NANOWIRE SYNTHESIS FROM VAPOR AND SOLID SOURCES

BACKGROUND

In the field of nanomaterials, nanowires comprising semiconductors are commercially desirable and can be implemented across a broad variety of applications including electronics and optoelectronics. However, while growth of semiconductor nanowires in small quantities and/or as thin films is common, both large-scale synthesis and bulk growth continue to present significant challenges.

Conventional processes for synthesizing nanowires include the vapor-liquid-solid (VLS) approach and the solid-liquid-solid (SLS) approach. Traditionally, SLS and VLS have been applied on relatively large, monolithic substrates to yield two dimensional growth (see **100** in FIG. **1***a*). FIG. **1***b* contains illustrations depicting VLS and SLS applied to monolithic substrates. In VLS growth **101**, the semiconductor material is supplied as a gas and is adsorbed by liquid nanodroplets of an appropriate catalytic material formed on a substrate. The nanodroplets serve as seeds for nanowire growth. The semiconductor material condenses at the interface between the droplet and the nanowire. The SLS process **102** is similar to VLS growth except that in SLS growth, the semiconductor material is supplied as a solid. The catalyst and the semiconductor material form a liquid mixture from which the semiconductor material condenses to form the semiconductor nanowire.

Traditionally, SLS and VLS have been applied on relatively large, monolithic substrates to yield two dimensional growth. When applying SLS or VLS to a monolithic substrate, nanowire synthesis is limited to growth directions away from the substrate. Furthermore, the nanowires being attached to the substrate conform to the surface **100** and do not fill the available volume. In one modification to the traditional approach, referring to FIG. **1***a*, the semiconductor material can comprise a powder, rather than a monolithic substrate, and the powder granules are coated with the catalyst. The use of the semiconductor powder can lead to three dimensional growth **104** that is easily scalable.

One common problem associated with SLS growth using semiconductor powders is that the composition of the nanowires resulting from SLS growth is inconsistent and hard to control. Furthermore, existing SLS and VLS approaches, whether implemented with powders or monolithic substrates, do not typically facilitate the synthesis of nanowires comprising multiple elements. Accordingly, a need exists for improved methods of synthesizing semiconductor nanowires.

SUMMARY

The present invention includes methods of fabricating nanowires comprising first and second elements. The methods can be characterized by coating solid powder granules, which comprise a first element, with a catalyst. The catalyst and the first element should form liquid when heated, mixed phase having a eutectic or peritectic point. The granules, which have been coated with the catalyst, can then be heated to a temperature greater than or equal to the eutectic or peritectic point. During heating, a vapor source comprising the second element is introduced. The vapor source chemically interacts with the liquid, mixed phase to consume the first element and to induce condensation of a product that comprises the first and second elements in the form of a nanowire. Accordingly, the methods of the present invention require the presence of both a vapor source and a solid source, and can be used to synthesize nanowires comprising multiple elements.

In preferred embodiments the product has a higher melting point than that of the first element. In a particular example, the first element comprises silicon. The second element can then comprise oxygen, nitrogen, carbon, or silicon. The resultant nanowires would then comprise silicon oxide, silicon nitride, silicon carbide, or substantially pure silicon respectively.

In one embodiment, silicon-containing nanowires synthesized according to embodiments of the present invention can be formed into an electrode in an energy storage device having a discharge capacity greater than or equal to 400 mAh/g. In another embodiment, the discharge capacity is greater than or equal to 1300 mAh/g. An exemplary energy storage device includes, but is not limited to a Li-ion battery.

Synthesis of nanowires comprising predominantly silicon can be accomplished according to embodiments of the present invention when both the solid source and the vapor source comprise silicon. A specific example involves using $SiCl_4$ as the vapor source. When the first element comprises silicon, a suitable catalyst, among others, can comprise nickel. In such an instance the nickel-coated silicon powder can be heated to a temperature between 900° C. and 1050° C.

While the methods of the present invention are well-suited for synthesizing nanowires comprising silicon, they are not limited to such. For example, the first element can comprise other semiconducting elements or elements that form semiconducting materials when combined with the second element. For example, the first element can comprise Ge or Sn. The second element can then comprise oxygen, nitrogen, carbon, or combinations thereof. Suitable catalysts can include, but are not limited to, Ni, Fe, Al, Au, and Cu or combinations thereof.

The purpose of the foregoing abstract is to enable the United States Patent and Trademark Office and the public generally, especially the scientists, engineers, and practitioners in the art who are not familiar with patent or legal terms or phraseology, to determine quickly from a cursory inspection the nature and essence of the technical disclosure of the application. The abstract is neither intended to define the invention of the application, which is measured by the claims, nor is it intended to be limiting as to the scope of the invention in any way.

Various advantages and novel features of the present invention are described herein and will become further readily apparent to those skilled in this art from the following detailed description. In the preceding and following descriptions, the various embodiments, including the preferred embodiments, have been shown and described. Included herein is a description of the best mode contemplated for carrying out the invention. As will be realized, the invention is capable of modification in various respects without departing from the invention. Accordingly, the drawings and description of the preferred embodiments set forth hereafter are to be regarded as illustrative in nature, and not as restrictive.

DESCRIPTION OF DRAWINGS

Embodiments of the invention are described below with reference to the following accompanying drawings.

FIG. **1***a* and **1***b* are illustrations depicting 2-D and 3-D growth using SLS and/or VLS processes.

FIG. **2** is a diagram of an exemplary apparatus for synthesizing nanowires according to embodiments of the present invention.