Potential impact.

General features and potential advantages of the NW-LED concept.

The choice of nanowires as the material to be used in LEDs has several advantages, among these are

(i) the ability to reach higher In-concentrations in the active QW-layers in a radial LED-structure enabling more long-wavelength emission,
(ii) (ii) the opportunity to design the individual nanowires into photonic cavities enabling optimal out-coupling of light, including reaching non-Lambertian angular distributions,
(iii) (iii) the ability to effectively obtain an emitting QW area that by far exceeds the planar foot-print of the LED device.
(iv) Furthermore, it is expected that it may become possible to design photonic crystal structures in the form of 2-dimensional nanowire arrays in which intended emission patterns, such as vertical emission, is enhanced while un-intended emission, such as in-plane emission, is strongly suppressed.

Today, it is possible to fabricate highly efficient blue and green NW-LEDs in the GaN-InGaN materials system, and red NW-LEDs in the GaAs-AlGaInP materials system. We expect also to very soon realize efficient yellow GaN-based NW-LEDs which will create the ideal system for color rendering optimization of R-Y-G-B (red-yellow-green-blue) individually addressable NW-LEDs. This will offer significant avenues towards application areas within advanced display applications as well as in lighting. A four-color emitter is able to reach color rendering index values exceeding 98, which is well beyond what the human eye can distinguish from the most ideal solar illumination conditions. With such a tri- or quadri-chromic illumination system that does not use any phosphors, the long-time color stability is expected to be highly superior in comparison with today’s UV/Blue-LED-pumped phosphors, also in terms of the efficiency in converting electrical in-put power to light.

In addition, the high quantum efficiency of the nanowire devices at low current densities make them especially suitable for display architectures where each nanowire or group of nanowires may form a pixel. In these architectures, the drive current per pixel is on the order of nanoamperes, necessarily meaning the current densities is below 1 A/cm^2. A great and challenging opportunity, quite unique to NW-LEDs, would be the implementation of a monolithic RGB, direct-view display technology that would be exceedingly bright and power efficient in comparison with any display technologies available today.

Present shortcomings in the planar LEDs for Solid State Lighting (SSL), and how nano-LEDs may offer solutions.

The status of the SSL lamps can be summarized as follows:

- The efficacy in commercial production is about 150 lm/W for cold white lamps, somewhat less (130 lm/W) for the warm white version.

- The target for the year 2000 in the US roadmap is 200 lm/W for both versions. This appears possible to realize within the present technology, but it is questionable if this goal is in accordance with an acceptable market price for the white LED lamps. The present problem with droop in the InGaN/GaN LEDs grown on foreign substrates forces the producers to use large chip areas (of the order 1 mm^2) for each planar LED. It is unavoidable that this will have a strong influence on the cost of these LED lamps, the cost could be lowered substantially of a much smaller chip size (and high drive current density) was used, which is technically feasible. The physical origin of droop is still under debate, and not definitely resolved. An interesting observation is that LEDs made on bulk GaN substrates with a low dislocation density ($< 10^6$ cm^{-2}) demonstrate much lower droop, suggesting that dislocations may play an important role.

The presence of defects (structural defects as well as point defects) in the present planar InGaN-GaN based LED structures is a problem that is not well documented in the literature. The common practice of growing the LED structures on foreign substrates unavoidably leads to a threading dislocation density of mid 10^8 to 10^9 cm^{-2} throughout the structure, as a consequence of the lattice misfit between the substrate and the layers in the LED structure during the growth cycle. The common wisdom is that this has little influence on the radiative efficiency of the LED structures at low injection currents. At high currents, i e under the conditions of droop, the situation is different, and it is known that dislocations act as nonradiative defects.

Another kind of structural defects occur as a consequence of the misfit strain between the different layers in the LED structure developing in the growth cycle. Misfit dislocations and stacking faults may develop in the interfaces between the layers, both defects are causing nonradiative recombination if present in the active region of an LED structure. Such problems are a main concern for the longer wavelength LEDs, where the lattice misfit between GaN and InGaN is largest. A solution would be to use InGaN templates for the growth of the LED structures. Such planar InGaN wafers are not yet available on the market, however.

In addition to these structural defects there are also problems with point defects in the planar LEDs. It is well known that the introduction of structural defects is typically accompanied by point defects, which form more readily in the local large strain fields from structural defects. Very little definite data are known about this problem in the InGaN material, however. It has e.g. been suggested that the so called “green gap” problem is related to deep level point defects, these have been characterized in DLTS experiments, but not identified so far [1].

Another limitation in the growth of planar InGaN-GaN LED structures is the limited In composition that can be incorporated in different InGaN surfaces. The c-plane orientation is known to be superior in this respect, c-plane InGaN can be grown over the entire range from GaN to InN, and is perfectly suited for the present SSL technology on sapphire. The limitation for c-plane InGaN structures is the so called Stark effect, i e the built in polarization field that causes an excessive internal electric field in the QWs, so that the QW thickness has to be as small as ~2 nm for longer wavelengths, not practical in a production environment. The In incorporation is improved if non-polar or semipolar planes are used, and wider QWs are then tolerated as the field is reduced. The strain is still very high, however, meaning that the strain-induced defects limit the radiative output of the long-wavelength LEDs beyond the green region for the standard InGaN-GaN growth technology on sapphire (or other foreign substrates).

Proof of concept research has been done on growth of planar InGaN-GaN LEDs on bulk GaN substrates. In the case of non-polar and semi-polar structures excellent results are demonstrated on small size GaN substrates of proper orientation [2]. The substrates are presently too small (about 10 mm size) for commercial production of LEDs at reasonable cost. In the case of c-plane GaN larger size substrates (2 inch diameter) exist, and industrial production of LEDs on bulk GaN has been started by Soraa Inc in USA. For the longer wavelengths the strain is still a severe limitation, as discussed above. As outlined below all-InGaN defect free structures seem to be needed for efficient long wavelength nitride LEDs. At present bulk InGaN substrates do not exist.

The above situation has led to an increased interest in nanostructures as a basis for visible LEDs. It is well known that the small dimensions of nanostructures allow at least partly a relaxation of built in strain in the structures, further the structural defects that are so dominant in the planar structures can be completely eliminated from the active region of the devices made on these nanostructures. By using a nitride buffer layer on top of a substrate, foreign substrates of any chosen dimension can be used without loss of the above properties, which means a low cost can be maintained for a high quality structure. We have previously discussed the properties of LEDs in the nanowire configuration, where the main emitting facets are the m-planes. The structures studied in this project have limitations at longer wavelengths due to the use of several GaN layers in the structure (causing high strain as discussed above), and also suffering from limited In incorporation in the m-planes during growth. The flexibility in nanostructure growth can be used to develop an all-InGaN LED structure for visible light nitride LEDs. Very regular arrays of such structures can be grown with aid of a suitable insulating mask material (i.e. SiN_x) in combination with nano- imprint lithography (NIL).We shall here discuss one possible such configuration, based on nano size c-plane features.

In Fig 1 is shown several examples of geometries of GaN nanostructures, that can be grown in one single MOCVD growth run, using a NIL patterned sapphire substrate with a GaN buffer layer. The right part of the figure shows c-plane platelets of different thickness. Very similar c-plane structures can as well be prepared in InGaN (also in a single growth run), with In compositions up to about 20%. TEM investigations show that such InGaN templates are typically free of structural defects. The c-plane top face may have a slight roughness as grown, then an overgrowth will produce a perfect template for further growth of a full LED structure, in this case an all-InGaN structure. For growth of green LEDs the In composition of the template can be about 10 %, for longer wavelengths out to red a 20% In template is suitable. Quantum well structures are then grown with traditional c-plane growth conditions with InGaN barriers of similar composition as the template. An AlGaN electron blocking layer can be added before the p-layer is grown to complete the LED structure.

In Fig. 2 are shown emission spectra from samples with different configurations of the QW region. Single QWs were used for these test samples.

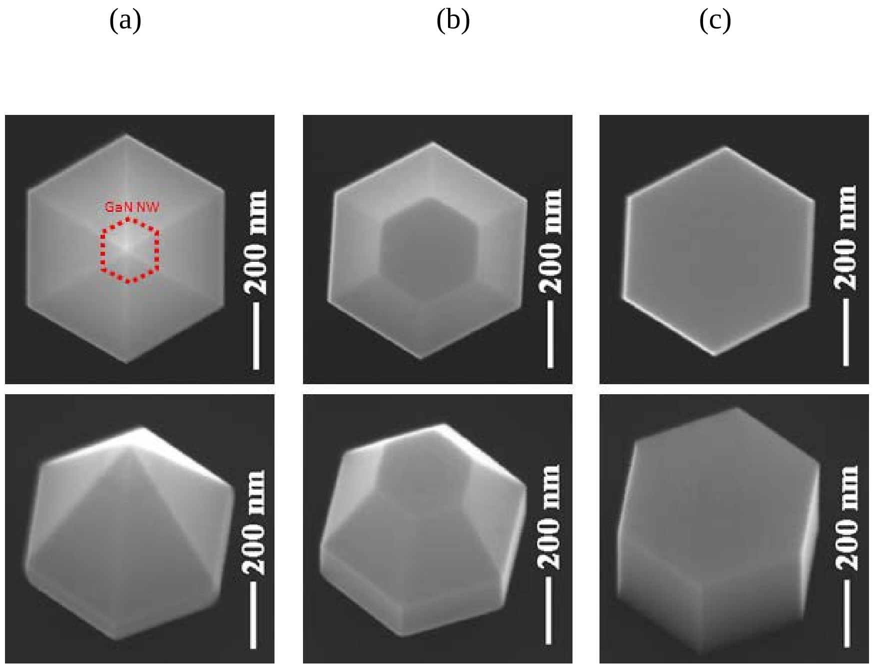

Figure 1. Top-view (top row) and tilted-view (bottom row) SEM images of GaN shell growth on GaN NWs. ***a****) Pyramidal shell growth without c-plane. Dotted lines show the profile of GaN NW.* ***b****) &* ***c****) show controlled platelet growth with varied c-plane size.*

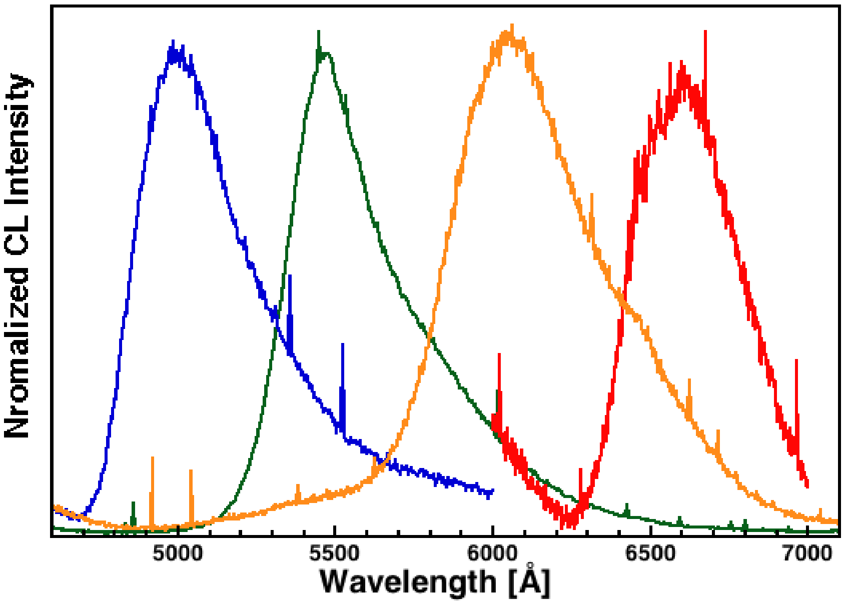

Figure 2. Emission spectra at room temperature from c-plane all-InGaN nanostructures with different active region QWs.

In figure 3a green prototype emitter with this configuration is shown with electrical injection.

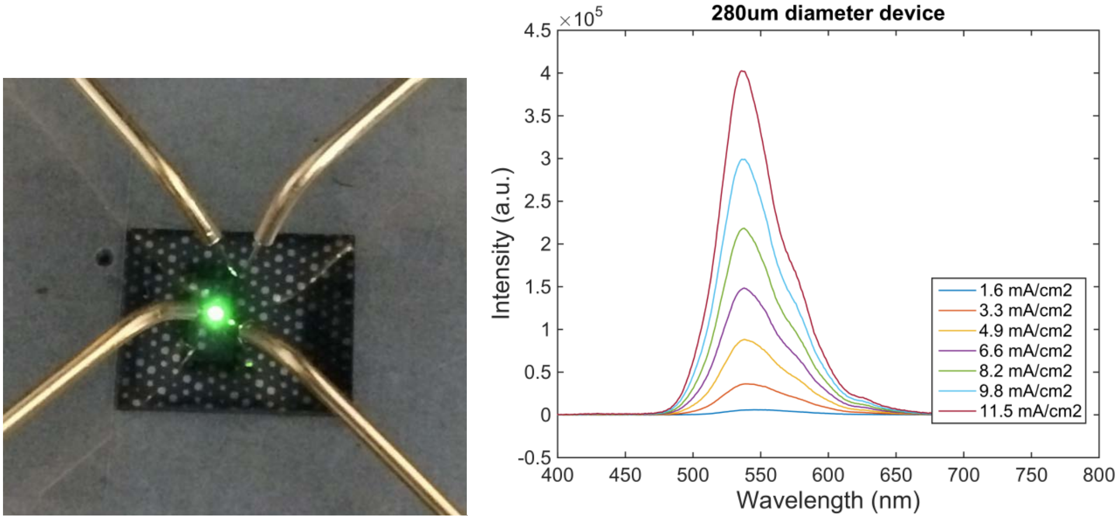

Figure 3. Left: picture of a green InGaN c-plane nano-emitter with electrical bias. Right: EL spectra at different current levels (room temperature).

Possible impact of all-InGaN nano-LEDs.

The above data are very preliminary and have not been optimized. It should be pointed out that in the planar technology the efficiency of nitride-based LEDs with emission above 600 nm is very low, best values reported are 1-2 % [3], which is insufficient for most applications and certainly for SSL. We want to be able to optimize these c-plane nanostructure LEDs so that the full potential of the InGaN material can be utilized. We are confident that the structures can be prepared without structural defects across all visible wavelengths, also the strain will be much reduced compared to the standard planar InGaN/GaN structures. This also means that there is a good chance that the point defects believed to be responsible for the so called green gap might be considerably reduced in concentration. A bonus with the low strain structures produced this way is that the quantum well in the active region can be kept much wider, thus simplifying the growth process.

The impact of a successful outcome of this all-InGaN approach for visible LEDs would be very large. If nitride based LEDs could be produced with similar efficiency from blue to red, there is finally a platform for the polychromatic solution for SSL, by mixing the light from efficient LEDs in all four colors blue, green yellow and red. The ability to do this in a single (InGaN) material system is definitely a technical advantage.

[1]. A. M. Armstrong et al, Applied Physics Express 7, 032101 (2014)

[2]. C.C. Pan et al, Applied Physics Express 5, 062103 (2012)

[3]. J-I Hwang et al, Applied Physics Express 7, 071003 (2014)

Wider socio-economic impact and societal implications of modern lighting solutions.

Appropriate lighting is a basic prerequisite for the quality of modern life. The electric light has enabled a great expansion of human activity. As an obvious and important example can be mentioned the value of better illumination on our roads during dark hours, improving traffic safety. Similarly, the effects of significantly improving night time illumination in pedestrian areas will lead to an important improvement in personal safety and comfort. For many of such public areas the value of the long life-times of LED-based SSL is significant, since the illumination systems can be designed without the need for frequent lamp replacements. This important advantage also holds for novel opportunities in architectural lighting, where lamp fixtures can be integrated with the buildings in many and novel ways. However, inappropriate light and light pollution also have serious side effects on human health and quality of life. Furthermore, the energy and materials used for lighting tend to have serious environmental consequences.

As a species, humans depend most heavily upon visual and endocrine regulatory information to interact with the environment. Some 80% of our sensing cortex in the brain is devoted to vision. All species, including humans, also depend upon the natural, 24-hour light-dark cycle to coordinate, literally, every physiological system in the body to live healthy and productive lives. Effective lighting is one of the important elements for a sustainable lifestyle. Thus far, most of the interest has focused on the amount of light and the efficiency of the light producing processes, often measured as lumens (lm) and lm/W. The primary aim has been to produce a sufficient amount of light at the lowest possible cost. Most of the consumer interest has focused on the cost of the light source. In a life-cycle perspective the energy cost has become a major part of the cost, in particular for lighting with ordinary incandescent light bulbs. Since the 1960s the professional market has become increasingly interested in more efficient light sources.

The evolving technology, primarily in Light Emitting Diodes (LED), is beginning to enable new tailor-made and dynamic forms of lighting. The commercial LED technology is approaching the same level of efficiency as fluorescent tubes. Incandescent lamps mainly produce heat, fluorescent tubes produce the light in an indirect way and LEDs produce the light in a direct, and thereby more effective and versatile way. The purchase price for high quality LED-based light sources is still relatively high, but the life-cycle cost is becoming more competitive. There is keen interest in light quality to enhance plant growth within intensive greenhouse production systems.

So far there has not been much public awareness of the importance of the quality of light. Since the 1990s, there have been significant breakthroughs in knowledge about the positive and negative effects of different kinds of light, on human health and comfort. There is also an evolving interest in light pollution, i.e. too much light and unsuitable kinds of light.

Plants and algae use light energy absorbed by chlorophyll in photosynthesis to produce carbohydrates from carbon dioxide and water. Besides this, the information carried by light is used to optimize plant growth and behavior, to guarantee the best chances of survival and reproduction. Different pigments other than chlorophyll absorb light for these processes and allow control of e.g., gas exchange, flowering, shade avoidance and production of phytochemicals. The light emitted from high-pressure sodium lamps used traditionally in greenhouses is quite poorly adjusted to what the plants use, which results in unnecessarily high energy costs. With LED light in greenhouses, the energy consumption can be drastically lowered, since the different wavelengths can be more balanced. Furthermore, light can be varied to stimulate specific processes such as the synthesis of specific plant products important to human health. One potentially very important application of this technology may be the use of the separate spectral components in novel applications such as green-house lighting systems, where indeed sharp spectral features in the blue and in the red regions can be designed to optimally induce growth of plants. This can be expected to lead to a new way of feeding our population by eco-friendly and efficient local food production, hence reducing expensive and polluting long-distance transportation. For local production of food in northern regions of Europe having short daylight periods during the winter season, it could become quite realistic to keep producing vegetables based on a combination of heat stored in the ground and highly efficient, and spectrally optimized, illumination using such LEDs.

In addition the versatility in regulating the emission wavelengths and power of these new light sources allow significant advances in other research fields, like visual science, medicine and psychology.

Main dissemination activities in the project.

As part of dissemination activities the partner groups have participated in other joint symposia with research groups with similar interest. One such event was the Lund-Tokyo-Copenhagen-Beijing Joint workshop on nanostructure quantum devices held in Lund-Copenhagen March 24-25 2013. At this event our development of regular Hall measurements on single nanowires was reported and demonstrated (Kristian Storm).

Another example of such an event was the second Industry-Academia Workshop on Nanophotonics for Energy Efficiency 11-12 Nov 2013 in Stockholm. This was a separately EC-supported activity with participation from many European countries. Bo Monemar gave a presentation of our work in NWs4LIGHT.

Another international event with connection to European Lighting Industry was “Symposium on Materials Science for Light Emitting Diodes”, organized jointly by Lund University and the local organization “Invest in Skåne” in Lund 14-15 Oct 2013. There were several participants from Japan, such as H Amano, Nagoya University, and S Kamiyama, Meijo University, they reported about LED developments in Japan, Lars Samuelson, Jonas Ohlsson and Bo Monemar gave presentations on our work at Lund University, such as the NWs4LIGHT. Several industries with interests in lighting also gave presentations, one example is IKEA.

On Feb 5 2015 The Lund University Open Innovation Center arranged a symposium “Multidisciplinary Lighting seminar”, with participation of researchers from social science, medical science, technology and several industrial partners. The event had several international invited speakers covering different aspects of future lighting solutions. Bo Monemar participated representing the Solid State Lighting Center at ULUND.

The above is just a few examples of many such events with useful interaction and contact with relevant lighting industry as well as with foreign research activities outside the project. It should be mentioned that Dr N Gardner at GLO has participated in important committees related to the SSL roadmap in the USA. This may be important for the future positioning of NW-LEDs in this application area.

An important element in the international and European dissemination work in this project has been plenary and invited presentations, given worldwide and primarily by the coordinator Lars Samuelson at ULUND. These were mostly angled at the development of growth technology and basic understanding of the NW properties, but included also results on the performance of the NW-LEDs produced in the projects. Several such presentations were also given by representatives of the GLO partner, mainly by Nate Gardner. In that case new information on growth of NW-LED structures and related device processing was demonstrated from a semi-industrial perspective, and relevant performance data were also transmitted. These presentations have showed the international research community where the leading edge in this field lies, and clearly indicated prospects for future applications, both in Solid State Lighting and in other fields like display screens. A complete list of these talks is given separately in the report D5.7.

In addition to these plenary and invited presentations there were many ordinary contributed oral and poster presentations at conferences and symposia in the field of nanostructures as well as light-emitting structures and devices. These contributions are listed in full in the report D5.7.

Exploitation activities in the project.

The exploitation of the foreground produced in the project has mainly relied on the industrial partner Glo AB in Lund, Sweden (GLO) and its subsidiary Glo-USA Inc. in Sunnyvale, USA (GLOINC). Via this partner several patents related to nano-wire LED technology have been issued during the project duration, as discussed separately in Sec. 4.2. GLOINC has set up a functioning processing plant in order to demonstrate the viability of the NW-LED approach. GLOINC demonstrated that it is possible to produce nanowire LEDs using a flip-chip process technology, thereby enabling the integration of these LEDs into systems with large numbers of devices where the otherwise-needed wire bonds are prohibitively expensive or result in yield or reliability problems of the integrated system. The produced devices have a performance close to the corresponding planar LEDs on the market, and also exhibit similar excellent data in reliability tests.

GLO has an extensive contact area with possible customers for NW-LEDs. It seems like the SSL market is not yet ready for the NW-LED introduction, a breakthrough for long wavelength nitride NW-LED structures would certainly change this situation. That is why we recently have put some substantial effort at ULUND to advance this part of the growth activities (see above). This part is presently producing new foreground that will be protected and hopefully lead to a game-changing production of polychromatic NW-LEDs with a much higher efficiency and lower droop than the present SSL solutions on the market.

In addition, the demonstrated high quantum efficiency of the nanowire devices at low current densities make them especially suitable for display architectures where each nanowire or group of nanowires may form a pixel. In these architectures, the drive current per pixel is on the order of nano-amperes, necessarily meaning the current densities is below 1 A/cm^2. A great and challenging opportunity, quite unique to NW-LEDs, would be the implementation of a monolithic RGB, direct-view display technology that would be exceedingly bright and power efficient in comparison with any display technologies available today.

Project website.

The website is found under Lund University at the address:

http://www.ftf.lth.se/research/links_to_some_projects/nws4light