C-8-6L

Extended Abstracts of the 2009 International Conference on Solid State Devices and Materials, Sendai, 2009, pp1058-1059

A Novel Compact-Model of Quasi-Ballistic Nanowire MOSFETs

Kenji Natori

Tokyo Institute of Technology, Frontier Research Center
J2-68 4259 Nagatsuta, Midori-ku, Yokohama, 226-8502, Japan
Phone: +81-45-924-5174, E-mail: natori.k.aa@m.titech.ac.jp

1. Introduction

Recently, nanowire transistors attract wide attention. The device structure, especially the gate-all-around structure (Fig. 1), allows close control of the channel current, and is regarded as a promising candidate for the next generation device. The quasi-ballistic or ballistic transport is inevitable in these nanoscale devices. We have already presented a compact model of ballistic nanowire MOSFETs [1,2].

In this paper, we present a novel compact model of the *Quasi-Ballistic* nanowire MOSFET by implementing carrier scattering effect in the original ballistic model. The newly developed scattering model, considering the energy relaxation as well as the elastic scattering, provides a better insight into device physics of transport compared to the conventional relaxation time approximation approach.

2. Compact Model

The current expression is provided by introducing the carrier transmission probability $T_i(\varepsilon)$ at energy ε from source to drain through the *i*-th subband, in the original current expression of the ballistic compact model, as,

$$I_{D,Qbal} = \frac{q}{\pi\hbar}\sum_i g_i \int \left[f(\varepsilon,\mu_s) - f(\varepsilon,\mu_D) \right] T_i(\varepsilon) d\varepsilon \quad (1)$$

where, μ_S and $\mu_D = \mu_S - qV_D$ are Fermi levels of the source and the drain electrodes, respectively, and g_i is the subband degeneracy. The expression of $T_i(\varepsilon)$ was derived by embodying the transport model[3,4] illustrated in Fig. 2. The scattering model includes the elastic scattering and the energy relaxation due to optical phonon emission. The elastic scattering considers various scattering processes through Matthiessen's rule. The potential profile in the channel approximates constant field curve (electric field *E*). Carriers are injected into channel with the energy around thermal energy, which is smaller than the optical phonon energy for silicon. At the beginning of the channel ($x < x_0$ in Fig. 2), where the kinetic energy of carriers are too small to emit the optical phonon, carriers suffer only the elastic scattering. Beyond the region, carriers are exposed to energy relaxation due to optical phonon emission. The enervated carriers that have emitted the optical phonon never reach source even if backscattered, and eventually sink in the drain. The transport model was formulated as a pair of the Equations of Continuity, shown in Fig. 3. Here $F(x)$ and $G(x)$ are respectively the positive- and the negative-velocity flux. The solution yields the transmission probability $T(\varepsilon)$ from source to drain, as shown in the figure. Evaluation of the current value proceeds in a similar fashion as in the ballistic compact modeling. The gate capacitance C_G employs the same expression[1,2]. The electrostatics around the bottleneck also brings about the same formula[1,2],

$$(V_G - V_t) - \alpha \frac{\mu_S - \mu_0}{q} = \frac{|Q|}{C_G} \quad (2)$$

where V_t is the threshold voltage, $\alpha \equiv 1 + C_p / C_G$ where C_p is the parasitic capacitance associated with the backgate, μ_0 is the minimum energy of the lowest subband. The channel charge density Q depends also on $T_i(\varepsilon)$ and

$$|Q| = \frac{q}{\pi}\sum_i g_i \left[\int_{-\infty}^{\infty} \left(1 + \exp\left\{ \frac{\varepsilon_i(k) - \mu_S}{k_B T} \right\} \right)^{-1} dk \right.$$
$$- \int_{-\infty}^{k_{i\,\min}} \left\{ \left(1 + \exp\left\{ \frac{\varepsilon_i(k) - \mu_S}{k_B T} \right\} \right)^{-1} \right.$$
$$\left. \left. - \left(1 + \exp\left\{ \frac{\varepsilon_i(k) - \mu_D}{k_B T} \right\} \right)^{-1} \right\} T_i\left\{ \varepsilon_i(k) \right\} dk \right] \quad (3)$$

Where $\varepsilon_i(k)$ stands for the *i*-th subband energy. Equations (1), (2), (3), the gate capacitance, as well as the transmission probability arranged for each subband constitute a compact model for evaluation of the *I-V* characteristics of a nanowire MOSFETs. One can evaluate I_D, if the subband parameters, the MOSFET structure and the applied biases are given.

4. Results

We try to evaluate the *I-V* characteristics of a silicon nanowire MOSFETs at room temperature employing the subband parameters of a silicon nanowire with (1.34 nm)^2 cross sectional area, by the Bologna University group[5](Fig. 4). Fig. 5 is the I-V_D characteristics for the case the diameter is 1.5 nm and t_{ox} =1 nm with the SiO_2 gate insulator (GAA). Cylindrical wire is assumed although the data in [5] is used. The elastic scattering parameter, B_0, is so chosen as is consistent with the mobility μ=700 cm^2/Vs. The ballisticity r defined as $r = I_{D,Qbal}/I_{D,Bal}$ is plotted in Fig. 6. The ballisticity is shown to be reduced to around 60% due to scattering. Figure 7 shows the ballisticity-gate overdrive

(V_G-V_t) relation. The bias dependence of the ballisticity is shown to be rather small. The scattering effect is remarkable within the narrow region in the effective kT-layer close to the source, and the dimension of the region is not much affected by biases. Figures 8 and 9 show how the ballisticity depends on the elastic-scattering (B_0) and energy-relaxation (D_0) probabilities.

4. Conclusion

A novel compact-model of quasi-ballistic nanowire MOSFETs is disclosed. It is suitable for assessment of the scattering effect in thin nanowire devices.

Reference

[1] K. Natori, Ext. Abst. SSDM 2008, pp.40, (2008).

[2] K. Natori, IEEE Trans. Electron Devices, vol.ED-55, pp.2877, (2008).

[3] K. Natori, Jpn. J. Appl. Phys., vol.48. pp.034503, (2009).

[4] K. Natori, Jpn. J. Appl. Phys., vol.48. pp.034504, (2009)

[5] E. Gnani, S. Reggiani, A. Gnudi, P. Parruccini, R. Colle, M. Rudan, and G. Baccarani, IEEE Trans. Electron Devices, vol. ED-54, pp. 2243, (2007).

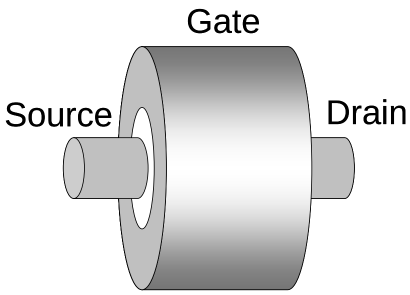

Fig. 1. Nanowire MOSFET with the Gate-All-Around(GAA) structure.

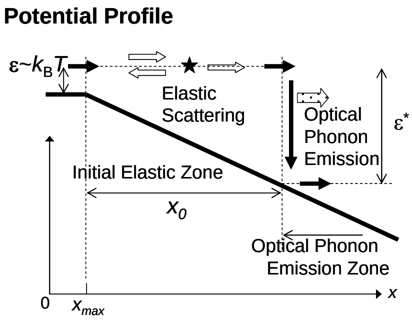

Fig. 2. Scattering model within the channel.

$$\sqrt{\frac{2}{m}(qEx+\varepsilon)}\frac{dF(x)}{dx}+\frac{B_0}{\sqrt{qEx+\varepsilon}}\{F(x)-G(x)\}=0$$

$$-\sqrt{\frac{2}{m}(qEx+\varepsilon)}\frac{dG(x)}{dx}+\frac{B_0}{\sqrt{qEx+\varepsilon}}\{G(x)-F(x)\}=0$$

$$T(\varepsilon)=\frac{\sqrt{2D_0}qE}{\left(\sqrt{B_0+D_0}+\sqrt{D_0}\right)qE+\sqrt{2mD_0}B_0\ln\left(\frac{qEx_0+\varepsilon}{\varepsilon}\right)}$$

Fig. 3. Equations of Continuity ($0 \le x \le x_0$) and the transmission probability from source to drain.

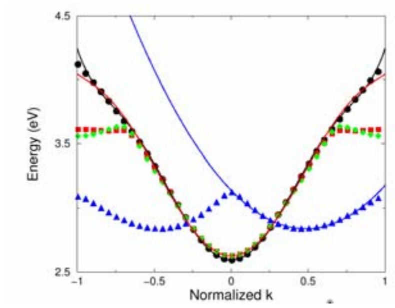

Fig. 4. The subband structure employed. [110]-square cross section with 1.34 nm side. (from DFT calculation by E. Gnari et al.[5])

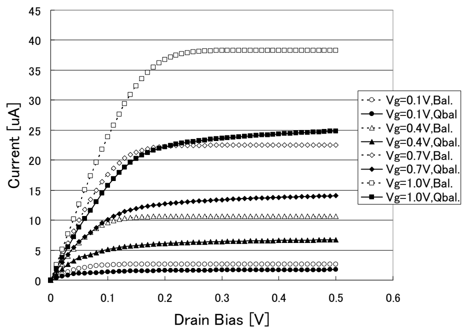

Fig. 5. I-V_D characteristics of the quasi-ballistic silicon nanowire MOSFET at room temperature.

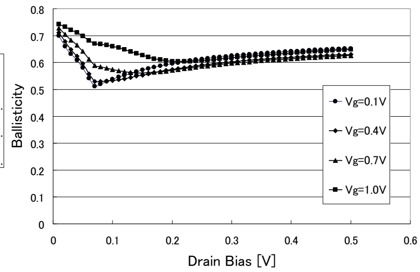

Fig. 6. Ballisticity–Drain bias characteristics of a quasi-ballistic silicon nanowire MOSFET.

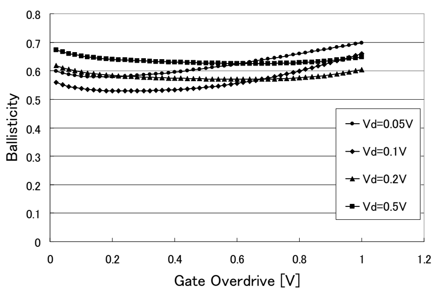

Fig. 7. Ballisticity – Gate overdrive characteristics of a quasi-ballistic silicon nanowire MOSFET.

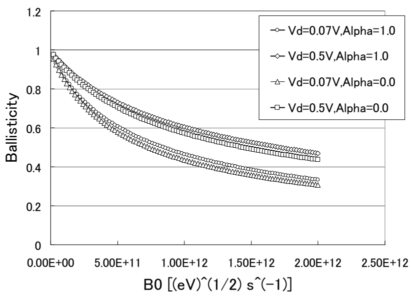

Fig. 8. Ballisticity-B_0 characteristics. Parameter B_0 is proportional to the elastic scattering probability.

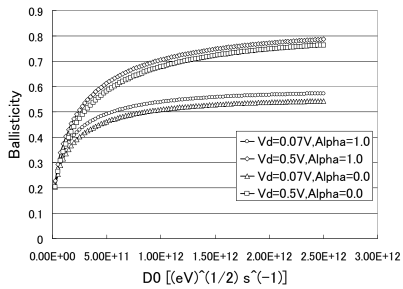

Fig.9. Ballisticity-D_0 characteristics. Parameter D_0 is proportional to the optical phonon emission probability.