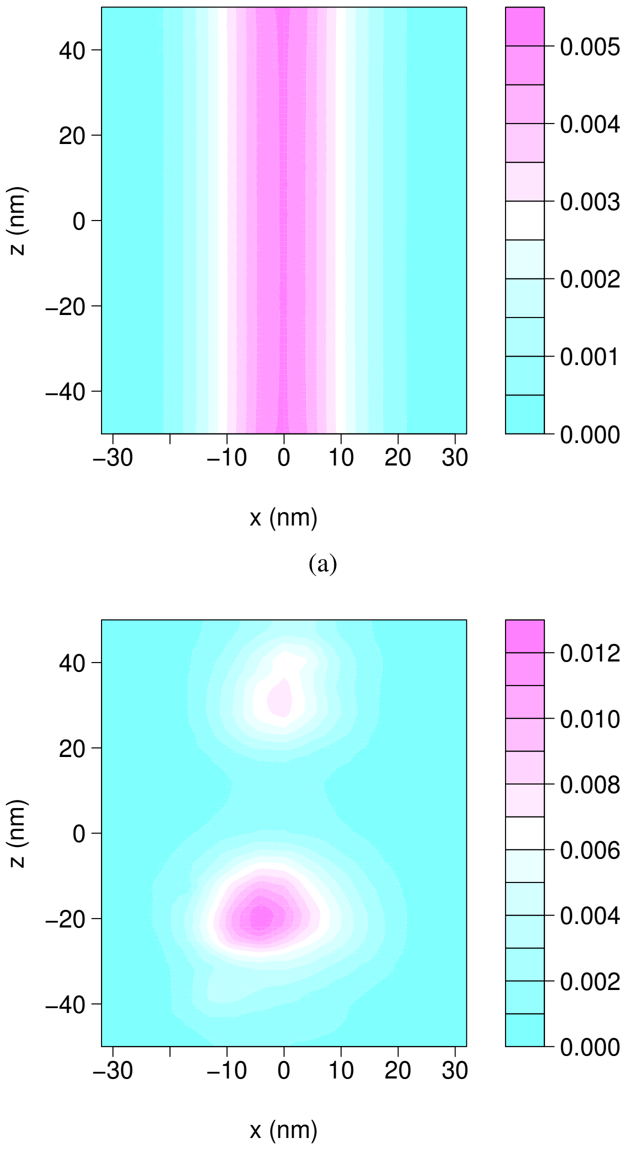
Fig. 4. Schematic picture of the surface potential $-q\psi$, its saddle point $-q\psi_{\mathrm{sp}}$, and the area A_{kT} in which $-q\psi$ is in the kT-range from $-q\psi_{\mathrm{sp}}$. Gate length and width directions are x and z, respectively.



(a)

(b)

Fig. 5. Surface potential distribution measured in volts in the kT-range from its saddle point. The gate length $L_\mathrm{g} = 65\,\mathrm{nm}$, the gate width $W_\mathrm{g} = 100\,\mathrm{nm}$, and the drain voltage $V_\mathrm{d} = 0.05\,\mathrm{V}$. Dopant distributions are (a) continuous and (b) discrete, respectively.

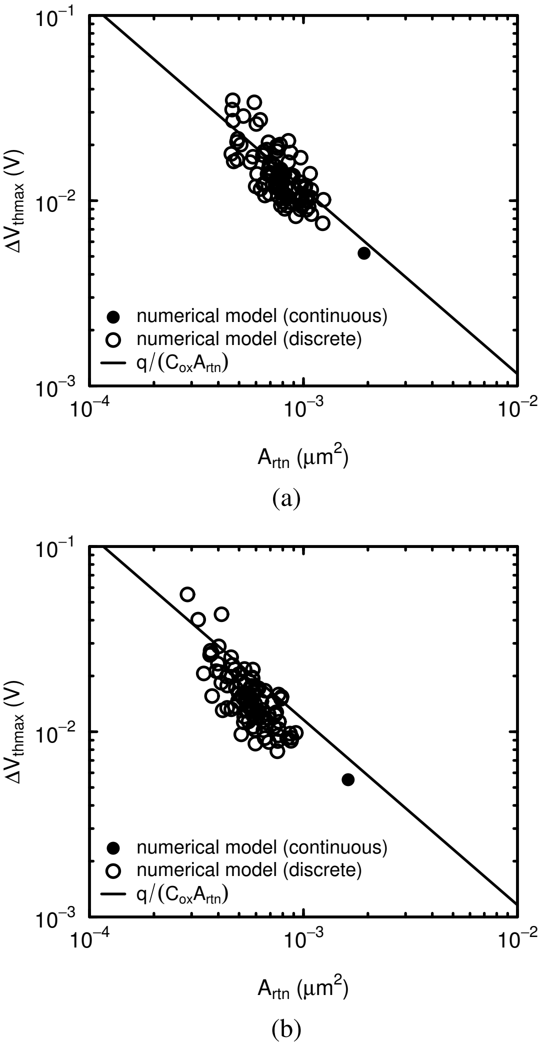


(a)

(b)

Fig. 6. RTN magnitude measured in volts as a function of the interface trap location. The gate length $L_\mathrm{g} = 65\,\mathrm{nm}$, the gate width $W_\mathrm{g} = 100\,\mathrm{nm}$, and the drain voltage $V_\mathrm{d} = 0.05\,\mathrm{V}$. Dopant distributions are (a) continuous and (b) discrete, respectively.

The maximum RTN magnitude is successfully expressed with a formula $q/(C_{\mathrm{ox}}A_{\mathrm{rtn}})$ when $V_{\mathrm{d}} = 0.05\,\mathrm{V}$ as shown in Fig. 7 (a). The nonuniform surface potential caused by random discrete dopant reduces the RTN region area, resulting large RTN magnitude. Although the formula tends to overestimate the maximum RTN magnitude when $V_{\mathrm{d}} = 1.25\,\mathrm{V}$ as shown in Fig. 7 (b), the linear relationship between the RTN magnitude and the inverse of the RTN region area is still valid. More elaborate definition of the RTN region would be required to explain the RTN magnitude in the saturation region.



(a)

(b)

Fig. 7. Maximum RTN magnitude as a function of the RTN region area. The gate length $L_{\mathrm{g}} = 65\,\mathrm{nm}$ and the gate width $W_{\mathrm{g}} = 100\,\mathrm{nm}$. The open circles indicate numerical simulation results of the statistical sample of 100 devices considering discrete dopant effects. (a) $V_{\mathrm{d}} = 0.05\,\mathrm{V}$, (b) $V_{\mathrm{d}} = 1.25\,\mathrm{V}$.

Statistical distribution of $1/\Delta V_{\mathrm{thmax}}$ simulated with discrete dopant is Gaussian in both linear and saturation regions as shown in Fig. 8, which is expected from the fact that $\Delta V_{\mathrm{thmax}}$ is inversely proportional to A_{rtn}. If the surface potential fluctuation is assumed to be a normally distributed Gaussian[8], A_{rtn} and $1/\Delta V_{\mathrm{thmax}}$ are Gaussian. Statistical distribution of $\Delta V_{\mathrm{thmax}}$ is, therefore, approximated by exponential or log-normal distribution, because an upper tail of the distribution of the inverse of a normally distributed Gaussian variable is longer than a lower tail.

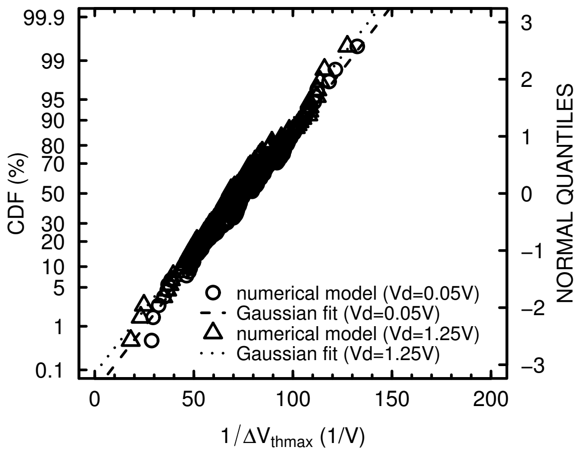


Fig. 8. Cumulative distribution function of the inverse of the maximum RTN magnitude. The gate length $L_{\mathrm{g}} = 65\,\mathrm{nm}$ and the gate width $W_{\mathrm{g}} = 100\,\mathrm{nm}$.

IV. CONCLUSION

The RTN magnitude was analyzed using three-dimensional device simulation. The maximum RTN magnitude is inversely proportional to the RTN region area. The RTN region is defined using the saddle point of the surface potential. The inverse of the maximum RTN magnitude exhibits a normal distribution.

REFERENCES

[1] N. Tega *et al., IRPS,* p. 541, 2008.
[2] A. Asenov *et al., IEEE T-ED,* p. 839, 2003.
[3] R. Gusmeroli *et al., IEDM Tech. Dig.,* p. 483, 2006.
[4] K. Sonoda *et al., IEEE T-ED,* p. 1918, 2007.
[5] A. Wettstein *et al., SISPAD,* p. 91, 2003.
[6] G. Ghibaudo, *Solid-State Electron.*, p. 563, 1989.
[7] K. Terada *et al., JJAP,* p. 953, 1979.
[8] I. D. Mayergoyz *et al., JAP,* p. 3019, 2001.