# Systematic Study on Size Dependences of Transport Parameters for Ballistic Nanowire-FET with Effective Mass Approximation

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**1. Introduction**

From the scaling limit issues in planar MOSFETs, 3D-MOSFETs including a FinFET have been focused for future LSI devices, owing to their ability to reduce the off-current ($I_{off}$), which eventually reduce power consumption. These 3D-MOSFETs also provide the large on-current ($I_{on}$) by adjusting the threshold voltage ($V_{th}$) to appropriate values. However, the total current required for driving the circuit would be limited due to their narrow cross section. This concern is also applied to Nanowire-FET, which is the ultimate 3D-MOSFET. Although the Nanowire-FET has a smaller cross section, a large $I_{on}$ can be obtained with reduced scattering by a one-dimensional transport [1].

To analyze transport characteristics of the Nanowire-FETs, a one-dimensional ballistic transport model using Landauer's formula has been studied [2]. In this study, size dependences of transport parameters of the Nanowire-FETs are systematically analyzed using the transport model and band structures with an effective mass approximation.

**2. Transport Model and Effective Mass Approximation**

Fig. 1 indicates an example of a potential and an *E-k* dispersion at a bottleneck in the one-dimensional ballistic transport model. A total current is determined by difference between a forward ($dE/dk$>0) and a back current ($dE/dk$<0) at the bottleneck, where the amount of each current is determined by a Fermi level of a source ($\mu_s$) and a drain ($\mu_s$-$qV_d$), and the $V_d$ denotes a drain voltage.

1) A gate overdrive, 2) a drain voltage, 3) a gate capacitance, 4) a temperature and 5) a band structure are needed to estimate a drain current in the transport model. 1) We assumed the gate overdrive of 1 V and 2) the drain voltages when drain currents saturate. 3) We assume $SiO_2$ as gate insulator and its thickness ($t_{ox}$) of 1 nm. The gate capacitances per unit length of a cylindrical nanowire model only depend on radius ($r$). 4) Temperature is set by 300K.

5) The band structures of nanowires are obtained with the effective mass approximation. A simple cylindrical well with an infinite potential is adopted for the approximation. A degeneracy of each sub-band is set by 2-fold and 6-fold, an effective mass along confinement direction ($m^*_r$) is set by 0.2 and 0.5, and an effective mass along transport direction ($m^*$) is set by 0.1 ~ 1.0. It can be expected that Si nanowires have the degeneracy, $m^*_r$ and $m^*$ between those ranges, because of 6 pockets of bulk Si in the *E-k* dispersion.

Finally, with $r$ of 0.5 ~ 5.0 nm, size dependences of transport parameters can be derived by the transport model and the effective mass approximation. Reasonable size dependences of the transport parameters for Si nanowires can be found in our calculations with those conditions although a sub-band split occurs in the the nano-size, and the potential of the well is finite.

**3. Size Dependence of Transport Parameters**

Fig.2 shows contour plots of the $\mu_s$ dependences on the degeneracy, the $m^*_r$, the $m^*$ and the $r$. Because a small density of states causes a high $\mu_s$, the $\mu_s$ becomes high in the small $m^*$ and $m^*_r$ and 2-fold degeneracy. Increasing $r$ makes the density of states and the gate capacitance increase simultaneously. The density of states in each one-dimensional sub-band is very large at their minimum edge, and becomes small with increasing energy. In the case of small $r$, because the first group of sub-bands only contributes to determine $\mu_s$, the dominant contribution becomes increased capacitance with $r$ growth which induces a large charge, so that the $\mu_s$ increases as the $r$ increases. One the other hand, as the $r$ increases, the $\mu_s$ increases and closes to edges of a second group of sub-bands eventually, and its increase is stopped and it starts decreasing. Therefore, the $r$ with maximum $\mu_s$ exists where $\mu_s$ is the same with different between the first and second group of sub-band.

Fig.3 shows contour plots of evolutions of a mean injection velocity ($\langle v_{inj}\rangle$). When the ballistic-FET is saturated, there is not back current, and the $I_{on}$ is determined by injection velocity of carrier. The evolutions of the $\langle v_{inj}\rangle$ with 6-fold degeneracy are just like those of the $\mu_s$ as expected. On the other hand, in 2-fold figures, the evolution of the $\langle v_{inj}\rangle$ is abnormal. Because increased states with $\mu_s$ growth in 2-fold degeneracy are much smaller than those with r growth, increased states with $r$ growth are the dominant contribution to increasing states as shown in Fig.4. The increased states with $r$ growth are not contribution to the $\langle v_{inj}\rangle$ increase, so that if there are few states as small $m^*$, small $m^*_r$, small $r$, and small degeneracy, the $\langle v_{inj}\rangle$ is almost not dependent on the $\mu_s$.

Fig.5 shows contour plots of evolutions of a normalized total capacitance ($C/W$). To estimate the performance of a multi channel Nanowire-FET, a normalized parameter ($W$) is set by $2r$+$2t_{ox}$ as shown in Fig. 6. The $C/W$ in a high $\mu_s$ is inverse proportion to the $\mu_s$ because quantum capacitance limit is achieved in the high $\mu_s$. Increasing $C/W$ with $r$ growth as shown these figures. Although the $C/W$ increases as $r$ increases, its cause is not same with that of increasing $C$ with $r$ growth. It is caused by a reduction of a curvature of the cylindrical model.

Fig.7 shows contour plots of evolutions of a normalized on-current ($I_{on}/W$). The $I_{on}/W$ denotes a multiplication the $\langle v_{inj}\rangle$ and the $C/W$, and its evolution is almost like $\langle v_{inj}\rangle$ in both 2-fold and 6-fold degeneracy. In the case of 6-fold degeneracy, maximum $I_{on}/W$ exists in $r$ range of 1 ~ 3 nm, and it becomes almost constant in large $r$. If scattering is considered, it has enhanced performance that Si nanowire is made as possible as small and close to the $r$ with the maximum $I_{on}/W$. In the case of 2-fold degeneracy, although they have minimum values in $r$ range of 1 ~ 3 nm, the $r$ below 5 nm makes the $I_{on}/W$ with scattering enhance.

**4. Conclusions**

We have mainly discussed the $r$ dependence of the transport parameters; the $\mu_s$, the $\langle v_{inj}\rangle$, the $C/W$ and the $I_{on}/W$. The extensive change of the $\mu_s$ occurs in the $r$ below 5 nm, and the maximum $\mu_s$ exist in the $r$ range of 1 ~ 3 nm. The <$v_{inj}$>, the $C/W$ and the $I_{on}/W$ have been strongly related to the $\mu_s$. In the $r$ below 5 nm, transport parameters have been also changed remarkably. The maximum and minimum $I_{on}/W$ have been obtained in the $r$ below 4 nm, while the $I_{on}/W$ has been constant in the $r$ above 4 nm.

**Acknowledgements**

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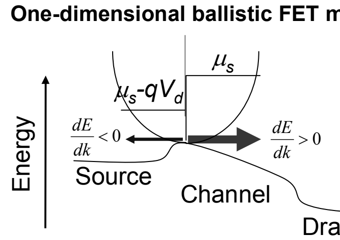


Fig. 1 one-diemensional ballistic-FET model. Total current is determined by difference between forward and back current.

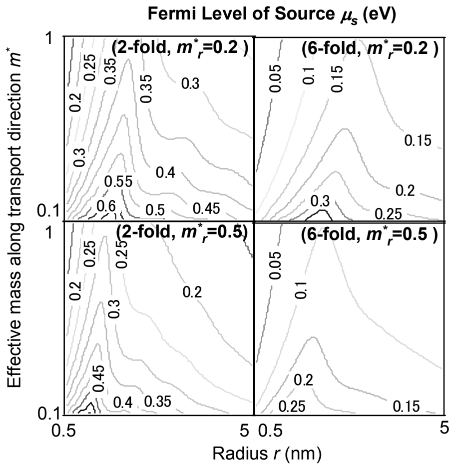


Fig.2 Contour plots of Fermi level of source ($\mu_s$) evolutions on the degeneracy, the effective mass along transport ($m^*$), confinement ($m^*_r$), and the radius ($r$). The maximum $\mu_s$ is obtained over $r$.

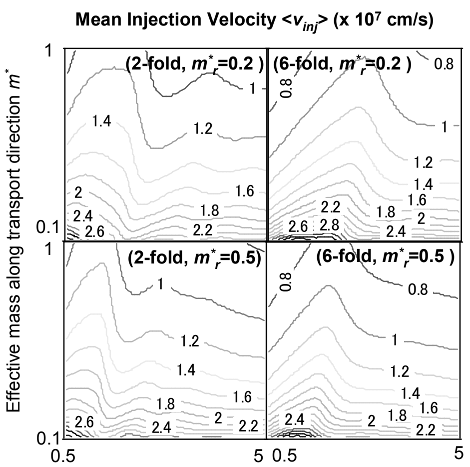


Fig.3 Contour plots of evolutions of mean injection velocity (<$v_{inj}$>). Evolutions of <$v_{inj}$> are almost like $\mu_s$.

**References**

[1] H. Sakaki, Jpn. J. Appl. Phys. **19**, L735 (1980).

[2] K. Natori, IEEE Trans. on Elec. Dev. **55**, 2877 (2008).

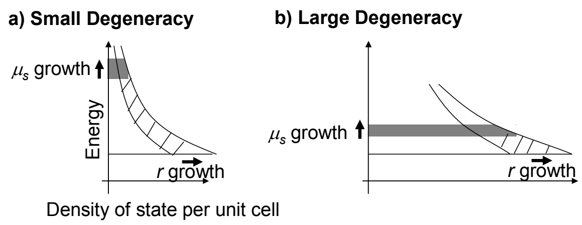


Fig. 4 Increasing states per unit cell by $\mu_s$ and $r$ growth in a) small and b) large degeneracy. Increased states with $\mu_s$ growth in small degeneracy are much smaller than those with $r$ growth as shown in a). Their work is contrary in large degeneracy.

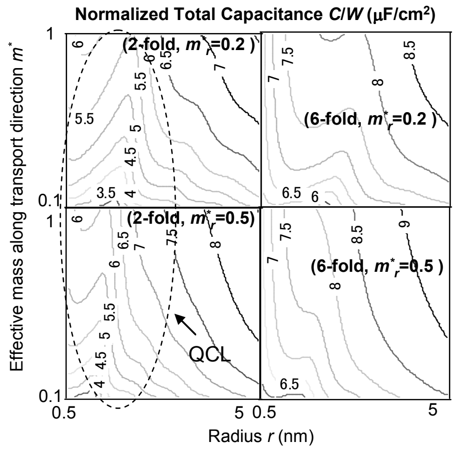


Fig.5 Contour plots of evolutions of the normalized total capacitance ($C/W$). The $C/W$ is inverse proportion to $\mu_s$ in high $\mu_s$ for quantum capacitance limit.

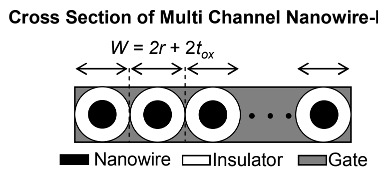


Fig.6 The cross section of a multi channel Nanowire-FET. The normalized parameter ($W$) denotes $2r+2t_{ox}$.

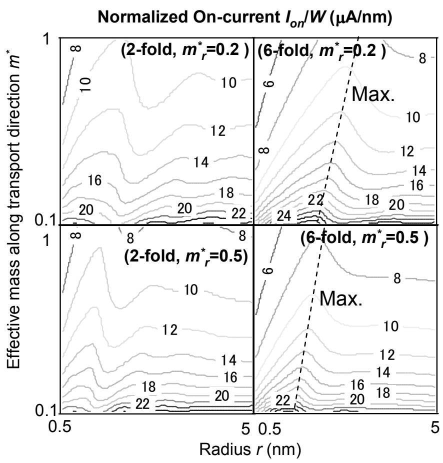


Fig.7 Contour plots of evolutions of the normalized on-current ($I_{on}/W$). The $I_{on}/W$ denotes multiplication the <$v_{inj}$> and the $C/W$.