Review article

Silicon nanowires-based sensors in liquid gas and in-vivo environments

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Abstract

Silicon nanowires (SiNW)- based sensor devices have attracted considerable interest as a general. It has become a very sensitive, electrical detection of biological and chemical species. Most studies that have been discovered are concentrated on the sensor and control analysis in aqueous solution, but the number of studies on devices using SiNW-based sensing gases and vapors is increasing. This review gives an easy overview of fabrication and properties, research papers related to the application of electrical SiNW-based devices in the gas and in-vivo environment were selected.

Keywords: Silicon nanowires, sensor, devices, in-vivo environment.

Introduction

A nanowire (NW) is defined as any solid material in the form of wire with diameter of 1 to 100 nm. Many different types of nanowires exist, including metallic nanowires (*e.g.*, Ni, Pt, Au) [1,2], semiconducting nanowires (*e.g.*, Si, InP, GaN, etc.)[3-5], and insulating nanowires (*e.g.*SiO2, TiO2)[6]. Molecular nanowires are composed of either organic or inorganic repeating molecular units. New forms of nanowires include core-shell superlattice nanowires. Compared to other low dimensional systems, nanowires have two quantum trends are limited, while still leaving the direction is not confined to one for connection to electric. This allows wires to be used in applications where electrical conductivity, instead of the transfer tunnel. nanowires were exhibited significantly different optical, electrical and magnetic properties than their bulk counterparts [7].

Fabrication of nanowirs

Fabrication of nanowires can be achieved either by top-down or bottom-up approaches.

Top-Down

The top-down approach often uses the traditional workshop or microfabrication methods where externally controlled tools are used to cut, mill, and shape materials into the desired shape and order. Means of conventional micro-machining technology based on photolithography, etching, and thermal oxidation processes are often being used for fabrication of nanowires.

Focused ion beam, also known as FIB, is a technique used particularly in the semiconductor industry, materials science and increasingly in the biological fields for site-specific analysis, deposition, and ablation of materials.

FIB systems operate in a similar fashion to a scanning electron microscope (SEM), however, FIB systems use a finely focused beam of ions (usually gallium) that can be

operated at low beam currents for imaging or high beam currents for site specific sputtering or milling [8, 9].

Following is a typical example for fabrication of silicon nanowires by the top-down approach. In this example, silicon nanowire arrays are prepared in silicon wafers by electrochemical etching method. In order to make vertical arrays of silicon wires with a high aspect ratio, wafer pieces are treated as follows:

A lithography pattern is prepared on a silicon oxide layer as a mask to obtain an ordered array of gold spots.

Electrochemical etching is performed with a mixed solution of hydrofluoric acid, dimethyl sulfoxide, and deionized water.

A thin aluminum layer with a thickness of 150 nm is deposited on the backside of the wafer to produce an ohmic contact between the Si wafer and working electrode using a direct current magnetron sputtering method.

An electrochemical etching system or reactive ion etching system is operated, obtaining arrays of silicon nanowires as seen in Fig 1 [10].

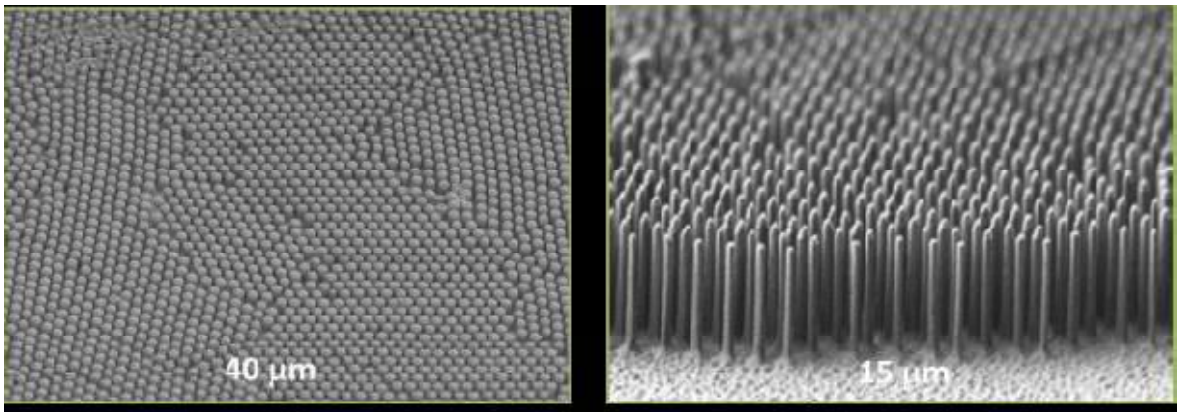


Figure 1. SEM images of the Si NW arrays fabricated by electrochemical etching. (a) Top view and (b) cross section view [10]

A modification of the top-down approach that was presented as aforementioned is illustrated in Fig 2. In this example, n-type (100) silicon wafers are used as the substrate. Silver films of varying thicknesses (8 to 30 nm) are deposited onto a hydrogen-terminated silicon substrate using thermal evaporation (Fig 2a). With high temperatures steel, topographic forms a thin film of silver film continuous conversion of an apartment of the network with nano-sized holes (Fig 2b), to bi-continuous structures, and finally nanoparticles. Si nanowire arrays can be obtained using the silver mesh for catalysis by immersing the silver-covered substrate into a mixed etchant solution consisting of hydrofluoric acid and hydrogen peroxide (Fig 2c). Silicon nano-holes can be achieved if a similar processing approach begins with

silicon substrates covered in silver nano particles (Figs 2e-g)[11].

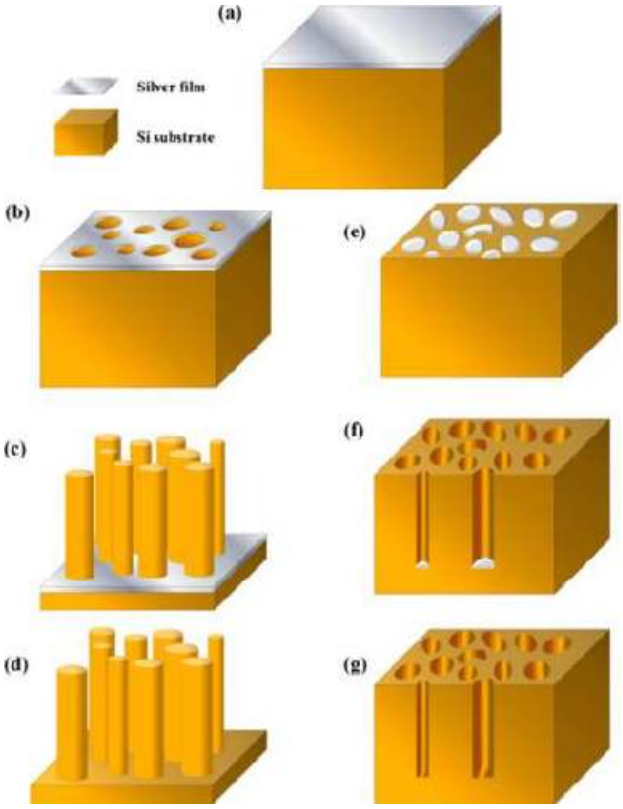


Figure 2. Illustration of the SiNW and SiNH array fabrication process.

Bottom-Up

New bottom-up techniques are being explored as a compliment to traditional top-down methods. Bottom-up techniques construct the desired features from fundamental building blocks without necessitating for patterning. There are multiple fabrication techniques that can be used for bottom-up approaches: Vapour-Liquid-Solid (VLS), Chemical Vapour Deposition (CVD), Laser ablation Catalytic Growth (LCG), Low temperature VLS, Fluid-Liquid-Solid (FLS), Solution-Liquid-Solid (SLS), Oxide Assisted Growth (OAG).

CVD/VLS APPROACH

In this method, a drop of liquid catalyst absorbs vapors and a solid nanowire is formed using metal nanoclusters as catalysts. Liquid alloy droplets of metal/Silicon are formed at high temperatures until super-saturation levels are reached-the actual concentration of the materials in the solution is higher than the equilibrium concentration. At this point, crystal growth can subsequently occur from nucleation seeds at the liquid-solid interface of the droplet and the substrate. The growth process lowers the free energy of the allow system, and the one dimensional crystal growth begins accordingly. This growth continues for as

long as the vapor components are supplied (Fig 3).

A phase diagram is usually used to determine the most favorable conditions for nanowire growth. For example, it can be seen from the diagram that the gold melting temperature is lower than that of silicon. In order to grow the nanowire, a temperature between the two melting points is selected. The main advantage of using a mechanism that utilizes a catalyst is that the direction and location of growth of nanowire can be controlled [12,13].

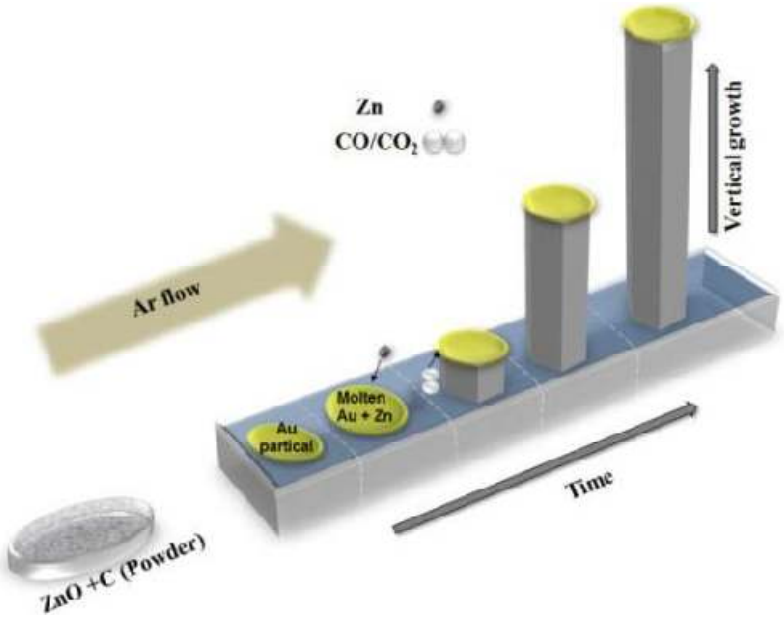


Figure 3. Schematic describing the VLS growth process.

Fabrication of nanowire devices by E-beam lithography

Electron beam lithography is a specialized technique for creating extremely fine patterns. A beam of electrons scans across a surface covered in a resist film that is sensitive to electron radiation. Energy from the electron beam is deposited in the desired pattern on the resist film. The removal of the undesired resist is similar to the process used in standard photo-lithography procedures. For example, in positive lithography only the chemically altered e-resist can be dissolved in a specific solvent (Fig 4). The main advantages of the e-beam fabrication approach of nanowires are the very high resolution that can be obtained with the e-beam, and the flexibility of the technique that allows the usage of a variety of materials and architectures. However, disadvantages exist as well. The procedure is one or more orders of magnitude slower than optical lithography. In addition, it is an expensive and complicated procedure [14].

Properties of nanowires

Nanowires are promising materials for many novel applications due to their unique electrical, optical, thermal, and mechanical

properties [15-18]. The large nanowire surface-to-volume ratio allows the creation of extremely sensitive charge/field sensors in chemical and biological systems for the detection of charged particles and molecules at low concentration as shown in Fig 4 [14]. In few instances, nanowires possess thermoelectric power (called the Seebeck coefficient) - a measure of the magnitude of an induced thermoelectric voltage in response to a temperature difference across that material. A representative example of this property is the hierarchical nanowire structure that is made of Indium telluride as in Fig 5.

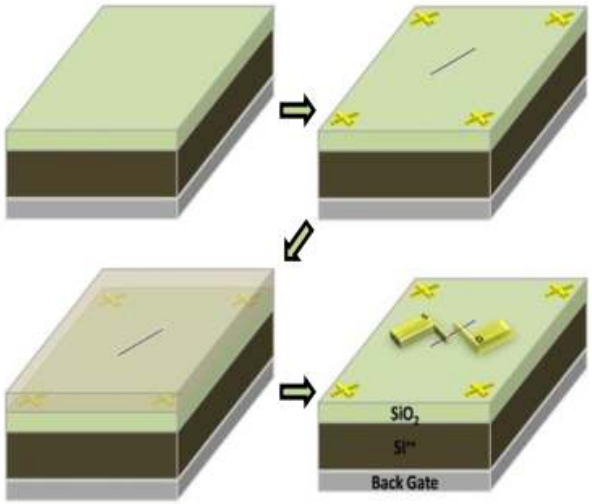


Figure 4. Illustration of nanowire fabrication via E-beam lithography [14].

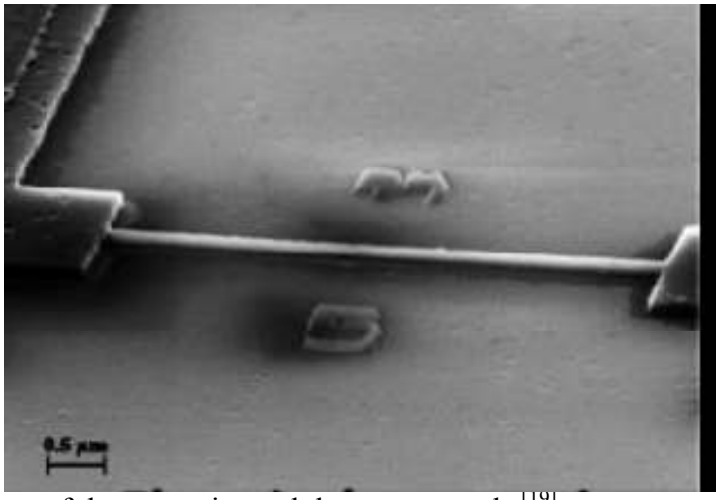


Figure 5. SEM image of the nanowire and the contact pads [19].

Electrical properties of nanowires

One-dimensional arrangements such as nano-wires have remarkable potential in nanoscale electronic devices. They are often configured in field effect transistor structures. Of the important factors determine the transport properties of wires include the wire diameter, which is

important for both the classical and quantum effects of size, material synthesis, and the conditions of surface, and the crystal quality, the crystal orientation along the wire axis of the material. Electronic transport phenomena in low-dimensional systems can be in two categories: ballistic transport, and Ballistic transport phenomena occur when the electrons can travel across the nanowire without any scattering This only happens for short nanowires with length similar to the mean free path of the carrier (electrons). For nanowires with lengths much larger than the carrier mean free path, the electrons (or holes) undergo numerous scattering events when travelling along the wire. In this case, the transport is in the diffusive regime, and the conduction is dominated by carrier scattering within the wires [20-24].

Thermoelectric properties of nanowires

Thermoelectric conversion relies on a difference between hot and cold areas in a device. Heat flowing from the hot side to the cold side creates current, which can be captured and used to power a device or stored for subsequent use. Fig 6 shows that transverse thermoelectric devices exhibit distinctive characteristics compared to ordinary thermoelectric devices as follows:

The voltage signal develops perpendicular to the applied temperature gradient (Fig 6a).

Compatibility between n-type and p-type thermoelectric material is not necessary since either is sufficient to construct the device.

The macroscopic physical properties of the multilayer material can be tuned by changing the combination and periodicity of the constituents. These features provide additional degrees of freedom when designing alternative thermoelectric devices [25].

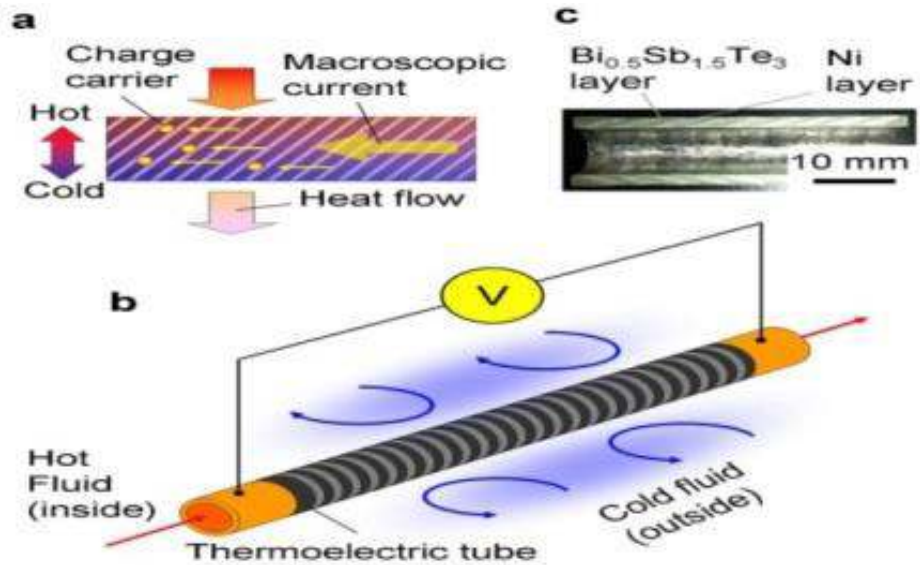


Figure 6. Illustration of a transverse thermoelectric device [25].

Mechanical properties of nanowires

Mechanical properties of silicon nanowires it shown that hardening of the wires is described well by Hertz theory and that the modulus of elasticity of silicon wires with various diameters from ~ 100 to ~ 600 nm is close to that of bulk silicon (Figs 7,8). This means that the modulus of elasticity of silicon wire diameters be independent of them if the diameter is greater than 100 nm. This supports the limited size effect (due to the surface) effect does not play a role in the behavior of flexible silicon wires with a diameter >100nm [26].

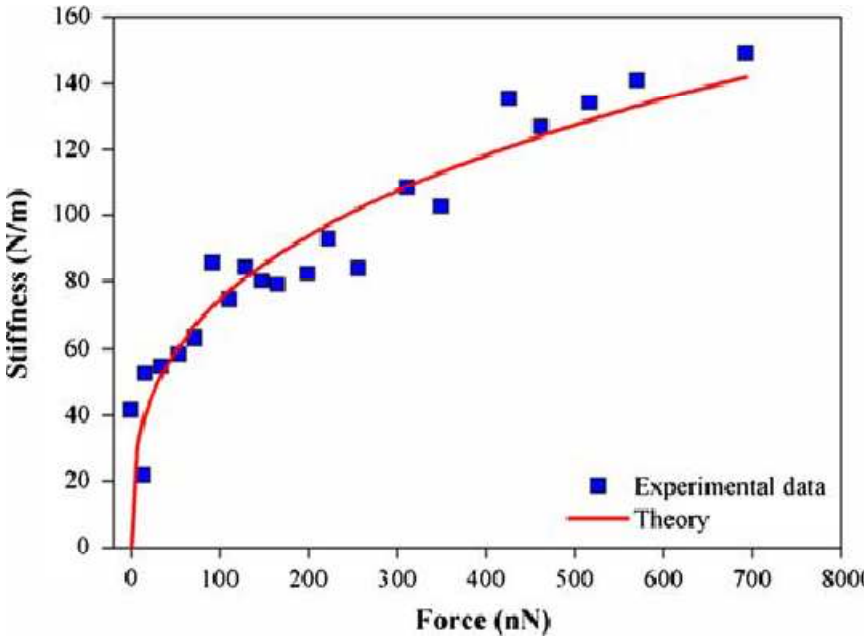


Figure 7. Stiffness of silicon nanowire, k_{NW}, with its diameter of 525 nm as a function of indentation force, F [26].

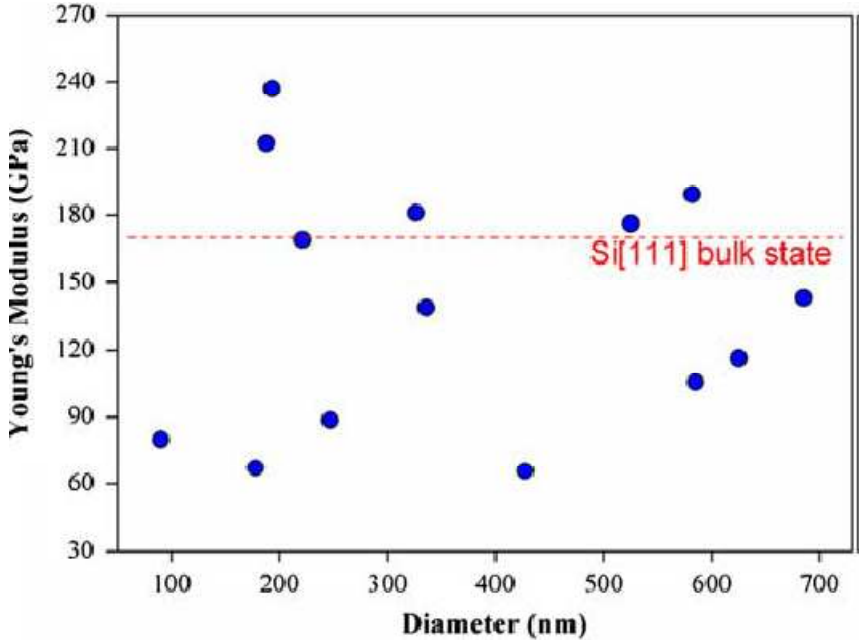


Figure 8. Young's modulus of various silicon nanowires with their diameters in the range of *100 to *600 nm extracted from AFM indentation [26].

Nanowires in sensing application in liquid or *in-vivo* environments

To understand how semiconducting nanowires can serve as chemical or electrical sensors, the physics of nanowires contacted between two electrodes and integrated in a platform of field effect transistors must be explained.

Electrical transport in Si NW

In Fig 9, a p-type nanowire (upper image) and n-type nanowire (lower image) are contacted at both ends to metal electrodes. This action depletes the holes in p-type SiNWs and, as a result, suppresses the conductivity of the Si NWs. For n-type Si NWs, this lowering of the bending bands leads to an accumulation of electrons in the n-type SiNWs and enhances the conductivity.

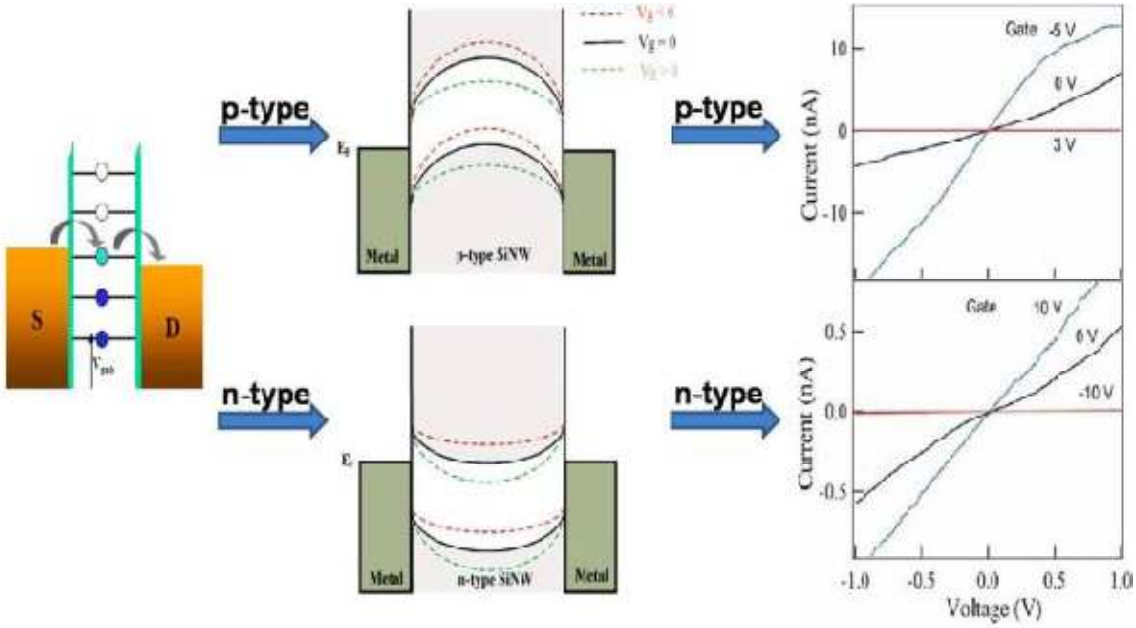


Figure 9. Electrical transfer in Si NW. (left) Energy band diagrams for p-type & n-type Si NW devices, (right) I-V data for p-type & n-type Si NW devices.

Surface modification of Si NWs

A selective sensor can generally be configured from silicon nanowire devices by linking recognition receptor groups to the nanowire surface. First, a molecular film is attached to the Si NW surface. The molecular layer can be used sometimes as an intermediator to connect other functional groups that cannot bond directly to theSi NW surface. In the Fig 10, the aldehyde-silane molecules on the surface are used as a mediator to connect antibodies that serve to sense the targeted molecule in the liquid phase.

In last step, the targeted molecules are attached to the molecular modification and the sensing process is accomplished [27].

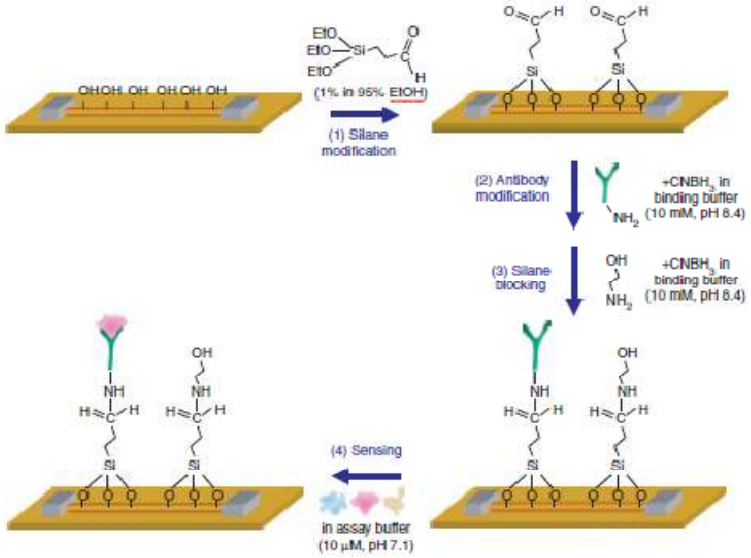


Figure 10. Antibody modification on Si NW, including: (1) aldehyde-silane modification; (2) antibody modification; (3) silane passivation by ethanolamine; and (4) sensing measurement [27].

Gas sensor based on FET with single Si NW

Functionalization of the Si NW oxide sheath with a monolayer of trichlorosilane (TS) molecules via Si−O−Si bonds is a simple and cost-effective approach to remove trap states and limit the associated hysteresis effect. As shown in the Figs 11a-e [28].

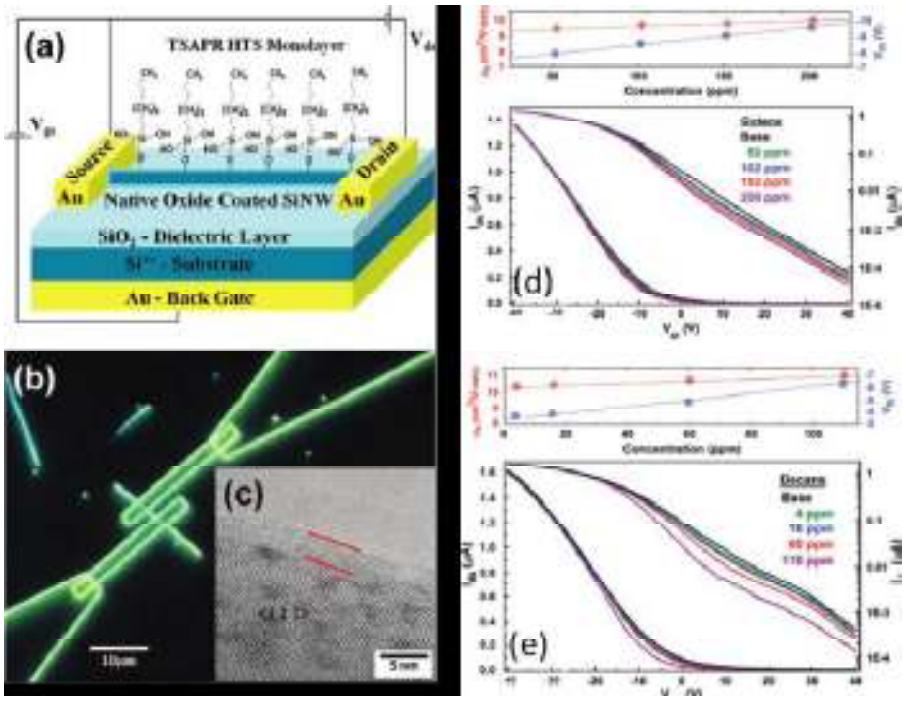


Figure 11. Gas sensor based on FET with single silicon nanowire. (a) A scheme of Si NW functionalized by a monolayer of trichlorosilane molecules, (b) dark field optical microscopy image of a representative Si NW FET, (c) TEM image of Si NW, (d) and (e) linear- scale (left y-axis) and logarithmic-scale (right y-axis) of current source-drain (*Ids)* versus back gate voltage (*Vg*) measurements with various concentrations of octane and decane, as well as dry air (base) [28].

Conclusion

SiNWs-based sensors have demonstrated sensitivity to a wide variety of gas analyses, which are important in industrial, environmental, top-down approaches are generally believed to be beneficial in terms of sensitivity and reproducibility due to better contacts and higher uniformity. top-down approaches are preferable in the preparation of devices that consist of large arrays of SiNWs to keep the difference between the nanowires and their contacts as low as possible [29].The main advantage of using a mechanism that utilizes a catalyst is that the direction and location of growth of nanowire can be controlled [11, 12], contacted at both ends of (n and p) type to metal electrodes depletes the holes in p-type and suppresses the conductivity. For n-type lowering of the bending bands leads to an accumulation of electrons in the n-type enhances the conductivity.

Acknowledgements

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References

[1] Salem AK, Chen M, Hayden J, Leong KW, Searson PC. 2004, Directed assembly of multisegment Au/Pt/Au nanowires. *Nano Lett* 4(6): 1163–1165.

[2] Tan Y, Fan, J, Chen G, Zheng N, Xie Q. 2011. Au/Pt and Au/Pt 3 Ni nanowires as self-supported electrocatalysts with high activity and durability for oxygen reduction. *Chem Commun* 47(42):11624–11626.

[3] Huang Y, Duan X, Cui Y, Lieber CM. 2002. Gallium nitride nanowire nanodevices. *Nano Lett* 2(2):101–104.

[4] Jiang X, Xiong Q, Nam S, Qian F, Li Y, Lieber CM. 2007. InAs/InP radial nanowire hetero structures as high electron mobility devices. *Nano Lett* 7(10): 3214–3218.

[5] Tomioka K, Motohisa J, Hara S, Fukui T. 2008. Control of InAs nanowire growth directions on Si. *Nano Lett* 8(10): 3475–3480.

[6] Zhang H, Luo X, Xu J, Xiang B, Yu D. 2004. Synthesis of TiO2/SiO2 core/shell nanocable arrays. *J Phys Chem B*.108(39): 14866–14869.

[7] Monro, T., Ebendorff-Heidepriem H. 2010. Fabrication of nanowires. *Google Patents*.

[8] Wirth R. 2004. Focused Ion Beam (FIB) A novel technology for advanced application of micro-and nanoanalysis in geosciences and applied mineralogy. *Eur J Mineral* 16(6): 863–876.

[9] Phaneuf M. 1999. Applications of focused ion beam microscopy to materials science specimens. *Micron* 30(3): 277–288.

[10] Baek SH, B. Noh Y, Park IK, Kim JH. 2012. Fabrication and characterization of silicon wire solar cells having ZnO nanorod antireflection coating on Al-doped ZnO seed layer. *Nanoscale Res Lett* 7(1): 1–8.

[11] Liu R, Zhang F, Con C, Cui B, Sun B. 2013. Lithography-free fabrication of silicon nanowire and nanohole arrays by metal-assisted chemical etching. *Nanoscale Res Lett* 8(1): 1–8.

[12] Alvi N, Ul Hasan K, Nur O, Willander M. 2011. The origin of the red emission in n-ZnO nanotubes/p-GaN white light emitting diodes. *Nanoscale Res Lett* 6(1): 1–7.

[13] Willander M, Nur O, ul Hasan K, Amin G, Soomro MY. 2014. Zinc Oxide Nanostructures: Synthesis, Characterization and Device Applications on Nonconventional Substrates. Zinc Oxide Nanostructures: *Adv Appl* 185.

[14] Donarelli M, Milan R, Ferroni M, Faglia G, Comini E, Sberveglieri G, Ponzoni A, Baratto C. 2015. Fabrication of single-nanowire sensing devices by electron beam lithography. *AISEM Annual Conference.2015 XVIII*..

[15] Hu J, Odom TW, Lieber CM. 1999. Chemistry and physics in one dimension: synthesis and properties of nanowires and nanotubes. *Acc Chem Res* 32(5): 435–445.

[16] Schmidt V, Wittemann JV, Senz S, Gösele U. 2009. Silicon nanowires: a review on

aspects of their growth and their electrical properties. *Adv Mater* 21(25-26): 2681–2702.

[17] Schmidt V, Wittemann J, Gosele U. 2010. Growth, thermodynamics, and electrical properties of silicon nanowires. *Chem Rev* 110(1): 361–388.

[18] Yang P, Yan H, Mao S, Russo R, Johnson J, Saykally R et al. 2002. Controlled growth of ZnO nanowires and their optical properties. *Adv Funct Mater* 12(5): 323.

[19] Presnov DE, Amitonov SV, Krutitskii PA, Kolybasova VV, Devyatov A. et al. 2013. A highly pH-sensitive nanowire field-effect transistor based on silicon on insulator. *Beilstein J Nanotechnol* 4(1): 330–335.

[20] Nehari K, Cavassilas N, Autran J, Bescond M, Munteanu D, Lannoo M. 2006. Influence of band structure on electron ballistic transport in silicon nanowire MOSFET's: An atomistic study. *Solid-State Electron* 50(4): 716–721.

[21] Cho KH, Suk SD, Yeoh YY, Li M, Yeo KH, Kim DW et al.2006. Observation of single electron tunneling and ballistic transport in twin silicon nanowire MOSFETs (TSNWFETs) fabricated by top-down CMOS process. in Electron Devices Meeting, 2006. *IEDM'06. International. IEEE*.

[22] Cui Y, Duan X, Hu J. 2000. Doping and electrical transport in silicon nanowires. *J Phys Chem B*.104(22): 5213–5216.

[23] Law M, Greene LE, Johnson JC, Saykally R, Yang P. 2005. Nanowire dye-sensitized solar cells. *Nat Mater* 4(6): 455–459.

[24] Yu JY, Chung SW, Heath JR. 2000. Silicon nanowires: preparation, device fabrication, and transport properties. *J Phys Chem B*.104(50): 11864–11870.

[25] Takahashi K, Kanno T, Sakai A, Tamaki H, Kusada H, Yamada Y. 2013. Bifunctional thermoelectric tube made of tilted multilayer material as an alternative to standard heat exchangers. *Sci Rep* 3.

[26] Sohn YS, Park J, Yoon G, Song J, Jee SW, Lee JH. et al. 2010. Mechanical properties of silicon nanowires. *Nanoscale Res Lett* 5(1): 211–216.

[27] Patolsky F, Zheng G, Lieber CM. 2006. Fabrication of silicon nanowire devices for ultrasensitive, label-free, real-time detection of biological and chemical species. *Nat Protoc* 1(4):1711–1724.

[28] Paska Y, Haick H. 2012. Interactive effect of hysteresis and surface chemistry on gated silicon nanowire gas sensors. *ACS Appl Mater Interfaces* 4(5): 2604–2617.

[29] Cao A, Sudhölter EJ, de Smet LC. 2013. Silicon Nanowire-Based Devices for Gas-Phase Sensing. *Sensors* 14(1): 245–271.