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An Analytical Compact Model of Ballistic Cylindrical Nanowire MOSFET

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1. Introduction

Recently, nanoscale MOSFETs have been extensively investigated, and channel length is around the mean free path of electron. Consequently, drain current is mainly due to electron of ballisitic mode. For control of short channel effects, gate-all-around(GAA)-MOSFET allows a good control of short channel effects in undoped channel. For calculating characteristics of I_{DS}–V_{GS}, previous works defined a number of equations or fitting parameters, and these parameters depended on device scale [3,4]. In this paper, we derive an analytical compact model of drain current in cylindrical GAA-MOSFET. This model represents in whole current region without introducing the threshold voltage, using the method applied to double-gate(DG)-MOSFET in [1]. With only one equation to be solved numerically, and only one fitting parameter(flat-band voltage), the surface potential, potential distribution in the channel, energy level of electron, electron density in the channel, and drain current at any gate voltage can be calculated self-consistently.

2. Compact Model

Assuming the circlular cross section, the model structure in this study is cylindrical GAA-MOSFET having intrinsic Si channel and gate oxide with SiO_2 equivalent thickness t_{ox} (Fig. 1 (a) and (b)). In Fig. 1 (c), $E_{c,max}$ is maximum energy level of conduction band energy minimum distribution at z_{max}. In the ballistic transport, drain current I_{DS} is determined by the electron velocity and the number of electrons having energies higher than $E_{c,max}$. Figure 1 (d) shows potential energy distribution in the quantum well at z_{max}. In this plane, electrostatic potential distribution is approximately given by

$$w(r) = w_s - \Delta V\left(1 - \frac{r^2}{a^2}\right),$$

where $w_s = E_s/(-e)$ is the surface potential, ΔV is a parameter determining potential shape, and a is radius of circular cross section. The schrödinger equation in such a potential energy distribution includes the following matrix elements:

$$V_{m(k,n)} = \int_0^a rR^{0*}_{m,k}(r)\left(-ew(r)\right)R^0_{m,n}(r)dr \ ,$$

where $R^0_{m,n}$ is a wave function in the cylindrical 2D quantum well. In Fig. 2 (a), $V_{m(k,n)}$ as a function of k rapidly decreases as k increases, assuming that n is arbitrary integer number. For $k \geq n+2$, it is adequately smaller than $V_{m(n,n)}$ to ignore $V_{m(k,n)}$ in Fig. 2 (b). Then, the schrödinger equation is equivalent to the following equation.

$$\begin{vmatrix} \alpha_n\left(E^0_{m,n} - E_{m,n}\right) + V_{m(n,n)} & V_{m(n,n+1)} \\ V_{m(n+1,n)} & \alpha_{n+1}\left(E^0_{m,n+1} - E_{m,n}\right) + V_{m(n+1,n+1)} \end{vmatrix} = 0,$$

where $E^0_{m,n}$ is the electron energy level in the cylindrical 2D quantum well and α_n is a constant value determined by Bessel function. In this equation, electron energy level $E_{m,n}$ at z_{max} is derived, assuming the ΔV is a perturbation to the electronic static in the quantum well (Table. 1 (a)). With $E_{m,n}$, the total charge Q_{total} at z_{max} is derived as a function of ΔV by integrating Fermi distribution function and one-dimensional density-of-state (Table. 1 (b)). In addition, Q_{total} is calculated by integrating Poisson's equation in the model potential at z_{max}. Boundary conditions of Poisson's equation relate $E_s/(-e)$ with ΔV and ΔV must satisfy the following equation obtained from Table.1 (b) and integrating Poisson's equation:

$$Q_{total}(\Delta V) = -4\pi\varepsilon_{si}\Delta V \ .$$

The constant ΔV is obtained by numerically calculating this transcendental equation. The energies $E_{c,max}$, E_s and $E_{m,n}$ are then calculated self-consistently using this ΔV, and I_{DS} is obtained easily from the coupled Natori formura [2].

3. Result & Discussion

Figures 3–5 show the results obtained using the presented compact model. Gate voltage dependences of E_s, $E_{c,max}$, $E_{0,0}$ are shown in Fig. 3. In the subthreshold region, E_s and $E_{c,max}$ linearly follow V_{GS} because the potential distribution in the 2D quantum well at z_{max} is nearly flat. Electron occupation rate for each subband are shown in Fig. 4. For radius 2nm, Fig. 4 shows that it is enough to consider only the lowest two subbands in the Q_{total}. Figure 5 demonstrates I_{DS}–V_{GS} and I_{DS}–V_{DS} characteristics obtained using our compact model. With our compact model, one I_{DS}–V_{GS} curve for 2nm is calculated within 2 minutes, while it would take much longer time with full numerical simulations.

4. Conclusion

An analytical compact expression of drain current for a ballistic cylindrical GAA-MOSFET is proposed. Surface potential, confinement potential shape, energy level of electron, density of electron in channel and drain current are obtained self-consistently by calculating numerically only one transcendental equation. Electron occupation rate for each subband as a function of radius has been analyzed with this model. I_{DS}–V_{GS} and I_{DS}–V_{DS} characteristics have been obtained within several minutes. We would compare between numerical simulations and compact model, and improve this model in future works.

References

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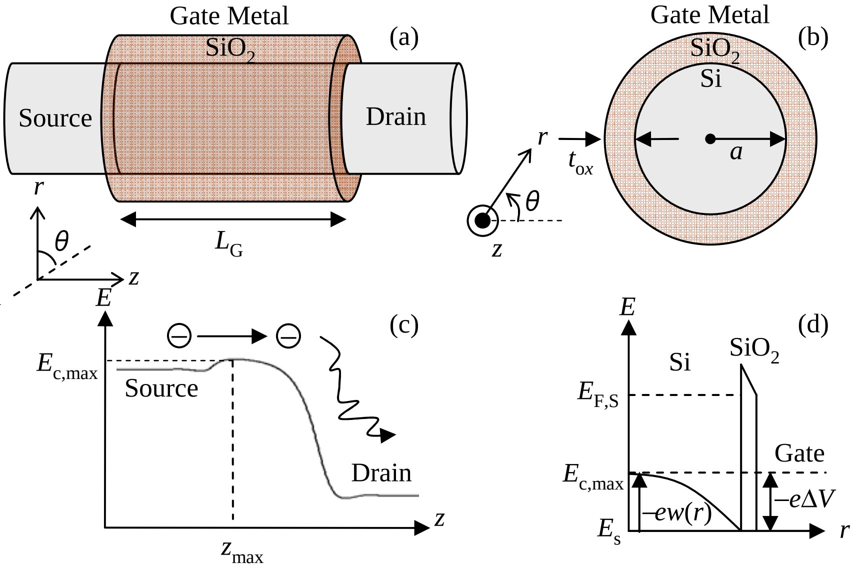
Table.1 Expressions for electron energy level and total charge using Fermi distribution function and one-dimensional density-of-states

(a) Electron Energy Level	$E_{m,n}=\frac{1}{2}\left\{\left(E^0_{m,n}+\frac{V_{m(m,n)}}{\alpha_n}\right)+\left(E^0_{m,n+1}+\frac{V_{m(n+1,n+1)}}{\alpha_{n+1}}\right)\right\}-\frac{1}{2}\sqrt{\left\{\left(E^0_{m,n}+\frac{V_{m(n,n)}}{\alpha_n}\right)-\left(E^0_{m,n+1}+\frac{V_{m(n+1,n+1)}}{\alpha_{n+1}}\right)\right\}^2+4\frac{V^2_{m(n,n+1)}}{\alpha_n\alpha_{n+1}}}$
(b) Q_{total}	$Q_{total}=\int_0^\infty dE_{total}D(E_{total}-E_{m,n})F(E_{total},E_F)$

Fig.1 GAA-MOSFET structures and schematic illustration of ballistic transport. (a) Schematic of cylindrical GAA-MOSFET. The z–axis, radius component r, and angular component θ are set as shown in the figure. (b) Schematic of cross section perpendicular to z–axis. Radius is a and gate oxide thickness is t_{ox}. Semiconductor wire material is Si and gate oxide is SiO_2. (c) Representation of ballistic transport in the z axis and conduction band energy distribution along the channel.
(d) Schematic of potential energy distribution in the r–θ plane at z_{max}. Fermi level at source is $E_{F,S}$, maximum energy level of distribution of conductionband minimum enery is $E_{c,max}$, SiO_2/Si surface potential eneryg is E_s and potential distribution in channel is $V(r)$.



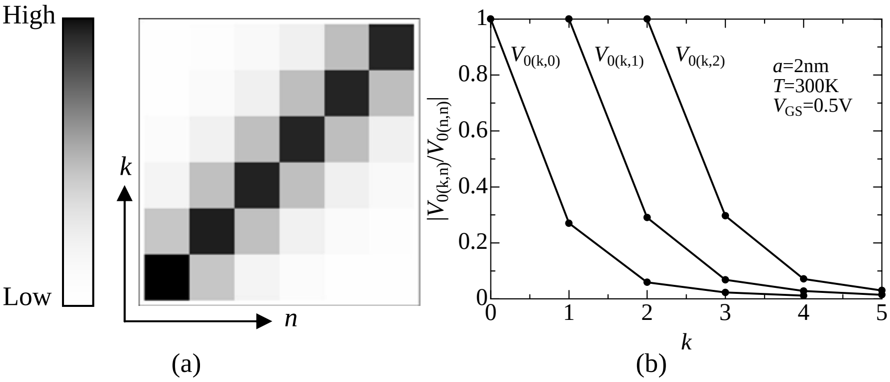


Fig.2 Magnitude of matrix elements $V_{m(k,n)}$, where integers m, n and k are the quantum number. (a) Density plot of $V_{0(k,n)}$ for $0 \le n,k \le 5$. Diagonal matrix elements have the largest value. (b) For n = 0,1,2, $|V_{0(k,n)}/V_{0(n,n)}|$ as a function of integer number k.

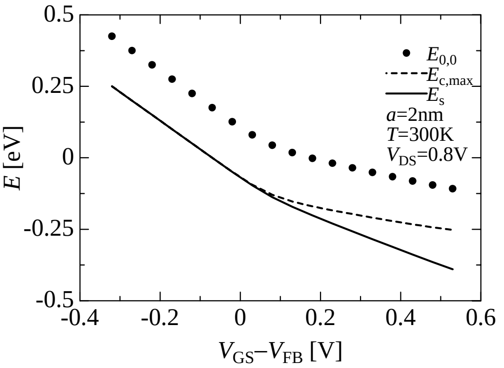


Fig.3 Solid line E_s, broken line $E_{c,max}$, and closed circle $E_{0,0}$ are calculated as a function of V_{GS}–V_{FB} using compact model. The source fermi energy $E_{F,S}$ is taken as referrence energy.

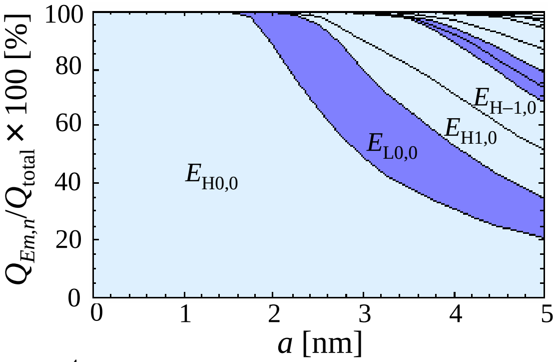


Fig.4 Electron occupation rates for each subband as a function of radius. For V_{GS}–V_{FB}=0.5V and V_{DS}=0.8V, $E_{Hm,n}$ and $E_{Lm,n}$ denote the electron energy having the effective electron mass $2m_l m_t/(m_l+m_t)$ and m_t in the r–θ plane, respectively, where m_l=0.91m^* and m_t=0.19m^* (m^* is electron rest mass). The $Q_{Em,n}/Q_{total}$ shows that how many subbands should be considered in drain current calculation.

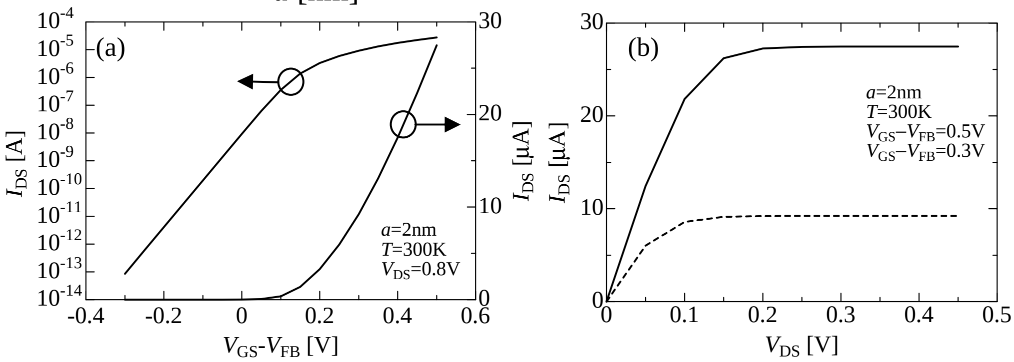


Fig.5 Calculated I_{DS}–V_{GS} and I_{DS}–V_{DS} characteristics for a = 2nm using compact model.
(a) Drain current as a function of V_{GS}.
(b) Drain current as a function of V_{DS} (solid curve:V_{GS}–V_{FB}=0.5V broken curve:V_{GS}–V_{FB}=0.3V).