Size Effects on Phase Formation and Electrical Robustness of Nickel Silicide Nanowires

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Abstract
We reported that the morphology, phase formation, and electrical resistivity of the Ni₅Siₓ NW have strong dependences on the geometrical size of the as-formed Si NW before silicidation. The electrical current stressing generated self-heating and thus local compressive stress buildup and relaxation near the locations where the Ni₅Siₓ NW ruptured.

1. Introduction
Nickel self-aligned silicidation technology, converting Si that is in direct contact with nickel into Ni₅Siₓ following thermal anneal, has been prevalently employed for the fabrication of nanocontacts for advanced MOSFETs thanks to the low process temperature, less silicon consumption, good electrical conductivity, and most importantly, reduced parasitic effects due to eliminated lithographic processes. The key to successfully realizing nickel-silicide nanocontacts lies in thermal stability of the material structure, phase, and electrical properties after long-duration electrical operation. Thereby the understanding of crystalline morphology, phase formation, and electrical endurance of nickel-silicide nanostructures of various sizes is of high importance to Si nanoelectronic devices.

In this paper, we report systematic study on effects of geometrical size of top-down fabricated single-crystalline Si (c-Si) nanowires (NWs) on the microstructure behaviors, phase formation, and their electrical reliability of nickel-silicide NWs prior to and following electrical stressing.

2. Experimental
The fabrication of Ni₅Siₓ NWs start with a silicon-on-insulator wafer, whose top layer of Si was thinned down to two thicknesses (H) of 50 and 80 nm using SF₆/C₄F₈ plasma etching. Rectangular-shaped Si NWs in width (W) of 50–500 nm and length of 2 μm were then generated using a combination of electron-beam lithographical patterning and plasma etching. When the Si NWs were formed along with their contact pads after top-down patterning processes, no surface protection was intentionally made leaving the top surface and sidewalls of as-formed Si NWs exposed to subsequently deposited Ni layers. The samples of Si NWs were cleaned with an HF dip prior to thermal evaporation of Ni, allowing Ni directly wrapping up the Si NWs. The film thickness of Ni is kept the same with that of as-formed Si, assuring enough Ni for full silicidation of the entire Si NW. Silicidation was then conducted using rapid-thermal anneal at 500 °C for 15 sec, followed by a wet chemical wash to remove unreacted nickel metal (Figure 1a).

3. Results and Discussion
Recall when a silicidation process is made to a Si substrate at 500 °C, in general, the so-formed Ni₅Siₓ film is nickel monosilicide (NiSi) that is highly desirable for use as the low resistive contact materials, and its thickness is thicker than that of consumed Si and Ni by factors of 1.2 and 2.2, respectively. Notably the silicidation of a Si NW at 500 °C induces an anisotropic volume expansion that appears to be highly dependent on the initial width and thickness of as-formed Si NWs (Figure 1b). Ni₅Siₓ NWs expand vertically in thickness by a constant factor of 1.37±0.1 with respect to all experimental c-Si NWs (H = 50, 80 nm and W = 50–500 nm), whereas the lateral expansion in Ni₅Siₓ NWs appears to be proportional to the ratio of thickness to width (H/W) of as-formed Si NWs, increasing from 1.06±0.02 to 1.35±0.10 with a decrease in the Si NW width from 500 to 50 nm (Figure 1c). The overall volume expansion factor for Ni₅Siₓ NWs to c-Si NWs ranges from 1.4 to 2.0, apparently larger than the value of 1.2 for NiSi in the thin-film form. This experimental finding suggests Ni-rich silicide phases formation for the Ni₅Siₓ NW instead of nickel monosilicide for the NiSi film, revealing that the so-formed silicide phase is strongly influenced by the NW size, i.e., narrower the NW, higher the Ni/Si ratio. The fact of the Ni₅Siₓ NW becoming more Ni-rich when reducing the NW width is further evidenced by the diffraction patterns and the corresponding electrical resistivity.

Figure 2a illustrates that the electrical resistivity of Ni₅Siₓ NWs generated by 50 nm-thick c-Si NWs initially declines from 83.8±6.0 to 35.8±12.4 μΩ-cm with a decrease in the Ni₅Siₓ NW width from 350 to 175 nm, and then inversely increases to 150±36.0 μΩ-cm when further reducing the Ni₅Siₓ NW width to 75 nm. Similar trends are also observed from the silicide NWs generated from both 80-nm-thick c-Si NWs. It was reported that the resistivity values for silicide NWs are comparable with the corresponding data (Table 1) of the silicides in their thin-film form [4]. Thereby the NW size-dependent electrical resistivity suggests three silicidation processes of NiSi₂, Ni₅Siₓ, and Ni₅Siₓ: for NWs with respective widths of 350–225, 225–120, and 120–65 nm, again evidencing the NW size dependence of the volume expansion (Figure 1c). The current-voltage (I-V) characteristics (Figure 2b) reveal the curve bending towards higher voltage due to self-heating of ~110nm-wide NiSi NWs, a phenomenon similarly observed from NiSi NWs fabricated using different methods [5]. The maximum current density prior to the NW breakup is high: ~ 5–6×10⁷ A/cm².
We attempted to conduct multiple I-V sweep tests on Ni$_2$Si NWs to get insights into the endurance of Ni$_2$Si NWs under electrical operations. The voltage sweeping was set from 0 to 10 V with a successive increase in the compliance current with a step of 1 mA after each sweep until an electrical continuity breakup of the silicide NW occurred. For a 228-nm-wide, 110-nm-thick Ni$_2$Si-Ni$_3$Si$_2$ NW, there appears to be no distinctive change in the crystalline morphology when successively increasing the compliance current from 1 to 7 mA, ultimately we observed a tremendous increase in the electrical resistivity (an electrical discontinuity) coupled with a rupture of the silicide NW once the compliance current reached to 10 mA (Figure 3). In fact, the evolution in morphology of the silicide NW with increasing the compliant current shows an initial contraction in the NW width and then an ultimate expansion near the rupture region. Similar morphology evolution was also observed from 139-nm-wide silicide NWs following electrical stresses. Figure 4 illustrates detailed analysis of CTEM and diffraction patterns for various locations within the silicide NW before and after electrical stress. The silicide phase of Ni$_2$Si in spacious contact pads appears to be invariant for both as-formed and ruptured NWs, whereas the crystallinity transition from single-crystalline to amorphous state around the discontinuous region suggests that current crowding generated tremendous self-heating within the silicide NW, leading to enormously nonuniform, local compressive stress buildup and relaxation near locations where the NW ultimately ruptured.

4. Conclusion
We reported that the morphology, phase formation, and electrical resistivity of the Ni$_x$Si$_y$ NW have strong dependences on the geometrical size of the as-formed Si NW before silicidation. A constant current stress test shows that the Ni$_x$Si$_y$ NW would be thermally ruptured by the self-heating and thus local compressive stress buildup and relaxation.

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References