LEDSiC kick-off meeting

Agenda:

- 13:00~13:20 **Haiyan Ou**: Welcome and 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**: presentation from Linköping University
- 14:20~14:50 **Peter Wellmann**: presentation from FAU
- 14:50~15:20 **Christian Gammeltoft Hindrichsen**: presentation from Topsil
- 15:20~16:00 Coffe break and network

- 16:00~16:30 **Flemming Jensen & Berit Herstrøm**: presentation from Danchip
- 16:30~17:00 **Meng Liang**, presentation from SEMI CAS
- 17:00~17:30 **Paul Michael Petersen**: presentation from Fotonik
- 17:30~18:00 short introduction of the 2 Ph D students (**Yi Wei, Li Lin**) and 1 postdoc (**Yiyu Ou**)
- Photo shot
- 19:00~ Dinner and network

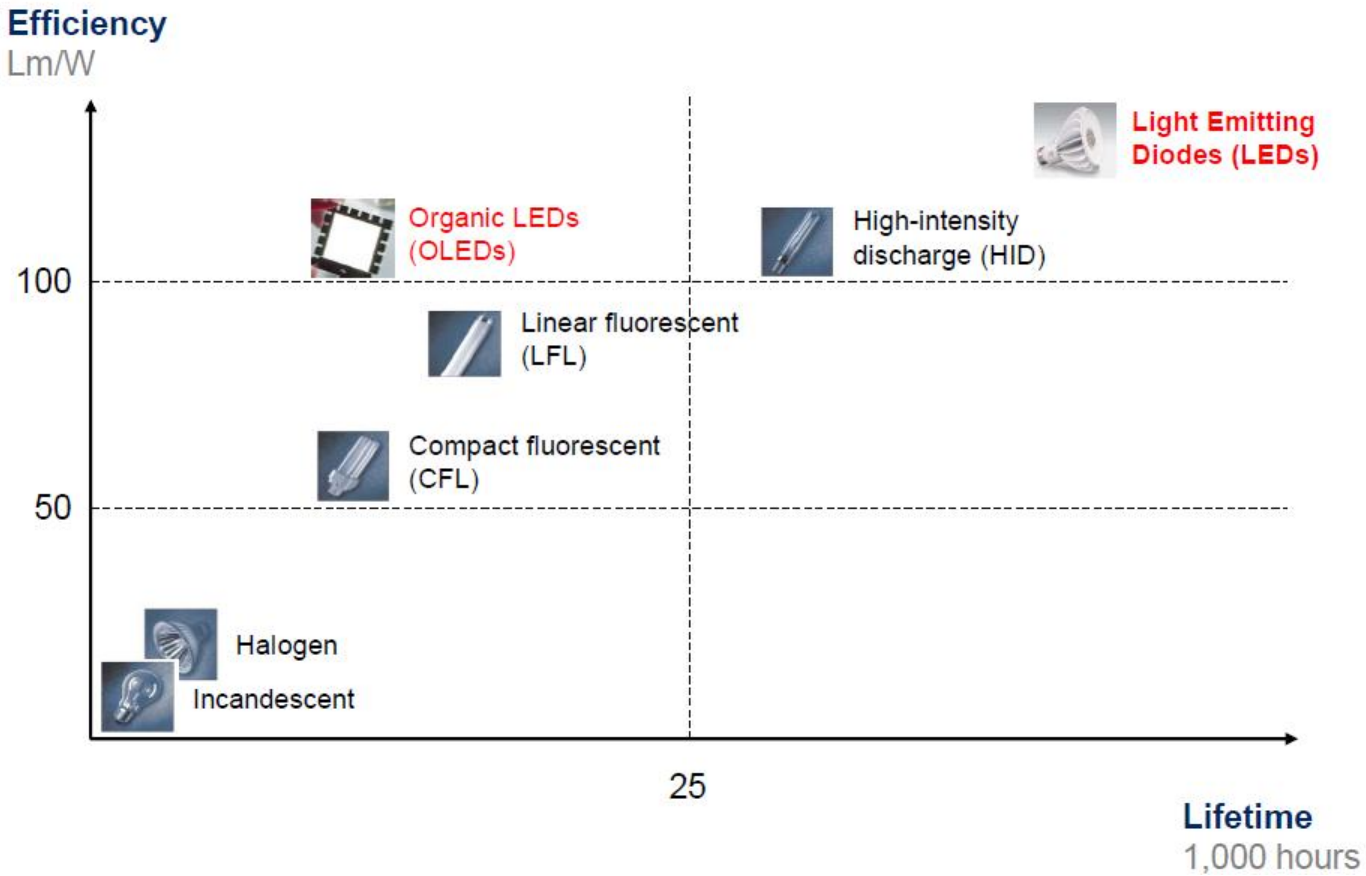
Restaurant Cofoco Abel Cathrines Gade 7, 1654 København
telephone: 33 13 60 60

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

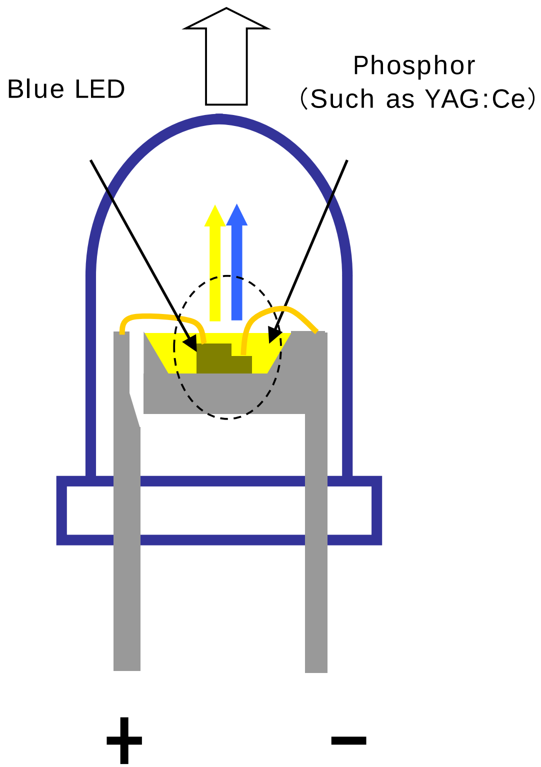
Acknowledgement:
Innovation Fund Denmark (No. 4106-00018B)

DTU Fotonik
Department of Photonics Engineering

LED: energy saving



White LED light source



Advantages:

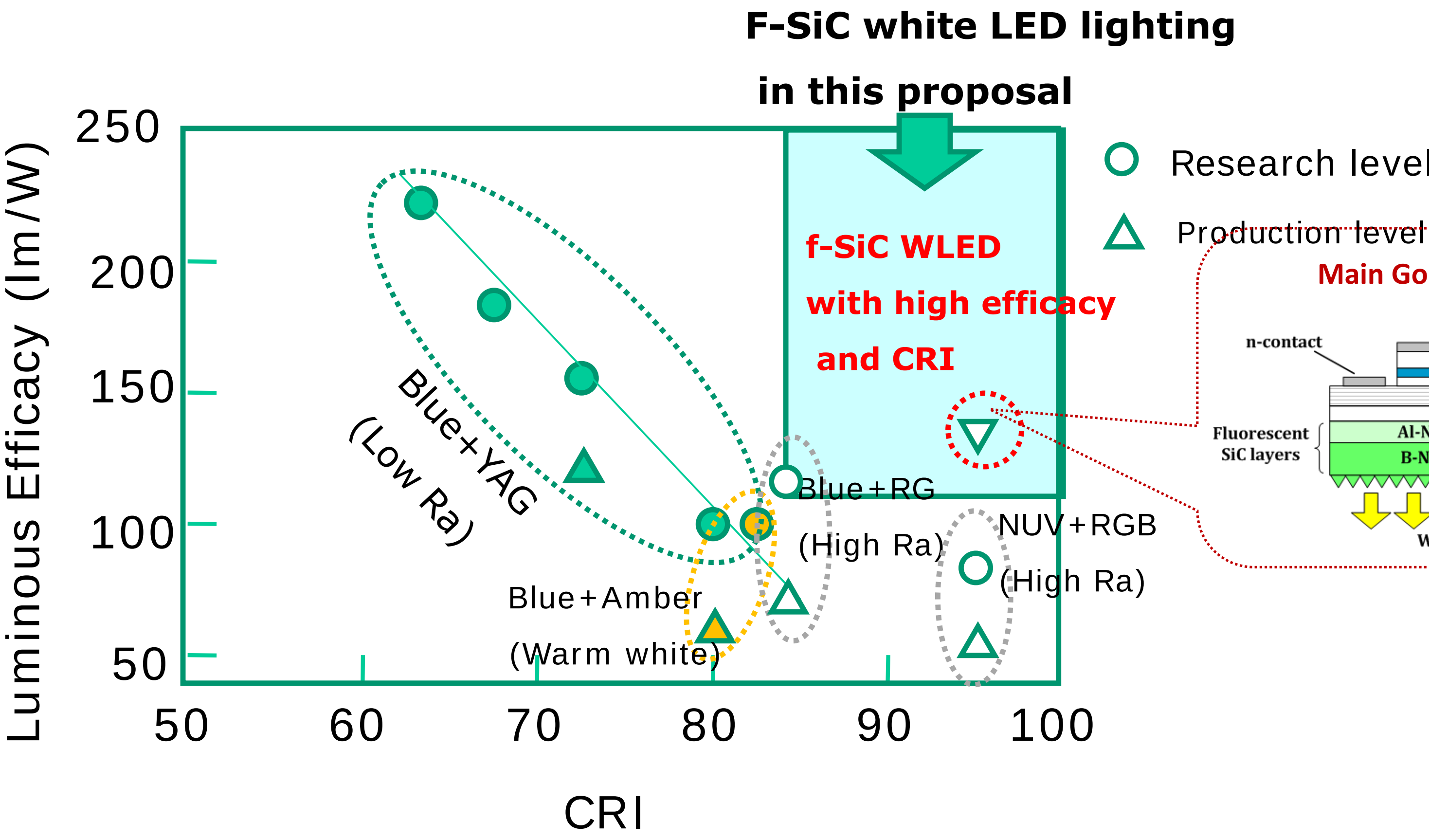
- Energy efficient
- Compact
- Long lifetime
- Spectral design flexibility

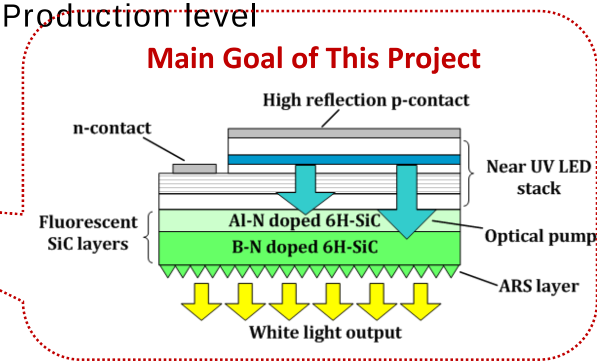
Disadvantages:

- Rare earth contained in the phosphors
- Fast degradation of phosphors
- Tradeoff between luminous efficacy and color rendering index

Introduction

- Project period: 3 years project starting from July 1st. 2015





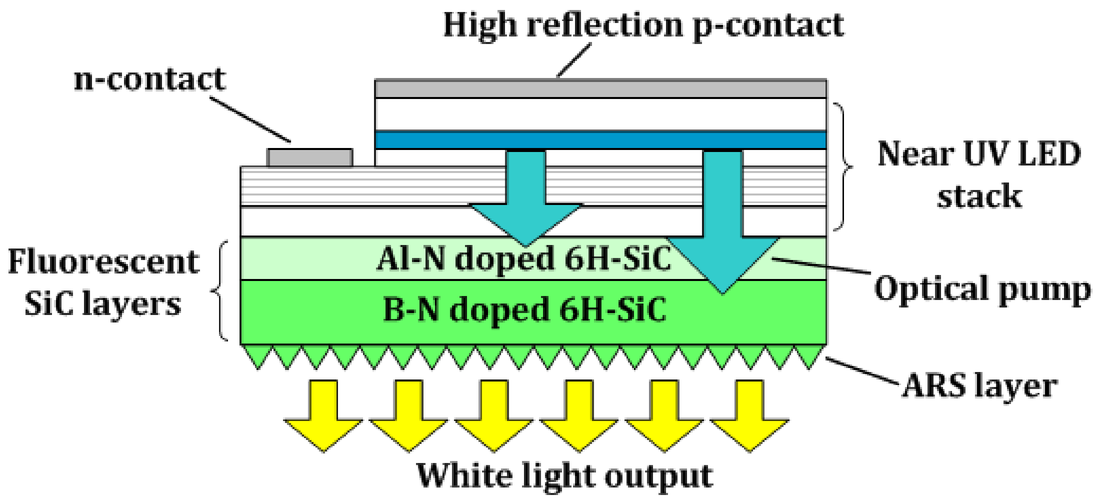
Objective of the project

- The general goal of the project is to research and develop an energy-efficient white LED light source on f-SiC substrate with an extremely high luminous efficacy and colour rendering index.

Technical goals for this new type of white LED are:

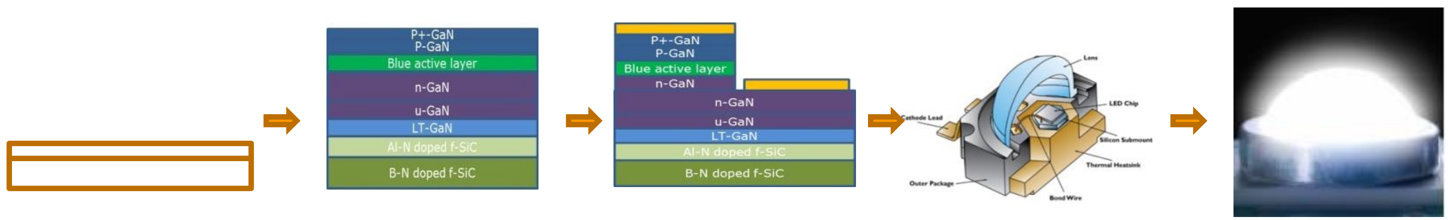
- To achieve a high luminous efficacy (i.e.>=100 lm/W)
- To achieve a high colour rendering index (i.e.>= 90)
- To achieve a long device lifespan (i.e.>= 600,000 hours)

Main results expected from the project



- Epitaxial growth: **boron-nitrogen (B-N)** and aluminum-nitrogen (Al-N) co-doped f-SiC
- MOCVD growth: GaN LEDs on f-SiC substrates
- A new post-growth LED processing line (photolithography, ICP etch, n and p contact, etc.) for LEDs on SiC substrate will be set up in the cleanroom of DTU Danchip
- **Surface nanostructuring** and passivation on both the f-SiC surface and GaN surface to enhance the light extraction efficiency
- **Surface plasmon** for emission efficiency enhancement
- **Graphene** as transparent contact for better electricity conduction
- F-SiC WLED demonstrated
- A new-designed lighting module demonstrated

Work packages



a) f-SiC growth

b) MOCVD growth

c) LED device processing

d) LED device package

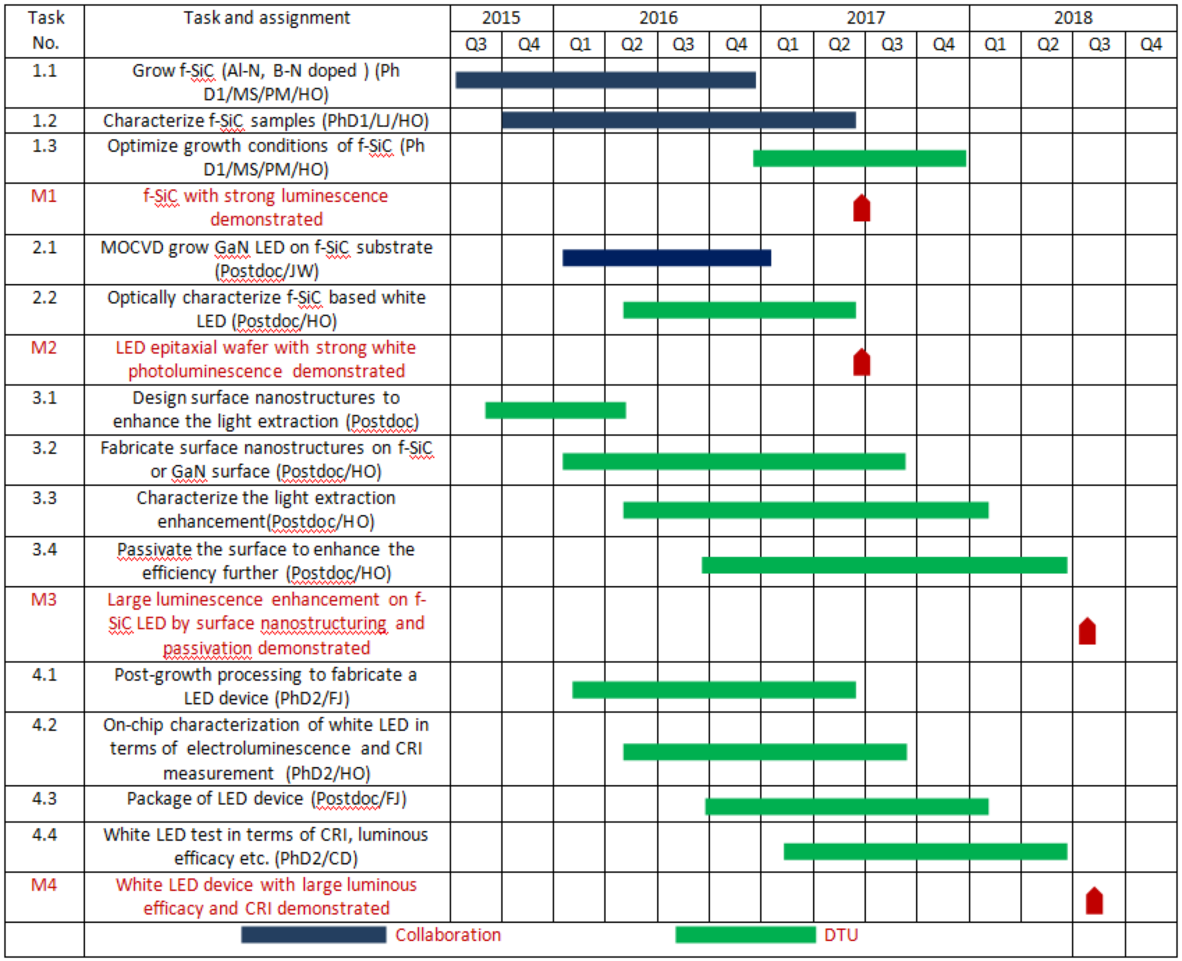
e) LED device for general lighting

- **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

Milestones

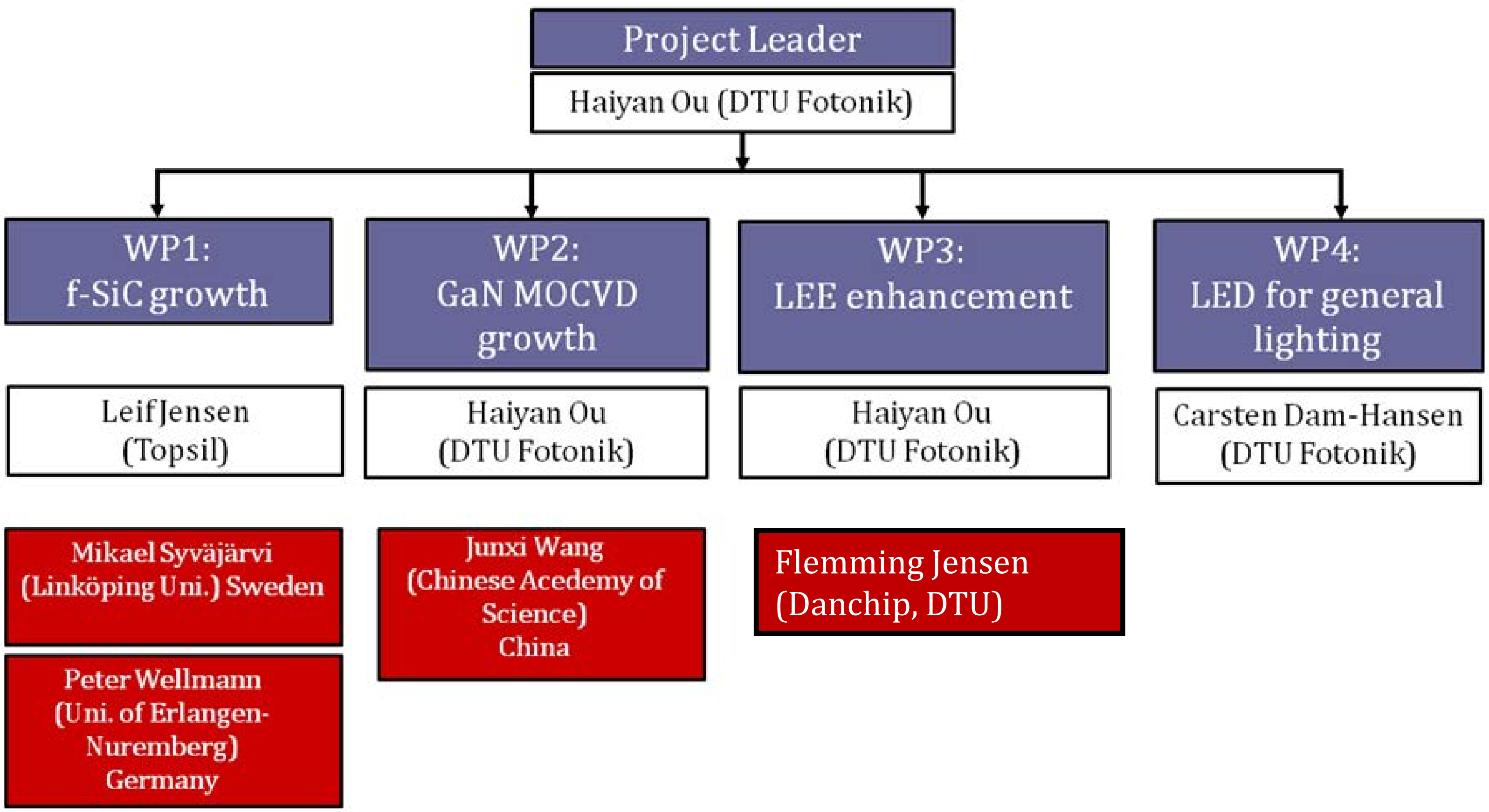
- M1: High efficiency f-SiC (Al-N and B-N doped) demonstrated. (Month 24)
- M2: White LED epitaxial wafer with strong luminescence demonstrated.(Month 24)
- M3: Large luminescence enhancement on f-SiC LED by surface nanostructuring and passivation. (Month 36)
- M4: White LED device with large luminous efficacy and CRI demonstrated. (Month 36)

Gantt-chart



Task No.
Task and assignment
2015
2016
2017
2018
Q3
Q4
Q1
Q2
Q3
Q4
Q1
Q2
Q3
Q4
Q1
Q2
Q3
Q4
1.1
Grow f-SiC (Al-N, B-N doped) (Ph D1/MS/PM/HO)
1.2
Characterize f-SiC samples (PhD1/LJ/HO)
1.3
Optimize growth conditions of f-SiC (Ph D1/MS/PM/HO)
M1
f-SiC with strong luminescence demonstrated
2.1
MOCVD grow GaN LED on f-SiC substrate (Postdoc/JW)
2.2
Optically characterize f-SiC based white LED (Postdoc/HO)
M2
LED epitaxial wafer with strong white photoluminescence demonstrated
3.1
Design surface nanostructures to enhance the light extraction (Postdoc)
3.2
Fabricate surface nanostructures on f-SiC or GaN surface (Postdoc/HO)
3.3
Characterize the light extraction enhancement(Postdoc/HO)
3.4
Passivate the surface to enhance the efficiency further (Postdoc/HO)
M3
Large luminescence enhancement on f-SiC LED by surface nanostructuring and passivation demonstrated
4.1
Post-growth processing to fabricate a LED device (PhD2/FJ)
4.2
On-chip characterization of white LED in terms of electroluminescence and CRI measurement (PhD2/HO)
4.3
Package of LED device (Postdoc/FJ)
4.4
White LED test in terms of CRI, luminous efficacy etc. (PhD2/CD)
M4
White LED device with large luminous efficacy and CRI demonstrated
Collaboration
DTU

Project structure and division into work packages



Consortium

Main participants	Organization	Competence	Contribution
Haiyan Ou (HO) Peter B. Poulsen(PP) Carsten Dam-Hansen(CD) Paul Michael Petersen (PMP)	DTU Fotonik	LED device fabrication and characterization, entrepreneurial	WP1~4
Mikael Syväjärvi (MS)	Linköping University	SiC epitaxy growth, dissemination through media and commercialization	WP1
Peter Wellmann (PW)	Erlangen University	Bulk SiC material growth, Doped source material, technology transfer, SiC on Si	WP1
Flemming Jensen (FJ)	Danchip	SiC processing	WP4
Junxi Wang(JW)	Institute of Semiconductors, CAS	MOCVD growth	WP2
Leif Jensen(LJ)	Topsil Group	Single crystalline Si	WP1,4

Advisory board

- Satoshi Kamiyama. Meijo University, Japan.
- ???

Previous collaboration within the consortium

- **NORLED project**: demonstration of intense yellow fluorescent SiC

Partners: DTU, Linköping University, FAU

Collaborator: Meijo University

- **SBLED project**: super bright LEDs using nanophotonics

Partners: DTU, ISCAS

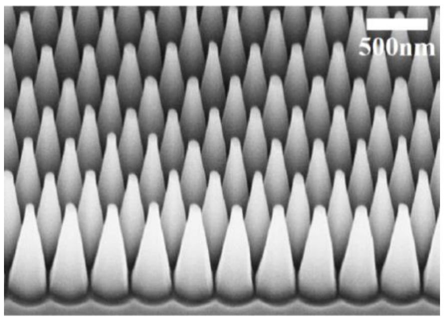
New partner:

Topsil group

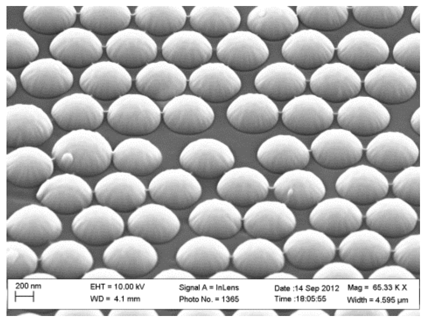
Relavant main results (1)

- Various methods have been developed to optimize the coupling efficiency at 4H and 6H SiC surface

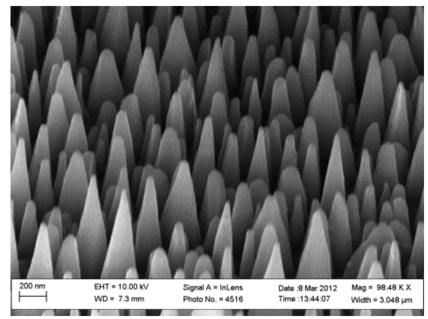
Periodic nanocone structures by E-beam lithography



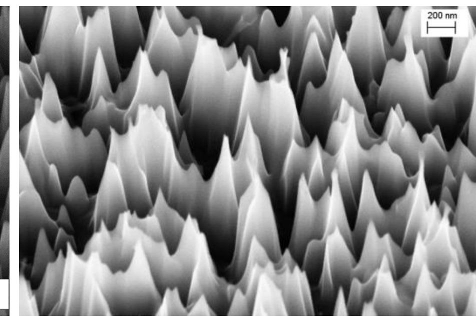
Periodic nanodome structures by nanosphere lithography



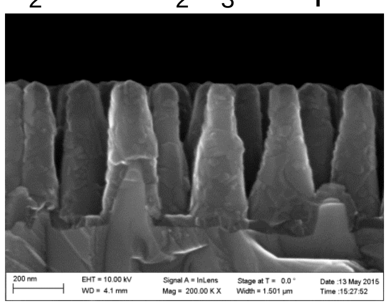
Random nanostructures by self-assembled metal NPs

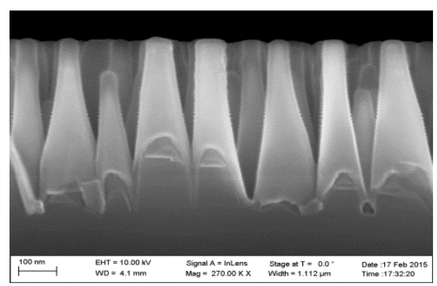


Random nanostructures by Al thin films

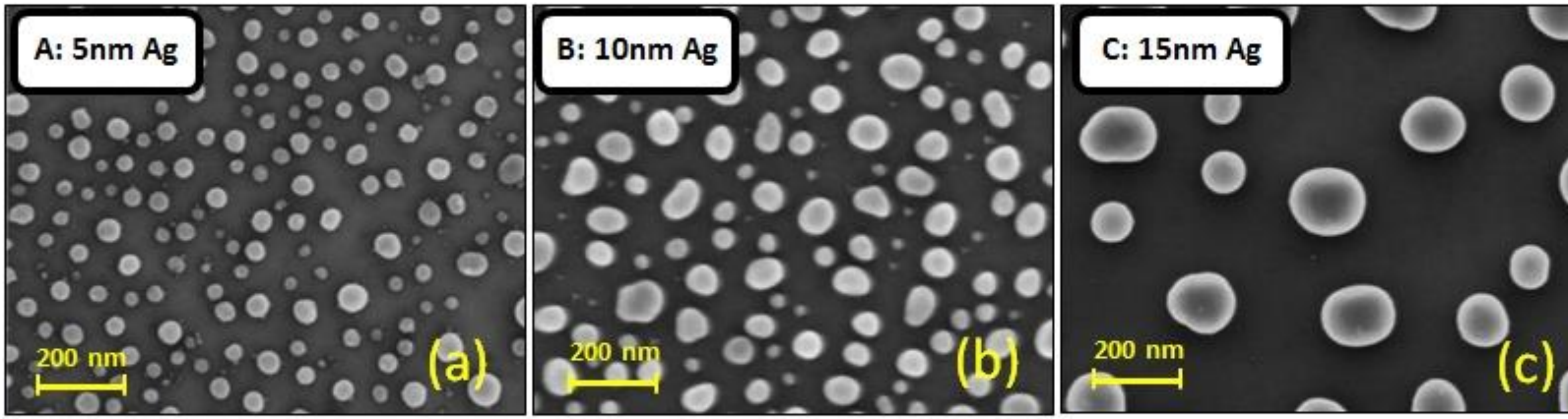


- ALD deposited TiO_2 and Al_2O_3 for passivation of the nanostructured surface

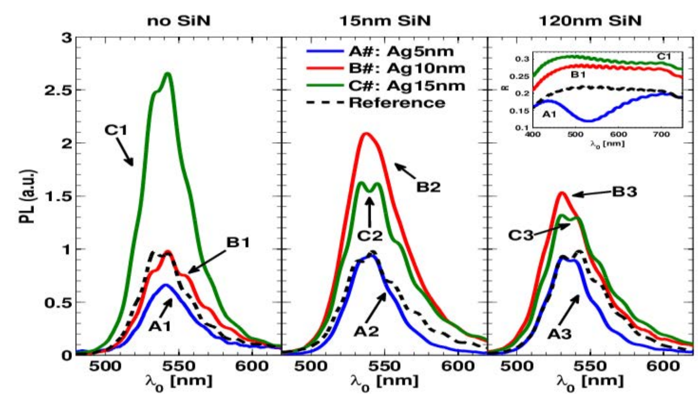




Relevant main results (2)

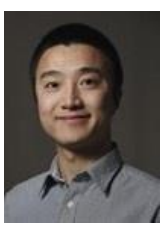


	A:5nm Ag Average size: 50nm	B: 10nm Ag Average size: 110nm	C:15nm Ag Average size: 160nm
1: no SiN	Sample A1	Sample B1	Sample C1
2: 15nm SiN	Sample A2	Sample B2	Sample C2
3: 120nm SiN	Sample A3	Sample B3	Sample C3



- Insertion of SiN layer improves the PL emission for sample Ax and Bx

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.

Project management

- Quarterly meetings between representatives of all Danish partners
- Quarterly online meetings with international partners
- Annual project meeting
- Final workshop at the end of the project

Present the main results, discussing future joint-applications

- Next project meeting

Late August~early September

Project progress update

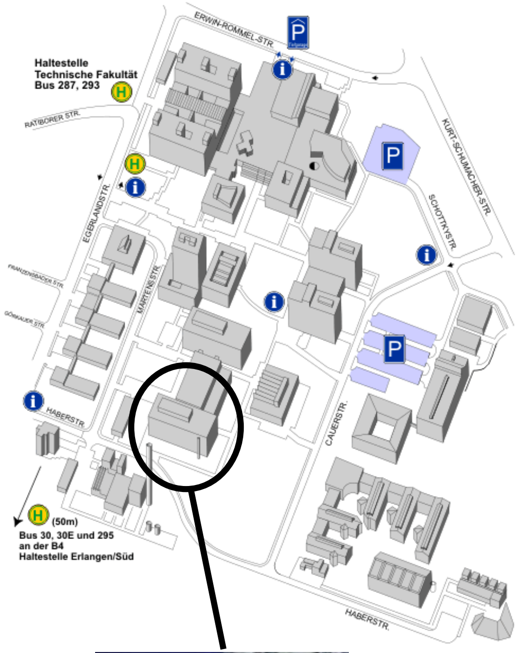
Advanced Doping of SiC

Prof. Dr.-Ing. Peter Wellmann
Crystal Growth Lab, Materials Department 6 (i-meet)
Materials for Electronics and Energy Technology
University of Erlangen-Nürnberg
Martensstr. 7, 91058 Erlangen, Germany.

peter.wellmann@fau.de

FRIEDRICH-ALEXANDER
UNIVERSITÄT
ERLANGEN-NÜRNBERG
TECHNISCHE FAKULTÄT

Materials Department in Erlangen



Materials Department – University of Erlangen

1. General Materials Properties
2. Science and Technology of Metals
3. Glass and Ceramics
4. Surface Science and Corrosion
5. Polymer Materials
6. **Materials for Electronics and Energy Technology**
7. Bio Materials & Materials for Medical Applications
8. Numerical Modeling of Materials
9. Micro- and Nanostructure Resaerch

Crystal Growth Lab

- Lab 1 in Erlangen (South Campus, Technical Faculty)
- Lab 2 in Fürth (Technikum 2, Uferstadt Fürth)

Crystal Growth Lab
(P. Wellmann)

Bulk Crystal Growth & Epitaxy ⟷ Thin Film Technology ⟷ Materials Characterization

Bulk Crystal Growth & Epitaxy

Bulk growth of SiC
- Modified-PVT method
- In-situ x-ray monitoring
- Doping

Epitaxy of SiC
- AIXTRON 200/4 reactor
- Nitride compatible

5 inductively heated growth setups

SiC high pressure solution growth setup

Thin Film Technology

Printing of nanoparticle electronic layers
- Spin coating
- Doctor blading
- Ink-jet printing

CI(G)S and CZTS solar cell materials
- Evaporation
- Sputtering

Nanoparticle layer (re-)crystallization

Materials Characterization

Electrical Techniques

Optical spectroscopy
- CL, PL, Absorption with special emphasis on topography

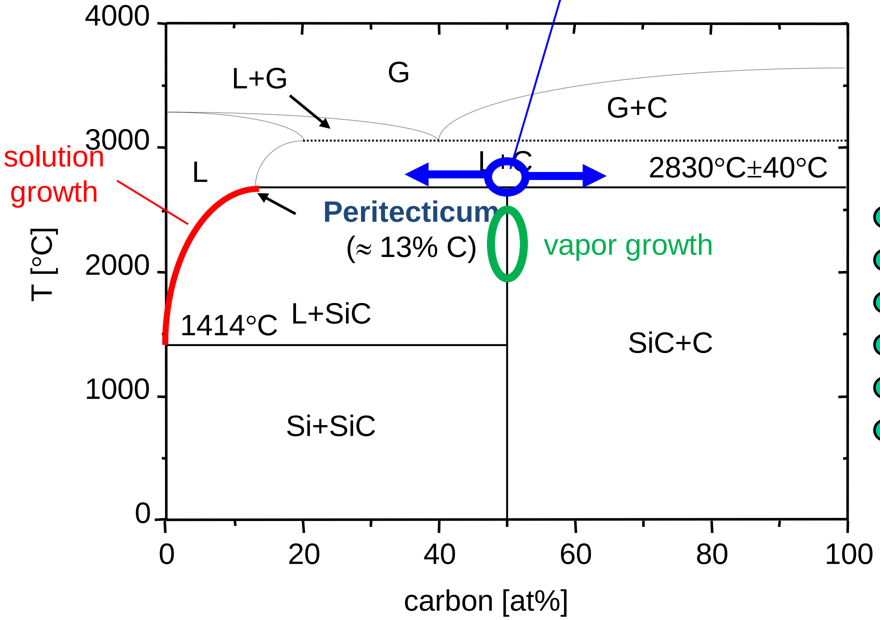
Structural Methods
- Defect etching
- SEM
- XRD (cooperation)
- Raman (cooperation)

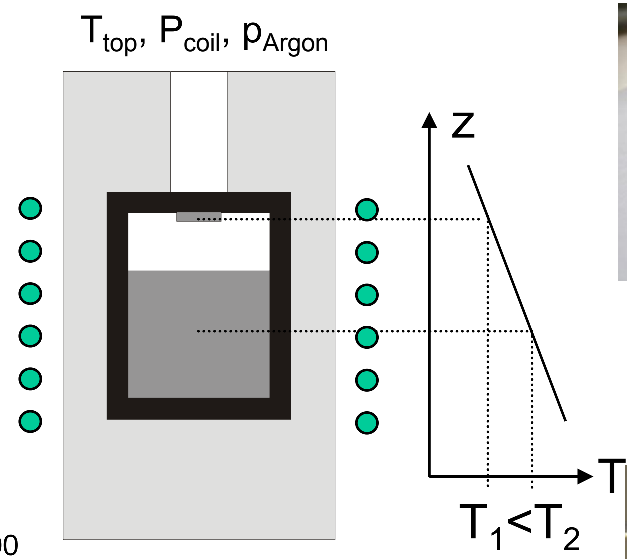
Chemical Analysis
- DSC, EDX

High Temperature growth of SiC

Bulk growth of SiC

peritectic decomposition of SiC
carbon + Si-solution (13% carbon)





3 inch 6H-SiC crystal

4 inch PVT reactor

→ **Sublimation growth**

PVT

Physical **V**apor **T**ransport

SUBLIMATION SiC powder

CRYSTALLIZATION at colder seed

designed & produced
by FAU

Processing

PVT activities

Source Material

- Own SiC powder production

Growth

- Seed mounting station
- 2”/3” two machines (one with insitu xrd)
- 4” two machines
- one large area process developing machine

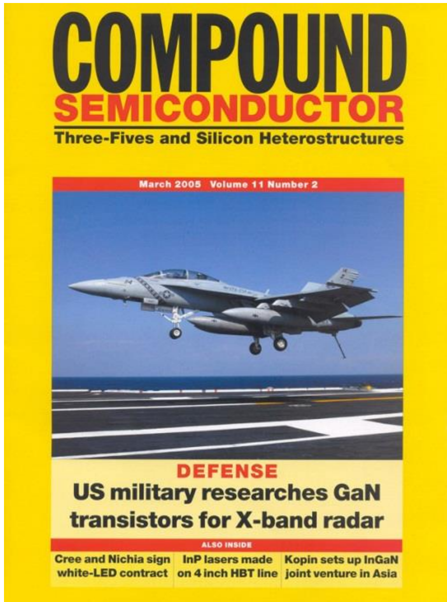
Wafering

- Grinding machine
- Saw
- Polishing (2 stations)

Characterization

- 4inch KOH defect etching
- Electrical, optical and structural characterization

SiC bulk growth process



SIC GROWTH

compoundsemiconductor.net

Additional pipework opens up transistor applications for SiC

Peter Wellmann, from the University of Erlangen, Germany, describes a new approach to silicon carbide substrate growth that could improve LED and Schottky-diode performance, as well as pave the way for new devices, such as insulated-gate bipolar transistors for power applications.

Commercial applications for silicon carbide (SiC) substrates are dominated by blue and white LEDs produced on 6H-SiC and high-voltage Schottky diodes grown on 4H-SiC. No other mass-produced devices currently benefit from SiC's intrinsic properties (high breakdown voltage, thermal conductivity and electron-saturation velocity), but this could change if improvements can be made to the material's doping uniformity and the range of dopants available.

Modified physical vapor transport (MPVT), an alternative method for bulk wafer growth, could be the answer. This approach has produced aluminum-doped substrates that are suitable for insulated-gate bipolar transistors (IGBTs) – devices that could be used in electrical power converters and power circuits for the control of higher-power electrical motors.

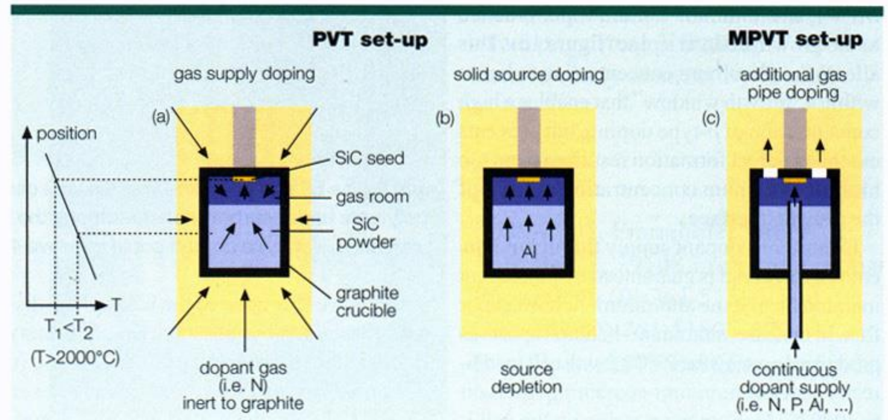


Fig. 1. (*a*) and (*b*) The conventional approach to silicon carbide crystal growth – PVT – hinders gas-phase control and prevents the growth of aluminum-doped SiC crystals with uniform doping profiles. (*c*) MPVT uses an additional gas pipe to fine-tune the gas-phase composition. This method achieves vastly improved aluminum-doping profiles in SiC.

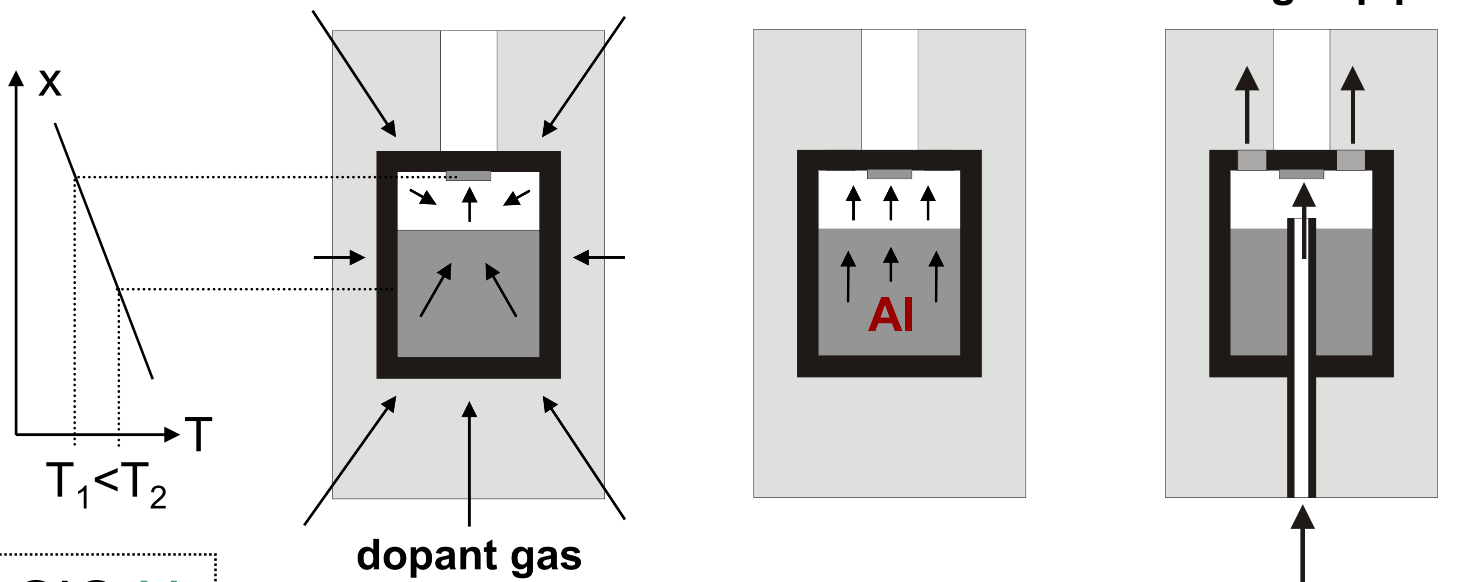
Doping & Defects

Modified-PVT – process principle (for improving doping)

PVT setup | **M-PVT setup**

Doping by

... gas supply | **... solid source** | **... additional gas pipe**



dopant gas (i.e. N_2)

doping species (i.e. N, P, Al, ...)

n-type SiC:N

p-type SiC:Al

Straubinger, Wellmann et al. *JCG* **240** (2002)

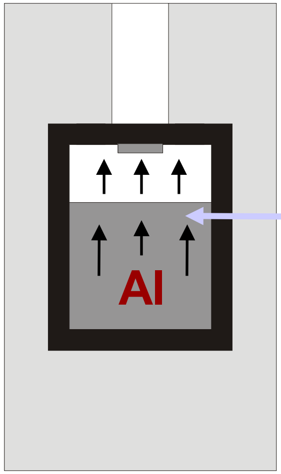
Wellmann, et al. *JCG* **275** (2005)

only gases inert to graphite (T>2000°C)

source depletion

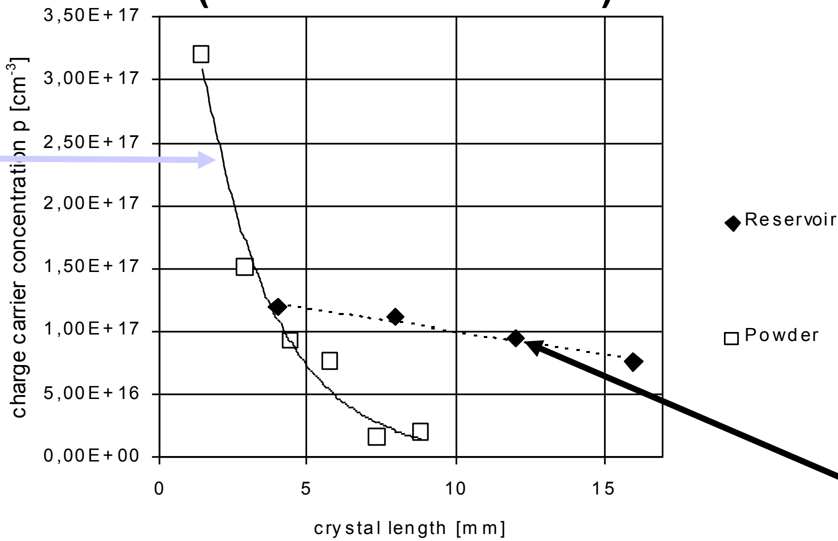
continuous dopant supply

Modified PVT setup – improved doping



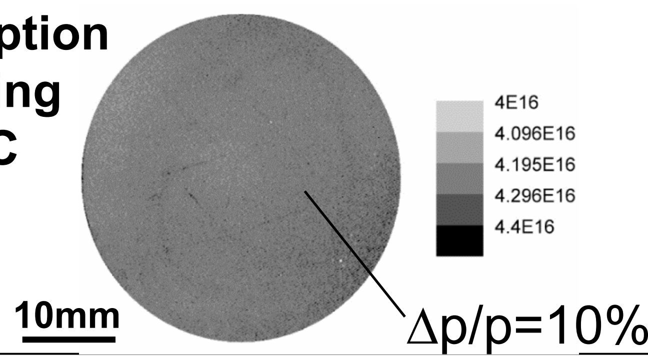
source depletion

p-6H SiC(aluminum) (Hall measurements)



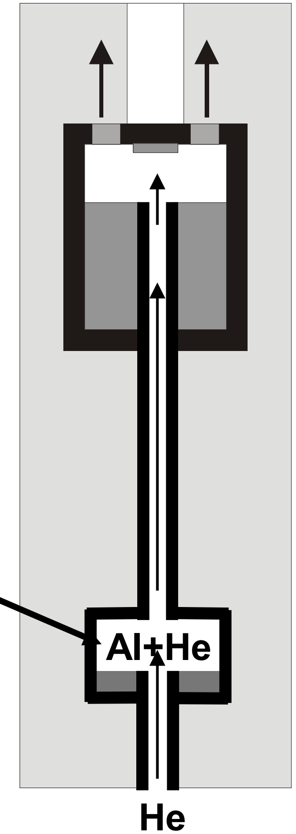
•data: M.Rasp, pers.comm. (1998).

absorption mapping 4H-SiC



Doping 4H-/6H-SiC:
ρ = 0.1Ωcm ... 0.2Ωcm

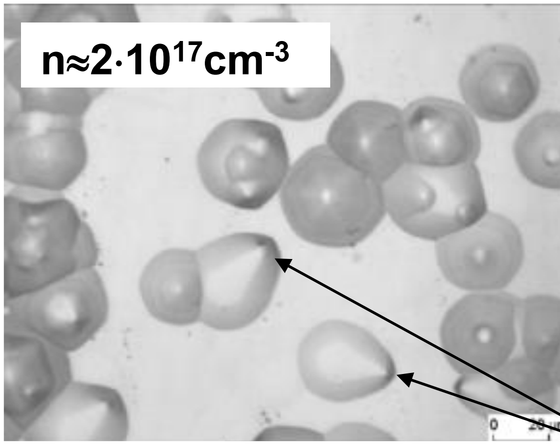
Wellmann, Müller, et al. *JCG* **275** (2005)



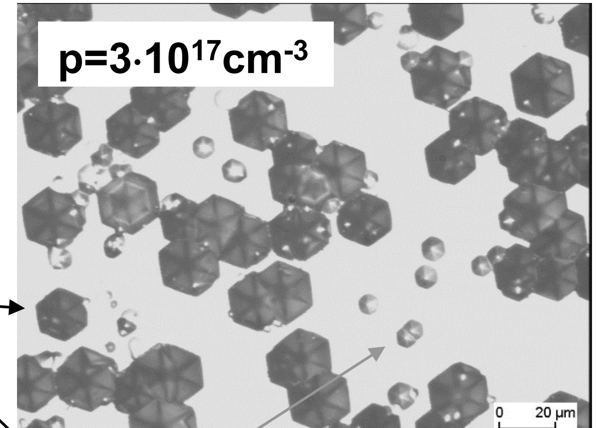
continuous dopant supply

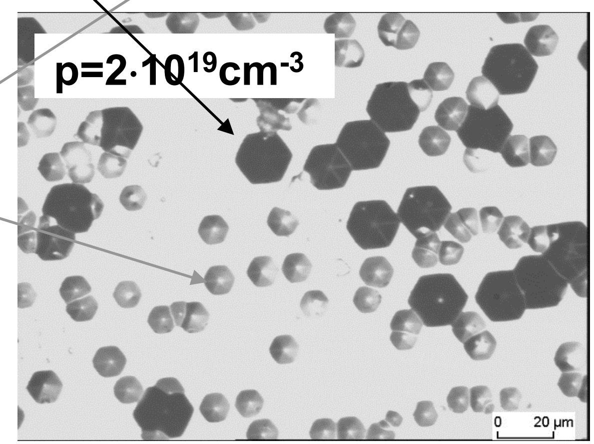
Defects in p-type SiC:Al - KOH-defect etching & light microscopy

n-type



p-type





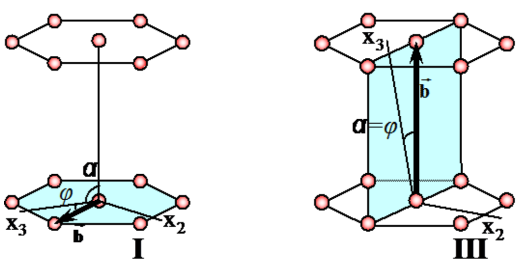
Screw Dislocations

"Basal-Plane" Dislocations

Edge Dislocations

"Basal-Plane" Dislocations

Screw or Edge Dislocations

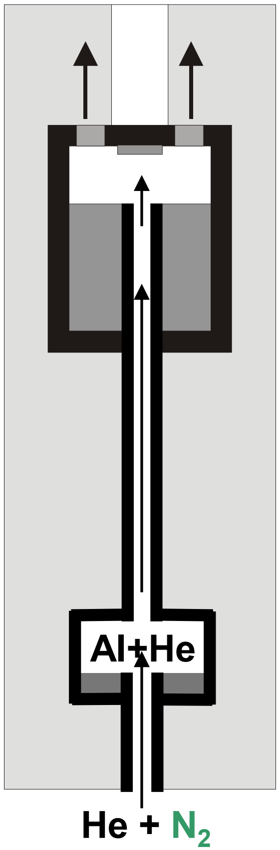


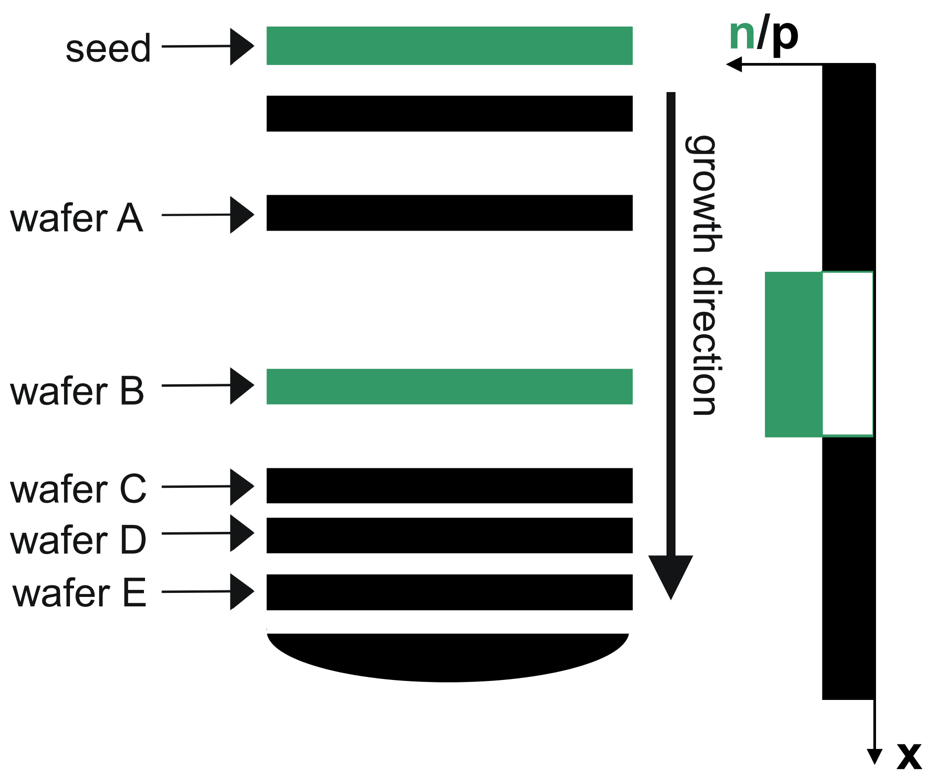
© Mark Ramm

Sakwe, Wellmann et al. *JCG* **289** (2006)

Experiment: p-type → n-type → p-type SiC crystal

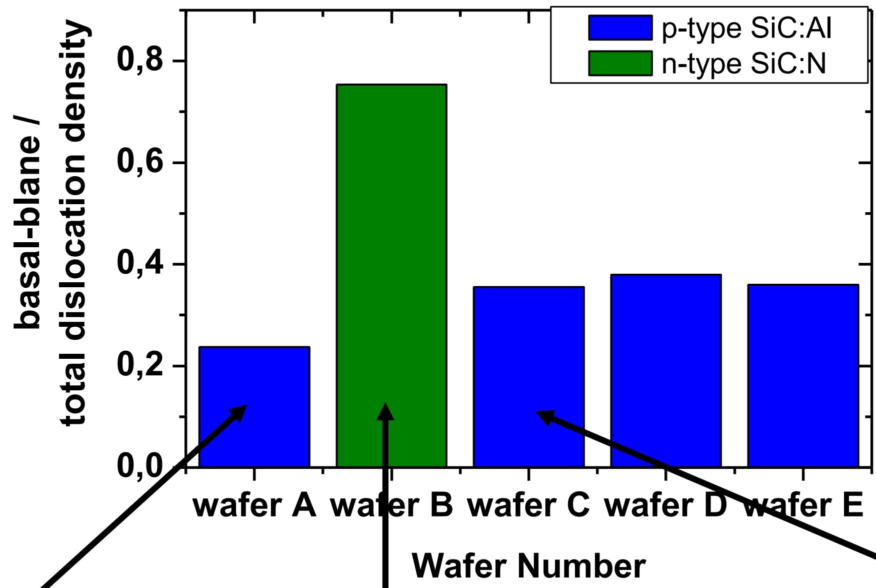
Wellmann et al.
Mat.Sci.Forum **527-529** (2006).





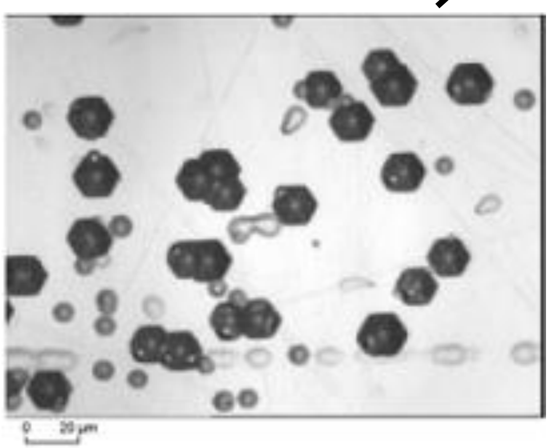
M-PVT setup for highly doped p-SiC:Al (ρ = 0.1…0.2 Ωcm)

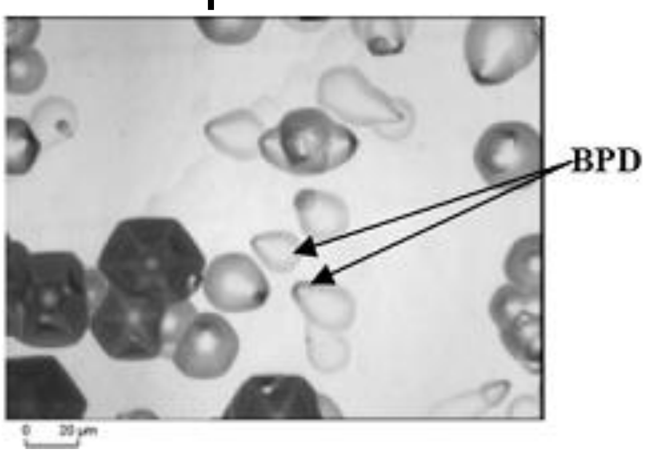
Basal Plane Dislocations – p-/n-/p-type doped 6H-SiC:Al crystal

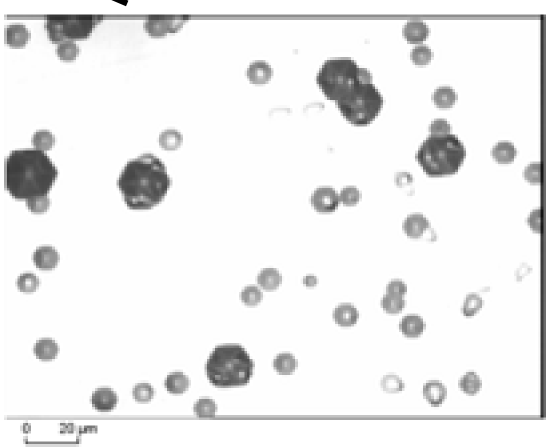


R. Müller, P. Wellmann et al. *Mat.Sci.Forum* **527-529** (2006).
Wellmann, Pons et al. *Surf.Coat.Technol*. accepted (2007).

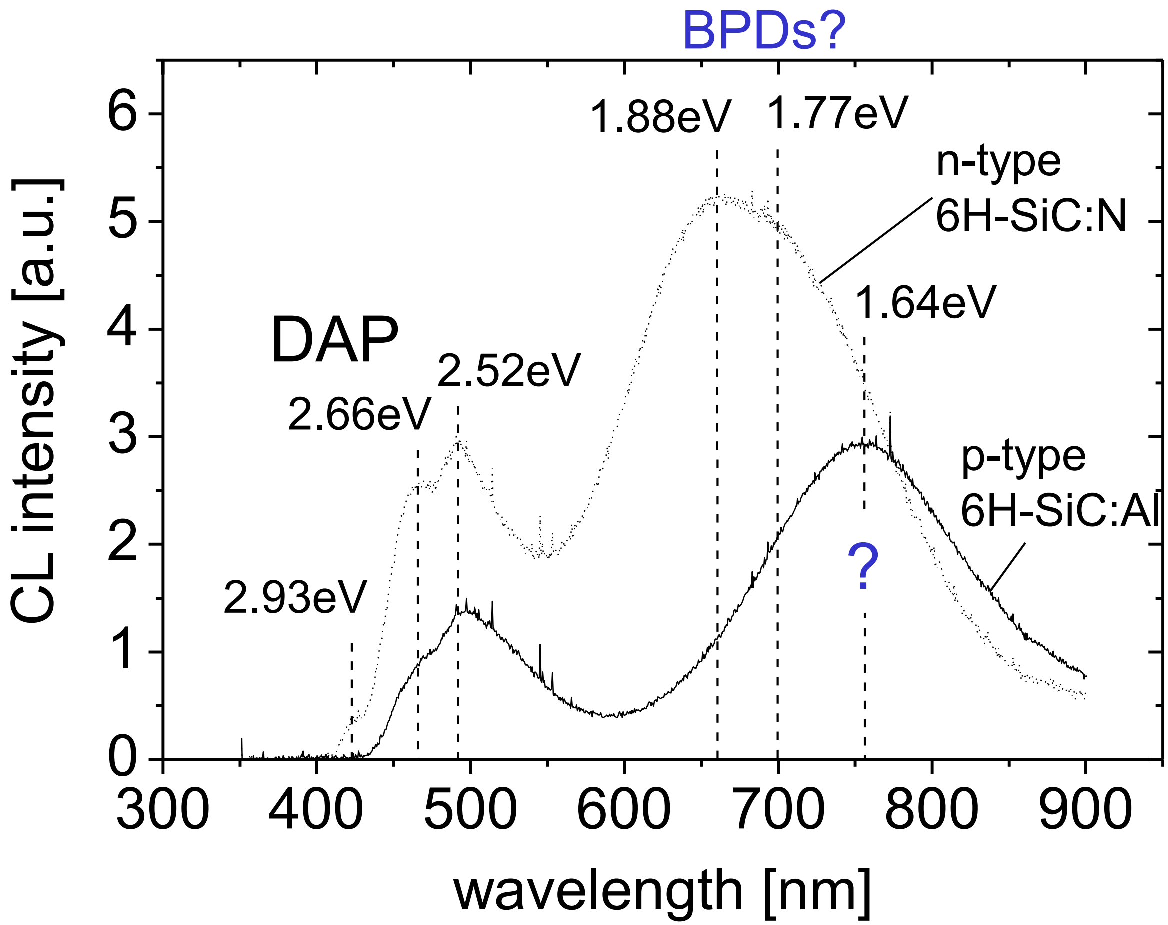
KOH defect etching
(0001) c-plane

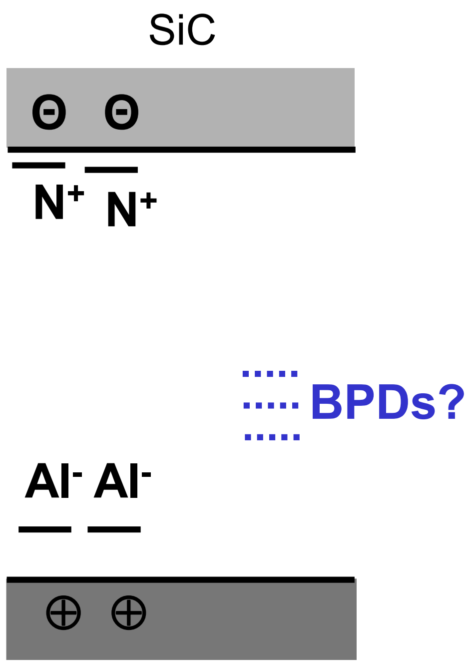






CL study n-type and p-type 6H-SiC





Wellmann et al.
Mat.Sci.Forum (2008).

NOTE: KOH-Defect etching on a-plane & off-axis c-plane:
We hardly obeserve Stacking Faults in as grown crystals

Knowledge Transfer

Mission – FAU Crystal Growth – Knowledge & Technology Transfer
… Services for Industrial Partners

The **Crystal Growth Lab** at the Materials Department 6 (University of Erlangen-Nuremberg) offers in conjunction with the University Knowledge and Technology Transfer Office **services for industrial partners** in the field of **high temperature crystal growth & technology**.

- R & D contracts
- growth machine design & prototyping
- process development
- supply of research grade materials
- training for industrial staff

In particular, high temperature **crystal growth and epitaxy** of wide band-gap semiconductors like **silicon** carbide and related materials belong to the key competences.

Contact: peter.wellmann@fau.de, crystals@fau.de
Lab information: Prof. Dr.-Ing. Peter Wellmann, Crystal Growth Lab
Materials Department 6, Martensstr. 7, 91058 Erlangen, Germany

SiC Research & Development

SiC Research & Development

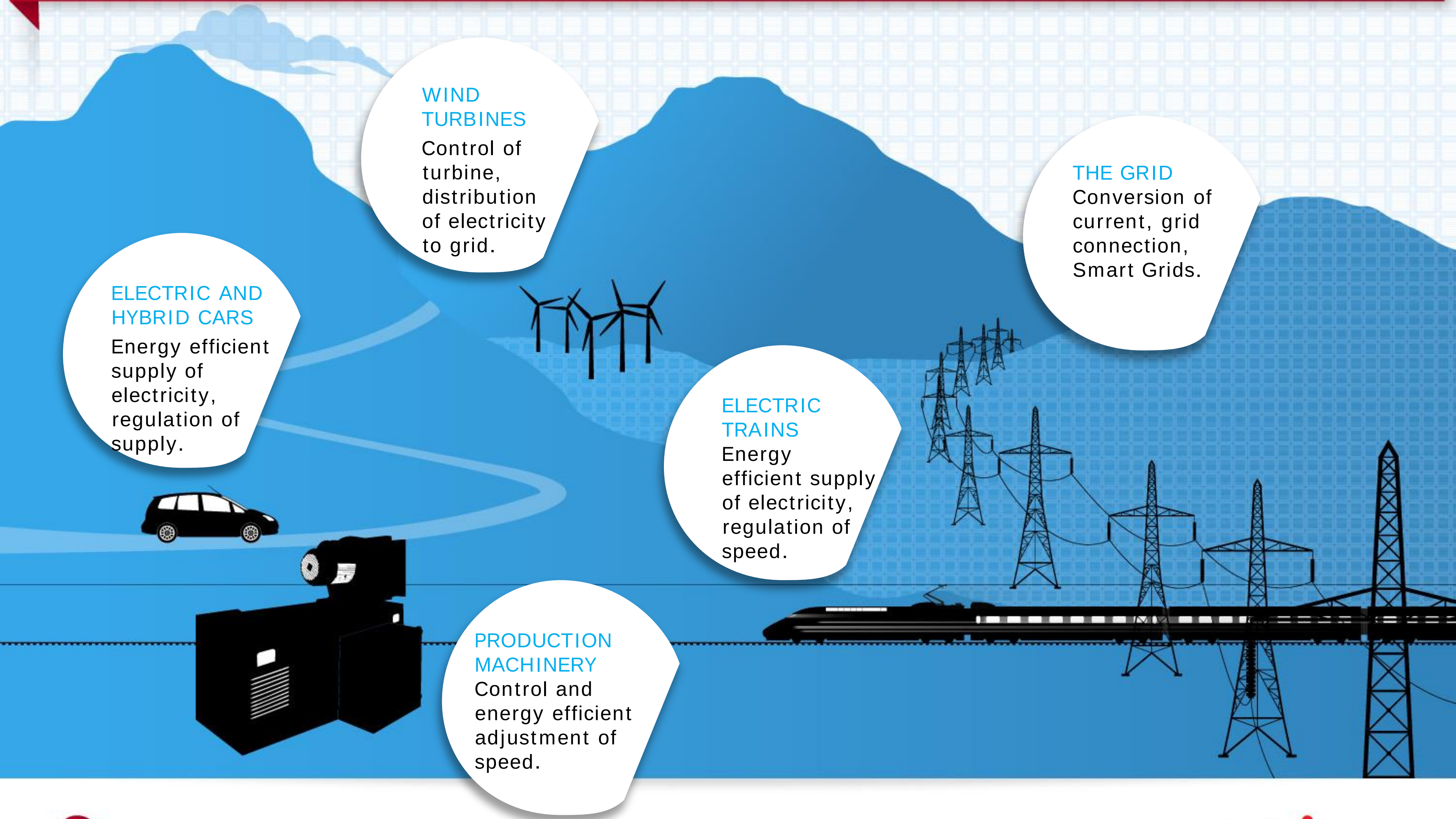
In addition to teaching of crystal growth we offer SiC Research and Development Projects with special emphasis on …

- … Seed development
- … Doping
- … Process visualization
- … Process automation
- … Growth Machine Development & Modification
- … Materials Inspection / Characterization
- … SiC powder studies
- … Anything special / non-standard

TOPSIL SEMICONDUCTOR MATERIALS A/S

September 2015

ULTRAPURE SILICON
ENABLING THE WORLD OF TOMORROW



NICHE MANUFACTURER OF HIGH PURITY SILICON WAFERS

- Specialised manufacturer of ultrapure silicon wafers to the global semiconductor industry
- Focus on premium quality silicon for the most demanding purposes
- Strong in-house silicon competencies and knowledge base - close cooperation with universities and research institutions world wide
- State-of-art technology, facilities and equipment
- Long track record, est. 1959 - long term customer relations
- Staff of 350 people, expected turnover of lower end of $43-46 million (2014)

TOPSIL

OUR BUSINESS IS CLOSELY LINKED TO THE SUCCESS OF OUR CUSTOMERS

- Mission: To provide solutions that enable customers manufacture advanced, energy efficient power components.

- Customers attach great importance to a flawless product, an efficient manufacture and a safe supply – therefore product quality, production efficiency and a smoothly running supply chain are fundamental to us.

- We engage in long term relations for our mutual long term success.

HIGH QUALITY IS PARAMOUNT TO TOPSIL

- Well established data management system, strict focus on meeting quality related goals throughout the production process
- Continuous improvements: Application of 6S and other Lean tools to improve performance and minimise waste
- TS16949, ISO14001 certification
- Compliance with SEMI standards


Lloyd's Register LRQA

CERTIFICATE OF APPROVAL

This is to certify that the Management System of:

Topsil Semiconductor Materials A/S
Siliciumvej 1
3600 Frederikssund
Denmark

has been approved by Lloyd's Register Quality Assurance to the following Management System Standard:

ISO/TS 16949:2009

The Management System is applicable to:

Design and manufacture of substrates for power components.

Approval
Certificate No: CPN0002403/1

Original ISO/TS 16949 Approval: 17th December 2012
Current Certificate: 11 March 2014
Certificate Expiry: 16th December 2015

Issued by: LRQA Danmark for and on behalf of Lloyd's Register Quality Assurance Limited

IATF Certificate No: 0152998

TOPSIL

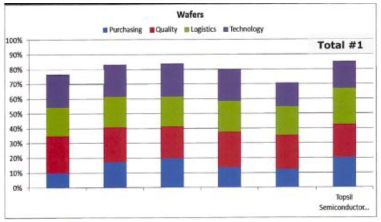
TECNICAL EXPERTISE FUNDAMENTAL FOR OUR BUSINESS

- More than half a century of dedication to the manufacture of ultra pure silicon
- Joint customer development programmes
- Close relations with research institutes and universities worldwide
- Access to fundamental studies – joint research programmes
- IP rights on key technology and equipment

TOPSIL

Topsil NTD material in high power applications


Frame Agreement
for the Purchase of Material
- hereinafter referred to as "Agreement" -
by and between
Topsil Semiconductor Materials A/S,



Large European IGBT manufacturer:

- Close partner ship since 2007 in 6″ NTD
- Partnership confirmed in 5 year frame agreement
- Obtained #1 supplier position in internal supplier evaluation
- Shipped >500.000 wafers for high power applications
- Periodically sole supplier for 6,5kV application

Leading global train manufacture:

- Topsil sole supplier of 8″ NTD material
- >30.000 wafers shipped since start of new factory

Leading Japanese EV car manufacture:

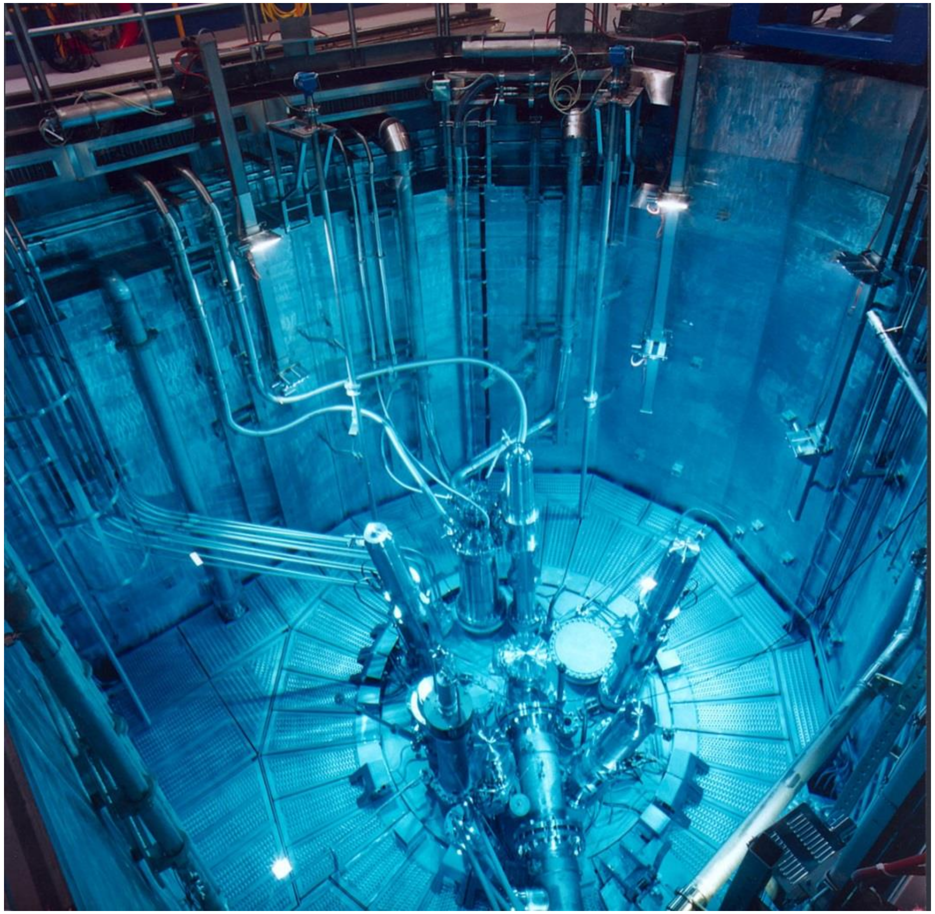
- Topsil selected for evaluation process for next gen vehicles
- NTD material approved

Company confidential

TOPSIL

NTD SILICON
SECURED LONG TERM CAPACITY AND SUPPLY

- Comprehensive network of irradiation partners worldwide.
- Long term relations – contracts, strong partnerships.
- Well defined planning and control procedures.
- World leader in irradiation capacity control.
- Close cooperation with irradiation partners to push limits of capabilities



NEW PLANT SUPPORTING NEXT GENERATION SILICON WAFERS

- Manufacture of small sizes (4'') up to 200mm float zone wafers
- Best available technologies – state-of-art equipment
- Optimised production flow, clean room facilities
- Increased capacity - scalable design
- Capacity of plant: Up to 2.2 million 150mm wafers per year.

DEDICATED SUPPLY CHAIN MANAGEMENT

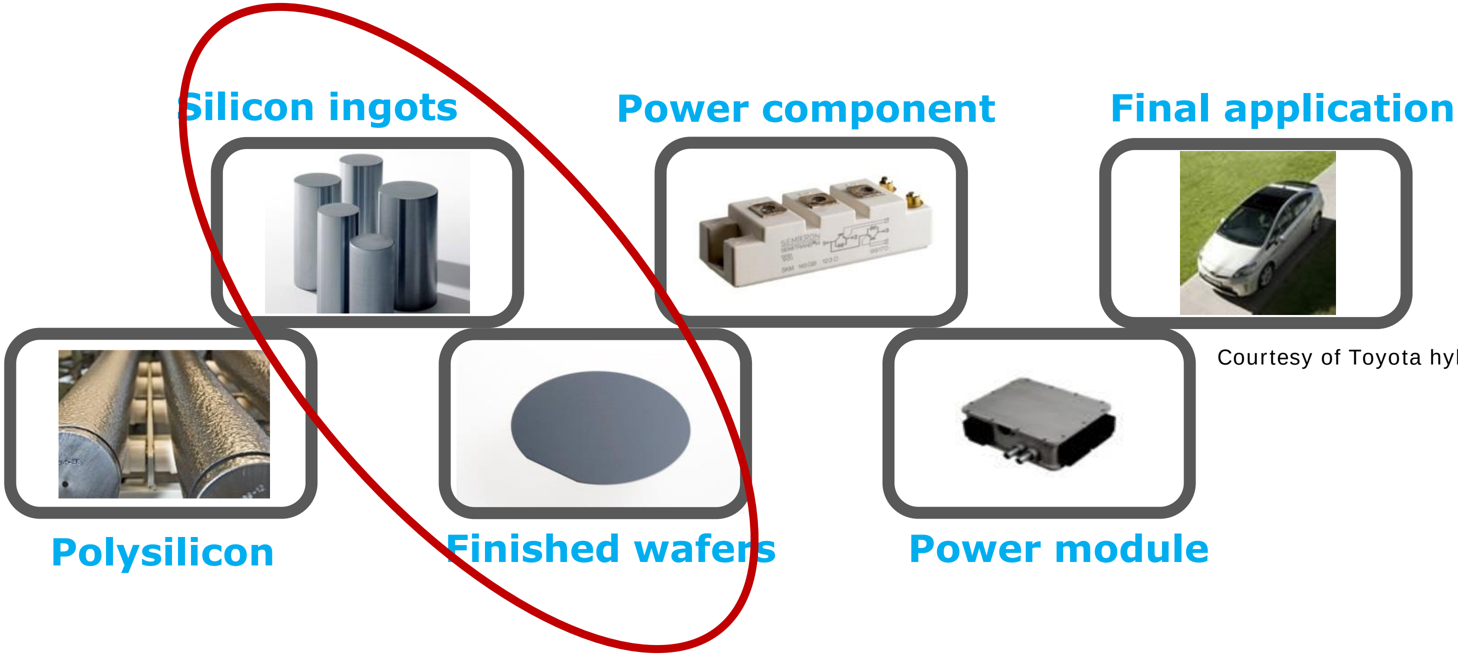
Substantial experience in managing complex supply chain - sound track record of on-time-delivery

- Broad management expertise in contract manufacturing
- Short decision making processes – agile organisation
- Flexible production – small and large quantities available on request
- Safe access to high quality poly silicon for float zone manufacture
- Strong network of irradiation partners for NTD manufacture
- In house wafering facilities
- On-time-delivery close to 100%

TOPSIL

PART OF INTERDEPENDENT VALUE CHAIN

- Our business is closely linked to the success of our customers – therefore quality, efficiency and a safe supply are fundamental to us
- Our corporate mission is to provide solutions that enable customers manufacture advanced, energy efficient power components.

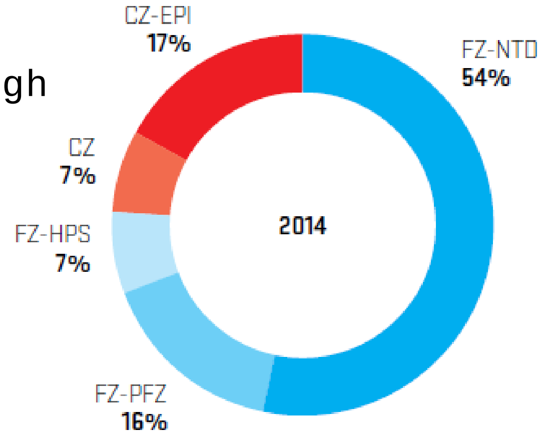


Courtesy of Toyota hybrid

WIDE PRODUCT RANGE – GLOBAL LEADER IN NTD

Main products for power devices

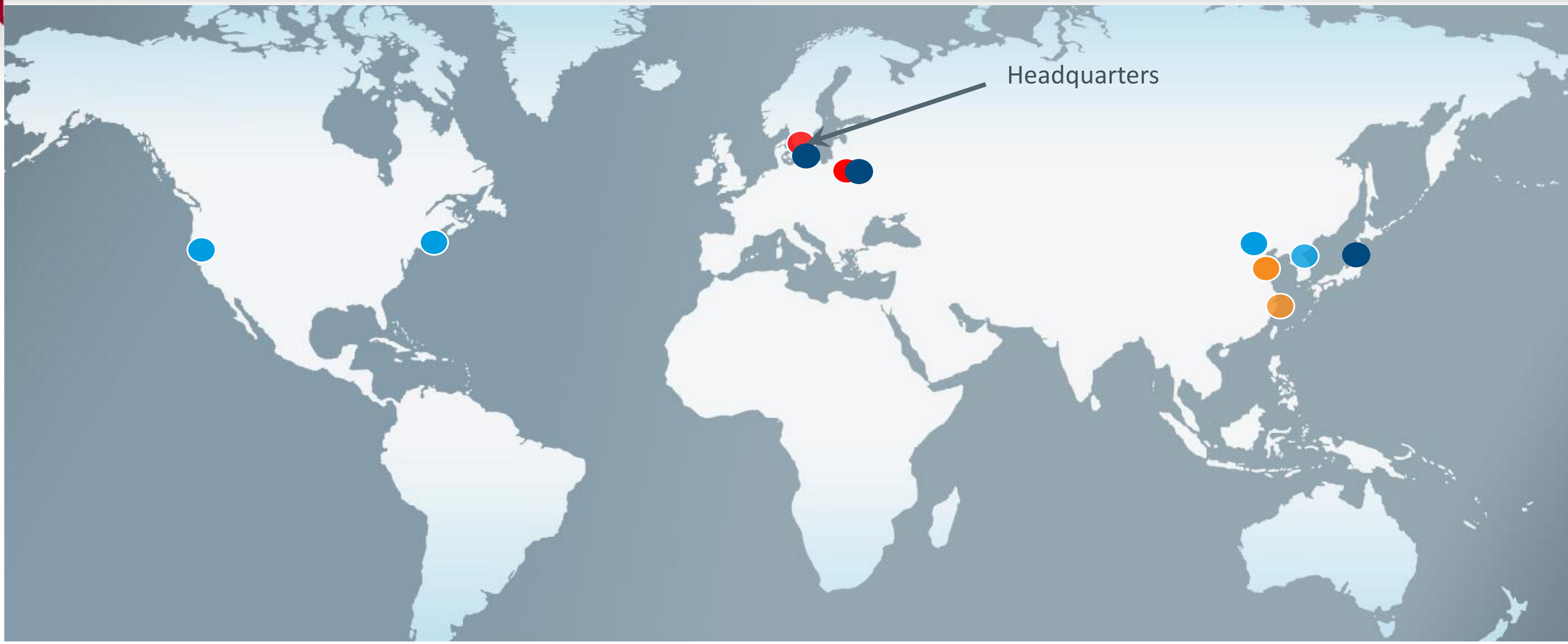
NTD: Neutron Transmutation Doped float zone silicon for high power devices
PFZ: Preferred float zone silicon for power applications
CZ EPI: EPI coated czochralski silicon for medium and low power devises



Specialty products:

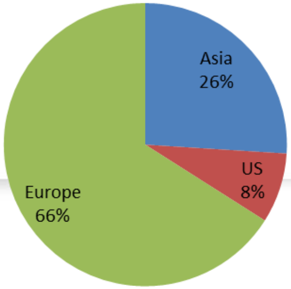
HPS	High Resistivity silicon for detector applications
UHPS	Uniform High Purity silicon for silicon drift detectors
HiRes®	High Resistivity silicon for communication devises
HiTran®	High Transparency silicon for infra red applications
PV-FZ®	Photo Voltaic Float Zone for high efficiency solar cells
GaN	Silicon wafers for GaN thin film growth

GLOBAL PRESENCE



- Production facilities
- Contract manufacturing
- Sales office
- Sales representation

Geographical markets 2014



CORPORATE LOCATIONS

State-of-art HQ and production facility , Copenhagen Cleantech Park, Denmark

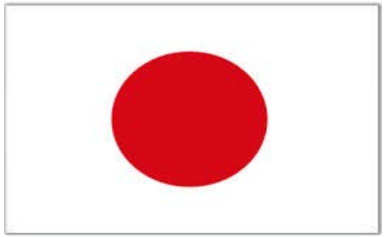
Topsil A.S., HQ – Denmark

- Production and development of ultrapure silicon (float zone technology)
- New plant, supporting next generation of products (200 mm), state of art facility and equipment
- Capacity of plant: Up to 2.2 million 150 mm. wafers per year.

Production facility, Warsaw, Poland

Topsil S.A. – Poland

- Production and development of other substrate (CZ and EPI technology)
- In-house wafering
- State of art equipment



Sales, Kyoto, Japan

Topsil KK – Japan

- Sales of Topsil silicon to the Japanese market

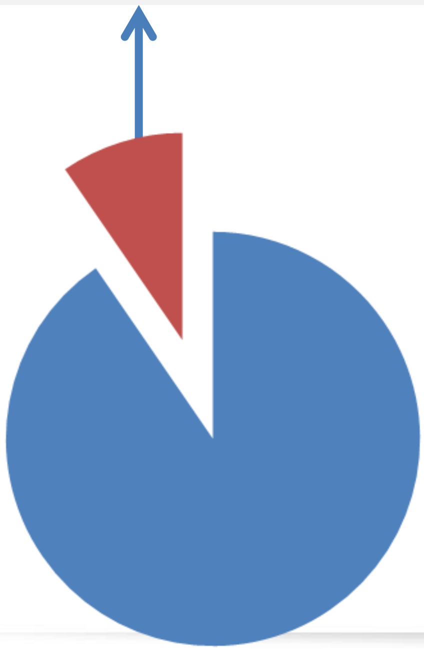
TOPSIL

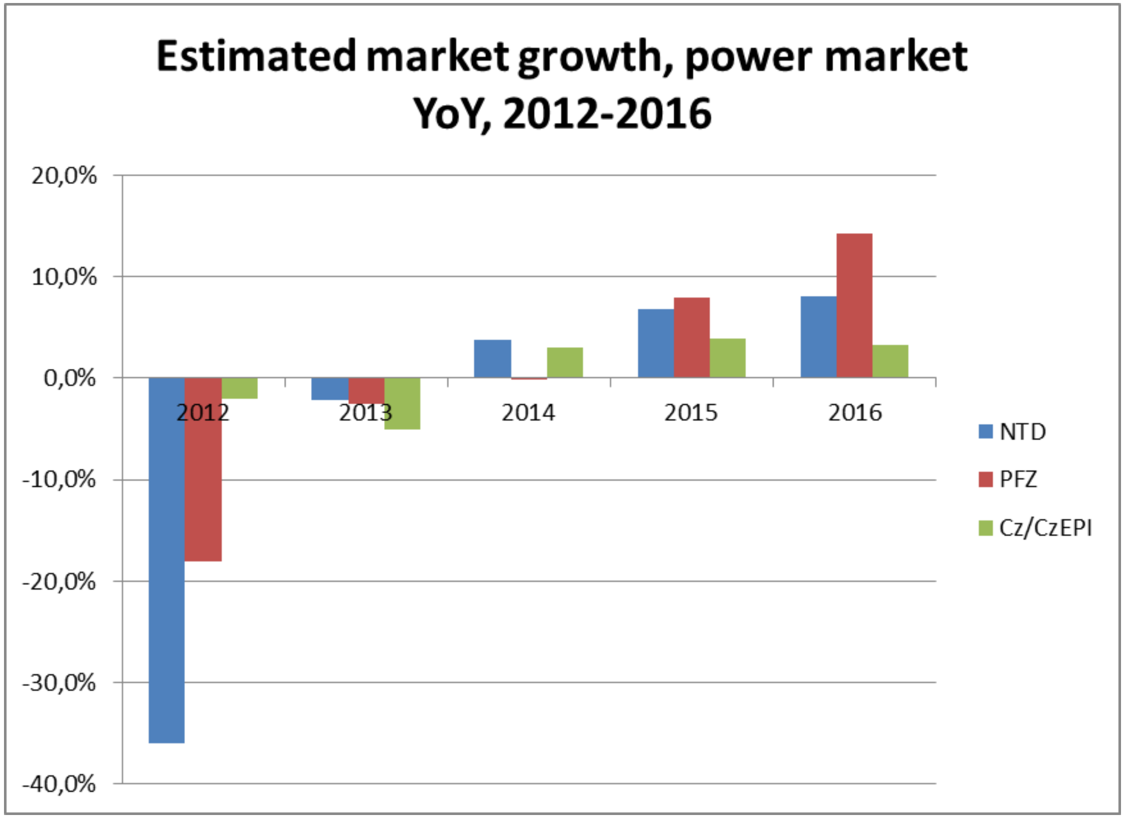
POWER MARKET, MARKET SIZE 2012 - 2016

The aggregated silicon market worth around USD 10 billion in 2014.

The power market accounted for about 10% of this market. Main substrates are NTD, PFZ and CZ/CZ-EPI.

Sources: SEMI, Yole Developpement, March 2015





Source: Yole Developpement, March 2015

APPLICATIONS, PRODUCT CAPABILITIES

APPLICATIONS FOR HIGH POWER

Industrial

- Motor drives
- UPS systems
- Power / frequency controllers
- Rectifiers

Energy distribution/renewables:

- Power controls for transmission
- HV-DC lines
- Wind turbine generator, inverter
- Inverters for PV installations

Transport

- High speed trains
- Electrical trains
- Metro/underground trains
- Tramp

APPLICATIONS FOR MEDIUM AND LOW POWER

Computer & mobile phones

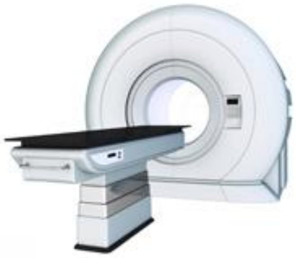
- Power supply for PC and mobile phones
- Wireless connections
- Flat screen controls

Audio- & video

- power supply
- Amplifiers
- Analogue / digital filters
- Signal processing

Detection and imaging

- Medical equipment
- Admission and Safety
- Sensors
- Photo

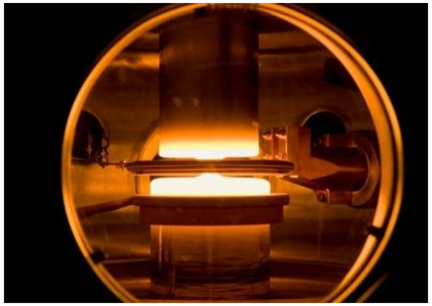


SPECIALISED PRODUCTS FOR POWER

FZ-NTD

Neutron transmutation Doped Float Zone

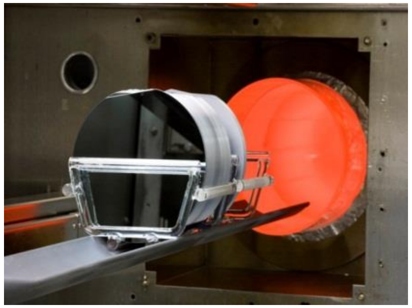
- For the most demanding components
- More power, higher voltage, lower loss



FZ-PFZ

Preferred Float Zone

- Optimised for wafer utilisation, volume production and high yield
- Superior control of electrical parameters

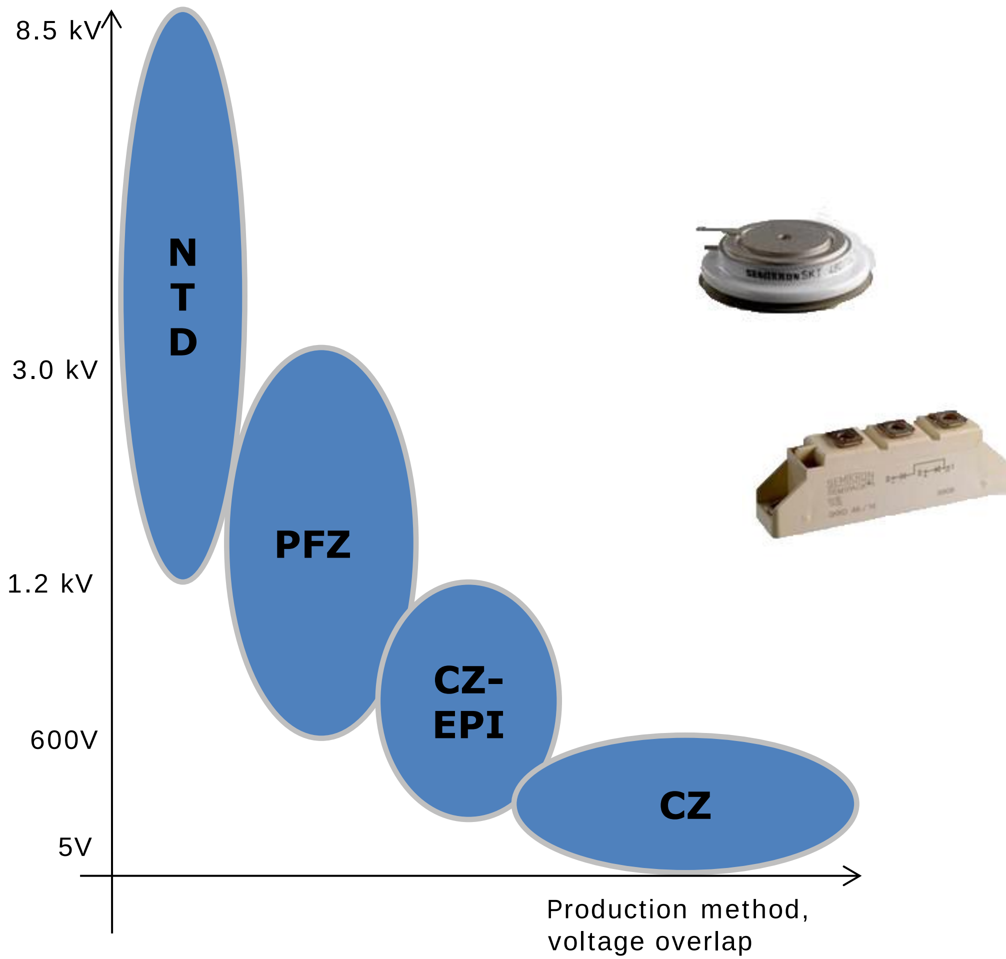


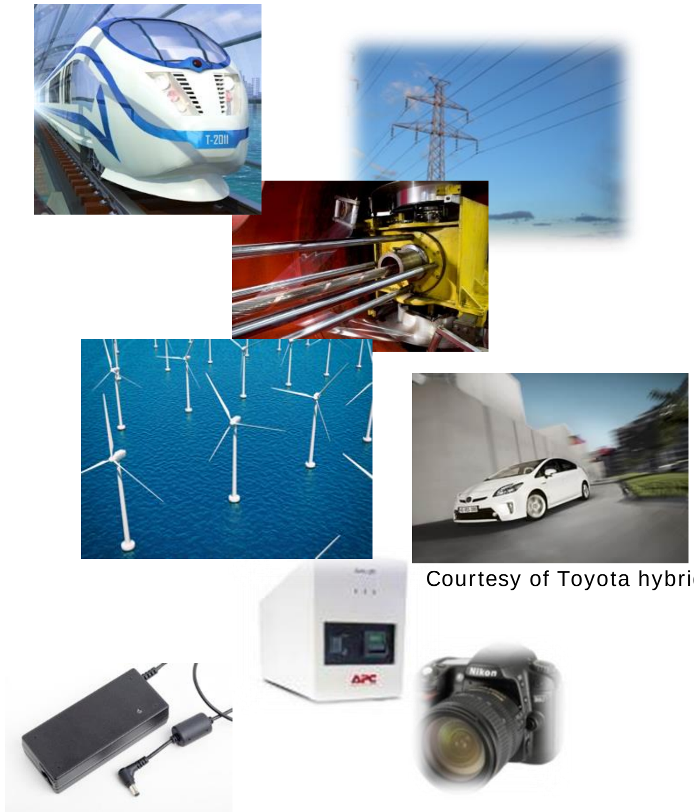
CZ-EPI

Czochralski EPI

- Wafers with tight control of mechanical and electrical parameters
- Leading edge propriety CZ and Epi technology

PRODUCTS, APPLICATIONS





Courtesy of Toyota hybrid

BASIC PRODUCT CAPABILITIES ≤ 150 MM.

	Float Zone	Czochralski
Diameter (mm):	76.2 - 153	76.2 - 153
Orientation:	<1-1-1> or <1-0-0>	<1-1-1> , <1-0-0> <1-1-0>
Doping:	n-type (Phosphorous) p-type (Boron)	n-type (Phosphorous) p-type (Boron) Arsenic, Antimony
Oxygen (atm. -3):	2.0×10^{16}	1.0×10^{18}
Resistivity (ohmcm):	HPS 3,500 → 30,000 NTD 20 → 4,000 PFZ 1 → 300 PV-FZ 0.5 → 10	Epi 0.2 → 70 (Si:As substrate) Epi 0.1 → 80 (Si:B substrate) Cz 0.001 → 60 resistivities
Wafer:	Etched Single side polished Double side polished	Single side polished Double side polished EPI Wafer

TOPSIL

FZ 200 MM. PRODUCT CAPABILITIES
PRODUCT KEY PARAMETERS

	NTD	PFZ	High resistivity material: HiRES®/HPS
Orientation:	<1-0-0>	<1-0-0>	<1-0-0>
Doping:	n-type (Phosphorous)	n-type (Phosphorous) p-type (Boron)	n-type (Phosphorous) p-type (Boron)
Oxygen atoms/cm³	$< 2.0 \times 10^{16}$	$< 2.0 \times 10^{16}$	$< 2.0 \times 10^{16}$
Metals E10 atoms/cm²	< 2	< 2	< 2
Resistivity (ohm cm):	20 – 800	20 – 100	3.500 – 30.000
Resistivity Tolerance %	< 7%	< 10%	< 50% *
RRV%	< 7%	< 14%	< 60% *

*Tolerances depending on resistivity target, test pattern and type

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Publications – access homepage www.topsil.com

HPS Product note: Topsil_HPS_Product_note_2013.pdf

UHPS Product note: Topsil_UHPS_product_note_2014.pdf

HiRES Product note: Topsil_HiRes_Product_note_2013.pdf
HiRES Application note: Topsil_HiRes_Application_note_2014.pdf
MEMS application note: Topsil_MEMS_Product_note_2013.pdf

HiTran Product note: Topsil_HiTran_Product_note_2013.pdf
HiTran Application note Topsil_HiTran_Application_note_2013.pdf

NTD Product note: Topsil_NTD_Product_note_2013.pdf
NTD Application note: Topsil_NTD_Application_note_long_version_2013.pdf
NTD Application 200mm Topsil_NTD_Application note_200mm_2014.pdf

PFZ Product note: Topsil PFZ product note
PFZ Application note: Topsil_PFZ-Application_note.pdf
PFZ Application 200mm: Topsil PFZ application note for 200mm

EPI CZ-EPI: Topsil_CZ-EPI_2010.pdf
PV-FZ Product note: Topsil_PV_FZ_Product_note_2014.pdf
PV-FZ Application note: Topsil_PV_FZ_Application note_2014.pdf
GaN Silicon for films: Topsil_GaN_Product_note_2013.pdf

Float Zone technology

SAND to POLYSILICIUM

SiO_2

Si + 3HCl -> $SiHCl_3$(l) + H_2
Destillation af $SiHCl_3$(l,g)

FZ silicon rods

SiO_2 + 2C -> Si(l) + 2CO
[Metallurical Grade Silicon - 98% purity]

$SiHCl_3$(g) + H_2(g) -> Si(s) + 3HCl(g)
[Electronic Grade Silicon – contaminates in ppt levels]

Powdered MG-Si is reacted with anhydrous HCl at 300 °C in a fluidised bed Liquid $SiHCl_3$ subsequently destilled

Pure $SiHCl_3$ is reacted with hydrogen at 1100°C for ~200 – 300 hours to produce a very pure form of silicon

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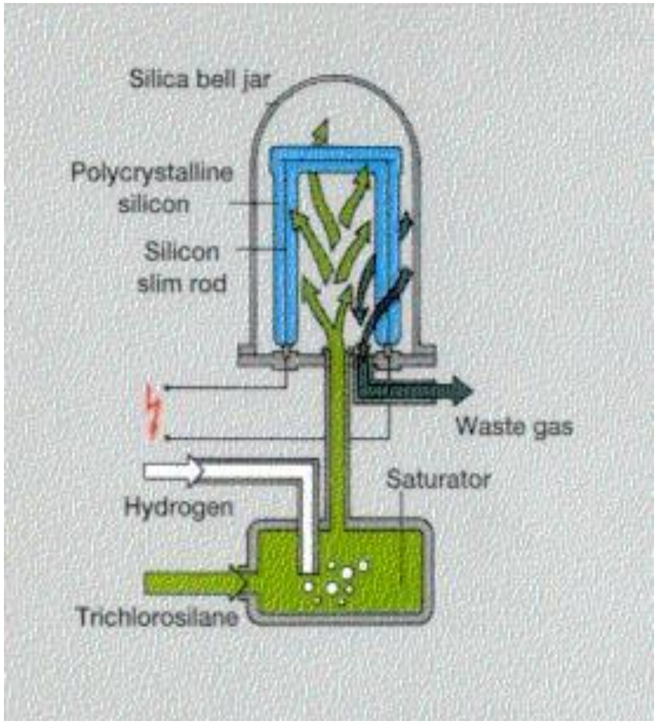
POLY - SIEMENS REAKTOR

Chemical decomposition of silicon-gas on a hot filament:

$2\ SiHCl_3\ (gas) + 2\ H_2\ (gas) \rightarrow 2\ Si\ (solid) + 6HCl\ (gas)$

or

$SiH_4\ (gas) + heat \rightarrow Si\ (solid) + 2H_2\ (gas)$



Silicon properties influenced:

- Doping level
- Doping type
- Compensation
- Trace element contamination

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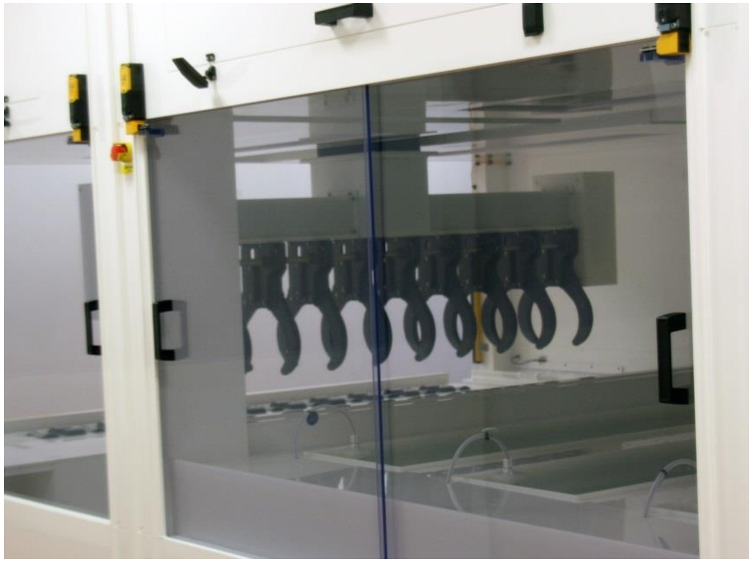
POLY for FZ – surface cleaning



Etching procedure

DI water + ultrasound > HNO_3:HF > HF > DI water > Drying

Product properties influenced:

- Surface chemical contamination (→ bulk crystal contamination)
- Surface particle contamination (destroy crystalline structure)

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FLOAT ZONE

Poly chamber

High frequency (HF) generator

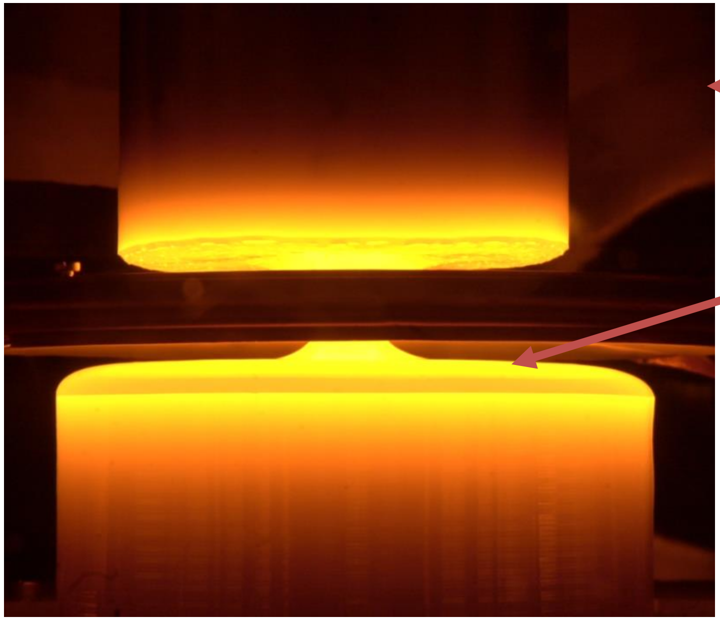
Process monitoring

Control panel

Monocrystal chamber

TOPSIL

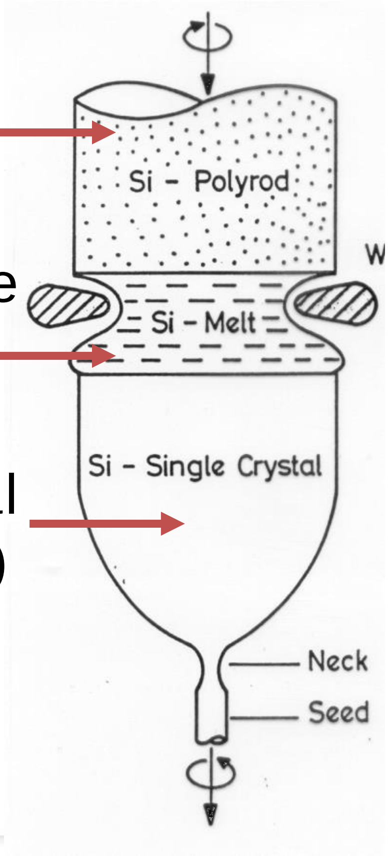
FLOAT ZONE



1. Feedrod (polysilicon)

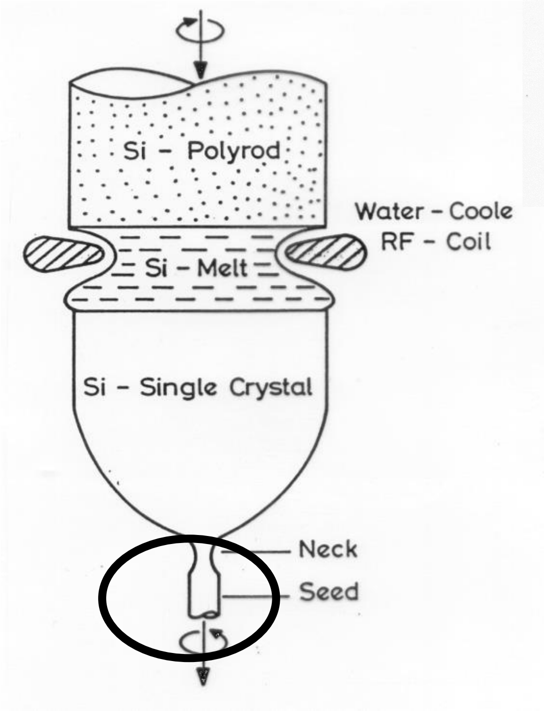
2. Molten zone (FZ-process)

3. Monocrystal (final product)

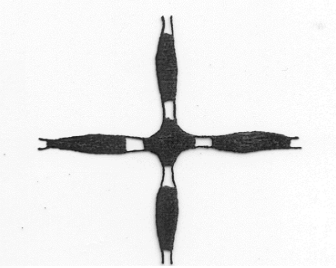


FLOAT ZONE

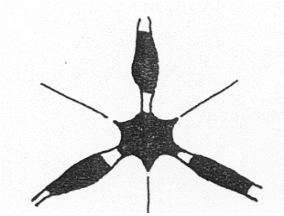
Seed crystal and necking



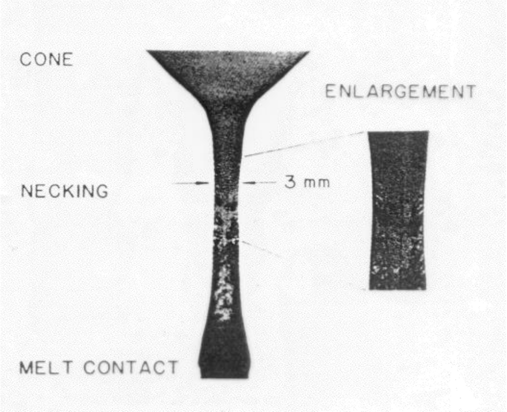
First contact between seed and melted silicon



<100> seed



<111> seed



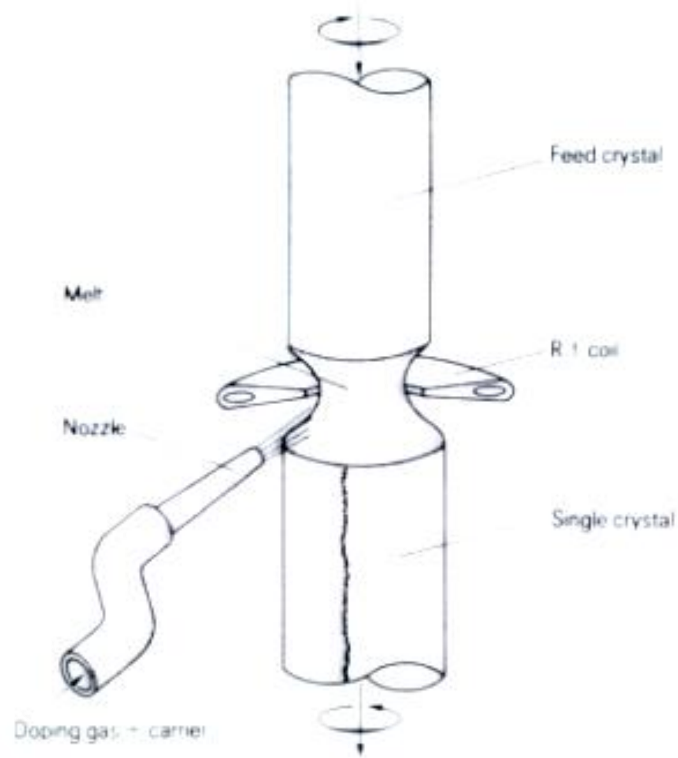
Necking

Product properties influenced:

- Crystalline orientation
- Dislocation free growth

Gas phase doping

Doping med Phosphorous and Boron



Gas doping:
Diluted Phosphine (PH_4) or Diboron (B_2H_4) in Argon blown directly into the molten silicon

Product properties influenced:

- Silicon resistivity

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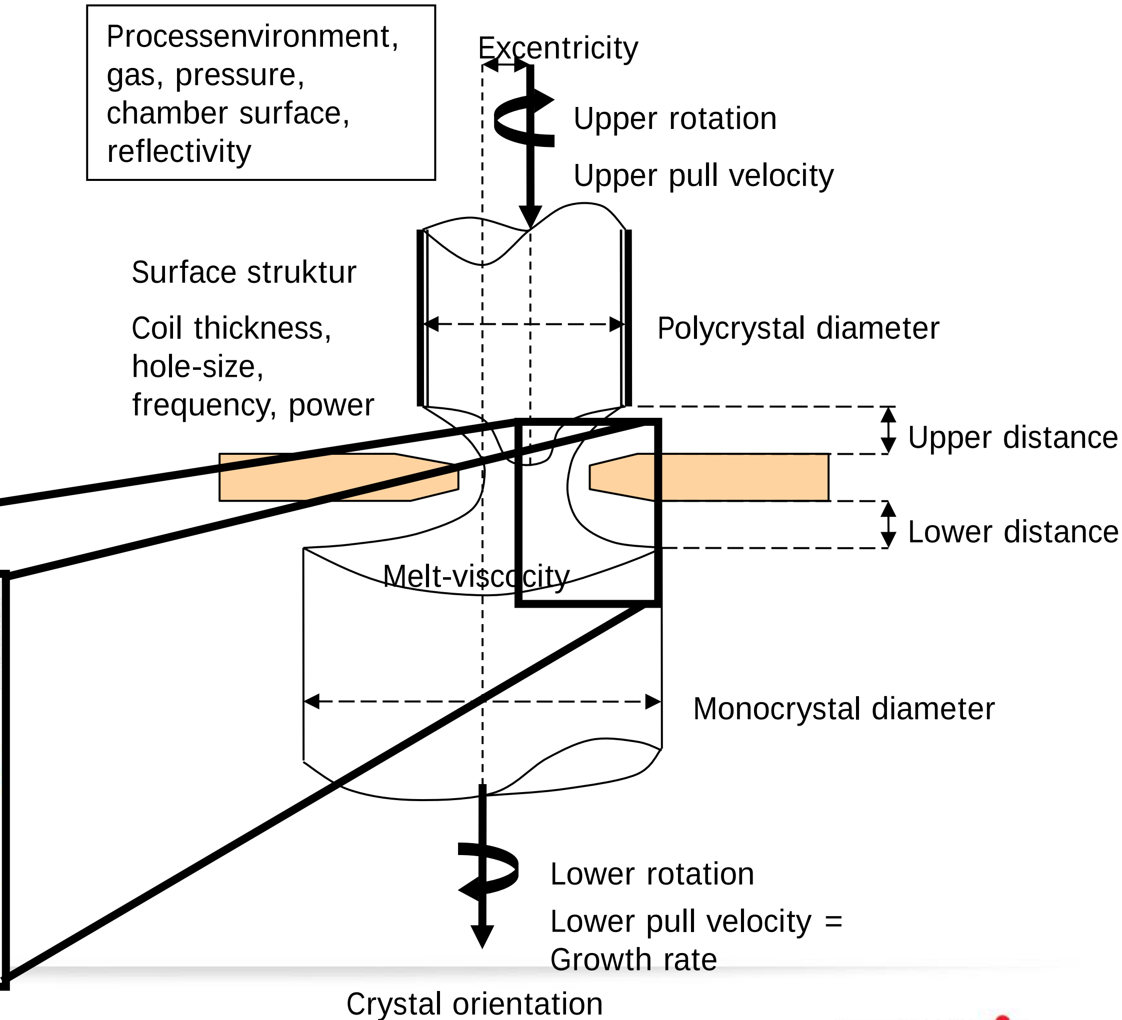
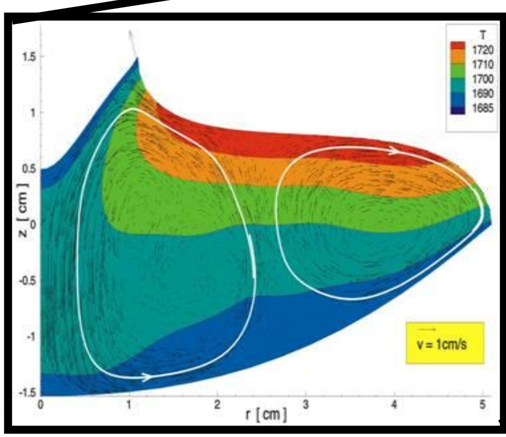
FZ parameters

Product properties influenced:

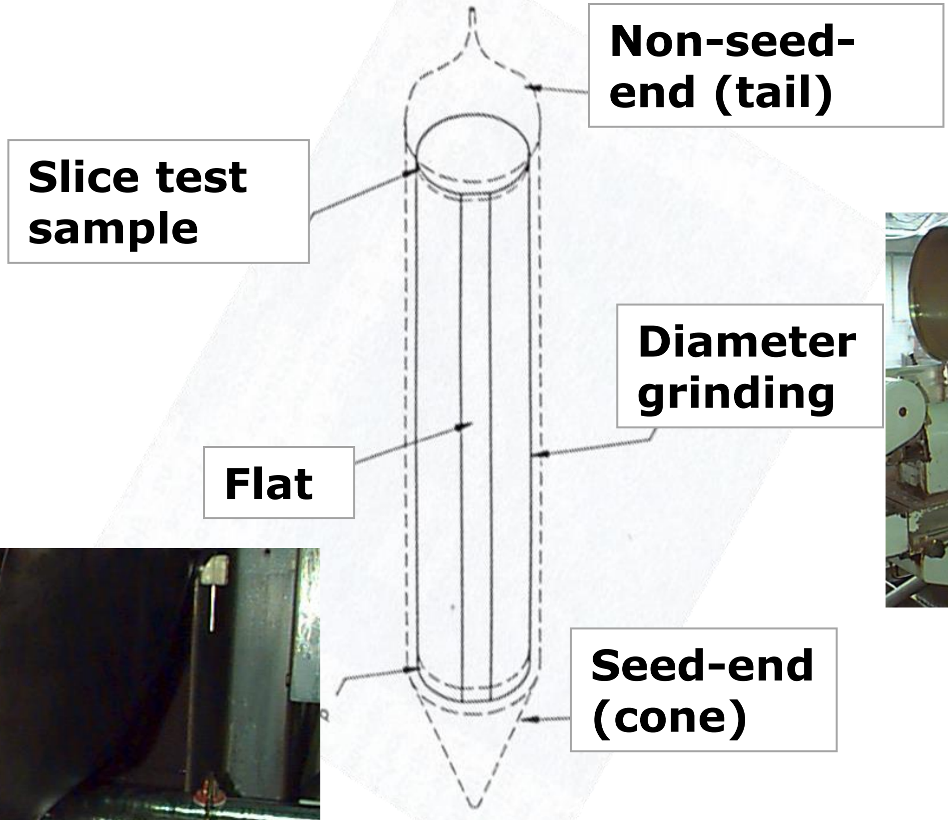
- Radial Resistivity Variation (RRV)
- Striations (micro-variations in resistivity)

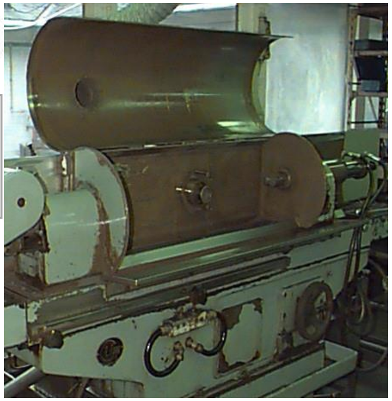


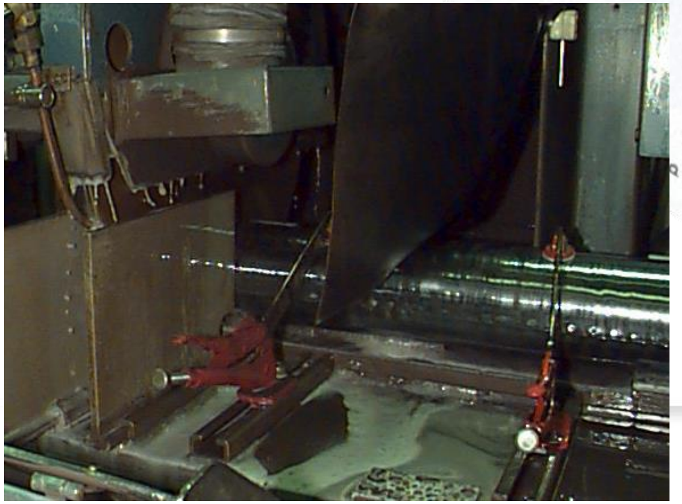


Crystal cutting and grinding

Mechanical shaping of ingot







Process parameters influenced:

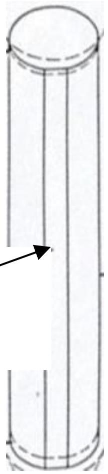
- Ingot length & diameter

MONO crystal

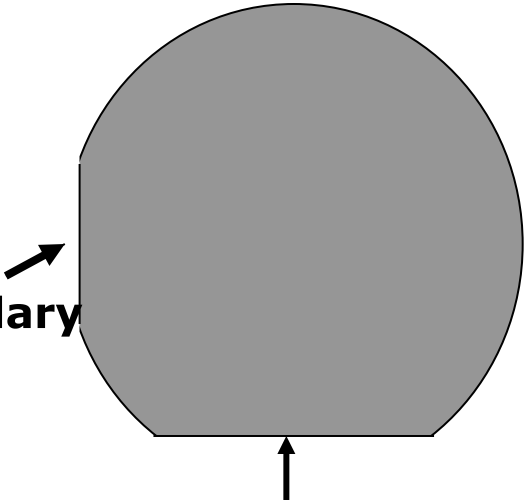
Mechanical shaping of ingot

X-ray

Flat grinding



Secondary flat



Primary flat

Process parameters influenced:

- Ingot length & diameter

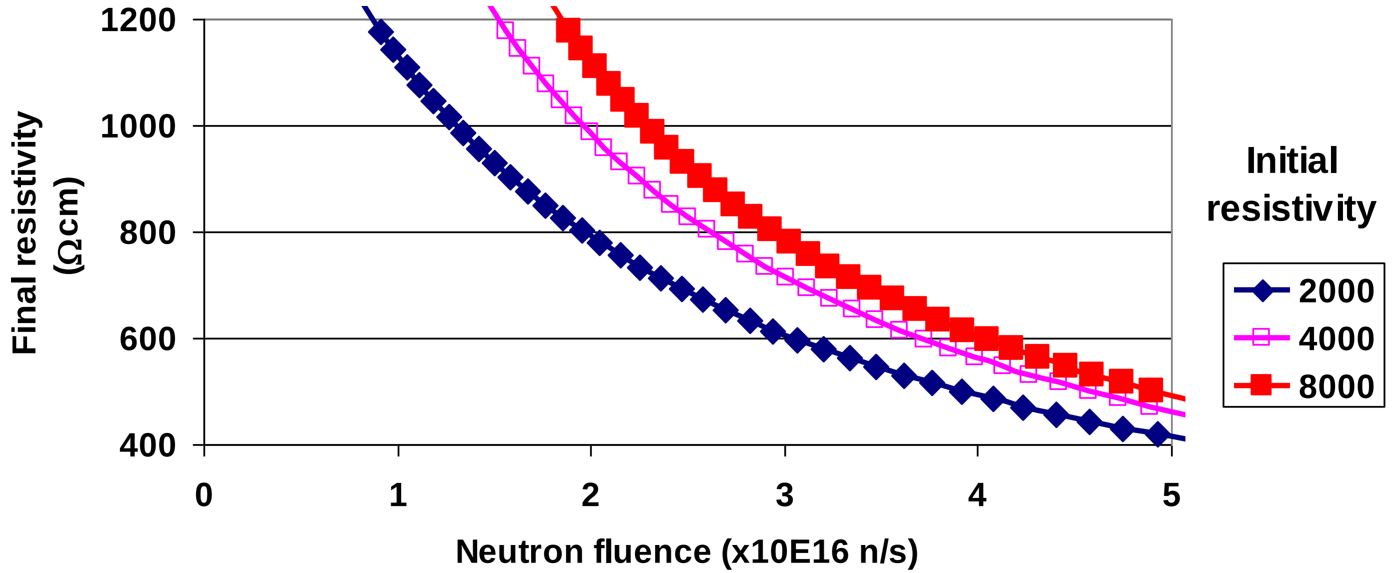
DOPING, NTD

Phosphorous doping by Neutron Transmutation Doping

Neutron irradiation reaction:

$^{30}Si(n,\gamma) \Rightarrow {}^{31}Si \Rightarrow {}^{31}P + \beta^-$ ($T_{½}$ = 2.62 hours)

$^{31}P(n,\gamma) \Rightarrow {}^{32}P \Rightarrow {}^{32}S + \beta^-$ ($T_{½}$ =14.3 days)



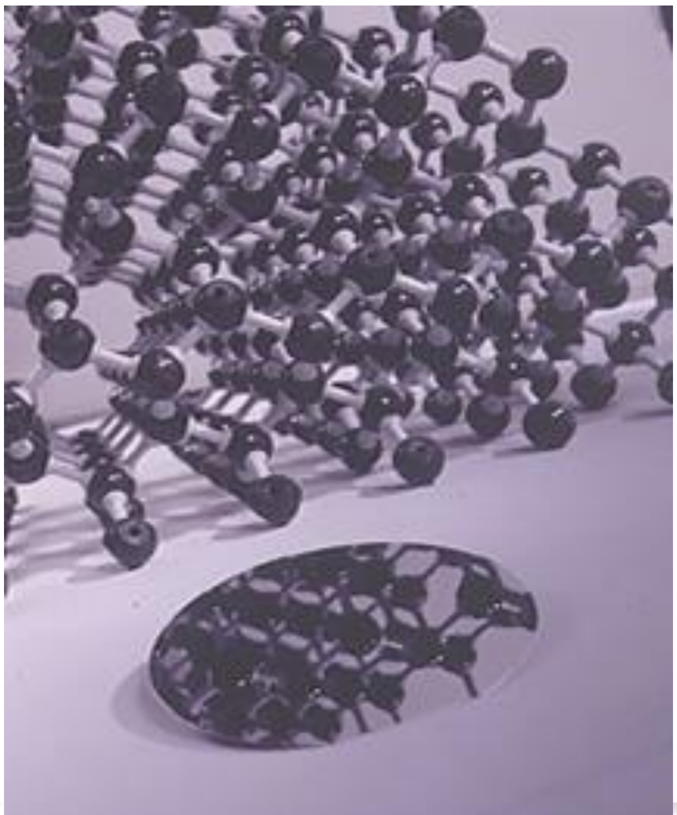
Product properties influenced:

•Phosphorous concentration (homogenous doped)

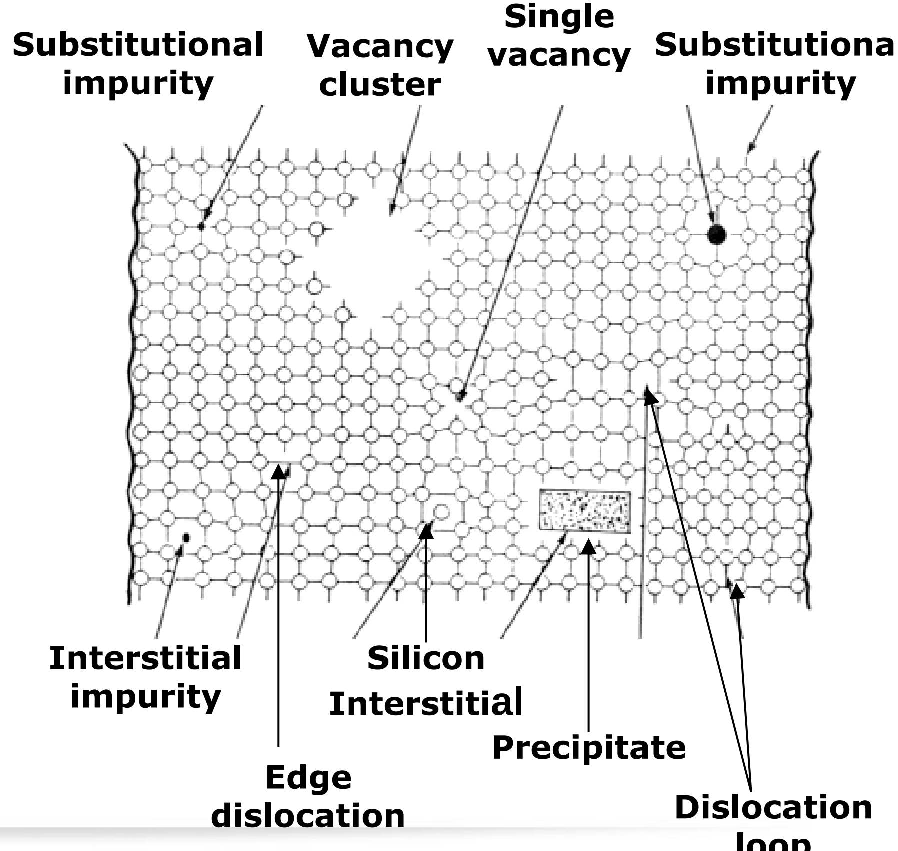
Crystal defects

Electrical, chemical and structural characterisation of monocrystal

Perfect crystal

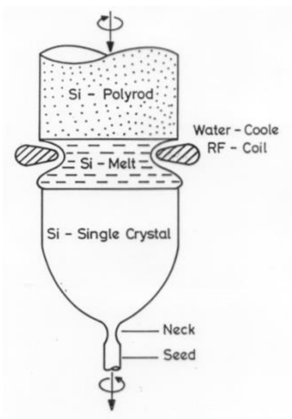


Non-perfect crystal

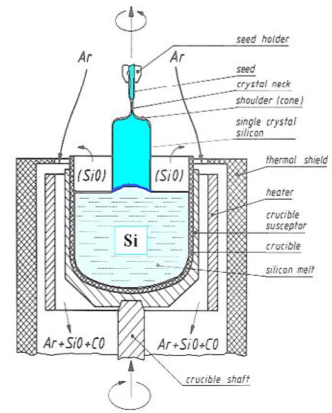


Comparing CZ & FZ

Float Zone



Czochralski



General benefits:

Accurate resistivity control

High resistivity (»100 Ωcm)

Fits to CZ IC process

No thermal donors

HPS ultra pure silicon

PV application:

Low oxygen (<10^{16} cm^{-3})

Long lifetime (>1000 ms)

No degradation

General benefits:

Large diameter 8″ – 12″

Low resistivity

Intrinsic gettering

PV application:

High oxygen (>10^{18} cm^{-3})

Short lifetime (<100 ms)

Carrier induced degradation

Comparing CZ & FZ

Parameter	FZ	CZ
Crystal diameter (mm)	< 200	< 450
Crystal length (mm)	< 1800	< 2000
Crystal weight (kg)	< 100	< 200
Growth velocity (mm/min)	< 3.5	< 2.0
Boron (k=0.8) (atoms pr. cm^3)	$5 \times 10^{11} – 1 \times 10^{17}$	$5 \times 10^{12} –1 \times 10^{20}$
Phosphorous (k=0.35) (atoms pr. cm^3)	$1 \times 10^{11} – 5 \times 10^{18}$	$5 \times 10^{12} –1 \times 10^{18}$
Carbon (k=0.07) (atoms pr. cm^3)	$1 \times 10^{15} – 5 \times 10^{16}$	$1 \times 10^{15} –3 \times 10^{16}$
Oxygen (k=1.2) (atoms pr. cm^3)	$1 \times 10^{15} – 2 \times 10^{16}$	$1 \times 10^{17} –1 \times 10^{18}$
Iron (k=10-5) (atoms pr. cm^3)	2×10^{12}	2×10^{12}
Total impurity incl. C, N, O and dopant (cm^3)	$<1 \times 10^{13}$	$<5 \times 10^{13}$
Crucible material	No crucible	Silica
Pressure (mbar)	5×10^{-4} – 5000	5 – 1000
Argon flow (Nl h^{-1})	0 - 2000	400 – 5000
Resistivity	High, > 10 Ωcm	Low, < 10 Ωcm
Mechanical growth conditions	Gravity destabilises melt and crystal	Gravity stabilises melt and crystal
Thermal growth conditions	Large gradients, transients	Small gradients, Minor transients
Application	High voltage devices, Bulk components	Low voltage device Surface components

THANK YOU

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Senior Silicon Scientist

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GaN-LED growth on SiC substrates

Dr. Meng Liang

Institute of Semiconductors, Chinese Academy of Science, China

State Key Laboratory of Solid-State Lighting, China

Contents

1.1 Why choosing the SiC as LED substrates

parameters	H-InN	H-GaN	H-AlN	sapphire	SiC
Lattice Constant (Å)	3.548	3.189	3.112	4.748	3.080
CTE Δa/a (1/K)	3.8×10^{-6}	5.59×10^{-6}	4.2×10^{-6}	7.3×10^{-6}	4.2×10^{-6}
Thermal Conductivity (W/cm/deg)	0.45	1.3	2.85	0.35	4.9

Advantages：

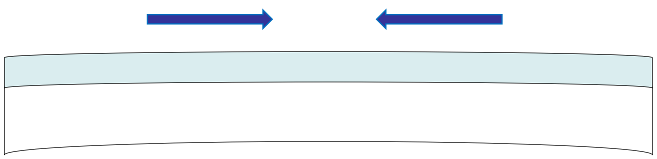
- lower lattice mismatch, 3.5%-- good for high quality epitaxal layer
- higher thermal conductivity– good for heat dissipating, improving the LED performance and extending life time , especially the high power LED
- lower CTE mismatch
- Besides, can be doped by Al, B, N etc, e.g. fluorescent SiC

LED on SiC with More than 300lm/W efficacy has been reported last year

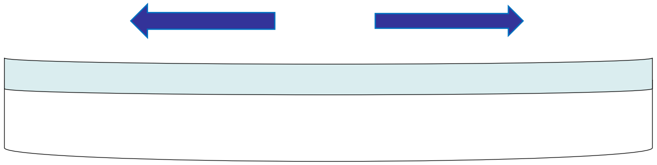
1.2 challenge for GaN growth on SiC

• Epitaxy layer crack
because of large tensile stress caused by the different CTEs of SiC and GaN when cooling down after growth process

• Be difficult for GaN to deposit on SiC directly because SiC is with high surface energy.



Compressive stress during growth process

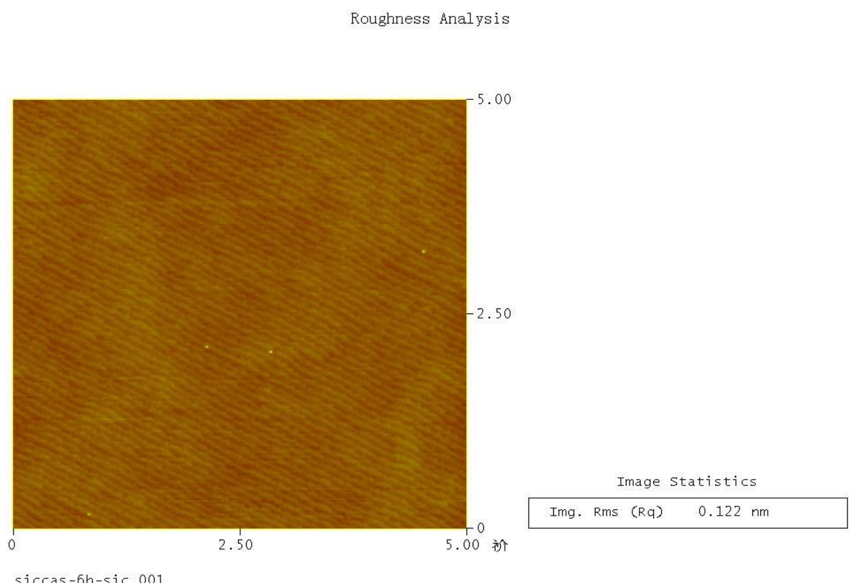


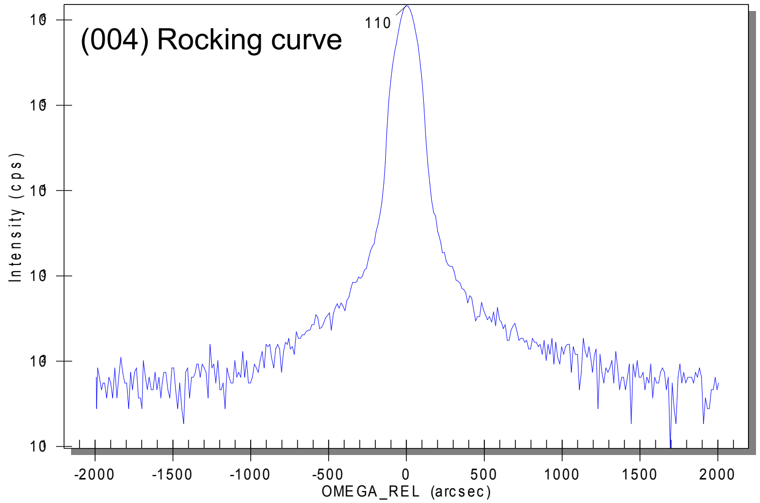
tensile stress after cooling down

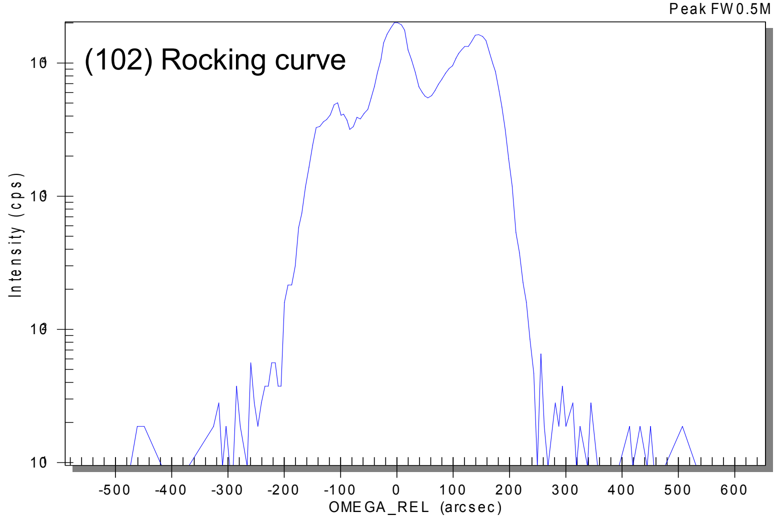
1.3 primary work about GaN growth on SiC

SiC substrates (bought from a company in China):

- FWHM of (004) Rocking curve is about 110 arcsec
- FWHM of (102) Rocking curve is about 400arcsec
- RMS of surface is 0.122nm



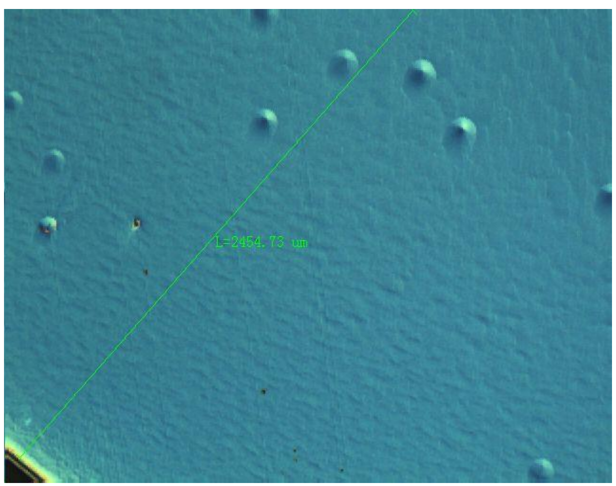




1.3 primary work about GaN growth on SiC

The thickness of AlN buffer :
5nm, 20nm,60nm and 100nm.
Growth temperature:900℃

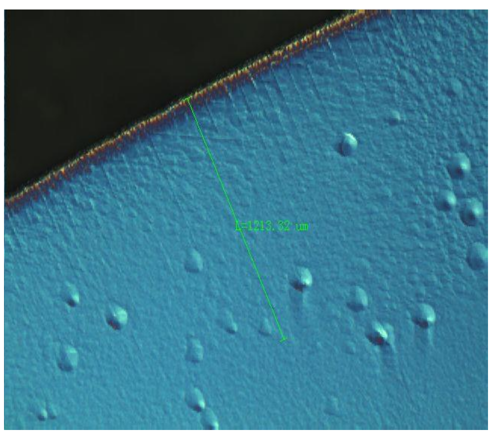
Results： cracks reduce as the thickness of buffer increases. But cracks on the edge still exist (in the area that about 2400um from the edge)



1.3 primary work about GaN growth on SiC

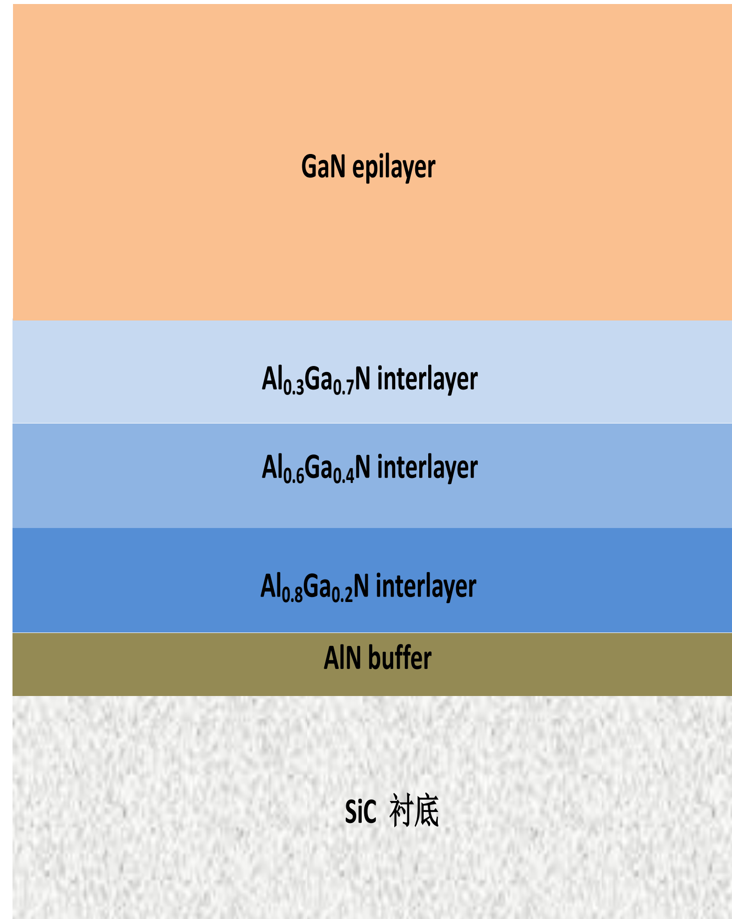
Use multi- $Al_xGa_{1-x}N$ interlayers to release the strain further.

Results： the cracking area narrow down, and about 1200um from the edge. And the center of wafer is crack free.



edge

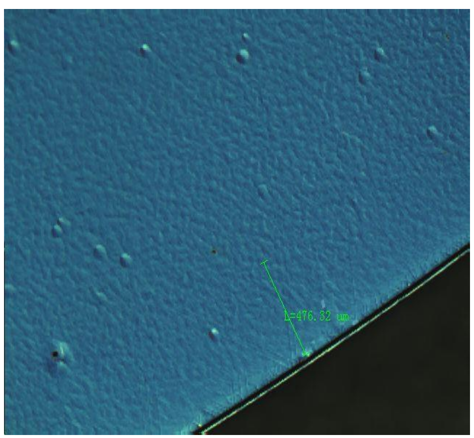
center

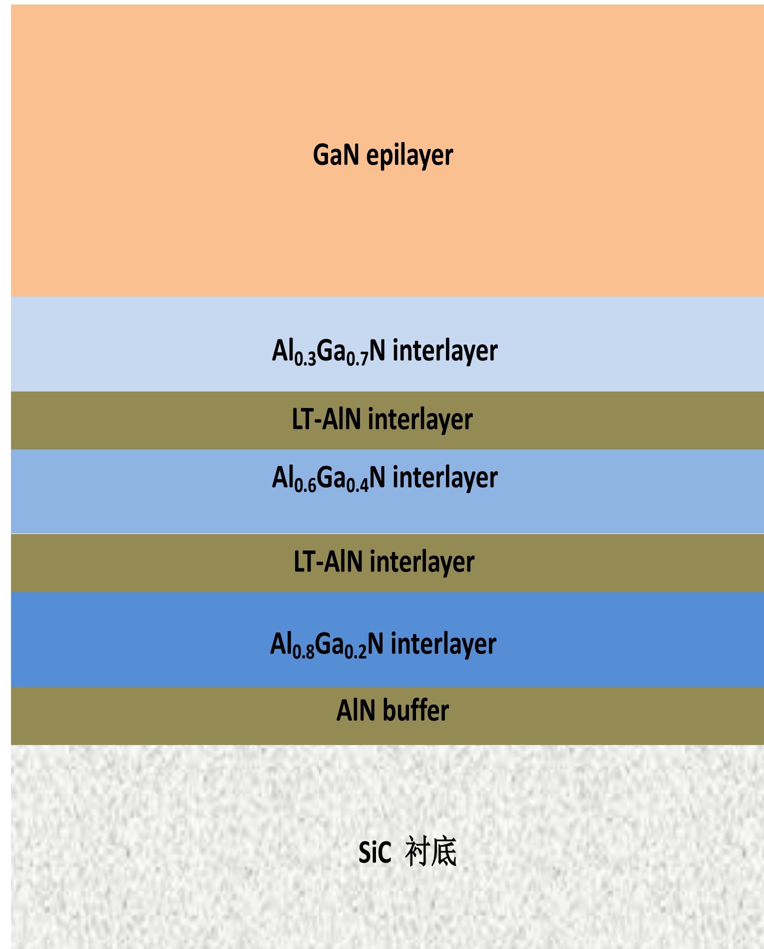


1.3 primary work about GaN growth on SiC

Use three pairs of Lt-buffer/$Al_xGa_{1-x}N$ interlayers to release the strain further.

Results： the area with cracks turn much smaller, the cracking area : about 500um from the edge.

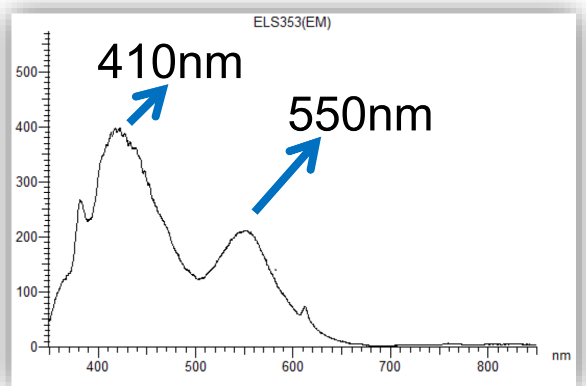




1.3 primary work about GaN growth on SiC

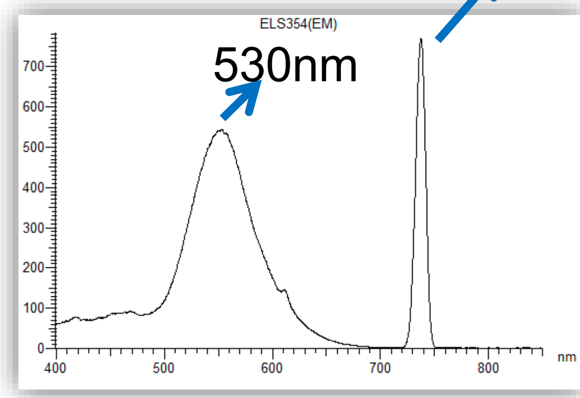
Fluorescence measure results of two f-SiC samples

ELS353

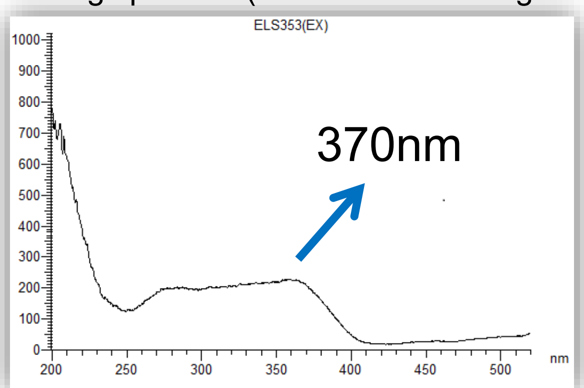


Emitting spectrum(excitation wavelength330nm)

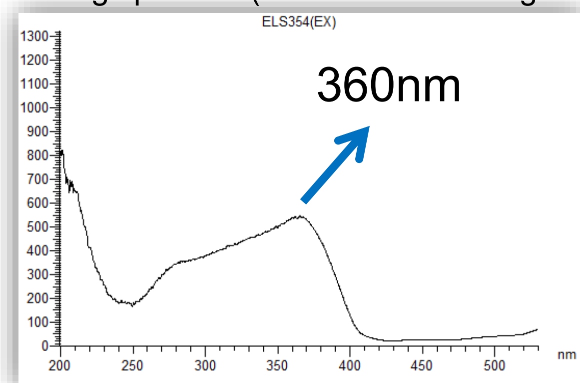
ELS354 730nm



Emitting spectrum(excitation wavelength365nm)



Excitation spectrum(emitting wavelength550nm)



Excitation spectrum(emitting wavelength530nm)

1.4 next stage plan

Next stage plan：

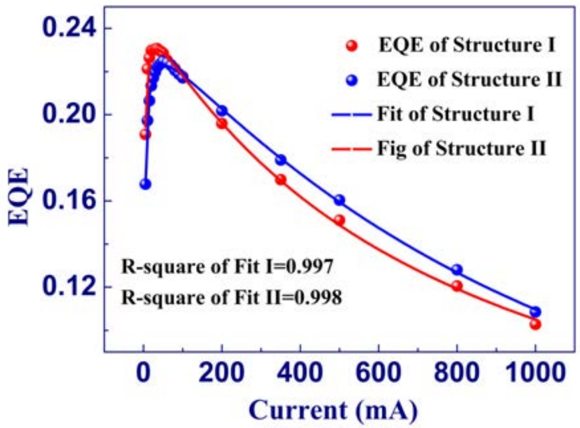
◆ continue to optimize the structures and growth conditions of AlN buffer and AlGaN interlayers to obtain crack free GaN/SiC wafer.

◆Base on the former work, growing the LED on SiC. Followed by chip process and test.

Contents

2.1 Efficiency droop at high current density (Droop effect)

➢ **What Causes Efficiency Droop ?**
No consensus till now.

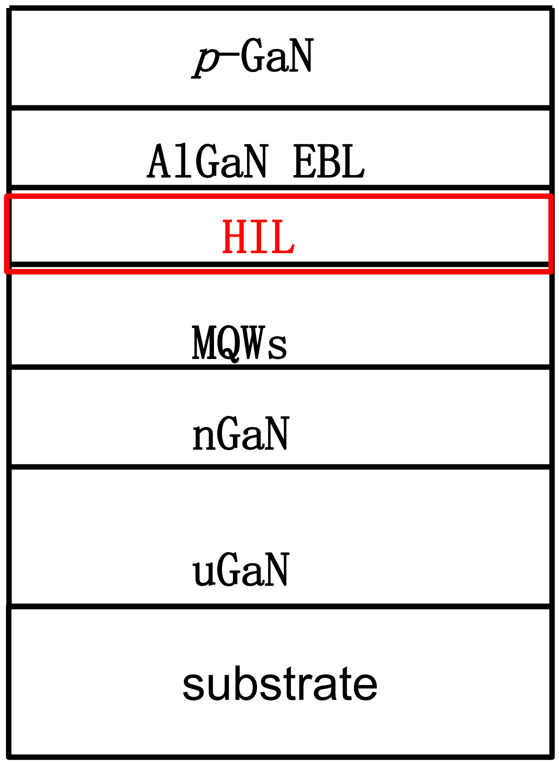


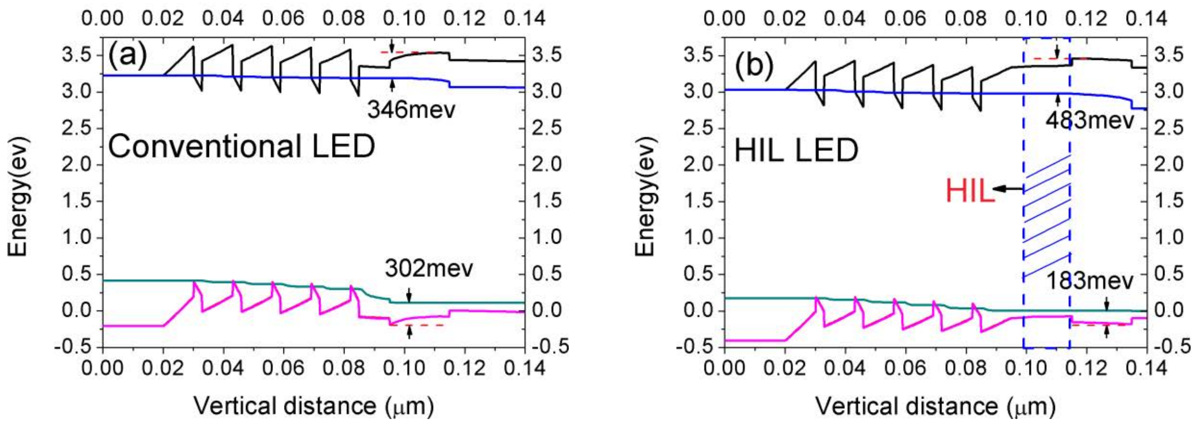
Several competing theories/explanations

1) Electron overflow at high current densities due to inadequate electrical confinement layers (RPI, GIT)
2) Electron overflow due to polarization fields in the MQW region (Rensselaer Ploytechnic Institute)
3) Auger recombination due to high carrier density (Lumileds, UCSB) Defects assist Auger, Auger electron (UCSB)
4) Poor hole transport in MQW (Virginia Commonwealth Univ.)

2.2 increase the hole injection efficiency

Insert a hole injection layer(HIL) to increase the hole injection efficiency

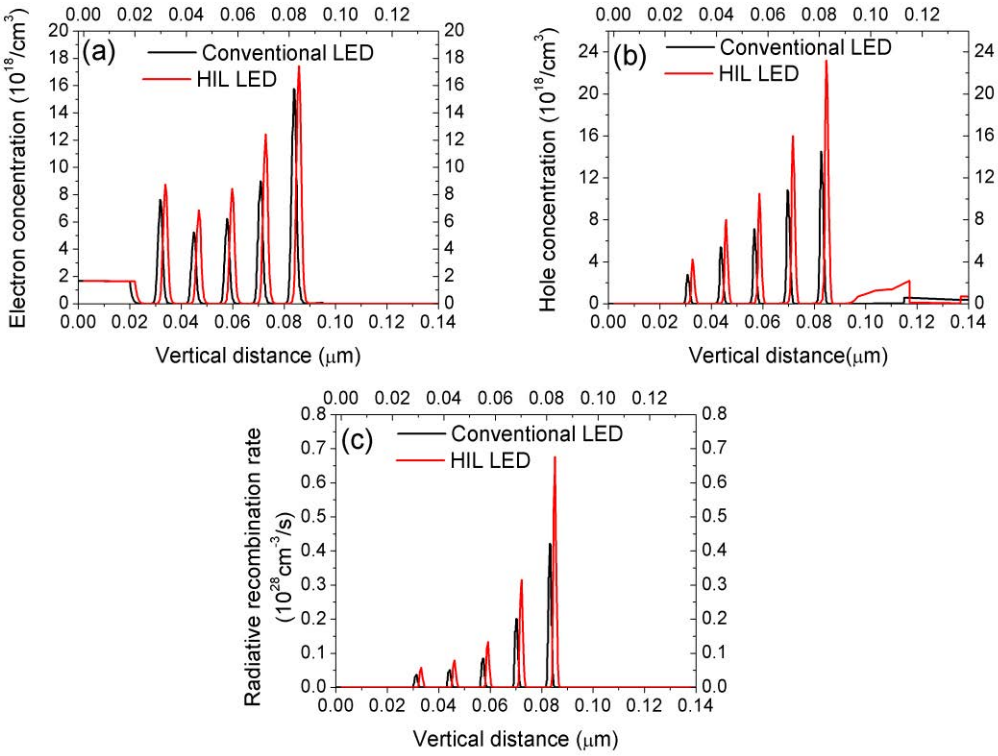




Effective potential height for hole in valence band ($\Delta\varphi_h$) is reduced from 289meV to 239meV.

Effective potential height for electron in conduction band ($\Delta\varphi_e$) of increases from 300meV to 439meV.

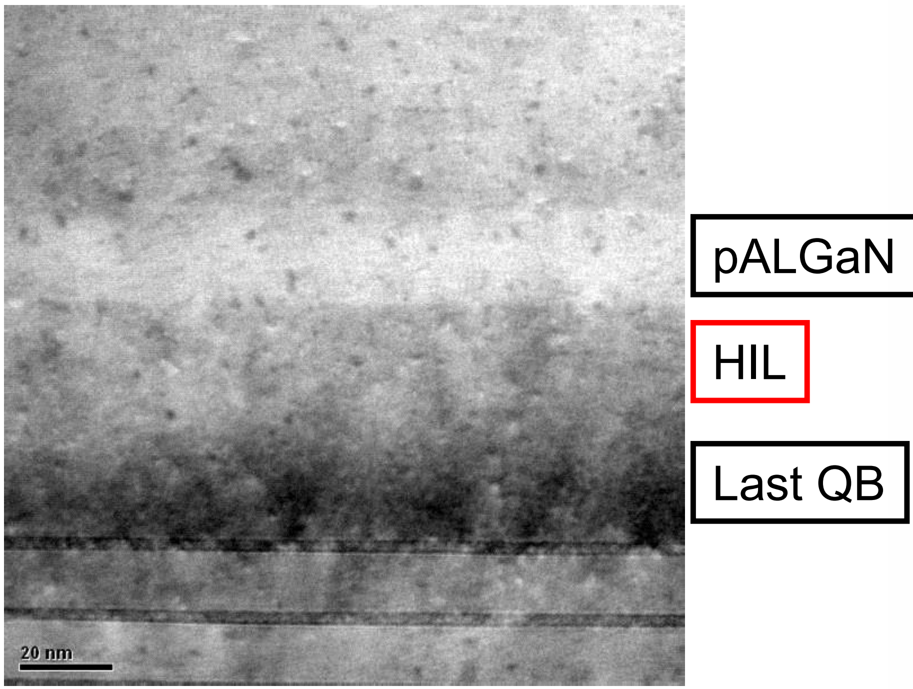
2.2 increase the hole injection efficiency

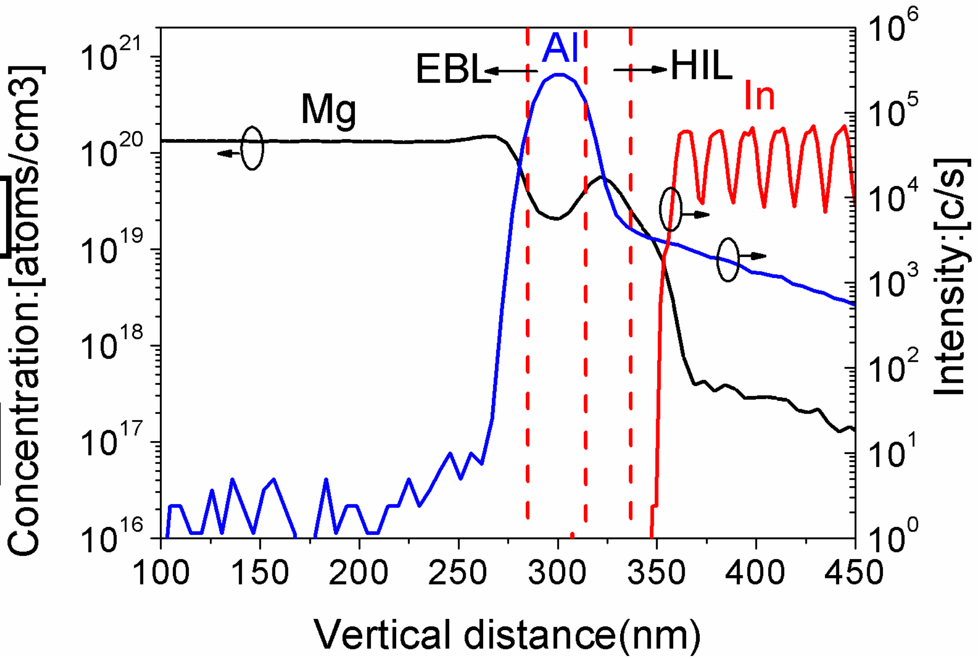


APSYS simulation results:

- Hole concentration in the last QW is $2.4*10^{18}$ cm^3 for HIL LED, which is 51% higher than that of $1.6*10^{18} cm^3$ for conventional LED.
- Hole distributes more uniform in HIL LED than in conventional one, while the calculated electron concentration in the active region in HIL LED is also higher than that of the conventional LED.

2.2 increase the hole injection efficiency





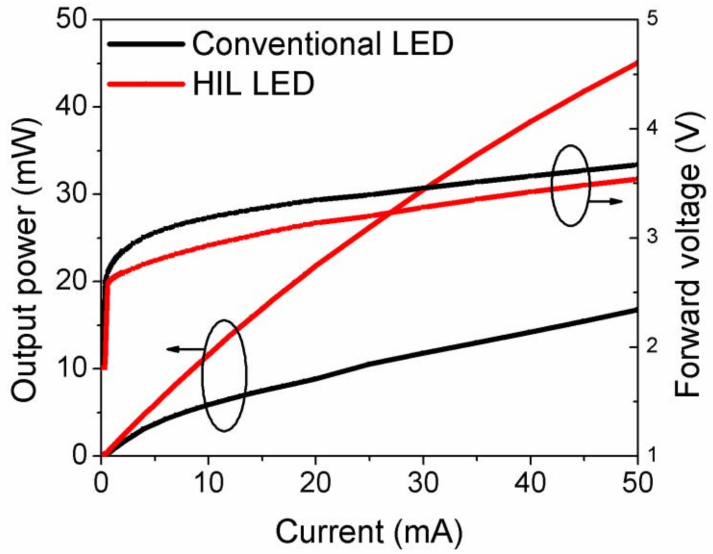
TEM of HIL LED

SIMS results of HIL LED

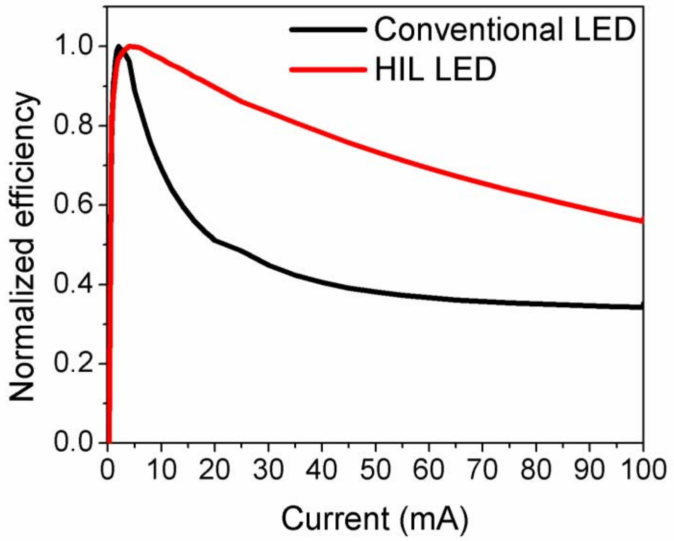
HIL thickness is estimated to be about 20–22nm as designed. And the Mg atoms concentration in HIL is about $5.9*10^{19}$ cm^3, a little higher than that of EBL ($2.2*10^{19}$ cm^3).

2.2 increase the hole injection efficiency

Measure after chip process



L-I-V characteristic of Conventional LED and HIL LED



Normalized efficiency of Conventional and HIL LED

The HIL LED shows a reduced efficiency droop behavior with the injection current increased. The efficiency droop of the HIL LED is 33% lower at 100 A/cm2, compared to the conventional LED.

2.3 double Electron Blocking Layers

- first EBL, AlGaN:Mg ($1.3\times10^{18}cm^{-3}$) :

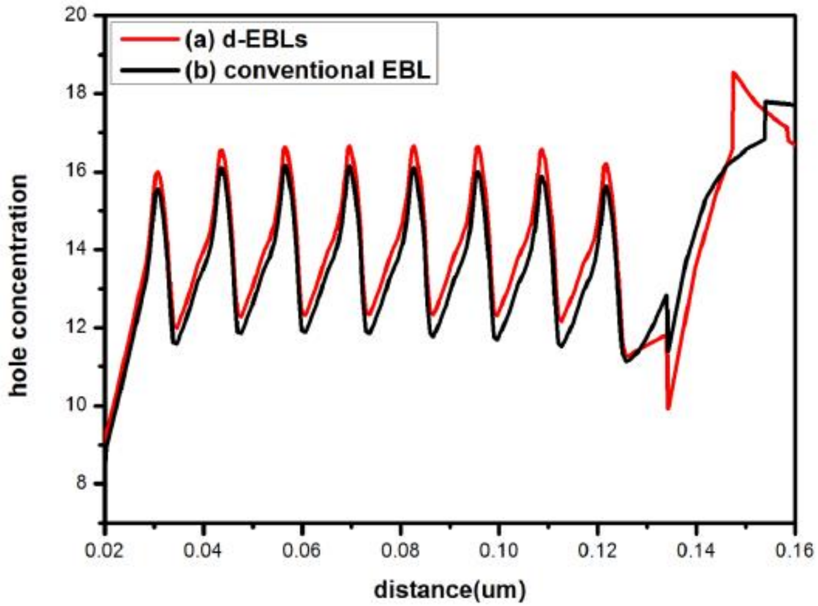
  on the top of last QB, 13nm ;

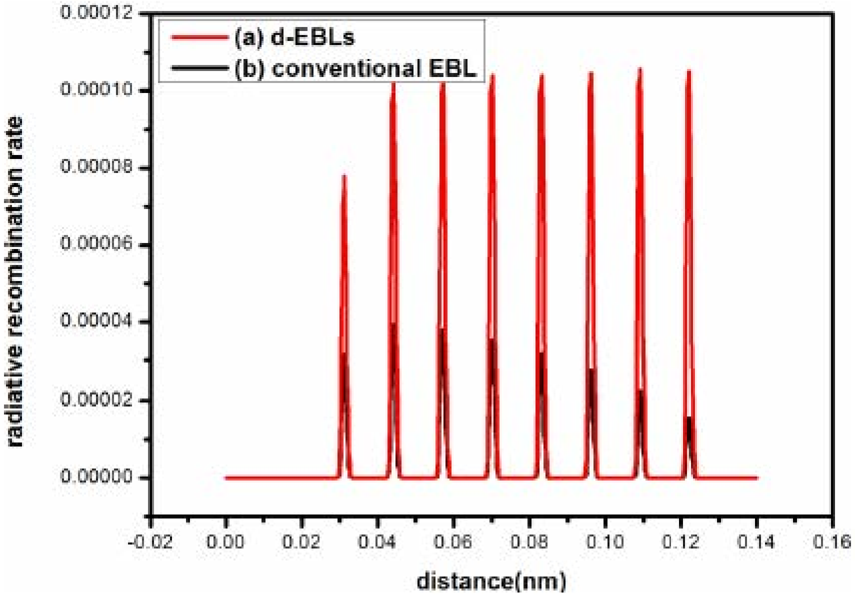
- 24nm-thick GaN:Mg ($2\times10^{17}cm^{-3}$) growth on first EBL

- second EBL, AlInGaN:Mg ($4\times10^{18}cm^{-3}$) ,20nm

2.3 double Electron Blocking Layers

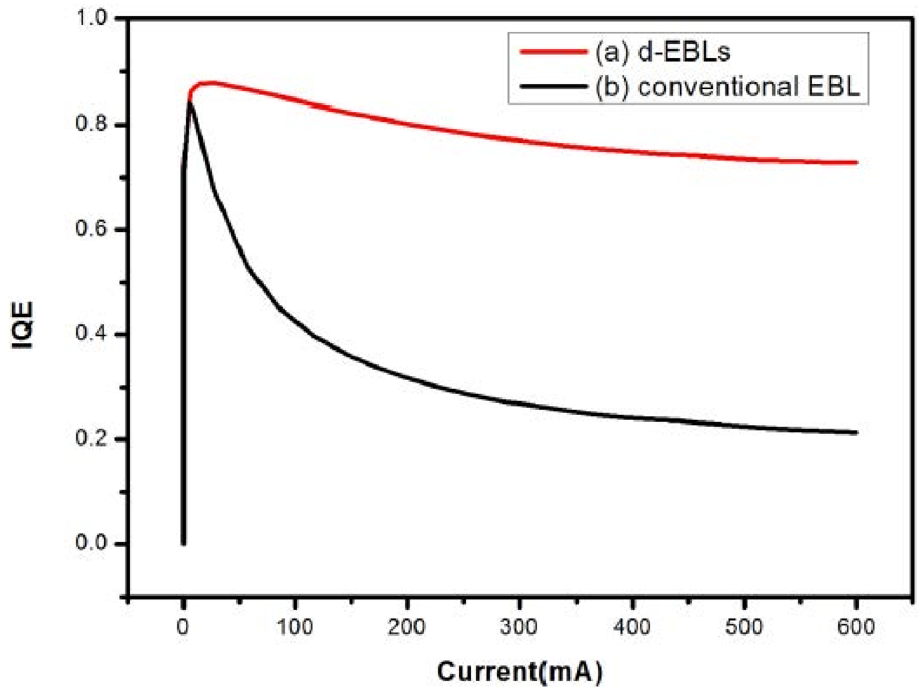
Apsys simulation





- Holes concentration in the d-EBLs structures remarkably increases
- the radiative recombination rate was uniform, and had been averagely tripled.

2.3 double Electron Blocking Layers

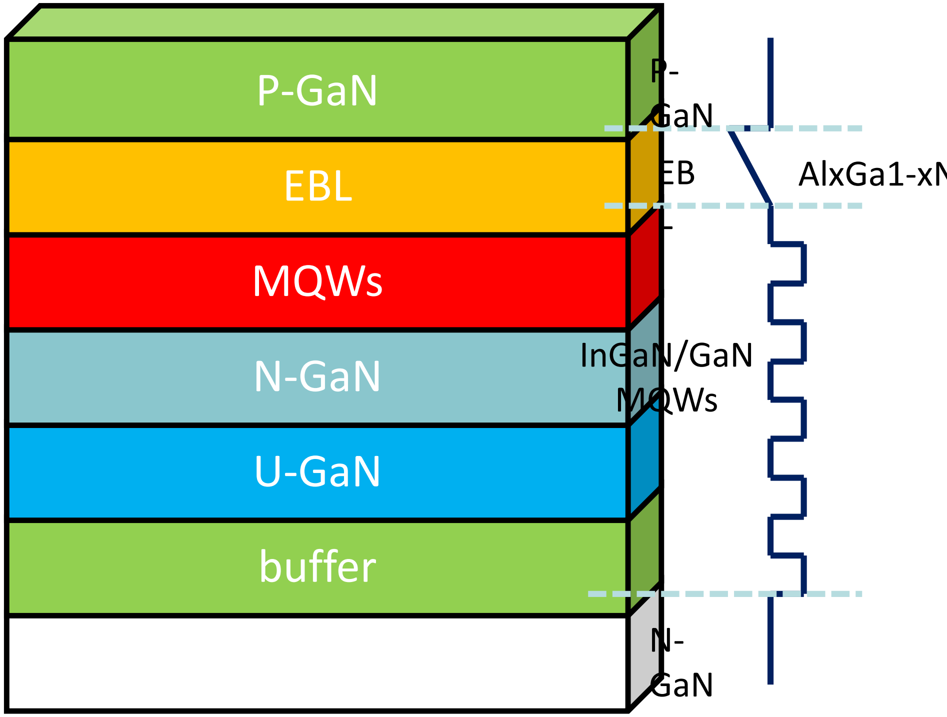


It can be noticed that the obvious suppression of IQE declined. The droop ratio has been reduced to 15.5% at the current density of 100 A/cm2.

2.4 next stage plan

continue to reduce the efficient droop via:

- Physical mechanisms
- Insert layer between MQW and n-GaN
- EBL Design
- high hole concentration p-GaN layer



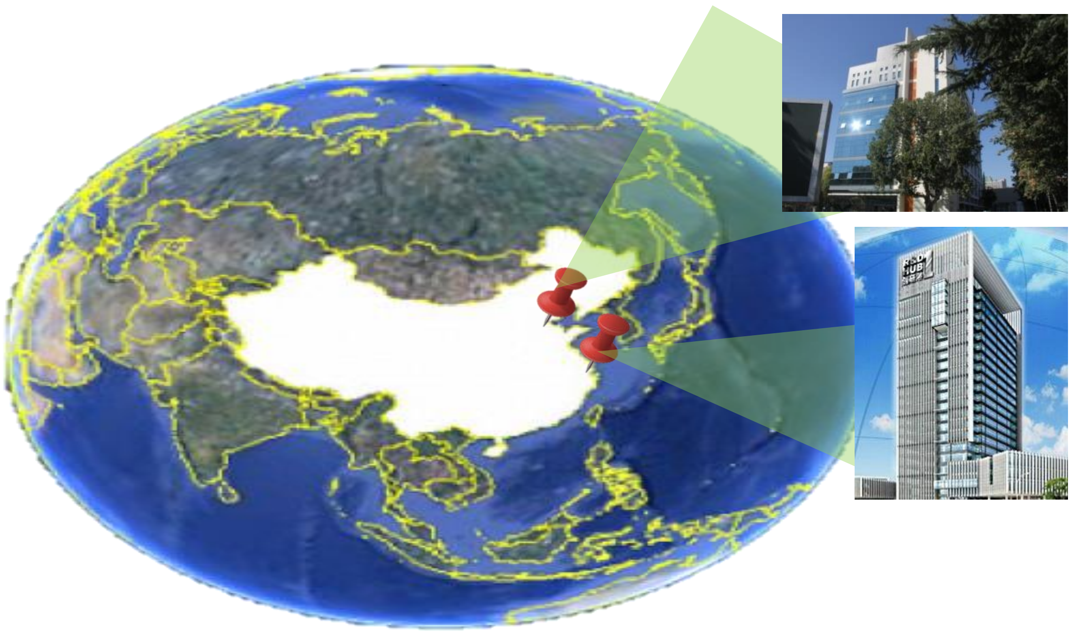
Contents

3 summery

- Use three pairs of Lt-buffer/$Al_xGa_{1-x}N$ interlayers to release the strain further. the area with cracks turn much smaller, about 500um from the edge.
- Insert a hole injection layer(HIL) to increase the hole injection efficiency, and The efficiency droop of the HIL LED is 33% lower than that of conventional LED at 100 A/cm2.
- double Electron Blocking Layers can obvious suppress IQE decline. The droop ratio is reduced to 15.5% at the current density of 100 A/cm2.

Contents

Solid State Lighting R&D Center, CAS
-State Key Laboratory of Solid-State Lighting



Currently located at Beijing and Changzhou

Participating academic organizations： Institute of Semiconductors/CAS; Changchun Institute of Optics, Fine Mechanics and Physics/ CAS, National Lighting Testing Centre; Tsinghua University; Delft University of Technology

Solid State Lighting R&D Center, CAS
-State Key Laboratory of Solid-State Lighting

In accordance with national development strategies

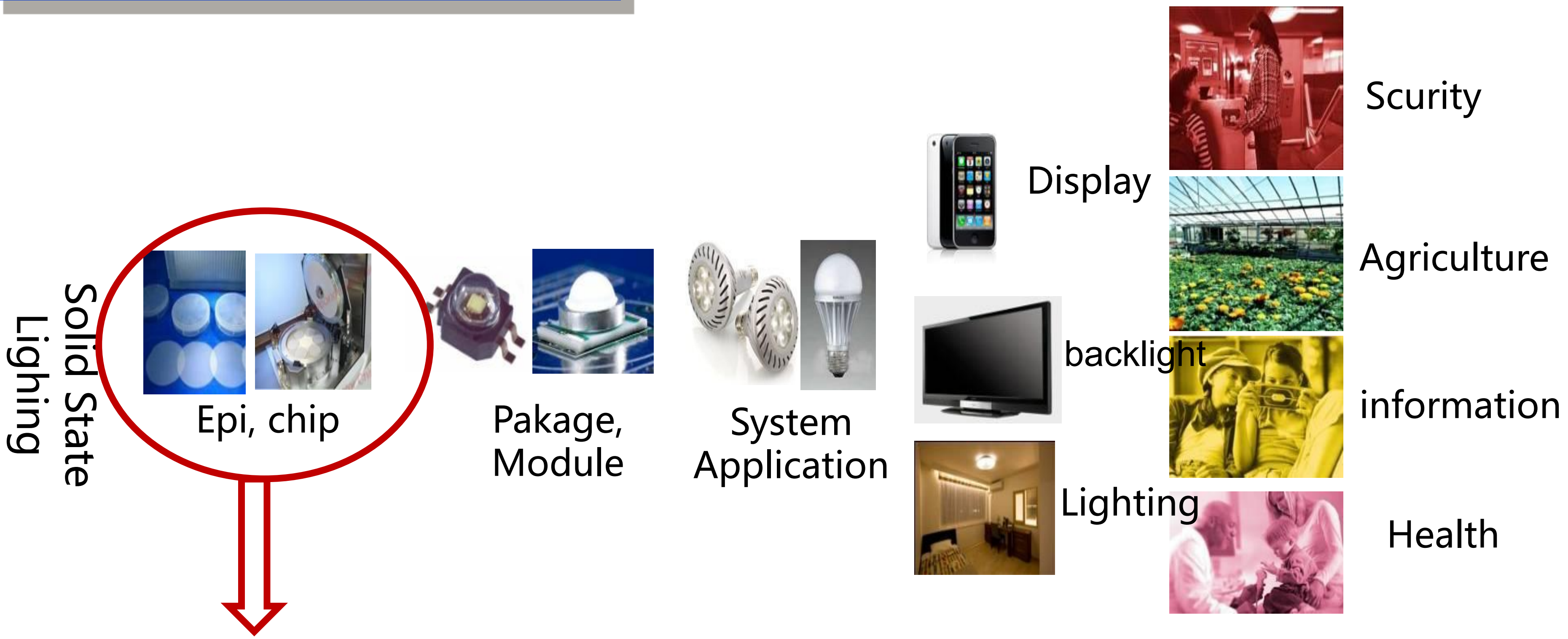
净化工艺线 (Cleanroom)

- To perform basic, forward-looking, and strategic science and technology research,
- To carry out research of key technologies
- To integrate resources toward an international collaboration
- Education and Base for talent training

2004,"National Semiconductor Lighting Project" launched by the Ministry of Science and Technology,

2006, the Semiconductor Lighting Research and Development Center, CAS was officially approved by the Chinese Academy of Sciences and established at the IOS, CAS

Research Field



Lighting, Beyond Lighting

Solid State Lighting R&D Center, CAS

- The center organized an energetic R&D team, including 10+ returned talents after studying abroad
- 29 professors and associate professors
- 40+ Ph.D. students & postdoc.
- Totally over 130 staffs

10 years of basic construction

1500 square meters clean room

半导体照明研发中心关键设备仪器--外延/芯片				
序号	仪器、设备名称	数量	金额(万元)	主要特点
1	MOCVD FCL	3	2000	1片2“，3片2”，7片2”
2	光刻机	2	210	生产型
3	电子束蒸发	1	120	产业化型：110片2”，ITO
4	ITO电子束蒸发	1	150	产业化型：110片2”，金属
5	ICP 干法刻蚀	1	200	产业化型 :7片2”
6	PECVD	1	160	产业化型 :32片2”
7	激光剥离系统	1	380	产能：40片2”/小时，成本：0.2S/片
8	晶片键合系统	1	80	高重复性、可靠性
9	多片衬底电镀台	1	15	36片2”
10	金属基底划裂系统	1	300	4片/h
11	其他	16	500	

半导体照明研发中心关键设备仪器—材料表征、检测分析		
设备名称	型号	主要参数
XRD	D8	单晶薄膜的高分辨XRD。
PL	PMS-50	GaN样品变温PL谱（4k-室温）
AFM	D3100	表面形貌,求表面起伏小于3微米
SEM	S4800	表面形貌，分辨率1 nm，可做能谱
SIMS	SIMS IV	分辨同位素
Hall	ECMS	材料的霍尔效应
热阻测试系统	T3Ster	
点测仪 WPSR-3100	日本Opto	快速准确的测试LED芯片的各个光电参数
分选机 WDS-3208	日本Opto	根据点测仪测得到的mapping
LED光强测试系统	SLMS-2021	分析LED光谱、光强、光通量、色度学参数.
半导体LED性能测试系统	4200-SCS	集成的示波器和脉冲测量功能;
LED荧光粉测试系统	Zetasizer Nano-ZS	测量范围：2-3000nm；ZETA电测定时粒度要求5 nm-30 μm。

sustainable developed technology radiation center and industrial service platform

Solid State Lighting R&D Center, CAS

MOCVD Epitaxy System

LED Chip Processing Line

High Speed Flip-Chip System for High Power LEDs

Sapphire Lapping and Polishing Equipment

Laser Lift-off System

High Power LED Chip Probing and Sorting System

Multi-Unit High Power LED Aging System.
With 1700 m2 Cleaning Room

Facilities of the Center

Facilities

➢LED MOCVD（3）

Facilities

➢Fabrication (19)

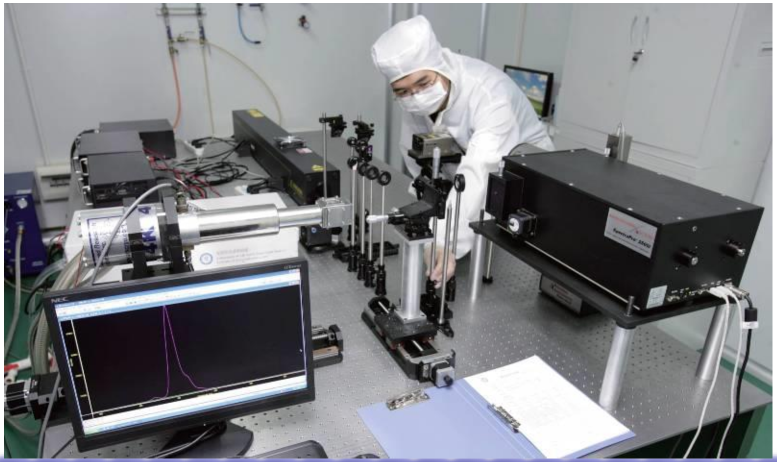
Laser Lift-off

EB

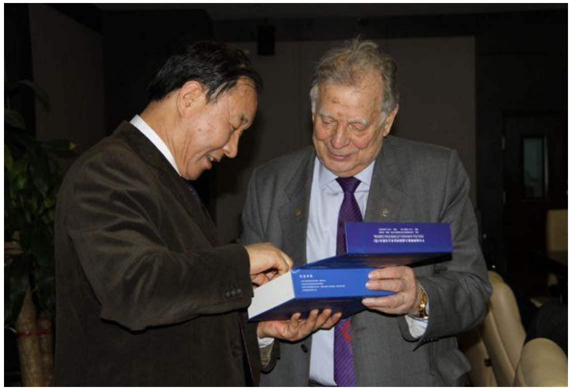
Lithography

Facilities

➢Characterizition (13)



International Cooperation and Exchange



So far, the SSL R&D center has established contacting and cooperative relationship with major research and academic organizations of over 20 countries. We have actively signed cooperation agreements and MOUs with the institutions and universities in America, Japan, Netherland, Russia, Korea, England and Germany, Gana, Singapore, Ireland.

LED characterization at DTU Fotonik

Paul Michael Petersen

Carsten Dam-Hansen, DTU Fotonik

DTU Fotonik
Department of Photonics Engineering

DTU Fotonik
Department of Photonics Engineering

DOLL
a Photonics GreenLab

DOLL – a Photonics Greenlab

Northern Europe's new large scale test and demonstration centre for lighting

Demark has a strong focus on dealing with climate changes

The Danish government has defined ambitious goals for reducing greenhouse gases.

2020-goal: Reduction of greenhouse gas emission by 40% compared to 1990

2050-goal: Total energy comsumption must be covered by sustainable energy.

DOLL – a photonics green lab

- ❑A Technical-scientific Lab – state-of-the-art instruments, development, tests and verifications

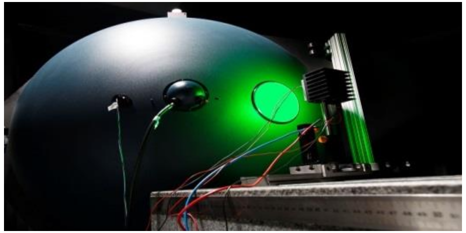
- ❑A Virtual lab – simulating lighting solutions in 3D, improving decision-making of innovative lighting

- ❑A Living Lab - the municipalities and housing companies are part of the innovation and development proces

The technical-scientific Lab

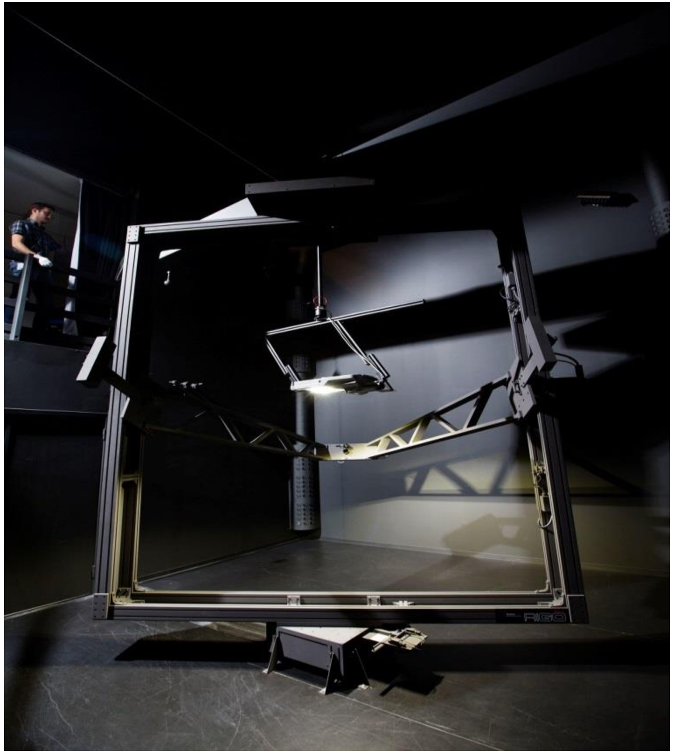
Photometric and radiometric testing facilities






Chief Scientific Officer
Jakob Munkgaard Andersen

Quality Lab



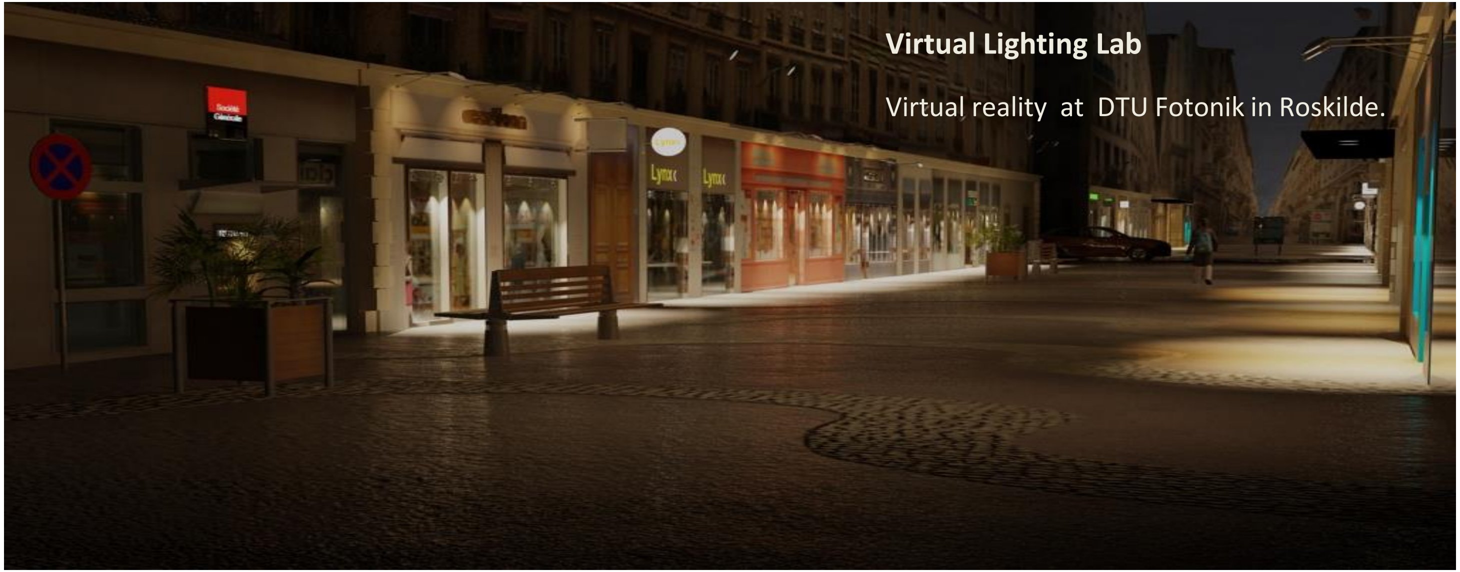
Goniophotometer measurements

Integrating sphere measurements

Total flux
Colour rendering
Correlated colour temperature
Colour coordinates
Spectral distribution
Light Intensity distribution
UV and IR measurements

Industrial innovation involving more than 50 companies

Virtual Lighting Lab



In Virtual Lighting Lab lamps and fixtures can be tested for efficacy, light scattering, reflection and glare. Companies, citizens, and politicians can b involved on a more serious level of the development phases and decision making procedures

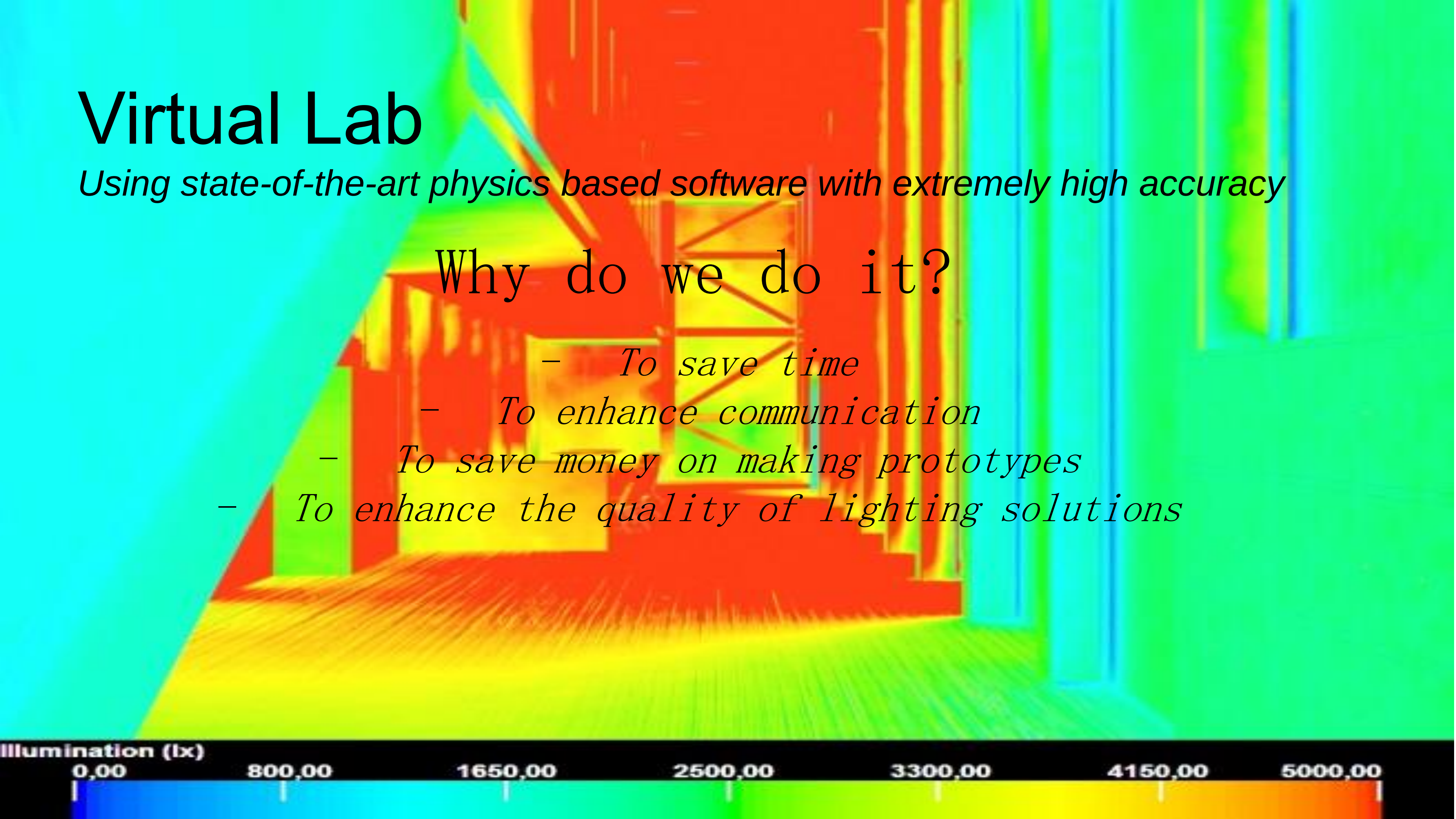
Europe's largest Showroom & Test Field for Intelligent Lighting & Smart Urban Services

Virtual Lab

Using state-of-the-art physics based software with extremely high accuracy

Why do we do it?

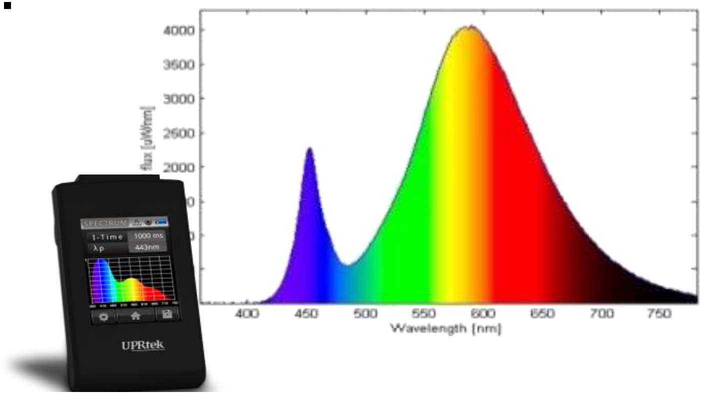
- *To save time*
- *To enhance communication*
- *To save money on making prototypes*
- *To enhance the quality of lighting solutions*



Test and characterisation

DTU Fotonik will provide characterization for the white LED light source in terms of liftspan, efficiency, color rendering index etc. when it is packaged.

We have a new photometric laboratory complying to the new international LED lamp and luminaire test standard.



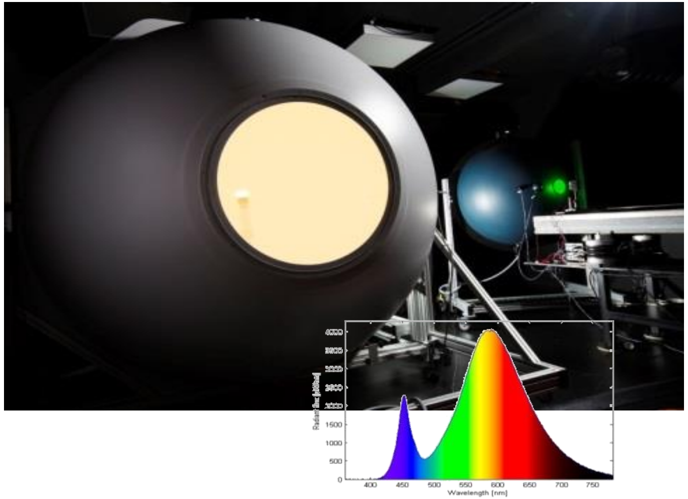
Integrating sphere lab

Total spectral flux measurements in forward flux configuration:

under current and temperature control

To evaluate:

- **Spectral power distribution, UV,Vis (and IR)**
- **Luminous flux**
- **Efficiency**
- **Correlated Color temperature, Duv**
- **Color rendering index, other color rendering metrics**
- **Luminous flux and color maintenance**

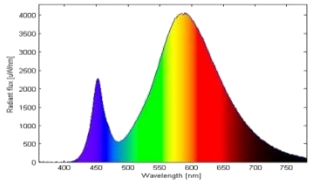


Test and characterisation

Gonio-spectro/photo-meter

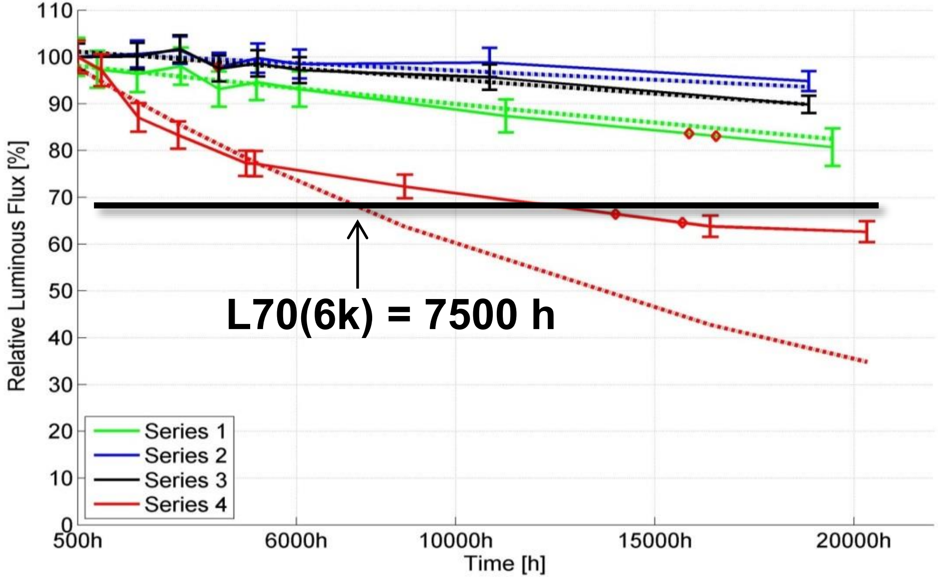
For measurement of angular dependent distribution of

- **Intensity and color (chromaticity)**
- **Spectral power distribution, UV,Vis (and IR)**
- **Correlated Color temperature, Duv**
- **Color rendering index**



Luminous flux maintenance

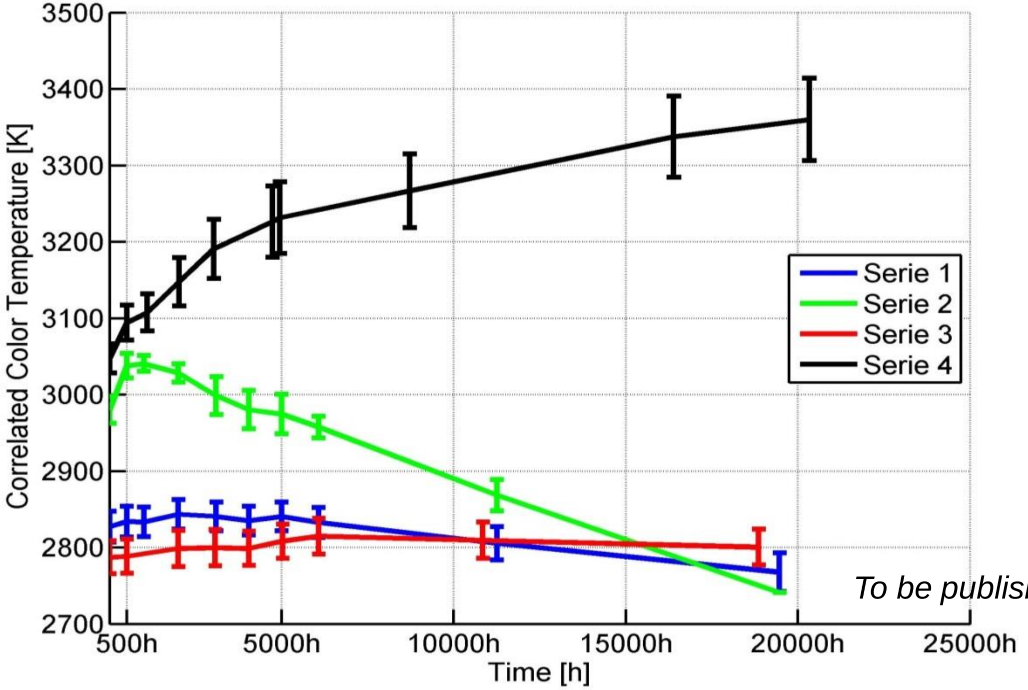
LEDs doesn't fail suddenly, but degrades slowly –
Long term measurements of lumen maintenace of 48 retrofit LED lamps over 20.000 h



Established IES standard for LED packages: LM-80 and TM-21
New IES standards for LED lamps: LM-84-14 and TM-28-14
Need for accelerated test methods, with on/off cycling

Color maintenance

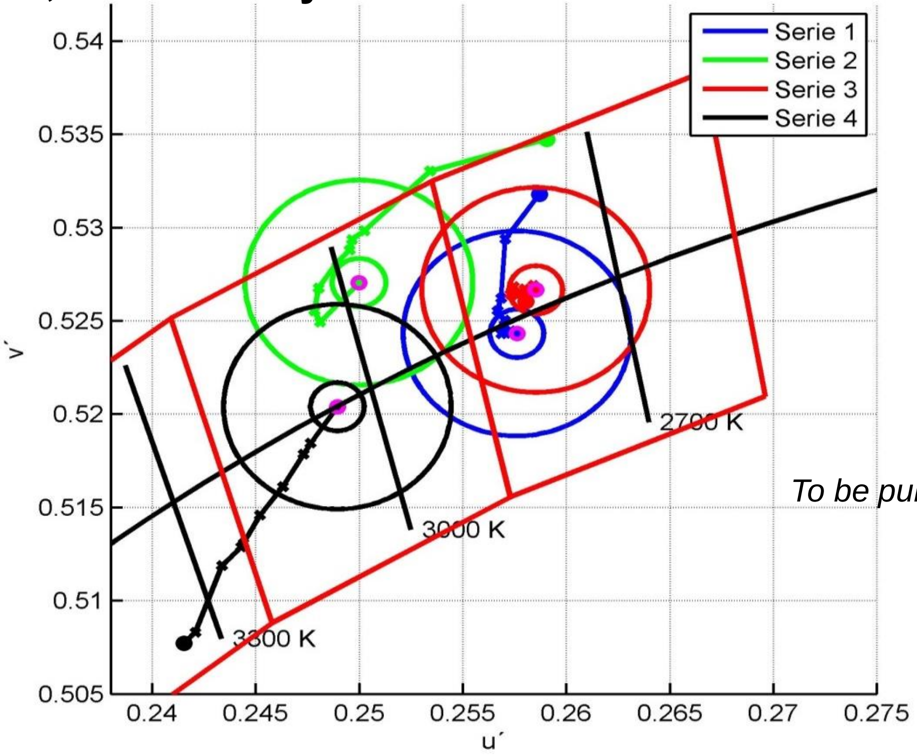
Correlated color temperature as a function of time:



To be published

Color maintenance

Color change even if CCT is constant, chromaticity coordinates as a function of time:



To be published

IEA SSL Annex

Efficient Electrical End-Use Equipment
International Energy Agency

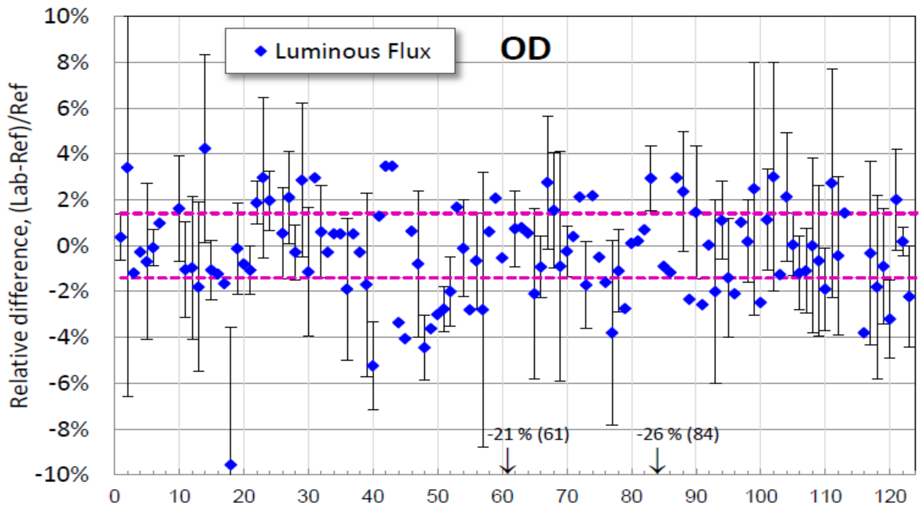
IEA SSL Annex, 2010-2014
extention 2014-2019

Launched in July 2010, the IEA 4E SSL Annex is a joint initiative of nine countries working together to address common challenges with SSL technologies. The aim is to provide tools for governments for evaluating the properties of SSL products, harmonise test methods and accreditation of labs, creating trust in SSL products

Danmark is member trough the Danish Energy Agency, v. Bjarke Hansen
Casper Kofod, Energy Piano, Carsten Dam-Hansen, DTU Fotonik

Worlds largest lab comparison

Test method investigated through an Interlaboratory comparison IC2013



110 laboratories particiated
Good agreement
flux ± 4 %, kromaticitet ± 0.004
Method is goodexcept for current
Final report http://ssl.iea-4e.org/

International test standard has been published:

CIE S 025/E:2015 Test Method for LED Lamps, LED Luminaires and LED Modules

EN 13032 Lighting Applications - Measurement and presentation of photometric data of lamps and luminaires - Part 4: LED lamps, modules and luminaires

Center for LED metrology (LEDMET)

- A four year R&D project aimed at upgrading lighting measurement within Danish industry. Work packages include:
  - Goniophotometric interlaboratory comparison
  - Realization of a primary spectral irradiance standard (UV-Vis)
  - Automated spectral BSDF measurements at multiple incidence angles

DTU Fotonik
Department of Photonics Engineering

DFM
Danmarks Nationale Metrologiinstitut

DELTA

DCL
Dansk Center for Lys

VISO SYSTEMS

PHILIPS

NORTH INVENT

U-vivo
UVC Disinfection of Medical Devices

martek MARINE

louis poulsen

Fionia Lighting

FOCUS-LIGHTING

danelec MARINE

I-NO

chroma viso
medical lighting solutions

BB&S

- en indlysende fordel
LEDPROOF

Research of fluorescent SiC at DTU Fotonik

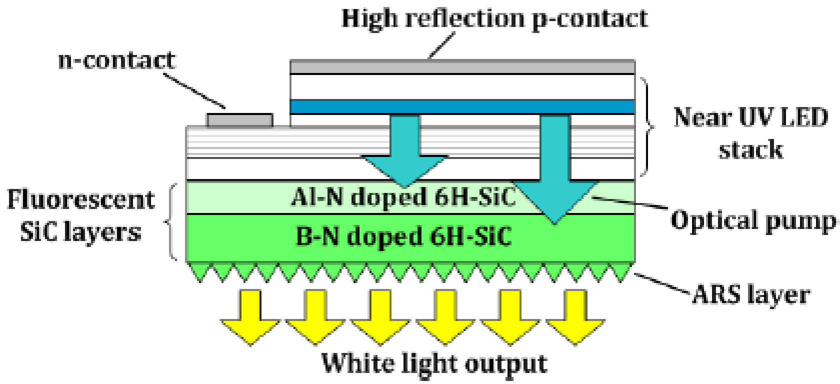
Yiyu Ou, Ph.D.

DTU Fotonik, Technical University of Denmark

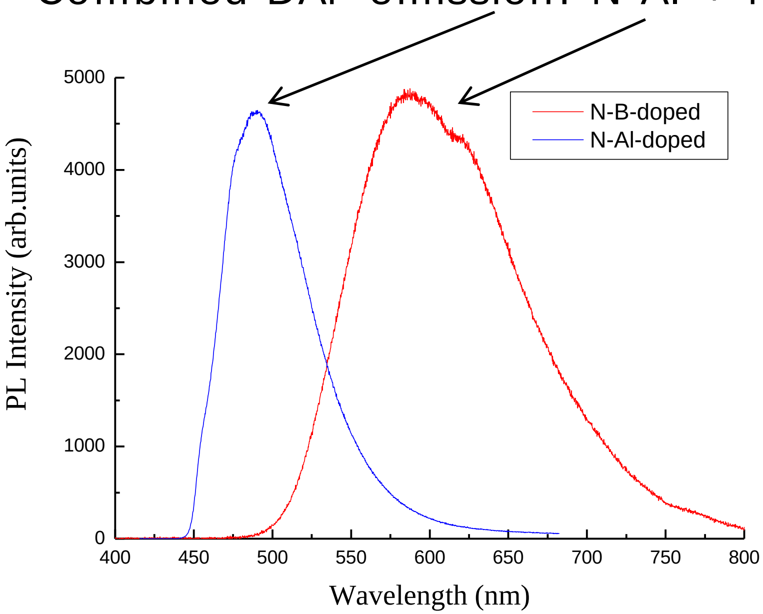
Outline

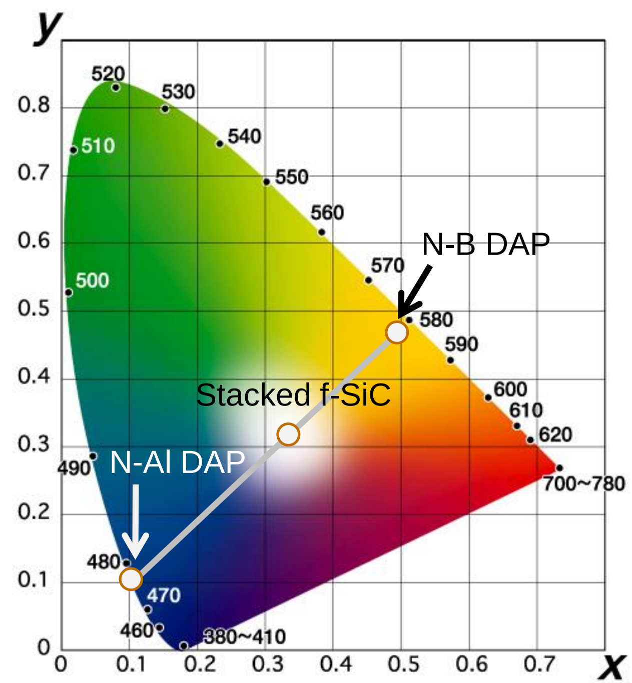
1. Fluorescent SiC: application and NORLED
2. Surface nanostructuring
3. Surface passivation
4. Future work

1. Fluorescent SiC: application



Combined DAP emission: N-Al + N-B





Fluorescent SiC (f-SiC):

- Invented by Kamiyama in 2004
- CRI > 90
- Expected luminous efficacy: 130 lm/W
- Long lifetime: 300,000 hours (phosphor-based white LED: 50,000 hours)
- No rare-earth material

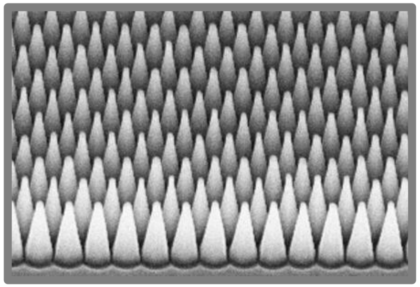
1. Fluorescent SiC: application

- Nordic Light Emitting Diode Initiative project (2010-2012)

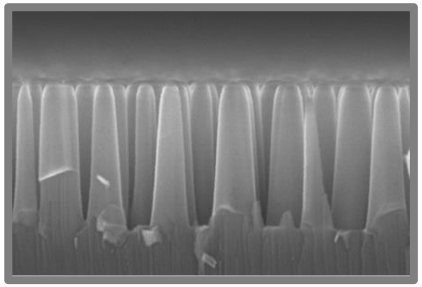
- DTU Fotonik in NORLED:
  - Optical characterization and analysis
  - Simulation of optical effect for nanostructured f-SiC
  - Fabrication of nanostructured f-SiC

2. Fluorescent SiC: surface nanostructuring

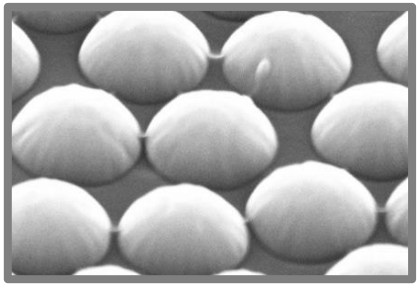
- To enhance the light extraction, different surface nanostructuring techniques were applied on fluorescent SiC



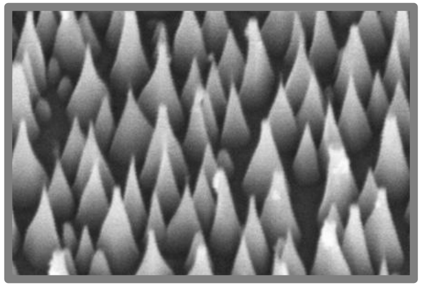
E-beam lithography
(Opt. Express 20, 7575, 2012)



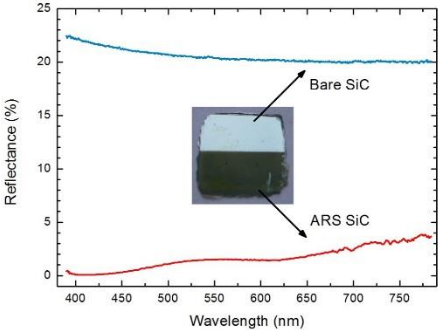
Self-assembled nanopatterning
(Opt. Lett. 37, 3816, 2012)

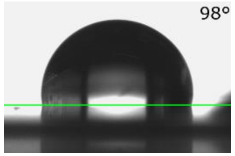


Nanosphere lithography
(Sci. Rep. 4, 4662, 2014)



Maskless nanopatterning
(Opt. Mat. Express 3, 1119, 2013)

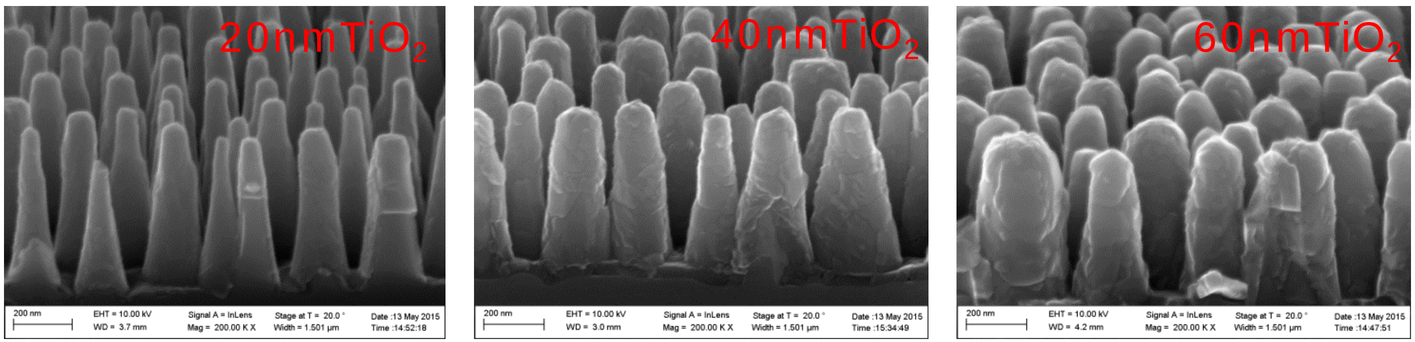


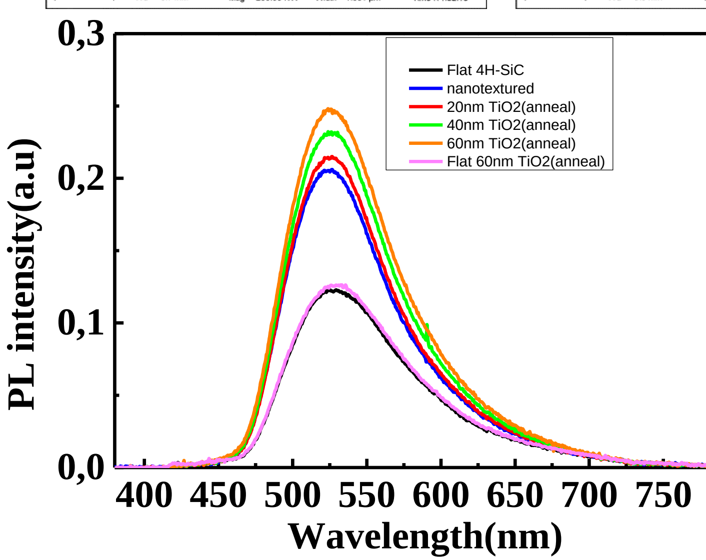


- Surface reflectance can be reduced from 20.5% to 1.01%
- Luminescence intensity can be enhanced by up to 115%

3. Surface passivation

- Etching damage on the nanostructure surface
- Method: thin film (Al_2O_3, TiO_2) deposition by using atomic layer deposition (ALD)

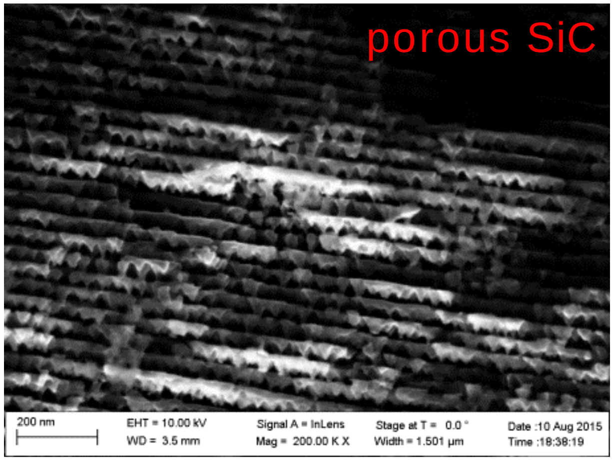


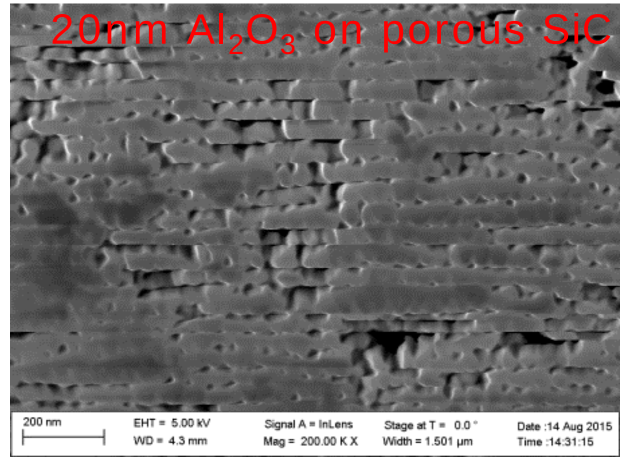


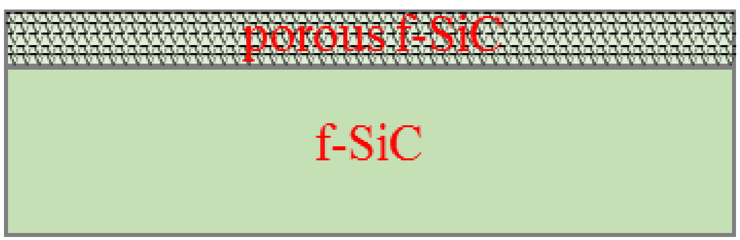
- Significant surface passivation effect
- Large emission enhancement

3. Surface passivation

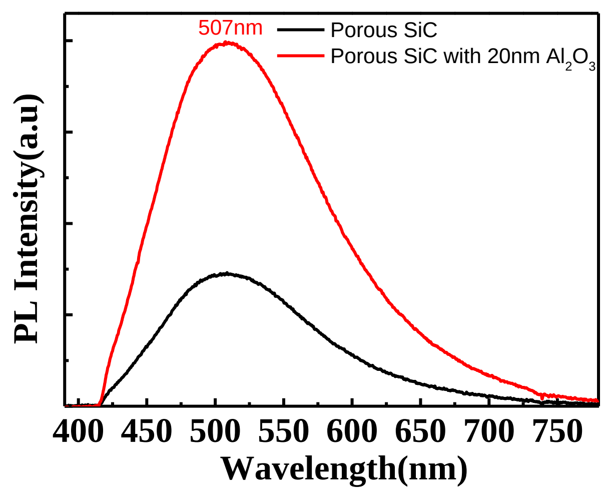
- Thin Al_2O_3 film deposition by ALD on porous SiC







- Porous f-SiC is a good approach to realize pure white light



4. Future work

- Further improve the surface passivation methods
- Make a highly-efficient pure white light emission

Questions

Thank you for your attention!