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Suppression of the rebound of hot-electrons from the drain region in ballistic transport due to device geometry: A Monte Carlo study

Takashi Kurusu and Kenji Natori

Institute of Applied Physics, University of Tsukuba
1-1-1 Tennoudai, Tsukuba, Ibaraki 305-8573, Japan
Phone: +81-29-853-6465, Fax: +81-29-853-5205 E-mail: kurusu@hermes.esys.tsukuba.ac.jp

1. Introduction

ITRS [1] predicts Si-MOSFETs with a 9nm physical gate length will be produced in mass production in 2016. In such nanoscale MOSFETs, the ballistic or quasi-ballistic transport is expected because the length scale of mean free path of a carrier and the channel length of MOSFETs are comparable to each other. Therefore, understanding physics of the ballistic or the quasi-ballistic transport is quite important to design nanoscale devices. We pointed out before that hot-electrons rebounded from the drain region significantly degrade device characteristics in the 1-dimensional ballistic n^+-i-n^+ structure [2]. It seems impossible to avoid the rebound of hot-electrons from the drain region in the 1-dimensional device structures, such as n^+-i-n^+ and n^+-n-n^+ diode, where the channel region has the same cross section of the channel region as that of the source and the drain regions. There is nothing to disturb the rebound of the hot-electrons in such 1-dimensional devices.

In this paper, we investigated the effect of the geometry of channel and drain regions on rebound of hot-electrons from the drain region. The 2-dimensional and the 1-dimensional ballistic n^+-i-n^+ diode are analyzed using semi-classical Monte Carlo simulator. We found that the rebound of hot-electrons from the drain region is suppressed in the 2-dimensional structure where the channel is narrower than the drain. We conclude that a device structure where the channel is narrower than the drain is effective in order to achieve the ideal ballistic transport.

2. Simulation Method

Figure 1 shows schematic structure of 1-dimensinal (1D) and 2-dimensional (2D) silicon n^+-i-n^+ diode we assumed. Monte Carlo (MC) method coupled with classical drift-diffusion (DD) simulator was used for analysis. The flow of the simulation is as follows: First, we perform the DD simulation to obtain the potential and electron distribution in the device (Figure 2, left). Second, we start the MC simulation using the potential and electron distribution obtained from the DD simulator, then potential is fixed during the MC simulation. In the 1D case, we used the potential at $y = W_{total}/2 = (2W_{OX}+W_{CH})/2$ as 1D potential along the channel (Figure 1, right). The core of MC simulator is the conventional one, where analytical band model considering anisotoropy, nonparabolicity and equivalent 6-fold valleys of the silicon band as described in Ref 2 is employed. We have assumed a boundary condition that the Si/SiO_2 interface is completely specular. Periodic boundary condition is applied in the direction of y-axis. We treated the contact as ideal ohmic one [4].

In all simulations, we assumed that the channel region is completely ballistic. All type of scatterings are ignored artificially in the channel region. In the source and drain region, the phonon and the ionized impurity scattering are considered. Inter-carrier scattering is ignored for simplicity. The lattice temperature assumed to be 300K.

3. Results and Discussions

Figure 3 shows distribution functions $f(x,v_x)$ within the channel on the condition of W_{CH} = 24nm and W_{OX} = 24nm at V_D = 0.5V. In the 2D case, the population of electrons due to the rebound is smaller than in the 1D case. Indeed, rebounded electrons with low energy seem to be few in the channel (Figure 6). As a result, the drift velocity within channel in the 2D case is larger than in the 1D result (Figure 4). Terminal current per unit channel width in the 2D case is also improved (Figure 5).

These results suggest that the assumed physical structure of the drain and channel region suppress the rebound of the hot-electron from the drain region. In the 2D structure in Figure 2 (b), where the channel width is narrower than drain's, the re-injection of hot-electrons from the drain into the source due to scatterings is suppressed by the physical structure of the device. The presence of the oxide region forbids hot-electrons randomized by scattering to be re-injected into the channel (Figure 7). Therefore, it is effective to select the narrow W_{CH} and wide W_{OX} for the suppression of the rebound of hot-electrons. This tendency is also shown in the terminal current characteristics.

4. Conclusions

We have investigated the electron transport of the ballistic 2-dimensional n^+-i-n^+ diode by the semi-classical Monte Carlo simulator from the viewpoint of suppression of the rebound of hot-electrons from the drain region. We found that the structure where the channel width is narrower than the drain width suppress the rebound of hot-electrons from the drain in ballistic devices. Therefore, the structure has narrow channel and wide drain is advantageous to achieve ideal ballistic transport. It is considered that the nanowire FET such as carbon nanotube FET, where the channel width is narrower than that of the drain, have essentially advantageous structure to suppress the rebound of hot-electrons.

References

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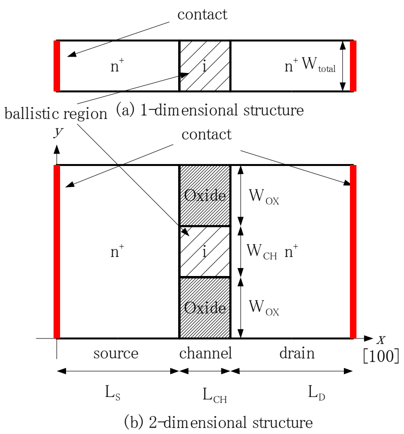


Fig. 1 Schematic structures of 1D and 2D diodes. We assumed L_{CH}= 48nm, $L_S = L_D$ = 100nm. $W_{total} = W_{OX}*2 + W_{CH}$. The donor density in the source/drain region N_D = 1E18 cm-3.

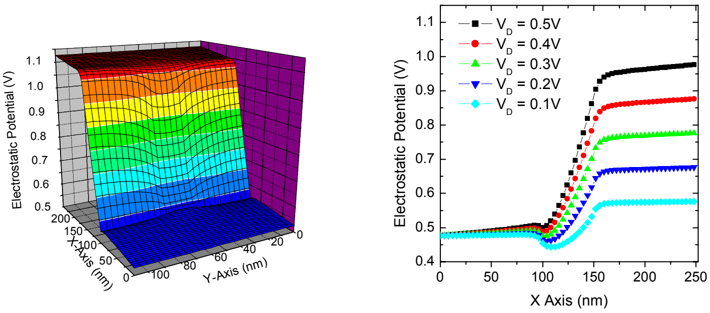


Fig. 2 Electrostatic potential obtained by classical drift-diffusion simulator. Left figure shows electrostatic potential at V_D = 0.5V. Right figure shows potentials at the center (y = $W_{total}/2$) of channel at various bias conditions.

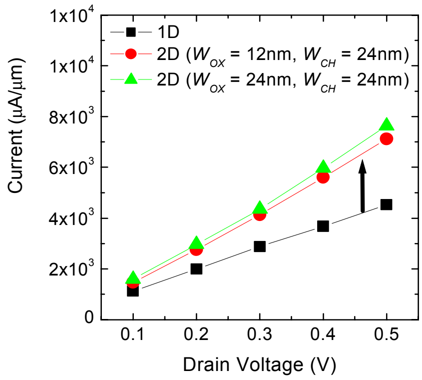
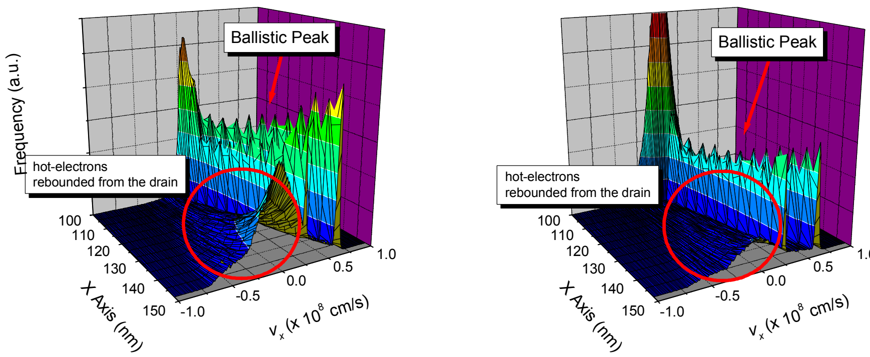


Fig. 5 Relationship of drain voltage to terminal current per unit channel width.



(a) 1D result (b) 2D result

Fig. 3 Distribution fucntions *f(x, vx)* within channel. The population of hot-electons rebounded from the drain region (indicated by circle) in the 2D case is smaller than in the 1D case.

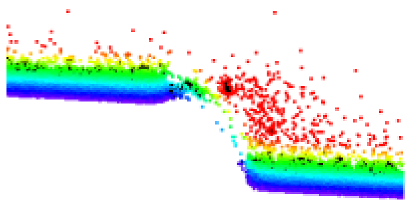
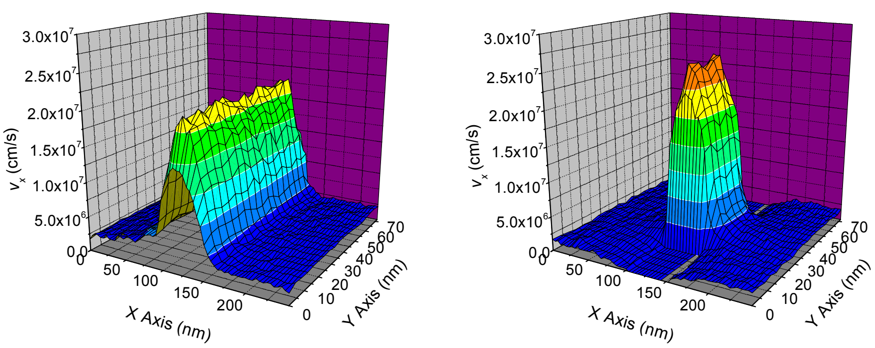


Fig. 6 Electron distribution in 2D diode at V_D = 0.5V.



(a) 1D result (b) 2D result

Fig. 4 Mean velocity (x-conpotent) distributions on the condition of VD = 0.5V. The maximum value of velocity in the 2D case is larger than in the 1D case.

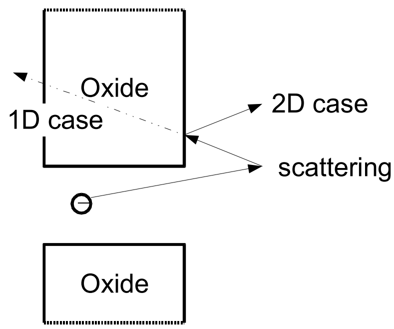


Fig. 7 Physical mechanism of suppression of the rebound of hot-electrons.