Comparative Study of Silicon Nanowire Transistors with Triangular-Shaped Cross Sections

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Abstract

Nanowire transistors with triangular cross sections (TNWT) are proposed and studied. TNWT's working mechanism and the influence of physical parameters are investigated with TCAD tools. It is found that TNWT's conducting area expands from the channel center to the triangle's vertices with higher gate bias. TNWT has larger cross section than its counterpart with inscribed circle nanowire, thus exhibiting higher drain current and cut-off frequency. Moreover, we also find that TNWT with moderate angle is less affected by SCE, and shows lower subthreshold slope.

1. Introduction

As device dimension keeps diminishing, numerous novel structures, such as silicon on insulator (SOI), Schottky barrier (SB) MOSFETs, and nanowire transistors (NWT), have been proposed to maintain large drain current and minimize short channel effect (SCE).[1-3] Among these devices, NWTs with gate-all-round (GAA) structure are reported to have excellent gate control and high I_{on}/I_{off} ratio.^[3] Recently, NWTs with triangular-shaped cross sections (TNWT) have attracted much attention, due to the manufacture characteristic of self-stoping on {111} planes with anisotropic wet etch.^[4] Another feature of TNWT is that the triangular cross section can be further reduced by oxidation thinning method without long-time high temperature procedure.^[5] Previously, several experimental studies have been conducted on TNWT fabrication.^[4-6] In this paper, we focus on analyzing the working mechanism of TNWT, and the influence of device parameters on TNWT's performance is also investigated by comparison.

2. Device structure and simulation parameters

The schematic structures of NWT and TNWT are shown in Figs. 1(a) and 1(b), respectively. For both NWTs and TNWTs, the gate length, L_{g} , varies from 10 to 16 nm, and the source/drain (S/D) length, $L_{s/d}$, varies from 10 to 20 nm. According to the experiment^[4], the channel is along <110> direction, and n-type channels are mainly focused in this program. The channel doping, N_{ch} , is 10¹⁵ cm⁻³, and the S/D concentration, $N_{s/d}$, is 10²⁰ cm⁻³. The cross sections of NWT and TNWT are illustrated in Figs. 1(c) and 1(d), respectively. For TNWTs, the height of the triangle, H, varies from 3 to 8 nm. The angle between {100} and {111} plane, θ = arctan 2^{1/2} ≈ 54.74°. For NWTs, the cross section is the inscribed circle of TNWT's triangle, and the nanowire diameter, $D = (3^{1/2} - 1) * H \approx 0.73H$. The drain voltage, V_{dd} = 0.5 V, and the equivalent gate oxide thickness, T_{ox} = 1 nm. The default gate work function, GWF = 4.2 eV, and work function engineering is applied to get proper voltage bias.

3. Results and discussion

The transfer curves of NWT and TNWT are displayed in figure 2. TNWT's drain current is higher than that of NWT, because of a relatively larger cross section. From the log plot, we can see that TNWT has higher I_{on}/I_{off} ratio. Figure 3 shows the electron current density distributions along (a) NWT's and (b) TNWT's channel, respectively. NWT's conducting area has a certain distance to channel surface, which is the result of density-gradient potential quantum correction model. TNWT transports carriers mostly in the center of the channel. Figure 4 explains this phenomenon by plotting the current density distributions perpendicular to channel with (a) $V_g = V_{off} + V_{dd}$, and (b) V_g $= V_{off} + 1$ V, respectively. With larger gate bias, TNWT's conducting area expands to the vertices of the triangle, because of the higher electric field at corners.

From Fig. 5 to Fig. 7, the effect of D & H on device performance is discussed. OFF-state current is fixed at 1 nA/µm, and normalized drain current is calculated for comparison. In figure 5, I_{on} of NWT and TNWT with $L_g =$ 16 nm increase as D & H increase, because conducting area has higher growth rate than device perimeter. I_{on} of $L_g = 10$ nm has a turning point, due to the increase of subthreshold slope (SS) induced by SCE. Figure 6 shows the relation between gate work function difference, ΔGWF , and physical parameters. When D & H increase, NWT and TNWT require larger work function to keep I_{off} fixed at 1 nA/µm. TNWT with $L_g = 16$ nm exhibits lower ΔGWF than NWT. The SS & DIBL versus H curves for TNWT is plotted in figure 7. When H increases, the drivability of TNWT is reduced, which leads to the increment of SS and DIBL. TNWT with $L_g = 16$ nm keeps SS < 70 mV/dec and DIBL < 20 mV which indicates excellent gate control over channel

20 mV, which indicates excellent gate control over channel. The influence of θ on TNWT's performance is studied in Figs. 8 and 9. Figure 8 shows the relation between I_{on} and θ . I_{on} of TNWT with $L_g = 10$ nm and H = 4 nm increases as θ increases, while there is a turning point for H = 6 nm. This is because L_g with H = 6 nm is influenced by the decrease of conducting area when $\theta > 45^\circ$, and short L_g with H = 4 nm mainly benefits from less SCE. In figure 9, it is seen that, for all structures, ΔGWF decreases as θ increases, because gate modulation ability is enhanced by large θ . The relation between SS and L_g is displayed in figure 10. TNWT with $\theta = 75^\circ$ has lowest SS, which exhibits better gate control property. TNWT with $\theta = 54.74^\circ$ shows nearly the same SS as NWT when $L_g > 10$ nm. In figure 11, we further investigate the relation between cut-off frequency, F_t , and dimension parameters. We can see that TNWT has higher F_t than NWT, because larger cross section provides higher transconductance and intrinsic gain. F_t of NWT and TNWT with $L_g = 10$ nm decrease when D & H > 5 nm, because short L_g loses control of channel due to SCE.

4. Conclusion

In this paper, the characteristics of TNWT have been simulated and investigated. It is found that TNWT's current mostly concentrates in the center of the channel, and expands to the corners of the triangle with high gate voltage. TNWT exhibits higher drive current and cut-off frequency, due to its larger cross section. It is also observed that TNWT with $L_g = 16$ nm has lower ΔGWF than NWT, and smaller SS & DIBL than $L_g = 10$ nm. As the expanding analysis, we find that TNWT with moderate θ can make tradeoff between larger conducting area and less SCE.

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Fig. 1 Schematic structures of (a) NWT and (b) TNWT; sketches of cross sections: (c) NWT and (d) TNWT.



Fig. 2 Transfer curves of NWT and TNWT. $L_{\rm g} = 16$ nm, and $L_{\rm s/d} = 20$ nm. H = 4 nm, D = 0.73H, $V_{dd} = 0.5$ V, and GWF = 4.2 eV.



Fig. 3 Electron current density distributions along channel: (a) NWT at 0.5D and (b) TNWT at 0.5*H*. H = 4 nm, and D = 0.73H.



Fig. 4 TNWT's electron current density distributions perpendicular to channel with 0.2 nm to channel/source interface: (a) $V_g =$ $V_{\rm off} + V_{\rm dd}$, and (b) $V_{\rm g} = V_{\rm off} + 1$ V. $V_{\rm dd} = 0.5$ V, I_{off} is fixed at 1 nÅ/µm.



Fig. 5 Normalized Ion versus D & H with different L_g for NWT and TNWT. $L_g = 10$ nm, and $L_{s/d} = 10$ nm; $L_g = 16$ nm, and $L_{s/d}$ = 20 nm. D = 0.73H. $V_{dd} = 0.5 \text{ V}$, and I_{off} is fixed at 1 nA/µm.



Fig. 6 Gate workfunction difference ΔGWF versus D & H with different L_g for NWT and TNWT. $\Delta GWF = GWF - 4.2 \text{ eV}$. D =0.73*H*. $V_{dd} = 0.5$ V. I_{off} is fixed at 1 nA/ μ m.



Fig. 7 SS & DIBL versus H for TNWT with different L_g . $L_g = 10$ nm, and $L_{s/d} = 10$ nm; $L_{\rm g} = 16$ nm, and $L_{\rm s/d} = 20$ nm. $V_{\rm dd} = 0.5$ V, and $V_{\rm ddlin} = 50$ mV.



Fig. 8 Normalized I_{on} versus θ for TNWT with different L_g . $L_g = 10$ nm, and $L_{s/d} = 10$ nm; $L_g = 16$ nm, and $L_{s/d} = 20$ nm. H = 4and 6 nm. $V_{dd} = 0.5$ V, and I_{off} is fixed at 1 nA/ μ m. TNWT with $\dot{\theta} = 54.74^{\circ}$ is marked with blue symbols.



Fig. 9 Gate workfunction difference ΔGWF versus θ with different L_g for NWT and TNWT. $\Delta GWF = GWF - 4.2 \text{ eV}$. H = 4 and6 nm. Ioff is fixed at 1 nA/um. TNWT with $\theta = 54.74^{\circ}$ is marked with blue symbols.



Fig. 10 SS versus L_g for different structures with different D & H. H = 4 and 6 nm, and D = 0.73H. $L_{s/d} = 20$ nm, and $V_{ddlin} = 50$ mV. $\theta = 15^{\circ}$, 54.74°, and 75°.



Fig. 11 Cut-off frequency F_t versus D & Hwith different L_{g} for NWT and TNWT. $L_{g} =$ 10 nm, and $L_{s/d} = 10$ nm; $L_g = 16$ nm, and $L_{\rm s/d} = 20$ nm. D = 0.73H. $I_{\rm d} = 100 \ \mu {\rm A}/\mu {\rm m}$.