Structural and electronic properties of silicon-on-insulator (SOI) nanowires with a cross section area of $20 \times 20$ nm$^2$ were investigated with high spatial resolution by multimode scanning probe microscopy (MSPM) in the constant force mode. The position-dependent tunneling current was measured in the interior of the Si nanowires whose surfaces were terminated with hydrogen and with ultrathin thermal oxide. The current value and fluctuations were reduced for Si nanowires terminated with an ultrathin oxide layer ($\sim 0.3$ nm), indicating the homogeneous surface passivation. The tunneling current decreased within a distance of $\sim 300$ nm from the Si pad electrode for both types of surface termination. Calculations of the tunneling current were performed based on the macroscopic conduction model including the conductance contributions of the nanowire volume and the surface states. In the model, the bulk carrier concentration and the surface state density were tuned to fit the experimental data for the small Si nanowires. The results support the length-dependent conductance of thin Si nanowires, demonstrating the ability of the technique for characterization of modern silicon-on-insulator devices.

Key words: silicon, scanning probe microscopy, nanowire, tunneling current, conductance
Fig. 2. AFM topograph (a) and current map (b) of a H-terminated NW taken at $V_S = -1.5$ V. Broken line in (a) indicates the SOI edge. White triangle marks a surface contamination. The gray scale is 3 nm in (a) and 80 pA in (b).

Additionally, annealing in a mixture of H$_2$ (5%) and N$_2$ gases was performed at 450 °C for 30 min to reduce the residual density of surface states on Si/SiO$_2$ surface.

2.2 Tunneling current maps

Measurements were performed in a non-contact atomic force mode with a metallic probe tip attached to a qLER cantilever. In the mode, the tip-surface distance was kept constant by maintaining the force acting on the metal probe tip in the repulsive regime. To control the tip-surface interaction force, we used the shift in the resonance frequency ($\Delta f$) of the qLER which vibrated at ~1 MHz ($Q$ factor ~45 000) with an amplitude of 0.1 nm.\[11,12,15\] In our setup, the tip-surface distance (the tunneling barrier) was ~0.5 nm on H-terminated surfaces.\[16\] When a bias voltage ($V_S$) was applied between the probe and the Si pad, mean tunneling current was recorded at each position of the probe tip.\[Fig.1\] All measurements were performed in dark at room temperature in an ultra-high vacuum chamber (a residual pressure of ~1.4 $\times$ 10$^{-7}$ Pa).

2.3 Tunneling current calculation model

Calculations of the tunneling current were performed considering resistances of the tunneling barrier and the NW volume connected in series as shown in Fig.1. In our calculations, we assumed that (1) the position dependence of the tunneling current is given mainly by the NW conductance; (2) the measured current is defined as a product of the tunneling factor and total amount of carriers supplied within the tip-induced band bending (TIBB) region in Si (the collection volume) beneath the probe tip.

Amount of supplied carrier at the probe position is obtained from the conductance of the NW including the bulk and surface contributions as

$$\frac{1}{R_{NW}(x)} = G_{NW} + G_{surface} = q\mu_x \left( \frac{N_x}{x} \right) + q\mu_x N_{SS} A_S,$$  \hspace{1cm} (1)

where $q$ is the NW cross section, $A_S$ is the surface collection area, $q$ is the elementary charge, $\mu_x$, $\mu_s$ are the effective mobility of carriers in Si bulk and the surface, respectively. $N_x$ and $N_{SS}$ are densities of the NW bulk carriers and the surface states, respectively. The quantity in brackets in Eq. 1 is an effective carrier concentration.

The tunneling resistance ($R_{tun}$) is related to the quantum mechanical tunneling probability, i.e. the tunneling factor. For a rectangular potential barrier, it is approximated by an exponential function

$$T_{tun} \propto e^{-\alpha d}; \quad \text{with } \alpha = b\sqrt{BH - \frac{V_{gap}}{2}}.$$  \hspace{1cm} (2)

where $d$ is a width of the tunneling gap, $V_{gap}$ is the potential across the gap, $BH$ is the effective potential barrier in the gap, and $b$ is the constant.

In metal-insulator-semiconductor structures,\[17\] the potential across the gap is defined by the strength of electric field in Si at the probe position ($\Phi_p$). Using the continuity of electric displacement across the silicon/vacuum interface, the potential across the gap is expressed as

$$V_{gap} = V_S - V_{NW} = d \frac{\varepsilon_0}{\varepsilon_S} \Phi_p = \frac{d}{\varepsilon_0} \left| Q_{SS} \right|,$$  \hspace{1cm} (3)

where $V_S$ is the applied voltage, $V_{NW}$ is the potential across the NW, and $\varepsilon_0$, $\varepsilon_S$ are the permittivity of vacuum and the dielectric constant of silicon, respectively. According to the Gauss’s law the charge per unit area in Si ($Q_{SS}$) at the probe position determines the electric field in the gap. Therefore, decrease of the effective carrier concentration in the collection volume results in decrease in the potential across the gap. Under the steady-state conditions, the potential distribution in the NW can be obtained from the solution of the Poisson equation at each probe position.\[17\] Here, we assume
that electric field is homogeneous in the NW volume, thus, the potential across the NW is given by

$$V_{ss} = V_x \left( \frac{\varepsilon_x x}{d \cdot \varepsilon_{in} + x \cdot \varepsilon_{in}} \right)$$  \hspace{1cm} (4)$$

The approximation is appropriate for intrinsic Si and a short and thin NW in our case.

Finally, amount of carriers supplied from the NW is obtained by integrating the respective carrier concentrations over the collection region. Because the tunneling factor depends on $V_{ss}$, decrease in NW conductance leads to decrease of the tunneling factor. Therefore, the tunneling current was calculated at each position of the probe along the NW.

We used bulk values of Si parameters. In particular, the mobility in the bulk and on the surface were taken to be equal $\mu_{in} = \mu_s = 400$ cm$^2$/Vs for Si nanowires.\[1\]

The radius of the collection region was taken to be 13 nm, corresponding to the Debye length for electron accumulation in Si at $V_x = -1.5$ V.\[17\] Since the density of surface states depends on the surface passivation, we used different $N_{SS}$ value and the gap width ($d$) for H-terminated and oxide-passivated surfaces to fit the measured data.

3. RESULTS AND DISCUSSION

3.1 Current map

Topographical images and current maps like those shown in Fig.2 were obtained simultaneously for a detuning of $\Delta f=0.6$ Hz and a probe-vibration amplitude of 0.1 nm. At $V_x=-1.5$ V, the mean tunneling current was uniform in the Si pad. Fine features in the interior of the NW were seen in the current map in Fig. 2(b), indicating the spatial resolution of a few nanometers.

3.2 Surface passivation effect

Line profiles of mean tunneling current in Fig. 3 were taken along the middle of the same NW after different surface passivation. The distance was measured from the position corresponding to the edge of the Si pad as indicated in Fig. 2. For both types of the surface passivation, the tunneling current gradually decreases within a distance of $\sim 300$ nm from the pad. For the H-terminated surface, the current decreases by 7 fold from $\sim 35$ pA at -100 nm to $\sim 5$ pA in the NW interior at 300 nm. For the oxide-passivated surface, the current decreases by $\sim 50$ fold from $\sim 4$ pA at -100 nm to $\sim 0.08$ pA at 400 nm.

The current was abruptly decreases at 280 and 390 nm for the H-terminated NW in Fig.3, where a surface contamination was present like that marked by triangle in Fig. 2(b). Homogeneity of the current was better for the oxide-passivated surface than that for the H-terminated surface, suggesting the stable and uniform passivation layer.

The current on the H-terminated surface was $\sim 9$ fold larger than that on the oxide-passivated surface in the pad region in Fig.3. In the NW interior the current ratio was $\sim 60$. The difference suggests large contribution of the surface conductance for the H-terminated NW. There are two factors reducing the tunneling current for the oxide-passivated NWs: (1) the width of the tunneling gap is increased due to the presence of the ultrathin oxide layer, and (2) the low density of surface states on the oxide-passivated surfaces results in low surface conductance. When the tunneling gap is large, the tunneling current is reduced in both the SOI pad and the NW interior because of exponential dependence of the tunneling current on the gap width. However, the observed current was significantly lower in the NW interior, suggesting that other effects are essential.

3.3 Current calculations

To assess the effects of the surface preparation, the

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|}
\hline
\textbf{parameter} & \textbf{H-terminated} & \textbf{Ultrathin Oxide} \\
\hline
$d$ (nm) & 0.6 & 0.9 \\
$N_0$ (1/cm$^3$) & $1.3 \times 10^{14}$ & $1.5 \times 10^{14}$ \\
$N_{SS}$ (1/cm$^3$) & $7.5 \times 10^7$ & $6 \times 10^6$ \\
\hline
\end{tabular}
\caption{Parameters used in the calculations of tunneling current profiles of 200x200nm$^2$ SOI NWs.}
\end{table}
tunneling current was calculated considering the contributions of both bulk and surface conductance. Figure 3 with the parameters indicated in Table 1 shows results of the calculations where values of \( N_0 \) and \( \sigma_0 \) were adjusted to fit the measured current. For the H-terminated surface, the best fit to the measured current was obtained with \( N_0 = 1.3 \times 10^{14} \, \text{cm}^{-2} \) and \( \sigma_0 = 7.5 \times 10^2 \, \text{cm}^2 \). For the oxide-passivated surface, we obtained \( N_0 = 1.5 \times 10^{14} \, \text{cm}^{-2} \) and \( \sigma_0 = 6 \times 10^2 \, \text{cm}^2 \). Here, we used a tunneling gap of 0.6 nm for H-terminated surface, and 0.9 nm (including a thickness of the ultrathin oxide layer of 0.3 nm) for oxide-passivated Si surface, as defined from the calibration. [14] We assessed variation in the derived concentrations assuming a tunneling gap uncertainty of 0.05 nm, a half of the probe vibration amplitude. With the tunneling gap reduced by 0.05 nm, the derived concentrations were decreased by a factor of ~2.6. Therefore, the obtained carrier concentration \( N_0 \) is in a range of 0.5 - 3.3 \times 10^{14} \, \text{cm}^{-2} \) for our undoped SOI samples.

The measured current profiles well agree with the current calculations results based on the conductance model including the bulk and surface contributions. The large discrepancy at the distance less than 100 nm is attributed to increase in the NW cross section area when large discrepancy at the distance less than 100 nm is obtained (Figure 3 with the parameters indicated in Table 1) shows results of the calculations where values of \( N_0 \) and \( \sigma_0 \) were adjusted to fit the measured current. For the H-terminated surface, the best fit to the measured current was obtained with \( N_0 = 1.3 \times 10^{14} \, \text{cm}^{-2} \) and \( \sigma_0 = 7.5 \times 10^2 \, \text{cm}^2 \). For the oxide-passivated surface, we obtained \( N_0 = 1.5 \times 10^{14} \, \text{cm}^{-2} \) and \( \sigma_0 = 6 \times 10^2 \, \text{cm}^2 \). Here, we used a tunneling gap of 0.6 nm for H-terminated surface, and 0.9 nm (including a thickness of the ultrathin oxide layer of 0.3 nm) for oxide-passivated Si surface, as defined from the calibration. [14] We assessed variation in the derived concentrations assuming a tunneling gap uncertainty of 0.05 nm, a half of the probe vibration amplitude. With the tunneling gap reduced by 0.05 nm, the derived concentrations were decreased by a factor of ~2.6. Therefore, the obtained carrier concentration \( N_0 \) is in a range of 0.5 - 3.3 \times 10^{14} \, \text{cm}^{-2} \) for our undoped SOI samples.

Reduction of the cross sectional area and surface roughness by oxidation can change the conductance of Si nanowires. [4] For doped Si NW with radius of 5-60 nm the resistivity increased due to change in the impurity activation energy by the quantum confinement effects. [18] In our case, for the undoped NW with a cross section of 20 \times 20 \, \text{nm}^2, reduction of width by ultrathin oxide is less than 1 nm, therefore, such effect is insignificant. Alternatively, deactivation of impurity atoms by hydrogen bonding in bulk Si has been known to result in decrease in the carrier concentration by 1-2 orders on magnitude. [19] Since the effective concentration \( N_0 \) is smaller for the H-terminated NW, deactivation of dopants is a plausible explanation. Further investigations of the conductance change with the annealing temperature are needed to clarify the origin.

4. CONCLUSION

Structural and electronic properties of silicon-on-insulator (SOI) nanowires with a cross section area of 20 \times 20 \, \text{nm}^2 were investigated with high spatial resolution by multimode scanning probe microscopy (MSPM) in the constant force mode. The position-dependent tunneling current was measured for Si nanowire surfaces terminated with hydrogen and with ultrathin thermal oxide. For both types of surface termination the tunneling current decreased within a distance of ~300 nm from the Si pad electrode. Calculations of the tunneling current based on the model including the volume and surface contributions resemble the experimental data for the small Si NWs. The results support the length-dependent conductance of thin Si nanowires, demonstrating the ability of the technique for characterization of modern SOI devices with a nanometer resolution.

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6. REFERENCES


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