Performance of Silicon Ballistic Nanowire MOSFET with Diverse Orientations and Diameters

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To investigate the performance of the silicon ballistic nanowire MOSFET with diverse orientations and diameters, the subband structure of silicon nanowire has been calculated by using the tight binding simulator, and observed the changing of a minimum energy in the conduction and the valence subband and effective mass of electron and hole. This paper also present a compact model, which is used in numerical evaluation of the current vs. voltage characteristics of ballistic devices. Finally, the drain saturation current of n- and p-channel device with different orientations and diameters is shown.

Introduction

The size of semiconductor device is continuously shrinking. ITRS 2008 predicts that the Micro Processor Unit with a 9.7 nm physical gate length will be manufactured in 2020 (1). Therefore, recently the possibility of ballistic or quasi - ballistic transport in future semiconductor devices draws more and more attention. Due to its ability to control the device current and to suppress the off-state leakage current, it is widely expecting that the nanowire metal oxide semiconductor field effect transistor (MOSFET) might be one of the candidates for future ballistic devices. The diverse diameters and transport orientations various effects on performances of the devices. Different orientations primarily influence the carrier velocity. The [100] and the [110] oriented devices show higher electron transport velocities and better current performance compared to the [111] direction (2). Besides, the effective mass of carriers will be affected by the size of the diameter. Based on a numerical simulation, to examine and compare the effects of above various parameters on ballistic Si nanowire MOSFET is the purpose of this research. This work mainly has two aspects: one is calculations of the subband structure of the nanowire with different diameters and orientations. The other is the characterization of the ballistic Si nanowire MOSFET. The subband structure of nanowire is calculated by using a sp3d5s* tight binding simulator, which was released as an enhanced version of the Bandstructure Lab on nanoHUB.org (3). The technical approach, used in the latter aspect, is a compact model.

Method

The tight binding model: The tight binding model is an approach to calculation of subband structure using an approximate set of wave functions based upon superposition of wave functions for isolated atoms located at each atomic site.

Compact model: The drain current of ballistic devices can be evaluated by compact model, which represents one-dimensional channel current, after the subband structures was obtained. According to the compact model, the device current in the ballistic limit is approximately expressed by Landauer's formula (4):

$$I_D = \frac{q}{\pi\hbar}\sum_i \int [f(E,u_S) - f(E,u_D)]T_i(E)dE \qquad [1]$$

where q is the carrier charge and $\hbar$ is the reduced Planck constant, the summation i is over the subbands, E is energy, u_s and u_D are the Fermi levels of source and the drain electrode, respectively, and $u_D = u_S - qV_D$,where V_D is the drain bias, $f(E,u)$ is the Fermi distribution function

$$f(E,u) = 1/[1+\exp((E-u)/k_BT)] \qquad [2]$$

k_B and T are the Boltzmann constant and temperature, respectively. $T_i(E)$ represents the transmission coefficient of the carrier in the *ith* subband from source to drain. $T_i(E) \approx 1$ within the energy region between the subband minimum at $x = x_{\max}$ and subband maximum at the drain edge $x = x_{\min}$ as shown in Figure 1.

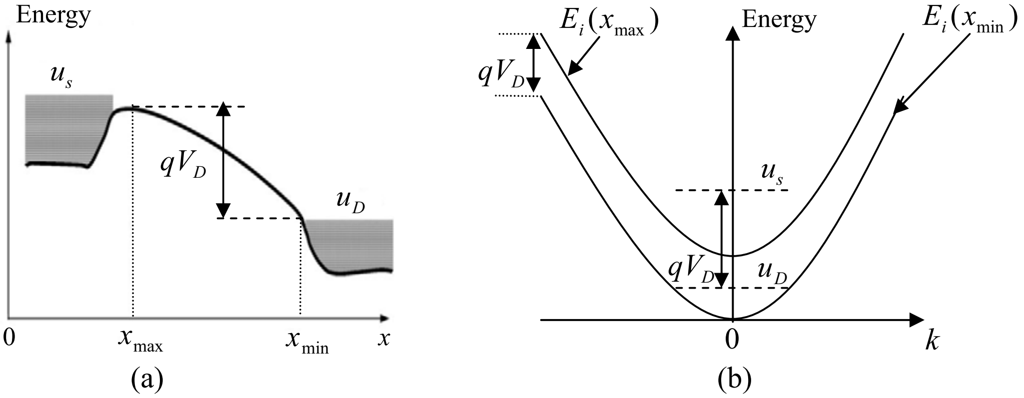


Figure 1. (a) Schematic diagrams of the potential energy profile along the channel, (b) energy subband of nanowire.

Thus, Landauer's formula [1] is evaluated with the use of Fermi distribution function [2] and one can obtain

$$I_D = G_0(\frac{k_B T}{q})\sum_i g_i(\sum_{dE\ /dk\ >0} \ln\{\frac{1+\exp[(u_S - E_{i\min(X\max)})/k_B T]}{1+\exp[(u_S - E_{i\max(X\min)})/k_B T]}\}$$

$$-\sum_{dE/dk<0} \ln\{\frac{1+\exp[(u_D - E_{i\min(X\max)})/k_B T]}{1+\exp[(u_D - E_{i\max(X\min)})/k_B T]}\})\ , \qquad [3]$$

where, $G_0 \equiv 2q^2/h = 77.8\ uS$ is the quantum conductance, g_i is the degeneracy of the ith subband. When $E_{i\max}(x_{\min})$ is mach larger than both of u_s and u_D, Eq. [3] is reduced to a simple form (5)

$$I_D = G_0(\frac{k_B T}{q})\sum_i g_i \ln\{\frac{1+\exp[(u_S - E_{i0})/k_B T]}{1+\exp[(u_D - E_{i0})/k_B T]}\} \qquad [4]$$

Where E_{i0} stands for the minimum of the ith subband at $x_{\max}$.

The following equation provides the Fermi level of source under gate voltage V_G (6-7)

$$(V_G - V_t) - \frac{u_s - u_0}{q} = \frac{|Q|}{C_G} \qquad [5]$$

Where, V_t is the effective threshold voltage, C_G is the channel–gate capacitance for cylindrical nanowire MOSFET, it is given by

$$C_G = \frac{2\pi\varepsilon_{ox}}{\ln(\frac{r+t_{ox}}{r})} \qquad [6]$$

Where, ε_{ox} is the dielectric constant of oxide thickness, r is the radius of the cylindrical wire, t_{ox} is the thickness of the insulator, $|Q|$ is the carrier charge density

$$|Q| = \frac{q}{\pi}\sum_i g_i[\int_{k_{i\min}}^{\infty} \frac{dk}{1+\exp\{\frac{E_i(k)-u_s}{k_B T}\}} + \int_{-\infty}^{k_{i\min}} \frac{dk}{1+\exp\{\frac{E_i(k)-u_D}{k_B T}\}}] \qquad [7]$$

Where, $dE_i(k)/dk \le 0$ for $k < k_{i\min}$ and $dE_i(k)/dk \ge 0$ for $k > k_{i\min}$.

Results

The calculated ballistic device is the gate all-around n- and p-channel cylindrical nanowire MOSFET as shown in Figure 2. The nanowires are aligned to different orientations ([100], [110], [111]), and have diameters ranging from 2nm to 10nm. The oxide thickness is 1.1nm.

Figure 3 (a) and (b) shows the calculated minimum energy of the conduction subband and the valence subband. The nanowire with a large diameter has low minimum subband energy, and the values of minimum subband energy in the all orientation are approximately close to 1.15ev in the conduction subband and 0.015ev in the valence subband when the diameter is 10nm. The band gap of nanowire becomes narrow as diameters increase in all orientation. The nanowire with [100] has a narrower band gap relative to [110], [111].

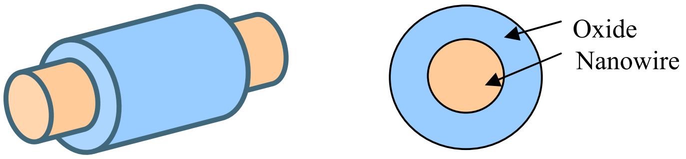
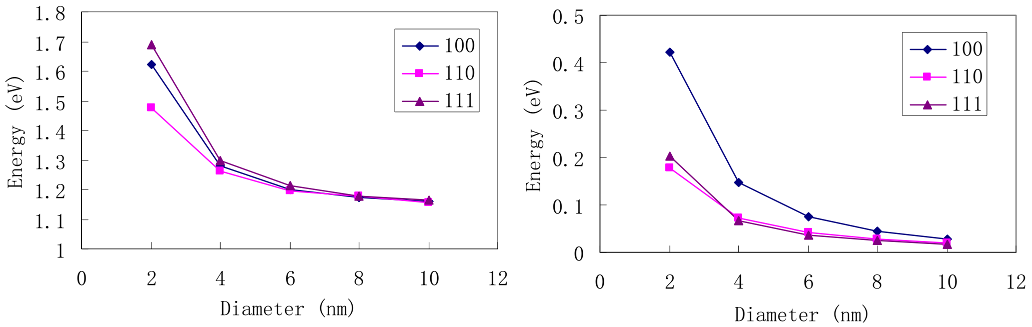


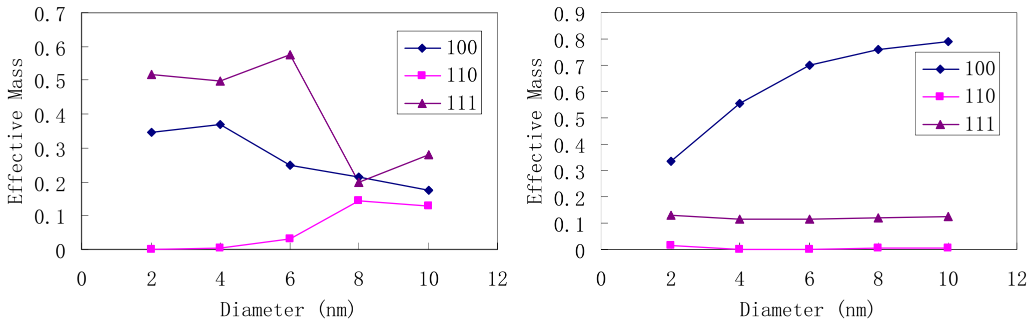
Figure 2. The structure of the analyzed nanowire MOSFET.



(a) (b)

Figure 3 (a) The conduction subband minima energy, (b) The valence subband minima energy.

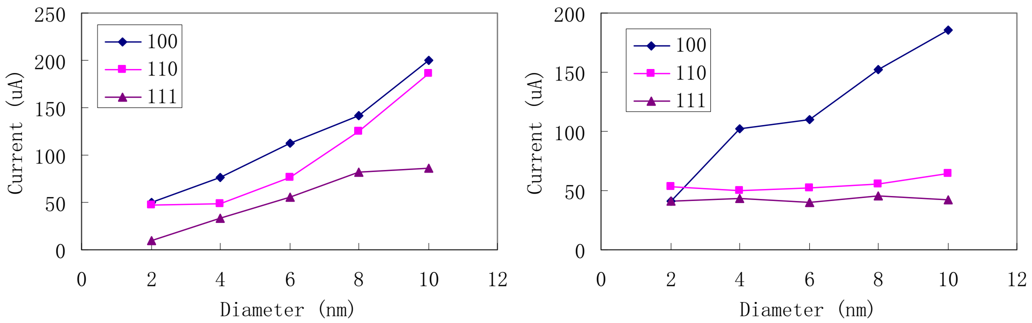
In Figure 4, (a) and (b) show the variation of effective mass of the electron and the hole at each orientation in first subband dependent on the diameter. The nanowire with orientation [110] has light electron and hole effective mass compare to other orientation under the same condition. The hole effective mass of [111] have almost constant values of about 0.12 $m_{0,}$ irrespective of the variation in the diameter. The hole effective mass of [100] became heavy as the diameters increase.



(a) (b)

Figure 4. (a) The electron effective mass, (b) The hole effective mass.

In this paper, the saturation drain current of the silicon ballistic MOSFET is calculated by compact model described as above. The saturation drain current variation versus diameters and orientations are evaluated with the gate voltage of 1V, the drain voltage of 0.5V at room temperature 300K.



(a) (b)

Fig. 5. (a) The saturation current of n-channel, (b) The saturation current of p-channel.

Fig. 5 (a) and (b) shows the calculated saturation drain current for the n-channel and the p-channel. The Si nanowire with a large diameter has high drain current, and large drain current can be obtained in the [100] orientation relative to other orientation when the diameter is larger than 2nm and orientation [110] can be obtain large drain current when diameter is smaller than 2nm under the same conditions.

Conclusions

The variation of minimum energy, the effective masses of electron and hole for the different orientations with different diameters have been calculated by the tight binding simulator. The value of minimum energy of the conduction and the valence subband decreases as the diameter increases for all selected orientation. The results show that Si nanowire with the orientation [100] can be the best channels for ballistic n-MOSFET when the diameter is larger than 2nm. The orientation [110] can be the best channels for ballistic p-MOSFET when the diameter is 2nm.

Acknowledgement

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References

1. International technology roadmap for semiconductors 2008 edition, http://www.itrs.net/
2. N. Neophytou, A. Paul, M. Lundstrom and G. Klimeck, IEEE Trans. Electron Devices, vol. 55, no. 6, pp.1286-1297, 2008.
3. [nanoHub] Bandstructure lab on nanoHUB.org https://www.nanohub.org/tools/bandstrlab/
4. M. Lundstrom and J. Guo, Nanoscale Transistors: Device Physics, Modeling and Simulation. New York: Springer-Verlag, ch. 5. 2006.

5. K. Natori, Y. Kimura, and T. Shimizu, J. Appl. Phys., vol. 97, no. 3, pp. 034 306-1–034 306-7,Jan. 2005.
6. D. Jimènez, J. J. Sáenz, B. Iniquez, J. Suné, L. F. Marsal, and J. Parllarès,J. Appl. Phys., vol. 94, no. 2, pp. 1061–1068, Jul. 2003.
7. K. Natori, IEEE Trans. Electron Devices, vol. 55, no. 11, pp. 2877-2885,Nov. 2008.