

Fabrication and characterization of β -Ga₂O₃ optical nanowires

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Received 17 May 2005; accepted 14 August 2005

Available online 23 September 2005

Abstract

Monoclinic gallium oxide (β -Ga₂O₃) nanowires with lengths of tens of micrometers and diameters ranging from 100 to 250 nm are synthesized using simple physical evaporation based on vapor–liquid–solid (VLS) mechanism. The as-synthesized straight β -Ga₂O₃ nanowires show excellent diameter uniformity and sidewall smoothness, making them suitable for optical wave-guiding. Light from a fiber taper is launched into the nanowire by means of evanescent coupling. Measured propagation loss of the nanowire at 633 nm wavelength is on the order of 10 dB/mm. Favorable mechanical strength of these nanowires for elastic bending is also observed. Our results suggest that β -Ga₂O₃ nanowires are promising building blocks for micro- and nanophotonic circuits and devices.

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PACS: 81.05.Y; 79.60.J

Keywords: Nanowire; Physical evaporation; Wave-guiding

1. Introduction

Nanowires from various materials (e.g. semiconductor, dielectric and metal) have been synthesized, characterized and functionalized for a variety of applications ranging from logic gates, nanolasers to nanosensors [1–3], forming the basis for a large number of applications in nanoelectronics, optoelectronics and photonics. Recently, the optical wave-guiding ability of nanowires has intrigued new interests for using them as subwavelength-width waveguides for future nanophotonic circuits and devices [4–8]. Dielectric and semiconductor nanowires with wide band gap and desired optical properties are of special interest because of their non-dissipative nature. Monoclinic gallium oxide (β -Ga₂O₃) is one of the important wide band gap ($E_g \approx 4.9$ eV) semiconductors that show good chemical and thermal stability and interesting luminescence properties [9]. β -Ga₂O₃ nanostructures such as nanowires are currently the subject of intense research because of their potentials for nanoscale electronic and optoelectronic devices [10–17]. However,

depending on the synthesis methods, such as arc discharge method [10], carbothermal reduction [11], thermal evaporation [12–16] and metalorganic chemical vapor deposition [17], most of the as-synthesized nanowires are somewhat curly or entangled, and the optical wave-guiding properties of β -Ga₂O₃ nanowires have not yet been studied. Here, we investigate the synthesis and wave-guiding properties of optical-quality β -Ga₂O₃ nanowires. Using a VLS method, long straight β -Ga₂O₃ nanowires are obtained with good diameter uniformity and sidewall smoothness. Light from a He–Ne laser (operated at 633 nm wavelength) is launched into nanowires by evanescent coupling, and is thus used to probe the propagation loss of the nanowires. Interesting properties such as elastic bending and cross-coupling of the nanowires are also investigated. Experimental results show that optical-quality β -Ga₂O₃ nanowires are promising for use as subwavelength-diameter optical waveguides in micro- or nanophotonic applications.

2. Synthesis and characterization

Previous research has shown that, among various techniques VLS growth is one of the effective methods to

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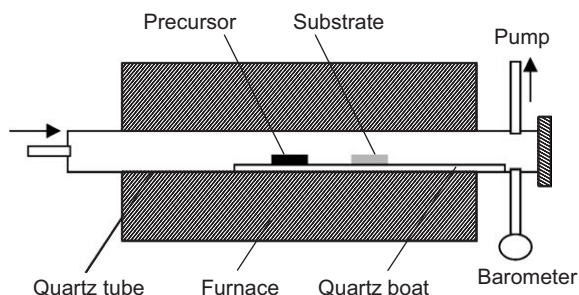


Fig. 1. Schematic diagram of the VLS growth system for β -Ga₂O₃ nanowires.

synthesize straight nanowires; hence, we use VLS-based physical evaporation to grow β -Ga₂O₃ nanowires in this work. As shown in Fig. 1, a small piece of GaAs wafer is used as precursor and is placed in the center of a furnace tube. Strips of Au-coated silicon wafers are used as substrates and are placed 3–5 cm away from the precursor. Before turning on the furnace, air is vacated from the quartz tube with a vacuum pump. When the furnace is heated to 500 °C, we introduce a constant argon gas flow (flow rate: 150 standard cubic centimeters per minute) into the tube and adjust the pumping rate to keep a pressure of 10^4 Pa inside the tube, and then raise the temperature to 1100 °C and stay 45 min for nanowire growth. After the growth, the furnace is naturally cooled to room temperature, and a dark-gray-colored product is found deposited on the substrates. The microstructure and photoluminescence of the composite is characterized using scanning electron microscope (SEM), transmission electron microscope (TEM), X-ray diffraction (XRD) and fluorescence spectrophotometer.

Typical SEM micrograph taken near the edge of the silicon substrate is shown in Fig. 2. The as-synthesized nanowires look straight and uniform. Measured diameters of the nanowires typically range from 100 to 250 nm with lengths of tens of micrometers. A close-up image of a 100-nm-diameter nanowire taken with a TEM is shown in Fig. 3, revealing excellent diameter uniformity and sidewall smoothness. XRD spectrum of the β -Ga₂O₃ nanowires is shown in Fig. 4, which is in good agreement with the reported data of bulk β -Ga₂O₃ crystals ($a_0 = 5.80$ Å, $b_0 = 3.04$ Å, $c_0 = 12.23$ Å, $\beta = 103.42^\circ$, JCPDS11-370), demonstrating that the composition is purely monoclinic gallium oxide (β -Ga₂O₃) structure.

Room temperature photoluminescence (PL) of the nanowires is investigated using a Hitachi F-4500 Fluorescence Spectrophotometer with an Xe lamp excitation at 250 nm wavelength. The PL spectrum given in Fig. 5 shows a strong broadband emission centered around 475 nm, which is consistent with those reported elsewhere, and indicates the potential for using these nanowires for active devices such as blue emitters [11,12,15,16].

The as-synthesized nanowires also show favorable mechanical properties for micromanipulation. Using scan-

ning tunneling microscope (STM) probes as tools, nanowires can be individually pushed and bent on silicon wafers without fracture. For example, in Fig. 6, a 150-nm-

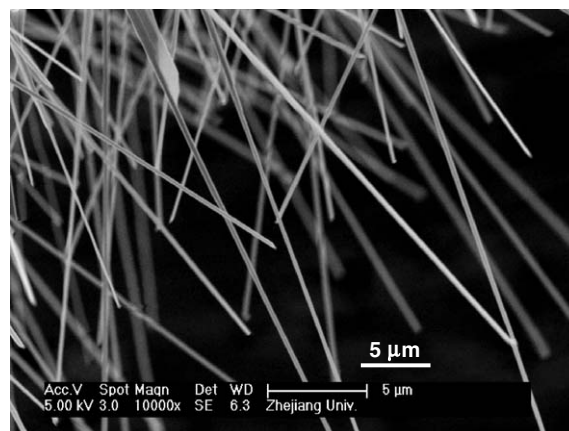


Fig. 2. SEM micrographs of the synthesized β -Ga₂O₃ nanowires.

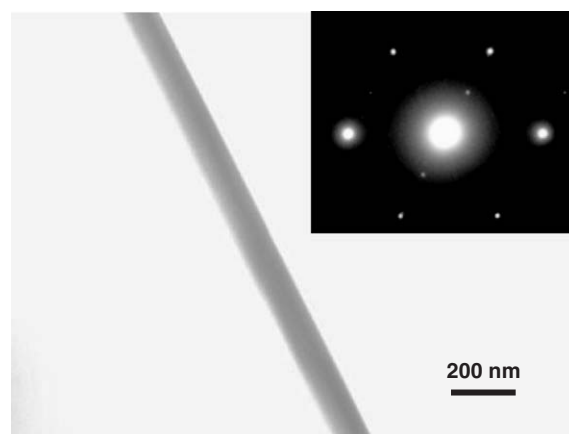


Fig. 3. SEM micrograph of a 100-nm-diameter β -Ga₂O₃ nanowire exhibiting uniform diameter and smooth surface. Inset, select area electron diffraction (SAED) image indicating a single crystalline structure of the nanowire.

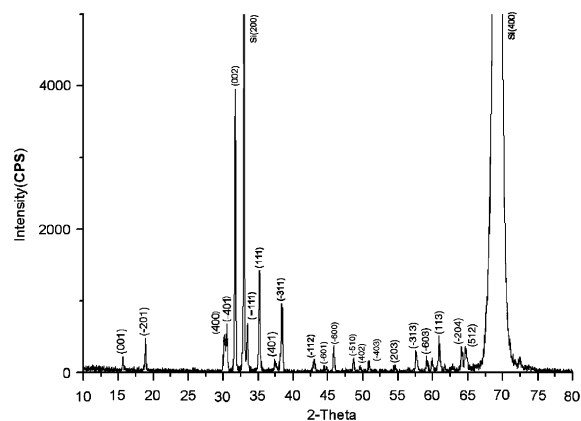


Fig. 4. X-ray diffraction spectrum (intensity versus 2θ) of the as-synthesized β -Ga₂O₃ nanowires.

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