Gate bias-dependent junction characteristics of silicon nanowires suspended between polysilicon electrodes

Yun-Hi Lee and Sungim Park

National Research Laboratory for Nano Device Physics, Department of Physics, Korea University, Seoul 136–713, Korea
E-mail: yh-lee@korea.ac.kr

Received 17 June 2011
Accepted for publication 23 October 2011
Published 28 December 2011
Online at stacks.iop.org/STAM/12/065004

Abstract

Realistic integration of 1D materials into future nanodevices is limited by the lack of a manipulation process that allows a large number of nanowires to be arranged into an integrated circuit. In this work, we have grown Si nanowire bridges using a thin-film catalyst in a batch process at 200 °C and characterized the produced devices consisting of a p+−Si contact electrode, a suspended Si nanochannel, and a polysilicon contact electrode. Both the electrodes and connecting lines are made of Si-based materials by conventional low-pressure chemical vapor deposition. The results indicate that these devices can act as gate-controllable Schottky diodes in integrated nanocircuits.

Keywords: Si nanowires, nanowire junction, low-pressure chemical vapor deposition, LPCVD

1. Introduction

Nanowires (NWs) can act as electrodes in future integrated nanocircuits, as actuators, and as a model system in the study of the size effects on the intrinsic material properties [1–14]. One of the most promising application areas for NWs is in biological systems, which consist of a myriad of highly interactive and complex interconnections and pathways operating at various length and time scales [1]. In particular, monitoring the activities of neurons and the intercommunication among them in the brain is essential for understanding neural networks. Passive microfabricated multielectrode arrays and active planar silicon field effect transistor (FET) arrays have been adopted for this purpose. A variety of NW-based electronic devices including FETs have been fabricated, but their applications have been hindered by the lack of an appropriate integration scheme based on well-established processes and materials. In this regard, junctions based on silicon nanowires (SiNWs) with a diameter below 100 nm may be the most promising components in the future bio-nanoelectronics, because they can be combined with well-established top-down technology and materials. Islam et al successfully created a Si nanobridge between two vertically arranged Si surfaces using a wet etching process [3, 6]. Goldberge et al recorded ohmic I–V curves from a similar SiNW bridge using tungsten probes, but did not perform more detailed measurements such as gate voltage dependence [15]. They used colloidal gold as the catalyst for the growth of the SiNWs and could not grow the nanowires at predetermined sites or prepare FETs out of them [15]. An IBM group studied the effect of surface migration of Au on the catalytic vertical growth of SiNWs on the Si(111) surface [16]. They concluded that the growth of long wires with a uniform diameter, using high-pressure or low-pressure chemical vapor deposition (LPCVD) method, depends critically on limiting the surface migration of Au.

In this work, we present the lateral growth of SiNW transistors using a nanometer-thick-Au film as a catalyst at a low temperature of about 200 °C. Furthermore, we report the electrical transport properties of these nanowires.

2. Experimental details

Aiming at their easier integration of SiNWs into technological processes, we carried out the lateral deposition of NWs...
Figure 1. Schematic of growth procedure implemented in this work.

between two adjacent poly-Si electrodes at low temperatures using a thin Au film as a catalyst in LPCVD. We emphasize that our approach is based on the standard Si batch process and can be directly applied to practical nanodevices using thin-film nanomaterials. Silicon-on-insulator (SOI) wafers with a Si(110) substrate were used as a handle layer (i.e. bottom layer), wherein the vertical (111) surfaces provided easy growth planes for the epitaxial NWs. All fabricated junctions were examined using a field emission scanning electron microscope (FESEM, Hitachi S4300). Individual SiNW was observed using a transmission electron microscope (TEM, JEM-3011), and their chemical composition was analyzed with an electron energy loss spectroscopy (EELS) system attached to the TEM. The electrical properties of devices consisting of a SiNW between p"Si and p"Si electrodes were evaluated using a Keithley 4200 system and a probe station, at room temperature under ambient lighting.

Figure 2. We used a heavily doped Si (100) wafer as the bottom (i.e. handle) substrate and a (110) or (100)-oriented p"Si layer as the top (working) layer. (a–c) Top-view SEM images of p"-poly Si electrodes and SiNWs between them. (d) Cross-sectional view of bottom of trench showing absence of SiNWs. (e) Magnified view showing Au nanoparticles on tips of growing SiNWs. Their chemical analysis is presented in figure 5.

3. Results and discussion

Figures 2(a)–(c) show the SiNW bridges grown at 200°C using heavily doped p-type (110) or (100) Si as a top layer. Numerous SiNWs cross the gaps regardless of the Si orientation. Because the Au film covered the entire sidewalls of the trenches, a large number of SiNW devices were produced between the p"Si contact electrodes. SEM images revealed that the lateral growth was nearly independent of the electrode width and the spacing between electrodes. Because of the low temperatures, this deposition process is compatible even with flexible (plastic) substrates. Figure 2(e) shows a
Figure 3. (a) Elemental maps of Si and O atoms in an individual SiNW. (b) TEM image of SiNW with the inset showing the corresponding selected area electron diffraction pattern. (c) Line-scan profiles of chemical composition across an individual nanowire. (d) EELS spectrum showing the Si-L\textsubscript{23} edges.

The spectrum was recorded from the middle of the image (b) and shows that the nanowire is composed of Si covered with a thin SiO\textsubscript{2} shell.

Magnified view of the ends of the SiNWs that were grown toward the opposite poly-Si electrode. The SiNWs that failed to connect the poly-Si electrodes clearly showed nanoparticles at their tips. This suggests a tip growth mechanism, which might determine the SiNW diameter (not shown in this paper).

The chemical composition of the NWs was measured by EELS during TEM observation. Figure 3(a) shows the Si and O elemental maps of the wire whose TEM image is magnified in figure 3(b). The line profile of figure 3(c) reveals that while Si was evenly distributed across the wire (considering its round shape), oxygen was more concentrated at the surface. We also detected minute amounts of nitrogen in the wire originating from the carrier gas during the NW growth. A well-crystallized core covered with an amorphous layer can be seen in figure 3(b). From the selected area electron diffraction pattern (inset in figure 3(b)), the spacing between adjacent fringes was estimated as 2.9–3 Å, which corresponds to the distance between the Si\textsubscript{111} planes [17]. According to a theoretical study [18] on the diameter-dependent crystallographic orientation of SiNWs grown by a vapor–liquid–solid (VLS) mechanism with a Au catalyst, the nucleated SiNWs are stable when their diameter $d$ exceeds a threshold value $d^*$. The diameter continues to grow until it reaches the size of the Au catalyst particle, $d_{\text{Au}}$, while maintaining the crystallographic orientation of the wire. The predicted growth directions of the final SiNW were (110) for $d_{\text{Au}} < 25$ nm and (111) for $d_{\text{Au}} > 25$ nm, in agreement with our experimental results. For example, the (111) SiNW shown in figure 3(b) had $d > 30$ nm. Schmidt et al and the group of Liber [19, 20] experimentally studied the diameter-dependent growth of epitaxial SiNWs on (100) Si substrates. Those reports suggest that the interplay between the surface energy and interfacial energy may determine the preferential growth direction of SiNWs with a Au catalyst and the existence of a critical diameter.

The Si-L\textsubscript{23} EELS peaks were shifted from 96–101 eV, expected for bulk Si, to 100–105 eV in SiNWs, which can be attributed to Si oxidation or quantum confinement [21].

Finally, to examine the electrical junctions between the NWs and the p\textsuperscript{+}-Si contact electrodes, we measured current ($I_{sd}$) as a function of applied voltage ($V_{sd}$) at different values of back gate voltage $V_g$ (figure 4(a)). The measured device included several bridges and was expected to act as a transistor. The $I–V$ curves were ohmic at low bias, with the resistance of a single junction estimated as a few hundred ohms. However, after several high-voltage cycles, the $I–V$ curves showed rectifying behavior at voltages beyond a few hundred mV, and this result was confirmed on several samples. The rectifying behavior of one-dimensional semiconductor nanostructures was also reported in [21–23].

In this case, we can refer to a report by the Hewlett-Packard group [3, 7]. They showed that the SiNW bridging connection at the opposite sidewalls of (110) Si was epitaxial, and reported the coherent formation of Si–SiNW–Si structures. Their TEM images revealed that the radial spread of Au–Si eutectic catalyzed the formation of like disk deposits and SiNW–SiO\textsubscript{2}–(111) Si structures. In our two-junction devices, we assume that one contact was ohmic and the other was a Schottky contact, thus resulting in Schottky-like $I–V$ curves. The barrier height of the Schottky contact was the difference between the bottom of the conduction band of the...
SiNW near the interface and the Fermi level in the contacted metal.

For the succeeding analysis, we assumed that one ohmic contact and one blocking contact were formed on each end of the intrinsic SiNW. The rectifying $I-V$ curves of figure 4(a) indicate that the work function $\Phi$ of one NW end has an intermediate value between those of the p-type poly-Si electrode ($\Phi = 3.9–5.2$ eV depending on doping level) and the opposite electrode contacting the Au nanoparticle-capped SiNW ($\Phi = 5.1$ eV for Au). The resulting barrier in the SiNW-Au-p$^+$-Si device leads to asymmetric contact properties for the carrier transport. Previous first-principle local-density cluster calculations predicted that a Schottky junction can be formed in nanoscale Au–Si(111) systems and that the barrier height varies from 0.5 to 1.35 eV depending on the geometry [24]. In our case of catalytic direct lateral growth, the formation of an asymmetric contact based on the tip-growth mechanism is very natural. As outlined in figure 4(d), the SiNW Schottky contact, combined with the p$^+$-poly Si electrode (ohmic for p-type carriers) and Au metal particles, creates a barrier for holes, resulting in the $I-V$ characteristics shown in figures 4(a) and (b). As expected, the device showed ohmic behavior under forward $V_{sd}$ bias and blocking characteristics under reverse bias. Figure 4(c) shows typical $I_{sd}-V_{sd}$ curves for the SiNW junctions under forward and reverse biases. The inset reveals that the channel was nearly metallic under forward bias, but under reverse bias, it displayed p-type semiconducting behavior, as shown in the main part of figure 4(c). As depicted in figure 4(d), the forward bias provided extra energy for holes to overcome the barrier, and thus reduced the gate voltage dependence of the current. On the other hand, the barrier between the SiNW and Au contact was increased by the application of reverse bias that reduced the current flow. Thus the conduction could be controlled by varying the gate voltage.

Figure 5 shows line profiles of chemical composition in the SiNW body (a) and at the tip (b). Figure 5(b) confirms that the nanoparticles attached to SiNWs were made of Au supporting the assumptions of our model.

4. Conclusions

We introduced a technology for manufacturing SiNW interconnects at a low temperature of about 200 °C. It relies on one-step direct lateral growth and uses standard Si materials and Si micromachining and processing technologies combined with a specific nanometer-thick Au film as a catalyst. We succeeded in the lateral growth of suspended SiNWs using (110) and (100) Si substrates (to be elaborated elsewhere) and in producing nanodevices from them.

Our future studies will focus on the control of the number of junctions between the electrodes and on the development of n-type and p-type channels via in situ doping. Au, which was used in this work, forms deep carrier traps in the bandgap of Si; therefore, new thin-film catalysts will be required for the compatibility of our growth method with the standard semiconductor technology.

Acknowledgments

The authors thank W. Byeon of the Microfabrication Center of KIST, Korea, for assisting with the entire fabrication process. This work was supported by a National Research Laboratory Project (2006–2011) of NRF and partially by the Mid-Career Researcher Program (2011) through NRF of MEST, Korea.

References

[1] Xie C, Hanson L, Cui Y and Cui B 2011 Proc. Natl Acad. Sci. USA 108 3894
[2] Tymieniecki M Z and Durrania Z A K 2011 Appl. Phys. Lett. 98 102113
[3] Islam M S, Sharma S, Kamins T I and Williams R S 2004 Nanotechnology 15 L5
[4] He R, Gao D, Fan R, Hochbaum A I, Carraro C, Maboudian R and Yang P 2005 Adv. Mater. 17 2098
[5] Hochbaum A I, Fan R, He R and Yang P 2005 Nano Lett 5 457
[6] Sharma S, Kamins T I and Islam M S 2005 J. Cryst. Growth 280 562
[7] Hannon J B, Kodambaka S, Ross F M and Tromp R M 2006 Nature 440 69
[8] Cui Y, Duan X and Lieber C M 2000 J. Phys. Chem. B 104 5213
[9] Yu J-V, Chung S-W and Heath J R 2000 J. Phys. Chem. B 104 11864
[10] Cui Y and Lieber C M 2001 Science 291 851
[11] Li D, Wu Y, Fan R, Yang P and Majumdar A 2003 Appl. Phys. Lett. 83 3186
[12] Cui Y, Wie Q, Park H and Lieber C M 2001 Science 293 1289
[13] Fan R, Wu Y, Li D, Yue M, Majumdar A and Yang P 2003 J. Am. Chem. Soc. 125 5254
[14] Azar M T, Nasiou M and Wang R 2005 Appl. Phys. Lett. 87 113102
[15] Goldberge J, Hochbaum A I, Fan R and Yang P 2006 Nano Lett. 6 973
[16] Ross F M, Tersoff J and Reuter M C 2005 Phys. Rev. Lett. 95 146104
[17] Kohno H, Ozaki N, Yoshida H, Tanaka K and Takeda S 2003
Cryst. Res. Technol. 38 1082
[18] Wang C X, Hirano M and Hosono H 2006 Nano Lett. 6 1552
[19] Schmidt V, Senz S and Gosele U 2005 Nano Lett. 5 931
[20] Wu Y, Cui Y, Huynh L, Barrelet C J, Bell D C and Lieber C M
2004 Nano Lett. 4 433
[21] Batson P E and Heath J R 1993 Phys. Rev. Lett. 71 911
[22] Manohara H M, Wong E W, Schlecht E, Hunt B D and Siegel
P H 2005 Nano Lett. 5 1469
[23] Yang M H, Teo K B K, Milne W I and Hasko D G 2006 Appl.
Phys. Lett. 87 253116
[24] Alshareef H N, Wen H C, Harris H R, Choi K, Luan H F,
Lysaght P, Majhi P and Lee B H 2005 Appl. Phys. Lett.
87 052109