A Unique Opportunity for Large Scale Fabrication of Semiconductor Nanowire-Based Devices

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ABSTRACT

A fabrication method is developed, which enables control over the location of horizontal nanowires (NWs) on a large scale and allows placement of electrical contacts on them. Using this technique, via a two step photolithography process, electrically addressable NWs were prepared. The first step is patterning the substrate with metal catalyst and growth of horizontal NWs on predefined locations. The second step is precise positioning of metal contacts on NWs. By adding a third step of photolithography, gate electrodes were placed on these devices to fabricate large number of NW field effect transistors. Electrical transport studies of individual and groups of NWs are performed which will be discussed in this presentation.

Keywords: nanowire device, directed assembly, zinc oxide, electrical characterization, nanowire transistor.

1 INTRODUCTION

Nanocrystals both metallic and semiconductor with different dimensionality are considered to be of significant importance as potential building blocks in fabricating nanodevices. These building blocks are mainly produced using "bottom-up" approaches in which chemical techniques are used in the fabrication of functional nanostructures. The ultimate aim is to produce hierarchical structures capable of performing sophisticated functions. However, the difficulties in the directed assembly and locating the nanocrystals on a solid surface have made this direction audacious and very challenging. In the case of 1D nanostructures, several strategies have been developed for directed positioning and alignment of NWs, including those exploiting electric fields [1] and fluid flow [2]. More recently, micrometer-size areas of aligned NWs have been formed using the Langmuir-Blodgett technique [3]. Also using a pattern transfer scheme millimeter long NWs have been fabricated [4]. All of these approaches require multi-step treatments such as removal of the NWs from substrate, dispersion in a solvent and application of an alignment technique or need delicate fabrications demanding a dexterous operator. So far in the majority of NW device assemblies, standing NWs as the starting point have been used, which results in some inherent limitations that were mentioned earlier. Here, it is proposed to use horizontal NWs as an alternative for nanodevice fabrication. Growth of one-dimensional crystals has been reported for rare-earth silicide NWs on Si (001) via a physical vapor deposition [5,6]. One disadvantage associated with such growth process was the presence of two possible growth directions with similar probability of occurrence. Using the same principles, we grow aligned and horizontal zinc oxide NWs on α- plane sapphire [7]. In this work, ZnO NWs and electrical properties of their devices are discussed.

2 EXPERIMENTAL

The strategy utilized for the horizontal growth of ZnO NWs begins with the patterning of an *a*-plane (11-20) sapphire substrate with narrow gold lines, oriented perpendicular to the growth direction of the NWs. gold lines are fabricated by depositing 10 nm of gold on *a*-plane sapphire, followed by over- coating it with few drops of 1% poly (ethyl methacrylate) in ethanol (MW 250,000) at 40 ºC. This is immediately followed by placing a micropatterned polydimethylsiloxane (PDMS) stamp on the polymer/substrate and removing it (after ~1 hrs) once the polymer is solidified at 25º C. The polymer lines are nominally 1.5 μm in width with a 400 nm spacing between them. The patterned substrate is submerged in an gold etchant solution for 20- 40 seconds (depending on the initial gold film thickness) followed by rinsing with deionized water (18 MΩ). The gold film protected by the polymer lines changes to parallel gold lines. These lines can be narrowed down to ~100 nm by increasing the etching time. The last step is dissolving the polymer lines in ethanol. The advantage of using narrow gold lines is that at high temperature, this morphology results in nanodroplets (nanoparticles) with the majority of them at the edges of the lines. These are the nanodroplets that promote the horizontal growth and result in formation of the aligned NWs.

3 RESULTS AND DISCUSSION

A SEM image of the grown NWs is shown in Figure 1a in which the traces of the gold lines can be seen. The growth direction of NWs is found to be ± $[1\text{-}100]_{sap}$.

During the growth of a NW, the gold droplet is fed via the vapor phase as it is pushed forward on the substrate. The observed growth direction does not show any correlation with sapphire surface atomic steps nor with the gas flow direction inside the tube furnace. The energy dispersive x-ray (EDX) analysis of these NWs confirms the presence of the ZnO.

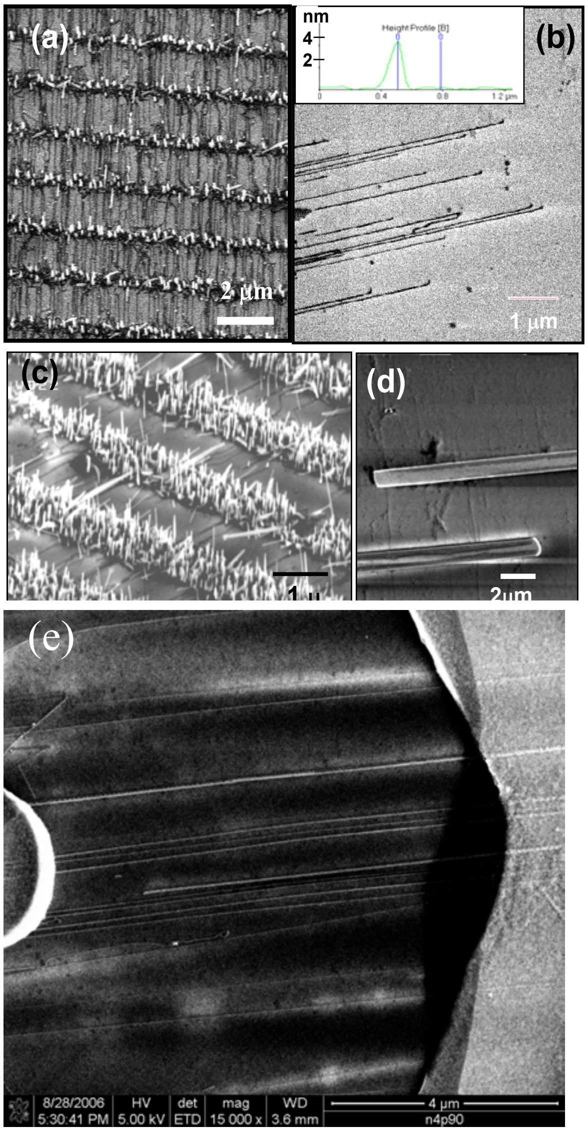

Figure 1: (a) Horizontal ZnO NWs (12 nm in diameter) grown from gold lines. (b) Very long NWs can be grown on sapphire if their path is clear. (inset) 4 nm NWs in height . (c) If the gold line thickness becomes more than 15 nm, majority of NWs grow off surface. (d) Two NWs between metal contacts for I-V measurement. (e) Amulti-NW device.

Electron back-scattering diffraction on horizontal NWs shows that the (0001) planes of ZnO grow parallel to the substrate (11-20) plane. The growth direction of NWs was also found to be <1-100>sap.

For gold lines thicker than about 15 nm, the vertical growth mode becomes dominant due to the increase in the gold nanodroplet size. An example of this case is shown in Figure 1c. NWs lose their straight growth direction upon reaching obstacles on the surface, thus in the process, it is important to have a clean surface between the gold lines. By varying the gold line thickness (below 10 nm), the width of horizontal NWs can be changed, although only a narrow range of diameters can be prepared due to the presence of a lower limit in the droplet radius formed at high temperature. These limitations can be overcome with the use of colloidal NPs and fabricating lines of gold NPs instead of evaporated gold lines. Using gold NPs, a variety of droplet size distributions, ranging from 1-20 nm can be prepared which result in NWs with diameter range between 1-20 nm. This technique allows one to grow very long NWs as long as the gold droplet at the tip is fed by Zn and O atoms (Fig. 1b). The diameter of the NWs remains constant during the growth process as well. Depositing gold by any technique that allows control over its registry could be used for NW device fabrication. In addition to soft lithography, we have used electron beam and optical lithography, and have been fabricated large numbers of nanodevices. In order to study the conductivity of ZnO NWs, electrical contacts made of Gold and Ti were placed on NWs using optical lithography (Fig.1d, 1e). Current/voltage measurement in Figure 2 shows the I_{SD}-V_{SD} characteristics of ZnO NWs. Rapid thermal annealing at 350 and 450 ºC was carried out and resulted in improving the conductivity of contacts. In this example, at low voltages, the linear behavior is an indication of Ohmic contacts. Although at higher voltages, the contact resistance results in a nonlinear behavior.

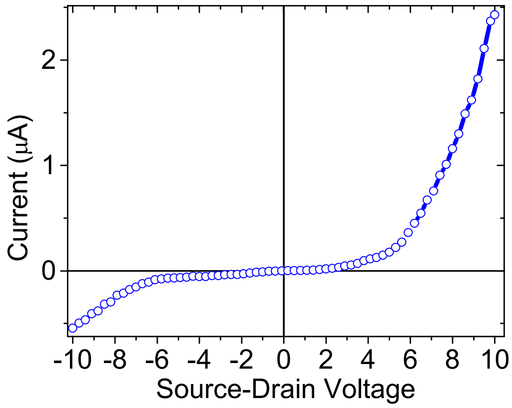

Figure 2: Typical I-V data scans for a multi-NW device. Although contacts are ohmic but the slope is an indication of a high contact resistance.

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