Bottom-gate and step-gate Polysilicon nanowires field effect transistors for ultrasensitive label-free biosensing application

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Abstract

Simple and low-cost polycrystalline silicon nanowires field effect transistor (poly-SiNWFET) are fabricated using two different configurations: step-gate and back-gate. The nanowires are synthesized using the sidewall spacer formation technique compatible with the well-known CMOS technology. Probe DNA strands immobilization is performed by the functionalization of poly-SiNWs using APTES and glutaraldehyde. Hybridization phenomenon is detected on electrical characteristics of the poly-SiNWFETs. The first results demonstrate that these devices are promising tools for low-cost, real time and label-free DNA sensing with detection limit at 1fM.

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1. Introduction

Development of new low cost devices that enable direct and highly sensitive detection of DNA hybridization stimulates a lot of research efforts. Particularly, devices based on silicon nanowires are emerging as ultrasensitive electrical sensors for the direct detection of biological species thanks to their small size and their high surface to volume ratio [1-4]. Because SiNWs synthesis can be compatible with the established silicon technology, enormous research efforts to design and develop new generation of high performance biological and chemical sensors by incorporating the SiNWs as the functional sensitive units are performed. In this paper, nanowires are synthesized following a top-down approach using the sidewall spacer formation technique [5-7]. Two different configurations of field-effect devices based on SiNWs devices are explored. The first one is a “step-gate” configuration where a step made of highly in

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situ doped polysilicon acting as support for the creation of silicon nanowires, and also gate contact. The second one is a “bottom-gate” configuration on highly doped silicon wafer used as gate electrode. The two mentioned structures are studied for DNA hybridization detection, using 25-mer complementary and 24-mer no-complementary DNA strands as a proof of concept.

2. Devices fabrication

2.1. Bottom-gate configuration

A highly N-doped substrate is first of all capped with two dielectric layers: the first one is a SiO₂ layer deposited by APCVD (Atmospheric Pressure Chemical Deposition) technique at 420°C; the second layer is a nitride deposited by LPCVD (Low Pressure Chemical Deposition) technique at 600°C. Another SiO₂ is deposited, patterned and dry-etched to realize a step (Fig. 1.a). The oxide step is then covered by a Si-poly layer deposited by LPCVD method at 550°C and crystallized at 600°C during 12 hours. Dry etching control of the polysilicon layer allows the silicon nanowires formation made of residual polysilicon (spacer) in the step side. The step oxide is finally wet-etched to set free the nanowires (Fig. 1.b) and also to increase the surface where DNA strands can bind. After oxide encapsulation of nanowires, two layers made of highly Si-poly and aluminum are successively deposited, patterned and etched to create drain and source contacts (Fig 1.c).

![Fig. 1. (a) vertical step made of oxide; (b) SEM image of a nanowire which is set free from the step oxide; (c) final structure of the bottom gate SiNW FET.](image)

2.2. Step-gate configuration

A 100nm thick highly in-situ doped polysilicon layer is deposited on insulated substrate. After patterning, by reactive ion etching (RIE) of the step-gate a 100nm thick APCVD oxide acting as gate insulator is deposited. Then, two layers of polysilicon layers are successively deposited. The first one is an undoped and the second one is a highly in-situ N-type doped. A patterning and a plasma etching of these two polysilicon layers are achieved to create an aperture in the gate insulator. Accurate control of the undoped polysilicon layer etching rate leads to the formation of nanometric size sidewall spacers used as undoped nanowires (Fig. 2 a). Source and drain regions are made of heavily in-situ N-type doped polysilicon. Then, the polysilicon nanowires are capped with a 70nm thick APCVD oxide. Finally, an aluminum layer is deposited by thermal evaporation and patterned to define gate, source and drain electrodes (Fig. 2b). Silicon nanowires based devices with 2 to 16 nanowires-channels, 100nm width and 3 to 20μm lengths are fabricated.
2.3. Surface functionalization

Because DNA cannot bind directly on the nanowires, a functionalization step is achieved to allow the probe DNA strands immobilization (Fig. 2c). The first step is the deposition of vapor of 3-aminopropyltriethoxysilane (APTES). Devices are heated to improve the polymerization. The next step is the glutaraldehyde deposition during 12 hours at room temperature in a desiccator in the presence of the linker. 25-mers synthetic oligonucleotides are used: 5-amino-modified DNA probe (NH2-5'-TCA-ATC-TCG-GGA-ATC-TCA-ATG-TTA-G3'), respectively complementary and non complementary targets (5'CTAACATTGAGATTCCCGAGATTGA3'), (5'TAAAGCCCAGTAAAGTCCCCCACC3').

3. Results

Electrical characteristics of such polySiNWs FET were previously demonstrated [8]. For DNA hybridization detection, the measurement protocol is as follow: a drop of solution containing DNA probes (400ng/µl) is loaded and rinsed after 1 hour with PBS. The electrical characteristic is collected and used as reference. Next, 10 µl of solution containing complementary DNA target is deposited and rinsed after an incubation period. Measurements are performed on the two configuration devices. In both cases, the characteristic reveals a shift of the transfer characteristic towards the negative voltages after the target DNA hybridization (Fig 4.a). This shift is explained by the detection of negatively-charged species carried by the phosphate groups of the hybridized complementary DNA. The negative charges resulted from hybridization greatly affect the channel conductance of the FET. They act as chemical gate that exert an electric field which may induce an excess of electrons towards the channel region, resulting in an increase of the current in the n-channel of the NW-FET at fixed positive gate bias. Fig 4 presents transfer characteristics for the two configurations of SiNW FETs before and after DNA targets hybridization. Comparison between the both characteristics is not so evident because nanowires size is not exactly the same, so the current levels are different. However, the two structures present a high sensitivity to DNA hybridization detection. Concentration as weak as 1fM is detected.
4. Conclusion

In conclusion, we present the process fabrication of two different configurations of field-effect devices based on SiNWs using classical silicon planar technology. We demonstrate that the devices can be functionalized and used as a label-free, ultrasensitive, and real-time tool for the detection of DNA hybridization. No-complementary and complementary DNA sequences were clearly discriminated and detection limit to 1fM range is observed. The first results using these polySiNWs based devices are promising for the development of low cost and ultrasensitive polysilicon nanowires based DNA sensors compatible with the CMOS technology.

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