Nanowires for solar cell applications

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Abstract

One-dimensional nanowires represent one of the most promising possibilities for the application of nanotechnology to a broad selection of areas. This field has been rapidly expanding over the past decade, with new methods of production, mechanisms of formation, measurements of properties and potential applications being published every day. Semiconductor nanowires in particular represent an exciting area of research, with potential to revolutionize the areas of electronics and optoelectronics. Several different devices based on 1D nanostructures have been demonstrated including light emitting diodes (LEDs) [1-5], field-effect transistors (FETs) [6-9], biosensors [10, 11], and solar cells [12, 13]. Considerable work remains before 1D nanostructures can be integrated into existing semiconductor technology, but the up-scaling problems are being addressed by several research groups [14]. In addition to biosensors, nanowires might also be used for other medical applications in the future. Patterned nanowire arrays have been demonstrated to work as guides and rectifiers of nerve cells on a substrate, which opens up new possibilities for neural network design [15].

Techniques to produce nanowires are normally divided into top-down and bottom-up methods. Nanowires can be produced by lithographically carving out the structures from the desired bulk material, referred to as top-down production. The major drawback of this method is that the surfaces of the structures are damaged during the process resulting in nanowires with a poor crystal quality. In addition the lithographic techniques may not be able to produce sufficiently small structures for further downscaling of devices. In order to produce small enough nanowires of high enough crystal quality, so called bottom-up production can instead be used. This means that the nanowires are formed by self-organization atom by atom in a highly controllable manner.

A variety of bottom-up methods have been used to produce nanowires, usually classified into solution methods and vapor phase methods [16]. The solution methods include pure solution chemistry methods as well as electrochemical deposition methods in combination with templates [17]. The major advantage with such a solution-based method is the ability to produce large amounts of material at low cost. On the other hand solution methods offer poor control of nanowire dimensions and positioning, properties crucial for device applications. Electrochemical deposition also has the drawback of generally poor nanowire crystal quality with a high number of defects, which is a major limitation in device applications, especially in the field of optics [17].

Vapor phase methods are extensively used for nanowire production [16], and include physical methods such as laser ablation and thermal evaporation, as well as chemical methods. In contrast to solution methods, they are steady-state growth techniques which provide a better control of the growth and morphology of the wires. Vapor phase methods, especially vapor phase epitaxy (VPE), dominate nanowire growth today and are most commonly used for production of semiconductor device structures [18]. Although these techniques are rather expensive, they are especially advantageous in two ways. First of all a huge range of vapor phase precursors exist, making it possible to grow nanowires of many different types of materials. Secondly, very high control of the growth process is possible, enabling the growth of complex nanowire structures.

In addition to the many different nanowire production methods existing, nanowires of a variety of materials have been produced. Among them metal nanowires, oxide nanowires, metal carbide nanowires, metal chalcogenide nanowires, and semiconductor nanowires have been demonstrated. For an extensive review of the materials systems used to produce nanowires see for example Rao et al. [16]. Here we discuss mainly semiconductor nanowires with the emphasis on III-V
semiconductor nanowires, which consist of one component from group III and one from group V in the periodic table. Typical examples are GaP, GaAs, GaSb, as well as InP, InAs, and InSb. The focus will be on nanowire growth by epitaxial methods such as vapor phase epitaxy (VPE), chemical beam epitaxy (CBE), and molecular beam epitaxy (MBE). The majority of semiconductor nanowires grown by epitaxial methods utilize a metal seed particle to initiate the growth [18] but particle-free growth of nanowires has also been reported [19, 20]. For particle-assisted growth the diameter of the seed particle, typically in the size range of tens of nanometers or less, determines the diameter of the nanowire. In most cases the seed particle consists of gold. Here, we will describe the growth of III–V semiconductor nanowires assisted by a metal seed and discuss the growth mechanism involved. We will describe the growth of axial and radial heterostructures and describe and discuss their morphological properties. The focus is on epitaxial III–V semiconductor nanowire structures, with the two materials GaP and InAs used as typical examples of structures with cubic (zincblende) and hexagonal (wurtzite) crystal structures. The general morphology of these structures will be described, as well as the relationship between morphology and crystal structure. We describe further the production of hierarchical branched nanowire structures by the sequential seeding of multiple wire generations with metal nanoparticles. Such complex structures represent the next step in the study of functional nanowires, as they increase the potential functionality of nanostructures produced in a self-assembled way. It is possible, for example, to fabricate a variety of active heterostructure segments with different composition and diameter within a single connected structure. Finally, we will present efforts to use the self-assembly of one-dimensional nanostructures in order to create novel devices and we will focus here on applications for solar cell devices.

References
Knut Deppert, born in 1957, graduated in crystallography from the Humboldt University in Berlin, Germany, where he also obtained his PhD degree in 1986. As post-doc, he worked on growth of crystal structures for optoelectronic devices at the Central Institute of Optics and Spectroscopy, Berlin. In cooperation with Lund University, he developed optical investigation methods for layer growth processes. In 1994, he turned his interests towards the generation of novel nanostructure materials using aerosol technology. With over 100 publications in international journals and 5 patents, Knut Deppert has pioneered nanoparticulate materials technology. Particularly should be mentioned the work on size-selected semiconductor nanoparticles, on tailored patterning with nanoparticles, and on the creation of one-dimensional semiconductor structures like wires and trees.

Besides advanced research activities, Prof. Deppert is deeply involved in the university education program on nanoscience and -technology, Engineering Nanoscience, at Lund University. This five years program is one of the very few complete curriculums in nanoscience starting at the university entrance level and leading to a Master's degree.