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Transport Physics of Quasi-Ballistic Nanowire MOSFETs

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1. Introduction

Nanowire transistors attract attention as a promising candidate for future component of the high density LSIs. It is a limiting structure of the down-sized device, and affords deep insight into operation of nanoscale devices. We have already proposed the compact models of ballistic and quasi-ballistic nanowire MOSFETs [1,2].

In this paper, we try to point out and discuss several important aspects in transport physics of nanoscale transistors, based on analysis of the nanowire device operation using the compact model.

2. Compact Model of Quasi-Ballistic Nanowire MOSFET

A compact model of the quasi-ballistic nanowire MOSFET shown in Fig. 1, is used for discussion. The model has already been developed and disclosed in SSDM 2009. Some points necessary for our discussion are briefly summarized here. Electric current expression is derived using Landauer formalism including the carrier transmission probability $T_i(\varepsilon)$ from source to drain for carrier energy ε,

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

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 model considers various scattering processes through Matthiessen's rule. The potential profile in the channel is approximated by a constant field curve (electric field E). Carriers are injected into channel with the kinetic energy around thermal energy, which is smaller than the optical phonon energy for silicon. At the beginning of channel ($x < x_0$ in Fig. 2, denoted by "initial elastic zone"), where kinetic energy of carriers are too small to emit optical phonons, carriers suffer only the elastic scattering. Beyond there, in the "energy relax zone", carriers are exposed to energy relaxation due to optical phonon emission. Emitting an optical phonon, enervated carriers never reach source even if backscattered, and eventually sink within the drain.

3. Transport Physics Extracted from Model Analysis

The transport physics in nanoscale MOSFETs are usually discussed in terms of the "*kT*-layer theory" proposed by the Purdue University group. It is effective and convenient for understanding the mechanism of device operation, but is sometimes too simplified to correctly represent the complicated operation mechanism. Our model shows close resemblance to the "*kT*-layer theory". Figure 2 suggests correspondence between the *kT*-layer and the initial elastic zone. Here we discuss some transport physics of the device comparing the *kT*-layer theory and our model.

(1) In *kT*-layer theory, carriers are subject to backscattering within the *kT*-layer, and those carriers that have gone beyond the layer never return to source. In our model, however, the "back-injection" from the energy relax zone into the initial elastic zone, depicted in Fig. 3, is present irrespective of channel length, and plays a crucial role. The magnitude depends on trade-off between the elastic back-scattering and the energy relaxation within the energy relax zone. Due to the current component, improvement of ballisticity brought about by channel-length reduction in nanoscale MOSFET is greatly suppressed even in $L \to 0$ limit, as shown in Fig. 4.

(2) The ballisticity b defined as $b = I_{D,Qbal}/I_{D,Bal}$ in nanoscale MOSFETs exhibits an anomalous behavior as a function of gate overdrive as is shown in Fig. 5. The ballisticity takes a comparatively large value in weak inversion, and the strong inversion seriously degrades the value. This is because the ballisticity in weak inversion is expressed as $b = (1-r)$ where r is the elastic backscattering coefficient evaluated at the beginning of the channel. While the index in strong inversion has a smaller value given by $b = (1-r)/(1+r)$ as is widely accepted.

(3) The Fermi energy of injected carriers measured from the subband bottom at the beginning of channel amounts to 100~120 meV. (Fig. 6) The magnitude larger than the thermal energy is an evidence of the strong degeneracy for injected carriers, and so implies enhancement of injection velocity compared to thermal velocity. The increase of the value with increase of V_D implies a characteristic DIBL (drain-induced barrier lowering) effect due to restriction of charge density caused by the applied gate overdrive.

(4) Figures 7 and 8 show how the ballisticity depends on the elastic-scattering (B_0) and energy-relaxation (D_0) probabilities, and imply the difference of role played by the elastic scattering and the energy relaxation. The decrease in B_0, the elastic backscattering probability, improves ballisticity, as in Fig. 7. But the decrease in D_0, the energy relaxation probability, degrades ballisticity as shown in Fig. 8, eventually reaching $b = 0$ in the limit of $D_0 \to 0$. The elastic scattering and the energy relaxation respectively play completely distinct roles in carrier transport.

4. Conclusion

Transport physics of nanoscale MOSFETs is discussed based on characteristics of nanowire MOSFETs. The compact model discloses various new effects.

Reference

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

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

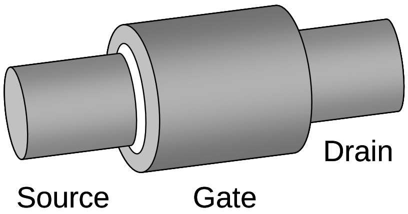

Fig. 1. Nanowire MOSFET with the Gate-All-Around(GAA) structure.

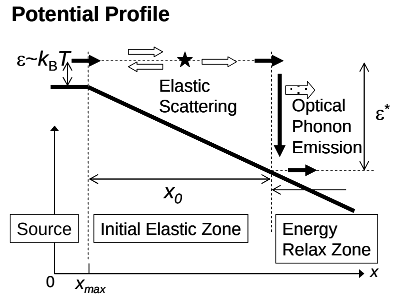

Fig. 2. Transport model of carriers with scattering in the channel.

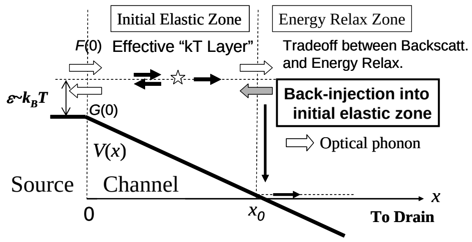

Fig. 3. Back-injection from the energy relax zone into the initial elastic zone is crucial for the transport.

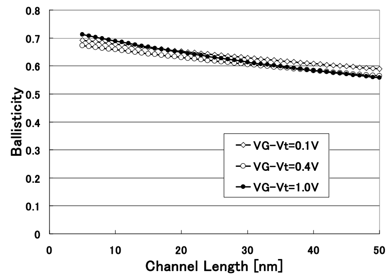

Fig. 4. Channel length dependence of the ballisticity. The ballistic transport is impossible even in $L \to 0$ limit.

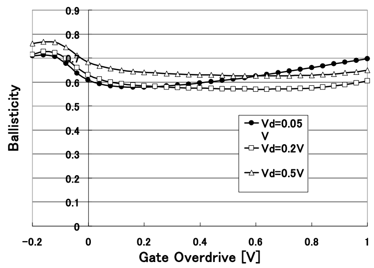

Fig. 5. Ballisticity as a function of the gate-overdrive. The enhancement in the weak inversion is shown.

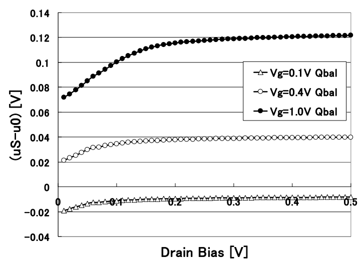

Fig. 6. The source Fermi level measured from the subband bottom, $(\mu_S - \mu_0)$, versus drain bias.

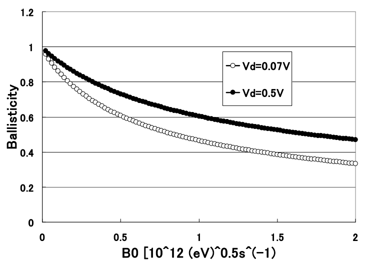

Fig. 7. Ballisticity versus B_0 proportional to the elastic backscattering probability.

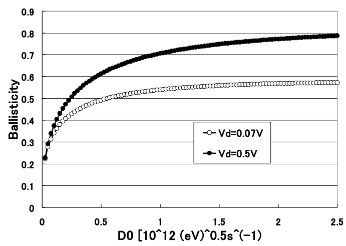

Fig. 8. Ballisticity versus D_0 proportional to the optical phonon emission probability.