The use of gold for fabrication of nanowire structures

Maria E. Messing, Karla Hillerich, Jonas Johansson, Knut Deppert and Kimberly A. Dick

Solid State Physics, Lund University, Box 118,
S-221 00 Lund, Sweden
E-mail: maria.messing@ftf.lth.se

Abstract

A common application of nanometer-sized gold particles is as seed particles for growth of semiconductor nanowires, which are believed to act as highly promising building blocks in future electronic devices. In a majority of the reports of successful nanowire growth, gold has been the seed particle material of choice. In this review article we identify the different types of gold particles used to initiate nanowire growth, namely gold particles made from thin films, gold particles defined by lithographic methods, colloidal gold particles and aerosol-generated gold particles. The production and deposition methods are described and the advantages and disadvantages of the particle types are discussed. In addition we discuss different properties that seem to make gold the most universal material for nanowire seed particles.

Keywords: gold, nanoparticle, nanowire, semiconductor, epitaxy

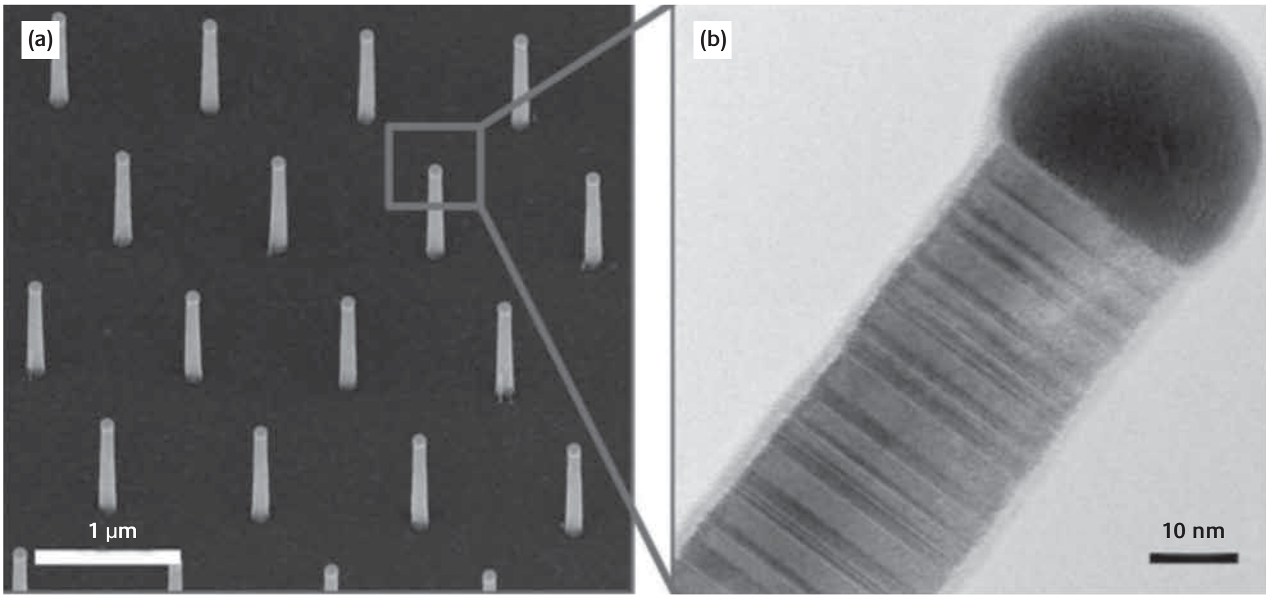
1 Introduction

It is well known that gold is used in the semiconductor industry of today to make contacts for electronics. A less-known application is as seed particles for growth of one-dimensional (1D) nanostructures, where gold is by far the most universal and commonly used material. 1D nanostructures are characterized by a large length-to-width ratio (Figure 1) and are referred to as rods, tubes, whiskers, wires, and belts, among others. Minor differences in dimensions between these structures occur in literature but no clear definition exists. In this review article the word nanowire will be used when discussing these highly promising 1D nanostructures. In recent years the interest in one-dimensional nanostructures has gained enormous attention worldwide due to their unique structural and physical properties and their potential as building blocks for future electronic and optoelectronic devices. 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 [12-14]. 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 [15]. 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 [16].

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 down-scaling 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 [17]. The solution methods include pure solution chemistry methods as well as electrochemical deposition methods in combination with templates [18]. 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

Figure 1



(a) SEM image (30° tilting angle) of GaAs nanowires seeded with gold particles produced by EBL. (b) TEM image of the top part of a GaAs nanowire, with the gold seed particle visible at the top

high number of defects, which is a major limitation in device applications, especially in the field of optics [18].

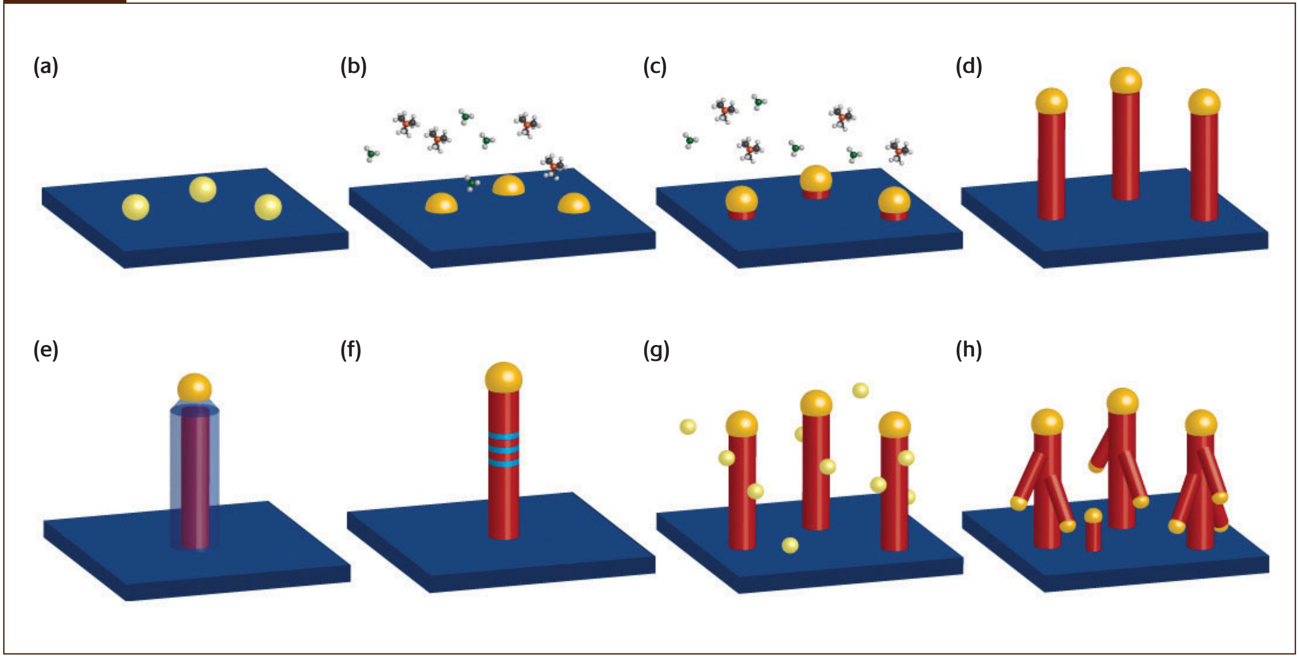
Vapor phase methods are extensively used for nanowire production [17], and include physical methods such as laser ablation and thermal evaporation, as well as chemical methods. In contrast to solution methods, they are steady-state growth techniques which provide a better control of the growth and morphology 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 [19]. 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. [17]. 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 of this review will be on nanowire growth by epitaxial methods such as vapor phase epitaxy (VPE), chemical beam epitaxy (CBE), and molecular beam epitaxy (MBE). Epitaxial (nanowire) growth means that a substrate with a specific crystal structure is used to orient the growth of the crystal (nanowire) in an ordered manner. The majority of semiconductor nanowires grown by epitaxial methods utilize a metal seed particle to initiate the growth [19] but particle-free growth of nanowires has also been reported [20, 21]. 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. Many different types of gold particles have been used such as colloidal particles, aerosol particles, particles made from thin films, and particles made by lithographic methods. Other types of metal particles have been used, but so far gold particle induced growth dominates the reports of successful nanowire growth.

Gold particle-assisted epitaxial growth usually starts with the deposition of gold particles on a clean substrate. In the case of semiconductor nanowires the substrate is normally a semiconductor material, either of the same material as the wire (homoepitaxy) or of a different type of semiconductor material (heteroepitaxy). The substrates with the deposited particles are, in the case of VPE, placed in a reactor cell with a laminar gas flow passing across the substrate surface. In the first step the substrate is heated to a desired growth temperature (Figure 2(a)). Once the growth temperature is reached, the precursor materials are introduced to the gas flow. In the case of CBE and MBE the vapor precursors in laminar gas flow are replaced by beams in vacuum. When the precursor materials come into contact with the gold particle at the elevated temperatures an alloy is typically formed (Figure 2(b)). This alloy particle could be either liquid or solid, depending on its melting temperature compared to the

Figure 2



Schematic demonstrating particle-assisted nanowire growth. (a) The seed particles are formed/deposited on the substrate and (b) by heating the substrate to a desired temperature and introducing growth materials an alloy is formed. (c) When a supersaturation of the alloy particle with growth material is achieved, nucleation occurs at the particle-substrate interface. (d) Nanowire growth occurs at the particle-wire interface as long as growth material is provided. (e) By switching to growth conditions favoring planar growth radial heterostructures, known as core-shell nanowires, can be grown. (f) Nanowires containing axial heterostructures with very sharp interfaces can be formed by switching between different growth materials. (g) If a second generation of gold particles is deposited onto the as-grown nanowires and (h) the growth process is repeated, branched nanowires for formation of nanowire networks can be grown

growth temperature. At a certain point when enough precursor material has been incorporated into the particle it will become supersaturated. This in turn leads to precipitation of the semiconductor material at the particle-substrate interface, referred to as nucleation (Figure 2(c)). By a continuous supply of growth precursors the nanowire growth occurs at the particle-wire interface (Figure 2(d)). The growth rate of nanowires depends to a large extent on the supersaturation, which in turn can be controlled by the precursor concentration and the growth temperature. Furthermore, by controlling the growth parameters more complex nanostructures can be formed. Nanowires containing radial heterostructures, so called core-shell wires [22] (Figure 2(e)), are grown by switching to growth conditions that favors layer growth. Axial heterostructure nanowires with very sharp interfaces are grown by switching on and off different precursor gas flows [23] (Figure 2(f)). Finally branched nanowires, for formation of nanowire networks, can be grown by depositing a new generation of gold particles onto the wires and repeating the growth process [24] (Figure 2 (g-h)).

The most common model to describe particle-assisted nanowire growth has been the vapor liquid solid (VLS) model, developed already in the 60's [25]. In this model vapor denotes the phase of the precursors, liquid the phase of the particle, and solid the phase of the wire. However, it has been reported that the particle could also be in a solid state when growth occurs, and the vapor solid solid (VSS) model has been suggested [26]. In addition the precursor supply phase must not necessarily be a vapor but could also be solid or a solution, described by the solid liquid solid (SLS) [27] and the solution liquid solid (SLS) [28] models respectively. None of these models fully explains the mechanism behind nanowire growth and the actual role of the particle is still under discussion. Moreover it is still not completely understood why gold particles are superior to particles of other materials in most cases of nanowire growth. In this review we discuss different properties that seem to make gold superior to other metals for initiating nanowire growth. Furthermore we describe the different types of gold particles used as seed particles for growth of semiconductor nanowires, how they are generated, and their respective advantages and disadvantages.

2 Different types of gold seed particles

In the many reports of successful growth of gold seeded nanowires several different types of gold particles as well as different methods for deposition of the various particles have been used. A certain particle type could be beneficial in one way but less useful from another point of view, and therefore it is not always obvious which particle type or deposition method to use. As a general rule of thumb the dimensions of the nanowire (diameter and length), its crystalline structure, and the surface coverage of nanowires needs to be uniform and fully controlled for large scale device production to be possible. If vertical device design, which means that devices are directly manufactured around the standing wires, are to be realized a complete control of the positioning of the seed particles is also required. Finally, to meet the cleanliness requirements of the semiconductor industry, all possible residues from the particle production step should be fully removed. In this section we will review the different types of gold particles used to grow semiconductor nanowires. We describe the production, the deposition methods and the possible advantages and disadvantages of the various particle types.

2.1 Particles made from thin films

Particles made from thin films are widely used for seeding of all types of semiconductor nanowires including elemental (group IV) wires [29], group II-VI wires [30], and group III-V wires [31]. The common procedure for generation of gold particles from thin films is thermal evaporation of the gold film directly onto the substrate. Typically the thickness of the film can vary between 0.1 nm and a couple of nanometers. Following deposition of the thin film, the substrate is transferred to the reactor cell in the growth apparatus. In addition in situ deposition, i.e. deposition of the film inside the growth reactor has also been reported [32]. In order to make the film split up into particles the reactor cell may be heated directly to the growth temperature or a prior annealing step may be used. During annealing the substrate is heated to a temperature slightly above the growth temperature and kept at that temperature for a certain period of time. Annealing time and temperature affect the diameter distribution and surface density of particles [33]. In addition, the thickness of the film (as described by Hiruma et al. [34]) as well as different surface preparation (as investigated by Plante et al. [33]) affect particle formation. It was found, for example, that nanowires grown from a too-thin film did not all grow straight and perpendicular to the substrate, which was the case for the nanowires grown from thicker films.

Although the gold particle formation from thin films can be controlled to some extent by film thickness, annealing time and temperature, and different surface treatments, the produced particles still suffer from problems. The diameters are polydisperse, and it is virtually impossible to achieve a low surface coverage and to independently control particle diameter and surface density. Moreover the obtained particle surface density and particle positioning are too random to really provide suitable seed particles for nanowire growth, if the wires are to be used for large scale device production. One advantage of the method is the easy and reasonably cheap production of particles on almost any substrate, making it suitable for example during investigations of nanowire growth from new materials systems. Another advantage is that the production method is a clean method since no chemicals are involved, especially if the thin film is deposited in situ.

2.2 Lithographically defined particles

The use of lithography to produce particles can be seen as a development of the thin film method, since here a thin film is evaporated onto the substrate as well. The difference is that a mask is applied to the substrate before the thin film is evaporated in order to define size, number concentration and position of the particles that will be produced. A variety of lithographic techniques have been used to produce gold seed particles. In general these methods require several steps including masking, thermal evaporation, lift-off, and sometimes an additional cleaning step. In most cases chemicals are used for production and/or removal of the mask. Lithography is said to be a top down technology and by combining it with the bottom up epitaxial growth methods well ordered arrays of uniform nanowires have been realized.

In the Nanosphere Lithography (NSL) method submicrometer sized polystyrene spheres are self-assembled into a monolayer with hexagonal close packed structure, which provides the basis of the mask [35, 36]. Small triangular holes are left open between the spheres. After thermal evaporation of the gold film the polystyrene mask is removed, leaving an ordered pattern of triangular gold particles on the substrate. ZnO [36] and GaAs [35] nanowire arrays have been grown using this method. Unfortunately the grown wires do not possess uniform diameters.

Porous anodic aluminum oxide (AAO) membranes have been used to produce masks providing ordered arrays of hexagonal gold particles. Arrays of ZnO nanowires have been produced by this method [37]. As for NSL the drawback of the method is the non-uniform diameters of the nanowires.

Apart from the above mentioned techniques more classical lithographical methods have been used to produce ordered arrays of gold seed particles. Greyson et al. [38] used photolithography to define patterns on a gold film covered by a photoresist, for growth of ZnO nanowires. However, the nanowires did not grow straight and several wires grew from each gold dot.

A more successful method for creating ordered gold particles with a narrow size distribution is electron beam lithography (EBL) where an electron sensitive resist is exposed by an electron beam. Compared to conventional photolithography, masks with much smaller features (down to around 10 nm) can be produced. Figure 1 (a) displays nanowires grown from EBL particles. Most types of semiconductor nanowires have been grown from EBL defined gold particles, including InP [39] and InAs [40] nanowire arrays with very uniform diameters and lengths.

Mårtensson et al. [41] also demonstrated the use of Nanoimprint Lithography (NIL), where a stamp is mechanically pressed into the resist to create the mask, to generate InP nanowire arrays. The major advantage of NIL compared to EBL is the much higher throughput since NIL is a parallel process. The stamp is usually produced by a serial process such as EBL, but once produced it can be used repeatedly.

When comparing gold particles made from lithographic techniques to the other types of gold particles described in this section the major advantage is clearly the precise control of the positioning of the seed particles and hence of the wires on the substrates. This might be crucial for large-scale production since it provides the opportunity of vertical device design. The drawbacks of the lithographically defined particles differ a bit between the different methods. NSL and the use of metal masks from AAO membranes suffer from the problem of non-uniform diameters. For EBL and NIL on the other hand the obtained control of diameter uniformity and the ability to very precisely tune the particle diameter are highly advantageous, but these methods are much more expensive and complicated. EBL is also limited by the low throughput due to the time consuming exposure step. However, the major drawback of all the lithographic techniques described is contamination problems due to the chemicals involved in the particle production processes.

2.3 Colloidal particles

In contrast to the other gold particle types described in this section that are produced by evaporation of a solid piece of gold, colloidal gold particles are synthesized by a chemical reduction reaction [42]. Hence the colloidal gold particles are provided in aqueous solutions and ligands are attached to the particles in order to keep them suspended in the solution and prevent them from agglomeration. Gold colloid particles are commercially available in a wide range of different diameters with a diameter dispersion of less than 10 %. Gold colloids have been frequently used as seed particles for growth of semiconductor nanowires including Si [43] and InGaAs nanowires [44].

The normal, very simple, deposition method of gold colloids is to place a drop of the solution directly onto the substrate. In order to get a more even distribution of the suspension rotation of the substrate can be performed afterwards. By varying the concentration of the colloid solution the number concentration of particles can be controlled to some extent. A concern for achieving a homogenous coating of particles is the surface properties (e.g. the charge) of the substrate relative to the properties of the colloid suspension. Therefore an intermediate layer formed by the surfactant poly-L-lysine (PLL), containing one positively charged end, is often added to help the negatively charged particles bind to the surface [45].

A few attempts to further control the deposition of gold colloids have been reported. Hochbaum et al. [45] restricted the growth of Si nanowires to certain areas of a substrate by using microcontact printing.

To get a very precise control of particle number concentration Böttger et al. [46] used electrospray deposition of the gold colloids (although the particles were still randomly distributed on the surface), and no PLL was needed for the particles to stick to the substrate. GaP nanowires and nanotrees were successfully grown from the electrosprayed colloids.

The obvious advantages of gold colloid particles include a simple and fast deposition, the availability of particles of a variety of different diameters with a narrow diameter distribution and the less costly production methods. Among the drawbacks the inability to control particle positioning needs to be mentioned. Moreover, unless the electrospray deposition method is used, the number concentration and homogeneity of particles on the substrate is not as controlled as for lithographically defined particles or aerosol-generated particles. Similar to the lithographically defined particles the major disadvantage is however the cleanliness problem. Organic remnants from the synthesis and stabilization processes and PLL from the deposition process provides highly contaminated particles not suitable for device production.

2.4 Aerosol-generated particles

The definition of an aerosol particle is a solid or liquid particle suspended in a gas [47]. Since normal air is a gas almost any air borne particle could be considered to be an aerosol particle. In this review however, we limit the expression to particles suspended in an ultra-pure carrier gas during generation.

Two slightly different methods to produce aerosol gold particles for seeding of nanowires have been used, namely the evaporation/condensation [48] method and the spark discharge method [49]. In the evaporation/condensation method a solid piece of gold is evaporated in a high temperature furnace, and then the vapor is transported away by an ultra-pure carrier gas. Upon cooling, the vapor nucleates and agglomerate particles are formed by condensation and coagulation of primary particles. A similar mechanism is responsible for production of agglomerate gold particles by the spark discharge method. The difference is that the vapor forms by a spark discharge between two gold electrodes causing the electrode material to vaporize. For both methods the generated particles are further carried into an aerosol nanoparticle system setup [50] to enable reshaping of the agglomerates into compact spherical particles and to provide controlled deposition of size-selected particles.

The as-produced gold particles have a high purity, monodisperse diameter [51], and can be deposited with an extremely controllable surface density and size on any type of substrate. For the spark discharge method successful seeding of GaP and InP nanowires have been reported [52], and for the evaporation/condensation method most III-V nanowires has been seeded including III-antimonides [53, 54], n- and p-doped InP [55], and core-shell GaAs-GaInP [22]. In addition aerosol gold particles have been shown to be very suitable for initiating the growth of complex branched nanowire structures by decorating already grown wires with a second and third generation of gold particles [24].

Comparing the aerosol particles to the other types of particles described in this section the major disadvantage compared to particles made by lithographic techniques is the random positioning of particles on the substrate. Ohlsson et al. [56] demonstrated a method to control the exact position of each particle on the substrate by using atomic force microscopy (AFM) manipulation. This provides a valuable demonstration of the possibility to position aerosol gold particles but is not a suitable technique for large scale device production. The disadvantage compared to thin film particles and colloidal particles is the less simple and more costly production. On the other hand the major advantage is that these particles are very pure and have a tunable monodisperse diameter. In addition a highly controlled deposition of particles of a given diameter and surface number concentration at reasonable throughput is possible; the even distribution of nanoparticles on 6” wafers has been demonstrated [57]. These are all properties that make aerosol particles highly interesting for large scale production of nanowire devices. If a method to control the exact positioning of the particles on the substrate can be developed the aerosol particles might even be the most promising particle type. So far, nanoparticles from the aerosol phase have been deposited in very controlled manner by locally electrostatic fields, which may open possibilities to create such a method [58, 59].

3 The superiority of gold as a seed particle material

Although gold is the most extensively used material for nanowire seed particles there is no complete explanation for why gold is superior to other materials. Different suggestions have been proposed such as the chemical inertness of gold, its thermal stability or that gold has the ability to form low-temperature liquid alloys with the growth species. In this section we discuss the different properties of gold particles and how they could affect nanowire growth. Moreover we suggest that it might be many small advantages added together, instead of one specific quality, which make gold particles the most universal choice for nanowire seeding.

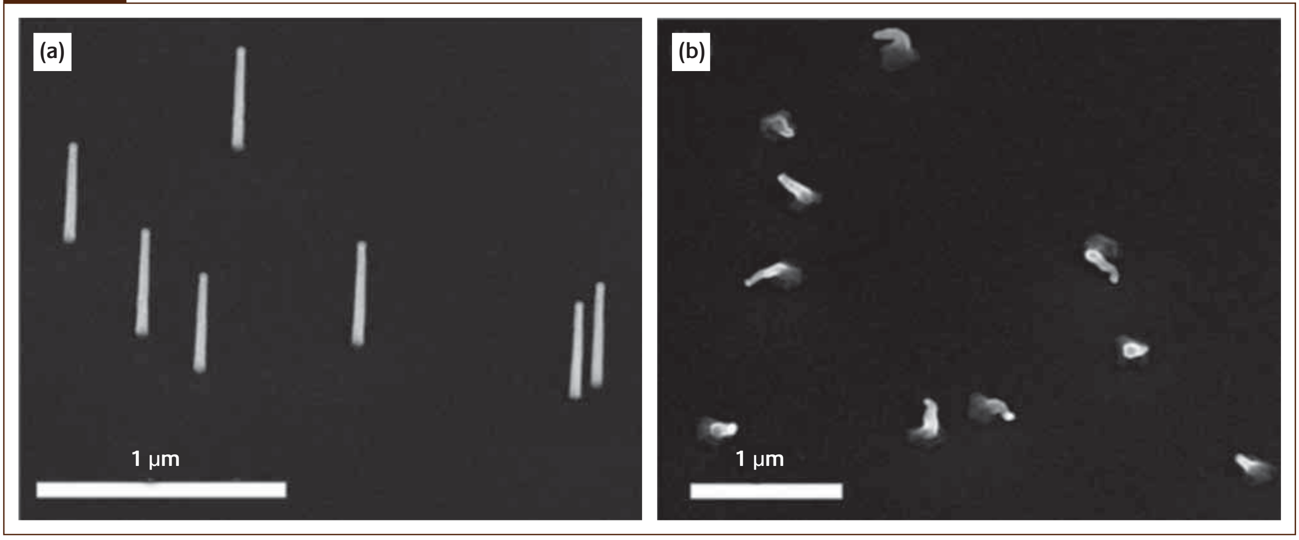
The requirement for all one-dimensional growth to occur is that growth in one direction is largely enhanced compared to growth in all other directions. In nanowire growth models such as the widely used VLS [25] model and the recently suggested, more general, preferential interface nucleation [60] model, kinetic and thermodynamic arguments are used to explain the growth mechanism. In both models the particle is thought to act as a collector for growth material. When the particle is supersaturated the growth material is precipitated and due to preferential nucleation at the particle/nanowire interface, growth occurs in only one direction if nucleation at all other interfaces is suppressed. These models explain to some extent the involvement of the particle in nanowire growth but are applicable to all types of particles, not only gold. Nebol’sin and Shchetinin [61] developed a model to predict suitable particle materials for growth of Si wires based on the wetting angle of liquid metal drops on Si. Although the predictions from this model do not generally agree well with experimental data, to date it is the only attempt to theoretically predict which metals will be appropriate for growing nanowires. Since no predictive model exists, experimental studies have been performed to determine which particle materials can be used to seed nanowires. Apart from improving the understanding of the mechanism behind nanowire growth, finding other particle materials than gold is useful from a device perspective since gold is not really compatible with the semiconductor industry of today [62].

From the comparative studies by Nguyen et al. [63] and Tuan et al. [64] where different metallic nanoparticles were used to seed the growth of SnO nanowires and Ge and Si nanowires respectively, it is clear that many types of metal particles could seed the growth of one-dimensional structures. However, for many particle materials wires were kinked, short or curly and sometimes had an amorphous structure. The major advantage when instead using gold particles as seeds is that it is easier to achieve high quality growth and often with a broad parameter window. High quality growth means a growth that provides a high yield of straight crystalline wires that are epitaxially grown in a certain crystal direction. Gold seeded nanowires usually grow in the <111> direction which means that when a <111> oriented substrate is used the nanowires grow perpendicular to the substrate (see Figure 1). In Figure 3 GaAs nanowires seeded with (a) gold particles and (b) palladium particles grown under similar conditions are shown. Even though nanowires are formed from the palladium particles they do not grow straight and are not epitaxial. This clearly demonstrates why gold particles often are the seed particles of choice.

One of the most common explanations why gold is such a suitable particle material to initiate nanowire growth is that many of the precursor materials used for growth are soluble in gold. In the case of the elemental (group IV) Si and Ge nanowires both materials form liquid alloys with gold at temperatures below the typically used nanowire growth temperatures. Also in the case of III-V nanowires low-temperature liquid alloys of gold-gallium and gold-indium exist. The III-V system is however a more complicated system compared to the elemental case, since there are two precursors (both the group III and group V) coexisting with the gold particle. One puzzling point is that no stable gold-arsenic or gold-phosphorus phases have been reported, something which for example raises the question on how the group V material gets incorporated into the nanowire. A possible explanation could be that the group V precursor travels along the growth interface or along grain boundaries if the particle is in a solid state [19].

In the original VLS model a requirement for growth to occur is that the seed particle must be in a liquid state. However, as mentioned in the introduction, nanowire growth could also occur from a solid gold-alloy particle phase [26]. This has been demonstrated for GaAs [26, 65], InAs [66], InP [67] and AlAs [68] as well as for Si [69] and Ge [29] where

Figure 3



SEM images (30° tilting angle) of GaAs nanowires seeded with 30 nm sized aerosol-generated (a) gold particles (b) palladium particles

growth occurred at temperatures below the melting point of an existing liquid gold-based alloy. In addition, most growths from particles of other materials than gold has been reported to occur from a solid seed particle, implying that it is not necessary to use a particle material that forms liquid alloys with the precursors for nanowire growth to take place. However, it could probably be an advantage since growth from solid seed particles often suffers from the problem of a less controlled growth direction. This might be due to the solid particles having more difficulties to epitaxially orient with the substrate. GaAs nanowires seeded with iron particles [70] and manganese particles [71], and Si nanowires seeded with copper particles [72] are all demonstrated to grow in several different directions. As an exception, controlled growth in the <111> direction of Si nanowires seeded with solid aluminum particles has been reported [73]. Another advantage of a liquid seed particle might be that it most likely provides a more uniform shape of the nanowires since the particles have a more uniform shape. Solid particles tend to be less uniform in shape and may even have varying facets, producing nanowires with a less uniform shape. On the other hand, gold is a very soft metal and therefore is more likely to form particles with reasonably uniform shapes even in the solid form, yet another advantage compared to other materials.

The final advantage of a liquid seed particle might be the enhanced growth rate compared to a solid seed particle. Normally the diffusivity through a solid alloy is slower than that through a liquid alloy, which should result in a decreased nanowire growth rate. For many materials growth with a solid particle would be impractically slow. For gold however, the diffusivities of In and Ga through a solid particle are very high and therefore should give reasonably high growth rates. This, in addition to the softness of solid gold, means that gold may be a suitable particle material in a solid state as well. Moreover, the high self-diffusion coefficient of gold, allowing for a quick formation of equilibrium shapes [74], could be one more small advantage of gold particles compared to particles of other materials.

A largely debated property of gold particles, when used as seeds for nanowire growth, is whether or not they act as catalysts for decomposition of the growth precursors. The common method to determine if a catalytic effect exists has been to compare the activation energies of the decomposition with and without the catalyst particles present. From such measurements both reports of unchanged activation energies [25, 75-77] and enhanced activation energies [78, 79] in the presence of gold particles have been demonstrated. The conclusion might therefore be that in some systems the gold seed particle can act as a catalyst but this is definitely not a demand for particle-assisted nanowire growth to occur. If a catalytic activity would be crucial in order to achieve nanowire growth other particle materials normally known to have a much higher catalytic activity than gold, e.g. platinum or rhodium, would be a more suitable choice.

A more interesting property to explain the suitability of gold particles for seeding nanowire growth may instead be that they are highly unreactive. Gold particles larger than 5 nm are known not to spontaneously oxidize in air [80], something that could be very advantageous. Particle materials that more easily bind oxygen are prone to form thin oxide shells when exposed to air. It is reasonable to believe that these oxide shells prevent the epitaxial orientation of the particle with the substrate, giving uncontrolled growth or even preventing any growth at all. Moreover the gold particles would not react with the typically used carrier gases nitrogen and hydrogen, which simplifies a continuous alloy formation between the gold and the growth precursor.

Compared to other materials, which might successfully seed growth of one type of nanowire at a specific set of growth conditions, gold works well as a seed for nearly any type of nanowire at a variety of different growth conditions. From the listed properties of gold particles in this section it might not be unrealistic to believe that all these properties together, rather than any single property, are what make gold the most universal material for nanowire seed particles. The fact that many precursor materials are soluble in both liquid and solid gold is of course highly important but an extra advantage in order to achieve uniform, controlled epitaxial growth might be that most of the formed gold-precursor alloys are in a liquid state. In addition the inertness to oxygen as well as the overall unreactivity of gold seems to be advantageous for nanowire growth. So far the particles of other materials used as seeds for nanowires may have some of these advantageous properties, but not all of them for all materials and growth conditions, and this is likely to be the reason why gold is the superior seed particle material.

4 Conclusions

Gold is an excellent material to facilitate the creation of novel semiconductor one-dimensional structures. Therefore gold is by far the most widely used seed particle material for growth of semiconductor nanowires. Although a few other materials have been reported to successfully initiate growth of nanowires, gold is the most universal particle material, capable of seeding a variety of different types of nanowires at a wide range of growth conditions. In this review we have identified and described the production and deposition methods of different types of gold particles used for nanowire growth, namely gold particles made from thin films, gold particles made by lithographic methods, colloidal gold particles and aerosol gold particles. In addition we have discussed the different advantages and disadvantages of each particle type if the nanowires are to be used for large scale production of semiconductor devices. Finally, we have discussed various properties of gold in order to find the reason for gold being superior to other materials for initiating growth of nanowires. Among the properties that could affect nanowire growth in a positive way, the ability of gold to easily form alloys with the growth precursors, its inertness to oxygen and the high diffusivities through gold might be highly essential. We suggest that instead of one specific property, all the beneficial properties added together are what make gold such a suitable material for nanowire seed particles.

Acknowledgements

This work was performed within the Nanometer Structure Consortium at Lund University and supported by the Swedish Research Council (VR), the Swedish Foundation for Strategic Research (SSF), the EU program AMON-RA (214814) and the Knut and Alice Wallenberg Foundation. Furthermore this report is based on a project which was funded by E.ON AG as part of the E.ON International Research Initiative. Responsibility for the content of this publication lies with the authors.

About the authors

Maria E. Messing obtained her Master degree in Engineering Nanoscience 2007 at Lund University in Sweden and she is now a PhD student at Division of Solid State Physics in Lund. Her research activities include the production and characterization of nanometer-sized aerosol particles and semiconductor nanowires.

Karla Hillerich is a PhD student at Solid State Physics at Lund University, Sweden. She studied Materials Science at Stuttgart University and Max Planck Institute for Metal Research, Germany, until 2007. Her research interests are nanowire fabrication and their characterization with focus on different material combinations.

Jonas Johansson is an assistant professor at Division of Solid State Physics at Lund University in Sweden, where he also obtained his Masters and PhD degrees. His major research interest is modeling the formation mechanisms of nanostructures but he is also interested in thermodynamics of small systems.

Knut Deppert is a professor at Solid State Physics at Lund University, Sweden. His research centers on the application of aerosol methods to generate novel nanomaterials and nanodevices, in particular, size selected semiconductor nanoparticles and the creation of one-dimensional semiconductor structures.

Kimberly A. Dick is a researcher at Solid State Physics at Lund University, Sweden, where she received her PhD in 2007. She completed undergraduate studies in chemical physics in Canada and the United States in 2003.
Her research focuses on nanowire fabrication and structures, with particular interest in nanowire growth mechanisms.

References

1 X.F. Duan, Y. Huang, Y. Cui, J.F. Wang and C.M. Lieber, *Nature*, 2001, **409**, 66

2 J. Bao, M.A. Zimmler, F. Capasso, X. Wang and Z.F. Ren, *Nano Lett.*, 2006, **6**, 1719

3 E.D. Minot, F. Kelkensberg, M. van Kouwen, J.A. van Dam, L.P. Kouwenhoven, V. Zwiller, M.T. Borgström, O. Wunnicke, M.A. Verheijen and E.P.A.M. Bakkers, *Nano Lett.*, 2007, **7**, 367

4 S.D. Hersee, M. Fairchild, A.K. Rishinaramangalam, M.S. Ferdous, L. Zhang, P.M. Varangis, B.S. Swartzentruber and A.A. Talin, *Electr. Lett.*, 2009, **45**, 75

5 C.P.T. Svensson, T. Mårtensson, J. Trägårdh, C. Larsson, M. Rask, D. Hessman, L. Samuelson and J. Ohlsson, *Nanotechn.*, 2008, **19**, 305201

6 Y. Li, F. Qian, J. Xiang and C.M. Lieber, *Mater. Today*, 2006, **9**, 18

7 J. Goldberger, A.I. Hochbaum, R. Fan and P. Yang, *Nano Lett.*, 2006, **6**, 973

8 S.A. Dayeh, D.P.R. Aplin, X. Zhou, P.K.L. Yu, E.T. Yu and D. Wang, *Small*, 2007, **3**, 326

9 L.E. Wernersson, E. Lind, L. Samuelson, T. Löwgren and J. Ohlsson, *Jpn. J. Appl. Phys.*, 2007, **46**, 2629

10 F. Patolsky, G.F. Zheng and C.M. Lieber, *Anal. Chem.*, 2006, **78**, 4260

11 Y. Cui, Q. Wei, H. Park and C.M. Lieber, *Science*, 2001, **293**, 1289

12 M. Law, L.E. Greene, R. Johnson, R. Saykally and P. Yang, *Nature Mater.*, 2005, **4**, 455

13 B. Tian, X. Zheng, T.J. Kempa, Y. Fang, N. Yu, G. Yu, J. Huang and C.M. Lieber, *Nature*, 2007, **449**, 885

14 H. Goto, K. Nosaki, K. Tomioka, S. Hara, K. Hiruma, J. Motohisa and T. Fukui, *Appl. Phys. Express*, 2009, **2**, 035004

15 C. Thelander, P. Agarwal, S. Brongersma, J. Eymery, L.F. Feiner, A. Forchel, M. Scheffler, W. Riess, B.J. Ohlsson, U. Gösele and L. Samuelson, *Mater. Today*, 2006, **9**, 28

16 W. Hällström, C.N. Prinz, D. Suyatin, L. Samuelson, L. Montelius and M. Kanje, *Langmuir*, 2009, **25**, 4343

17 C.N.R. Rao, F.L. Deepak, G. Gundiah and A. Govindaraj, *Progress in Solid State Chemistry*, 2003, **31**, 5

18 H.J. Fan, P. Werner and M. Zacharias, *Small*, 2006, **2**, 700

19 K.A. Dick, *Progress in Crystal Growth and Characterization of Materials*, 2008, **54**, 138

20 B. Mandl, J. Stangl, T. Mårtensson, A. Mikkelsen, J. Eriksson, L.S. Karlsson, G. Bauer, L. Samuelson and W. Seifert, *Nano Lett.*, 2006, **6**, 1817

21 J. Noborisaka, J. Motohisa and T. Fukui, *Appl. Phys. Lett.*, 2005, **86**, 213102

22 N. Sköld, L.S. Karlsson, M.W. Larsson, M.E. Pistol, W. Seifert, J. Trägårdh and L. Samuelson, *Nano Lett.*, 2005, **5**, 1943

23 M.T. Björk, B.J. Ohlsson, T. Sass, A.I. Persson, C. Thelander, M.H. Magnusson, K. Deppert, L.R. Wallenberg and L. Samuelson, *App. Phys. Lett.*, 2002, **80**, 1058

24 K.A. Dick, K. Deppert, M.W. Larsson, T. Mårtensson, W. Seifert, L.R. Wallenberg and L. Samuelson, *Nature Mater.*, 2004, **3**, 380

25 R.S. Wagner and W.C. Ellis, *Appl. Phys. Lett.*, 1964, **4**, 89

26 A.I. Persson, M.W. Larsson, S. Stenström, B.J. Ohlsson, L. Samuelson and L.R. Wallenberg, *Nature Mater.*, 2004, **3**, 677

27 H.F. Yan, Y.J. Xing, Q.L. Hang, D.P. Yu, Y.P. Wang, J. Xu, Z.H. Xi and S.Q. Feng, *Chem. Phys. Lett.*, 2000, **323**, 224

28 T.J. Trentler, K.M. Hickman, S.C. Goel, A.M. Viano, P.C. Gibbons and W.E. Buhro, *Science*, 1995, **270**, 1791

29 S. Kodambaka, J. Tersoff, M.C. Reuter and F.M. Ross, *Science*, 2007, **316**, 729

30 L.C. Campos, S.H. Dalal, D.L. Baptista, R. Magalhães-Paniago, A.S. Ferlauto, W.I. Milne, L.O. Ladeira and R.G. Lacerda, *Appl. Phys. Lett.*, 2007, **90**, 181929

31 K. Hiruma, M. Yazawa, T. Katasuyama, K. Ogawa, K. Haraguchi, M. Koguchi and H. Kakibayashi, *Appl. Phys. Rev.*, 1994, **77**, 447

32 S. Kodambaka, J.B. Hannon, R.M. Tromp and F.M. Ross, *Nano Lett.*, 2006, **6**, 1292

33 M.C. Plante, J. Garrett, S.C. Ghosh, P. Kruse, H. Schriemer, T. Hall and R.R. LaPierre, *Appl. Surf. Sci.*, 2006, **253**, 2348

34 K. Hiruma, K. Haraguchi, Y. Masamitsu, Y. Madokoro and T. Katsuyama, *Nanotechn.*, 2006, **17**, S369

35 J. Bauer, V. Gottschalch, H. Paetzelt, G. Wagner, B. Fuhrmann and H.S. Leipner, *J. Cryst. Growth*, 2007, **298**, 625

36 H.J. Fan, B. Fuhrmann, R. Scholz, F. Syrowatka, A. Dadgar, A. Krost and M. Zacharias, *J. Cryst. Growth*, 2006, **287**, 34

37 H.J. Fan, W. Lee, R. Scholz, A. Dadgar, A. Krost, K. Nielsch and M. Zacharias, *Nanotechn.*, 2005, **16**, 913

38 E.C. Greyson, Y. Babayan and T.W. Odom, *Adv. Mater.*, 2004, **16**, 1348

39 T. Mårtensson, M. Borgström, W. Seifert, B.J. Ohlsson and L. Samuelson, *Nanotechn.*, 2003, **14**, 1255

40 L.E. Jensen, M.T. Björk, S. Jeppesen, A.I. Persson, B.J. Ohlsson and L. Samuelson, *Nano Lett.*, 2004, **4**, 1961

41 T. Mårtensson, P. Carlberg, M. Borgström, L. Montelius, W. Seifert and L. Samuelson, *Nano Lett.*, 2004, **4**, 699

42 G. Schmid, *Chem. Rev.*, 1992, **92**, 1709

43 Y. Cui, L.J. Lauhon, M.S. Gudiksen, J. Wang and C.M. Lieber, *Appl. Phys. Lett.*, 2001, **78**, 2214

44 Y. Kim, H.J. Joyce, Q. Gao, H.H. Tan, C. Jagadish, M. Paladugu, J. Zou and A.A. Suvorova, *Nano Lett.*, 2006, **6**, 599

45 A.I. Hochbaum, R. Fan, R. He and P. Yang, *Nano Lett.*, 2005, **5**, 457

46 P.H.M. Böttger, Z. Bi, D. Adolph, K.A. Dick, L.S. Karlsson, M.N.A. Karlsson, B. Wacaser and K. Deppert, *Nanotechn.*, 2007, **18**, 105304

47 K. Willeke and P.A. Baron "Aerosol measurement: Principles, Techniques and Applications" (Van Nostrand Reinhold, New York, **1993**)

48 H.G. Scheibel and J. Porstendörfer, *J. Aerosol Sci.*, 1983, **14**, 113

49 S. Schwyn, E. Garwin and A. Schmidt-Ott, *J. Aerosol Sci.*, 1988, **19**, 639

50 M.H. Magnusson, K. Deppert, J.O. Malm, J.O. Bovin and L. Samuelson, *J. Nanopart. Res.*, 1999, **1**, 243

51 L.S. Karlsson, K. Deppert and J.O. Malm, *J. Nanopart. Res.*, 2006, **8**, 971

52 M.E. Messing, K.A. Dick, L.R. Wallenberg and K. Deppert, *Gold Bull.*, 2009, **42**, 20

53 P. Caroff, J.B. Wagner, K.A. Dick, H.A. Nilsson, M. Jeppsson, K. Deppert, L. Samuelsson, L.R. Wallenberg and L.E. Wernersson, *Small*, 2008, **4**, 878

54 M. Jeppsson, K.A. Dick, H.A. Nilsson, N. Sköld, J.B. Wagner, P. Caroff and L.E. Wernersson, *J. Cryst. Growth*, 2008, **310**, 5119

55 M.T. Borgström, E. Norberg, P. Wickert, H.A. Nilsson, J. Trägårdh, K.A. Dick, G. Statkute, P. Ramvall, K. Deppert and L. Samuelson, *Nanotechnology*, 2008, **19**, 445602

56 B.J. Ohlsson, M.T. Björk, M.H. Magnusson, K. Deppert, L. Samuelson and L.R. Wallenberg, *Appl. Phys. Lett.*, 2001, **79**, 3335

57 M.L. Ostraat, J.W. De Blauwe, M.L. Green, L.D. Bell, M.L. Brongersma, J. Casperson, R.C. Flagan and H.A. Atwater, *Appl. Phys. Lett.*, 2001, **79**, 433

58 T.J. Krinke, K. Deppert, M.H. Magnusson and H. Fissan, *Part. Part. Syst. Charact.*, 2002, **19**, 321

59 H. Kim, J. Kim, H. Yang, J. Suh, T. Kim, B. Han, S. Kim, D.S. Kim, P.V. Pikhitsa and M. Choi, *Nature Nanotech.*, 2006, **1**, 117

60 B.A. Wacaser, K.A. Dick, J. Johansson, M.T. Borgström, K. Deppert and L. Samuelson, *Adv. Mater.*, 2009, **21**, 153

61 V.A. Nebol'sin and A.A. Shchetinin, *Inorg. Mater.*, 2003, **39**, 1050

62 J.B. Jackson, D. Kapoor, S.G. Jun and M.S. Miller, *J. Appl. Phys.*, 2007, **102**, 054310

63 P. Nguyen, H.T. Ng and M. Meyyappan, *Adv. Mater.*, 2005, **17**, 1773

64 H.Y. Tuan, D.C. Lee and B.A. Korgel, *Angew. Chem. Int. Ed.*, 2006, **45**, 5184

65 H.J. Joyce, Q. Gao, H.H. Tan, C. Jagadish, Y. Kim, X. Zhang, Y. Guo and J. Zou, *Nano Lett.*, 2007, **7**, 921

66 K.A. Dick, K. Deppert, T. Mårtensson, B. Mandl, L. Samuelson and W. Seifert, *Nano Lett.*, 2005, **5**, 761

67 K.A. Dick, K. Deppert, L.S. Karlsson, L.R. Wallenberg, L. Samuelson and W. Seifert, *Adv. Funct. Mater.*, 2005, **15**, 1603

68 K.A. Dick, S. Kodambaka, M.C. Reuter, K. Deppert, L. Samuelson, W. Seifert, F.M. Ross, *Nano Lett.*, 2007, **7**, 1817

69 P. Qi, W.S. Wong, H. Zhao and D. Wang, *Appl. Phys. Lett.*, 2008, **93**, 163101

70 I. Regolin, V. Khorenko, W. Prost, F.J. Tegude, D. Sudfeld, J. Kästner, G. Dumpich, K. Hitzbleck and H. Wiggers, *J. Appl. Phys.*, 2007, **101**, 054318

71 F. Maretelli, S. Rubini, M. Piccin, G. Bais, F. Jabeen, S. De Franceschi, V. Grillo, E. Carlino, F. D'Acapito, F. Boscherini, S. Cabrini, M. Lazzarino, L. Businaro, F. Romanato and A. Franciosi, *Nano Lett.*, 2006, **6**, 2130

72 J. Arbiol, B. Kalache, P. Roca i Cabarrocas, J.R. Morante and A. Fontcuberta i Morral, *Nanotechn.*, 2007, **18**, 305606

73 Y. Wang, V. Schmidt, S. Senz and U. Gösele, *Nature Nanotech.*, 2006, **1**, 186

74 H.A.C. McKay, *Transact. Faraday Soc.*, 1938, **34**, 0845

75 M. Borgström, K. Deppert, L. Samuelson and W. Seifert, *J. Cryst. Growth*, 2004, **260**, 18

76 P. Paiano, P. Prete, N. Lovergine and A.M. Mancini, *J. Appl. Phys.*, 2006, **100**, 094305

77 A.I. Persson, L.E. Fröberg, S. Jeppesen, M.T. Björk and L. Samuelson, *J. Appl. Phys.*, 2007, **101**, 034313

78 M.A. Verheijen, G. Immink, T. Desmet, M.T. Borgström and E.P.A.M. Bakkers, *J. Am. Chem. Soc.*, 2006, **128**, 1353

79 S. Kodambaka, J. Tersoff, M.C. Reuter and F.M. Ross, *Phys. Rev. Lett.*, 2006, **96**, 096105

80 B. Hvolbæk, T.V.W. Janssens, B.S. Clausen, H. Falsig, C.H. Christensen and J.K. Nørskov, *Nano Today*, 2007, **2**, 14