Final report

1.1 Project details

Project title	Efficient light emitting diodes
Project identification (program abbrev. and file)	64014-0103
Name of the programme which has funded the project	EUDP
Project managing company/institution (name and address)	Light Extraction ApS Address: Ørsteds Plads 343, 2800 Kongens Lyngby
Project partners	Technical University of Danmark Address: Ørsteds Plads 343, 2800 Kongens Lyngby
CVR (central business register)	Light Extraction ApS: 34903948 Technical University of Danmark: 30060946
Date for submission	30-04-2016

1.2 Short description of project objective and results

English version:
Light Extraction (LE) improves the efficiency of light emitting diodes (LED). Our method is based on industrially reproducible nanostructures that are more efficient than the microstructures the industry uses today. The purpose of the project is to - together with DTU Photonics - demonstrate the method in practice and adapt it to the specifications of the LED manufacturers.

In this period, we have developed a new way of compact periodic structures patterning without any costly material in the process. This method can be used on LEDs with smooth surfaces. In the meanwhile, another method mainly based on dry etching technique has been invented to be applied to high power vertically structured LEDs with structured (or uneven) surfaces. Both methods result in an enhancement of more than 50% in photoluminescence (PL).

Danish version:
Light Extraction (LE) forbedrer effektiviteten af lysemitterende dioder (LED). Vores metode er baseret på industrielt reproducerbare nanostrukturer, der er mere effektive end de mikrostrukturer industrien anvender i dag. Formålet med projektet er - sammen med DTU Fotonik - at demonstrere metoden i praksis og tilpasse den til de specifikationer der er anvendt af LED producenter.

I denne periode har vi udviklet en ny måde hvorpå kompakt periodiske strukturer produceres uden dyrere materialer i processen. Denne metode kan anvendes på lysdioder med glatte overflader. I mellemtiden er der blevet opfundet en anden metode hovedsagelig baseret på tør æts teknik, der skal anvendes til high-power vertikalt designet LED'er med struktureret (eller ujævn) overflade. Begge metoder resulterer i en forøgelse på mere end 50% i fotoluminescens (PL).

1.3 Executive summary

Although the market for LED is booming, LED manufacturers are under great pressure to continually reduce prices and increase their competitiveness.

The LED manufacturers are among the world's largest companies and primarily based in the Far East. Both things make cooperation with the companies to be a resource intensive and time-consuming task. The project enables us to demonstrate the solution in practice and tailor it to customers' requirements.

During this project, we have developed two different nano-patterning methods in order to fabricate nanostructures on galiumnitrid (GaN) LED since most of the LED manufacturers are using GaN rather than other materials.

One method, based on UV lithography and dry etching, realizes periodic regular cone structures which can be used on LEDs with smooth surfaces. This method doesn't need any expensive material or metal and can be easily transferred to LED wafers of any size. The highest enhancement of PL for a certain size is 78%.

The other method is developed specifically for high power vertically structured LED which is commonly used in industry nowadays. Since the wafer of this type has uneven surface and can not be treated in high temperature or strong acid environments, fabrication mainly based on dry etching is deveoped. Compact stochastic nano pillar structures are formed and PL improvement of over 180% has been achieved.

1.4 Project objectives

Nowadays, LED producers annually spend more than € 1 billion on R & D, most of which is estimated to be geared towards developing more efficient LEDs. The less effective the LED is, the less light it emits and the hotter it gets. Low efficiency also leads to greater energy needs and more heat creates the need for mechanisms to release it.

Suppression of total internal reflection loss (TIR), arising from the abrupt refractive index difference at the interface between LED surface and surroundings, is crucial for enhancing the light extraction efficiency. Surface patterning can effectively reduce TIR loss, thus increase LED efficiency. The usual patterning way in industry is quite simply, yet not very effective in enhancing LED efficiency due to the relatively large structures formed on the surface. Several research results have shown that it would be ideal if the surface texture size can be compared to or even less than the wavelength of the light emitted (400 nm for blue light LED). Before this project started, it is already possible to create such structures, but only with methods that are lengthy and thus costly. And time is a very important factor since the major manufacturers produce 4-5 billion LEDs per month.

For this reason, LED manufacturers today have to live with microstructures that are several times greater than the optimum. LE has developed a solution for large-scale production of nanostructures. The method results in an efficiency improvement of the pre-packaged LED chips, which are estimated to be 3-5%.

Although the structures have already been developed to usable level, for manufacturers to take the solution for themselves, it is necessary to demonstrate it on the individual producer's own LEDs, then to adapt structures to their specific preferences, and finally implement the method in manufacturer's production line.

There are some challenges in the project:

- The method can not be used for realizing structures with any size we want. To meet the requirements of different producers, we need to adjust the method or develop new ways.
- Since the method has never been tried on the manufacturers' LED wafer, the surface, structure and special materials of the wafer will all affect the feasibility of the method.
- When transferring the method to other manufacturing environments, the machines must, however, be aligned.

The project is developed in collaboration between the two parties: LE that has developed the patterning method on GaN LED and DTU Photonics which has major research competence to adapt and further develop the structures in the state of art cleanroom of DTU Danchip.

At the beginning of the project, we continued to simulate the light extraction efficiency of different structures, then communication with Osram AG, Germany was established. In order to form compact periodic structures with desired size and geometry by Osram's request, we successfully developed a new method based on UV lithography and dry etching by the end of August, 2015. The fabrication optimization work was done in the following 4 months. The project was unexpectedly postponed for 3 months due to the failure of the cleanroom facilities. Compared to the application proposal, there is a slight deviation due to the personnel re-organization at Osram. The person we had the contact at the beginning of this project has left the design department. We didn't get the chance to test the structure on their LED wafers. However, another LED producer Shineon, China showed their interest in our method and sent their LEDs to us in December, 2015. The LED was vertically structured with uneven surface, thus UV lithography was no longer applicable here even though we tried to adjust the method in January, 2016. Besides, the wafer couldn't be treated in strong acid or high temperature environment which meant metal mask we usually use couldn't be used directly on it. After 1 month' trial, an improved way of nanostructure patterning using metal mask and mainly based on dry etching technique was developed and tested on Shineon's LED wafers. Project technical and commercial milestones and implementation were given in table 1 and 2.

Table 1. Project technical milestones and implementation

M1 (2015.08)	Develop nanostructure with desired size and geometry by Osram's request **Implementation: Complete**
M2 (2015.10)	Test nanostructures on Osram's LED wafer and do characterization **Implementation: Test on Shineon's LED instead of Osram's**
M3 (2015.11)	White paper on the website and for use in professional publications + DTU publishing and patenting **Implementation: Complete**
M4 (2015.12)	Redesign the website when the documentation and demonstration results are available **Implementation: Complete**
M5 (2016.01)	Implementation to at least one customer's production line **Implementation: Complete with the Swiss customer.**

Table 2. Project commercial milestones and implementation

CM1	
CM2 (2015.09)	Sign non-disclosure agreement with Osram before test our technology on their LED wafer to protect our knowledge **Implementation: Complete with Shineon insteady of Osram**
CM3	
CM4 (2015.11)	Present our technology at LED/nanotechnology exhibition, conference and relevant social media **Implementation: Complete**
CM5 (2016.01)	Generic model agreement draft + 1 contract signed **Implementation: Complete with a Swiss customer with the generic model agreement draft.**

1.5 Project results and dissemination of results

The project's main objective is to develop and demonstrated the method to the world LED producers and attract their attention and interest to use this approach in their production.
To achieve this goal, main activities described in 1.5.1 are included in the project:

1.5.1 Project activities

- Development (Light Extraction & DTU Photonics)

a. Continued optimization of structures form, height, diameter and spacing
b. Adapting the method to various size of wafers
c. Adaptation of the method to different LED structures
d. Continuation of the method to be used on materials other than GaN (e.g. SiC)

- Demonstration (Light Extraction & DTU Photonics)

a. Simulation of different structures efficiency
b. Test on customer wafers

- Documentation (Light Extraction & DTU Photonics)

a. White papers from Light Extraction

b. Research results from DTU Photonics
c. Third-party rating from LED companies

- Marketing (Light Extraction & DTU Photonics)

a. Participation in conferences - like their own submissions
b. Participation in trade fairs - both as exhibitors and partly for the opportunity to seek out and meet with future customers
c. Mention of the solution and / or white papers in professional publications d. Redesign and expansion of website

- Commercialization (Light Extraction)

a. Establishment of generic model agreement for technology transfer
b. Further support of the obtained value
c. Outreach direct sales to manufacturers via its own network
d. Field sales to manufacturers through innovation centers in Shanghai, Seoul and Silicon Valley
e. Implementation of customers' production lines
f. Patenting

1.5.2 Technical Results

For the technical activities, we have done some simulations of different LED structures and optimized structure form, height, diameter and spacing. Moreover, two new ways of patterning for different utilizations were developed in the cleanroom in the project.

- *Compact periodic cone-structure patterning*

For wafers with smooth surface, we have developed a surface compact periodic cone-structure forming method on GaN based on UV lithography and dry etching technique without any costly materials. Although it is only tested on small chips and 2” wafers, it can be easily transferred to 4” and even 6” wafers when they become commercially available. Moreover, test on other materials, e.g. SiC, has also been successfully done. The following are the results of this method.

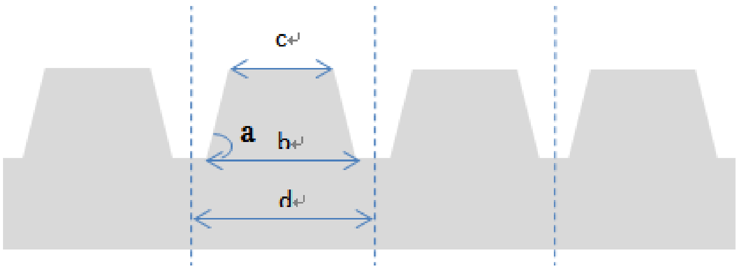

Fig 1. Schematic cross-sectional view of the chip with surface compact cone structures.

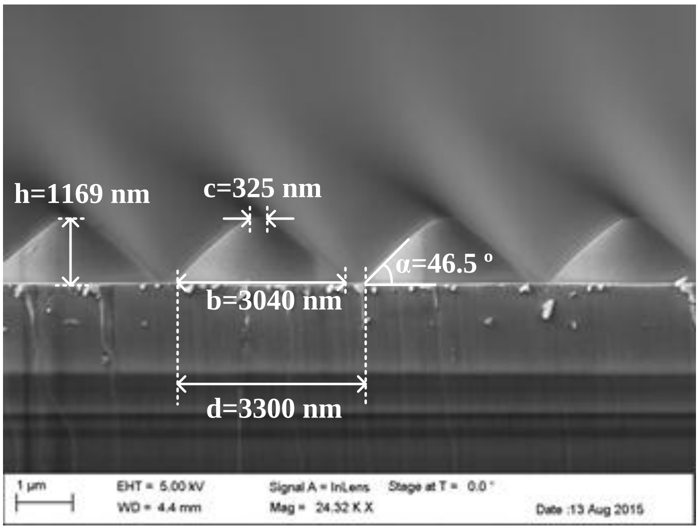

Fig 2. SEM picture of cross-sectional view of the chip with surface compact cone structures.

Figure 1 shows the schematic cross-sectional view of the chip with surface compact cone structures. According to the optimized simulation results, the dimensions and period of the cone structures should meet some requirements. As shown in Fig. 1, c and b are the diameters of the upper and lower surfaces of the cone structures, respectively. d and a are the periodic length and angle of the cones, respectively. Since the resolution of the aligner is 1 μm, the designed gap value "g" between two cones of the resist is designed to be 1 μm and 800 nm. Meanwhile, three different periodic lengths (d=1600 nm, 2600 nm and 3300 nm) were chosen in the fabrication.

As shown in Fig. 2, compact cone structures with designed dimensions of d=3300 nm and g=1 μm were fabricated on GaN. The diameters of the upper and lower surfaces of the cones are 325 nm and 3040 nm respectively. The cone height and angle are 1169 nm and 46.5° respectively.

Two other cone structures on GaN with designed dimensions of d=2600 nm and d=1600 nm were shown in Fig. 3(a)-(b) and (c)-(d), respectively. The dimensions and period of the above three cone structures were displayed in tab. 3 and they well fullfilled the requirements.

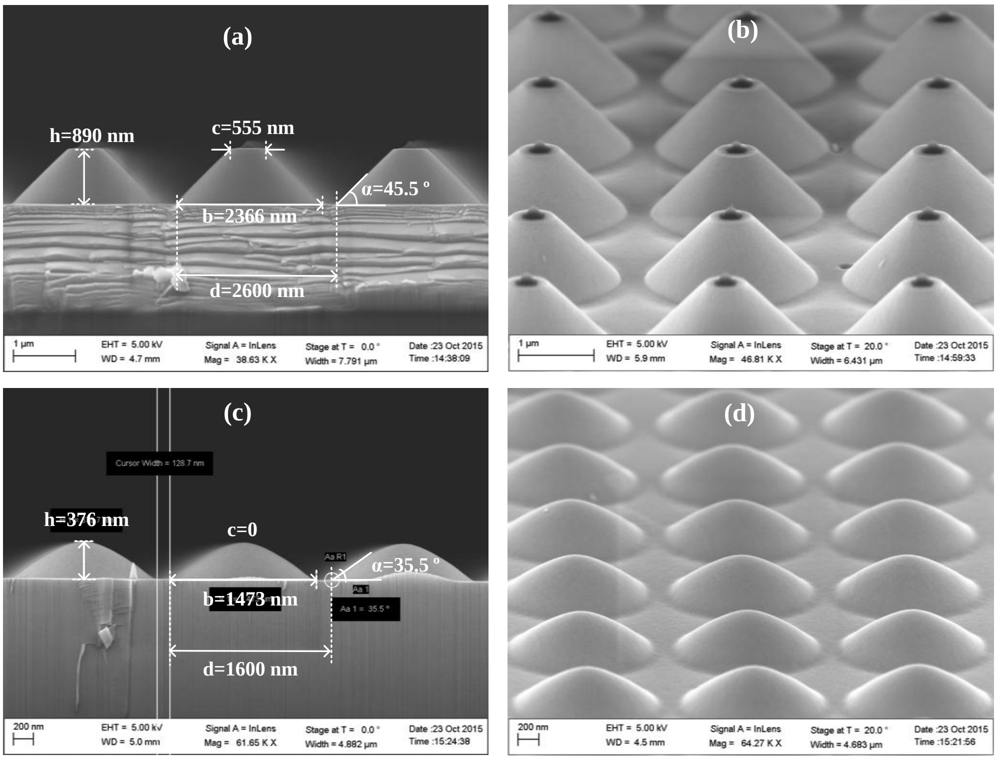

Fig 3. SEM pictures of compact cone structures with dimensions of (a) and (b) d=2600 nm, g=1μm; (c) and (d) d=1600 nm, g=800 nm.

Table 3. cone structures with different dimensions

Designed dimensions	period d (nm)	c & b length (nm)	a (degree)	height (nm)
G1000D3300	3300	325 & 3040	46.5	1169
G1000D2600	2600	555&2366	45.5	890
G800D1600	1600	0 & 1473	35.5	376

In order to evaluate the PL enhancement of the GaN chips after surface treatment using our method, cones with different etching depth were fabricated and the PL spectra of the chips were measured and compared. SEM pictures of compact cone structures with heights of 575 nm, 923 nm and 1169 nm were shown in Fig. 4(a)-(c), respectively. The designed period and gap were 3300 nm and 1 μm, respectively despite the different heights. Compared with the LED without any surface treatment, the measured PL at the peak wavelength of the ones with the above three cone heights structures were enhanced obviously by 47%, 78% and 68%, respectively, as we can see in Fig. 5. The optimized cone height in this case is about 900 nm.

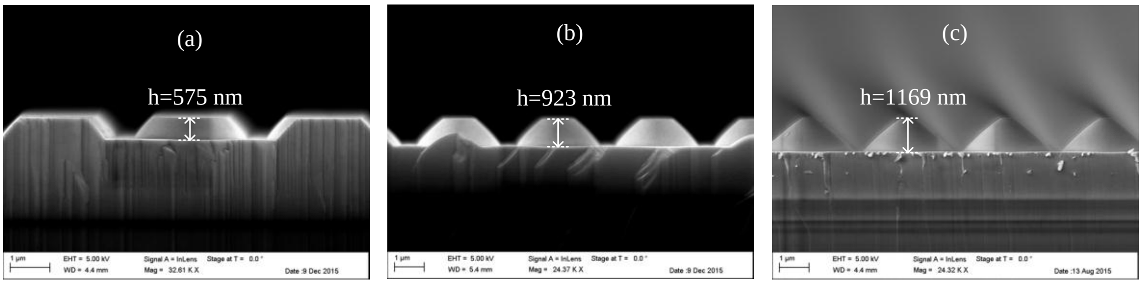

Fig 4. SEM pictures of compact cone structures with heights of (a) 575 nm, (b) 923 nm and (c) 1169 nm. The designed periods and gaps of the three cones are 3300 nm and 1 μm, respectively.

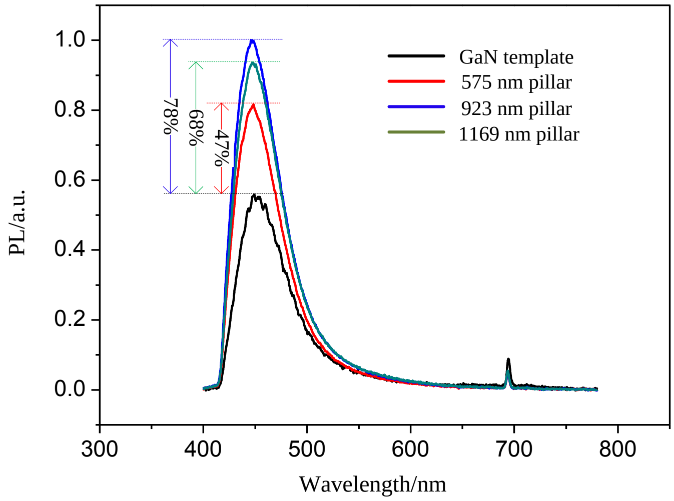

Fig 5. Measured PL spectra of the GaN chips with/without surface compact cones structures.

SEM pictures of compact cone structures with heights of 166 nm, 209 nm, 262 nm and 322 nm were shown in Fig. 6(a)-(d), respectively. The designed period and gap of the four different height cones were 1600 nm and 800 nm, respectively. Compared with the LED without any surface treatment, the PL of the ones with the above four cone structures were enhanced by 13%, 19%, 47% and 32%, respectively, as we can see in Fig. 7. The optimized cone height in this case is about 260 nm.

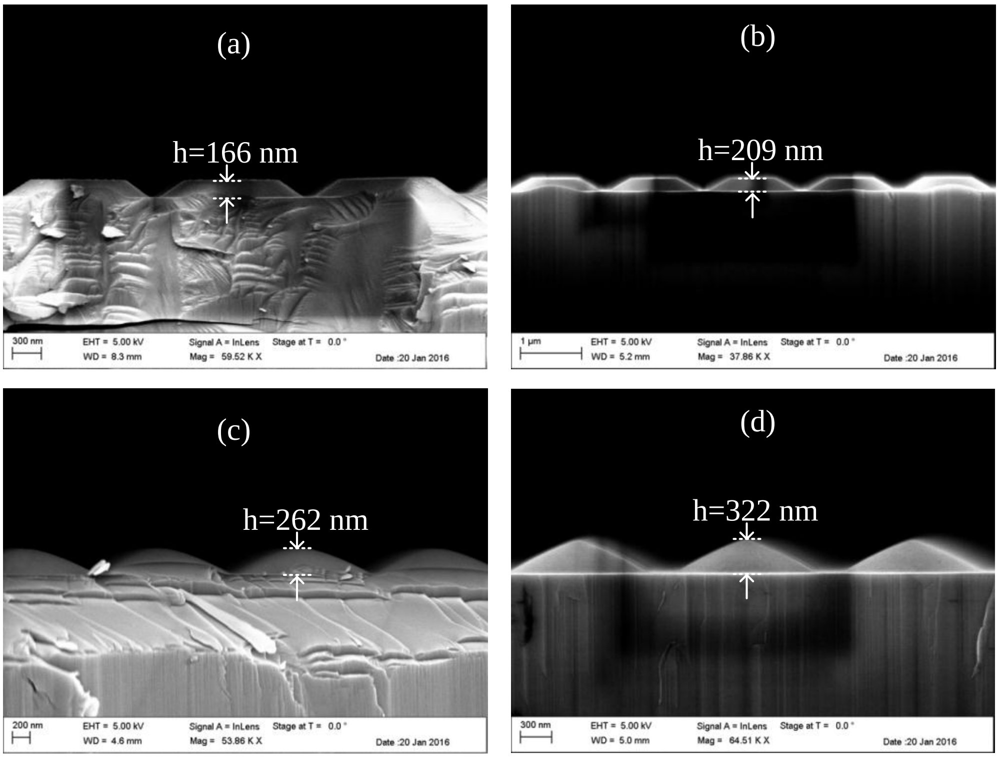

Fig 6. SEM pictures of compact cone structures with heights of (a) 166 nm, (b) 209 nm, (c) 262 nm and (d) 322 nm. The designed periods and gaps of the three cones are 1600 nm and 800 nm, respectively.

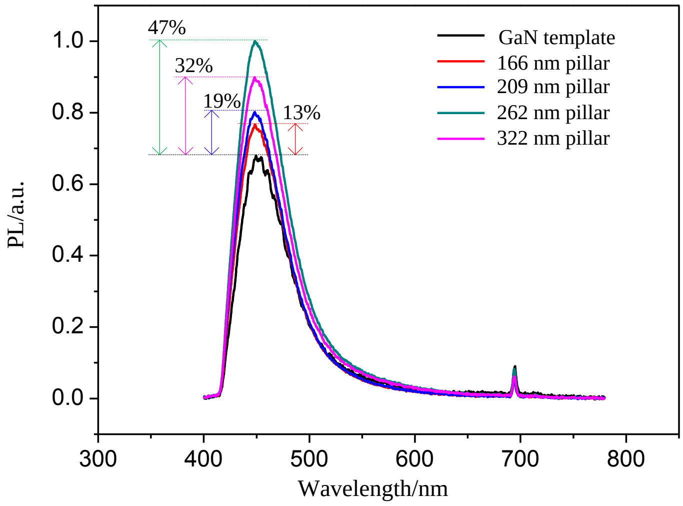

Fig 7. Measured PL spectra of the GaN chips with/without surface compact cones structures.

➤ *Compact stochastic nano pillar-structure patterning*

The other method was developed especially for vertically structured LED with uneven surface to form compact stochastic nano pillar structures because the first method could not be applied in this case. The height of the pillars varies from 100-200 nm and the width varies in dozens of nano meters, as shown in Fig 8. The measured PL spectral in Fig. 9 shows an enhancement of 185% at the peak wavelength.

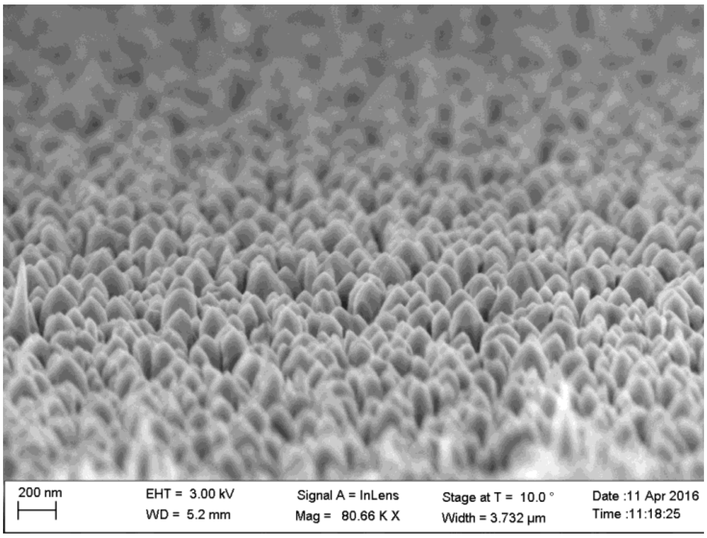

Fig 8. SEM picture of tilted view of compact stochastic pillar structures.

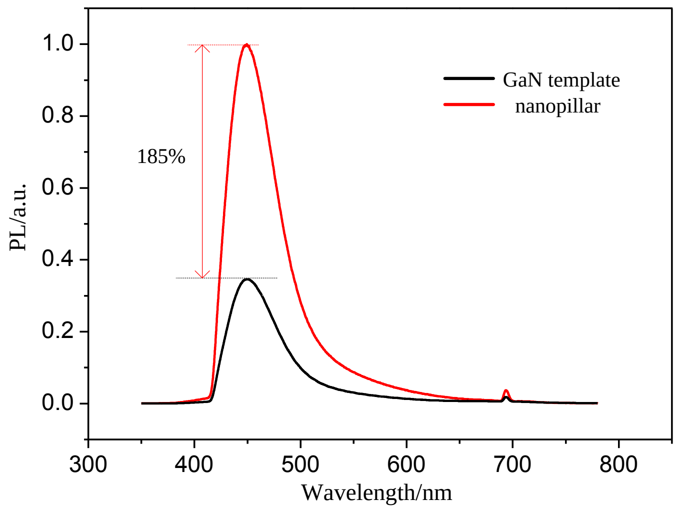

Fig 9. Measured PL spectra of the GaN chips with/without surface compact nanopillars.

We have tested our method on Shineon's LED and a PL enhacement of 50% was achieved. Now the LED was sent back to Shineon for their post processing, measuring and rating.

Although the project was delayed due to the failure of the cleanroom facilities and we met some unexpected situations in the collaboration with Osram, we realized all the technical objectives in this project and the relevant results had been put on LE's website[1].

1.5.3 Commercial Results

The project results will be disseminated through the development of one or two white papers that describe application, effectiveness and economy of nano structures, partly through the publications.

Both project participants are associated in a pan-European research project "Fluorensic SiC", providing for the development of new type white LED. The participants of the project come from eight European research institutions and companies from Germany, Norway, Portugal and USA. Although LE has no economic return, it can build networks with all these participants for the exchange of knowledge and skills.

Publication:

1. Y. Ou, K. Wu, D. Iida, A. Fadil and H. Ou, "Luminescence enhancement of green nGaN/GaN nanopillar LEDs," The 3rd International Conference on Light-Emitting Devices and Their Industrial Applications, Yokohama, Japan, April (2015).
2. Y. Ou, A. Fadil and H. Ou, "Fabrication of InGaN/GaN nanopillar light-emitting diode arrays," The 3rd European-Asian Workshop in Light-Emitting Diodes, Copenhagen, Denmark, March (2015).
3. W. Lu, Y. Ou and H. Ou, "Transmittance enhancement in 6H-SiC with nanocone structures," The 3rd European-Asian Workshop in Light-Emitting Diodes, Copenhagen, Denmark, March (2015).
4. "Surface nanostructuring and passivation for light coupling at the interface of SiC based optoelectronic devices", NACSIC Workshop, Oslo, Norway, May (2015)[2].
5. H. Ou, Y. Ou, W. Lu, A. Fadil, A. Argyraki, M.Kaiser, P. Wellmann, V. Jokubavicius and M. Syväjärvi, "A new type of white light-emitting diode light source basing on fluorescent SiC", 12th China International Forum on Solid State Lighting, SLCHINA 2015, Shenzhen Convention & Exhibition Center, China, November (2015)[3-4].
6. H. Ou, W. Lu, Y. Ou, V. Jokubavicius, M. Syväjärvi, P. Schuh, P. Wellmann, Y. Iwasa and S. Kamiyama, "Passivation of surface-nanostructured f-SiC and porous SiC", 4th International Workshop on LEDs and Solar Applications, Nagoya, March (2016)[5].

Dissertation:

June 2015: Meeting with Invest in Denmark (Shanghai)
June 2015: Attend the Security Document World Conference and Exhibition (SDW2015), UK
April 2015: Meeting with Danish Innovation Center (South Korea)
April 2015: Attend the 3rd International Conference on Light-Emitting Devices and Their Industrial Applications (LEDIA '15), Japan
March 2015: Attend the 3rd European-Asian workshop on Light-Emitting Diodes, Denmark
January 2015: Meeting with Danish Innovation Center (Silicon Valley)

Light extraction participated in the 12th China International Forum on Solid State Lighting, SLCHINA 2015, Shenzhen Convention & Exhibition Center, China. The forum gathered the main players in the LED field both from industrial and research institute. LE contributed an invited talk at the forum and attracted quite a few potential customers, including ShineOn.

The solution was mentioned on a Chinese website[6].

Export and employment:

LE has already had successful direct sale to one customer (export to another country). The price model includes two parts: for pure research and development and for production. If the customer is going to use our product in their product, they will pay one-time license fee.

One postdoc from DTU Fotonik and one R&D engineer from LE were hired to carry out the technical work in the project.

1.6 Utilization of project results

1.6.1 Marketing plan:

Since the nano structure patterning methods develped in the project result in an obvious enhancement of PL of GaN LED. Both LE and DTU expect to sell the method to the LED producers. The method will be marketed globally by three primary channels: publicity in the specialized press, participation in conferences and trade shows, and direct contact with the individual producers. The sale process is expected to follow this template:

- Introductory mail (own network) or introduction via innovation centers
- Conference call
- Conclusion of secrecy agreement
- Production of structures on the customer's own wafers.
- Wafers returned and the customer evaluate the effectiveness
- If still interested, then negotiated price and terms for the upcoming technology transfer.
- The method is implemented on the customer's production lines
- Light Extraction develop further and then sells optimized solution for the same customer.

The process is designed so to minimize the risk of the two biggest barrier - namely, risk of disclosure of business critical knowledge and the risk of adverse effects on the customer's existing production - destroying the business opportunity. The order also has the advantage that both parties know the exact efficiency improvement to negotiate price. That should make it easier to find a price that is satisfactory to both parties.

1.6.2 Competition:

The project meets the greatest competition from the companies' own development departments. There are few and small other companies trying to offer a similar solution, and as far as project participants' knowledge, these solutions all suffer from being too slow - and thus expensive - to be relevant to the industry. Our methods are situable for large-scale production without any costly material which meet the requirements of the industry.

1.6.3 Market potential:

The market for LED chips is over € 10 billion, and covered by over 50 producers, of which the top 10 possess about 70%. The producers are primarily located in the Far East.

Manufacturers typically allocate 10% of their turnover to R&D. An insider in the industry estimate that 60-70% of R&D activities are aimed at efficiency. The project expects to contribute an improvement of efficiency equals to what the industry achieved in one year. In that sense, one can assert that there is a potential market of several billion kroner.

However, it is certainly not the case that it will be possible for the project to collect the amount at the levels. However, the figures illustrate that there should be a quite interesting market opportunity.

The project's advantage is that the method is already expected to be competitive with the existing solutions. It is also expected to be of advantage for manufacturers to relatively easily get to test the effectiveness of the method on their own LEDs before they need to spend resources to negotiate and implement.

1.6.4 Commercial activities

LE is in the process of selling. The buyer is from Switzerland.
LE has signed NDA with one Chinese LED manufacture, has applied our technology on their wafers, and is waiting for their test results. After receiving positive test results from the chinese LED manufacture, LE is in a very good position to sell the license to it.

1.6.5 Patent

During the project period, one PCT application (201380033611X) was filed in China. One new patent could be filed. But limited by the resource LE has, we will keep it as business secret at the current stage.

1.6.6 Energy-policy objectives

There are many ways to describe the effect of more efficient light sources. 19% of the global electricity consumption is used for lighting. Konsulenthuset McKinsey has calculated that the shift to LED is the most cost effective way when it comes to reducing anthropogenic emissions of CO_2. From the financial's perspective, it means a global annual saving of almost

1,000 billion kroner. In the end, it is expected that both manufacturers and end customers increasingly switch to LED.

The project will help to accelerate the shift to LED. First, by helping to improve buyers' economy when selecting the light source regardless of the choice made in the supermarket or for professional use, and partly by enhancing efficiency to increase the number of applications and thus contribute to even greater dissemination of LED.

We can not calculate the actual environmental impact that our contribution to the LED market, but with aforementioned key figures in mind, we can deduce that if our solution with new applications can contribute to the growth of the LED market one percentage point higher than expected every year, up to 2020, this will correspond to a growth in the value of the overall market of approximately 85 billion danish kroner. This calculation is made only for illustration. We do not have the knowledge needed to make an approximate correct calculation. Since the method is 'just' a change of a few process steps in the production of LEDs, and the only effect on LEDs is that they are more effective, the method requires no adjustments to the Danish energy system. To the extent that the method helps to accelerate the adaption of LED and to the extent that it improves LED's efficiency, it contributes directly to the achievement of the Strategy for Energy Efficiency.

1.7 Project conclusion and perspective

Together with DTU Photonics, Light Extraction has invented two new methods of compact nano structure patterning on GaN wafer, resulting in an improvement of more than 50% in photo luminescence. The methods can be used, respectively, on LEDs with smooth surface and/or vertical structures. Both of them are suitble for large-scale production in industry. Test of the methods on commercial LEDs has been done and the follow-up work is in progress.

he demand for more efficient LEDs come especially from producers' B2B-customers. These customers are partly manufacturers of various luminaries, partly manufacturers of televisions, tablets and phones etc., where LED are used to illuminate screens from behind. The higher the efficiency is, the less the LEDs to be used and the cheaper the products become. Moreove, LEDs with higher efficiency open the doors to new applications, such as car headlight, outdoor lighting and ultraviolet light emitting, which may be used in disinfection of air and fluids.

The demand for more powerful and cheaper LEDs can be clearly seen in the development, where the price of LED falls 30% per year while the efficiency increases.

There are over 50 LED manufacturers in the world, and although they each have their different ways of producing LEDs, they are all facing the same technical challenge in relation to the structure patterning of surfaces. Our technology can help them solve this problem and increase the efficiency of LED. Futhermore, technology development is always needed for the fast changing LED structures and packages to meet requirements for different applications from company to company.

Annex

[1] http://lightextraction.com/
[2] http://www.sintef.no/en/events/nacsic/
[3] http://www.lightingchina.com/news/44874.html
[4] http://www.sslchina.org/en/
[5] http://www.4nanoenergy.fotonik.dtu.dk/News-and-Events/4th-International-workshop-on-LEDs-and-solar-applications
[6] http://www.china-led.net/news/201507/02/29464.html