

# Single Ion and Multi Ion MOSFETs Simulation with Density Gradient Model

Toru Toyabe

Toyo Univ. Bio-Nano Electronics Research Centre, Kawagoe, Saitama 350-8585,  
Japan  
Tel:81-49-239-1439, Fax: 81-49-231-5026, Email: [t\\_toya@cs.toyo.ac.jp](mailto:t_toya@cs.toyo.ac.jp)

## Abstract

This paper deals with drain current characteristics for ultra small SOIMOSFETs which include single ion or multi ions in the channel. A robust 3D device simulator with density gradient model is developed. Simulation results for discrete dopants devices are discussed comparing with the ones for continuous dopant devices.

## 1 Introduction

Continued device scaling into decananometer range requires that simulation tools can treat quantum mechanical effects. Discreteness of ionized impurities in the channel cannot be ignored for these devices. The density gradient model has been attracting much attention as a means that can efficiently describe the quantum confinement effects using the first order quantum corrections [1],[2],[3]. In this paper a robust 3D device simulator with density gradient model is developed and used for analyzing drain current characteristics of decananometer SOIMOSFETs containing a single or small number of ionized impurities.

## 2 Model

In the density gradient model, a quantum mechanical correction  $\Lambda$  is introduced into an electron transport description like the drift-diffusion approximation [3]. Then, the electron current density  $\mathbf{J}_n$  is expressed as

$$\mathbf{J}_n = -q\mu_n n \nabla \phi_n = -q\mu_n n \nabla \left( \psi - V_T \ln \frac{n}{n_i} - \Lambda \right) \quad (1)$$

with electron density  $n$ , electron charge  $q$ , electron mobility  $\mu_n$ , electron quasi-Fermi potential  $\phi_n$ , electrostatic potential  $\psi$ , thermal voltage  $V_T$ , intrinsic carrier density  $n_i$ . The quantum correction  $\Lambda$  is given by

$$\Lambda = -2b_n \frac{\nabla^2 \sqrt{n}}{\sqrt{n}} = -\frac{\hbar^2}{2qmr} \frac{\nabla^2 \sqrt{n}}{\sqrt{n}} \quad (2)$$

where a parameter  $r$  is assumed equal to one corresponding to strong quantum confinement [4].

The system of equations is given by

$$\nabla \cdot (\epsilon \nabla \psi) = q(n - p - N_B) \quad (3)$$

$$2b_n \frac{\nabla^2 \sqrt{n}}{\sqrt{n}} = \phi_n - \psi + \frac{k_B T}{q} \ln \frac{n}{n_i} \quad (4)$$

$$\nabla \cdot (n \mu_n \nabla \phi_n) = G - R \quad (5)$$

$$\nabla \cdot (p \mu_p \nabla \phi_p) = R - G \quad (6)$$

For the transport of holes no quantum correction is considered, since n-channel devices are dealt with in this paper. Robust and efficient computation has been carried out by choosing  $\psi, \phi_n, \sqrt{n}, p$  as fundamental variables as shown in the following section.

### 3 Simulation Results

A structure of n-channel SOIMOSFET is shown in Fig.1. The source and drain n layers are set by usual continuous Gaussian distribution with steep gradient in lateral directions. The channel region between n layers is intrinsic and two discrete acceptor ions are set on two mesh points, respectively. Fig.2 shows electron density profiles of the SOIMOSFET. Quantum mechanical electron confinement under the gate oxide and just above the buried oxide as well as influence of two acceptor ions can be seen. Drain current characteristics of a SOIMOSFET with 10 acceptor ions randomly placed in the intrinsic region are shown in Fig.3. Classical drift diffusion model and density gradient model are compared with each other. Drain current from

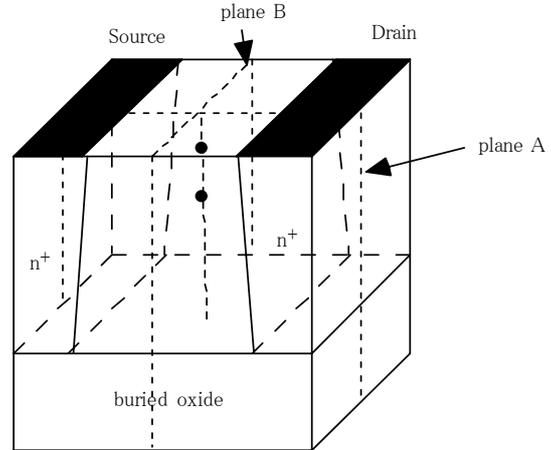


Fig.1. N-SOIMOSFET structure. Gate and oxide exist above,  $t_{ox}=4\text{nm}$ . Thickness of Si is 50nm, channel width 10nm, channel length not clearly determined,  $10 \sim 20 \text{ nm}$ , buried oxide thickness, 30nm. Two acceptor ions are placed artificially on a cross line of plane A and Plane B.

DD model is higher than the one from DG model, as reported by several authors, for example [4]. Ten single ion SOIMOSFETs in which the ion is placed randomly in the intrinsic region are simulated and  $I_d - V_g$  characteristics are shown in Fig.4. It is seen that the variance is not so large. Also for 5 ions devices and 10 ions devices, raw

data are shown in Fig.4. The single and 5 ions devices shows punch through characteristics, while 10 ion devices has cutoff capability. Averages of the drain currents for each ten devices are shown in Fig.5 and compared with the ones obtained for conventional constant impurity doping. The curves for single, 5 and 10 ions coincide very well with the ones for 1, 5, and  $10 \times 10^{17} \text{ cm}^{-3}$ , respectively. The coincidence for single ion case is remarkable considering that single ion is placed quite randomly in the intrinsic region. It should be noted that single ion devices like in Fig.1 have not pn junction and channel length can not be clearly defined. Correspondence of 1 ion to  $1 \times 10^{17} \text{ cm}^{-3}$  result in that the effective volume the channel region is  $10^{-17} \text{ cm}^3$  and the effective channel length is 20 nm since definitely depth of Si layer is 50 nm and the width is 10 nm. The value 20 nm is compared with 17 nm which is a spacing between source and drain junctions if continuous channel doping of  $1 \times 10^{17} \text{ cm}^{-3}$  is assumed.

Finally devices in which ions exist in regular positions are examined. Characteristics of devices in which ions are in a line with equal spacing are shown in Fig.6. Ions are in a line

at a depth of 4nm with a direction of channel length for devices designated by (1) and with a direction of channel width for devices designated by (2). In both cases of 5 and 10 ions,  $I_d$ - $V_g$  characteristics of regular ion devices are quite different from the ones of random ion devices. Regular 10 ion devices show even punch through characteristics, while random 10 ion devices does not. Thus, the conventional continuous doping can be a good approximation for random ions in decananometer range, but entirely not for regularly placed ions.

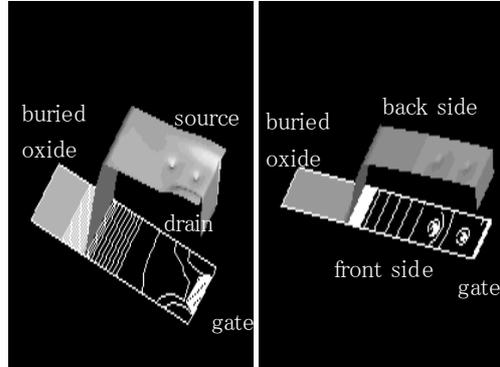


Fig.2 Electron density profile on the plane A (left) and on the plane B (right)

It should be noted that the

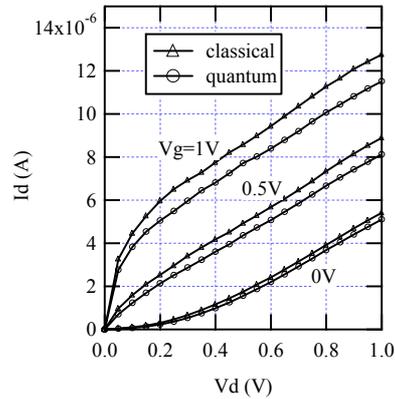


Fig.3 Drain current obtained by classical DD and DG models. Random 10-ions SOIMOSFET.  $V_d=0.5V$ .

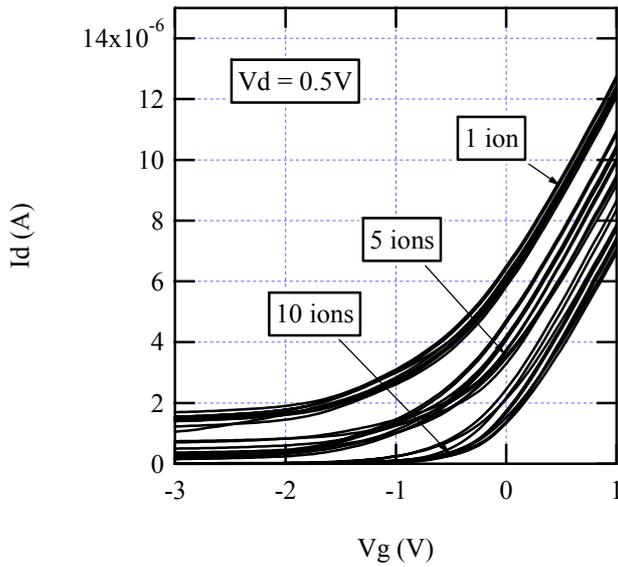


Fig.4. Id-Vg curves of ten single-ion SOI MOFETS and ten 5-, 10-ions ones each. Ions are randomly placed.

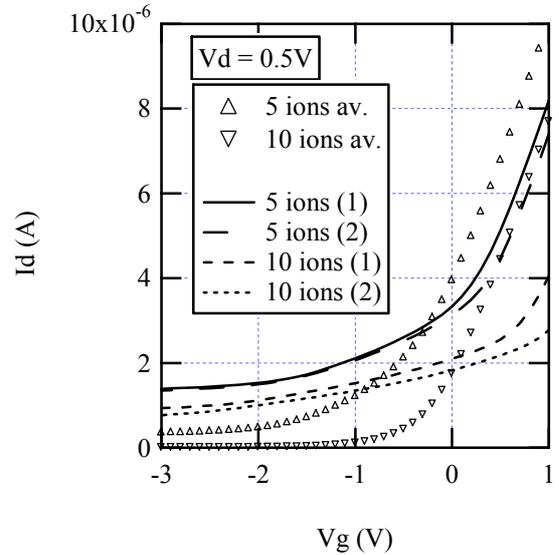


Fig.5. The averages of Id for random discrete ion devices, and Id for continuous doping devices.

#### 4 Conclusions

A robust 3D device simulator with density gradient model is developed to analyze effects of random or regular discrete dopants in ultra small SOIMOSFETs. It is shown that drain current characteristics for a few dopants or even a single dopant devices are on the average close to the ones for continuous dopant devices, if the dopants distribute at random, but not if they distribute regularly.

#### Acknowledgment

This work has been partially supported by The Asahi Glass Foundation.

#### References

- [1] M. G. Ancona and H. F. Tiersten, Phys. Rev. B, vol.35, pp.7959-7965, 1987.
- [2] C.S. Rafferty, B. Biegel, Z. Yu, M.G. Ancona, J. Bude and R. W. Dutton, SISPAD 1998, pp.137-140.
- [3] A. Asenov, G. Slavcheva, A.R. Brown, J.H. Davies and S. Saini, IEEE Trans. Electron Devices, vol.48, pp.722-729, 2001.
- [4] E. Lyumkis, R. Mickevicius, O. Penzin, B. Polsky, K. El Sayed, A. Wettstein and W. Fichner, SISPAD 2002, pp.271-274.

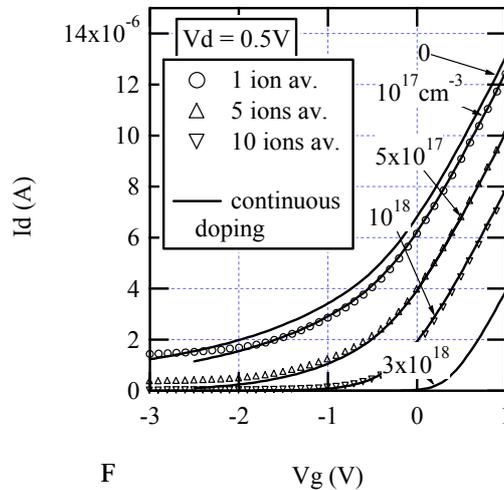


Fig.6. Id for devices with 5 or 10 ions lining up. The symbols are for averaged ones in Fig.5.