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Research Article

Templated Fabrication of InSb Nanowires for Nanoelectronics

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Among various ways to produce nanowires, anodic alumina membrane- (AAM-) based synthesis has constantly received much attention, because AAM has a uniform and parallel porous nanostructure which makes it an ideal template material for fabricating highly ordered nanostructures. In this paper, we report fabrication of InSb nanowire arrays with diameter of 200 nm and 30 nm by direct current electrodeposition inside the nanochannels of anodic alumina membranes without subsequent annealing. The nanowires have four major growth directions, (220) being the most dominant with structure defects such as twins. The transmission electron microscopy (TEM) and scanning electron microscopy (SEM) results demonstrate that these InSb nanowires are uniform with diameters about 200 nm and 30 nm, corresponding to the pore diameter of the AAMs. The I-V measurement of a single nanowire is also reported with encouraging preliminary results.

1. INTRODUCTION

InSb is well known for its direct narrow band gap (0.18 eV at 300 K) and various applications in electronic and optoelectronic devices with a very high-electron mobility ($8 \times 10^4\ \mathrm{cm^2V^{-1}s^{-1}}$at 300 K), electron velocity, and ballistic length (up to 0.7 μm at 300 K), and ideal candidates for detector arrays operating in the infrared wavelength, high-speed electronic devices, and magneto resistive sensors [1]. In the past few years, there has been increasing interest in nanostructure III-V semiconducting materials due to their potential applications. Different methods have been used to fabricate the nanowires, such as vapor-liquid-solid (VLS), physical vapor deposition (PVD), and hydrothermal methods [2–10]. Comparatively, the pulsed electrodeposition process, using anodic alumina membranes (AAM) as template, is an effective and inexpensive method to fabricate nanowires. However, although it is considered that the electrodeposition of high-quality compound InSb with precise stoichiometry at ambient temperature from aqueous solutions is a challenge, it is surprising that only a few studies on this important issue have been reported [11–13]. Other than thin films on a substrate [14–16], fabrication of InSb nanowires and nanocables by simple electrodeposition in anodic alumina membranes was reported [17]. Transport properties along with thermal properties of InSb nanowires have been shown very recently [18–22]. But these properties were reported only for the whole template or membrane embedded with nanowires and single nanowire properties are not measured or reported so far. Also, no attention has been given to the photoconduction properties of InSb nanowires despite the exciting possibilities for using InSb nanowires in optoelectronic circuits or as infrared detectors. We have synthesized InSb nanowires with single-crystal structures, diameters as small as from 30 to 200 nanometers by electrochemical deposition in the porous anodic alumina template and exploring the possible applications for nanoelectronics devices such as field effect transistors and Infrared photodetectors [23–28].

2. EXPERIMENTAL PROCEDURES

2.1. Synthesis

The AAMs were purchased from Whatman Inc. Florham Park, NJUSA and Synkera Technologies, Inc. (Longmont, Colo, USA). The diameters of the pores in the AAMs are about 30 nm and 200 nm, and the thickness of all AAMs

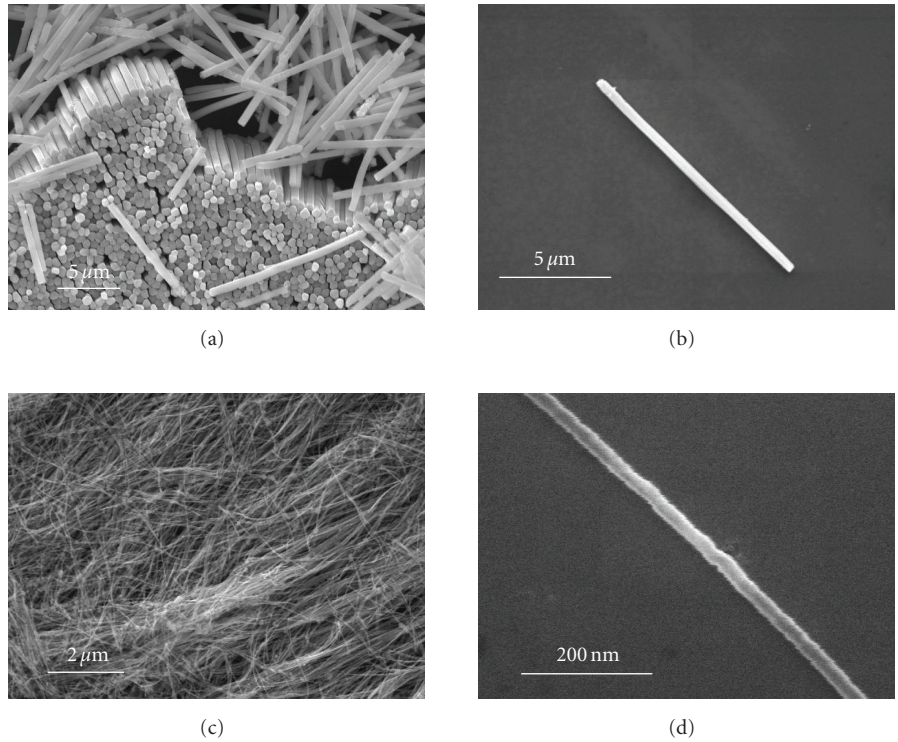

Figure 1: (a) SEM of a bundle of aligned nanowires released from AAM with 200 nm pores, (b) SEM of a single 200 nm-diameter InSb nanowire, (c) SEM of a bundle of nanowires after they are removed from the template with 30 nm pores, and (d) SEM of one single isolated 30 nm-diameter InSb nanowire.

used here is about 60 μm. A layer of Au about 200 nm in thickness was sputtered onto the bottom side of the AAMs to serve as a conduction contact. The electrodeposition was carried out in a typical three-electrode electrochemical cell equipped with a platinum electrode as the counter electrode, Ag/AgCl as reference electrode, and the AAMs with Au back layer as the working electrode controlled by a potentiostat/galvanostat (Princeton Applied Research Company (Oak Ridge, Tenn, USA), model: Potentiostat 263A). All chemicals were analytical grade used without further purification. We had performed a series of experiments and optimized the deposition parameters as follows: 0.1 M $SbCl_3$, 0.15 M $InCl_3$, 0.36 M citric acid, and 0.17 M potassium citrate at pH 1.8. The citrate ions are used as the complexion agents to bring the deposition potential of In and Sb closer to maintain binary growth. The deposition was conducted for 40 minutes under the deposition potential of -1.5 V versus Ag/AgCl reference electrode at room temperature. After the deposition, the sample was washed several times in distilled water and rinsed with acetone.

2.2. Characterization

The as-synthesized products were characterized by X-ray diffraction (XRD) machine (BRUKER AXS, Inc. Madison, WI USA, model: D8 Advance), transmission electron microscope (FEI Company (Hillsboro, Ore, USA), model: CM 300), and Scanning electron microscope (JEOL Company (Tokyo, Japan), model: JSM-6300) equipped with energy dispersive X-ray spectroscopy. For TEM analysis, the products were immersed in 3 M NaOH solution for several minutes to centrifuge and were washed with distilled water to remove the dissolved AAMs and the remaining NaOH solution; the nanowires were dispersed in deionized water. Then, drops of the solution were dripped onto copper grids coated with holey carbon film. For SEM observation, the products were treated with 3 M NaOH for about 30 minutes and washed with distilled water then was placed on Si substrate.

3. RESULTS AND DISCUSSION

SEM observations in Figure 1(a) show that the InSb nanowires are uniformly distributed, highly ordered, parallel to each other, and their diameters are all about 200 nm, corresponding to the pore diameter of the AAM used. It can be seen in Figure 1(b) that the nanowires are uniform in diameter and have a smooth surface. Figures 1(c) and 1(d) show the bundles of nanowires after removing from a membrane with 30 nm pores. Depending on the pore diameter of the AAM, InSb nanowire arrays with different diameters can be obtained. The length of InSb nanowires varies between 5 μm to 20 μm, which corresponds with the deposition time used and also the speed of the centrifuge during cleaning. The length of the nanowires can be modulated by changing the thickness of the AAM or the pulsed deposition time. Figures 2(a) and 2(b) show a typical EDS spectrum of InSb nanowire and the XRD patterns, respectively. The diffraction peaks can be indexed to a cubic zinc-blended phase of InSb

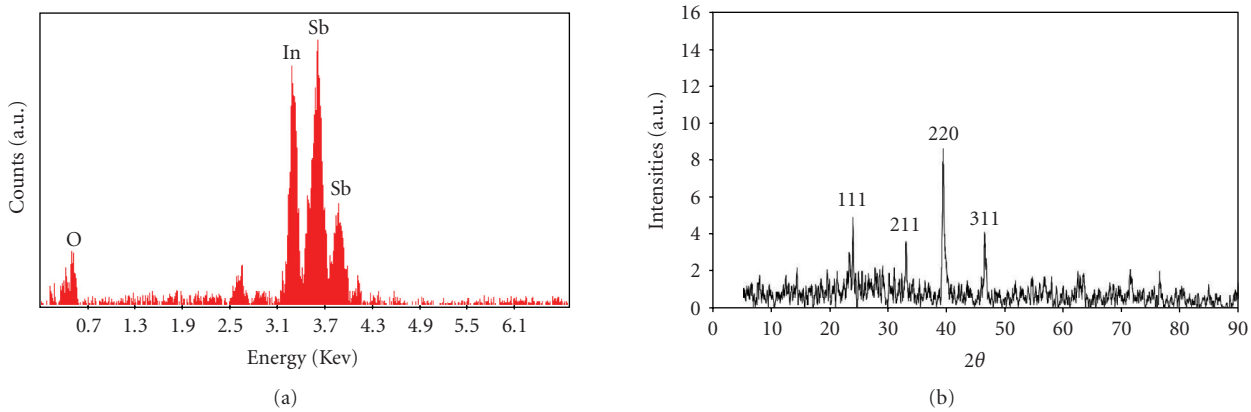

FIGURE 2: (a) Energy dispersive spectrum of a single InSb nanowire, (b) XRD pattern of InSb nanowire arrays show four preferred directions of growth.

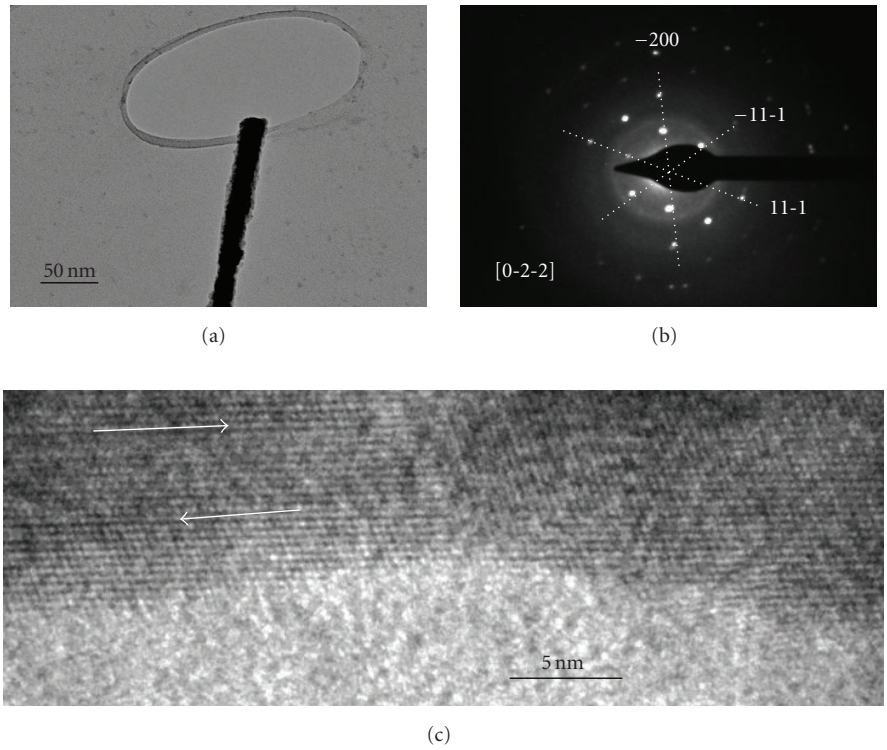

FIGURE 3: (a) Electron transparent edge of an InSb nanowire in a TEM bright field image, (b) selected area diffraction pattern (SAED) shows hexagonal pattern on a (0-2-2) zone axis, and (c) high-resolution TEM image of the junction between an atomically abrupt inter-twinning. The arrows are showing the junctions.

crystal from the American Mineralogist Crystal Structure Database (AMCSD). One can see that the intensity of the diffraction peak at $2\theta = 39.34^\circ$ is relatively stronger than the other diffraction peaks, demonstrating that the InSb nanowires deposited in AAM grow preferentially along (220) crystal direction.

The transmission electron microscope (TEM) images of one single InSb nanowire released from AAMs is shown in Figure 3(a). The corresponding selected-area electron diffraction (SAED) pattern indicates that the InSb nanowires are single crystalline in Figure 3(b). The SAED pattern was taken along the nanowires, but changes along the length of the nanowires. This means that the nanowires are single crystal with a slight structural deformation along the length which is seen in the high resolution TEM (HRTEM) image in Figure 3(c). The HRTEM obtained from the nanowire shown in Figure 3(a) is shown in Figure 3(c) depicting the twinning pattern present in the crystal structure. The deformations may be due to the release process of nanowires from the membrane, which involves etching with NaOH, washing

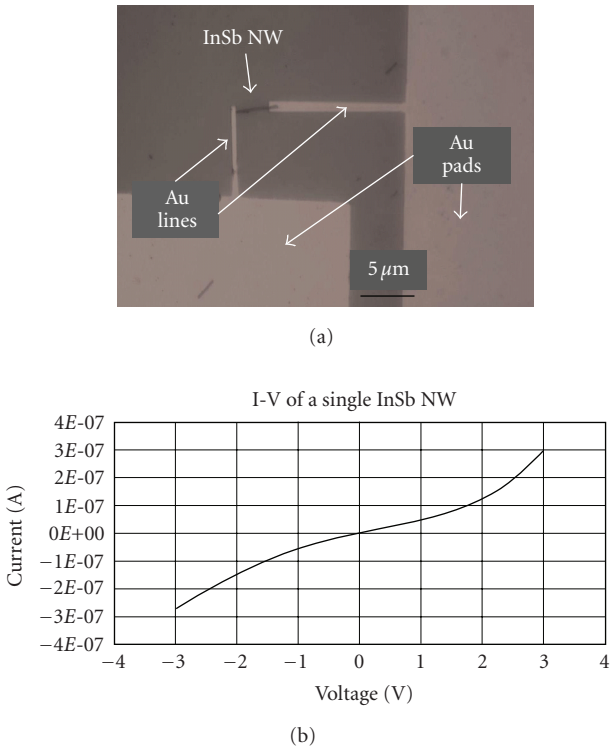

Figure 4: (a) Au-InSb-Au contacts (Schottky) made by electron beam lithography (EBL) technique for a single NW, (b) I-V characteristics show the nonlinear rectifying effect due to the metal-semiconductor-metal contacts.

with acetone and isopropanol and finally centrifuging in deionized water.

Numbered grids were written onto a silicon wafer using electron beam lithography technique (EBL) for fabricating test beds for electrical measurements. The synthesized InSb nanowires were suspended in deionized water and transferred onto each grid. A scanning electron microscope was used to locate and image the deposited wires. With the images as reference, contacts to the nanowires were designed using an SEM/E-beam Lithography system (Carl Zeiss Company, model: Leo SUPRA 55). The Si chip was spin-coated with a polymer resist layer (PMMA) for using with electron beam lithography, which involves exposing the resist layer to high-energy electrons in a pattern defined by the drawing programmed in the lithography system. Through developing, the resist is removed from the exposed areas. A layer of Au is evaporated for making contact patterns to the measurement devices. After metals are deposited, the remaining polymer is removed using acetone and the EBL patterns of gold lines were found on top of the nanowires at the desired sites (Figure 4(a)). Electrical measurements were made using a semiconductor parameter analyzer (Agilent Technologies, Inc. Santa Clara, CA USA, model: 4155C) coupled with a probe station (Signatone Corporation Gilroy, CA USA, model: H 100) by applying a constant voltage across the nanowire and current was measured. Figure 4(b) shows that the I-V curves exhibit a nonlinear characteristic and might be referred to the Au/InSb/Au junction structure. It is well known that contacts made by EBL shows rectifying behavior which can be explained considering the existence of two back-to-back Schottky barriers connected in series to both extremes of the nanowire, that is, Au-InSb-Au. The observed rectifying behavior at room temperature tends to disappear at higher temperatures which is being studied at present and will be reported in near future. Nevertheless, it could be ascertained to the fact that conduction electrons possess enough mobility to overcome the energy barrier existing in Schottky junctions.

4. CONCLUSION

In summary, near-stoichiometric InSb nanowires have been synthesized by using dc electrodeposition inside the nanochannels of AAMs without subsequent annealing. Achievement of better control of stoichiometry than demonstrated here may be possible and will be important for future device applications. The nanowires also conduct almost no current in the dark, but when hit with light, they conduct 10000 times more current which was also found recently. This photoconduction property could lead to a variety of tiny optoelectronic devices potentially useful in future generations of nanoelectronics, chemical sensors, and eventually provide clues to the fabrication of tiny solar cells. The light-induced conductivity increase and the temperature dependent behavior of the nanowires will be reported in near future.

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