The 5th International Workshop on LEDs and Solar Applications

September 13-14, 2017

Copenhagen, Denmark

Organizers:

Haiyan Ou; Yiyu Ou

DTU Fotonik, Technical University of Denmark

Preface

The 5th international workshop on LED and solar applications aims at promoting scientific exchanges in the field of novel materials for LEDs and photovoltaics, LED technologies, PV technologies, and industrial applications of LEDs. It also provides a platform for inspirations and collaborations on research and development of LEDs and PVs. Compared to the previous workshops, this one sees increasing number of contributions on the LED applications, such as application of LEDs in visible light communications and life science etc. These new application trends hopefully also provide new opportunities to broaden the research areas on materials and devices.

The 1.5 day workshop is financially supported by the ongoing project “A new type of white light-emitting diode using fluorescent silicon carbide (LEDSiC)”, Innovation Fund Denmark (No. 4106-00018B).

Program

Place: Meeting room 'Charlie', S-huset, building 101, DTU Lyngby campus
Anker Engelunds Vej 1, 2800 Kgs. Lyngby

September 13th, 2017

Session I: LED technologies
(Chair: Prof. Haiyan Ou)

13:30~13:50	Welcome address (Haiyan Ou)
13:50~14:15	Satoshi Kamiyama, Meijo University, Japan "How to increase the emission efficiency of fluorescent SiC?"
14:15~14:40	Kai Tang, SINTEF Materials and Chemistry, Norway "Liquid Phase Epitaxial Growth of Al-doped f-SiC for White Light-Emitting Diodes"
14:40~15:40	Break and poster session
15:40~16:05	Weifang Lu, Technical University of Denmark, Denmark "Effect of dopants on the morphorlogy of porous SiC"
16:05~16:30	Yi Wei, Technical University of Denmark, Denmark "Detection of effective recombination centers in fluorescent SiC using thermally stimulated luminescence"
16:30~16:55	Li Lin, Technical University of Denmark, Denmark "Current Spreading Layer with High Transparency and Conductivity for near-ultraviolet light emitting diodes"

September 14th, 2017

Session II: Novel materials for LEDs and PV
(Chair: Prof. Paul Michael Petersen)

09:00~09:25	Mikael Syväjärvi, Linköping University, Sweden "New applications areas of silicon carbide"
09:25~09:50	Sara Engberg, Technical University of Denmark, Denmark "Effect of alkali elements in thin-film Cu_2ZnSnS_4 solar cells produced by solution-processing"
09:50~10:15	Meng Liang, Chinese Academy of Science, China "Ohmic contacts with high reflectivity to p-GaN by inserting ITO interlayer"
10:15~10:40	Klaus Rosenfeldt Jakobsen, Innovation Fund Denmark "TBD"

10:40~11:00	Break and poster session

Session III: Industrial application of LEDs
(Chair: Prof. Satoshi Kamiyama)

11:00~11:25	Lars Dittmann, Technical University of Denmark, Denmark “System design for visible light communication”
11:25~11:50	Ngoc Mai Nguyen, University of California, Berkeley, United States “How to treat alzheimer with new LED light technology”
12:00~13:20	Lunch
13:20~13:45	Paul Michael Petersen, Technical University of Denmark, Denmark “New dental applications with LEDs”
13:45~14:10	Carlo Volf, Psychiatric Center Copenhagen, Rigshospitalet, Denmark “Treating depression using LED and daylight”
14:10~14:35	Jakob Hildebrandt, Technical University of Denmark, Denmark “Light Intervention for athletes”
14:35~15:00	Break and poster session

Session IV: PV technologies
(Chair: Prof. Mikael Syväjärvi)

15:00~15:25	Michael Schöler, Erlangen University, Germany “Evaluation of defects in 3C-SiC grown by Sublimation Epitaxy using 3C-SiC-on-Si seeding layers”
15:25~15:50	Peter Poulsen, Technical University of Denmark, Denmark “Plateau Sun Hub, Solar powered table for charging phones and playing music”
15:50~16:15	Joanna K. Symonowicz, Technical University of Denmark, Denmark “Novel Field test design and initial result for AC and DC characterization for PV-panels”
16:15~16:40	Gisele Benatto, Technical University of Denmark, Denmark “Development of outdoor luminescence imaging for drone-based PV array inspection”
16:40~17:05	Ashwin Hariharan, Technical University of Denmark, Denmark “Application of quantum well photovoltaic cells for thermophotovoltaic applications”
17:05~17:30	Closing remarks and poster award (Haiyan Ou)

Content

Effect of dopants on the morphology of porous SiC

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***Abstract*—Porous SiC samples with different doping level were fabricated and investigated by using anodic oxidation method. The morphology of the porous structures was explained by space charge layer width, which was affected by the free carrier-dopants concentration.**

Keywords—porous; dopants; space charge layer; morphology

I. INTRODUCTION

Porous SiC is a high-potential sensing material due to its large internal surface area and high activity in surface reactions [1]. The porous SiC structures can accommodate the strain and threading dislocations to obtain high quality epilayers [2]. In addition, the porous SiC yields remarkable luminescence, which may expand their application to the field of light-emitting diodes [3-5]. The optical and electronic properties of porous SiC are mainly determined by the morphological properties of porous structures [6, 7]. In this work, the effect of dopants on the morphology of porous SiC has been investigated and its influence on the luminescence properties was discussed.

II. RESULTS AND DISCUSSIONS

Two porous samples a and b were fabricated by using anodic oxidation method. The anodic oxidation was carried under a pulsed current of 1.25 mA in a HF diluted solution with UV illumination for 960 min. Sample a was prepared on lab-grown pure 4H-SiC, while sample b was fabricated on 4H-SiC substrate highly doped with boron and nitrogen. The thickness of porous layer for samples a and b is 7.9 μm and 16 μm, respectively. Obviously, the etching rate for sample a is lower than that in sample b with high doping level of B and N.

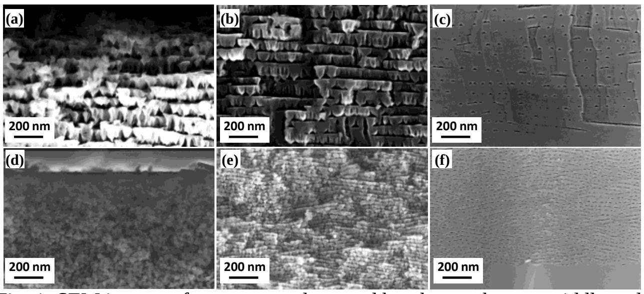

Fig. 1. SEM images of porous samples a and b: taken at the top, middle and bottom area of the porous layer.

The cross-sectional SEM images in Fig. 1(a)-(c) and (d)-(f) show the SEM images of top, middle and bottom layer in porous sample a and b, respectively. One can see that the pore size of the top layer in sample a (50 nm) is larger than that in sample b (20 nm), while the density of pore is much lower. This phenomenon might be explained by the dependence of space charge layer width on the substrate resistivity (doping level). During anodic oxidation, the charge near the surface of the SiC substrate usually redistribute, resulting in three important regions of the potential drop are distinguished: the space charge region in the SiC bulk due to ionized donors, the immediately adjacent layer of ions in the solution, and the diffuse ionic layer in the electrolyte. Theoretically, the space charge layer can be estimated according to the Poisson equation ($L = \sqrt{\frac{2\varepsilon_{sc}\varepsilon_0\phi_{sc}}{eN_d}}$, ϕ_{sc} potential of space charge, free carrier-dopants concentration N_d , $\varepsilon_{sc} \approx 10$).

Therefore, the higher concentration of dopants in SiC substrates will lead to the formation of smaller pores as well as a smaller spacing between the pores. On the other hand, because the porous layer were formed at the same conditions, i.e, the same total charge was injected into the samples, the etched off material from both samples was same during anodic oxidation process. Thus, smaller pore diameters and thicker porous layer are observed in SiC substrates with B-N dopants.

III. SUMMARY

In conclusion, the dopants in SiC substrate have significant influence on the morphology of porous structures. It is explained that the observed structures were related to the space charge layer (potential distribution) near the SiC/electrolyte interface. The pore diameter decreased with a high doping level, due to decreased width of space charge layer.

ACKNOWLEDGMENT

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Ohmic contacts with high reflectivity to p-GaN with ITO interlayer

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***Abstract*—a metal stack of Ni/Ag/Pt/Au with a 1nm-thick ITO (indium-tin-oxide) interlayer which formed highly reflective and ohmic contacts to p-GaN had been investigated.**

Keywords—GaN, Indium-Tin-oxide(ITO), ohmic contacts, reflectivity, light emitting diodes(LEDs)

I. INTRODUCTION

In the present study, p-ohmic reflectors for GaN-based LEDs were formed on p-GaN by a metal stack of Ni/Ag/Pt/Au with a very thin ITO interlayer. A thin ITO layer was used as an interlayer between Ni/Ag/Pt/Au and p-GaN to improve conductivity of p-type contacts, while the interlayer was so thin that its effect on the light absorption could be negligible. This configuration can decrease the annealing temperature to overcome the deterioration of the ohmic behavior and optical properties during the high-temperature annealing. And then the metal stack was given annealing cycles from 300 to 600℃. The results indicated that p-ohmic reflectors with 1nm-thick ITO interlayer obtained good performance after annealing under a low temperature of 300℃. This indicated that the configuration is a promising p-ohmic reflector for the high-power GaN-based LED in Flip-chip or vertical structure.

II. FIGURES AND TABLES

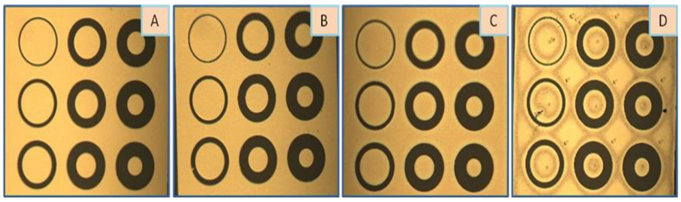

Fig. 1 Optical surface images(×100) of p-ohmic reflector with ITO interlayer after annealing at 300℃(A), 400℃(B), 500℃(C), 600℃(D)

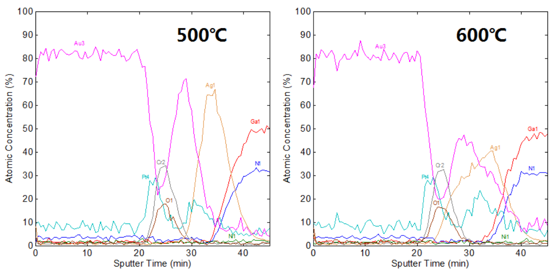

Fig. 2Element depth profiles of p-ohmic reflector with ITO interlayer after annealing at 500℃ (left) and 600℃ (right)

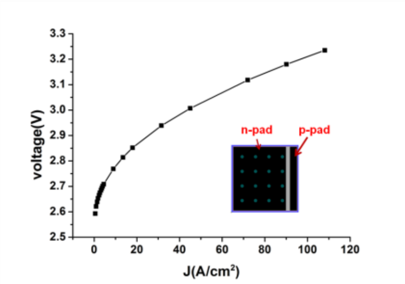

Fig. 3 Characteristics of the FCLEDs with the p-ohmic reflector

III. SUMMARY

In summary, we have presented highly reflective Ni/Ag/Pt/Au ohmic contacts to p-GaN with 1nm-thick ITO interlayer. The SCR of the sample which annealed at 300℃ in N2 for 10min reaches $2.16\times10^{-5}\Omega\cdot cm^2$, while the optical reflectance of this sample is 84% at wavelength of 460nm. The thin ITO layer plays a key role in lowering the annealing temperature and makes the p-ohmic reflectors having the good electrical and optical properties. The FCLEDs with the configuration are fabricated, and forward voltages are as low as about 2.9V at injection current density of $31A/cm^2$.

ACKNOWLEDGMENT

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Current Spreading Layer with High Transparency and Conductivity for near-ultraviolet light emitting diodes

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***Abstract*— Transparent conductive aluminum-doped zinc oxide (AZO) layer was deposited on GaN-based near-ultraviolet (NUV) light emitting epitaxial wafers as current spreading layer by a sputtering process. Efforts were made to improve the electrical properties of AZO in order to produce ohmic contact.**

Keywords— near ultraviolet light emitting diodes; transparent conductive current spreading layer; aluminum-doped zinc oxide

I. INTRODUCTION

Transparent conductive current spreading layer (CSL) is more advantageous in improving light extraction efficiency for NUV LEDs than conventional Ni/Au and indium tin oxide (ITO) is a widely used transparent conductive CSL for LEDs. However, ITO is expensive because of its In-content [1] while AZO is a well-known alternative candidate to ITO since it has similar electrical and optical properties but is low-cost, nontoxic and more stable at high temperatures [2]-[3]. There has been very few research reported on using AZO-based reflective CSL for GaN-based NUV LEDs with flip-chip configuration. Hence, this work focuses on modifying electrical behavior of AZO on p-GaN to produce ohmic contact. In the future, AZO-based CSL will be used together with Al reflector to form AZO-based reflective CSL in flip-chip NUV LED application.

II. EXPERIMENTS AND RESULTS

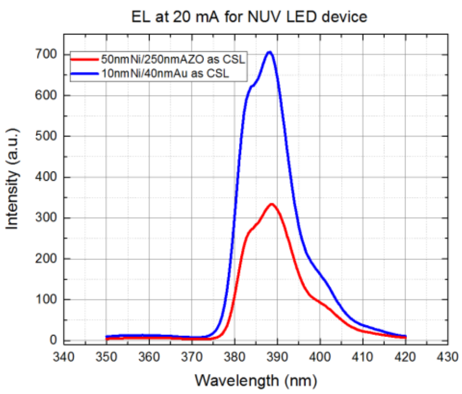

Fig. 1. EL of LEDs with different CSLs

Six types of AZO-based CSLs including as-deposit 110nm AZO, annealed 110nm AZO, annealed 5nm Ni/ as-deposit 110nm AZO, annealed 5nm Ni/ annealed 110nm AZO, annealed 5nm Ni/as-deposit 250nm AZO and annealed 5nm Ni/annealed 250nm AZO were fabricated on the mesas of NUV LED wafers. Ni and AZO were deposited by e-beam evaporation and DC sputtering respectively. After deposition, Ni was annealed in air at 550 ℃ for 5 min. 110nm AZO and 250nm AZO were annealed at 550℃ for 5min in N_2 and at 800℃ for 1min in N_2 respectively.

I-V measurement was carried out on the 6 types of CSLs. In the end, annealed 5nm Ni/annealed 250nm AZO gives the best I-V properties since it almost presents ohmic behavior. One NUV LED device with annealed 5nm Ni/annealed 250nm AZO as its CSL was fabricated and its electroluminescence (EL) graph together with that of an LED using conventional Ni/Au CSL were displayed in Figure 1. The EL intensity of the LED with Ni/AZO is weaker than that of the LED with Ni/Au due to the high specific contact resistivity of Ni/AZO.

III. SUMMARY

I-V behavior of CSLs with different compositions, AZO thicknesses and annealing conditions were tested and compared. The annealed 5nm Ni/annealed 250nm AZO presents the best electrical properties. Afterwards, an NUV LED with transparent conductive Ni/AZO was fabricated. Although EL can be observed, its intensity is still lower than that of the LED with Ni/Au. This is because the contact between Ni/AZO and p-GaN is not perfect ohmic indicating much larger specific contact resistivity than that of Ni/Au. Although Ni/AZO possesses higher transparency than that of Ni/Au, its electrical behavior still needs further modification.

ACKNOWLEDGMENT

This work was supported by Innovation Fund Denmark (project No 4106-00018B).

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Liquid Phase Epitaxial Growth of Al-doped f-SiC for White Light-Emitting Diodes

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Keywords— fluorescent silicon carbide, LPE growth, Al-doped, equilibrium analysis, growth rate

The present paper focuses on our recent experimental results of growing a new type of compound semiconductor crystal, i.e. fluorescent silicon carbide (f-SiC), using the liquid solution phase epitaxial (LPE) technology. This new type of f-SiC based white LEDs (WLEDs) represents higher luminous efficiency, better light quality and longer lifespan, compared to the current yellow phosphor based white LEDs.

Liquid phase epitaxy technology can yield a high crystalline quality in terms of structural perfection owing to the fact that it is a near equilibrium crystalline growth process. In addition, the technological equipment required for LPE is relatively inexpensive. The fundamental backgrounds for LPE growth of Al-doped 6H-SiC are first introduced and elaborated by new thermodynamic and crystal growth models. Based on theoretical analyses, the new designed experimental apparatus is then constructed. The experimental results are presented and discussed. Since operational temperature of LPE growth is much lower than that currently used in physical vapour transport (PVT) process, it is expected to save the energy consumption for SiC crystal growth.

Effect of alkali elements in thin-film Cu_2ZnSnS_4 solar cells produced by solution-processing

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The effect of adding Li, Na, and K to Cu_2ZnSnS_4 nanoparticle thin-film absorber layers has been investigated. Among them, K is found to enhance grain growth as well as increase the photoluminescence of the films.

Cu_2ZnSnS_4; nanoparticles; solution-processing; thin-films; photovoltaics

Thin-film photovoltaics consisting of $Cu_2InGaSe_2$ and CdTe as the absorber layer exhibit high power conversion efficiencies of 22.6% and 22.1%, respectively, and are already available on the solar panel market, [1]. However, due to the relatively poor material abundance of In, Ga, and partly Te, and the toxicity of Cd, it is crucial to look for substituting compounds, and Cu_2ZnSnS_4 (CZTS) is one promising alternative. CZTS has reached a record efficiency of 9.5%, it has a high absorption coefficient of >10^4 cm^{-1}, and a direct band gap of 1.45 eV, which additionally would make it an interesting material for a tandem solar cell with silicon, [2].

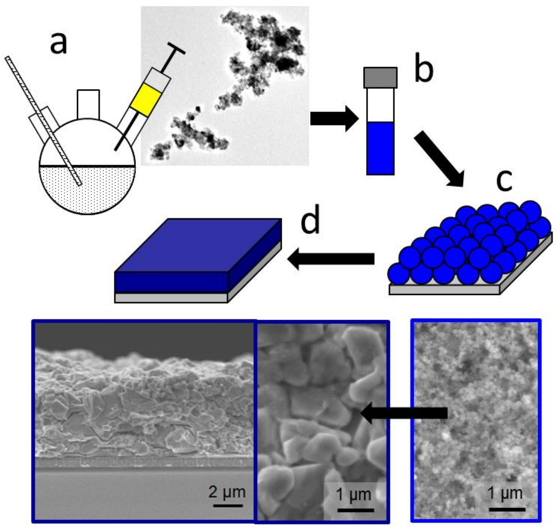

Fig. 1. Solution-processing route for fabrication of CZTS nanoparticle thin-film absorber layers in the top, and scanning electron microscopy (SEM) images displaying as-deposited films and annealed films in the bottom, adapted from [3]. The solution-processing route includes (a) nanoparticles synthesis, (b) ink formulation, (c) thin-film deposition, and (d) annealing. We find that it is necessary to incorporate an alkali element in the film during annealing to achieve grain growth.

The work presented in this talk concerns CZTS thin films fabricated from nanoparticle inks, which should offer large-area deposition through inexpensive means (Fig. 1(top)). One challenge faced in this field of solution-processing is to achieve a film morphology that is similar to vacuum deposited films; annealed nanoparticle thin films are commonly small-grained and porous, [4,5]. As grain boundaries are believed to be a site for recombination for the charge carriers, larger and denser grains are desired.

We have studied the incorporation of various alkali elements, *i.e.* Li, Na, and K, directly in the CZTS nanoparticle inks, and studied their effect on grain growth, photoluminescence, and optical band gap, [6]. Interestingly, K and in some cases Na enhance sintering and aid in creating a dense thin film. Without adding an alkali element, the morphology of the annealed film is similar to the as-deposited film in Fig. 1(c). However, when K or Na is introduced, the film structure changes as displayed in Fig. 1(d). The samples are furthermore characterized by Raman spectroscopy and X-ray diffraction, and the composition is determined by energy-dispersive X-ray spectroscopy.

The advantageous effect of alkali elements on CZTS thin-film solar cells has been documented before, however not for nanoparticle samples.

ACKNOWLEDGMENT

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Evaluation of defects in 3C-SiC grown by Sublimation Epitaxy using 3C-SiC-on-Si seeding layers

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***Abstract*— The cubic polytype of SiC suffers from high defect densities that hinder the realization of reliable devices. By variation of growth parameters like temperature and growth time we conducted a series of experiments and characterized these layers with regard to the protrusion density and the stacking fault density.**

***Keywords*— 3C-SiC; sublimation epitaxy; defects; protrusions; stacking faults**

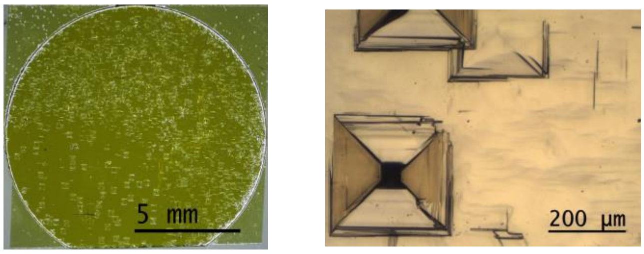
I. INTRODUCTION

The cubic polytype of SiC shows technological challenges for the bulk-growth such as a high supersaturation, a silicon rich gas phase and a high vertical temperature gradient. Moreover, 3C-SiC suffers from high defect densities that hinders the realization of applications. However, promising opportunities for electronic devices such as MOSFETs can be predicted for high quality material due to the high electron mobility and the wide bandgap. Therefore, considerable efforts are made to reduce defects in 3C-SiC.

We have developed a transfer method [1] for high quality 3C-SiC-on-Si seeding layers (grown by CVD) to SiC carriers to use them in sublimation epitaxy (SE). By variation of growth parameters like temperature and growth time we conducted a series of experiments growing layers of 3C-SiC with various thickness. Later on we characterized these layers using KOH etching and optical microscopy to evaluate the morphology of the surface and the stacking fault (SF) density. In our previous work we already described defects on the surface in the shape of four-sided pyramids featuring the (111) planes. The origin of these protrusion defects can be assigned to the nucleation step during the initial growth of 3C-SiC-on-Si in the CVD process.

II. EXPERIMENTAL AND RESULTS

In Figure 1(a) a 3C-SiC layer with a diameter of 12.7 mm is shown that was grown in a 2 inch sublimation epitaxy setup realized in a standard inductively heated PVT-reactor. Figure 1(b) depicts the pyramid-shaped protrusion defects.



(a) (b)

Fig. 1. 3C-SiC layer with a diameter of 12.7 mm grown by sublimation epitaxy (a) and magnified image of the protrusion defects (b)

KOH etching at 530 °C for 5 min and optical microscopy was performed to evaluate the stacking fault density. In Figure 2 the SF-density at the sample surface is shown for varying thickness of 3C-SiC.

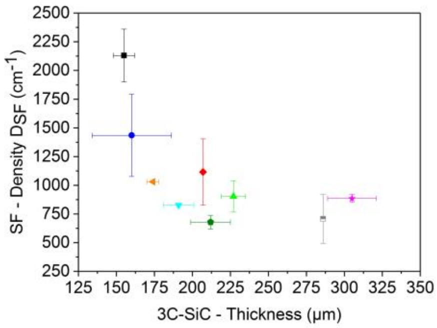


Fig. 2. Stacking fault density plotted versus the thickness of as-grown layers showing a decreasing trend for increased thickness.

III. SUMMARY

Using our transfer process and the subsequent SE growth we can show that the predetermined number of protrusions on the surface remains the same. Furthermore, by etching the (100) surface of our samples using KOH, we can observe a decrease in the density of stacking faults with increasing 3C-SiC thickness.

REFERENCE

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Detection of effective recombination centers in fluorescent SiC using thermally stimulated luminescence

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***Abstract*— Two n-type 6H fluorescent SiC (f-SiC) samples have been characterized using thermally stimulated luminescence (TSL) spectroscopy, where the dominant carriers recombination regime has been found via the numerical simulations.**

***Keywords*— 6H SiC; TSL; re-trapping**

I. INTRODUCTION

Fluorescent silicon carbide (f-SiC) is the emerging material for white light-emitting diodes (LED) thanks to its high conversion efficiency from near-ultraviolet (NUV) to visible light [1-2]. In order to get the deep understanding of how the donor-acceptor pair (DAP) recombination regime in f-SiC will affect its internal quantum efficiency (IQE), it is crucial to find out the specific site-dependent dominance of the DAP recombination in f-SiC. In this paper, two different n-type 6H f-SiC samples were characterized by thermally stimulated luminescence (TSL) spectroscopy, by further applying monomolecular and bimolecular thermal activation energy model developed by Halperin A. et al. [3] with our own modification according to the special case for the f-SiC material, we were able to find out the dominant carriers recombination regime and the dominant donor level in f-SiC.

II. RESULTS AND DISCUSSION

The results of the numerical simulation have fitted well with the corresponding main TSL peaks of each sample as shown in Fig. 1, where the calculated and the measured ratio (ELS569 to ELS118) of TSL peak values of these two samples were both ~2.31. The left shoulder of the fitted curve of ELS569 was a bit lower than that of the measured curve, this was caused by unfinished DAP luminescence [4]. In the inset of Fig. 1, the right shoulder of ELS569 is always higher than that of ELS118 (for ELS118, nearly close 0), and this phenomenon guided us to find out the second trap center in ELS569 which induced the second TSL peak with much lower TSL intensity and wide spread along the temperature. The effective donor level were calculated to be 43.4 meV and 42.3 meV for ELS118 and ELS569 respectively, where we can find that both ELS118 and ELS569 are dominated by two processes: the free-to-bound recombination and the DAP recombination with the donor levels related to the hexagonal site (~81 meV [5]). Furthermore, TSL processes for these two samples are both found to be re-trapping dominant, and there is even stronger re-trapping process in ELS569.

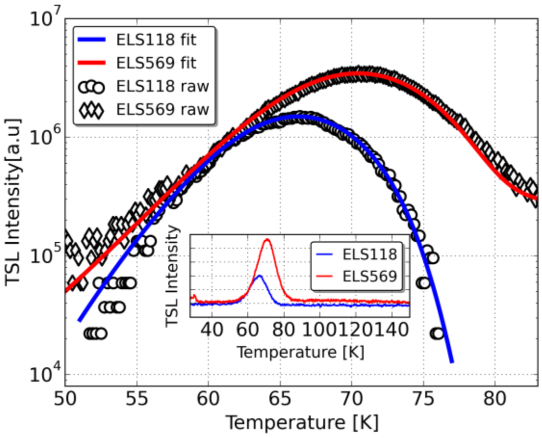

Fig. 1. The main plot: the measured and simulated main TSL curve of the two 6H f-SiC samples, the inset: the whole TSL curves with y-axis set as linear mode.

III. SUMMARY

In conclusion, we have investigated the dominant occupancies of the donor levels of two 6H f-SiC samples by applying the TSL method and the corresponding numerical simulation, and the radiative recombination is found to be dominated by both the free-to-bound and the DAP recombination related to hexagonal sites on donor levels. The strong re-trapping process was found on both samples.

ACKNOWLEDGMENT

We would like to thank Assoc. Prof. Mikael Syväjärvi and Dr. Valdas Jokubavicius from IFM, Linköping University for providing 6H f-SiC for this research. This study was supported by Innovation Fund Denmark (No. 4106-00018B).

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Light interventions: a novel approach for sustaining sleep quality and quantity of elite swimmers under conditions of shifted circadian rhythm

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ABSTRACT

For the 2016 Olympics at Rio De Janeiro the Danish swimmers was facing a very important problem, how to maintain a good sleep quality, quantity and high performance potential[1,2], while being subject to large shift in circadian rhythm. In the present study we suggest an alternative approach for sustaining sleep quantity and quality, namely light interventions. A light program, comprising of alternating blue enhanced white light and blue suppressed white light, was designed to complement the activities of elite Danish swimmers after arriving to preparation/training camp; mimicking the conditions expected in the 2016 Summer Olympics in Rio (5-10 hours shift in circadian rhythm). The sleep patterns of the swimmers were monitored throughout two different phases: the baseline period, registered both before and after the intervention; and the preparation period (intervention). Sleep duration, efficiency, latency, percentages of light, deep or REM sleep were the variables under investigation. The sleep output was modeled (ANOVA) with subject as a random effect and phase as fixed effect. It was observed that the light program during the intervention phase significantly enabled the conservation of sleep quantity and quality of the swimmers, despite the shifted circadian rhythm. The hypothesis of no effect of phase of experiment on sleep duration, efficiency, latency, percentage of light, deep and REM sleep were all accepted with p. values 0.17, 0.53, 0.90, 0.38, 0.57 and 0.52, respectively. The swimmers commented only positively the light interventions and decided to use them at Olympics 2016. No side effects were observed.

Light interventions could become an alternative simple tool for coaches and elite swimmers to improve sleep patterns in occasions of disturbed circadian rhythm conditions (different time zones, uncomfortable competition times). Contrary to other methods for improving sleep pattern (e.g. sleeping pills) light interventions carry minimal risk for severe side effects[3].

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Sun Hub – Energy hub for outdoor tables

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***Abstract*— The scope of this work is to disclose the results from development process of solar powered hub. The concept has been designed, dimensioned, prototyped and in the summer of 2017 and tested at the Roskilde Festival.**

Keywords*— *Stand-alone, solar products, solar cells, LED

I. INTRODUCTION

Solar products has earlier on been more primitive, basically powering products from the sun to save on cables which in e.g. a lighting installation in Denmark represent around the same cost as the cost of the lamp being installed. In this study we report a solar powered hub, as an add-on to a table in the urban environment for charging mobile phones , tablets and other handheld devices through USBs, charging laptops through AC connections, providing opportunity to stream music via Bluetooth and play it from a handheld device to the table and lastly to provide LED lighting on the table during the dark hours.

A rending of the Sun Hub can be seen on Figure 1 below.

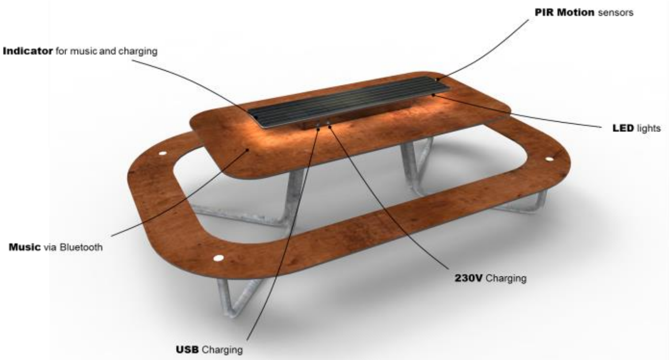

Fig. 1. Rendering of Sun Hub with the suggested components implemented in the commercial Plateau table..

For dimensioning, some assumptions were made to both fit the dimensions of the Plateau table where the hub can be mounted as an add-on feature, and to satisfy the need for the different functions the Sun Hub makes available to the user.

II. SUMMARY

A mock-up of the Sun Hub was made and implemented on the Plateau table to test if the size made available space for comfortable sitting and working with a laptop on the table. Furthermore, an electronic mock-up was made to test the component and especially the losses in the system. Since the project did not have financing for developing dedicated and optimized electronics, e.g. a low power commercial inverter needed to be used being very inefficient and having a 6W standby consumption. Also a commercial board with Wireless Digital Bluetooth with Audio Receiver Amplifier Board was used having about 0.6 W stand by consumption. Since the Bluetooth will be searching for a phone to pair with all the time and the DC/AC inverter being on standby also 24 hours it was decided to turn these functions on only, when PIR was activated opening a window of 10 minutes (being renewed every time PIR is activated again). The hub has 2 sockets for USB charging and 2 sockets for AC charging. The latter is sharing the 100 W inverter, so only 100W can be drawn from the 2 sockets in total. This means that very powerful laptops cannot charge at maximum rate, but will have a longer charging time which is a compromised that has to be made. A rather simple microcontroller based controller PCB was made to control the individual components and with the measured losses in the system, a mathematical model could be made. Assuming that the Sun Hub are placed in a not shadowed environment in Denmark in a typical meteorological year (TMY), an energy balance could be made based on the measurements of the charge efficiencies and standby consumptions of the components. The power consumption is very different for the different functions, and the availability is controlled by the microprocessor prioritizing 1. USB charging, 2. Streaming music and 3 AC charging of laptops as seen on figure 2.

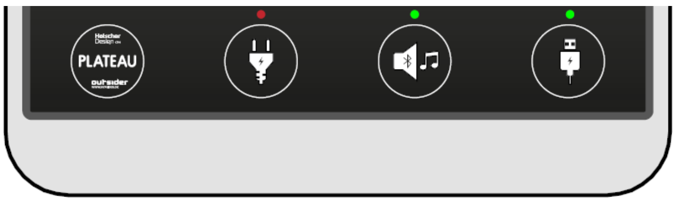

Fig. 2. Energy prioritizing for the individual functions

The microcontroller turns off the individual functionality at different programmed thresholds changing the indicator from green to red. The table always leaves energy for lighting to the night – even when all indicators are red. The Sun Hub has been produced as 3 prototypes and tested at the Roskilde Festival summer 2017. An anthropology study was made to identify how the user felt about the table, its functions, its user interface etc.

ACKNOWLEDGMENT

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Novel Field test design and initial result for AC and DC characterization for PV-panels

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***Abstract*—This work describes the design and initial test results of a field test for PV modules, where the PV modules the majority of the time operates to produce power at their maximum power point. Sequentially the individual modules are switched into a measurement circuitry for IV curves and impedance spectra, with the aim to correlate fault mechanisms to power loss.**

***Keywords*— Field testing, Silicon PV panels, Degradation**

I. INTRODUCTION

Controlled field test of modules is important in order to estimate the impact on faults in the field [1], and correlate degradation mechanism to power loss under real operating conditions. In this work we describe a field test, where the modules under test the majority of the time delivers power to grid via commercially available power electronics for PV, and periodically the individual modules is switched into a measurement circuit where IV-curves and impedance spectra is recorded.

II. DESIGN

The overall objective of this work was to establish a field test that enables panel characterization during operation, to investigate how faults on PV modules develop during normal operation. The objective described above was achieved by connecting the modules to commercially available load electronics for grid connection. A relay system was made which can switch the modules into a "measurement bus" facilitating a measurement of an IV–curve and acquisition of an impedance spectrum. The overall principle is shown in Fig. 1. and the load system is designed with the aim to maximize the time each module is operating in its maximum power point.

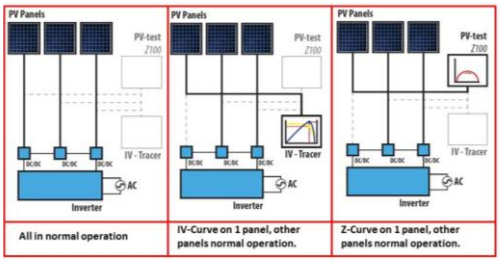

Fig. 1. Working principle of the field test.

III. EXPERIMENTAL PLAN

Modules that had undergone mechanical load test were mounted on the field test together with virgin modules of the same type and batch. Prior to mounting on the Field test indoor IV curves and electroluminescence images of the modules where acquired, Fig. 2.

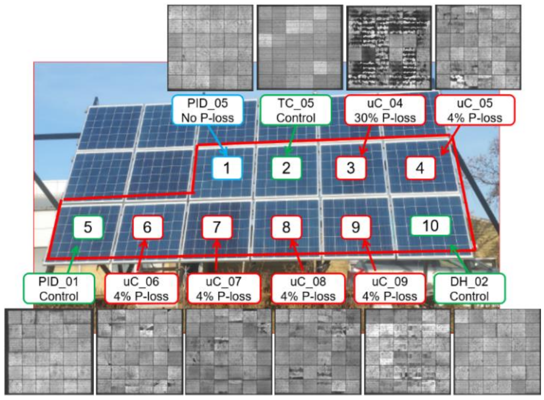

Fig. 2. The field station built at DTU Risø Campus for measuring current-voltage (IV) and IS spectra of PV panels along with weather conditions.

An initial result show that the indoor measurement at STC is generally 2-3 % higher compared to the outdoor clear sky measurements correct to STC before applying the spectral mismatch correction. The field test has now been running for more than a year, and future work includes investigation of the power loss and the development of the micro cracks during this year of field aging.

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The work was funded by the Energy Technology Development and Demonstration Program (EUDP).

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Development of outdoor luminescence imaging for drone-based PV array inspection

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***Abstract*— This work has the goal to examined experimentally PV module imaging methods under natural light conditions, that will be used in a fast, accurate and automatic drone-based inspection system for PV power plants.**

Keywords*— *drone-based PV inspection; electroluminescence; photoluminescence; image processing; outdoor defect detection

I. INTRODUCTION

Regular fault detection for effective maintenance is highly important to ensure expected return on investment (ROI) of small and large-scale photovoltaic (PV) installations. Present day PV panels are designed to operate for 25-30 years, however field experience shows that after 11-12 years of operation 2% or more of all PV panels fail [1].

In practice, the frequency and inspection detail level is often limited by manpower and cost. Presently, drone-based infrared (IR) thermography inspection of solar plants is a reality [2], [3]. The accuracy of thermographic fault detection though, presents limitations – primarily related to deconvoluting the failure signature into failure type and severity, which can be overcome when performed in combination to electro-(EL) or photo-(PL) luminescence imaging of the panels. The combination of defect detection techniques has been already tested in laboratory [1], [4], although many limitations still need to be addressed in order to obtain image acquisition outdoors and integrate, automate and optimize the imaging system in a drone. The concept of PL/EL in a drone is illustrated in Fig. 1.

Fig. 1. Sketch of the concept of automatized drone inspection.

In this work, we present the results corresponding to the development of two luminescence-imaging strategies for PV modules defect detection in outdoor conditions, with the aim of choosing the most suitable method for implementation on a drone-based PV plant inspection system.

II. SUMMARY

The experimental tests performed in this work are focused on investigating EL and PL imaging techniques that are suitable for implementation into a drone-based inspection system. The PL technique avoids the need for electrical contact into the solar panels, which is a time limiting factor for drone-based inspection, especially in large-scale solar plants.

First, we investigate a modulated EL imaging method under daylight conditions, to determine the necessary camera and measurement parameters. A sequential image acquisition system was implemented in order to enhance the quality of the EL images obtained at high noise level during the day.

In the second part, we examine a PL imaging method under natural low light conditions, using a line-scanning laser for PL excitation. The PL signal acquired with such light source would be feasible for outdoor PL imaging, as the optical power is concentrated in a line as the image is build up with image processing.

ACKNOWLEDGMENT

The authors acknowledge the financial support from Innovation Fund Denmark for the DronEL project.

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Thermophotovoltaic application of III-V semiconductors

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***Abstract*— Thermophotovoltaic system presents excellent opportunities to combine two different fields. The conditions under which semiconductors operate are much different from solar spectrum. This research deals with understanding the implication on the semiconductor under such conditions.**

***Keywords*— TPV, GaSb cell, Drift-Diffusion modeling**

I. INTRODUCTION

In thermophotovoltaic system, photocells are used to convert radiation from an artificial radiation source, e.g. heated by a combustion flame, into electricity. Few of the technological difficulties for such systems include (1) low conversion efficiency of thermal input to electrical output, (2) controlling the spectrum of radiation to match the internal quantum efficiency of the photocell. III-V semiconductors like gallium-antimonide are ideal for such systems. Due to low bandgap value at 0.72 eV, maximum of percentage of radiation from an emitter at 1700-2000 K could be used. In thermophotovoltaic conditions, the semiconductor is operating under high-injection of photons and high temperatures with power densities up to 1-20 W/cm^2 and 50-70 ºC [1]. Such conditions have implications on carrier transport through the material. This research deals with understanding these implications on the macroscopic parameters like open circuit voltage, short circuit current and internal series resistance more effectively for thin film III-V semiconductors.

II. FIGURES AND TABLES

Figure 1 represents the general schematic for a TPV system. The emitter emits radiation at a broadband wavelength and the filter is responsible for the spectral control of radiation towards the PV cells. Thermalization losses are released as a heat from the PV cell. Note that radiation leakage is ignored.

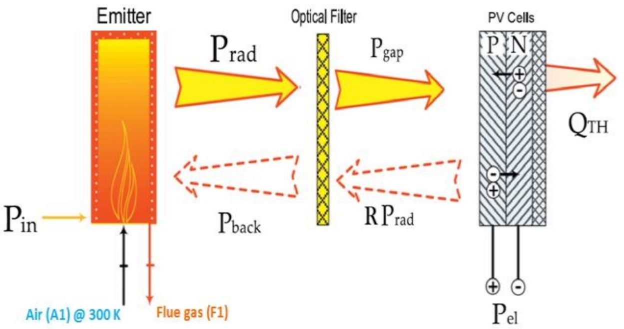

Fig. 1. Schematic of a thermophotovoltaic system

III. BACKGROUND

To better understand the effects of carrier distribution on the macroscopic properties, it is extremely vital to recognize the lifetime of carriers in the semiconductor. To account for this, the coupled continuity equation along with Poisson's equation for charge distribution must be solved.

$$D'.\nabla J_n - U(n) = -G(x) \quad (1)$$

$$D'.\nabla J_p - U(p) = -G(x) \quad (2)$$

$$\nabla E(x) = \rho(x)/\epsilon \quad (3)$$

J_n and J_p are current densities contributed from both Ohmic or drift component and diffusion component. D' represents the ambipolar diffusion constant which is considered for carrier transport at high injection scenario [2]. U and G are the dynamic recombination processes occurring. ρ is charge density distributed in the system at any point. The nature of problem presented here is high nonlinear and it is not clear how the various material and diode parameters interact to produce the photocurrent [3]. The solution is also affected by which side of the cell is first interacting with the radiation [4].

IV. SUMMARY

A preliminary simulation result from the analytical modeling indicated that for a gallium-antimonide cell with n-type emitter had better quantum efficiency than with a p-type emitter. This may be due to extremely low mobilities of holes in gallium antimonide. But more rigorous experimental and numerical validations are required to confirm this.

ACKNOWLEDGMENT

This project was carried as a master thesis under Prof. Haiyan Ou, DTU Fotonik.

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Silicon carbide growth avenues for prospective energy applications

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***Abstract*—From scientific and innovation point of view, new materials concepts based on SiC provide new grounds. Since 2010 we have explored alternative energy approaches, and overview some growth routes of emerging concepts using silicon and carbon materials approaches.**

***Keywords*— energy; materials; crystal growth**

I. INTRODUCTION

An avenue opened up by growth aspects of fluorescent 6H-SiC for a new type of white LED in general lighting [1-3]. This research area in materials science includes control of relative n and p-type doping to yield luminescence, and exploration of low off-axis epitaxial growth.

An area which could have great potential is boron doped cubic silicon carbide (3C-SiC) for photovoltaics [4]. The 3C-SiC growth is challenging to control. We have developed a growth process using a modified version from the conventional physical vapor transport method. The primary factor for polytype formation is the growth temperature, while the one to achieve large domains is governed by the off-angle of the surface to provide domain enlargement which facilitates material of high structural quality.

II. FIGURES AND TABLES

The off axis has a profound effect on the growth both in case of fluorescent SiC and cubic silicon carbide. Common is that low off axis material favor a stability criteria.

The LED technology using fluorescent silicon carbide is based on photoluminescence from near ultraviolet nitride layer into doped thick SiC epitaxial layers stacked on each other. The resulting donor to acceptor pair luminescence in the first layer with nitrogen (donor) and boron (deep acceptor) on top of a second layer having nitrogen and aluminium (shallow acceptor) provides a pure white light. The cubic silicon carbide could be a potential route for exploring intermediate band solar cell, solar driven hydrogen generation by water splitting, splitting of CO2, and thermoelectrics.

III. SUMMARY

In this presentation we will review the alternatives of material concepts for SiC, and present the status of research area.

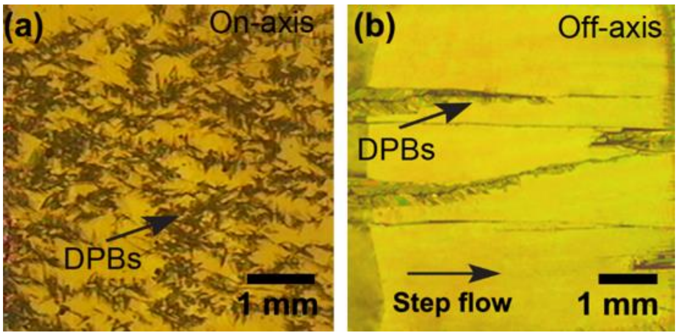

Fig. 1. Comparison between on and off axis substrate for 3C-SiC growth and domain formation.

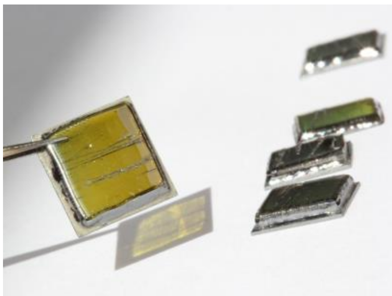

Fig. 2. Resultant 3C-SiC with only few domains over 7x7 mm area.

ACKNOWLEDGMENT

This work was supported by Innovation Fund Denmark (project No. 4106-00018B), Swedish Research Council (contracts 621-2014-5825, 621-2014-5461), ÅForsk foundation, Swedish Energy Agency and Swedish Governmental Agency for Innovation Systems (Vinnova), Norwegian Research Council (SunSiC project).

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New dental applications with LEDs

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***Abstract*— Visible and ultraviolet LEDs will in the future give rise to new dental applications. Fluorescence imaging, photodynamic therapy and photoactivated disinfection are important future candidates for diagnostics and treatment in dentistry.**

***Keywords*— LED; dentistry; optical diagnostics; bacteria.**

INTRODUCTION

Development of new Light Emitting Diode (LED) technology considerably reduces the electricity consumption in many lighting applications [1]. Therefore, there is a rapid growth in lighting based on LEDs. In addition to the energy savings, however, LEDs have many potential medical applications that will be important in the future. Red, yellow, green, blue and ultraviolet colours can be obtained from LEDs that will give rise to applications within diagnostics and treatment of diseases. In this letter we will discuss how LEDs in the future may be used in dental applications.

SUMMARY

Today LEDs are used for general lighting and photo polymerization in dental clinics but the ability to design the colour composition of LEDs will in the future make it possible to improve the ability to visually identify plaque, veins and bacteria in the oral cavity. Recently, we provided empirical evidence [3] that specific colour design of white light LED illumination can affect the human ability to identify veins. Narrow band imaging with LED enhances images of capillaries in the surface layers of the human tissue.
Blue (390-440nm) for surface vessels and green (525 nm 550 nm) for deeper vessels. Therefore, medical doctors and dentists have a new tool for probing changes in capillaries and veins. White light LED sources based on color mixing is superior to fluorescent light for detection of inflamed lesion in the oral cavity [4-5]. Light induced fluorescence using blue LEDs is a clinical tool for diagnostics of tumours and bacteria. In combination with a photosensitizer the light may lead to cell necrosis and the procedure is used in photodynamic therapy or disinfection of bacteria in the dental root canal.

Fig. 1. Blue light in the tooth

UV-LED is a new LED light source that may be used for disinfection without the need for a photosensitizer. At DTU Fotonik we work on the development of UV-LEDs that are optimised for disinfections of specific bacteria [5]. We have shown that for bacteria in biofilms specific wavelengths in the UV B region are more effective than UV C for killing bacteria[6-7]. Furthermore, the UV B wavelength that is found effective for killing bacteria in biofilm, is part of the wavelength that exists in daylight. This gives new possibilities for applications within oral disinfections. In the talk we will discuss the latest results of the efficiencies of killing bacteria using UV-LEDs and how these light sources potentially may be used to kill bacteria in the tooth root canal and also for the treatment of periodontitis.

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How to treat Alzheimer's with new LED light technology

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***Abstract*— We have developed a new therapeutic LED lamp that modulates with 40 Hz the neuron responses in different parts of the brain without affecting the human vision. The lamp may in the future be used to treat patients with Alzheimer's disease**

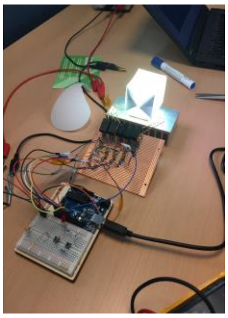
Keywords*— *LED; Alzheimer's; optogenetic; light therapy (3-5 words)

I. INTRODUCTION

Light-emitting diodes (LEDs) have been long utilized as a light source for industrial and commercial environments. In the past 10 years, it has become the dominant technology used for backlight displays such as ipads, laptops, and television sets. Its potential to be utilized for medical application have recently been examined for circadian disruption and neuropathological diseases such as Alzheimer's. In this lettter, we will discuss how new LED technologoy can be utilized to treat or prevent the progression of neurodegenerative diseases.

II. FIGURES AND TABLES

Fig. 1. First mock up of how the light protoype.



III. SUMMARY

One of the biggest demographic challenges in Europe and the US is the rapidly growing number of people with Alzheimer's and dementia (~30% of the world population has or will develop the neurodegenerative disease). Dementia is one of the leading causes of death among those 60 years and over. The increase in the number of Europeans and Americans living with dementia is already creating immense challenges for the health and social systems costing upwards of 259 billion dollars in healthcare. For most people, the cognitive decline starts with a failing memory and a lack of perception and attention. One of the things that have been attributed to the progression of Alzheimer's is the altered oscillatory rhythmic activity that could lead to cognitive abnormalities and beta amyloid developmet in the brain [1]. This desychronization of neuronal oscillations can be detected prior to the development of symptoms of Alzheimer's. Recently the use of ligth therapy as a non-invasive tool has been explored in the treatment of Alzheimer's. Studies have shown that flickering light at 40 hertz can reduce the beta amyloid plaque production (early clinical signs of Alzheimer's) in mice by stimulating the brain wave activity in the visual cortex [2]. However, trials on mice cannot be duplicated in humans due to the negative side effects of flickering that can induce very same positive effects. The current study addresses the side effects induced by flickering lights by utilizing the brains ability to detect and respond to specific wavelength that differ from the wavelength sensitivity of the eye vision [3], that are no longer perceived as a flicker by the visual cortex but the increase in gamma oscillations still be detected.

ACKNOWLEDGMENT

Lance Kriegsfeld (UC Berkeley, Department of Psychology)
Marcus Schultz Carstensen (DTU, Department of Physics)

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Treating Depression using LED and Daylight

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Keywords— Daylight; LED-lighting; Architecture)

I. INTRODUCTION

Despite developments in pharmacotherapy and psychotherapy a substantial part of patients with depression only recover incompletely during hospitalization. LED-lighting, rich in the blue short-waved spectral range, is an acknowledged antidepressant agent, which can play an important role in effective treatment of depression.

In a new project we develop and test a new dynamic LED-lighting solution for inpatient wards, an architectural light therapy concept *Lattitude Compensated Architectural Lighting* (L-CAL). Through an architectural lighting design, the light is dosed from 06.00 – 23.00 from low intensity warm white light (2.000 K) in the evening, to bright light (6.500 K) in the morning and early daytime. Opposed to normal light therapy, the built-in light therapy concept provides light therapy during the whole hospitalization.

The concept is based on an observational study Ward-light performed in 2015, suggesting that there is a large potential of improving the light at north-west-facing wards, compared to south-east-facing wards. Inspired by the architectural planning of the original Nightingale Wards, with facades facing south-east and south, in order to make the most of the sunlight, the trial implements "A Sunny South East Side" to the darker north-west and north facing wards. The objective of the randomized trial is to investigate whether this sunlight therapy solution, based on dynamic LED-light (FIG 3), has an antidepressant effect on depressed inpatients when compared to conventional LED-lighting.

In the project ROOM-LIGHT we plan to develop and implement a new energy-saving LED-lighting in a psychiatric ward. The project implements better artificial lighting for the benefit of sleep improvement, mood stabilization, faster recovery from depression and energy consumption subsequently collecting data on health and energy. The wards are facing SE and NW (Fig. 1.). The project studies the differences in sunlight and subsequently improve the light in the wards, using dynamic LEDs

Fig. 1. NW-facing ward vs SE-facing ward. Registration from the project WARD-LIGHT

II. SUMMARY

In collaboration with DTU Photonics and Chromaviso A/S we have developed new, innovative LED-luminaires and a new way of measuring both daylight and artificial lighting during the day and during the year. Using sensors in each ward we collect data across seasons in test scenario and control scenarios, respectively. The test scenario is equipped with an especially designed dynamic LED-lighting concept developed for treatment of depressed patients, including a sill-mounted dynamic LED-luminaire, a wall-mounted dynamic LED-luminaire, and ceiling-mounted dynamic LED-luminaires. The control scenario is equipped with a wall-mounted constant LED-luminaire and two ceiling-mounted LED-luminaires. In the project we collect data on daylight and LED-light for both test and control rooms. Through blinded, randomized controlled trials we collect data in an expected sample-size of 100 – 120 patients over a period of two years.

ACKNOWLEDGMENT

The project is sponsored by: Danish Energy Association, 348-026, The Research Foundation of Copenhagen Capital Region, The Toyota Foundation and Fogh ́s Foundation.

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The New Method of the PV Panels Fault Detection Using Impedance Spectroscopy

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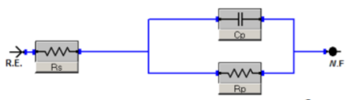
***Abstract*— The aim of our project is to develop a new method for photovoltaic (PV) panel fault detection based on analyzing impedance spectroscopy (IS) spectra. Although this technique was successful in assessing the state of degradation of fuel cells and batteries [1, 2], it has never been applied to PV cells on a wide scale. This step forward could be a turning point in PV fault identification as it provides a method that is easily implemented in the field and cheaper than the traditional techniques [3].**

Keywords*— *fault detection, impedance spectroscopy, silicon PV panels

I. INTRODUCTION

The IS measurements provides a complex impedance value (Z_{PV}) for a range of AC signal frequencies. Using a fitting method on the measured data, it is possible to extract the parameters of the PV panel equivalent circuit [4] (see fig. 1). Analysis of the extracted parameters such as parallel capacitance C_p, parallel resistance R_p, and series resistance R_s, should allow us to rate the degradation state of PV module´s individual parts [3,4].

II. FIGURES AND TABLES



$$Z_{PV} = \left[R_s + \frac{R_P}{(\omega R_P C_P)^2+1}\right] - j\left[\frac{\omega R_P{}^2 C_P}{(\omega R_P C_P)^2+1}\right]$$

Fig. 1. The complex impedance Z_{PV} equation of a PV panel (bottom) and its equivalent circuit model (top).

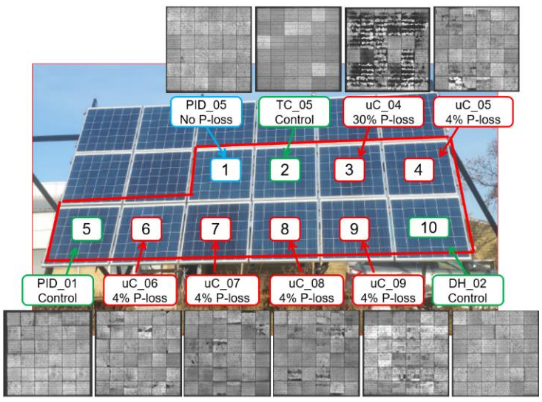


Fig. 2. The field station built at DTU Risø Campus for measuring current-voltage (IV) and IS spectra of PV panels along with weather conditions.

III. SUMMARY

We have built a field station at which IV, IS and weather conditions measurements are performed on 10 silicon solar panels (see fig. 2). Tests run from dawn until dusk and a fitting procedure is applied after a day of data collection. Six of the modules had been subjected to stress tests and exhibit power losses (P_{loss}) of 4% or 30% due to micro cracks. All the panels has been previously tested indoors by IS technique in dark conditions and by IV one in multi-irradiation conditions.

So far, the IS technique was only successful in the dark indoors conditions. We observe that the R_p values of control modules are 2,5x higher than the ones of modules with P_{loss}. Also, the module with 30% P_{loss} exhibits 2,5x higher R_s value than the rest of modules. These changes indicate a mechanical performance failure, which should be further investigated by IV measurements. Once G>100 W/m^2 the shapes of collected IS curves are the same for all degradation groups and, thus, extracted R_p, R_s, and C_p parameters do not differ either. This may be due to incorrect performance of our field test bed.

In the future we hope to be able to assess the P_{loss} value only through the field IS measurements. However, in order to achieve our goal, we first need to upgrade outdoor test bed and perform more indoor stress tests as a reference for the outdoor data.

ACKNOWLEDGMENT

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New Light Source Setup for Angle Resolved Light Absorption measurement of PV samples

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***Abstract*—Here, we introduce measurements of angle resolved light absorption by PV cells, using broadband laser driven white light source with a bright, stable, broad spectral range and well collimated light.**

***Keywords*— absorption; collimated; reproducibility; laser**

I. INTRODUCTION

The light absorption of solar cells under working conditions is affected by several factors. In particular, this absorption effect of PV is studied with different type of light sources. In our set up we have used a new type of broad band light source. In their paper D. T. Reindl, W. A. Beckman, and J. A. Duffie studied the effect of diffuse irradiation as function of irradiation angle [1]. C Protogeropoulos and A Zachariou described reflectance characteristics of PV modules using a visible light source [2]. R. Santbergen and R.J.C. van Zolingen studied the effect of light absorption on the temperature of the PV modules [3]. In our case, we have built a set-up that allows automatized, reliable measurements of the light absorption of solar cells as function of incidence angle with collimated light (with an angular divergence of about 0.1 °). Hence, this set-up has many advantages, such as, the spectrum and intensity of the light source remain constant and high respectively throughout the test and the rotation stage can move easily and accurately with the given range of angles. The light source used here provides bright illumination across the UV-VIS-NIR range (190nm to 2100 nm) together with high spatial and power stability. Moreover, the light source is well collimated by collection optics to give a stable and reliable power measurement

II. Methods

The whole measurement system consists of laser driven broad light source, rotation stage with a sample holder and current measurement transducer which is controlled by a LabVIEW controlled PC. The schematic diagram of the setup is shown in the Fig. 1. The UV filter was used just after the light source to remove the UV-C part for safety. The measurement room was kept at a temperature of 21 °C using an air conditioning system.

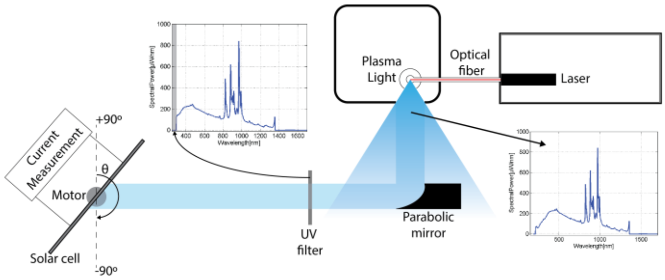

Fig. 1. Light absorption measurement setup of PV samples

III. Results and Summary

For the test we have used several PV modules. The samples varied with their glass structures or raw materials they are made of or the type of encapsulants used. The samples size are limited to less than 20 cm so that they will be stable on the holder while measurements. The setup used a laser driven light source which has high brightness, due to the excitation of very small plasma with a laser source. Moreover, it is a broad-spectrum light (190nm to 2100nm) with high spatial and power stability. This property of the light source gives a high SNR with a small integration time of the detector. We have calculated and checked the reproducibility of our measurement by repeatedly acquiring current at different angles (between +90 ° and -90 °) for a reference sample. After this reproducibility measurement then we have measured all the samples a number of times in the same way as a reference sample. In all the measurements we determined the highest relative standard deviation to be 0.7 % for angles of incidence larger than ± 80 °.

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Validation of the spectral mismatch correction factor using an LED-based solar simulator

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***Abstract* — LED-based solar simulators are gaining popularity in the PV characterization field. There are several reasons for this trend, but the primary interest is often the potential of tuning the light source spectrum to a closer match to the AM 1.5G reference spectrum than traditional Xenon or metal-halide light sources provide. In this work we will use an EcoSun10L LED module tester from Ecoprogetti to perform short circuit current (I_{SC}) measurements under various class A, B and C spectra. We will apply a spectral mismatch correction to the measured I_{SC} under each test spectrum per IEC 60904-7. In all scenarios, a small area mono-Si cell is used the reference cell and a similar mono-Si cell is used as the PV device under test (DUT). Finally, we quantify the variation of the DUT's measured and spectrally corrected I_{sc} under the class A, B and C test spectra.**

I. Introduction

Characterization of photovoltaic (PV) devices at standard test conditions (STC) assumes a test spectrum of AM 1.5G. Since test labs typically do not have the capability to measure precisely at this reference spectrum, a spectral mismatch correction factor (MM) is used. Procedures for calculation and application of the MM are documented in IEC 60904-7. Furthermore, the uncertainty of the MM has been researched elsewhere in the literature [1] and [2].

The Department of Photonics Engineering at Denmark's Technical University (DTU) uses an EcoProgetti EcoSun10L for PV module characterization. This solar simulator has a 1.2m x 2.0m test area that is illuminated by 77 LED boards. Each board contains an array of LEDs consisting of 12 different colors, 8 of which are addressable and can be configured by the operator.

The MM factor is derived as shown in (1) where $E_{ref}\lambda$ is the AM 1.5G reference spectrum. The EcoSun10L solar simulator is in theory capable of performing relative spectral response measurements by activating one LED channel at a time and measuring the photo-current output. This data would provide $S_{DUT}\lambda$, but we will use external quantum efficiency (eQE) measurements from the PV device under test (DUT) manufacturer instead as it contains more than 8 data points per curve as well as measurements > 950nm. The solar simulator spectrum is measured at the center of the test plane with an Avantes AvaSpec-2048 spectroradiometer (Fig. 1). Calibration of the spectroradiometer is performed on site with a Tungsten-Halogen reference lamp. The spectral measurements from the Avantes provide $E_{meas}\lambda$. Finally, $S_{ref}\lambda$ is the spectral response of the reference cell. For this variable we will use the eQE data for a calibrated mono-Silicon reference cell manufactured by ReRa and measured by PV Calibration Facility Nijmegen. The Isc values of these reference cells are mismatch corrected.

$$MM = \frac{\int E_{ref}(\lambda)S_{ref}(\lambda)d\lambda \int E_{meas}(\lambda)S_{DUT}(\lambda)d\lambda}{\int E_{meas}(\lambda)S_{ref}(\lambda)d\lambda \int E_{ref}(\lambda)S_{DUT}(\lambda)d\lambda} \quad (1)$$

The correction is applied by dividing the measured Isc (I_{sc_meas}) by the MM factor, which results in a spectrally corrected Isc (I_{sc_corr}). Note that the MM factor is equal to 1 when the test spectrum matches the reference spectrum or when the spectral response of the DUT matches that of the reference cell.

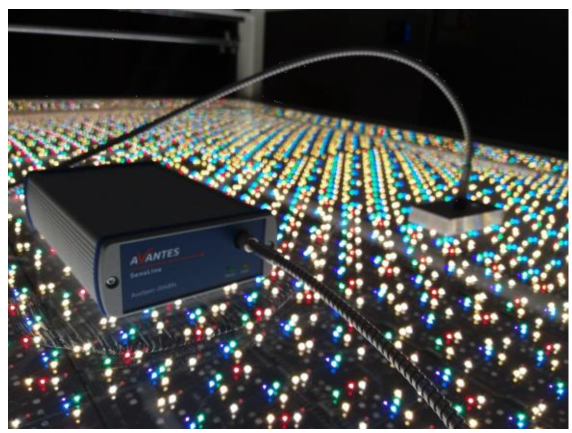

Figure 1: Measurement of the EcoSun10L spectrum with the Avantes Spectroradiometer.

We will use a second reference cell of similar characteristics as a DUT. The MM has been calculated for both cells using the Ecosun10L spectrum measured at our lab, and the difference is smaller than 0.7 %. We expect to increase this value by generating spectra of classes B and C.

II. Results

The emission spectra of the 8 configurable LED channels in the EcoSun10L are shown in Fig. 2. The emission of each channel is normalized to the peak value. The 8 channels consist of UV, blue, green, cool white, natural white and three channels for infra-red (IR) light. Each IR channel has 2 or 3 LEDs in series, which is why channels 6, 7 and 8 in Figure 2 have 2 or 3

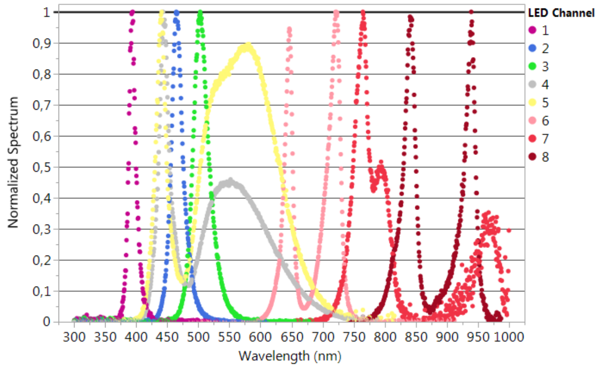

Figure 2 : Normalized emission spectra of the 8 LED channels within the EcoSun10L solar simulator.

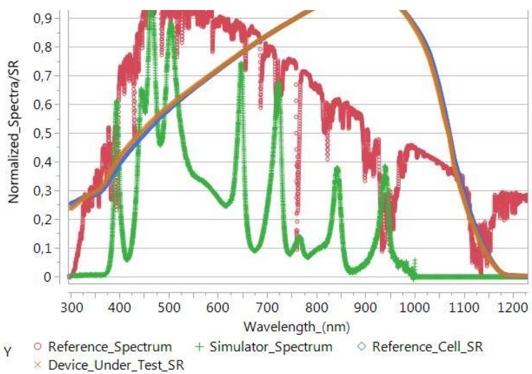

Figure 3: Overlay of the AM 1.5G reference spectrum, a class A spectrum measured in the EcoSun10L solar simulator, spectral response of the mono-Si reference cell and DUT.

emission peaks. The intensity of each channel can be individually adjusted to create a desired spectrum.

Fig. 3 shows an overlay of the AM 1.5G reference spectrum, the default EcoSun10L spectrum when all 8 LED channels are turned on, the mono-si DUT and reference cell. The EcoSun10L spectrum in Fig. 3 is configured for a class A spectral match.

IEC 60904-9 defines three solar simulator classifications for spectral match relative to the reference spectrum – class A, class B and class C. Fig. 4 shows how the distribution of the

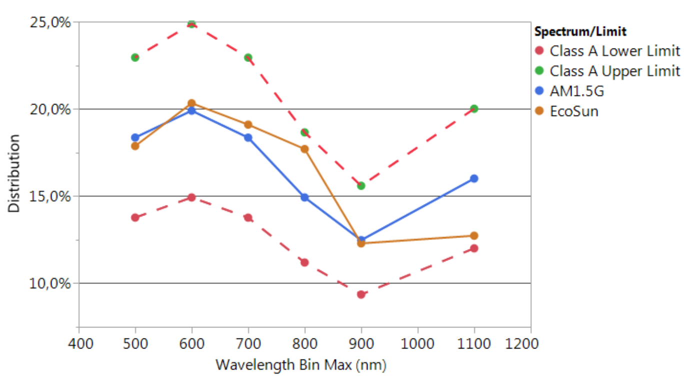

Figure 4: Spectral match of the default EcoSun10L class A spectrum

class A test spectrum matches that of the reference spectrum. In the final work, this plot will be improved as we will generate six unique test spectra, two spectra from each IEC class. We will perform Isc measurements on our DUTs under each test spectrum and apply the MM factor to each measurement to obtain I_{sc_corr}. Finally, we will analyze the introduced variation on the measurements under each test spectrum using a statistical process control (SPC) platform. These corrected measurements will be compared also with the calibration corrected values.

III. Conclusions

For the final poster, six unique class A, B and C test spectra will be generated with an LED-based solar simulator. Measurements will be performed on two monocrystalline reference cells with calibrated Isc value, one acting as a DUT. The Isc measurements will be corrected with a spectral mismatch correction factor. The accuracy of the correction will be quantified through SPC. Through this experiment we intend to validate if the spectral mismatch procedure can correct a PV measurement to the AM1.5G spectrum, irrespective of the test spectrum. Based on the results that are generated, we will be able to say to what extent the test spectra's similarity to AM1.5G is important. For example, if the I_{sc_corr} value is constant irrespective of class A, B or C spectra, we will be able to conclude that as long as one accurately knows what the test spectrum is, the spectral match is of secondary importance.

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Workshop Participant Biographies

Amdemeskel Mekbib received the MSc in Advanced Optical Materials from Friedrich Alexander University, Germany in 2014. From early 2015, he joined Technical University of Denmark, where he is doing his graduate study at Photonics department in the LED and Laser Diode group on material characterization and spectroscopy. His scientific background is in the areas of materials and devices for optical spectroscopy and imaging, photovoltaics, and light emitting. He has published more than 5 papers.

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Gisele Benatto is graduate in Physics by the Londrina State University in Brazil. At the same university, she received her master's degree on optical properties of materials applied on solar cells, using photoluminescence (PL). Early 2017, she completed her PhD at DTU Energy department, which was focused on large-scale manufacture of polymer solar cells, lifetime testing, and environmental impact of photovoltaic technologies. Now as a Postdoc in Photovoltaics, her research has emphasis on the combination of optical emissions, such as photo and electroluminescence (PL and EL), and PV knowledge into the development of PV plant inspections. Her contribution to literature comprises more 15 published articles in high impact peer reviewed journals in the PV field.

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Sara Lena Josefin Engberg received her B.Sc.Eng. in Physics and Nanotechnology at the Technical University of Denmark (DTU) in 2011, and her M.Sc.Eng. in Nanotechnology at the University of Pennsylvania (UPenn) in the US in 2013. She carried out her Ph.D. studies at DTU Fotonik under the supervision of Dr.scient. Jørgen Schou and with visits to Nanyang Technological University (NTU) in Singapore under supervision of Prof. Yeng Ming Lam. Her research interests are within the fields of material's science for energy and the environment, in particular colloidal science and thin-film solar cells.

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Ashwin Hariharan received the BE in mechanical engineering from Gujarat technical university in 2008 and MSc degree in sustainable energy engineering in thermal science, Technical university of Denmark in 2017. From 2012, he worked as a project engineer for several process industry projects. He conducted his master thesis on subject of thermophotovoltaic semiconductor modeling, nanofabrication, characterization, and system modeling under Prof. Haiyan Ou, Prof. Brian Elmegaard and Prof. Anders Ivarsson in 2017. His scientific interest is in the areas of semiconductor device physics and thermal system modeling, photovoltaics, and transport phenomena. He is currently working on his publication on characterization of multiple quantum well solar cells for thermophotovoltaic applications.

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Jakob Hildebrandt has a M.Sc. from Technical University of Denmark. He is an assistant professor in the Diode Lasers and LED Systems group.
Jakob has been responsible for several lightning research projects, among them are; a light system for improved performance and sleep rhythm for the national Danish swimmer team, and a light project for elder suffering from dementia in a nursing home. Jakob has also developed several unique lighting solutions, one of which he won the 2015 UNESCO light year innovation price in Denmark.

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Satoshi Kamiyama received the BE in 1985 and PhD degrees in 1995 in electronics from Nagoya University, Japan. From 1985 to 1988, he was a member of technical staff at Central Research Laboratory, Omron Co. Kyoto, Japan, participating in the development of semiconductor opto-electronic devices. From 1988 to 1999, he joined Central Research Laboratory, Panasonic Co. Osaka, Japan, where he was pursuing research in the field of III-V and II-VI compound-based semiconductor lasers. Since Apr 1999, he had been a member of technical staff in Meijo University, Nagoya, Japan, where he worked research of group-III nitride materials and devices. He was adopted as an associate professor in 2001, and was promoted to a professor in 2007 at Meijo University, where he has continued to conduct the research of group-III nitride materials and devices. His scientific background is in the areas of III-V, II-VI, and IV-IV groups compound semiconductor materials and their photonic devices. He has published more than 240 journal papers.

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Meng Liang, Ph.D., Research Assistant, semiconductor lighting R & D center, Institute of Semiconductors, Chinese Academy of Sciences. Focus on the area of nitride materials growth, LED device processing and fabrication, and LED light designing and heat management. He has made pioneering contributions in the development of Solid-State Lighting in China and participated in the many national projects of nitrides field about high power LED structure design and key technology research.

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Li Lin received the Bachelor of Science in Department of Optical Communication Science and Technology from Shandong Jianzhu University in 2012 and MSc in Department of Photonics Engineering from Technical University of Denmark in 2015 and MSc in Department of Physics and Technology from Yunnan University in 2015 and currently has her PhD Study in Department of Photonics Engineering from Technical University of Denmark since 2015. Her scientific focus is in the areas of light emitting diode device fabrication and light extraction efficiency improvement for gallium nitride-based near-ultraviolet light emitting diodes.

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Weifang Lu received the bachelor's and master's degree in physics from Xiamen University in 2011 and 2014, respectively. From 2014 and she is currently working toward a PhD degree in Photonics Engineering department from Technical University of Denmark. Her current research interest is related to porous f-SiC based white light emission. She has been working with the fabrication and surface passivation of porous SiC in collaboration with LED group at Meijo University. She has published, as an author and co-author, about 15 journal papers.

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Ngoc Mai Nguyen received a bachelors in Microbiology from the University of California Berkeley in 2010 and began her graduate work in Integrative Biology and Neuroscience shortly after. As part of two labs - the Kriegsfeld lab (Studying circadian disruption and its effects on neurodegenerative diseases) and Tyrone Hayes' lab - she is in the unique position to study the role of aromatase in sexual differentiation of the brain using a comparative approach, as well as the deleterious effects of endocrine disruptors on these systems. Currently, she is working under Lance Kriegsfeld (UCB) studying the effects of circadian disruption in mice and collaborating with Jes Broeng at the Technical University of Denmark to incorporate photonics in the treatment of circadian disruption and neurodegenerative diseases such as Alzheimers and dementia.

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Haiyan Ou received PhD degree in semiconductor devices and microelectronics from the Institute of Semiconductors, Chinese Academy of Sciences in 2000. From 2000, she joined Technical University of Denmark, where she was promoted as associate professor in 2005. She has been a JSPS (Japanese Society for Promotion of Science) fellow at Meijo Univeristy (Japan), and a visiting professor at the Institute of Semiconductors, Chinese Academy of Sciences (China). Her scientific background is in the areas of materials and devices for optical communication, photovoltaics, and light emitting. She has published more than 180 journal and conference papers. She is the founder of Light Extraction ApS, the winner of strategic research award for research with great innovation potential, and editor for Scientific Reports, a journal from Nature Publish Group. As PI, she has led a couple of national projects on novel LED materials and advanced LED devices, and she is managing a 6-7 persons' team daily.

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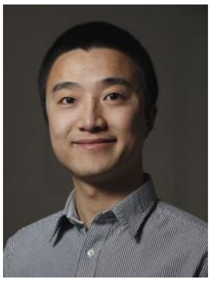

Yiyu Ou received the MSc degree in photonics from Chalmers University of Technology in 2009 and the PhD degree in photonics from Technical University of Denmark in 2013. From 2013, he joined Light Extraction Aps (Denmark) as head of technology, where he lead the R&D work to provide novel nano-fabrication solutions. He is currently a post-doc researcher at the Technical University of Denmark. His scientific background is in the areas of energy-saving materials and devices, nanophotonics and LED lighting for industrial applications. He has authored and co-authored more than 70 journal and conference papers.

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Paul Michael Petersen is Full Professor in New Light Sources at the Technical University of Denmark. His research focuses on lasers, LEDs and biomedical optics. P. M. Petersen has authored more than 150 international scientific publications and holds 15 patents. P. M. Petersen is chairman of *DOLL – a Photonics Green lab* that tests and develops new lighting technology based on LED and diode laser technologies. From 2002 until 2012 he was appointed adjunct professor in Optics at the Niels Bohr Institute, Copenhagen University.

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Peter Behrensdorff Poulsen received the MSc in Materials Science from the Technical University of Denmark (DTU) in 2002. From 2003, he joined the Danish Technological Institute, where he led the research on industrialization of dye sensitized solar cells. In 2006 he founded Faktor 3 (www.faktor-3.dk) together with an industrial designer, a company dedicated to making high-end PV products available to the market. Peter joined the Department of Photonics Engineering at DTU in 2008 as a project manager and has been doing research within light emitting diodes and photovoltaics since together with a strong research team. He is the leader of the PV research team in Roskilde doing teaching, research, innovation and consultancy within applied photovoltaics. Furthermore, he cofounded Nordic Firefly in March 2017, a spin-off company from DTU Fotonik/Elektro proving high efficient converter electronics for solar lighting products.

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Nicholas Riedel graduated from the California State University system with a B.S. in Electrical Engineering and an M.S. in Environmental Engineering. Upon graduating he spent 3.5 years working at CFV Solar (part of Fraunhofer USA) focusing on projects in PV performance, reliability and safety. In 2016 he came to Denmark and joined DTU Fotonik where he focuses on topics in applied photovoltaics.

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Michael Schöler received the M.Sc. in materials science from University of Erlangen-Nürnberg (FAU) in 2017. In 2013 he joined the Crystal Growth Lab of Prof. Peter Wellmann at FAU. His field of research is crystal growth and epitaxy of silicon carbide. He works in chemical vapor deposition (CVD), physical vapor transport (PVT) growth, solution growth and sublimation epitaxy (SE) of different silicon carbide polytypes. His research focus is the growth of cubic silicon carbide (3C-SiC).

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Joanna Symonowicz received a double BSc degree in Physics and Architecture from Wroclaw University of Science and Technology in 2015 and 2016, respectively. She is now perusing her MSc degree in Physics on thin film solar cells at the University of Copenhagen in collaboration with Technical University of Denmark. Since 2017 she has also been a student worker at the Department of Photonics Engineering, Technical University of Denmark, where she is working on developing a new technique of solar cells faults detection based on analyzing its impedance spectra. Her main interest is a basic research on photovoltaic materials and their implementation to architecture.

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Mikael Syväjärvi received PhD in Materials Science 1999 at Linköping University. His research area is in energy and environmental semiconductor materials and nanomaterials. His experience is in liquid phase epitaxy, seeded sublimation bulk growth and sublimation epitaxy of silicon carbide, as well as graphene and carbon allotropes on silicon carbide. The aim of the materials is for optoelectronics in white LEDs, highly efficient and high temperature photovoltaics, thermoelectrics, hydrogen generation by solar driven water splitting, as well as sensors and biofuels cells. Mikael Syväjärvi has an entrepreneurial research profile and has founded spin off companies based on growth methods developed in relation to his research interest.

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Sune Thorsteinsson received his M. Sc. in applied physics at the Technical University of Denmark in 2006. Since 2009 he has been working with Photovoltaics, where he has developed advanced solar modules and later went into research at the Technical University of Denmark, where the research areas are standalone lighting systems, building integrated photovoltaics and reliability. Sune is the technical manager for the research team within applied photovolataics. Sune is further cofounder of the company Nordic Firefly founded March 2017, a company supplying high efficiency power electronics for standalone lighting systems, and has several conference contributions within the field of photovoltaics.

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Carlo Volf received a PhD degree in Architecture at the Aarhus School of Architecture, Institute of Architecture, in 2013. In 2013 he joined the capital region Region H and worked on several architectural projects; New Herlev Hospital, New Hospital Hvidovre, New Psychiatry Bispebjerg a.o. He is a founding member of The International Velux Daylight Academy. Carlo Volf has received several prizes for his work with light, latest receiving the UNESCO Year of Light Prize in 2015. He is an appointed lecturer and appointed censor at both The Royal Academy of Architecture and Aarhus School of Architecture. His scientific background is founded in the areas architecture, light and health. He has published several papers and latest also contributed to The Light Book, Science Magazine.

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Yi Wei is a Ph.D candidate supervised by Assoc. Prof. Haiyan Ou at Technical University of Denmark (DTU), he joined the Group of Diode Lasers and LED Systems leaded by Prof. Paul Michael Petersen at DTU Fotonik in 2015. His scientific interests include optical/electrical characterization of hexagonal structured SiC, carriers dynamics calculation of hexagonal structured SiC, finite-difference time-domain (FDTD) simulation on plasmonic structure and wide bandgap semiconductors.

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