Silicon nanowires for advanced sensing: Electrical and electromechanical characteristics and functionalisation technology

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In this talk, we focus on the silicon nanowire (SiNW) sensor head, a key component of the NEMSIC smart sensing system. Our recent progress is overviewed on selective functionalisation technology for SiNWs, the electrical and electromechanical characteristics for SiNWs and design and fabrication of in-plane resonant suspended gate FET (IP-RSGFET), one of NEMSIC sensor devices.

1. Development of selective surface functionalization methods for silicon nanowires

A working functionalization protocol for Si oxide surfaces based on NH_2 SAMs was developed for selective SiNW surface functionalization for biosensing applications. Two approaches were considered: (1) Joule heating ablation of a sacrificial layer only on the NWs followed by the localized deposition of the functional NH_2SAM anchoring molecules and biotin attachment (Fig. 1) and (2) electron-beam lithography on the NWs area and removal of the sacrificial layer followed by the localized deposition of the functional NH_2SAM anchoring molecules and biotin attachment. In the first approach, a finite element analysis (FEA) program was first conducted to simulate the localized Joule heating on a single SiNW by varying applied bias voltage. Such localized heating was utilized to selectively ablate a 100-nm-thick protective MET-2D polymer or SAMs layer on the chosen SiNW surface. For both approaches, selective functionalization was confirmed by AuNPs decoration of the -NH_2 functionalities. The ebeam approach based on MET-2D polymer resist was particularly successful, enabling 100% selective functionalization on the NWs (Fig.2). Nano probe AFM characterization of functionalized SiNW devices was also conducted in order to demonstrate selective functionalization. Force-distance curves were measured between the avidin-functionalised cantilever and the bio-functionalized (APTS + glutaraldehyde (GA) + Biotin) Si NWs. Attractive force was successfully observed for the top surface of the SiNW and the vicinity area in a clear contrast to the zero interaction observed for the field region (Fig. 3).

2. Study of the impact of suspension and surface functionalization on electrical characteristics

We investigated the effects of suspension and surface functionalisation on the conduction properties of SiNWs. The conductance was found to change by the suspension process while it showed the similar trend against the temperature before and after the suspension. The reduction of the conductance after the NH_2SAM/GA/Biotin functionalisation was also found (Fig. 4) which can be explained assuming the possible charge transfer mechanism from the SiNW to the molecular layers. We observed the temperature insensitivity of the conductance of the functionalised SiNWs (Fig. 5). This feature is expected to be extremely useful for practical sensing applications. Low frequency noise (LFN) characteristics were also studied for the SiNWs as they may provide more information about the effects of surface states on electron transport and are therefore important to discuss the sensitivity limit of the conduction-based detection scheme of Si NWs. The standardised current noise spectral density S_I/I_d^2 was measured at 10 Hz by varying the side gate voltage. While the conduction current increased increasing the gate voltage from -10 V to 0 V, S_I/I_d^2 was reduced by approximately 2 orders of magnitude (Fig. 6). This fact indicates that the LFN of our SiNWs is primarily determined by mobility-fluctuation.

3. Design and fabrication of in-plane resonant suspended gate FETs (IP-RSGFETs)

A suspended SiNW sensor head was adopted as a vibrating gate for the IP-RSGFET (Fig. 7). The resonator architecture has amplified output signal due to the integrated lateral FET. 3D FEM analysis of impacts of surface functionalization on resonant frequency was conducted, in particular showing the effect of different coating configurations on the mass responsivity (Fig. 8). A hybrid NEM-MOS circuit model was also built to analyze the complete sensor structure. Mass responsivity less than 1 zg/Hz shows its fascinating potential for sensing small changes in the mass. The latest experimental results on basic operation will be discussed for fabricated IP-RSGFETs.

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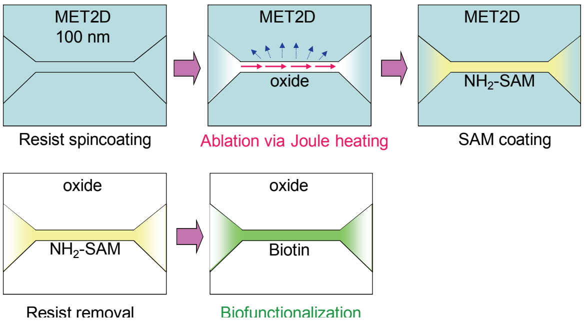

Fig.1 Selective NH_2-SAM/GA/Biotin functionalisation procedure by Joule heating method.

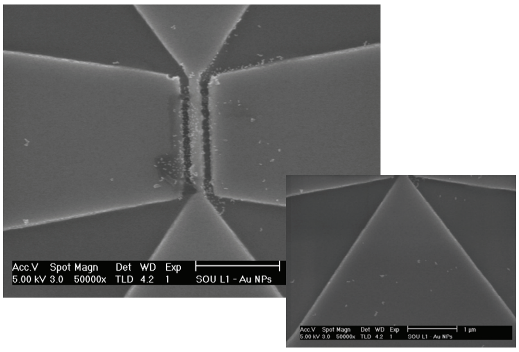

Fig.2 A SEM image of a AuNP coated SiNW with selectively NH2SAM functionalized surface.

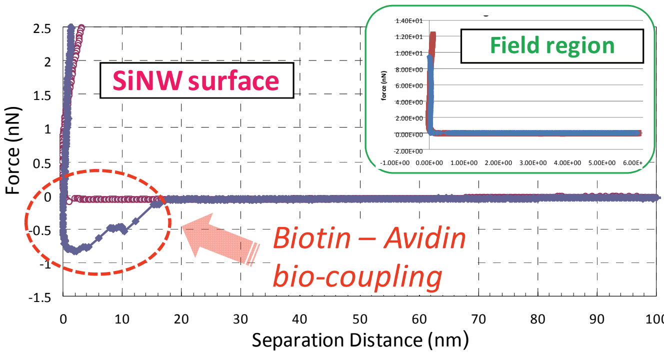

Fig.3 Force-distance curve observed for avidin-functionalized AFM tip and biofunctionalized SiNW. The inset shows the curve for unfunctionalized field region.

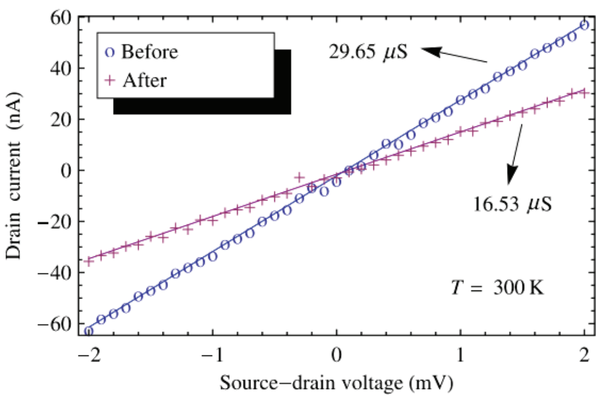

Fig.4 I-V characteristics at 300K for SiNW before and after NH_2SAM/GA/Biotin functionalization..

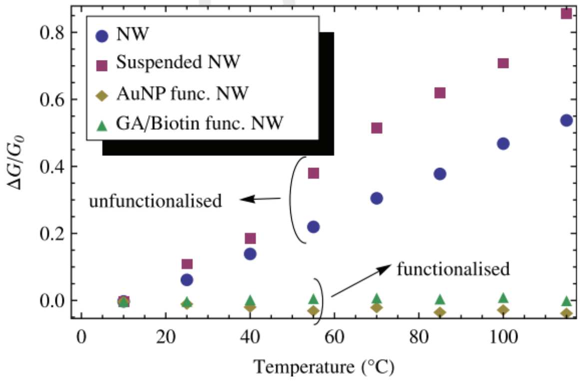

Fig.5 Normalized temperature dependence of conductance variation for various SiNWs..

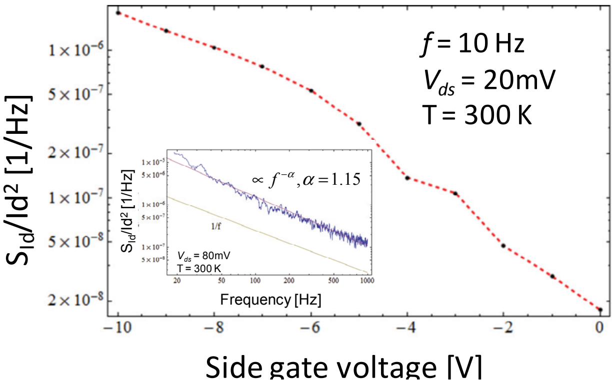

Fig.6 LF noise intensity as a function of side gate voltage. The inset shows LF noise spectrum.

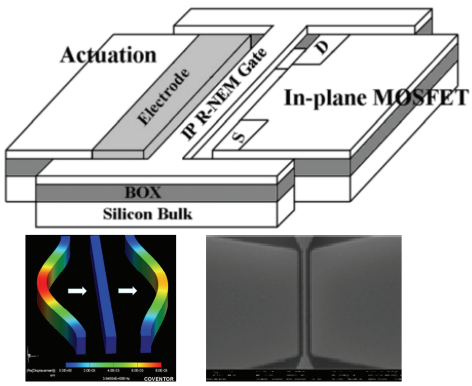

Fig.7 A schematic diagram of IP-RSGFET.

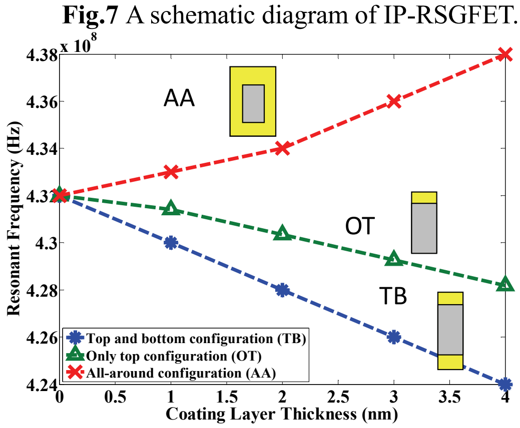

Fig.8 Resonance frequency vs suface coating layer thickness calculated for three different coating configurations..