ABSTRACT
We demonstrate the hydrogen ion sensing capability of Schottky contacted silicon nanowire field-effect transistors (FETs) prepared by simple process steps, and propose possible applications for the detection of a biomolecular interaction. A high sensitivity of 2nA/pH and a significant current variation of 20%/pH were acquired in the pH 7 region. The real-time measurement of the silicon nanowire FETs for the various pH solutions reveals the response time of 1min or less. An excellent reproducibility and the comparably stable current at each pH level were observed, implying acute sensing ability.

KEYWORDS: Schottky contact, Silicon nanowire, biosensor, field-effect transistor

INTRODUCTION
As label-free detection of a biomolecule in single molecular level has been a key issue in life and medical science, the recently reported silicon nanowires (SiNWs) opened its feasibility [1]. However, the synthesized SiNWs still have such questions to solve as controlling the size and aligning the position of SiNWs. The SiNW sensors fabricated by ‘top-down’ approach also showed their potential without cumbersome alignment problem [2]. Nevertheless, additional source/drain doping and activation processes were necessary to form reliable ohmic contacts.

Therefore, we proposed Schottky barrier silicon nanowire field-effect transistors (SB-SiNWFETs) [3] as a platform of SiNW-based biosensors. Since the source/drain contacts of SB-SiNWFET biosensor are Schottky rather than ohmic, the source/drain electrodes are simply formed by metal deposition without complex doping and thermal treatment steps. The applicability of SB-SiNWFET to biosensors is discussed here by measuring the variation of pH.

THEORY
The configuration of the device structure of the SB-SiNWFET biosensor is illustrated in Fig. 1(a), and the working mechanism of this device for pH sensing is demonstrated by schematically drawn energy-band diagrams in Fig. 1((b)-(d)). At a small positive drain voltage the Schottky barrier is high enough to block jumping of electron (Figure 1(c)). When a sufficient gate voltage is applied, the barrier width approaches a few nanometers, a new transport phenomenon, tunneling through the barrier, can takes place (Figure 1(d)). If the channel region is exposed to the solutions with various pH levels, the band bending occurs in accordance with pH level.
Fig. 1. (a) the configuration of the device structure of SB-SiNWFET biosensor. (b) the schematically drawn energy-band diagrams of the SiNW channel at the condition below turn-on gate voltage and zero drain bias, (c) at the condition below turn-on gate voltage and positive drain bias, (d) at the condition above turn-on gate voltage, positive drain bias, and high or low pH condition. The left-handed inset shows the scanning electron microscopy (SEM) images of the fabricated SiNW region after RIE. The right-handed inset shows the microscopic image of the sensing area of the fabricated device. The SiNW channel is revealed via the patterned SU-8 layer (passivation layer).

EXPERIMENTAL

The device fabrication sequence is as follow. We used SIMOX (Separation by IMplantation of OXygen) wafers, which have a 50nm-thick silicon-on-insulator (SOI) layer on top of a 375nm-thick buried oxide (BOX) layer. Electron beam lithography (EBL), and reactive ion etching (RIE) patterned the SiNW channel. Photolithography patterned the Ti/Au electrical lines. Then, a SU-8 layer was used to isolate the metal lines from the analytical solutions. The microscopic images of the sensing area of the fabricated device are shown in the insets of Fig. 1.

RESULTS AND DISCUSSION

Fig. 2 shows the typical drain current $I_D$ versus the gate voltage $V_G$ characteristic of the fabricated devices. One can see that the current flow is significantly suppressed at low gate bias due to high and thick Schottky barrier. Linear current increment was observed over 15V of gate bias due to the tunneling of electrons via sufficiently narrowed Schottky barrier.

In order to see whether SB-SiNWFET can be used as a biosensor, we applied a drop of 10μl of pH solution over the sensing area where the SiNW was exposed. As can be seen in figure 2(b), a positive shift (negative shift) of threshold voltage was appeared when pH is increased (decreased). The threshold voltage shift and the sensitivity were experimentally measured of 7.1V/pH and 2nA/pH, respectively (Figure 2(c)). The ratio of current variation per pH is 20%/pH at pH 7 region. In order to inspect the real-time response to pH, a PDMS cap was bonded onto the SU-8 layer. As shown in Figure 2(d), the device responds to the various pH solutions with response time of 1min or less, and shows the excellent reproducibility and the comparably stable current with negligible drift at each pH levels, implying acute sensing ability.
Fig. 2. (a) $I_D-V_G$ characteristic at room temperature. The inset shows $I_D$ on a log scale. (b) $I_D-V_G$ characteristics in response to pH at $V_D (=1V)$. The inset shows the reproducible variation of $I_D$ versus pH characteristics at $V_G (=30V)$. (c) The threshold voltage shift and the percent ratio of the current variation at each pH level, which is normalized with the gate voltages and the current values at pH 7, respectively. (d) Real-time current response to the variation of pH at constant $V_D (=1V)$ and $V_G (=30V)$.

CONCLUSIONS

In summary, we successfully developed a simple structured Si-NWFET biosensor using Schottky source/drain contact without complex doping process, and confirmed its possibility to the detection of a biomolecular interaction by inferring the sensitive pH response (20% variation per pH at pH 7).

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