Simple approach to $\beta$-SiC nanowires: Synthesis, optical, and electrical properties

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High-quality $\beta$-SiC nanowires were synthesized on activated carbon fiber via a thermal evaporation method without the use of metal catalyst. Their structure and chemical composition were studied by Raman spectroscopy and high-resolution electron microscopy. Field effect transistors were fabricated to investigate the $\beta$-SiC nanowire electrical behavior possessing n-channel characterization. The carrier mobility of the devices was 15.9 cm$^2$/V s when the $V_{ds}$ is 0.01 V. This result contributes to the development of efficient nanodevices based on $\beta$-SiC nanowires, as well as nanocomposites. © 2006 American Institute of Physics. [DOI: 10.1063/1.2398902]

Recently, a variety of quasi-one-dimensional (1D) nanostructures, such as nanotube, nanowire, nanobelt, and nanosprings, have been investigated intensively because of their application in nanocomposites and future electronic components including field effect transistors. 1–5 Silicon carbide have very unique properties, such as band gap, excellent thermal conductivity, chemical inertness, high electron mobility, and biocompatibility, which promise well for applications in microelectronic and optoelectronics and have thus attracted much interest from the materials and devices communities. 6–8 In particular, silicon carbide nanowires are expected for the reinforcement of various nanocomposite materials or as nanoelectrodes in harsh environment, due mainly to their super mechanical properties and high electrical conductance. Research on silicon carbide 1D nanowires would be highlighted both from the fundamental research standpoint and for what concerns the potential application in nanodevices and nanocomposites. So far, $\beta$-SiC nanowires were synthesized from various methods, such as carbon template, 9,10 arc discharge, 11 chemical vapor deposition via silicon precursor, 12 and catalyst assisted vapor liquid solid mechanism. 13 However, these products are available at the cost of either high purity or expensive carbon nanotube or the hazardous and easily explosive silicon (carbon) precursor of SiH$_4$ or SiCl$_4$ (CH$_4$). In addition, the synthesized materials were low yield and purity and time consuming. Thus, large-scale synthesis of $\beta$-SiC nanowires still remains a challenge to be considered for above mentioned disadvantage. Recently, we have developed a simple method for synthesizing $\beta$-SiC nanowires in high frequency induction heating of SiO powders, and as-synthesized $\beta$-SiC nanowires are high purity and freestanding. The optical and electrical transport properties are also reported in this letter.

The preparation of $\beta$-SiC nanowires was achieved using SiO powders as the source materials in a vertical quartz tube (of outer 80 mm and length of 120 cm) and a high frequency induction heating cylinder made of high purity cylinder graphite crucible coated with an activated carbon fiber (ACF) thermonisulating layer. In brief, The SiO powder was placed into the high cylinder graphite crucible, and then the chamber was flushed with high purity of 100 SCCM (SCCM denotes cubic centimeter per minute at STP) Ar to eliminate O$_2$ by means of rotary vacuum pump for many times. Afterwards, the furnace was rapidly heated from room temperature to around 1450 $^\circ$C within 2 min and maintained for reaction for 15 min with a flow of Ar under a total pressure of 50–100 Torr. After the furnace was cooled down until room temperature in the flowing Ar, the ACF surface was deposited with a thick layer of light-blue fluffylike products with a thickness of several millimeters shown in the inset of Fig. 1. It can be seen that many mushroomlike lumps grew perpendicularly on the surface of the ACF.

The x-ray diffraction (XRD) pattern (Fig. 1) suggests that the as-synthesized product consists of the crystalline zincblend (cubic) form of $\beta$-SiC with the unit constant of $a$ =4.358 Å, close to the standard value for $\beta$-SiC (4.349 Å (JCPDS Card No: 75-0254). A broad peak at 2$\theta$ = ~20°–30° may be attributable to some amorphous materials with the product. Besides, there is a low-intensity peak (marked with S) at a lower diffraction angle than that of the

![Fig. 1. (Color online) (a) XRD pattern of the as-synthesized products. Inset: (b) the digital camera photo of the products.](image-url)
strong (111) peak, which usually ascribes to the stacking faults in the (111) plane.\textsuperscript{15}

A low-magnification scanning electron microscopy (SEM) image shown in Fig. 2(a) reveals that the product consists of numerous wirelike nanostructures (a large amount of straight, curved, randomly oriented, and freestanding nanowires) with a length of up to tens of microns. Figure 2(b) shows the chemical composition of the nanowires characterized by energy dispersion spectroscopy (EDS). It is found that the nanowires are mainly composed of Si, C, and O.

Low-magnification transmission electron microscopy (TEM) image of the sample shows that the diameter of the nanowires is \( \sim 6 \text{ nm} \) and uniform [Fig. 2(c)]. A high-resolution transmission electron microscopy (HRTEM) shows that a \( d \) spacing of 0.25 nm corresponds to the (111) plane spacing, indicating that nanowire grows along [111] direction [Fig. 2(d)]. Moreover, high density of stacking faults in \( \beta \)-SiC nanowires was found, similar to the already reported results.\textsuperscript{12} The intensity ratios of the XRD peak of nanowires at 33.6\(^\circ\) and 41.4\(^\circ\) (\( I_{33.6}/I_{41.4} \)) were used to compare the stacking faults content in the nanowires,\textsuperscript{16} and Takayama \textit{et al.} indicated that the content of stacking faults increased with decreasing the diameter of nanowires.\textsuperscript{17} With regard to energetic consideration, the formation of stacking faults during the growth of SiC nanowire is favorable due to the contribution of the stacking faults themselves with lower energy.

Figure 3 shows a typical Raman spectrum from \( \beta \)-SiC nanowires measured at room temperature. Wave laser with 632.8 nm was used as excitation source. The peaks corresponding to the modes of transverse optical (TO) at 781 cm\(^{-1}\) and longitudinal optical (LO) phonons at approximately 923 cm\(^{-1}\) characterize the crystalline structure of \( \beta \)-SiC. Both peaks have significant redshifts of 15 and 40 cm\(^{-1}\) with respect to the TO and LO photomodes of bulk \( \beta \)-SiC,\textsuperscript{18} respectively, which could either be ascribed to quantum confinement effects\textsuperscript{19} or the defect (stacking faults) and inner stress during the growth.\textsuperscript{20} According to Yong-Laplace equation, the SiC nanowire during the growth would be subjected to a local pressure,

\[
\Delta P = \frac{Y}{r_{\text{nanowire}}} \quad \text{(1)}
\]

where \( r_{\text{nanowire}} \) is the nanowire radius.

The additional inner stress \( \Delta P = 140 \text{ MPa} \) would be formed by assuming that \( Y = 2830 \text{ erg/cm}^2 \) and \( r = 20 \text{ nm} \) and such a large pressure could cause the defects (already stated in TEM images) during the growth state.

The electrical transport measurements were done on the devices with two Au electrodes connected by a single \( \beta \)-
SiC nanowire shown in the lower inset of Fig. 4. The Au electrodes were fabricated by conventional photolithography. The HF-treatment SiC nanowires were sonicated in to a suspension in alcohol and then dispersed onto a Si/SiO2 substrate with predefined gold electrodes acting as source and drain electrodes. The n-type silicon layer served as the back of the field effect transistor (FET) devices, similar to that reported in Ref. 21. Annealing was done in Ar at 700 °C for 5 min to improve the quality of Au–SiC nanowire contact. The measurements were conducted by using Agilent 4156C semiconductor characterization system.

Figure 4 shows an asymmetric and nonlinear $I_{ds}-V_{ds}$ curve of β-SiC-FET. Such behavior is typical for nanowire devices with Schottky barrier contact on both sides.22 It is very clear that current magnitude increases with the increase of the gate voltage, suggesting n-type behavior of the β-SiC nanowire channel. It was suggested that the β-SiC nanowire field effect transistor could act as a building block for components in nanodevices. The SiC nanowire channel current, analogous to the behavior of CMOSFET in the linear $I_{ds}-V_{ds}$ region, can be expressed as

$$I_{ds} = \mu C_g (V_{gs} - V_{th} - \frac{1}{2} V_{ds}) V_{ds}/L^2,$$

where $V_{th}$, $L$, and $C_g$ are the threshold voltage, the length of the channel, and the gate-channel capacitor, respectively. Moreover, $C_g = \varepsilon e \varepsilon_0 d L / \ln(2h/r)$, where $\varepsilon$, $h$, and $r$ are the dielectric constant, the thickness of silicon dioxide, and the radius of the SiC nanowire, respectively. Differentiating Eq. (2), the conductance can be easily expressed as

$$\frac{dI_{ds}}{dV_g} = \mu C_g V_{ds}/L^2.$$  

Using $\varepsilon = 3.9$, $h = 500$ nm, $L = 1.5 \mu m$, and $r = 10$ nm, it obtained $\mu = 15.9$ cm$^2$/V s. The formula for $V_{th} = 0.01$ V, $\mu = 15.9$ cm$^2$/V s is less than that of 37 cm$^2$/V s in the β-SiC thin film FET at room temperature.23 The lower carrier mobility is believed to be the lattice defects and electron-electron interaction. Moreover, the transconductance obtained from the linear portion of the curve (the left inset of Fig. 4) is $5 \times 10^{-7}$ A/V.

In conclusion, a technique for synthesizing single-crystalline SiC nanowire free from metal catalyst in a relatively simple fashion was proposed. By heating SiO powders, large-quantity and high-purity β-SiC nanowires sheathed with SiO$_2$ were deposited on the ACF acting as a thermoinsulating layer. Raman scattering characterization showed that the TO and LO phonon modes of the SiC nanowires had larger redshifts compared to those of bulk β-SiC. The electrical measurement from single β-SiC nanowire based field effect transistor shows that β-SiC nanowire is characteristic of n-channel behavior. The synthesized SiC nanowire offers interesting prospects for the application in building block of nanodevices and reinforcement compositions.

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