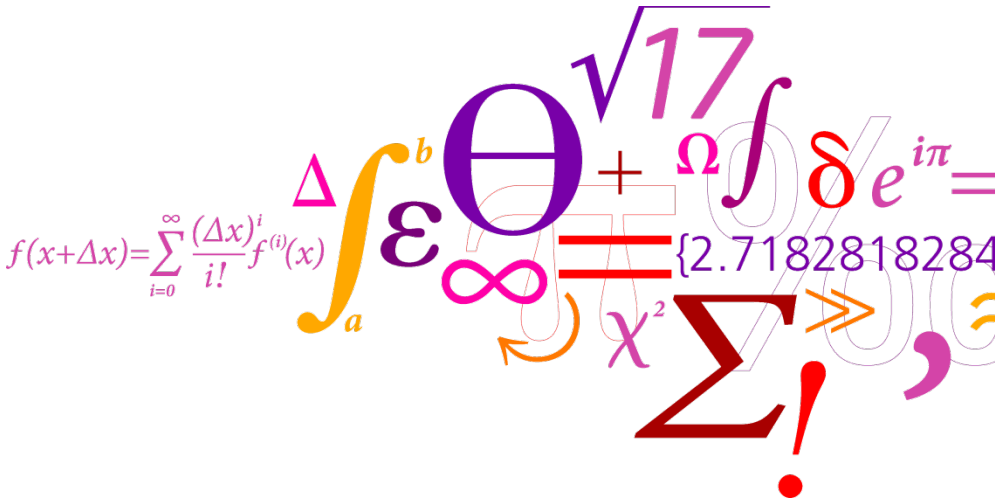
A new type of white light-emitting diode using fluorescent silicon carbide (LEDSiC)

Acknowledgement:
Innovation Fund Denmark (No. 4106-00018B)



DTU Fotonik
Department of Photonics Engineering

Agenda

- Participants: Mikael Syväjärvi, Valdas Jokubavicius, Philipp Schuh On behalf of Peter Wellmann, Leif Jensen, Berit Herstrøm, Peter Behrensdorff Poulsen, Carsten Dam-Hansen, Paul Michael Petersen, Li Lin, Yi Wei, Yiyu Ou, Weifang Lu, Haiyan Ou, Satoshi Kamiyama, Matsuo, Iwasa, Meng Liang, Xiaoyan Yi, Zhiqiang Liu, Junxi Wang

- Location: **S08 in building 101**

Agenda on Sept. 8th

- 13:00~13:20 Haiyan Ou: Welcome and Status Introduction of the LEDSiC project
- 13:20~13:50 Satoshi Kamiyama: Recent progress on f-SiC and white LED
- 13:50~14:20 Mikael Syväjärvi, Valdas Jokubavicius: presentation from Linköping University
- 14:20~14:50 **Main results on 'Photoluminescence and infrared reflectance in porous 6H-SiC passivated by atomic layer deposited films' by Weifang**
- 14:50~15:20 Meng Liang, 'High quality nitrides growth technology on SiC substrates' from SEMI CAS

Agenda on Sept. 8th (continue)

- 15:20~16:00 Coffee break and network
- 16:00~16:15 Main results on ’fluorescent SiC based hybrid white LED ’ by Yiyu
- 16:15~16:30 ‘Optical characteristics of plasmonic LEDs with and without dielectric films’ by Matsuo
- 16:30-17:00 Main results on ‘Dynamics of Carrier Lifetime in f-SiC’ by Yi

- 17:00~17:10 Photoshot
- 17:10-18:00 Prototype demonstration and lab tour
- 19:00~ Dinner and network

Brede Spisehus | I.C. Modewegs Vej | 2800 Kgs. Lyngby

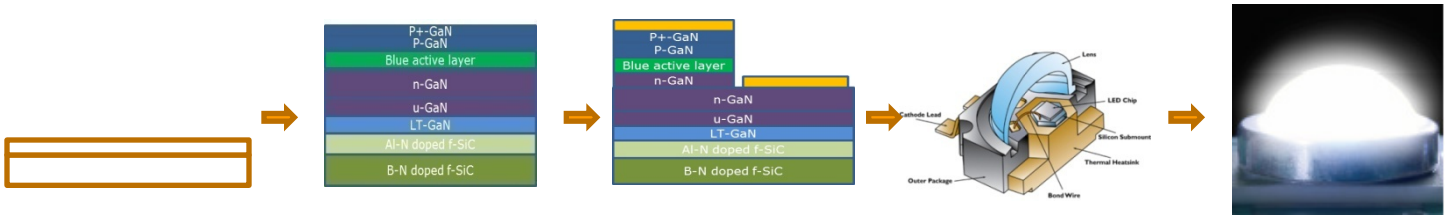
Agenda on Sept. 9th

- 9:00-9:30 **Peter Wellmann, Philipp Schuh: presentation from FAU**
- 9:30~9:45 'Dependence of doping concentration on optical properties of porous SiC' by Iwasa

- 9:45-10:15 Main results on 'Light extraction efficiency enhancement and fabrication of NUV-LED devices' by Li
- 10:15-10:30 Main results on 'Near UV LED package' by Jiehui

- 10:30-11:00 Coffee break and network
- 11:15~11:50 Group discussion (material group led by Leif and device group led by Carsten)
- 11:50~12:00 Group presentation
- 12:00~12:15 Concluding remark by Haiyan
- 12:15~14:00 Lunch and discussion

Work packages



a) f-SiC growth

b) MOCVD growth

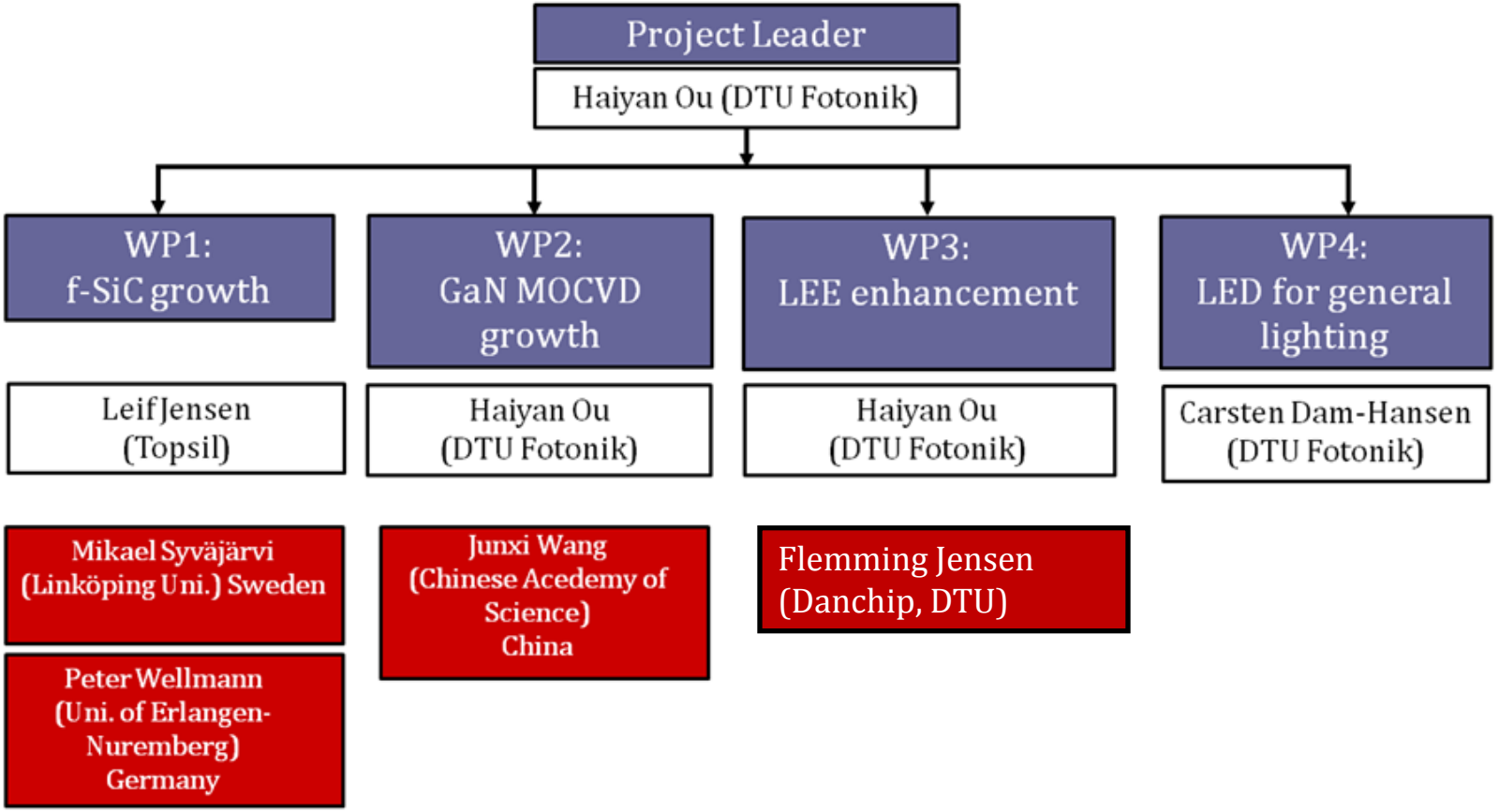
c) LED device processing

d) LED device package

e) LED device for general lighting

- **WP#1** f-SiC growth and optimization
- **WP#2** MOCVD growth of GaN based LED on f-SiC
- **WP#3** Efficiency enhancement of LED in term of light extraction
- **WP#4** Processing and optical characterization of white LED device for general lighting

Project structure and division into work packages



Advisory board

- Prof. Satoshi Kamiyama, Meijo Unviersity

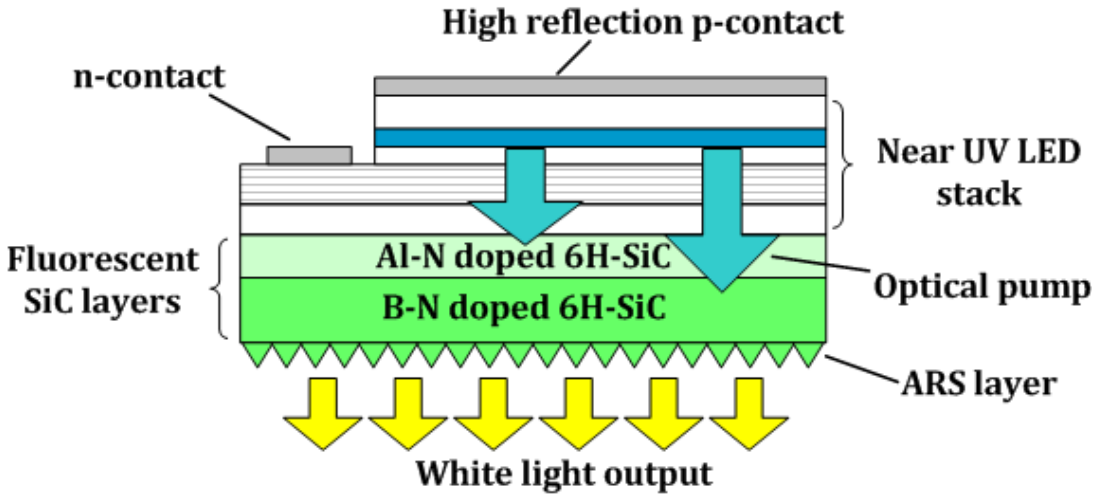
Main manpower:

Main participants	WP involved	Focus	Main activities
Ph. D student **Yi Wei**	WP1	f-SiC material growth	1. Growth of source material using physical vapor deposition (PVD) method 2. Growth of epitaxial layer using fast sublimation growth process (FSGP) 3. Material characterization (SIMS, X-ray diffraction, carrier lifetime, photoluminescence etc.) for optimization of the material growth
Ph. D student **Li Lin**	WP2, WP3, WP4	The fabrication and optimization of LEDs for general lighting	1. Post processing of the LED devices including mesa etching, electrode deposition, etc. 2. Surface nanostructuring and passivation; 3. On-chip LED tests (IV curve, IP curve, efficiency, CRI, etc.) 4. Package of the LED devices 5. LED test and evaluation for general lighting
Postdoc **Yiyu Ou**	WP1, WP2, WP3, WP4,	MOCVD growth of GaN on top of f-SiC for a complete LED device The fabrication and optimization of LEDs for general lighting	1. High efficiency GaN LED growth on f-SiC by using MOCVD 2. Material characterization of the grown GaN LED by using SEM, TEM, X-ray diffraction, etc. 3. Optical characterization of the complete LED device by using electroluminescence for efficiency and CRI, etc.

Main manpower+:

Main participants	WP involved	Focus	Main activities
Ph. D student **Weifang Lu**	WP1	f-SiC material growth	1. Passivation of surface textured f-SiC 2. Fabrication and passivation of porous SiC
Visiting Ph. D student **Jiehui Li**	WP3, WP4	The fabrication and package of LEDs for general lighting	1. On-chip LED tests (IV curve, IP curve, efficiency, CRI, etc.) 2. Package of the LED devices 3. LED test and evaluation for general lighting and visible light communication
Visiting Ph D student from Oct. 1st, 2016 **Xiaoyan Wu**	WP1,	Material characterization of f-SiC	

Status

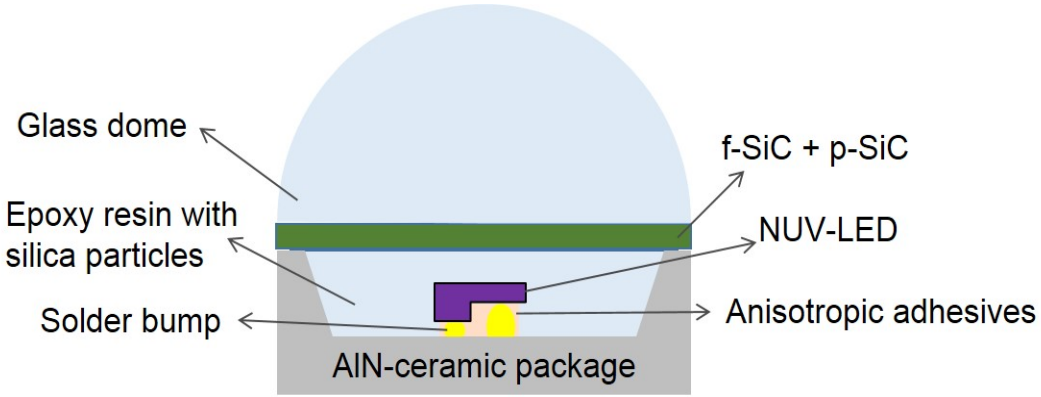


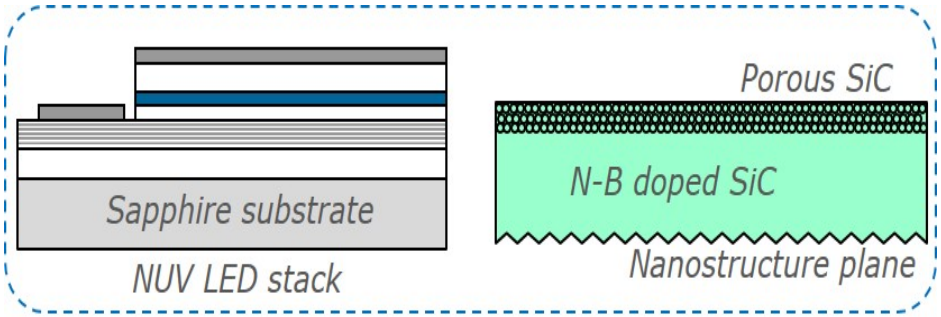
- Epitaxial growth: **boron-nitrogen (B-N)** co-doped f-SiC
- MOCVD growth: near-UV GaN LEDs on sapphire substrates

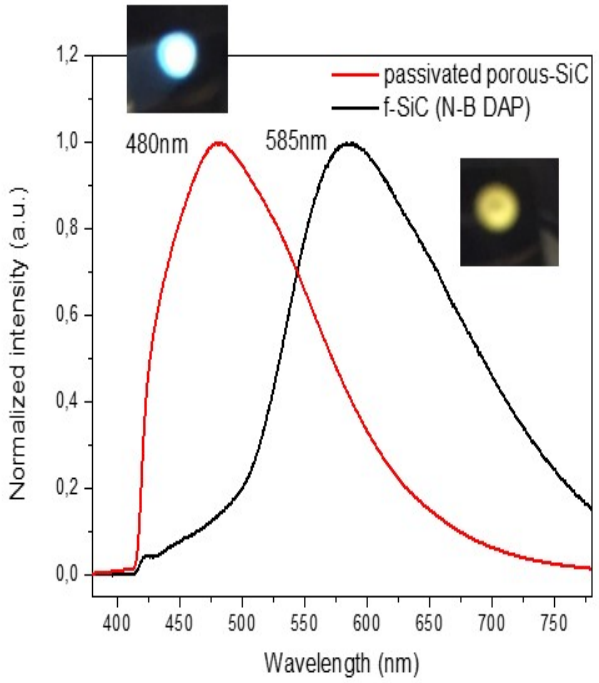
At DTU:

- **Hybrid f-SiC based white LED**
- A post-growth **LED processing flow** (photolithography, ICP etch, n and p contact, etc.) being developed in the cleanroom of DTU Danchip, surface nanostructuring of GaN for extraction efficiency enhancement
- **LED package** for system application
- **Porous SiC** and passivation for an alternative light source
- **Carrier dynamics investigation of f-SiC** for emission efficiency enhancement

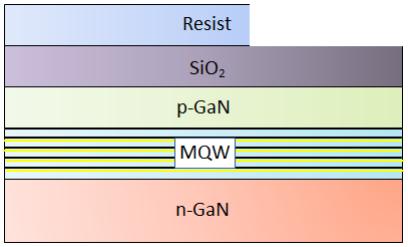
Fluorescent SiC based hybrid white LED



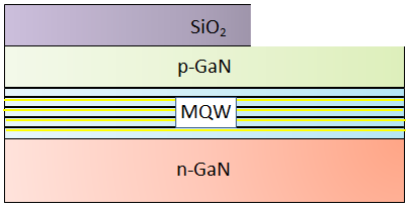




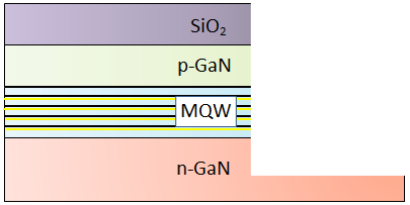
Fabrication of GaN LED devices



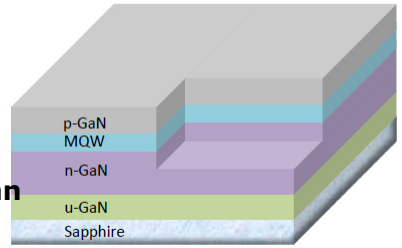
Photolithography



Etch of silicon dioxide by BHF
& After etch and resist removal

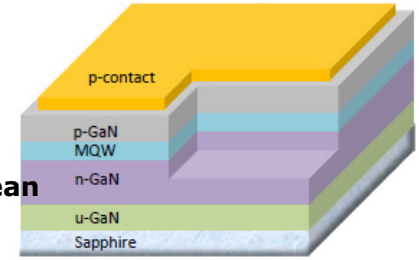


ICP etch of GaN



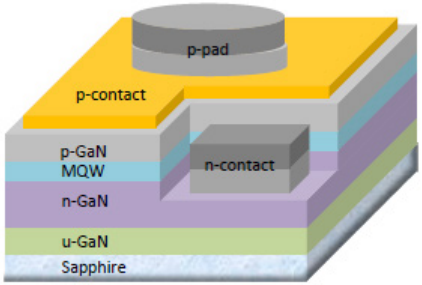
Removal of silicon dioxide

5% HF clean

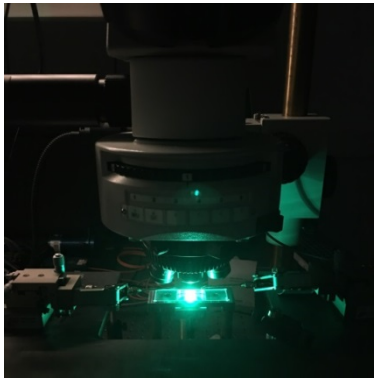


CSL deposition

5% HF clean

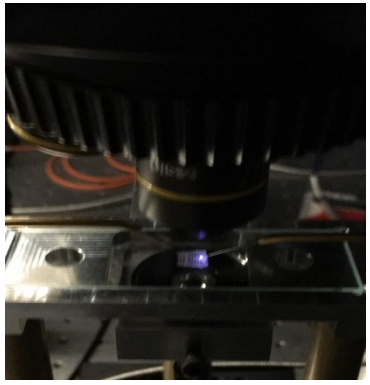


Contacts deposition

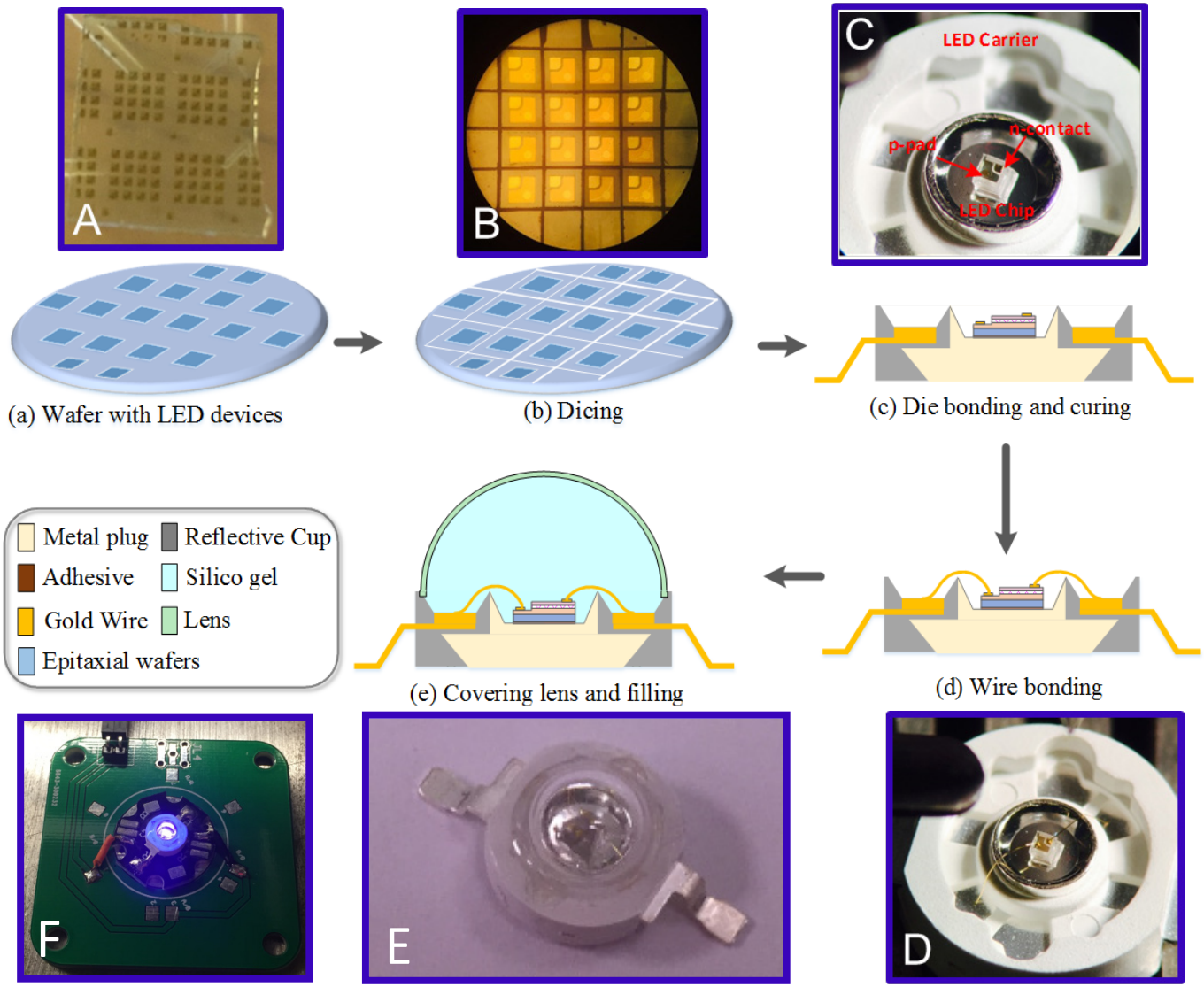


510 nm at 60 mA

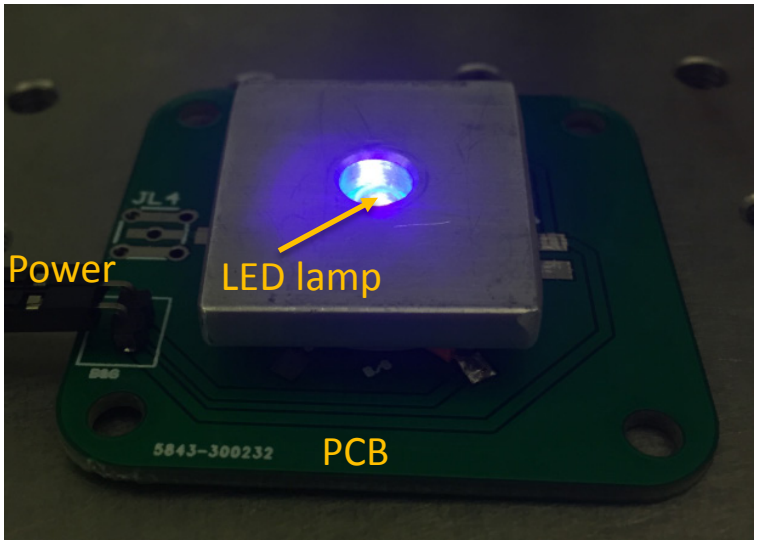
385 nm at 15 mA



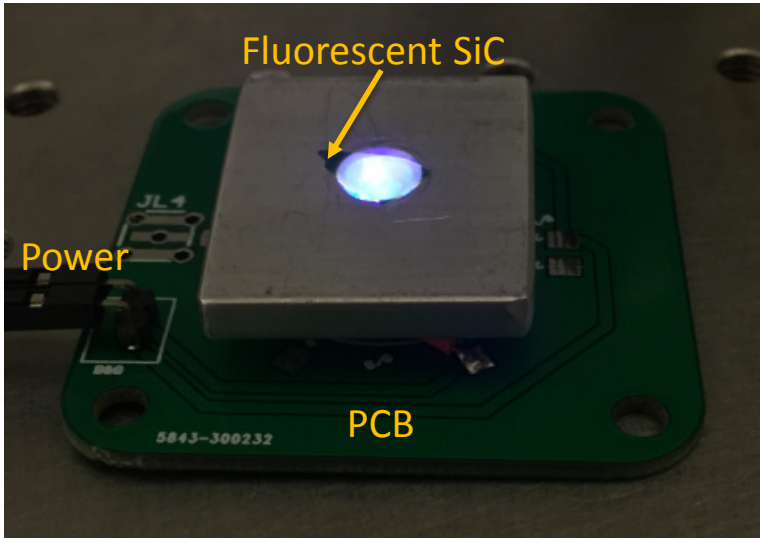
❑LED package processes:



❑Demonstration



Without fluorescent SiC



With fluorescent SiC

Porous SiC fabrication and passivation by atomic layer deposited Al_2O_3 and TiO_2 film

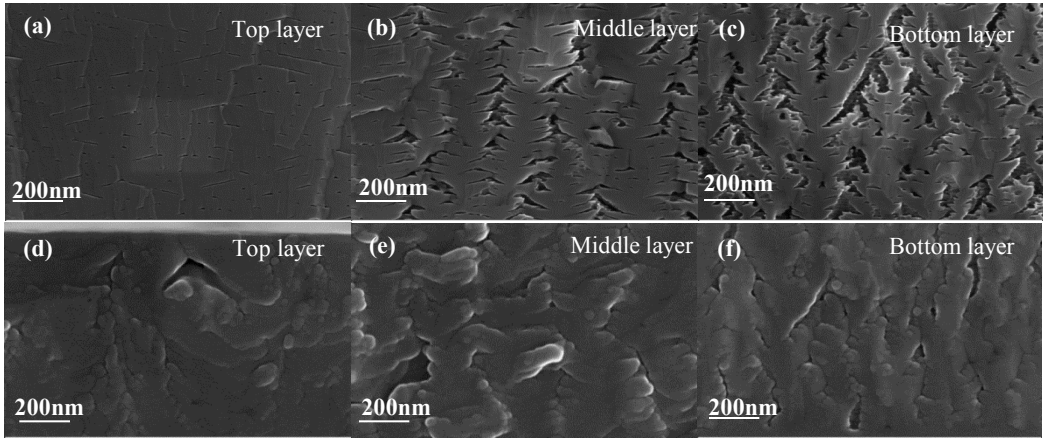
The surface chemistry reaction during Al_2O_3 and TiO_2 ALD (atomic layer deposition) deposition:

1st half-reaction: $Al\text{-}OH + Al(CH_3)_3 \rightarrow Al\text{-}O\text{-}Al(CH_3)_2 + CH_4$

2nd half-reaction: $Al\text{-}O\text{-}Al(CH_3)_2 + 2H_2O \rightarrow Al\text{-}O\text{-}Al(OH)_2 + 2CH_4$

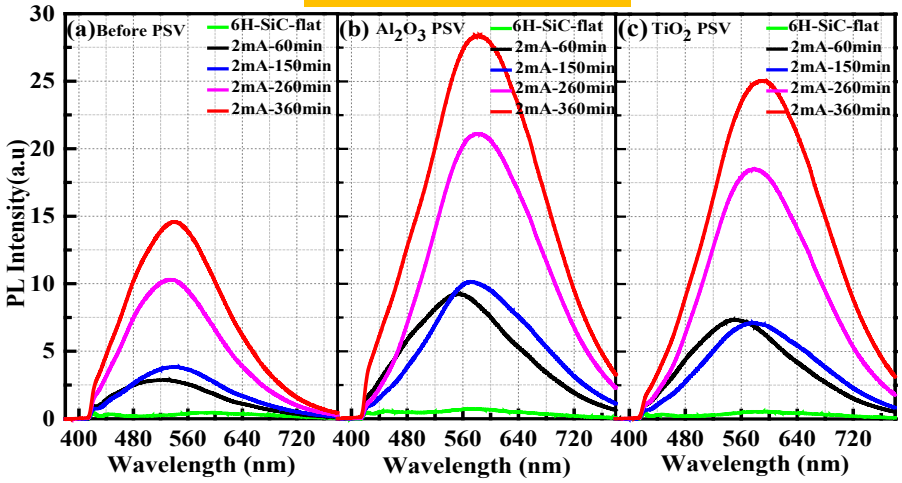
1st half-reaction: $Ti\text{-}OH + TiCl_4 \rightarrow Ti\text{-}O\text{-}TiCl_3 + HCl$

2nd half-reaction: $Ti\text{-}Cl + H_2O \rightarrow Ti\text{-}OH + HCl$

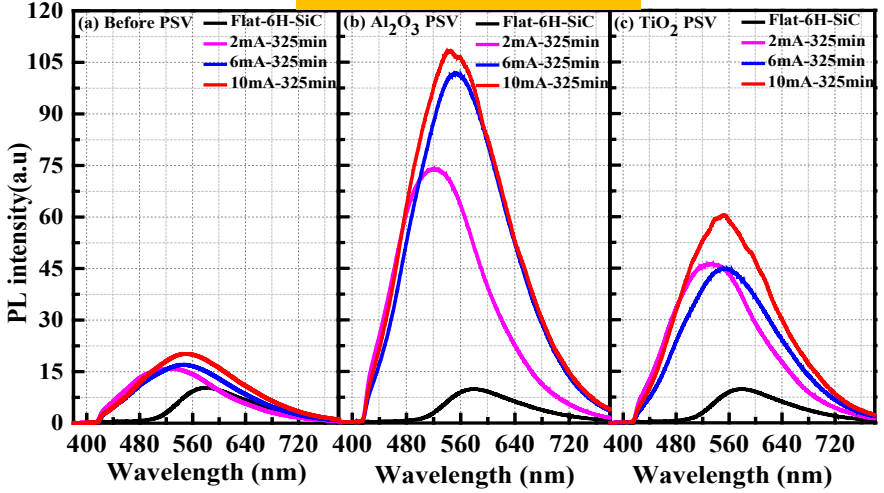


Cross-sectional SEM images of SiCrystal sample (360 min): (a) top layer, (b) middle layer and (c) bottom layer, and the corresponding layer covered with 20 nm thick TiO_2 .

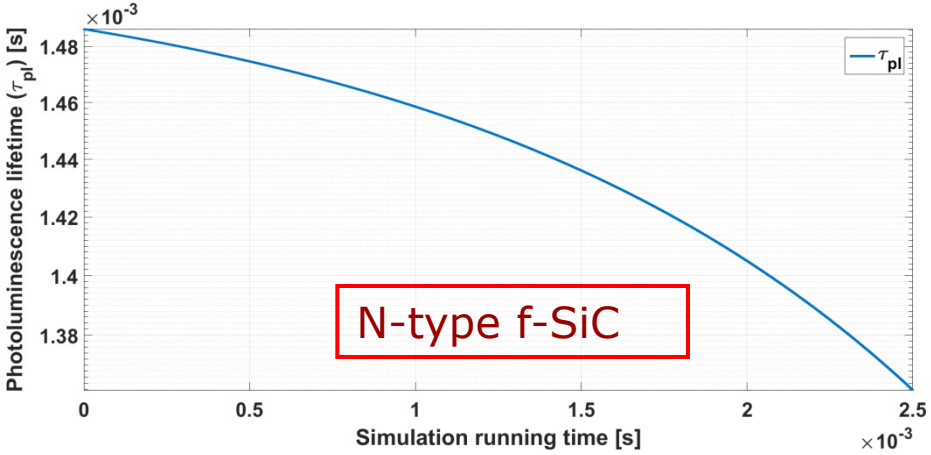
SiCrystal samples

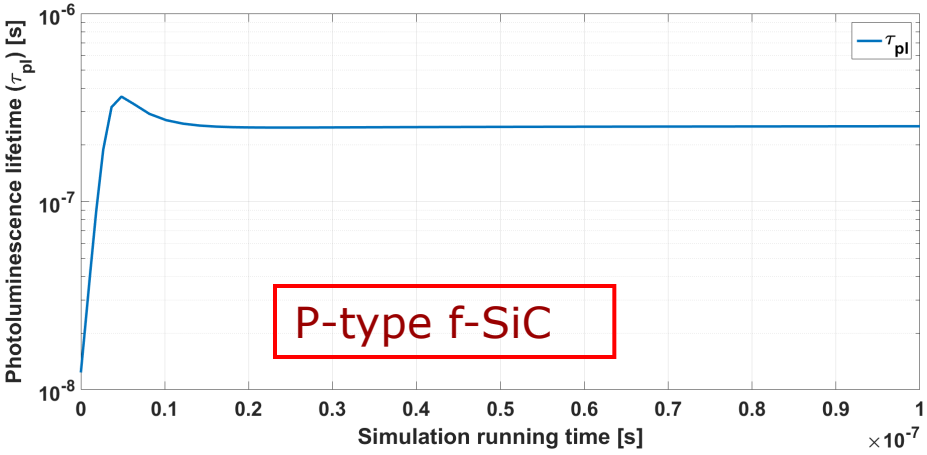


Tankeblue samples



Carrier lifetime simulation results for N-type and P-type f-SiC





$$\frac{1}{\tau_{PL,N}(t)} = \frac{1}{\tau_p(t)} + \frac{1}{\tau_n(t)}\left[\frac{\delta n(t)}{n_0 + \delta n(t)}\right]$$

Measured τ_{PL}	Simulated τ_{PL}
0.5292 [ms]	1.36 [ms]

Predicted defect E1/E2 concentration: $>5 \times 10^{13}[cm^{-3}]$

$$\frac{1}{\tau_{PL,P}(t)} = \frac{1}{\tau_n(t)} + \frac{1}{\tau_p(t)}\left[\frac{\delta p(t)}{p_0 + \delta p(t)}\right]$$

Measured τ_{PL}	Simulated τ_{PL}
0.1615 [us]	0.2518 [us]

Predicted defect E1/E2 concentration: $\sim 5 \times 10^{15}[cm^{-3}]$

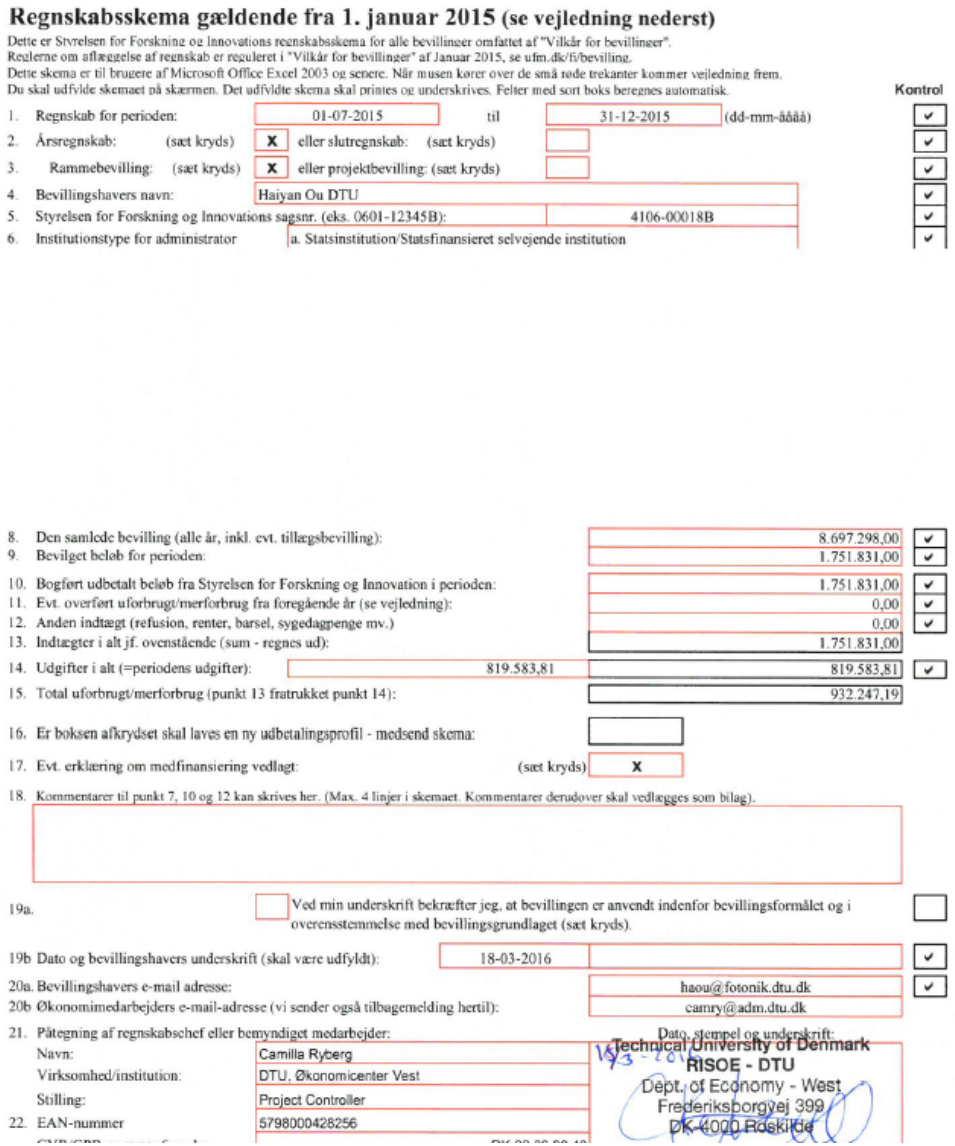
Funding status

- Financial statement for 2015

The budget is made from Jule 1st, 2015,

But the project started from Sept.1 st 2015

Salary and cleanroom expenses



Regnskabsskema gældende fra 1. januar 2015 (se vejledning nederst)

Dette er Styrelsen for Forskning og Innovations regnskabsskema for alle bevillinger omfattet af "Vilkår for bevillinger".
Reglerne om aflæggelse af regnskab er reguleret i "Vilkår for bevillinger" af Januar 2015, se ufm.dk/fi/bevilling.
Dette skema er til brugere af Microsoft Office Excel 2003 og senere. Når musen kører over de små røde trekanter kommer vejledning frem.
Du skal udfylde skemaet på skærmen. Det udfyldte skema skal printes og underskrives. Felter med sort boks beregnes automatisk.

					Kontrol
1.	Regnskab for perioden:	01-07-2015	til	31-12-2015 (dd-mm-åååå)	✓
2.	Årsregnskab: (sæt kryds)	X	eller slutregnskab: (sæt kryds)		✓
3.	Rammebevilling: (sæt kryds)	X	eller projektbevilling: (sæt kryds)		✓
4.	Bevillingshavers navn:	Haiyan Ou DTU			✓
5.	Styrelsen for Forskning og Innovations sagsnr. (eks. 0601-12345B):	4106-00018B			✓
6.	Institutionstype for administrator	a. Statsinstitution/Statsfinansieret selvejende institution			✓

8.	Den samlede bevilling (alle år, inkl. evt. tillægsbevilling):		8.697.298,00	✓
9.	Bevilget beløb for perioden:		1.751.831,00	✓
10.	Bogført udbetalt beløb fra Styrelsen for Forskning og Innovation i perioden:		1.751.831,00	✓
11.	Evt. overført uforbrugt/merforbrug fra foregående år (se vejledning):		0,00	✓
12.	Anden indtægt (refusion, renter, barsel, sygedagpenge mv.)		0,00	✓
13.	Indtægter i alt jf. ovenstående (sum - regnes ud):		1.751.831,00	
14.	Udgifter i alt (=periodens udgifter):	819.583,81	819.583,81	✓
15.	Total uforbrugt/merforbrug (punkt 13 fratrukket punkt 14):		932.247,19	
16.	Er boksen afkrydset skal laves en ny udbetalingsprofil - medsend skema:			
17.	Evt. erklæring om medfinansiering vedlagt: (sæt kryds)		X	
18.	Kommentarer til punkt 7, 10 og 12 kan skrives her. (Max. 4 linjer i skemaet. Kommentarer derudover skal vedlægges som bilag).			
19a.	Ved min underskrift bekræfter jeg, at bevillingen er anvendt indenfor bevillingsformålet og i overensstemmelse med bevillingsgrundlaget (sæt kryds).			
19b	Dato og bevillingshavers underskrift (skal være udfyldt):	18-03-2016		✓
20a.	Bevillingshavers e-mail adresse:		haou@fotonik.dtu.dk	✓
20b	Økonomimedarbejders e-mail-adresse (vi sender også tilbagemelding hertil):		camry@adm.dtu.dk	
21.	Påtegning af regnskabschef eller bemyndiget medarbejder:		Dato, stempel og underskrift:	
	Navn:	Camilla Ryberg		
	Virksomhed/institution:	DTU, Økonomicenter Vest		
	Stilling:	Project Controller		
22.	EAN-nummer	5798000428256		

Technical University of Denmark
RISOE - DTU
Dept. of Economy - West
Frederiksborgvej 399
DK-4000 Roskilde

Publications

- Journal contribution

1. Yiyu Ou, Daisuke Iida, Ahmed Fadil, Haiyan Ou, 'Enhanced Emission Efficiency of Size-Controlled InGaN/GaN Green Nanopillar Light-Emitting Diodes' International Journal of Optics and Photonic Engineering, vol: 1, issue: 1 (2016)
2. Ahmed Fadil, Daisuke Iida, Yuntian Chen, Yiyu Ou, Satoshi Kamiyama, Haiyan Ou, 'Influence of near-field coupling from Ag surface plasmons on InGaN/GaN quantum-well photoluminescence', Journal of Luminescence, vol: 175, pp: 213–216 (2016)
3. W. Lu, Y. Ou, P. M. Petersen, and H. Ou, "Fabrication and surface passivation of porous 6H-SiC by atomic layer deposited films," Optical Materials Express 6(6), 1956-1963 (2016).
4. W. Lu, Y. Ou, V. Jokubavicius, A. Fadil, M. Syväjärvi, P. M. Petersen, and H. Ou, "Wavelength-conversion efficiency enhancement in nano-textured fluorescent 6H-SiC passivated by atomic layer deposited titanium oxide," Physica Scripta 91, 074001 (2016).
5. Weifang Lu, Yiyu Ou, Valdas Jokubavicius, Ahmed Fadil, Mikael Syväjärvi, Volker Buschmann, Steffen Ruttinger, Paul Michael Petersen, Haiyan Ou, 'Photoluminescence Enhancement in Nanotextured Fluorescent SiC Passivated by Atomic Layer Deposited Al2O3 Films' Materials Science Forum, vol: 858, pp: 493-496, 2016
6. Yiyu Ou, Ahmed Fadil and Haiyan Ou, 'Antireflective SiC Surface Fabricated by Scalable Self-Assembled Nanopatterning', Micromachines, 7, 152 (2016)
7. Valdas Jokubavicius, JianwuSun, XinyuLiu, GholamrezaYazdi, Ivan.G.Ivanov, RositsaYakimova, MikaelSyväjärvi, 'Growth optimization and applicability of thick on-axis SiC layers using sublimation epitaxy in vacuum', Journal of crystal growth, 448, 51-57 (2016)
8. Ahmed Fadil, Yiyu Ou, Daisuke Iida, Satoshi Kamiyama, Paul Michael Petersen and Haiyan Ou, ' Combining surface plasmonic and light extraction enhancement on InGaN quantum-well light-emitters' Nanoscale, (2016) Accepted

Publications

- Conference contributions

1. Yiyu Ou, Meng Xiong, Weifang Lu, Ahmed Fadil, Valdas Jokubavicius, Mikael Syväjärvi, Paul Michael Petersen, Haiyan Ou,'Hybrid surface structures for efficiency enhancement of fluorescent SiC for white LED application' 4th International workshop on LEDs and solar applications, 2016, Nagoya **(Invited)**
2. Haiyan Ou, Weifang Lu, Yiyu Ou, Valdas Jokubavicius, Mikael Syväjärvi, Philipp Schuh, (Invited author) ; Peter Wellmann, Yoshimi Iwasa,Satoshi, Kamiyama, 'Passivation of surface-nanostructured f-SiC and porous SiC' 4th International workshop on LEDs and solar applications, 2016, Nagoya **(Invited)**
3. Ahmed Fadil, Yiyu Ou, Daisuke Iida, Oleksii Kopylov, Haiyan Ou, 'Electrically driven surface plasmon light-emitting diodes', 4th International workshop on LEDs and solar applications, 2016, Nagoya **(Invited)**

4 Weifang Lu, Yoshimi Iwasa, Yiyu Ou, Satoshi Kamiyama, Paul Michael Petersen, Haiyan Ou, 'Photoluminescence enhancement in porous SiC passivated by atomic layer deposited Al2O3 films',Conference on Lasers and Electro-Optics 2016, 2016, San Jose, California

5. Jiehui Li, Ahmed Fadil, Haiyan Ou, Nan Chi, 'Enhancement of the Modulation Bandwidth for surface Plasmon coupled LEDs for Visible Light Communication', Conference on Lasers and Electro-Optics 2016, 2016, San Jose, California
6. Ahmed Fadil, Yiyu Ou, Daisuke Iida, Oleksii Kopylov, Haiyan Ou, ' Investigations of thin p-GaN light-emitting diodes' Conference on Lasers and Electro-Optics 2016, 2016, San Jose, California
7. Li Lin, Flemming Jensen, Berit Herstrøm, and Haiyan Ou, "Luminescence enhancement of near ultraviolet light-emitting diodes," **Accepted** by Optical Sources and Applications in Asia Communications and Photonics Conference in Wuhan, China (2016)
8. Yi Wei, Ahmed Fadil, Haiyan Ou, 'Localized Surface Plasmon on <6H> SiC with Ag Nanoparticles', **Accepted** by 11th European Conference on Silicon Carbide & Related Materials in Halkidiki, Greece (2016)

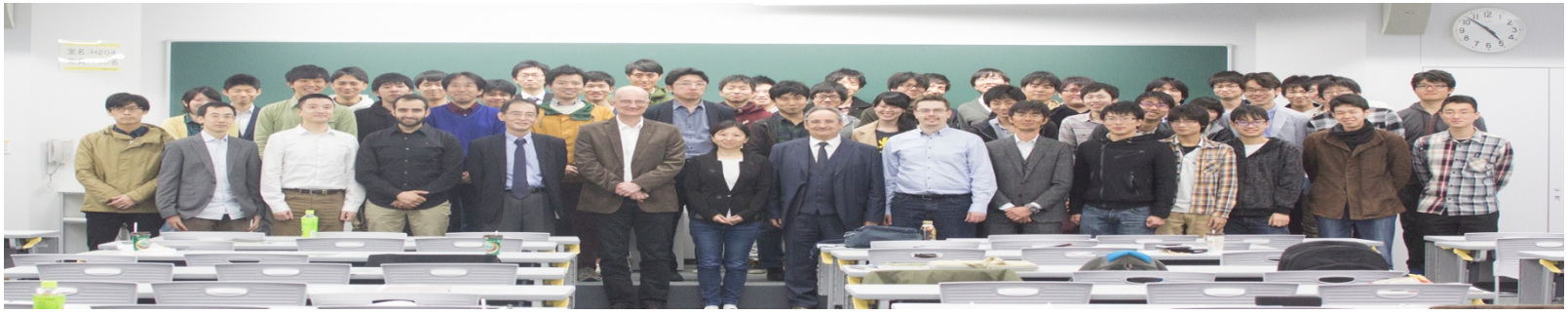
Added resources

- Attracted a new grant from research council of Norway with collaboration of SINTEF

- Attracted two exchange Ph.D students from Fudan university in China and State Key Laboratory of Functional Materials for Informatics Shanghai Institute of Microsystem and Information Technology Chinese Academy of Sciences

Project management

Order	Meeting date and place	Participants	Program	Follow-up
1.	Kick-off,Sept.2, 2015 DTU	All partners, Satoshi Kamiyama	refer	
2.	Dec.11, 2015, DTU	Internal (2PhD students+1 postdoc+Haiyan)		1. Report hand-in before March 1, 2016 2. Li, Commercial LED epiwafers on SiC substrate
3.	March 30, 2016, Meijo	Workpackage leader		
4.	April 6th, 2016, DTU	Danish partners		
5.	September 8-9, 2016, DTU	All partners		
6.	Dec. xx, 2016, DTU	Danish partners		



Summary

- Economics is under control according to the budget by our project controller Miss Camilla
- 8 journal contributions and 8 conference contributions
- The progress of the project is satisfactory

Group discussion

- The main achievement of the past year
- The goal for the next year
- Challenges and solution

Plan for the next year:

- E-MRS spring meeting 2017

Symposium on 'Wide bandgap semiconductors for LEDs, solar and related energy technologies'

Personnel exchange:

- Weifang will stay at Meijo universiy for 3 months from Oct.1, 2016
- Yi will stay at Erlangen univeristy for 3 months from Oct. 1, 2016

Funding application:

- Innovative Training Networks (ITN) application, Marie Skłodowska-Curie Actions
- Sina-danish cooperation

Material group discussion summary

- 6H-SiC – off axis 1.4 deg ~ 2” diameter. Nitrogen content 8e18 -25 wafers from TankBlue, SiCrystal or SICC for all project parties. Cree for semi insulating and low defects a possibility. EPI or Dies.
- Al-N co doping focus – no boron in reactor < 1e17, passivation of defects methods by controlling cooling down and switching gas methods.
- **Porous structure:** Structure direct current vs. puls current method. – tune to blue emission shift of
- f-SiC growth 1.4 deg focus fro NUV-LED.

- **Sample size :**2” - 1/4 growth focus

- **Material thickness:** 50 um for Al-N and 200 um for B-N – Optimize thickness difficult to handle thin wafers. Polish SiC to 100 – 150 um thickness experiment

- **Problems:** Lattice mismatch critical thickness for stacking faults and dislocations. 8e18 Nitrogen in SiC to avoid

Device group discussion summary

Achievements:

- 510 nm Green LED GaN based EL (testing packaging processes)
- NUV LED on sapphire substrate GaN based EL packaged

Goals for the coming year:

- Flip chip bonded NUV LED (on sapphire) on ceramic carrier with f-SiC on top
- Hybrid f-SiC (without porous layer) based ”white” LED in ceramic carrier
- Blue emission from porous SiC will be a second step (wait for material optimization).
- Measurements on NUV devices, total spectral flux and efficiency.
- Measurement on ”white” LED
- Temperature controlled setup for testing

Challenges

- Saphire or SiC sustrate? What should we do with light extraction enhancement?
- Reflective material for top side (p)
- Flip chip bonding on carrier
- Mount with adhesive to support chip
- Mount f-SiC on top of carrier, cutting to round shape
- What is the end product?

Succes criteria:

Packaged white LED

- Flux? 4 lm
- Efficiency? 12.8 lm/W
- White light? CCT? CRI?