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ScienceDirect
Physica E 38 (2007) 64–66
PHYSICA E
www.elsevier.com/locate/physe

Scalable silicon nanowire photodetectors

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Available online 3 January 2007

Abstract

This paper presents photodetectors having vertically stacked electrodes with sub-micron (~300 nm) separation based on silicon nanowire (SiNW) nanocomposites. The thin-film-like devices are made using standard photolithography instead of electron beam lithography and thus are amenable to scalable low-cost manufacturing. The processing technique is not limited to SiNWs and can be extended to different nanowires (NWs) (e.g., ZnO, CdSe) and substrates. The current–voltage characteristics show Schottky behaviour that is dependent on the properties of the contact metal and that of the pristine SiNWs. This makes these devices suitable for examination of electronic transport in SiNWs. Preliminary results for light sensitivity show promising photoresponse that is a function of effective NW density.

PACS: 81.07.−b; 73.63.−b; 78.67.−n

Keywords: Nanowires; Nanocomposites; Photodetectors; Schottky diodes

1. Introduction

There is a growing interest in the use of semiconductor nanocrystals and NWs for photodetectors and solar cells due to their tunable feature size and large surface area [1–4]. McDonald et al. [2] have shown that PbS nanoparticle-based photodetectors can be tuned for enhanced response to infrared by controlling the feature size of the particles. Tunable infrared photoconductivity is particularly attractive for potential biomolecular studies and related applications [3]. Although nanocrystal–organic composites provide sensitive nanoscale semiconductor junctions, separation and extraction of generated carriers to electrodes is not efficient in the low mobility organic medium. Recently, Law et al. [1] have reported the use of aligned NWs in dye-synthesized solar cells to enhance extraction of generated carriers, leading to higher external quantum efficiencies [1,4]. While the surface and feature size of NWs can provide the benefits of nanocrystals, they can lead to better extraction of photo-generated carriers along the high mobility NW core. However, carrier extraction in dye-synthesized solar cells [1,4] is still hampered by electrode separation of more than 20 μm in view of the limited lifetime of the photo-generated carriers.

In this paper, we present our preliminary results for thin-film-like photodetectors based on SiNW/silicon oxide nanocomposites. The device fabrication steps are presented in the next section. For fabrication of electrodes, standard photolithography is used, which is in contrast to the conventional route for fabrication of single-NW devices based on e-beam lithography. As a result, the fabrication steps can be extended to a very large-scale integration (VLSI) technology. In the following section, we systematically study current–voltage characteristics in forward and reverse bias along with their light sensitivity, which are dependent on transport properties of the pristine SiNWs and contact metal properties.

2. Fabrication

Fig. 1 illustrates the schematic cross-section of the photodiode structure with vertically stacked electrodes. SiNWs embedded in a matrix material bridge the electrodes.

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1386-9477/$ - see front matter © 2007 Published by Elsevier B.V.
doi:10.1016/j.physe.2006.12.054

The matrix material and SiNWs constitute the nanocomposite that enables electrode fabrication.

SiNWs are grown from photolithography located gold nanoparticles using plasma-enhanced chemical vapour deposition (PECVD) [5] similar to the vapour–liquid–solid (VLS) method [6]. Gold nanoparticles are prepared on cleaned p-type silicon substrates by annealing of a thin (~3–10 Å) gold layer, which leads to the formation of gold nanoparticles with desired diameter. The samples are then subjected to hydrogen plasma in a PECVD system followed by introduction of silane (SiH_4) at 10 Torr and 300 °C for 5 min. Fig. 2(a) depicts a scanning electron microscope (SEM) picture of the grown SiNWs from a photolithography patterned 5 μm gold circle. The SiNWs have a crystalline core with a thin oxide shell as seen from the high-resolution transmission electron microscopy (HRTEM) image shown in Fig. 2(b).

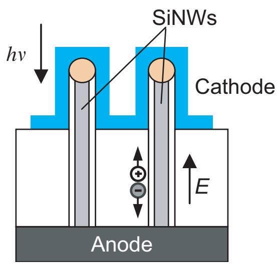

Fig. 1. Schematic cross-section of a SiNW diode with vertically stacked electrodes.

The matrix material of hydrogen silsesquioxane (HSQ) solution acquired from Dow Corning is spin coated on the substrate. The composite film is then cured in a quartz furnace tube at 390 °C for 1 h. HSQ is commonly used as an insulation layer between subsequent metallization layers in integrated circuit (IC) technology [7,8]. Fig. 3 illustrates SEM images of the SiNW in the oxide matrix. As can be seen, the SiNWs are forced to lie flat or tip out of the oxide matrix depending on the wire length and diameter. Some wires are bunched together to form hillocks due to the capillary force of the drying solvent.

In the next step, an Ti/ITO layer (5/80 nm) is sputtered onto the surface and patterned using photolithography and lift-off. Fig. 4(a) shows the photomicrograph of a row of square photodiodes fabricated on a 100 μm wide strip of grown SiNWs, demonstrating the scalability of the process to high throughput fabrication technology.

3. Measurement results and discussions

Fig. 4(b) depicts the current of the ITO/SiNW photodiode as a function of negative and positive ITO electrode bias measured using a Keithley 236 source measure unit. The current–voltage characteristics are similar to that of a metal–semiconductor Schottky diode, which can be

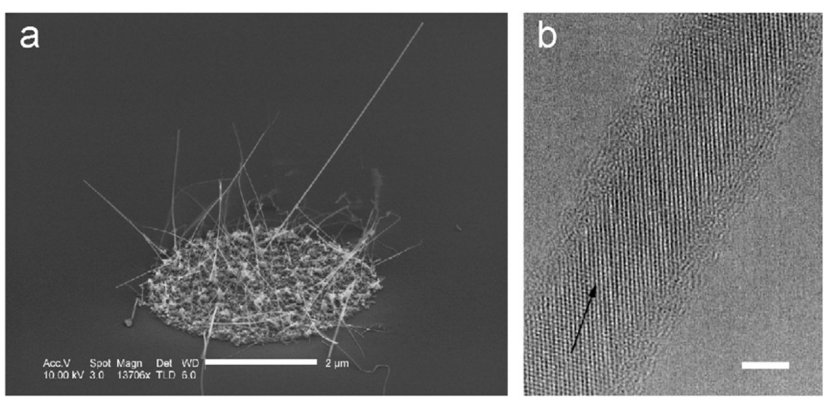

Fig. 2. (a) SEM image of SiNWs grown on a catalyst island, (b) HRTEM image of SiNWs grown in PECVD (scale bar: 3 nm, arrow: ⟨1 1 1⟩ orientation).

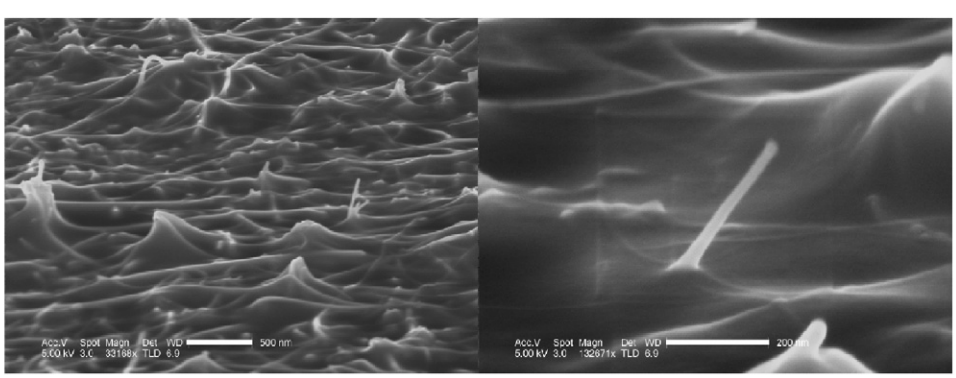

Fig. 3. SEM images of SiNWs in silicon oxide matrix, showing wires tipping, forced to lie flat and bunching together during the deposition of the matrix material.

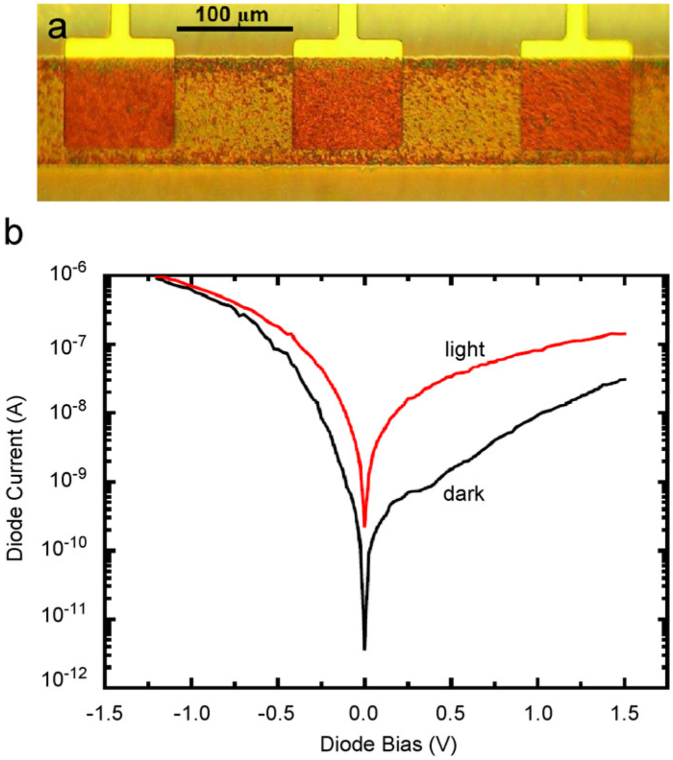

Fig. 4. (a) A top view photomicrograph of scalable ITO-SiNW photodiodes on a SiNW growth strip. (b) Measured current–voltage characteristics of the photodiode under dark and light conditions.

attributed to the junction between the top metal and the SiNWs with an approximate density of 10 NWs/μm^2. The current is attributed to the conduction through the SiNWs, as the leakage current for a test device with pure HSQ was less than 10 pA, which matches the typical leakage current density of $<0.1\,\mu A/cm^2$ for this insulating material [7,8]. It should also be noted that the influence of gold nanoparticles at the tips of the SiNWs on the current–voltage characteristics and photoresponse of the device cannot be ruled out. The device turns ON for negative voltages of the ITO cathode with a switching ratio of more than three orders of magnitude. The reverse dark current at 0.4 V cathode bias is relatively high ($\sim$100 nA/cm^2) [9], which is expected for Schottky contacts accentuated by the relatively small ($\sim$300 nm) vertical electrode separation. In the forward bias (negative cathode voltages), the current increases exponentially following by a space charge limited current (SCLC) region at high negative voltages. The high ideality factor of around 3 can be attributed to the possible impact of trapped charges in the oxide shield around the SiNWs, which can deplete the semiconductor core of carries. Forward bias or light exposure can inject carriers and increase the current, as seen in the low negative bias region of Fig. 4(b). In addition, there is variation in the length of the wires that could lead to a distribution of turn ON voltages for the different wires and a wide turn ON region for the device. Interestingly, the significant hysteresis that is present in the measurement of single-SiNW devices with bare NW surfaces in air [10] is not observed in our devices due to the effective passivation of the NW surface by the silicon oxide matrix. The light source is a Bausch and Lomb 20 W halogen lamp with an 8 times objective lens for focusing the incident light. The photocurrent is more than an order of magnitude higher than the dark current at 0.4 reverse bias. Use of a rectifying semiconductor contact layer can decrease the dark current and improve the photocurrent of the device.

4. Conclusions

Integration of nanostructures such as nanowires and nanoparticles for scalable electronic and optoelectronic devices is the major challenge for commercialization of nanotechnology. Here, we report fabrication of scalable and addressable SiNW photodiodes on photolithography located SiNWs with promising photoresponse. The characteristics of the photodiodes are dominated by the Schottky contact between ITO and SiNWs and the properties of the SiNWs. The high dark current can be suppressed by the use of a rectifying contact layer as a move toward the manufacture of p–i–n SiNW photodiodes with increased light sensitivity.

Acknowledgements

The authors would like to thank Advance Nanotech for financial support and C. Ducati for HRTEM images. PS also acknowledges NSERC of Canada.

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