

Introducing a New Method of Nanowire Synthesis

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ABSTRACT

Nowadays, we are observing a very great interest in nano-structures such as quantum dots (zero-dimension) and wires (one-dimension). There is a vast number of methods to produce nano-structures, and in particular nanowires. The purpose of this research is to introduce a new method of Nanowire Synthesis that has lots of benefits compared with other methods. To achieve the goal, first the importance and different methods of nanowires synthesis are discussed; then, we will review different methods and mechanisms to generate 1D nanostructures and nanowires. After that, the most methods that are applied in generating nanowires are well explained. Finally, a most recent method is introduced; it has been predicted that this method (electron beaming) will have a very strong effect on the ways of manufacturing nanowires.

Keywords : Nanowire Synthesis, Electron Beaming, Nanostructure

I. INTRODUCTION

Nowadays, we are observing a very great interest in nano-structures such as quantum dots (zero-dimension) and wires (one-dimension) (Brewer, Zhang, Dong, Rutherford, & Tian, 2007). This tremendous interest caused by their size-dependent properties. One-dimensional (1D) semiconductor nanostructures are of particular interest because of their widespread applications in energy, electronic and environment. (Chu, Sasanipour, Saeedi, Baghban, & Mansoori, 2017) However there are a vast number of fields for 1D semiconductor nanomaterials to be applied, many areas require more development. (Grange, et al., 2009) In particular, the fabrication of desired 1D nanomaterials with fitted atomic structures and their assembly into functional devices are still major challenges for the scientist who are working in nanotechnology. (Hanrath & Korgel, 2003) Nanowires are solid, rod-like materials with a diameters between 1 and 100 nanometer (10^{-9} meters). Many different types of nanowires exist, including metallic (e.g., Ni, Pt, Au), semiconducting (e.g., Si, InP, GaN, etc.), and insulating

(e.g., SiO_2 , TiO_2). Molecular nanowires are composed of repeating molecular units either organic (e.g. DNA) or inorganic (e.g. $\text{Mo}_6\text{S}_9\text{-Ix}$). In the physics of nanoscale structures, quantum effects play an increasingly prominent role (Kolasinski K. W., 2006). Quantum wires have illustrated great electrical transport properties that have not been seen in bulk materials. The reason is because, in quantum wires, electrons could be quantum-confined laterally and thus could occupy discrete energy levels that are different from the energy bands found in bulk materials (Kolasinski K. W., 2006). As a result of low electron density and low effective mass, the quantized conductivity is more easily observed in semiconductors, e.g., Si and GaAs, than in metals (Kolasinski K. W., 2006). In addition to the opportunity to describe the new physics illustrated by nanowires, much effort has been devoted to fabricating high-quality semiconductor nanowires by employing different methods because of the importance of semiconductor materials to the electronics industry. Saeedi (2017) used a Meta-heuristic method to develop an integrated supply chain model (Saeedi, Developing an Integrated

Closed-Loop Supply Chain Model By Considering Social Responsibility and Solving the Model Using Meta-Heuristic Methods, 2017).

On semiconductor nanostructures, etching processes always lead to significant surface damage, and thus surface states are introduced to the nanostructures (Torabi, Kiaian Mousavy, Dashti, Saeedi, & Yousefi, 2018). Such damage may not be serious for the structures in the micrometer range (Vizcaíno & Núñez, 2013). However, structures with dimensions in the nanometer range are very sensitive to the surface states or impurities induced by fabrication processes (Torabi, Kiaian Mousavy, Dashti, Saeedi, & Yousefi, 2018). One-dimensional (1D) nanostructures formed “naturally” (also called self-organized growth) without the aids of ex situ techniques, such as chemical etching, are desirable not only in fundamental research but also in future nanodevice design and fabrication (Kolasinski K. W., 2006). Hessami et al. (2017) found some method to solve the serious problem of cost overruns and scheduling delays in the transportation construction industry (Hessami, et al., 2017).

II. Nanowire Synthesis

There are some basic approaches for nanowires synthesis:

2.1. Top-down and bottom-up.

A top-down approach means to reduce a large piece or bulk of material to small parts, by different ways and techniques such as lithography or electrophoresis. A bottom-up approach makes the nanowire by combining constituent adatoms. Nowadays, most nanowire synthesis techniques are based on a bottom-up approach because of their speed of growth and their costs.

The 1D nanostructures can be produced by mechanical and chemical routes. Nonlithographic methods, such as electron-beam, proximal-probe patterning, x-ray, or extreme-UV lithography, all have been applied successfully in industrial scale. However these techniques are successful ones in

industrial scale, these methods are limited because of high cost, low volume, and complexity in manufacture in comparison with the simple and inexpensive solution syntheses. Essentially, the formation of 1-D nanostructure is the process of crystallization. In chemical routes, the bottom-up approach usually was applied to generate the one-dimensional nanostructure.

Fig. 1 schematically demonstrates some of these techniques for controlling nucleation and crystal growth in the scale of nano: (1) a solid with anisotropic structure crystallographic was used for 1-D growth (see Fig. 1A); (2) the symmetry of a seed reduced by a liquid-solid interface (see Fig. 1B); (3) growing from a variety of 1-D templates (see Fig. 1C); (4) capping molecules introduced to control the growth rates of facets of a seed (see Fig. 1D); (5) 0DNMs self-assembled into 1DNMs (see Fig. 1E); and (6) size reduction of 1-D microstructures (see Fig. 1F).

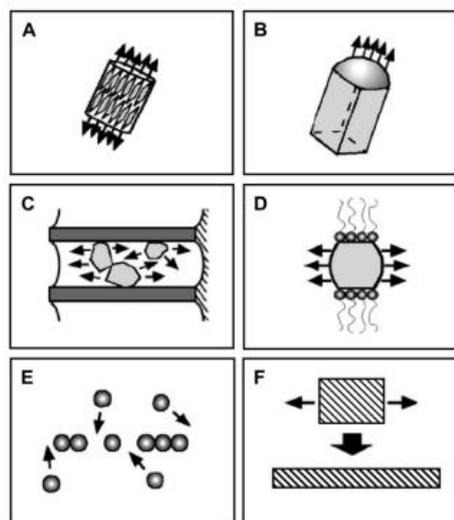


Fig. 1. Schematic illustrations of six different strategies that have been demonstrated for achieving 1-D growth: (A) direction by the anisotropic crystallographic structure of a solid; (B) confinement by a liquid droplet as in the vapor-liquid-solid process; (C) direction through the use of a template; (D) kinetic control provided by a capping reagent; (E) self-assembly of 0-D nanostructures; and (F) size reduction of a 1-D microstructure. (From Xia YN, Yang PD, Sun YG, et al. One-dimensional nanostructures: synthesis, characterization, and applications. *Adv Mater* 2003;15:353-89; with permission.)

Nanowire production uses many common laboratory methods, such as suspension, electrochemical deposition, vapor deposition, and VLS growth. Ion track technology make us able to grow homogeneous and segmented nanowires down to 8 nm diameter.

2.2. Suspension

This method is a very popular method. A suspended nanowire is a wire made in a high-vacuum chamber

held at the longitudinal extremities. There are three ways for producing suspended nanowires:

- The chemical etching of a larger wire.
- The bombardment of a larger wire, typically with highly energetic ions.
- Indenting the tip of a STM in the surface of a metal near its melting point, and then retracting it.

2.3 VLS Growth

One of the most popular method for creating a nanowire is Vapor-Liquid-Solid (VLS) synthesis. This process can make crystalline nanowires of some semiconductor materials. It uses as source material either laser ablated particles or a feed gas such as silane.

The VLS technique was first described by Wagner and Ellis in 1964. They used Au particles as catalysts to grow crystalline semiconductor whiskers from vapor sources such as SiCl_4 or SiH_4 . The Al particles deposited on the surface of a Si substrate react first with Si to form Al-Si alloy droplets at a certain temperature. In the case of Si deposition from the vapor mixture of SiCl_4 and H_2 , the reaction between SiCl_4 and H_2 happens at a temperature above 800 °C without the assistance of catalysts. Below this temperature, almost no deposition of Si occurs on the substrate surface. At a temperature above 363 °C, Al particles can form Si-Al eutectic droplets on Si surfaces, and the reduction of Si occurs at the Al-Si droplets due to a catalytic effect. The Al-Si droplets absorb Si from the vapor phase resulting in a supersaturated state. Since the melting point of Si (1414 °C) is much higher than that of the eutectic alloy, Si atoms precipitate from the supersaturated droplets and bond at the liquid-solid interface, and the liquid droplet rises from the Si substrate surface.

The typical feature of the VLS reaction is its low activation energy compared with normal vapor-solid growth. The whiskers grow only in the areas seeded by metal catalysts, and their diameters are mainly determined by the sizes of the catalysts. The VLS method can result in unidirectional growth of many

materials. It has become a widely used technique for fabricating a variety of 1D nanomaterials that include elemental semiconductors, II-VI semiconductors, III-V semiconductors, oxides, nitrides and carbides.

The experimental setup of the VLS reaction has been reported in previous work. In brief, for Si nanowire growth, the sources can be SiH_4 mixed in H_2 at a typical ratio of 1:10. The reaction gases have to be diluted to about 2% in an Ar atmosphere. The pressure for the reaction is about 200 Torr, and the flow rate is kept at 1500 sccm. Al nanoparticles can be prepared simply by first depositing an Al thin film on a Si substrate using sputtering or thermal evaporation and then annealing the thin film to form droplets.

Because of the oxide layer on the substrate surface or impurities on the catalyst surface induced by the lithography technique, Al catalysts may not wet the substrate surface. For Si nanowires with diameters larger than 20 nm, their growth is generally along the $\langle 111 \rangle$ direction. Thin Si nanowires with diameters smaller than 20 nm, however, show interesting growth behaviors for example the diameter-dependent and temperature-dependent growth direction.

Before growing Si nanowires, activation of Al nanoparticles may be needed. An inactivated Al particle will not lead to nanowire growth. The activation of Al-Si alloy droplets can be carried out in Ar or H_2 atmospheres. We have found that plasma treatment is effective for cleaning and activating the surfaces of Au catalysts. HCl mixed in the reaction gases can also effectively activate Au particles. However, the activation temperature largely relies on the diameters of Al catalysts. For large Al catalysts (diameter > 50 nm), the activation temperatures can be 800 °C or higher. Large Al catalysts can easily wet a Si substrate at sufficiently high temperatures and thus Si nanowires grow epitaxially even on an untreated substrate. In the growth of thin Si nanowires (diameter <20 nm), the growth temperatures are about 500 °C. Too high activation temperatures may cause evaporation of the catalysts. The vacuum condition is another critical experimental parameter that affects nanowire growth.

Low vacuum conditions may cause evaporation of Si from the substrate surface and thus result in a rough surface.

Under isothermal conditions, the crystalline structures of Si whiskers are generally perfect, though steps and facets occur on the whiskers' surfaces. Twinning structures and twin-dendrites (or branched whiskers) have been frequently observed in the whiskers. Though the cross-section of most whiskers is round (determined by the metal droplets), ribbon-like whiskers with a rectangular cross-section often coexist and show the $h1\ 1\ 1i$ or $h1\ 1\ 2i$ growth direction. Dislocations or other crystalline defects are not essential for the growth of the whiskers via the VLS method. In different semiconductor material systems, whiskers with similar morphologies and structures have been fabricated by the VLS reaction and a variety of whisker forms have been obtained. Although the VLS technique has been widely used for the fabrication of nanowires in recent years, the real absorption, reaction and diffusion processes of source atoms through the catalyst are complicated and largely depend on the experimental conditions and the material systems. Many experiments have shown the deviation of some nanowire growth from the classical VLS mechanism. For example, it has been observed that nanowires of Ge, Si, GaAs and InAs can grow even at temperatures below their eutectic points. There has been a long-standing debate on whether the metal catalysts in these cases are solid particles or liquid droplets.

There are two main uncertainties in this debate: (1) because of the nanosize effect, the melting temperatures of nanoparticles are always lower than those of bulk materials and (2) it is not possible to measure the real temperature at the catalyst tips. In fact, in some cases, nanosized metal droplets are in a partially molten state. The surface and interface regions are liquid, while the cores of the droplets are solid.

The VLS mechanism is very successful in generating large quantities of 1D nanomaterials (single nanowires and heterostructured nanowires) with uniform crystalline structures not only in

semiconductors but also in oxide, nitride and other material systems. However, it seems to be difficult to grow metal nanowires by the VLS method. The disadvantage of the VLS method may be the contamination caused by the necessary use of a metal particle as the catalyst. This may result in the change in the nanowire's properties. However, by selecting an appropriate catalyst, the affection of the contamination for specific properties of the nanowire can be minimized.

VLS synthesis requires a catalyst. For nanowires, the best catalysts are liquid metal (such as Gold or Aluminum) nanoclusters, which can either be self-assembled from a thin film by dewetting, or purchased in colloidal form and deposited on a substrate.

The source enters these nanoclusters and begins to saturate them. On reaching supersaturation, the source solidifies and grows outward from the nanocluster. Simply turning off the source can adjust the final length of the nanowire. Switching sources while still in the growth phase can create compound nanowires with super-lattices of alternating materials.

A single-step vapor phase reaction at elevated temperature synthesises inorganic nanowires such as $Mo_6S_9-xI_x$. From another point of view, such nanowires are cluster polymers.

2.4 Solution-phase synthesis

The major advantages of the solution-based technique (in aqueous or non-hydrolytic media) for synthesizing nanomaterials are high yield, low cost and easy fabrication. The solution based technique has been demonstrated as a promising alternative approach for mass production of metal, semiconductor and oxide nanomaterials with excellent controls of the shape and composition with high reproducibility. In particular, this technique is able to assemble nanocrystals with other functional materials to form hybrid nanostructures with multiple functions with great potential for applications in nanoelectronic and biological systems. The nanocrystals synthesized in aqueous media may often suffer from poor crystallinity, but those synthesized under

nonhydrolytic conditions at a high temperature generally show much better crystal quality. For the formation of nanowires from solution, several routes have been developed, such as metal-catalyzed solution-liquid-solid (SLS) growth from metal seeds, self-assembly attachment growth, and anisotropic growth of crystals by thermodynamic or kinetic control.

Many nanowires grown from solution methods largely rely on “structural directors”, including:

- (1) “soft templates,” such as surfactants and organic dopants and
- (2) “hard templates,” such as anodized alumina membranes containing nanosized channels, track-etched polymer porous membranes, and some special crystals containing nanochannels.

Through DC or AC electrochemical deposition, various materials can be introduced into the nanochannels of the hard template. In some cases, vapor molecules may selectively diffuse into the channels because of special chemical properties of the nanochannel walls. Without the assistance of structural directors, anisotropic growth of crystals induced by different surface energies can lead to the formation of elongated nanocrystals. However, the differences in the surface energies of most materials are not large enough to cause highly anisotropic growth of long nanowires. By adding surfactants to the reaction solution, some surfaces of nanocrystals can be modulated, i.e., the surfactant molecules selectively adsorb and bind onto certain surfaces of the nanocrystals and therefore reduce the growth of these surfaces. This selective capping effect induces the nanocrystal elongation along a specific direction to form nanowires. The selective capping mechanism has been evidenced recently in many nanomaterials such as metal nanowires, metal oxide nanowires and semiconductor nanowires. Although structural directors are often used for the synthesis of nanowires, the actual growth process is poorly known. As a matter of fact, in many cases, the structural directors may not exist or the materials are self-constitutive templates. The formation procedure of nanowires in

solution is complicated and the selection and function of the structural directors require further and systematic investigation.

2.5 Non-catalytic growth

There is another method to make nanowires without the need of catalysts which is in the gas phase. The simplest techniques to obtain metal oxide nanowires use ordinary heating of the metals in high temperatures, higher than recrystallization, in oxidative atmosphere (oxygen or air).

Overall, if you do some research on the topic of nanowire synthesis, you may find some other ways and methods of producing nanowires or you can find other categories that show some other techniques of nanowire synthesis. On the other hand, it can be observed that scientists are making some improvement and development in this field every day. In the next pages, I will explain about the characteristics of VLS technique which makes it the most popular method of nanowire synthesis and what are the challenges with using this technique.

III. The reasons of popularity of VLS method

If you are studying or working in a field related to nanowires synthesis, it is almost impossible that you are not heard about the VLS technique. What are the characteristics of this method that makes it such popular? Below there are 6 most important of these characteristics which helps you to have a better understanding from this method compared with other techniques:

- Low temperature and low cost (in compared with other types)
- Adaptable to a wide variety of structures (based on catalyst and reactant choice)
- Low defect density (relatively)
- Rapid growth (fairly a rapid one as you can see in a video that I will show you in a few minutes)
- Direct growth on substrates

- Scalable to large areas and reactor volumes (so this method can be applied in mass production)

In order to apply this method, you must be able to control it to make the nanowire with you ideal characteristics. This method has 3 important stages which are:

1. Preparation of the catalyst
2. Nucleation
3. Growth

In order to control VLS growth of nanowires technique to make the nanowire with you ideal characteristics, there are some key questions that should be answered before and while you are using this method; these key questions are:

- What determines the NW relationship with the catalyst?
- What are the ideal (direct) chemical precursors?
- Is the catalyst solid or liquid?
- How does the catalyst change during growth?
- How is the precursor incorporated at the catalyst?
- What are the effects of individual process variables on the outputs of interest?
- What limits catalyst lifetime, and why does the catalyst deactivate?
- What are the precise effects of oxidizing and reducing agents (sometimes impurities) on:
 - The catalyst size and structure
 - The gas-phase reaction(s)
 - The gas-catalyst reaction(s)

IV. The challenges of using VLS method

As you can see from the last part, the most important challenge while using this method is the number of variables. In order to do a good process of VLS method, there are so many variables and so many questions that should be controlled and answered, respectively. Actually, there are so many inputs that

can change the situation of our process in order to achieve our goal of making our ideal output.

The inputs are:

Catalyst and support:

- Material and composition
- Practical size
- Chemical state (annealing)
- Surface roughness

Reaction conditions:

- Substrate temperature
- Pressure
- Reactant composition
- Buffer/etchant composition
- Supply rates
- Flow profiles/dynamics
- Time and temporal adjustment

And the outputs are:

- Diameter and wall structure
- Length, growth rate, lifetime
- Defect density
- Properties: electrical, mechanical, thermal, optical, etc.

V. Electron Beaming Method

After understanding the most popular method of nanowire synthesis and its' advantages and disadvantages it is time to become familiar with the newest method that make us able to create nanowires with the thinnest wide till today. This method is electron beaming method.

Since 2000, MBE and CBE techniques have been employed to synthesize Si, II-VI and III-V compound semiconductor nanowires based on the VLS growth mechanism.

MBE and CBE techniques provide an ideal clean growth environment, and the atomic structures, doping states and junctions (or heterostructures) can be well controlled. Combined with the VLS, these techniques are able to produce high-quality

semiconductor nanowires. Different from other synthesis techniques, MBE works under ultra-high vacuum conditions. The mean free path of the source molecules under vacuum conditions of 10^{-5} Torr is about 0.2 m. The evaporated source atoms or molecules from the effusion cells behave like a beam aiming directly at the substrate. The growth, surface structures and contamination can be monitored in situ by reflection high-energy electron diffraction, Auger electron spectroscopy and other surface probing techniques. MBE has several advantages over other synthesis techniques: (1) the ultra-high vacuum can reduce contamination/oxidation of material surfaces; (2) the low growth temperature and the growth rate prevent inter-diffusion in the nanostructures; (3) in situ monitoring of growth is possible; (4) since all growth parameters can be adjusted precisely and separately, the intrinsic nanowire growth phenomena can be studied individually.

For a classical VLS reaction, the metal particles are essential for the catalytic decomposition of the precursors. For MBE growth, however, no molecules or precursors need to decompose. The function of the metal particles is twofold:

- (1) absorption of atoms from vapor phases or substrate surfaces. The driving force is to lower the chemical potentials of the source atoms and
- (2) precipitation or crystallization of the source materials at the particle-substrate interface. The preparation of the substrate surface is critical for growing high-quality nanowires.

After wet-chemical cleaning, the substrate has to be deoxidized. Substrate de-oxidation is essential because the oxide layer on the substrate influences the nanowire growth direction. A poorly treated substrate results in random growth directions. The deoxidation temperature depends on the substrates used. For a GaP(1 1 1) substrate, for example, annealing at 600 °C is essential. For the growth of II-VI (e.g., ZnSe and ZnS) nanowires, the synthesis is carried out using

compound-source effusion cells at temperatures above 500 °C. According to in situ observations of the reflection high-energy electron diffraction patterns during the growth, Au nanoparticles are in a molten state at this temperature. In practice, Au nanoparticles are not necessarily molten droplets. In fact, the nanowires can grow at a temperature below the eutectic point. However, the deposition of the source atoms on the substrate surface becomes significant at a low temperature. Then, the surface diffusion becomes an essential mechanism. Excess adatoms are driven to the low energy state of the molten metallic particles or the molten interfaces at these particles. The growth temperature is a critical factor for the formation of high-quality ZnSe nanowires. On the one hand, the deposition of ZnSe on the substrate is restrained when the substrate temperature is substantially higher than 300 °C.

Therefore, almost no ZnSe deposition occurs on the fresh surface of the substrate. On the other hand, a certain high temperature is needed in order to activate the Au alloy particles on the substrate and to “catalyze” the growth of the ZnSe nanowires epitaxially on the substrate. Due to the surface melting effect, it is possible to grow ZnSe nanowires at a low temperature of about 390 °C. In this case, the deposition of ZnSe on the substrate surface is significant, and the quality of the nanowires is poor compared with the quality of nanowires grown at a higher temperature. These nanowires contain high-density defects, e.g., stacking faults and twinings. However, a too-high growth temperature results in coarsening of the Au catalyst and a low growth rate and, in turn, leads to non-uniform diameters of the ZnSe nanowires. The resulting growth rate of the nanowires is mainly determined by the ZnSe flux at a fixed temperature. At 530 °C, the growth rate of ZnSe nanowires is about 0.1 nm/s.

CBE is a hybrid form of molecular beam epitaxy. Different from MBE (using solid sources evaporated at high temperatures), gas sources are used (also called gas source molecular beam epitaxy). CBE works at an

ultrahigh vacuum condition so that the mean-free paths between molecular collisions become longer than the source inlet and the substrate. The gaseous source materials are introduced (the gas transport is collision free) into the reaction chamber at room temperature in the form of a beam. From Au-catalyzed CBE, high-quality 1D heterostructure nanowires (InAs/InP) with diameters of about 40 nm have been fabricated. Very thin InP barrier layers with thicknesses of 1.5 nm and excellent interface structures have been demonstrated by this method. The growth direction and defect density in the nanowires grown by CBE and MBE are influenced by several factors. Twinning or stacking faults are the main defects that very often occur in thicker nanowires and cause a change of the nanowire growth direction. For ZnSe nanowire growth, the growth temperature and the ratio of the source elements are the main reasons causing the defects. The defect density is also dependent on the growth direction. We have observed that $[0\ 0\ 1]$ growth nanowires contain fewer defects compared with nanowires grown in other directions, and ultra-thin nanowires (diameter < 10 nm) generally contain few defects. The growth directions of ultra-thin II-VI compound nanowires are mainly determined by the diameters or the sizes of the catalysts and the growth temperature.

As it is explained, this is not a new method, but the way that it is used is new and by using this method, it will enable us to create nanowires only three atoms wide. It is One thousandth the width of the nanowires used to connect the transistors in today's integrated circuits.

This method has been developed by a PhD student Junhao Lin (Oak Ridge National Laboratory). He has found a way to use a finely focused beam of electrons to create nanowires which are only three atoms wide. His achievement is described in an article published online on April 28, 2014 by the journal *Nature Nanotechnology*.

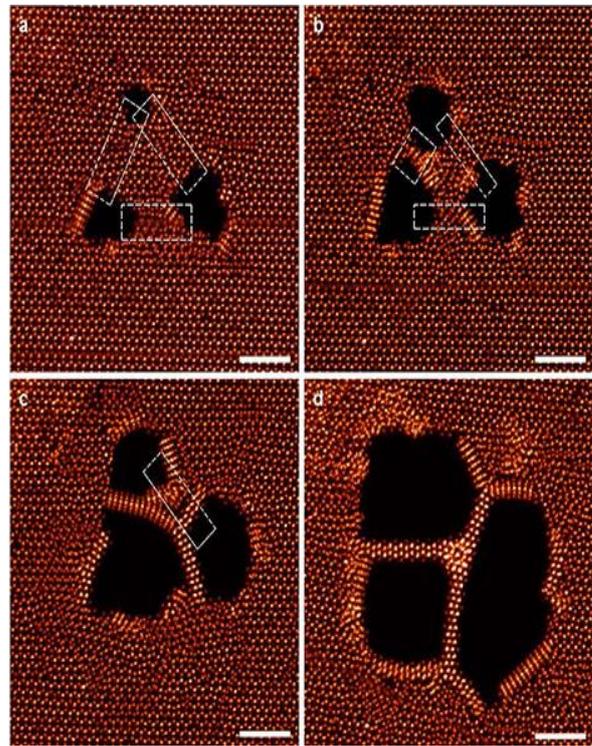


Fig. 2 Series of still scanning electron micrographs (a to d)

Fig. 2 is a series of images while using electron beam method. It shows how the electron beam is used to create nanowires with three atoms wide. *This figure taken through an electron microscope shows how narrow ribbons of the monolayer material TMDC forms tiny wires only three atoms wide by the process of self-assembly when exposed to a weak beam of electrons. Even when there are large variations in the shape of the ribbon, the material forms identical nanowires because they are a preferred configuration.*

The nanowires that have been applied in this method are made from a special family of semiconducting materials that naturally form monolayers. These materials, called transition-metal dichalcogenides (TMDCs), are made by combining the metals molybdenum or tungsten with either sulfur or selenium. The best-known member of the family is molybdenum disulfide, a common mineral that is used as a solid lubricant.

Due to the fact that this technique uses electron irradiation, it can in principle be applicable to any kind of electron-based instrument, such as electron-beam lithography.

VI. The application of this method

It is too early to predict what kinds of applications it will produce, but if you let your imagination go, you can envision tablets and television displays that are as thin as a sheet of paper that you can roll up and stuff in your pocket or purse

VII. Conclusion

Overall, in the last years, the recent properties of 1D nanomaterials have been extensively studied. In addition to the opportunity to describe the new physics demonstrated by 1D nanostructures, much effort has been devoted to fabricating high-quality semiconductor and oxide nanoscale wires based on the bottom-up, self-assembly process by employing different techniques. The classical VLS process which was developed in the 1960s is still applicable to the growth of many nanoscale wires produced today. Various new techniques have been developed by which high-quality ultra-thin nanowire structures have been fabricated, such as oxide-assisted CVD, chemical solution techniques and metal-catalyzed MBE and CBE. In particular, the MBE and CBE techniques provide an ideal clean growth environment and allow high levels of control over atomic structures, chemical composition, defects, doping states, junctions, and so forth. These methods are promising to produce desired 1D nanomaterials with tailored atomic structures and to integrate functional nanostructures into devices. 1D nanostructures grown by these technologies have been seen to exhibit interesting and sometimes unusual growth phenomena. With the extensive studies throughout the years, our understanding of the basic process of 1D nanostructure formation (nucleation, growth, defects, junctions and interfaces) has been greatly enhanced. For 1D semiconductor and oxide nanomaterials to have wide practical applications, however, many areas require more development.

The fabrication of desired functional 1D nanostructures with fully controlled interface structures or junction and chemical composition, and their assembly into functional devices are still major challenges for nanotechnologists. The solution-based technique has been demonstrated as a promising alternative approach for mass production of metal, semiconductor and oxide nanomaterials with excellent controls of the shape and composition with high reproducibility. Its major limit is that the growth mechanisms are poorly known and most structural director agents are chosen by the way of trial and error. Many questions about the synthesis of nanowire structures via highly anisotropic growth of nanocrystals in semiconductor and metal oxide materials, their reactivity and stability still need to be further addressed. Most 1D nanostructures are formed under non-equilibrium state and controlled by kinetic processes. Theoretical works have helped our realization of the mechanism of some growth and provided certain prediction on recent structures. Much more efforts are still needed for more complicated systems involving new structural morphologies and new processes.

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