Liquid-Gated Silicon Nanowire Field-Effect Transistors Covered with Ultrathin Diamond-Like Tetrahedral Amorphous Carbon

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Label-free, low-noise, and ultrahigh-sensitive biosensors based on liquid-gated (LG) silicon (Si) nanowire (NWs) field-effect transistors (FETs) have recently emerged as promising diagnostic tools to be employed for healthcare monitoring and point-of-care applications[1,2]. However, the sensing capabilities and performance of such devices still depend critically on several factors including the quality and intrinsic properties of the materials used. Especially, the important role in determining device performance is assigned to the gate insulator layer which acts as a sensing surface in such NW-based biosensors. Being directly exposed to the electrolyte solution, the surface of NWs is affected by the ionic solution which leads to irreversible degradation of the material properties and, thus, to deterioration of operation parameters of underlying FETs. Therefore, the development of reliable Si NW FET biosensors requires optimization of experimental conditions and thus further improvement of material quality enabling hysteresis- and leakage-free operation of such NW FET-based devices in a liquid media. In this study, we fabricated and investigated the electrical performance of LG Si NW FETs covered with a new gate dielectric stack that consists of an 8 nm thin thermally grown SiO_2 layer and the diamond-like film: 5 nm thin tetrahedral amorphous carbon (ta-C) film. Owing to their outstanding mechanical properties, thermal stability, and large bandgap[3], ta-C films possess an exceptional potential to be used as a novel coating gate dielectric material for such LG NW FET devices. It should be noted that to the best of the authors' knowledge, ta-C has not been considered for this application yet.

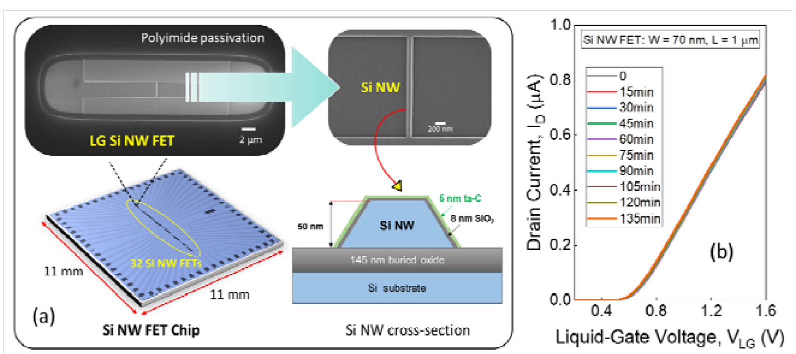

Figure 1. (a) Illustration of the fabricated Si NW chip with a linear layout that contains 32 independent LG NW FETs. Nanowire structures are additionally coated with a 5 nm ta-C layer to provide better performance and working stability while operating in a liquid environment. (b) Typical long-term transfer I–V characteristics measured for n-type Si NW FET with the NW width of 70 nm and length of 1 μm. The tested device was liquid-gated in PBS buffer solution with pH = 7:4 and ionic strength of 10 mM.

The schematic illustration and composition of a typical fabricated Si NW chip containing 32 independent single Si NW FETs are shown in Figure 1(a). The devices were fabricated using a previously reported protocol[2]. The surface of the chip was covered with a 1.5 μm thick polyimide passivation layer to protect the device against a liquid media during electrical measurements. Openings in the passivation layer providing the access of the liquid solution only to NW regions defined by photolithography patterning. Initially, Si NWs were covered with the 8 nm thin SiO_2 layer that was thermally grown during the fabrication process. To ensure better performance and working stability while operating in a liquid, the nanostructures were additionally covered with the 5 nm thin ta-C film. The diamond-like film was deposited using a laser arc method which enables ta-C layer formation with significantly reduced defect densities[4]. The ta-C was deposited with a moderate sp^3-content of about 60% and a density of 2.7 g/cm^3. Figure 1(b) shows a set of transfer curves measured for 70 nm wide and 1 µm long ta-C-covered Si NW FET immersed in PBS buffer solution with pH = 7.4 and ionic strength of 10 mM. As can be seen, the device demonstrated good working stability and repeatability even being exposed in the ionic solution for a long period of time. It should be emphasized that the leakage current through the front-gate dielectric layer when measured in the liquid-gated configuration, remained negligibly small (below 10 pA) confirming good stability properties of the fabricated sensors.

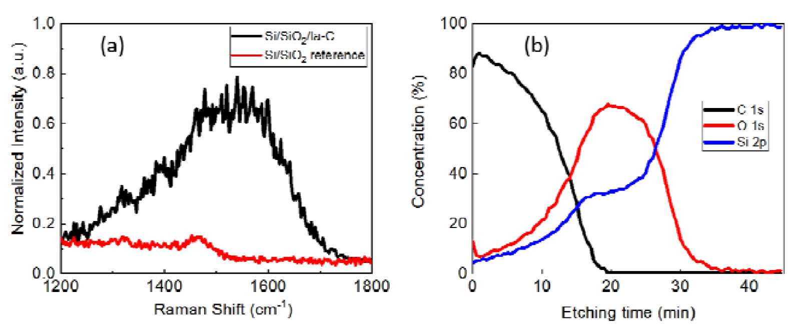

Figure 2. (a) Typical resonance Raman spectra measured on the bare Si/SiO_2 sample (red curve) and the Si/SiO_2 sample covered with a 5 nm thin ta-C layer (blue curve). (b) XPS measurements verifying the presence of the amorphous ta-C coating on top of the SiO_2 layer. The sample was depth profiled by etching with Ar^+ ions at 0.5 kV energy. Concentrations for all other elements were below the detection limit which confirms the high quality of the deposited hydrogen-free ta-C film.

Raman and X-ray photoelectron spectroscopy (XPS) measurements have been subsequently performed to confirm the efficient deposition of thin ta-C films on the SiO_2-covered samples. The corresponding results are shown in Figures 2(a) and 2(b), respectively. The appearance of the broad peak near 1550 cm^{-1} in the Raman spectrum clearly indicates the presence of the low sp^3 amorphous carbons[5] as expected after the deposition of the ta-C film. The result is consistent with the data obtained from XPS analysis showing that the uniform hydrogen-free ta-C layer has been successfully deposited on top of the SiO_2-covered Si structures. Thus, in this study, we showed that Si NW FETs covered with ta-C/SiO_2 gate dielectric stack demonstrate good electrical properties and acceptable stability while operating in liquids even for a long time. The performed Raman and XPS spectra measurements confirm the efficient ta-C coating of the fabricated devices. The designed devices are promising for biosensing applications with good stability and reliability in bioliquids and body fluids.

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