Supporting Materials

Ultra-short Channel Silicon Nanowire Transistors with Nickel Silicide Source/Drain Contacts

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Etching of native oxide on Si NW channel:

The native oxide on Si nanowire channel is subjected to 300 keV electron beam radiation in TEM, which may create defects in this dielectric layer at the Si/oxide interface and degrade the gate control over the channel. To prevent the formation of such defects, we performed a special process to remove the native oxide on Si channel before introducing the sample into TEM chamber.

A straightforward dip in buffered oxide etch (BOE) will result in dissolution of Si nanowire (Figure S1a) through the following two-step reaction^{1,2}:

To prevent supplying Ni ions from reaction (1) to reaction (2), we deposited a thin amorphous Si layer to protect the Ni electrodes during the BOE etching (Figure S1b, S1d). The BOE is diluted with 6 part water and the etch time is 20s, which is calibrated to remove about 3.5 nm of the thermal oxide. With a-Si protection layer, the Si NW is intact after BOE etch as demonstrated in Figure S1d.

Figure S1. (a) SEM image showing that the unprotected segment of the Si NW close to the Ni contact is etched during a BOE dip. (b) Top-view cartoon illustrating the use of a PECVD amorphous silicon layer to protect Ni from the BOE etchant. (c) With an amorphous Si protection layer, the Si NW remains intact after a BOE dip as highlighted by the red arrow, which contrasts the situation of the unprotected NW in (a). (d) A low magnification TEM image showing the a-Si protection layer whose boundary is highlighted with dashed black-lines.

Figure S2. (a) A short Si channel. The scale bar is 10nm. (b) HRTEM image of the source/channel and drain/channel interface, showing the leading phase to be NiSi_2 even when the channel is very short.

Evaluation of the series resistance of nickel silicide S/D extension segment:

In our shortest channel (17 nm) device, which has the longest silicided NW segments, the on-state channel resistance is 37 k Ω . We experimentally determined the resistance of a fully silicided nanowire of the same length (Figure S3a), as 1.3 k Ω , using a two-terminal I-V measurement. In addition, we combine the phase information obtained from TEM and resistivity value from Table S1 to calculate the total resistance of a fully silicided nanowire segment of the same length to be 856 Ω . Both our measurement and calculation imply that the S/D series resistance is negligible compared with the channel resistance for all our investigated devices.

Table S1. Structural data and electrical resistivity of various type of nickel silicide phases

phases	crystal system	a/ $\text{\AA}$	b/ $\text{\AA}$	c/ $\text{\AA}$	density g/cm ³	V per Si atom $\text{\AA}^3$	Resistivity $\mu\Omega\text{cm}$
$\text{Ni}_{31}\text{Si}_{12}$	hexagonal	6.671	-	1.228	7.56	39.6	60*
$\delta\text{-Ni}_2\text{Si}$	orthorhombic	4.99	3.72	7.06	7.37	32.8	25*
$\theta\text{-Ni}_2\text{Si}$	hexagonal	3.836	-	4.948	7.88	30.7	25***
NiSi	orthorhombic	5.175	3.332	5.609	5.97	24.1	13*
NiSi_2	cubic	5.395	-	-	4.83	19.7	24**
Si	cubic	5.430	-	-	2.33	19.9	-

* value taken from reference ³

** value taken from reference ⁴

*** We did not find a resistivity value for $\theta\text{-Ni}_2\text{Si}$. Therefore, we assume the resistivity of $\theta\text{-Ni}_2\text{Si}$ is the same as that of $\delta\text{-Ni}_2\text{Si}$.

Figure S3. (a) TEM image of a fully silicided Si NW. The scale bar is 1 μ m (b) Corresponding two terminal IV curve of the device in (a).

Figure S4. The gate capacitance per unit length as function of length obtained from full 3D simulation of NW devices with different channel lengths and the asymptotic limit of infinite long NW obtained by 2D simulations.

Figure S5. Transfer curves of the same device (channel length = $0.83 \mu\text{m}$ and NW diameter = 35 nm) before and after post-metal-gate annealing in forming gas at 300°C for 1min. The annealing step helps to improve on-current and inverse subthreshold slope. The

Figure S6. Comparison of simulated devices with 10^{16} cm^{-3} , 10^{18} cm^{-3} and $5 \times 10^{18} \text{ cm}^{-3}$ p-type doping densities: (a) Transfer curves, and (b) valence band-edge profiles in the on-state ($V_{ds} = -1 \text{ V}$, $V_g = -4 \text{ V}$).

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