



Nanoscience for Sustainable Energy

HEINER LINKE AND LARS SAMUELSON | NANOLUND



Nanoscience is the art of understanding and using the new physical behavior exhibited by very small material components – and it offers a wealth of opportunities to help achieve a sustainable energy supply. This is one of the aims of NanoLund, the Center for Nanoscience at Lund University with more than 200 scientists at the faculties of engineering, science and medicine. A special focus is on materials science and applications of nanowires – thin needles about 100 nanometers in diameter (a nanometer is one billionth of a meter). The use of nanowires allows us to achieve entirely new combinations of materials that previously were impossible, and allow, for example, for more efficient solar cells, light emitting diodes and devices that convert heat into electricity.

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A GLOBALLY sustainable energy supply will be possible only if we harvest many types of renewable energy sources (such as wind, sunlight, waves and tides) in combination with reduced energy consumption. In other words, we must find better and more efficient ways of converting one form of energy into another. Crucially, this must be done in a way that is sustainable in the broadest meaning of the word: the novel techniques must be economically affordable, must have no adverse impact on environment and health, and must be achievable within the scope of Earth's natural resources, including its supply of raw materials. Nanoscience – the art of understanding and using the new physical behaviour exhibited by very small material components – offers a wealth of opportunities to help achieve a sustainable energy supply. Therefore, sustainable solutions to more efficient energy conversion are naturally one of the overarching aims of NanoLund, the Center for Nanoscience at Lund University.

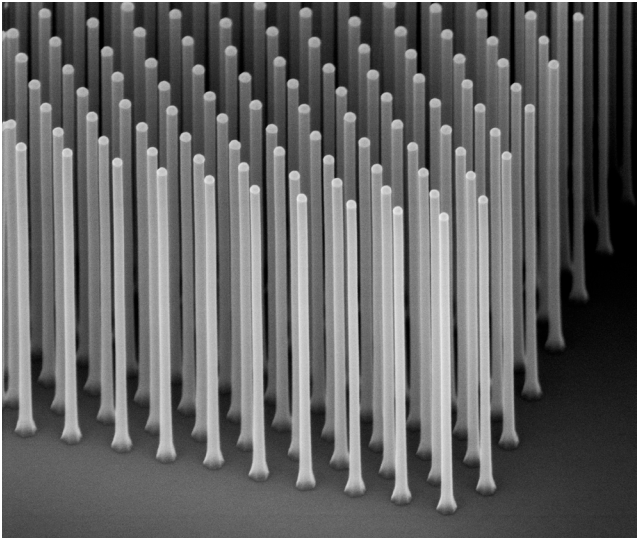
On the following pages we describe our activities in this area, ranging from basic research all the way to technology that is about to hit the market, and from education to collaboration with industry. Using several specific examples, such as the use of sunlight to generate electricity and efficient illumination techniques based on light emitting diodes, we will describe how nanostructures can make energy conversion more efficient, while at the same time drastically reducing the amount of raw materials needed. We will describe our efforts to ensure the safe handling of nanomaterials, from their invention to their use in products. And we will describe how we take a long-term view, developing entirely new physics concepts for energy conversion at the smallest scale, which could lead to methods for efficient energy conversion that are not known today and that may be implemented decades from now.

Nanowires: tiny needles with unique properties

When the size of the components of a material are reduced below about a tenth of one micrometre (thousands of times smaller than the diameter of a human hair) we can achieve entirely new optical, electrical and mechanical properties. For example, nanoparticles made of gold do not have the characteristic shiny metal colour, but instead assume a gentle red – a testament to the different way the nanoparticles interact with visible light, compared to a larger “bulk” piece of gold.

For the past dozen or so years, scientists at Lund University have been focusing on a specific type of nanomaterials called *nanowires*. These are thin needles about 100 nanometres in diameter (a nano-metre is one billionth of a metre). The focus in Lund is on semiconductor nanowires made from elements from groups III and V of the periodic system. These materials are already widely used for electronics and optoelectronics: in mobile wireless networks, fibre optics, and light-emitting diodes.

Nanowires are made in a way that is very similar to the way crystals form naturally. By supplying the raw materials (the elements from which the target crystal is made) at a temperature and pressure close to where a crystal forms spontaneously, nanowires can be nurtured to grow to the desired length from a seed particle whose size determines the resulting needle's diameter. The wires of the highest quality (with the best electrical and optical properties) are achieved when supplying the growth elements in gas form. This is the approach pioneered in Lund and a small number of other places around the globe in the early 2000s, and perfected since then. So why have more than a hundred scientists in Lund spent over ten years focusing all of their attention on tiny needles? A key reason is that the use of nanowires allows us to achieve entirely new combinations of materials that previously were impossible. This is important because all electronic and



A regular array of nanowires, grown from seed particles (still visible on top of the wires) that were positioned on the substrate using nanofabrication techniques. The diameter of the wires is about 100 nanometres, more than a hundred times thinner than a human hair.

A regular array like this one can serve as antennas to effectively absorb or emit light of a certain wavelength. The photograph was taken using an electron microscope. Photo: Gustav Nylund, Lund University.

optoelectronic devices are enabled by effects that occur at the interface between two materials. However, in traditional electronics (where large plates of material, called wafers, are processed in one piece) severe limitations are imposed by what materials can be combined: both materials must have precisely the same distance between their atoms, or else cracks will form that destroy the electronic and optical properties. With nanowires, we do not have this limitation: the wires are so thin that cracks don't propagate along the wire, or don't even form in the first place. As a consequence, we can use a much wider range of semiconductor materials to be sandwiched together in

nanowires, with superior electrical and optical properties. This gives us the opportunity to construct better, higher performing semiconductor devices for a very large range of applications, ranging all the way from quantum mechanical devices to faster electronics and advanced medical devices.

Furthermore, the small dimensions of nanowires are comparable to the wavelength of visible light, and to the wavelength (or size) of electrons. By carefully choosing the dimensions of the wires and their components, and by creating regular arrays of nanowires in highly controlled patterns, it is possible to create completely new electronic and optical properties. More energy with less material: nanowire solar cells

Solar cells (photovoltaic cells) are semiconductor devices that capture light (photons) arriving from the sun, and use their energy to push electrical charges through a wire – creating electric power. The amount of energy available from the sun is staggering; the light delivered by the sun to the surface of the earth in one hour would be sufficient to cover humanity's energy needs for an entire year!

Why, then, do we not already use this almost inexhaustible amount of available solar energy to cover most or all of our electricity needs?

One answer is that we simply haven't got round to it yet. In fact, the amount of solar power conversion capacity installed on fields and rooftops worldwide has been increasing exponentially for the past 15 years, and solar power is here to stay. However, for this trend to continue, and for photovoltaic energy to grow into a truly substantial contributor to electricity needs worldwide, we must further increase the efficiency at which solar cells convert light into electricity. This is because higher efficiency will reduce the amount of raw material (currently mostly silicon) needed to produce the same amount of photovoltaic power, and will thus reduce the cost and

increase sustainability. Nanowires offer unique opportunities to create more efficient and cost-effective solar cells. In 2013, nanoscientists at Lund University and their international collaboration partners attracted much attention by producing the solar cell with the highest efficiency ever achieved using nanowires, 13.8%. This may not sound very impressive compared to the best commercial, wafer-based (planar) silicon devices (23%) or to the record-high values of up to 44% achieved in research labs elsewhere for concentrator solar cells. However, crucially, by using nanowires, the Lund team achieved this efficiency with only 3% of the active material that would have been needed with traditional techniques. This dramatic reduction in material use, which offers great promise for future cost reductions, was achieved by very carefully positioning the nanowire solar cells in the form of an antenna array, which absorbed the sunlight very effectively, such that much less material was needed to capture the light.

This is only the beginning for nanowire-based solar cells. Advanced solar cells, such as those planar cells that achieve conversion efficiencies above 40%, use several layers of material, each converting one part of the solar spectrum into electricity. Such multi-junction solar cells are the next step also for nanowires, which will be helped by the fact that nanowires are much more suited for sandwiching materials on top of one another.

Aerotaxy: flying nanowires boost traditional solar cells

The techniques described above still have one major drawback: they rely on traditional crystal growth methods, where nanowires can be only grown one layer at a time and on expensive substrates. We have recently demonstrated a radically new method of manufacturing nanowires, offering unprecedented growth speeds and material production

capacity. In this growth method, nanowires grow as an aerosol (in the form of particles “flying” in a stream of gas) without the use of any substrate. The method has been named *aerotaxy*. Using aerotaxy, wires can be grown in a continuous flow in large quantities, and one vision is to simply add a layer of nanowires on top of traditional silicon solar cells, boosting their efficiency by enabling them to more efficiently access a wider part of the solar spectrum. Fundamental studies of aerotaxy are presently funded by a grant from the Knut and Alice Wallenberg Foundation, and the technique is being upscaled for pilot production by Sol Voltaics AB in Lund.

Pleasing the eye: LEDs made for humans

General lighting – street lamps, household and factory lighting – today consumes as much as 20–25% of the developed world’s electric power. One reason for this is that traditional incandescent light bulbs and halogen lamps are very inefficient, since they produce much more heat than light. Even the use of the more efficient compact fluorescent lamps is unsustainable, since they contain the environmentally hazardous element mercury. The most energy-efficient lighting technology available is light-emitting diodes (LEDs). Today, white LED lamps have efficiencies of 30–50% in converting electrical power to light, which is ten times higher than traditional incandescent lamps. This is currently achieved by using a blue-emitting LED that is used to “pump” a phosphor material that emits in the green and red spectral regions, on average seen by the human eye as “white” light. One major challenge and opportunity for the future will be to directly create the three basic colours, i.e. red, green and blue (RGB), with LEDs, which would increase efficiency and long-term stability. Furthermore, light produced by combining the three LED sources can be “mixed” to tune the colour temperature to optimally match the preferences of the human eye, and

adjusted for use in specific work or social environments. The nanowire technology developed in our laboratory enables the best blue and green LEDs for such lighting applications, and we are currently developing efficient red nanowire LEDs, something that would be impossible with traditional planar LED technology. The Lund technology for nanowire-based LEDs has been transferred to the spin-off company Glo AB, which currently has more than 60 employees and is pursuing pilot production of perfectly mixed RGB light for displays as well as for lighting applications.

Electricity from heat

If you take a piece of electric conductor, such as a semiconductor, and heat one end while keeping the other cold, a small electric current can be generated. This effect, called thermoelectricity, can be used to convert heat directly into electric power, without a turbine or other mechanical device. Thermoelectric devices could thus be used to extract useful electricity from heat sources that now go to waste: for example from the heat emitted from cars' exhaust pipes, or from the temperature difference between a residential gas burner and the water for the shower.

However, current thermoelectric devices are not efficient enough to make their use in these applications worthwhile. Furthermore, some of the most efficient thermoelectric materials available are rare or toxic (or both!), making their large-scale use unsustainable.

Semiconductor nanowires have unique properties that make them very interesting candidates for future, efficient thermal-to-electrical energy converters. Firstly, their small diameter effectively blocks heat flow, reducing heat loss and making them more efficient. Secondly, their electronic properties – which determine the amount of electric power they can

produce from a given amount of heat – can also be improved by tuning the wire diameter. At least, this was predicted more than 20 years ago by MIT professor Mildred Dresselhaus, but, until recently, had never been realised in practice.

Lund researchers very recently demonstrated, for the first time, that nanowires indeed can produce more power from heat than the same material in bulk form. At the moment, this has only been shown at very low temperatures where such devices are not useful for electric power generation. Nevertheless, the breakthrough sets the stage for future, efficient nanowirebased thermoelectric converters in your car or home.

Safety: is “nano” always good?

Nanoscience is about understanding and eventually taking advantage of the new properties a material exhibits on the nanoscale, for example in the form of nanoparticles or nanowires. However, there is no guarantee that these novel properties are always exclusively positive. In fact, it is well known that some types of nanoparticles, when inhaled or ingested, can be hazardous to human health. A number of factors can play a role: for example, the particle’s catalytic properties, which can be much enhanced by its large surface-to-volume ratio, its size and shape (making it difficult for the cells of the immune system to absorb the particle) or other properties. Just as for any new chemical, it is very important to evaluate a nanomaterial’s safety before it is used in the lab or in products, and to consider exposure risks to workers and customers throughout a product’s life cycle. This applies to solar cells or LEDs as much as for any other nanomaterial-based device or product.

The exposure routes (the ways by which humans or other organisms may touch, inhale or ingest a nanoparticle) of nanomaterials are different from those of bulk materials.

New methods need to be developed to measure and evaluate health and environmental risks during production and use of nanoparticles.

Within the Lund nanoscience environment, more than 20 scientists with backgrounds in occupational health, physics and chemistry combine their expertise to evaluate safety aspects of nanoparticles in general and of nanowires in particular. This includes the development of methods to accurately measure, for example, the quantity of airborne nanowires that may end up in the lungs of workers in university laboratories as well as in start-up companies that commercialise nanowirebased technology.

Novel concepts

The uses of nanowires described above primarily concern improvements to technology that existed long before the advent of nanowires. Could nanoscience also offer entirely new routes to efficient energy use that have never been tried before? We believe that the answer is “yes”, and have initiated several fundamental science thrusts to explore such possibilities.

One example is the use of molecular devices for energy conversion. The prime example of such systems can be found in biology, where molecular motors (complex protein-based molecules) perform useful tasks such as intracellular transport. To do this, molecular motors convert chemical energy directly into mechanical work with higher efficiency than even the most sophisticated car engine. To learn from nature, we construct artificial molecular motors and explore synthetic nanodevices powered by biological molecular motors. As part of a collaboration financed by the European Union, we explore computing devices that use molecular motors instead of electrons, and that use a hundred times less energy than traditional electronic computers. We also study forms of energy

conversion that are entirely different from anything that is used in existing technology. For example, we are learning how information can be transformed into useful energy in devices that can “observe” and take advantage of fluctuations of a small object such as an electron or molecule. This work involves a reformulation of thermodynamics on the nanoscale, since the classical thermodynamic theory was developed specifically for large-scale steam turbines or car engines, and cannot be used to understand energy conversion on the tiny scale of single molecules.

Looking ahead, there are many more opportunities for Lund nanoscience to address society’s grand challenges, leading to a better life for many. In one focus area we will target *Nanoscience for the benefit of the developing world*. Current research will help provide affordable access to both solar power and efficient LED lighting in the developing world, and will thus help improve living conditions and support children’s education. Further development of LEDs will allow us to efficiently produce deep-ultraviolet light to kill microorganisms, for use in water purification systems. Lund micro- and nanotechnology can also be used to develop cheap, hand-held devices for quick diagnostics for use in remote health clinics.

We also foresee the use of nanowire probes in neuroscience and in cancer and diabetes research and treatment, in collaboration with the strong Lund-based research efforts in these areas (including the Neuronano Research Center, EXODIAB and BioCARE). The ability to probe, manipulate and monitor one or many individual cells may help answer important scientific questions in these fields.

Fundamental and applied science, education and innovation

The science described above is possible only in a highly integrated research environment that spans basic and applied research, materials science and physics, chemistry and biology, technology, and medicine. It is our mission to do both: focus on addressing important problems of today, while also allowing blue-sky research to thrive and provide novel approaches to solving the problems of tomorrow.

One of our most important roles is the education of nanoscientists for careers in academic research as well as in industry, with the ability to integrate knowledge and skills from many disciplines, and with a deep understanding of the need to apply this expertise safely and sustainably. We do this in our flagship degree programme Engineering Nanoscience, as well as in the education of the approximately 100 doctoral students engaged in Lund nanoscience. Currently, we are developing an internship programme with the aim of offering our doctoral students the opportunity to gain industrial work experience for a few months during their studies.

However, to turn ideas into commercial technology that can improve our lives, great interdisciplinary science and bright young people alone are not enough: it is a long road from basic research to a profitable product. Working jointly with regional policy-makers, research institutions and entrepreneurs, we are therefore currently planning for an expansion of the fundamental research facilities towards nano-production. It is our vision to ultimately create a complete innovation ecosystem, comprising all steps in the innovation production chain, using resources jointly operated and owned by academia and industry. This vision includes ProNano, a pilot production facility that will preferably be located in the Science Village area close to the MAX IV and ESS facilities,

with much of the necessary infrastructure and support facilities needed for industrial development. In this way, we will be able to vertically integrate unique competences all the way from education and basic research, via applied R&D and pilot facility establishment, to enable the development of an advanced industrial infrastructure for nanomaterials production. Our research can thus reach its full potential in terms of its benefit to society. □



Lars Samuelson initiated the Nanometer Structure Consortium in 1988, shortly after being recruited to Lund as a young Professor of Semiconductor Electronics. In the late 1990s he focused the consortium's work on nanowires. He is the founder of several spin-off companies, including Glo AB, which commercialises nanowire-based light-emitting diodes (LEDs).

About Nanoscience at Lund University

Founded in 1988 as the Nanometer Structure Consortium (nmC), NanoLund is today Sweden's largest research environment for nanoscience, engaging more than 240 scientists and PhD students at the faculties of engineering, science and medicine at Lund University. Its vision is to bring together the most creative minds in a worldleading interdisciplinary research environment to help overcome society's grand challenges by pushing the frontiers of nanoscience.

To support these strategic aims, we provide multiple platforms for interdisciplinary exchange and collaboration across faculties and continuously develop joint, coherent goals. We fund strategically important projects, develop and maintain joint infrastructure for academic and industry users, and offer education in nanoscience at all levels, including a five-year programme in Engineering Nanoscience that is closely integrated with our research. Our effective innovation pathways have created several spin-off companies that currently employ more than 150 people.

Nanoscience at Lund University changed name to NanoLund in June 2015

www.nano.lu.se



Heiner Linke is a Professor of Nanophysics at Lund University and the director of NanoLund since 2013. He joined Lund University in 2009, following eight years at the physics department and Materials Science Institute of the University of Oregon. His research focuses on energy conversion at the nanoscale in both semiconductors and biomolecular systems.



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AT THE FOREFRONT
OF NANOSCIENCE

LUND UNIVERSITY
NanoLund
Box 118
221 00 Lund
Sweden
www.nano.lu.se