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Enhancement of detection by selective modification of silicon nanobelt field-effect transistors via localized Joule heating

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ABSTRACT

We utilized localized Joule heating to ablate methoxy-poly (ethylene-glycol)-silane (mPEG-sil) modified on the p^- region of an n^+–p^-–n^+ silicon nanobelt field-effect transistor (SNFET). SNFETs with selective modifications of 3-aminopropyltrimethoxysilane (APTMS) and NHS-biotin on the ablated region exhibited a faster sensing response rate and a higher sensitivity in real-time detection of Streptavidin (SA). Characterization of the ablated region via lateral force microscopy and the fluorescence image show that the ablation region occurs only in the p^- region near the drain side and is believed to be a result of the impact ionization mechanism during Joule heating. Moreover, a bias of 20 V pulse voltage for 1 ms successfully ablates mPEG-sil and reduces the device off leakage current by 1 order after Joule heating. However, Joule heating with a pulse voltage larger than 20 V (1 ms) yielded an increase of device off leakage owing to damage to gate dielectrics during Joule heating. A comparison of real-time detection of SA between selectively and non-selectively modified chips shows that selectively modified ones exhibit a better limit of detection (LOD) that is one order lower than non-selectively modified ones, and a sensing response rate twice as fast as the non-selectively modified one for every target concentration.

1. Introduction

Silicon nanodevices, especially silicon nanowires, have been applied in the biosensing for over 10 years. These structures with high surface-to-volume ratios result in high sensitivity to changes in surface potential. Although nanowires have demonstrated the ability to detect biomarker into the subpicomolar range [1–6], sufficiently thin nanoribbons also are sensitive enough [7,8] while operating in the so-called subthreshold region [9]. Nonetheless, previous efforts in biosensing still have room for improvement. For example, sensing response rate is not fast enough when the concentration of targets is low. Simulation results have demonstrated that a faster sensing response rate can be achieved by passivation of the non-reacted regions while leaving only high sensitive regions exposed to the targets [10]. This selective modification is aimed to solve this issue by allowing specified chemical linkers or biomolecules to bind on a wanted location. Several techniques have been developed to selectively modify SAM on a silicon dioxide surface and have reported selective patterning of SAM from micro- to nanoscale [11–15]. However, all of these techniques have either simple process or accurate deposition ability, but not both. Researchers have recently developed a new technique that can carry out selective modification while combining both advantages [16]. They used the localized Joule heating to ablate the PTFE film on the silicon nanowire devices for further surface modifications. Since the heat is only confined to the silicon nanowire because it has the highest resistance in the structure, the ablated regions only occur along the silicon nanowire. However, PTFE is difficult to ablate via heat due to its high boiling point; other study has used PMMA as a passivation material and has demonstrated the same function [17]. Nonetheless, PMMA usually causes non-specific binding during real-time detection, and still requires an additional process to passivate the non-reacted regions, which may cause contamination of the modified molecules in the ablated regions when the PMMA removal process is proceeding. Another method investigated a bottom-up method for selective modification, but integrate of all processes on the chip to achieve mass production was difficult [18]. Furthermore, mPEG-sil has been employed to reduce the non-specific binding of proteins [19,20]. In this research, we simplify the selective modification process and use highly sensitive SNFET, performing localized Joule heating to selectively remove the mPEG-sil passivation layer, with subsequent modification by chemical linkers. In addition, real-time detection of SA is performed and compared for selectively and non-selectively modified chips.

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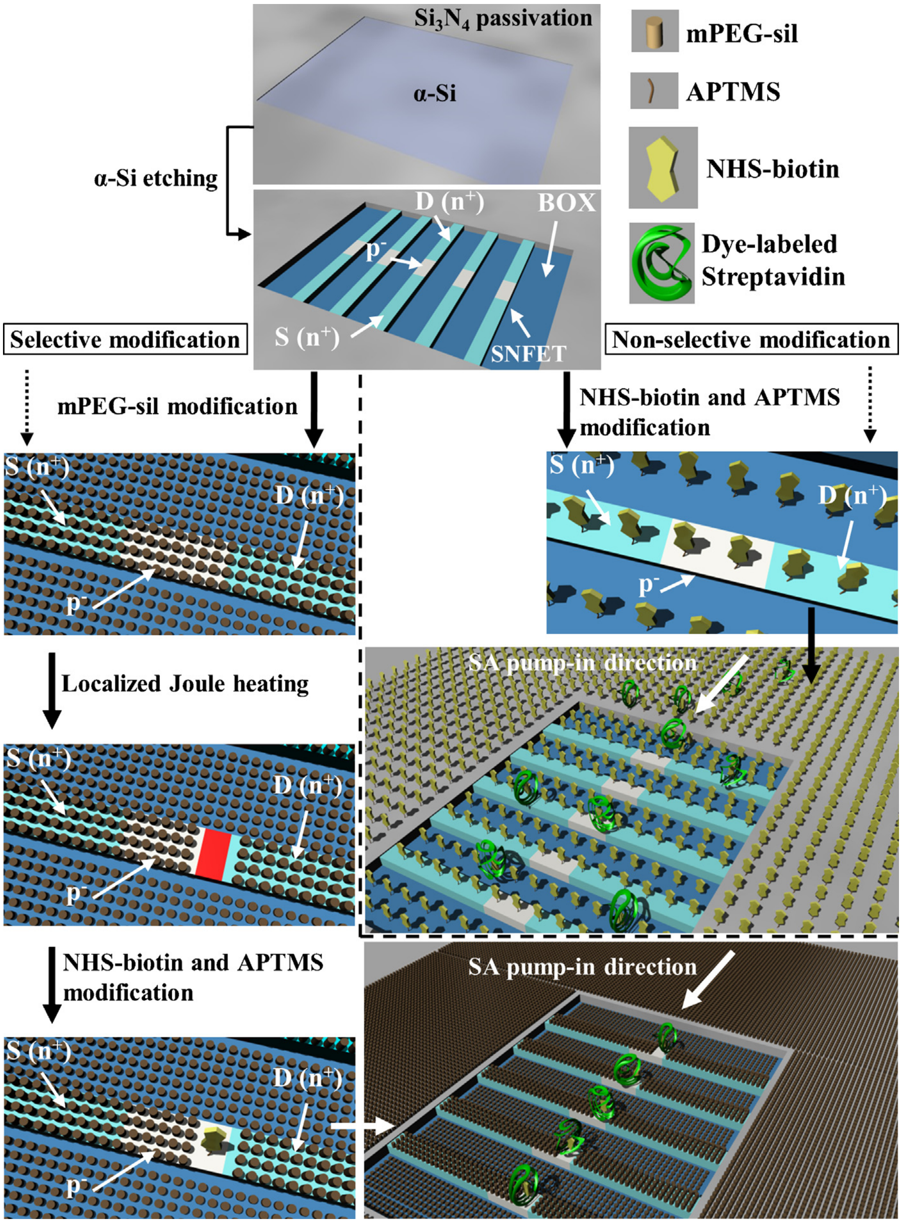

Fig. 1. Schematic diagrams showing the process of selective modification and detection of SA on SNFETs. Selective (left part) and non-selective modification (right part) processes are separated by dashed line.

2. Experimental

2.1. Device fabrication

The devices were fabricated from p-type SOI wafers with a 70-nm-thick top silicon and a 150-nm-thick buried oxide. The patterns of SNFETs were defined by photolithography using I-line stepper, and followed by Si etching via reactive ion etching (RIE). The length and width of each nanobelt is 13 μm and 500 nm, respectively. After RCA cleaning, an 8-nm-thick thermal oxide and a 100-nm-thick α-Si were grown. The contact region, which heavy doping region is also defined by photolithography and leaving a 2-μm-long intrinsic region in the middle of the nanobelts was then implanted with arsenic at a dose of 3×10^{15} cm^{-2} at 30 keV. After dopant activation, the Al-Cu alloy was deposited with a sintering process to form ohmic contact. Finally, 500-nm-thick Si_3N_4 was deposited on the devices as a passivation layer. Before modification of mPEG-sil, the α-Si layer was etched by XeF_2 isotropic silicon etching system (XACTIX). The outer Si_3N_4 layer is used as a hard mask to resist F^- attack, with the etching selectivity between Si_3N_4 and Si with XeF_2 at least 100:1. Detail fabrication processes were illustrated in the Supplementary data.

2.2. Surface modification

2.2.1. Immobilization of mPEG-sil and APTMS

SNFETs were cleaned by UV/ozone for 10 min prior to modification of mPEG-sil. The mPEG-sil (Mw = 460–590 Da) was prepared as a 6 mM mPEG-sil solution with 1% tetraethyl ammonium (TEA) as a catalyst and then reacted with the surface of chip for 24 h on a hotplate at 60 °C. After the reaction was finished, devices were cleaned sequentially with anhydrous toluene and alcohol for 5 min to remove unreacted molecules. Finally, the sample was rinsed with DI water and blown dry in a nitrogen stream. 3-aminopropyltrimethoxysilane (APTMS) (Sigma) was then deposited with a concentration of 2 mM in DI water for 10 min,