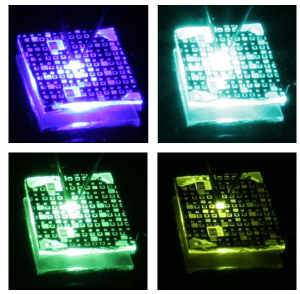


Group III-Nitride LEDs

Michael Kneissl

Institute of Solid State Physics, Technische Universität Berlin
Ferdinand-Braun-Institut (FBH), Berlin

GaNeXT Summer School, June 13-14, 2025 (Porquerolles, France)

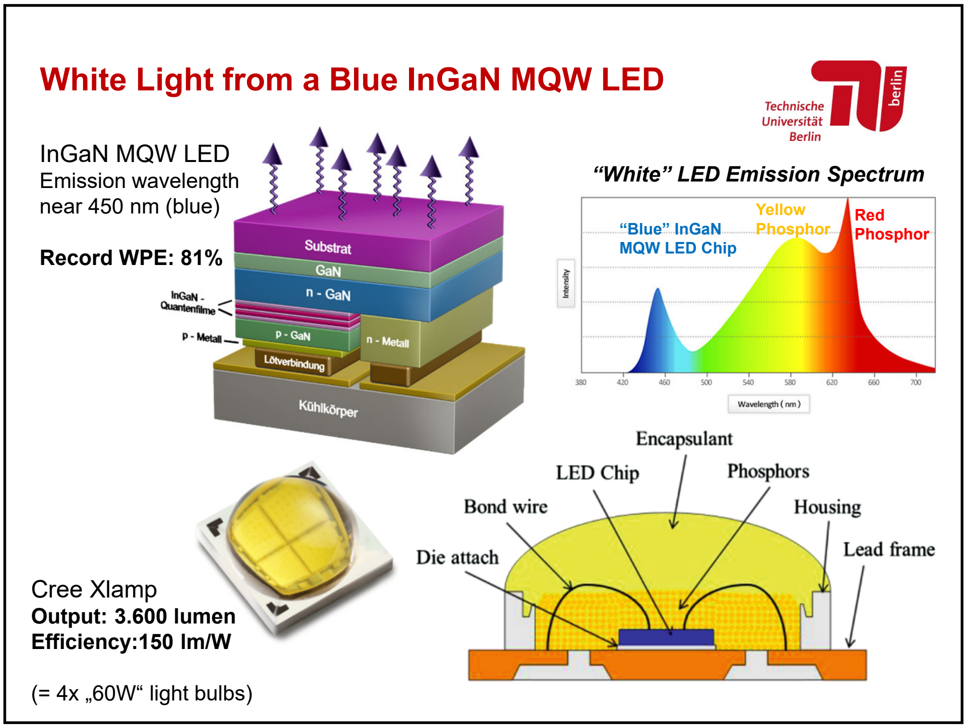
1

Outline

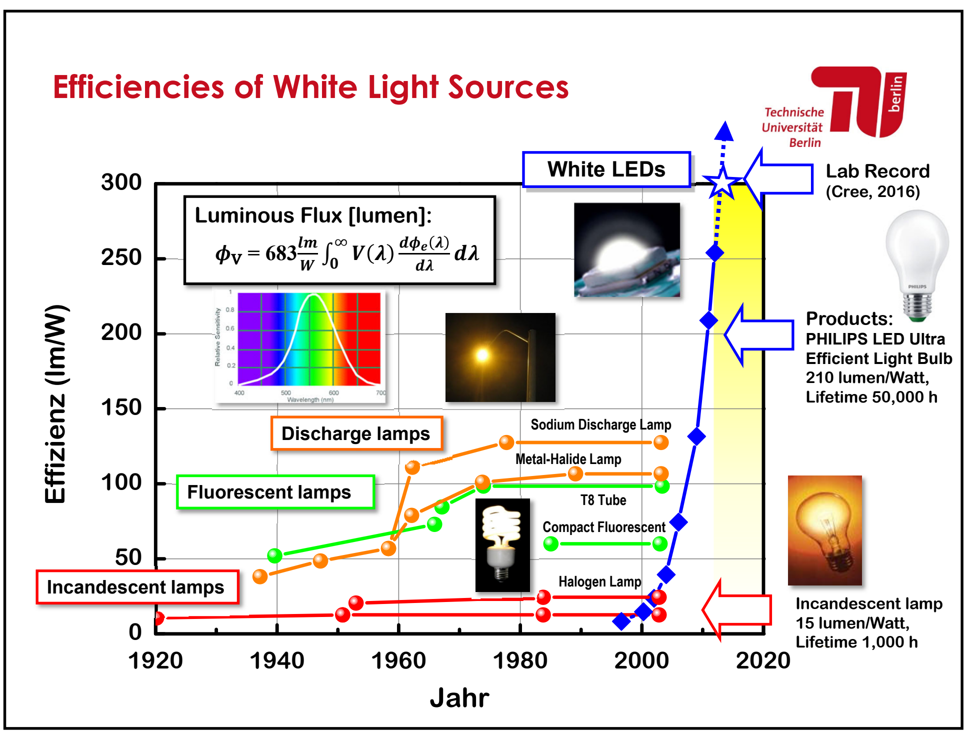
- ➢ A short history of visible light emitting diodes
- ➢ Recombination processes in LEDs
- ➢ Pushing the LED efficiency to its limits
- ➢ Pushing the wavelength limit: UVC-LEDs
- ➢ AlN/sapphire template technologies and their effect on the UVC-LED efficiency
- ➢ Going deeper: Far-UVC LEDs
- ➢ Applications and state of the art of far-UV-LEDs
- ➢ What is limiting the efficiency of Far-UVC-LEDs and what to do about it?

M. Kneissl | Institute of Solid State Physics
Page 2

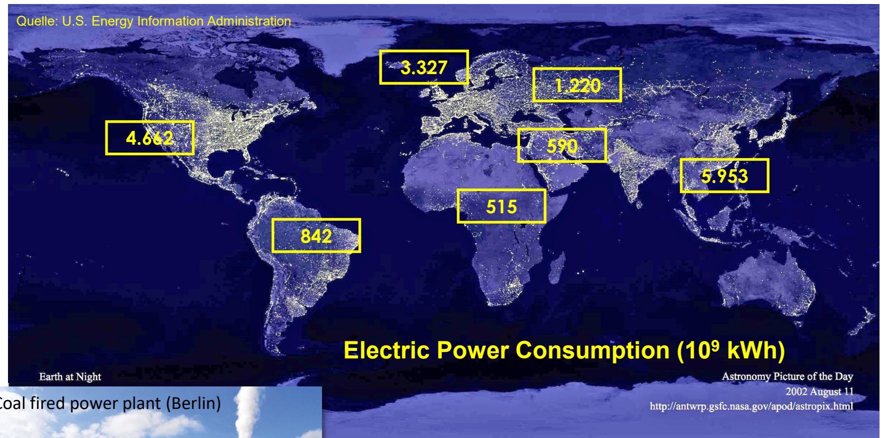
2


White Light from a Blue InGaN MQW LED
Technische Universität Berlin
InGaN MQW LED
Emission wavelength near 450 nm (blue)
Record WPE: 81%
Substrat
GaN
n - GaN
InGaN - Quantenfilme
p - Metall
p - GaN
n - Metall
Lötverbindung
Kühlkörper
"White" LED Emission Spectrum
"Blue" InGaN MQW LED Chip
Yellow Phosphor
Red Phosphor
Intensity
Wavelength (nm)
Encapsulant
LED Chip
Phosphors
Bond wire
Housing
Die attach
Lead frame
Cree Xlamp
Output: 3.600 lumen
Efficiency:150 lm/W
(= 4x „60W" light bulbs)

3


Efficiencies of White Light Sources
Technische Universität Berlin
White LEDs
Lab Record (Cree, 2016)
Luminous Flux [lumen]:
$\phi_V = 683\frac{lm}{W}\int_0^\infty V(\lambda)\frac{d\phi_e(\lambda)}{d\lambda}d\lambda$
Products: PHILIPS LED Ultra Efficient Light Bulb 210 lumen/Watt, Lifetime 50,000 h
Discharge lamps
Sodium Discharge Lamp
Metal-Halide Lamp
Fluorescent lamps
T8 Tube
Compact Fluorescent
Halogen Lamp
Incandescent lamps
Incandescent lamp 15 lumen/Watt, Lifetime 1,000 h
Effizienz (lm/W)
300
250
200
150
100
50
0
1920
1940
1960
1980
2000
2020
Jahr

4



Coal fired power plant (Berlin)

Lighting uses **20%** of the world-wide electric power, corresponding to **$3.4 \cdot 10^{12}$ kWh** per year

This is equivalent to **1100 Coal-fired Ppower plant** (500 MW each) or **3 billion t CO_2** per year

This is equivalent to the CO_2 emission of **$1.7 \cdot 10^9$ passenger cars** per year

5

Application for visible LEDs

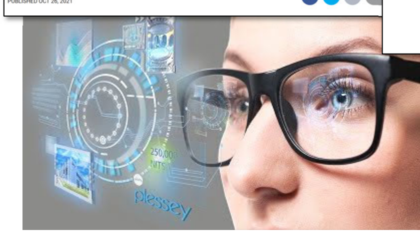

Facebook To Invest $10B This Year In VR And AR To Help Fuel The Metaverse

Facebook is spending a lot of money on its metaverse, all in the hopes that people will eventually forget that it's a social media company.

BY TOM WILTON
PUBLISHED OCT 26, 2021


CNET
Tech Money Home Wellness

Google Acquires MicroLED Startup Raxium for Future AR and MR Tech

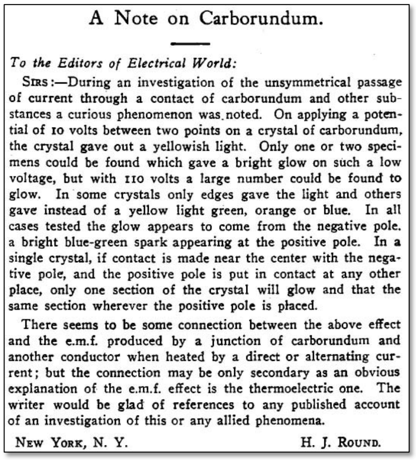


Apple, Facebook, Sony, Samsung, LG etc. investing many billion $ in micro-LEDs for AR & VR displays, smart watches, phones, TVs ...

6

“… a bright glow” from a carborundum diode.”

Technische Universität Berlin



A Note on Carborundum.

To the Editors of Electrical World:

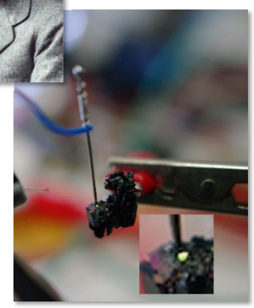
SIRS:—During an investigation of the unsymmetrical passage of current through a contact of carborundum and other substances a curious phenomenon was noted. On applying a potential of 10 volts between two points on a crystal of carborundum, the crystal gave out a yellowish light. Only one or two specimens could be found which gave a bright glow on such a low voltage, but with 110 volts a large number could be found to glow. In some crystals only edges gave the light and others gave instead of a yellow light green, orange or blue. In all cases tested the glow appears to come from the negative pole, a bright blue-green spark appearing at the positive pole. In a single crystal, if contact is made near the center with the negative pole, and the positive pole is put in contact at any other place, only one section of the crystal will glow and that the same section wherever the positive pole is placed.

There seems to be some connection between the above effect and the e.m.f. produced by a junction of carborundum and another conductor when heated by a direct or alternating current; but the connection may be only secondary as an obvious explanation of the e.m.f. effect is the thermoelectric one. The writer would be glad of references to any published account of an investigation of this or any allied phenomena.

NEW YORK, N. Y. H. J. ROUND.

*H.J. Round, "A note on carborundum", Electrical World, **49**, 309 (1907)*

Henry Joseph Round (1881-1966)



Electroluminescence from a point contact with a silicon carbide (SiC) crystal

7

History of Light Emitting Diodes (LEDs)

Technische Universität Berlin

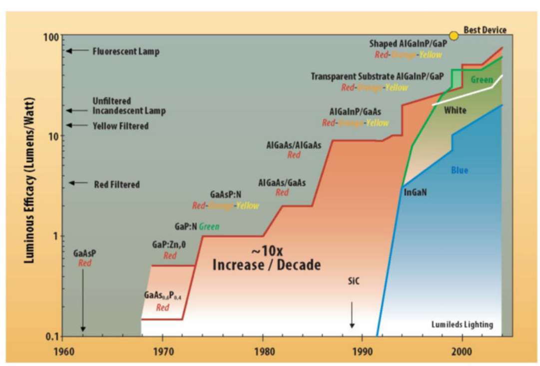
1907 Electrically excited light emission from SiC crystals, by H.J. Round, Marconi Corp.

1927 Demonstration of a SiC-based light emitting device, O. Lossev

1962 First **pn-junction LED** (GaAsP) by Nick Holonyak, GE Corp.

1968 First **commercial** production of **LEDs** (GaAsP) by Monsanto Corp.

1971 First “blue” emission from a **GaN MIS Diode**, by Jacques Pankove & Herbert Maruska, RCA

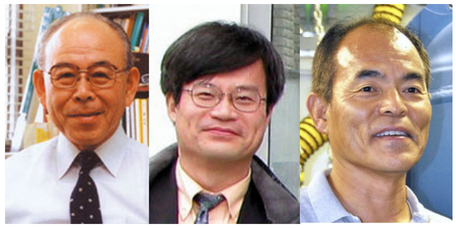


Blue-white emission from a GaN MIS diode (J. Pankove 1971)

8

Nobel Prize in Physics 2014

Technische Universität Berlin



Isamu Akasaki
Mejio University, Japan

Hiroshi Amano
Nagoya University, Japan

Shuji Nakamura
UC Santa Barbara, USA

"… for the invention of efficient blue light-emitting diodes which has enabled bright and energy-saving white light sources"

Breakthroughs for III-nitride LEDs

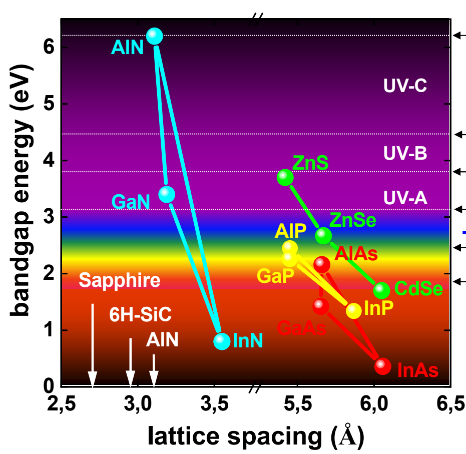
- **1989** Successful **p-doping of GaN**, by Akasaki & Amano, Nagoya U.
- **1992** First **GaN pn-junction LED** by Akasaki & Amano, Nagoya U.
- **1993** First **blue InGaN DH LEDs** by Nakamura, Nichia Corp.
- **1994** First commercial **blue InGaN LED** by Nichia Corp.
- **1996** First commercial **white InGaN LED** by Nichia Corp

"The Nobel Prize in Physics 2014" (7 Oct 2014): *www.nobelprize.org/nobel_prizes/physics/laureates/2014*

9

Group III-nitride based light emitters

Technische Universität Berlin



Group III-nitrides cover the entire **visible, UVA**, **UVB**, and large portions of the **UVC** spectral range.

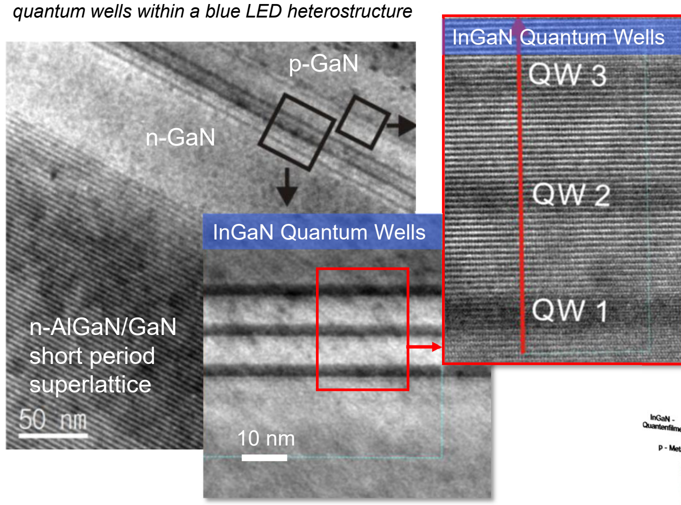
*$In_{0.2}Ga_{0.8}N$-based blue LEDs emitting near **450 nm***

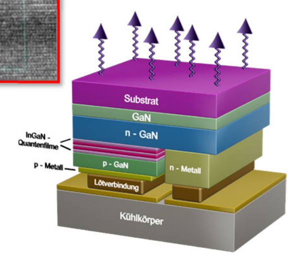
Page 10

10

InGaN/GaN quantum wells for blue LEDs

Transmission electron microscopy images of InGaN quantum wells within a blue LED heterostructure





11

Efficiency of Light Emitting Diodes (LEDs)

$$WPE = \frac{P_{out}}{I \cdot V} = \eta_{EQE} \frac{\hbar\omega}{e \cdot V}$$

Wallplug Efficiency (WPE)

$$\underbrace{\eta_{EQE} = \eta_{inj} \cdot \eta_{rad}}_{= \eta_{IQE}} \cdot \eta_{ext}$$

External Quantum Efficiency (EQE)

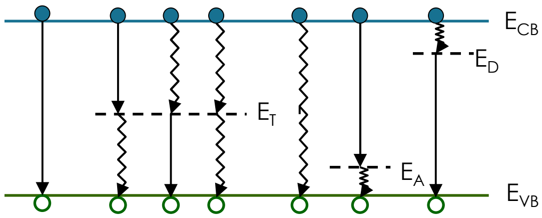
		Blue InGaN LEDs [1]	
Injection Efficiency:	η_{inj}	>95%	
Radiative Efficiency:	$\eta_{rad} = \frac{1/\tau_{rad}}{1/\tau_{rad} + 1/\tau_{nr}}$	>95%	**EQE~81%**
Extraction Efficiency:	η_{ext}	~90%	

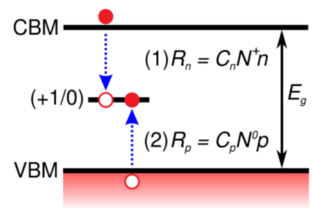
Current record for blue LEDs: EQE = 84%, WPE = 81% [1]

[1] Narukawa et al., J. Phys. D: 43 354002 (2010)

12

Shockley-Read-Hall Recombination Processes



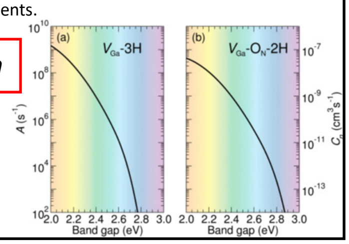


SRH coefficient: $A = N \frac{C_n C_p}{C_n + C_p}$

with N = defect concentration

SRH recombination at a (+1/0) charge state defect level. SRH process: (1) electron capture with rate Rn followed by (2) hole capture with rate Rp. C_n and C_p are the electron and hole capture coefficients.

Shockley-Read-Hall recombination rate*: $R_{SRH} = An$



A = $10^6 \ldots 10^{12}$ s^{-1} $\tau_{SRH} = A^{-1} = \mu s \ldots ps$

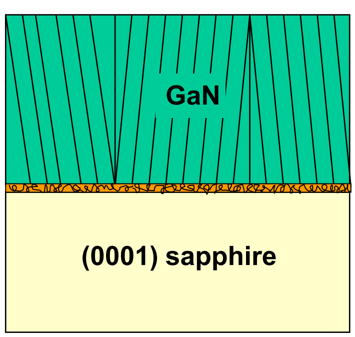
(SRH recombination time)

C.E. Dreyer et al., Appl. Phys. Lett. 108, 141101 (2016)

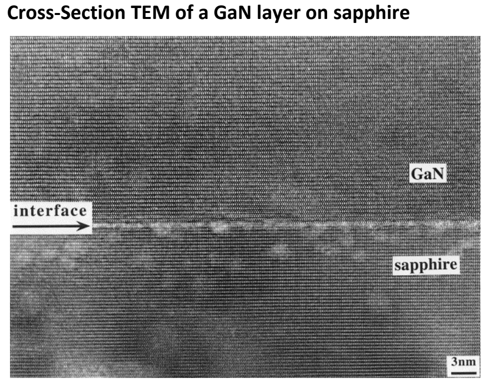
13

GaN Heteroepitaxy on Sapphire Substrates

Material	(a) / A	(c) / A	Δa/a (%)
GaN	3.189	5.185	-
AlN	3.111	4.980	+2.50
Al_2O_3	4.758	12.991	+16.1
6H-SiC	3.08	15.12	+3.54



Cross-Section TEM of a GaN layer on sapphire



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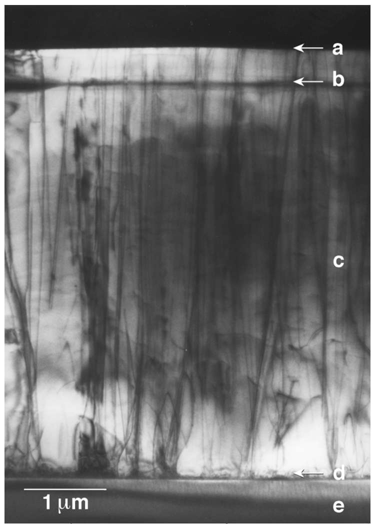
Page 14

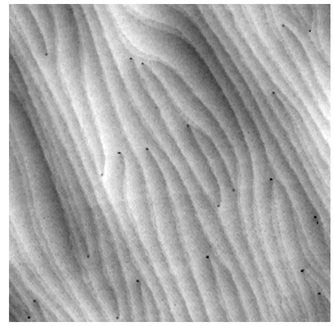
14

Threading dislocations in GaN blue LEDs

Cross-Section TEM of a GaN-based blue LED on sapphire



Atomic Force Microcopy (AFM) image of a GaN layer grown on sapphire



As a consequence of the large lattice mismatch between GaN and sapphire a high **density of threading dislocations (TDD)** is formed at the GaN/sapphire interface

=> **TDD in the range 10^{10} … 10^{8} cm^{-2}**

Page 15

15

Radiative Recombination Rate

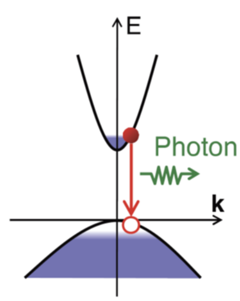
Radiative recombination rate:
(Spontaneous emission)

$$R_{sp} = -\frac{dn}{dt} = Bpn = \frac{n}{\tau_{rad}}$$

Radiative recombination time: $\tau_{rad} = \frac{1}{Bp}$

Radiative (bimolecular) recombination coefficients*

Materials (bulk)	E_{gap} [eV]	B [cm^3s^{-1}]	τ_{rad} [s]**
Si	1.12	$1.8*10^{-15}$	$3.0*10^{-5}$
GaAs	1.42	$2.1*10^{-10}$	$5.1*10^{-9}$
GaN	3.42	$7.0*10^{-11}$	$1.4*10^{-8}$



**assuming n = 10^{18} cm^{-3}

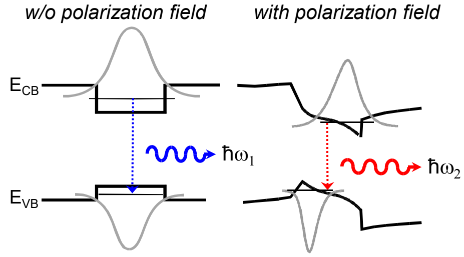
*originally described by A. Einstein (1916) as spontaneous emission coefficient A_{21}

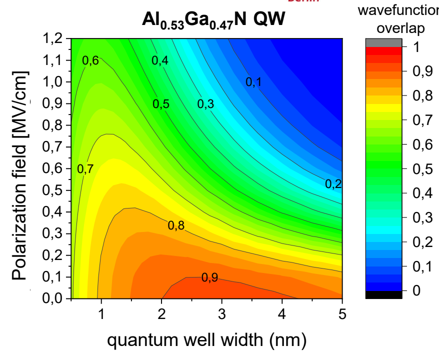
16

Radiative Recombination in Quantum Wells

Technische Universität Berlin

Quantum-Confined Stark Effect





Rad. recombination coefficent in QWs: $B_{QW} = B_{bulk}\ |F_{cv}|^2$

Electron-hole wave function overlap: $F_{cv} = \int \psi_c(z)\psi_v(z)\mathrm{d}z$

B coefficient affected by

- Electron-hole wave-function overlap
- Phase space filling $B(n) = \frac{B_0}{1+(n/n_0)^b}$

$n_0 = 3{*}10^{19}$ cm^{-3}
b = 0.8

*QW width = 15 nm **assuming p = $3{*}10^{18}$ cm^{-3}

Quantum Well	B_{QW} [cm^{3}s^{-1}]	τ_{rad} [s]**
InGaN (415 nm)*	$5{*}10^{-11}$	$6.6{*}10^{-9}$
InGaN (460 nm)*	$5{*}10^{-12}$	$66{*}10^{-9}$

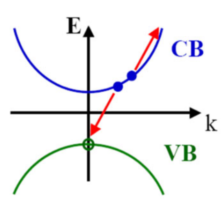
A. David et el., Appl. Phys. Lett. 97, 033501 (2010)
E. Kioupakis et al., New J. Phys. 15, 125006 (2013)

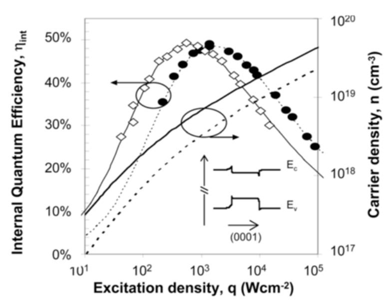
17

Auger-Meitner Recombination in Group III-Nitrides

Technische Universität Berlin

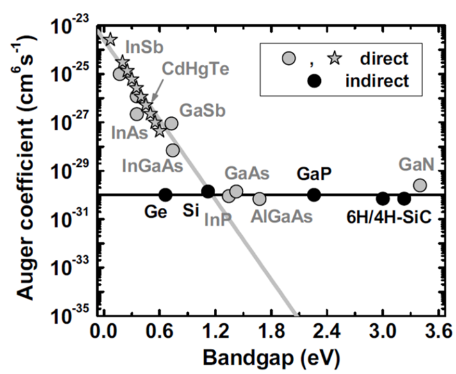
Auger-Meitner Recombination





Measured photo-excited EQE, IQE, and carrier density for InGaN DH structures with different TDD densities (4E8 cm^{-2} vs. 2E7 cm^{-2}). An ABC model fits yielded an Auger-Meitner coefficient of C= 1.4 - $2.0{*}10^{-30}$ cm^6/s.

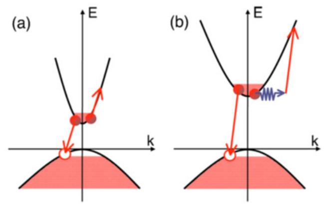
Auger-Meitner recombination coefficients C for direct and indirect bandgap semiconductors vs. bandgap energy



K. A. Bulashevich et al., phys. stat. sol. (c) 5, 2066 (2008)
E. Kioupakis et al., Appl. Phys. Lett. 98, 161107 (2011)
Y. Shen et el., Appl. Phys. Lett. 91, 141101 (2007)

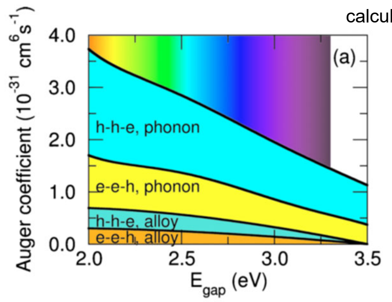
18

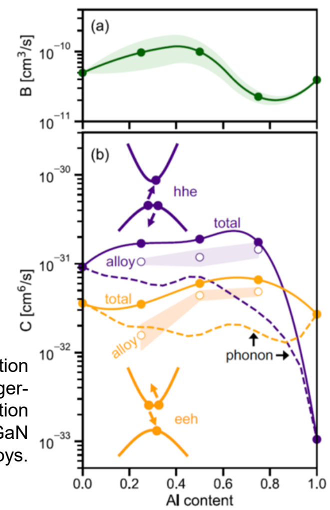
Auger-Meitner Recombination in III-Nitrides



Top: Schematic diagram of direct (a) and phonon-assisted (b) Auger-Meitner processes.

Bottom: Auger-Meitner coefficients for InGaN calculated from DFT.



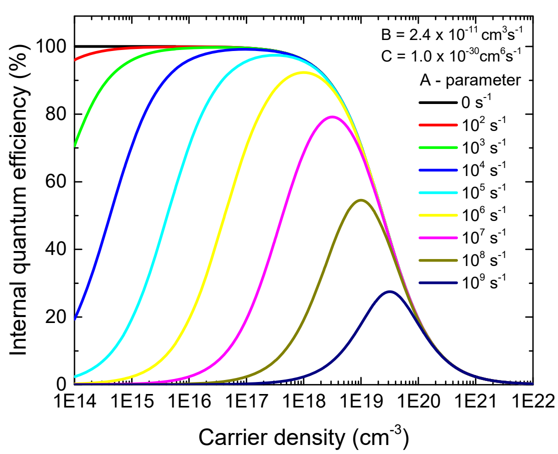


Radiative recombination coefficient B and Auger-Meitner recombination coefficients C for AlGaN alloys.

K. A. Bulashevich et al., phys. stat. sol. (c) 5, 2066 (2008)
E. Kioupakis et al., Appl. Phys. Lett. 98, 161107 (2011)

19

ABC-Modell and IQE of Light Emitting Diodes



Simulated IQE for AlGaN QWs based on ABC-model

Internal quantum efficiency η_{IQE} given by

$$\eta_{IQE} = \eta_{inj} \cdot \eta_{rad}$$

with η_{inj} = injection efficiency
η_{rad} = radiative efficiency

Radiative Efficiency:

$$\eta_{rad} = \frac{R_{rad}}{R_{rad} + R_{nr}} = \frac{Bn^2}{An + Bn^2 + Cn^3} = \frac{1/\tau_{rad}}{1/\tau_{rad} + 1/\tau_{nr}}$$

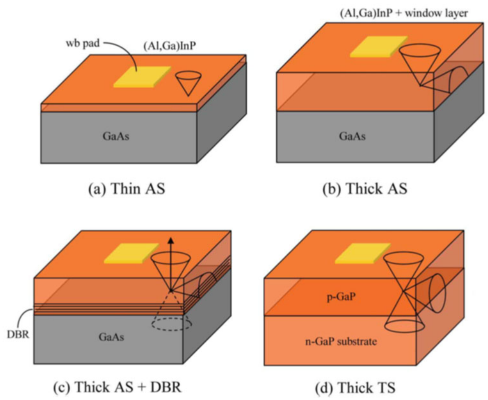
20

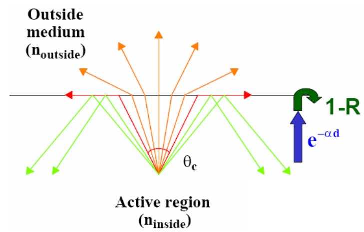
Light Extraction from „Red“ InGaAlP LEDs

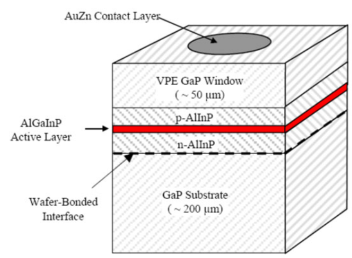
- Large refractive index step (semiconductor/air)
- Narrow light escape cone, small critical angle

  Θ_c ~ 17.1° (GaAs, n = 3.5) => LEE = 2.2%

  Θ_c ~ 23.6° (GaN, n = 2.5) => LEE = 4.2%



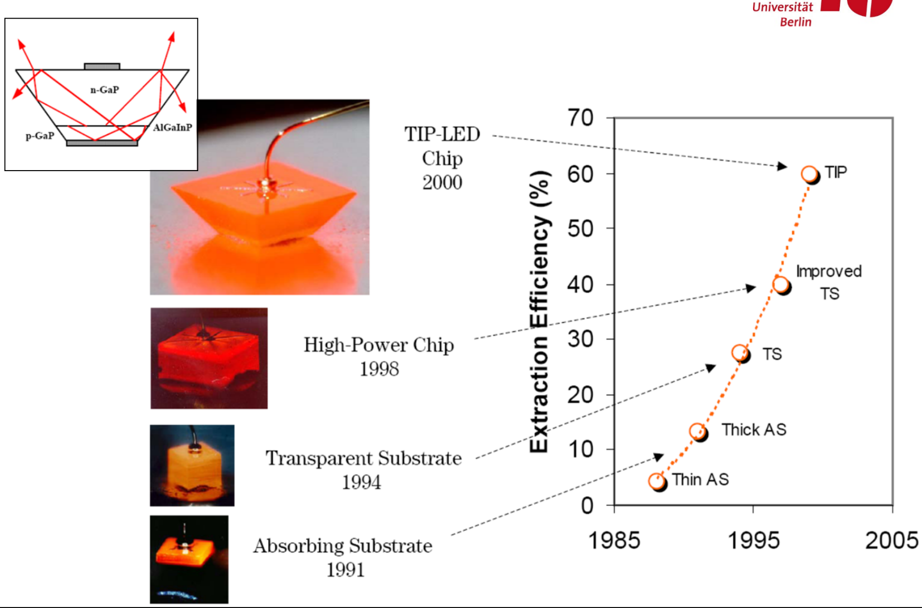




Transparent-Substrate ("TS") AlGaInP

21

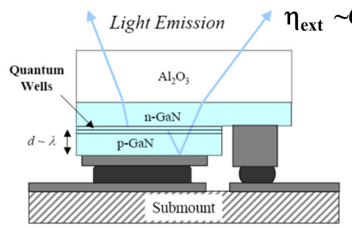
Enhanced Light Extraction from InGaP LEDs



22

Light Extraction Efficiency η_{ext}

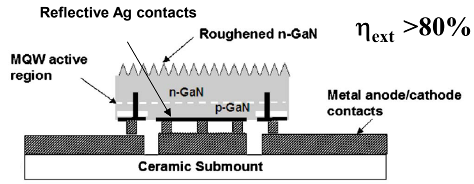
Microcavity Flip-Chip (FC) LED with Ag Reflector

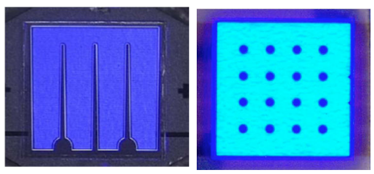


η_{ext} ~60%

InGaN Thin Film Flip-Chip (TFFC) LED

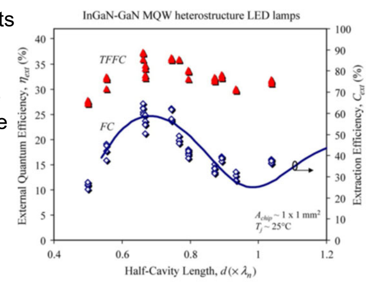
η_{ext} >80%





Micro-cavity effects in InGaN LEDs

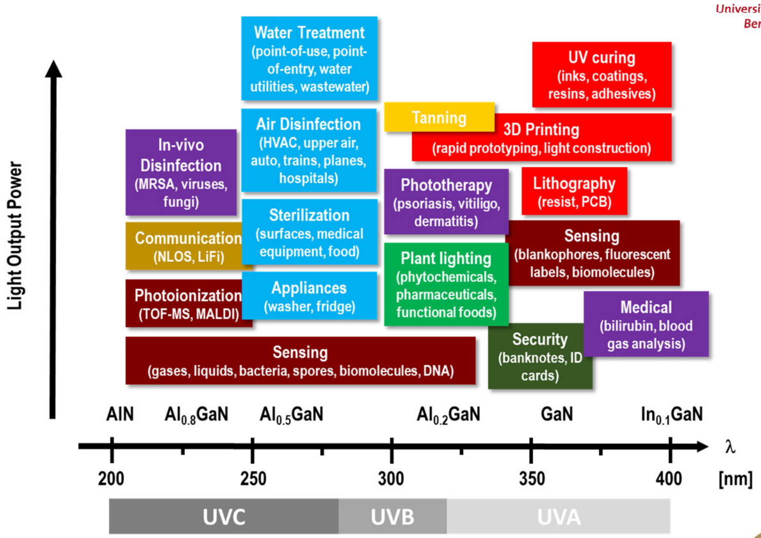
Increase radiative recombination due to Purcell effect



Y. Shen, et al., Appl. Phys. Lett. 82, 2221 (2003)
Shchekin et al., Appl. Phys. Lett. ***89****, 071109 (2006)*

23

Applications of UV Light Emitters



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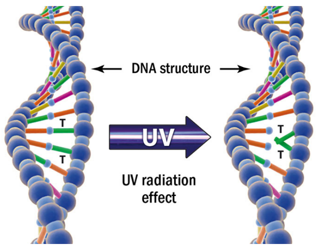
Page 24

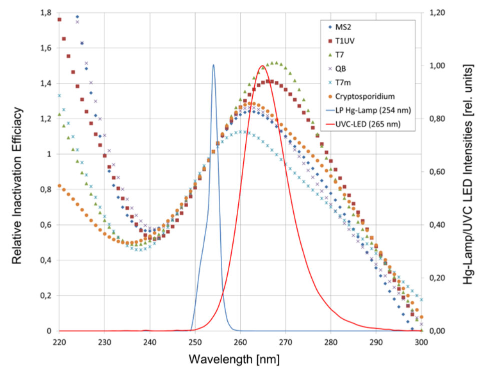
24

How does UV disinfection work?

- UVC acts on C=C double bonds in thymine (T)
- Formation of dimers and 6-4 photo products
- Replication of DNA prohibited



Sara E. Beck et al., Water Research ***70****, 27 (2015)*



Requirements for UV disinfection

- Disinfection band: 250nm - 280 nm
- **Germicidal effectiveness** curve peaking around **265 nm**
- Required **UV dosage 40 mWs/cm²** (covering most organisms)

25

The global drinking water dilemma

Population without access to safe drinking water

UVC-LED point-of-use water disinfection module with a 40x 50mW UVC-LED array

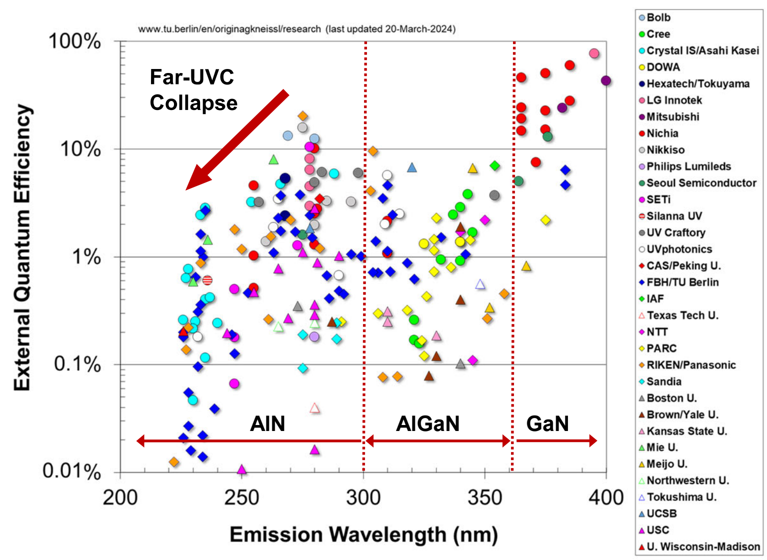
- More than **one billion people** lack clean drinking water[1]
- Water-born diseases claim the lives of 5000 children every day[1]
  - → Point-of-Use **UVC-LED water purification** system
  - → Zero maintenance, rugged, solar-powered
  - → **1 Watt** of UVC light to provide **300 liters / hour** [2]

[1] Water for Life: Making it Happen, WHO and UNICEF, ISBN 9241562935 (2005)
[2] M.A. Würtele et al., Water Research ***45****, 1481 (2011)*

26

External Quantum Efficiencies of UV-LEDs

Updated March 20th, 2024, from M. Kneissl et al., Nature Photonics 13, 233 (2019)



27

Performance Comparison: Blue vs. UVC-LEDs

Wallplug Efficiency: $$WPE = \frac{P_{out}}{I \cdot V} = EQE \cdot \eta_{elect}$$

External Quantum Efficiency: $$EQE = \eta_{rad} \cdot \eta_{inj} \cdot \eta_{extr}$$

Internal Quantum Efficiency: IQE

Radiative efficiency (RRE): η_{rad}

Injection efficiency (CIE): η_{inj}

Extraction efficiency (LEE): η_{extr}

Electrical efficiency (V): η_{elect}

	Blue LEDs[1]	UVC-LED 2022 [2,3]	Far-UVC-LED 2023[4,5]
λ	**460 nm**	**268 nm**	**233 nm**
η_{rad}	96%		43%
η_{inj}	98%		26%
IQE	**94%**	**77%**	**11.2%**
η_{extr}	89%	16%	8.8%
η_{elect}	95%	67%	63%
EQE	**84%**	**12.3%**	**0.98%**
WPE	**81%**	**8.3%**	**0.63%**

[1] *Y. Narukawa et al., J. Phys. D: Appl. Phys.* ***43****, 354002 (2010)*
[2] *J. Zhang et al.*, Semicond. Sci. Technol. **37,** 07LT01 (2022)
[3] *J. Zhang et al.*, Appl. Phys. Lett. **122**, 101106 (2023)
[4] *T. Kolbe et al., Appl. Phys. Lett.* **122**, 191101 (2023)
[5] *A. Muhin et al.*, Ph.D. Thesis, TU Berlin (2024)

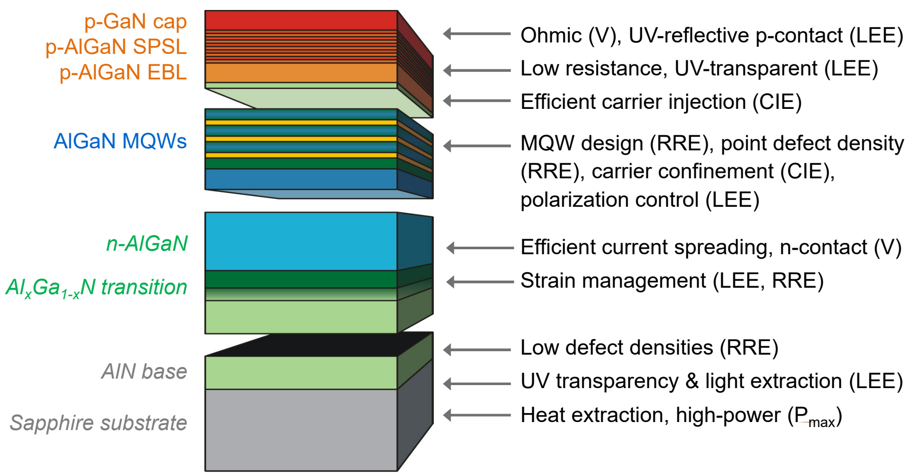
M. Kneissl | Institute of Solid State Physics
Page 28

28

Challenges for High Efficiency UV LEDs

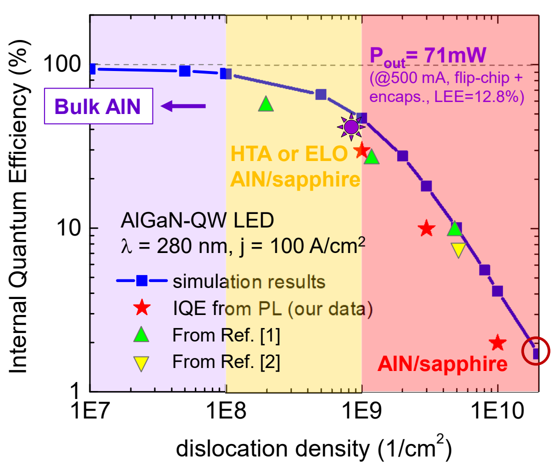
$$\mathrm{WPE} = \mathrm{EQE} \cdot \frac{\hbar\omega}{V}$$

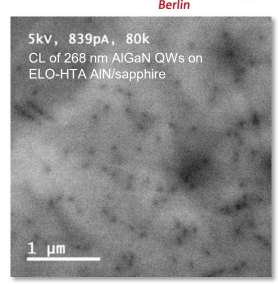
$$\mathrm{EQE} = \mathrm{CIE} \cdot \mathrm{RRE} \cdot \mathrm{LEE}$$

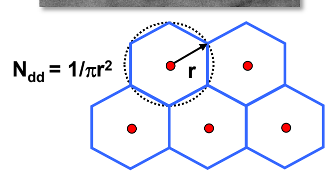


29

Effect of Dislocations on the IQE of UVC-LEDs







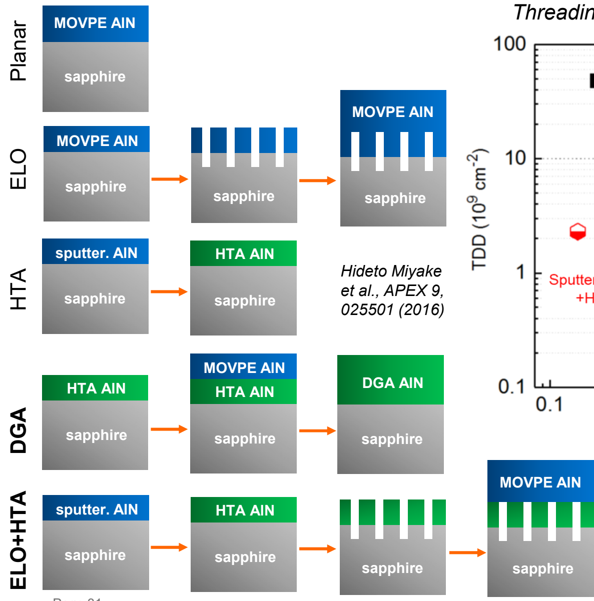
Simulation parameters[3]:
- AlGaN MQW LEDs
- λ = **280 nm**, j = 100 A/cm^2
- **No SRH** from **point defects**

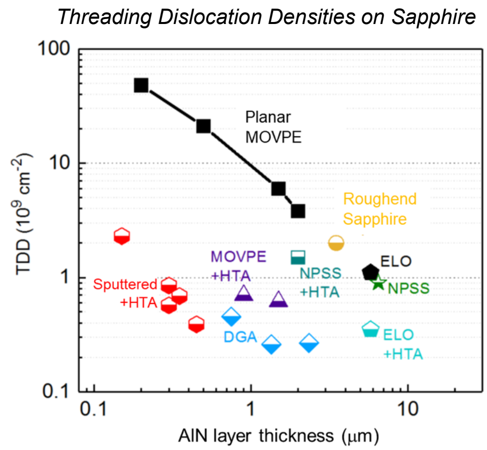
[1] *Ban et al., Appl. Phys. Exp.* ***4****, 052101 (2011)*
[2] *Mickevicius et al., Appl. Phys. Lett.* ***101****, 211902 (2012)*
[3] *Karpov et al., Appl. Phys. Lett.* **81**, 4721 (2002)
[4] *A. Muhin et al., phys. stat. sol. (a), 2200458 (2022)*

Page 30

30

AlN on Sapphire Template Technologies





[1] *Sylvia Hagedorn et al., phys. stat. sol. (a)* ***217****, 1901022 (2020)*
[2] *Sylvia Hagedorn et al., phys. stat. sol. (b)* ***258****, 2100187(2021)*

Page 31

31

Cathodoluminescence (CL) of AlGaN MQWs on different AlN/sapphire templates

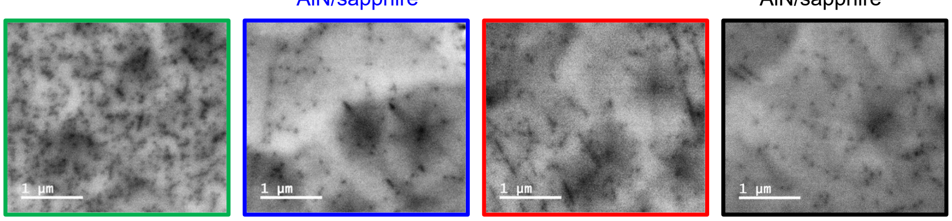
Threading dislocation density (TDD) determined by panchromatic CL

→ Non-radiative recombination resulting in dark-spots

→ Distinction between edge and screw type threading dislocations possible

→ Lowest **dark-spot-density (DSD)** on HTA ELO AlN/sapphire

planar AlN/sapphire	planar HTA AlN/sapphire	ELO AlN/sapphire	HTA ELO AlN/sapphire



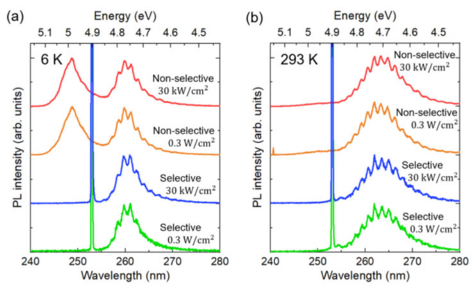
DSD: 3.5 × 10^9 cm^{-2}	DSD: 1.1 × 10^9 cm^{-2}	DSD: 1.4 × 10^9 cm^{-2}	DSD: 0.9 × 10^9 cm^{-2}

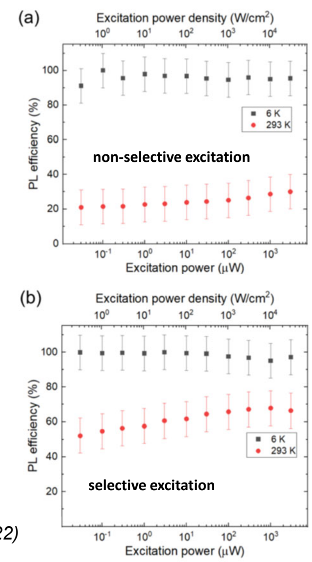
Page 32

32

RRE in 265 nm AlGaN MQWs from resonant PL

PL spectra of AlGaN MQWs at 6 K and RT





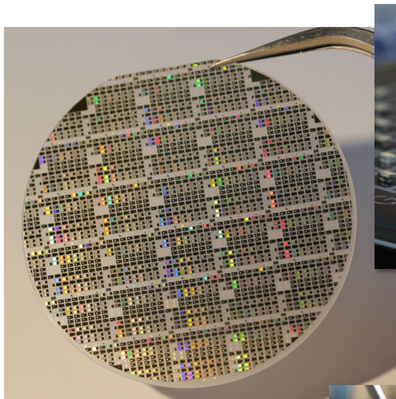
- RRE from excitation-power-dependent PL at low (T = 6K) and room temperature (RT)
- Accurate determination of RRE under selective excitation conditions
  - ⇒ **RRE = 50%-60% for 265 nm QWs on AlN ELO**
  - ⇒ **IQE ~30% from EQE of LEDs**
  - ⇒ **CIE not unity!**

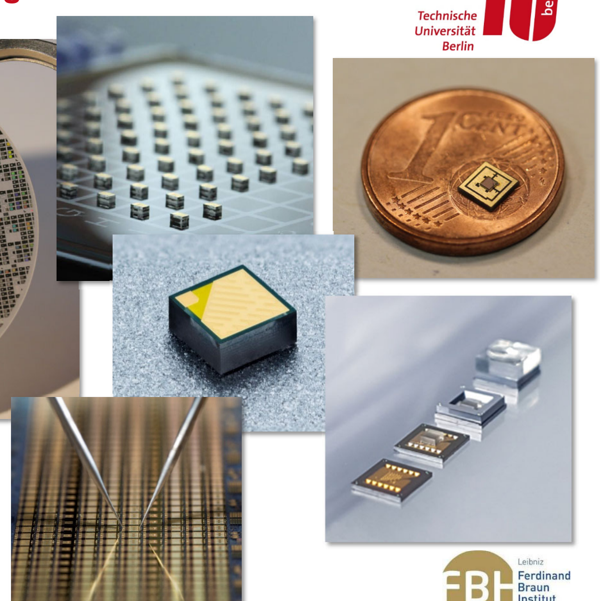
S. Tanaka, et al., Jpn. J. Appl. Phys. **61**, 112002 *(2022)*

Page 33

33

Fabrication technologies for UV-LEDs





From wafer-level micro-fabrication to flip-chip mounted & packaged UV-LEDs

Page 34

34

265 nm LEDs on HTA ELO AlN/Saphire

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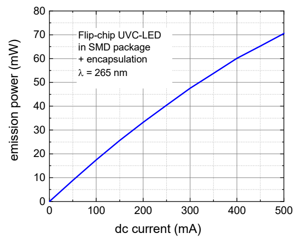
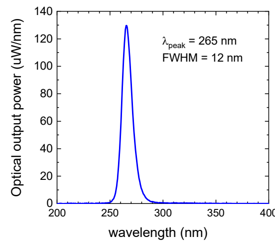
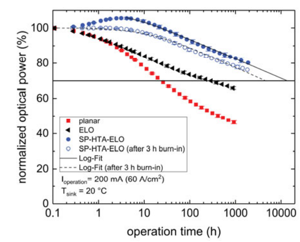




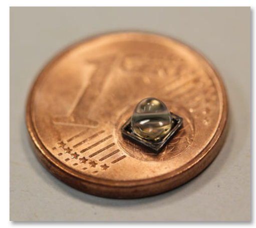


- 265 nm flip-chip UVC-LED on AlN ceramic package
- Improved IQE and lifetimes on HTA ELO AlN/sapphire
- Absorbing p-side, UV-transparent encapsulant

→ Increase in LEE by encapsulation

→ CW power P_{out} **= 71 mW @500mA** for 265 nm

→ **L_{70} lifetimes ~ 10.000 hours**



N. Susilo et al., Photonics Research ***8****, 589 (2020)*
J. Ruschel et al., Appl. Phys. Lett. ***117****, 241104 (2020)*

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Page 35 35

35

Determination of RRE & CIE in 265 nm UV-LEDs

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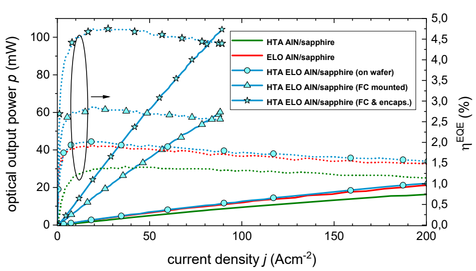
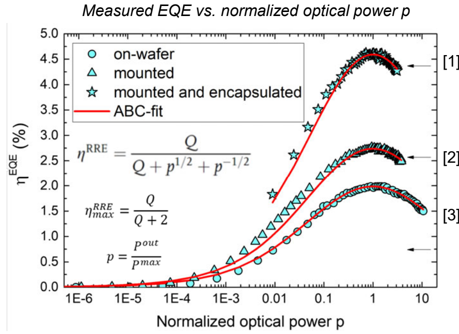
Measured output power & EQE vs. current density



Measured EQE vs. normalized optical power p



$$\eta^{RRE} = \frac{Q}{Q + p^{1/2} + p^{-1/2}}$$

$$\eta_{max}^{RRE} = \frac{Q}{Q+2}$$

$$p = \frac{p_{out}}{p_{max}}$$

- EQE from (pulsed) LIV measurements
- LEE from **Monte Carlo ray-tracing** simulation
- **Titkov method**: ABC-model fit of EQE vs. normalized optical power allows determination of **RRE** (if CIE & LEE are independent of p)
- **CIE** from EQE/(RRE*LEE)

	η_{max}^{RRE} (%)	η^{CIE} (%)	η^{LEE} (%)
FC LED & encapsulent*	60±3	58±8	12.8±1.3
FC LED*	58±4	51±7	9.2±0.9
LED on-wafer*	62±3	48±7	6.7±0.7

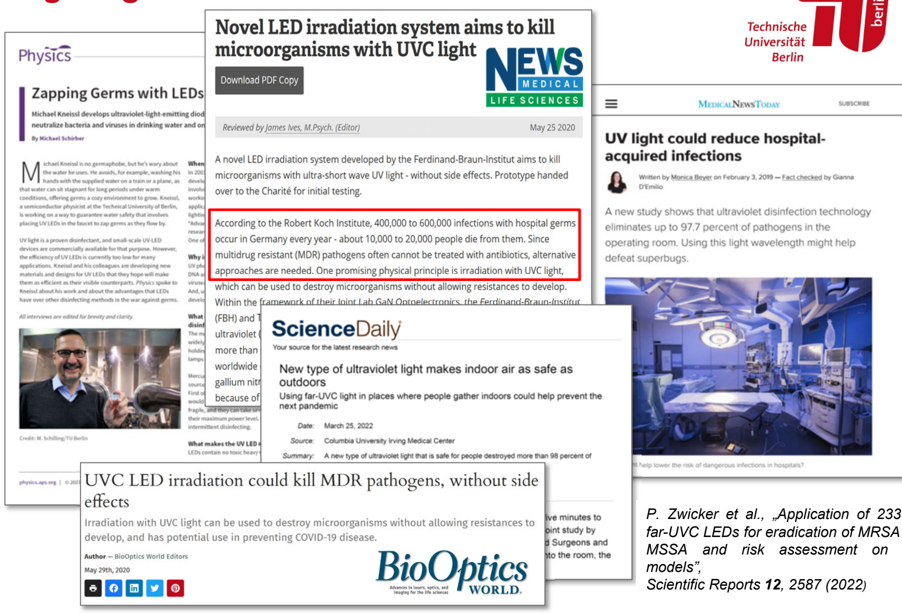
A. Muhin et al., phys. stat. sol (a), 2200458 (2022)
I.E. Titkov et al., IEEE J. Quantum Electron. **50**, 911 (2014)

**all LEDs on HTA-ELO AlN*

36

36

Fighting Germs with far-UVC Emitters



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*P. Zwicker et al., „Application of 233 nm far-UVC LEDs for eradication of MRSA and MSSA and risk assessment on skin models", Scientific Reports **12**, 2587 (2022)*

Far-UVC-LEDs for in-vivo disinfection

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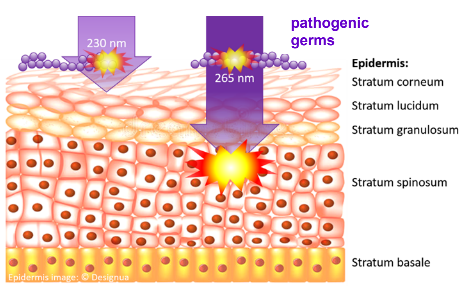
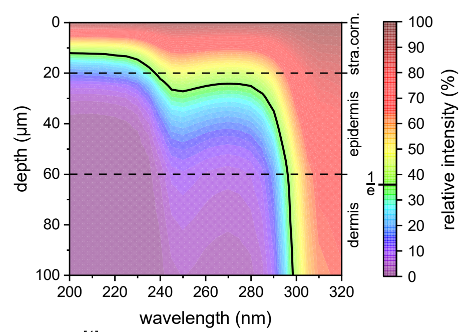
Interaction of UV light with the human skin



Simulated UV penetration depth into human skin [2]



- Strong **increase in protein absorption** for λ < 240 nm[1]
- Light from far-UVC LEDs (<235 nm) does not penetrate living skin layers
  - ⇒ **in-vivo disinfection without damage** to human skin
- In-activation of multidrug resistant bacteria (e.g., MRSA) on skin surface
  - ⇒ No risk of developing resistance
  - ⇒ Required **dose levels for MRSA: ~40 mJ/cm²**

*[1] Manuela Buonanno et al., PLOS ONE **8**, e76968 (2013)*
*[2] Lorin Busch et al., J. Photochem. & Photobiol., B: Biology **247**, 112784 (2023)*

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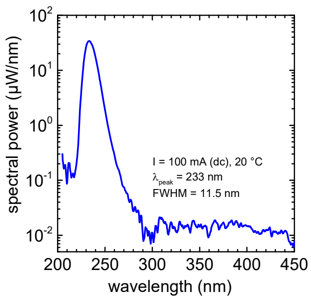
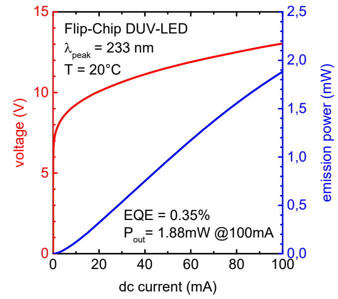
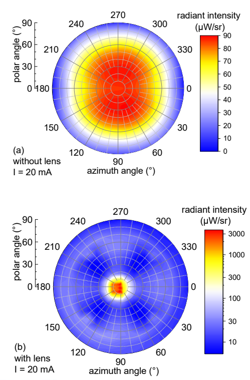
Performance of 233 nm LEDs on sapphire

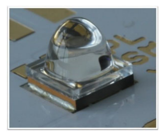






- Flip-chip UVC-LEDs with output power of 1.88 mW @200mA **(EQE_{max} = 0.35%)**
- Emission peak @ 233 nm, FWHM = 11.5 nm
- Very little defect EL (<10^{-3}), but 18% of UVC light emitted wavelengths >240 nm

  ⇒ **Short-pass bandpass filter** required



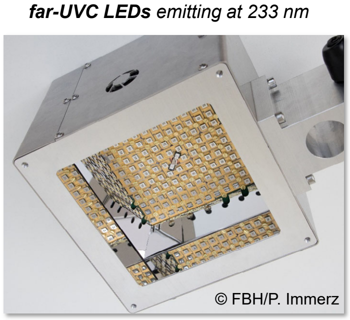
N. Lobo-Ploch et al., Appl. Phys. Lett. **117**, 111102 *(2020)*

Page 39

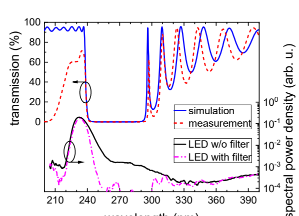
39

A spectrally pure 233 nm irradiation module

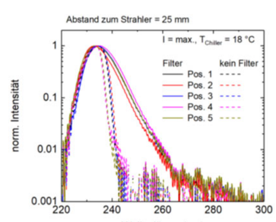
*Irradiation module with an **array of 120 far-UVC LEDs** emitting at 233 nm*



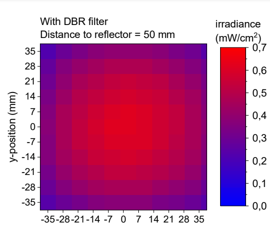
DRR filter transmission spectra



LED spectra w/ & w/o filter



Irradiance Distribution



- **HfO_2/SiO_2 DBR short-pass bandpass filte**r to eliminate emission >240 nm
- Modul with integrated DBR filter with **irradiance of 0.51 mW/cm²** (uniformity >90%)

➔ Dose levels of 40 mJ/cm² reached in <80s

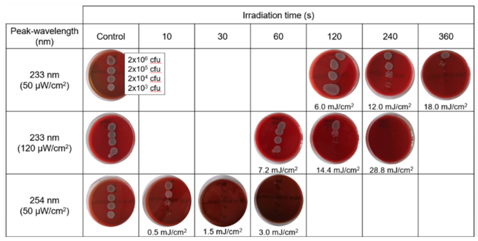
J. Glaab et al., Scientific Reports **11**,14647 (2021)

Page 40

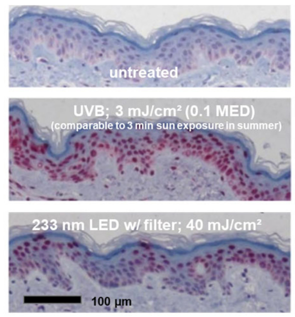
40

In-vivo disinfection with far-UVC LEDs

MRSA disinfection test (bacterial suspension on blood agar)



DNA damage (CPD) in human skin



- **3-log inactivation** of **MRSA** with 29 mJ/cm^2
- Clinical studies show minor DNA damage to human skin, corresponding to ~0.1 MED
- **No DNA damage detectable** after 24h (natural repair mechanisms of the skin)
  - ⇒ **Successful in-vivo disinfection of MRSA without skin damage**
- Future: Application to other pathogens (e.g. fungi, virus)

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*P. Zwicker et al., Scientific Reports **12**, 2587 (2022)*
*J. Schleusener et al., Mycoses **66**, 28 (2023)*

Page 41

41

Analysis of EQE collapse in Far-UVC-LEDs

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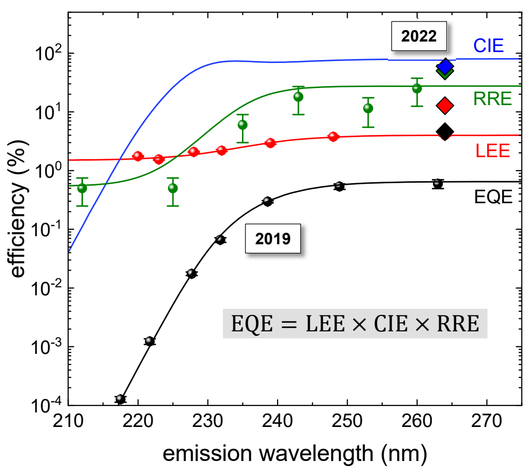

- Steep drop in **EQE** for **λ <240 nm**
- Drop in **LEE** for λ <240 nm, but **less than 3x** (change DOP)
- **RRE** drops from ~60% @ λ = 265 nm to <1% for λ ~225 nm (Temp- & P_{exc}-dependent PL)
  - ➔ **Increase in point defect density for high [Al] ?**
- **CIE** ~50% @ λ = 265 nm, but **strongly decreasing** at DUV wavelengths λ < 230 nm
  - ➔ **Increased carrier leakage (small band-offset, Mg-doping)**

*M. Guttmann et al., Jpn. J. Appl. Phys. **58**, SCCB20 (2019)*
*S. Tanaka et al., Jpn. J. Appl. Phys. **61**, 112002 (2022)*
A. Muhin et al., phys. stat. sol (a), 2200458 (2022)

Page 42

42

Improving CIE & RRE in Far-UVC LEDs

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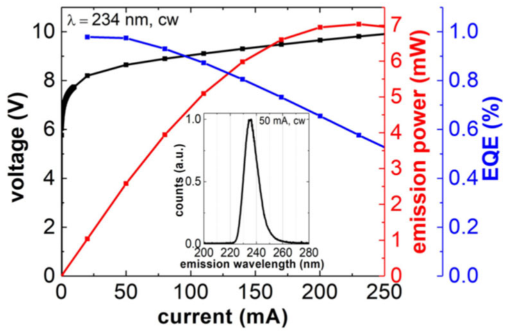
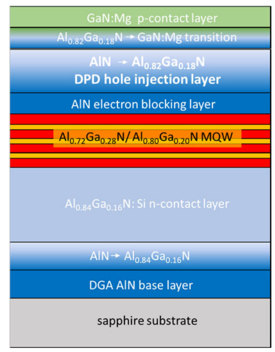
LIV characteristic of a 234 nm LED with a distributed polarization doped (DPD) hole injection layer





- 3rd generation of far-UVC LEDs with distributed polarization-doped (DPD) p-AlGaN hole injection layer on DGA AlN/sapphire (TDD~2.1*10^8cm^{-2}) [1]

P_{out} = 7 mW, EQE_{max} = 0.98% emitting @ 234 nm

[1] Tim Kolbe et al., Appl. Phys. Lett. **122**, 191101 *(2023)*

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Page 43

43

Analysis of EQE collapse in Far-UVC-LEDs

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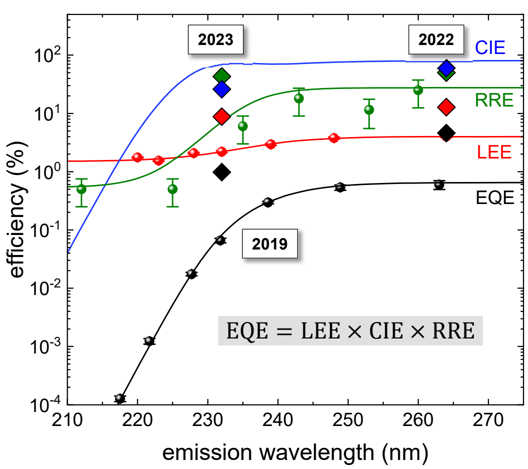


- Improved **EQE** for **λ = 233 nm for next generation of far UVC-LEDs**
- Est. **LEE = 8.8±0.8%** from Monte-Carlo simulation (flip-chip mounting, polarization control)

Analysis based on Titkov model:

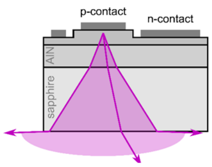
- Est. **RRE_{max} = 43±4%** (reduced TDD, point defects)
- Est. **CIE = 26±8%**

M. Guttmann et al., Jpn. J. Appl. Phys. ***58****, SCCB20 (2019)*
S. Tanaka et al., Jpn. J. Appl. Phys. **61,** 112002 *(2022)*
A. Muhin et al., phys. stat. sol (a), 2200458 *(2022)*
A. Muhin, Ph.D. Thesis, TU Berlin (2024)

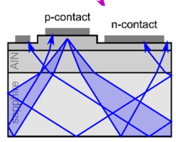
Page 44

44

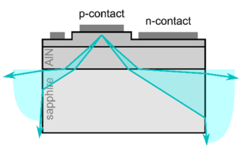
Light Extraction from UVC-LEDs



Emission through the substrate backside

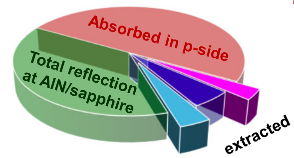


Total reflection at bottom and sidewall surfaces



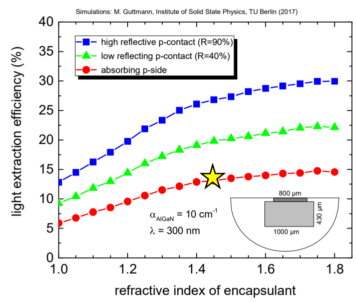
Emission through the (transparent and smooth) sidewall surfaces

Paths of created photons



⇒ LEE is only 5-7% for a bare LED chip

Enhanced light extraction by encapsulation



Measures for enhanced light extraction

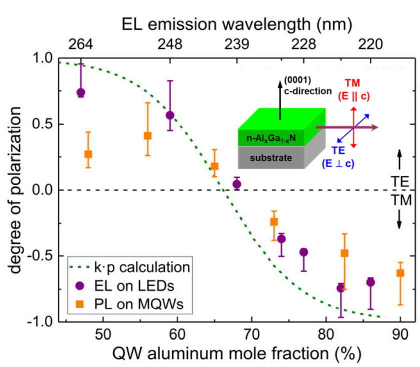
- Encapsulation with UV-transparent polymers
- UV-reflective contacts (e.g. Rh, Ni/Al)
- Nano-patterned (sapphire) substrates

Page 45

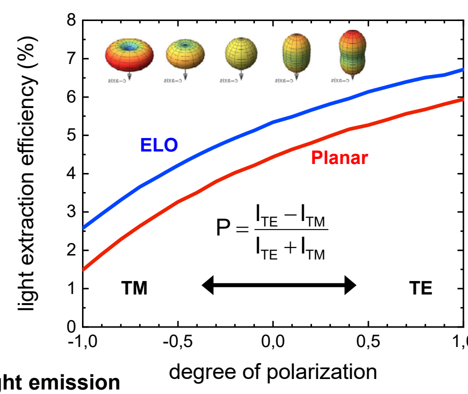
45

Light extraction efficiency in far-UVC LEDs

DOP vs. aluminum mole fraction in QW



Simulated light extraction efficiency (LEE)



- **LEE** strongly affected by **polarization of light emission**
  - ⇒ Re-ordering and change of polarization of valance bands with increasing aluminium mole fraction in $Al_xGa_{1-x}N$ QWs (Γ_7 vs. Γ_9)
  - ⇒ **Transition to TM** polarized emission for λ <240 nm
  - ⇒ Drop in LEE for far-UVC LEDs

*M. Guttmann et al., Jpn. J. Appl. Phys. **58**, SCCB20 (2019)*

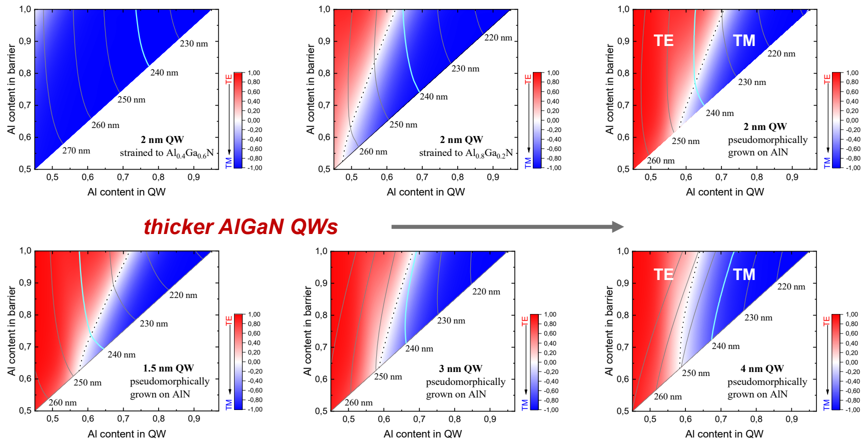
46

Impact of strain & AlGaN QW width on TE/TM emission

Technische Universität Berlin

larger compressive strain

thicker AlGaN QWs



Simulated AlGaN QW emission based on **k·p** perturbation theory

→ Enhanced TE emission for compressively strained & thin QWs

*C. Reich et al., Appl. Phys. Lett. **107**, 142101 (2015)*

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Seite 47

47

Effect of strain on TE vs. TM emission

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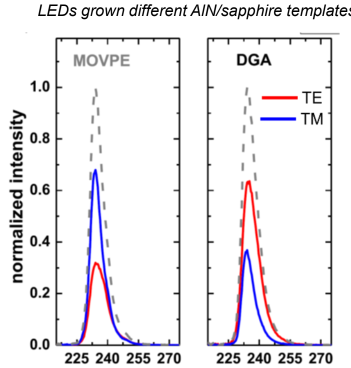
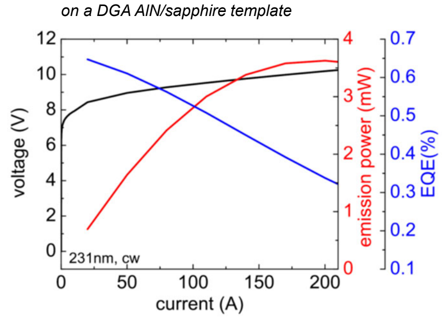
TE vs TM polarized emission from AlGaN MQW LEDs grown different AlN/sapphire templates



LIV characteristic of a 231 nm LED grown on a DGA AlN/sapphire template



- 231 nm LEDs grown on AlN/sapphire with different a-plane lattice constants
  - => Larger compressive strain for AlGaN MQWs grown on DGA AlN/sapphire
  - => DoP increases from -0.23 (on MOVPE) to +0.38 (on DGA)
  - => Increase in LEE by 30% expected

Arne Knauer et al., Appl. Phys. Lett. 122, 011102 (2023)

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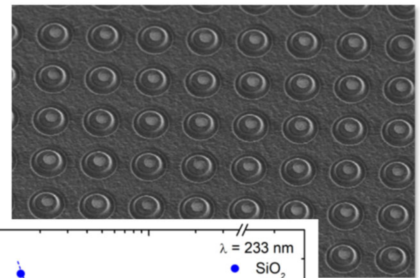
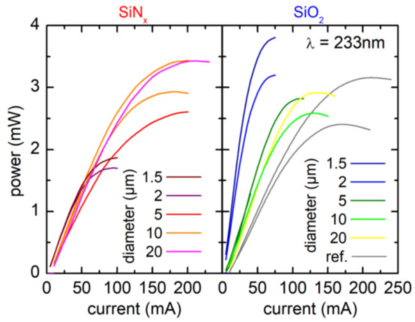
Page 48

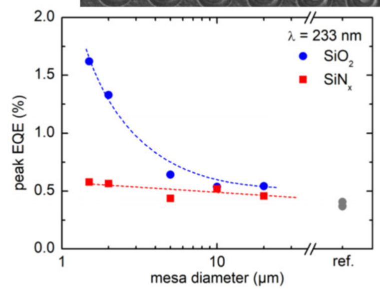
48

Enhanced LEE in 233 nm µ-LEDs

Light output of µ-pixel array far-UVC-LEDs emitting at 233 nm with SiN_x vs. SiO_2 dielectrics on mesa sidewalls







Far-UVC µ-LED arrays with slanted mesa sidewalls and SiO_2 dielectric

4x LEE enhancement for 233 nm LED with pixel diameters of d = 1.5µm

=> **Far-UVC µ-LED arrays** with **EQE_{max} = 1.6%**

Jens Rass et al., Appl. Phys. Lett. 122, 263508 *(2023)*

Page 49

49

Acknowledgements

Institute of Solid State Physics, TU Berlin:

G. Cardinali, S. Graupeter, M. Guttmann, J. Höpfner, C. Kuhn, A. Muhin, F. Mehnke, F. Nippert, M. Schilling, N. Susilo, L. Sulmoni, T. Wernicke

Ferdinand-Braun-Institute, Berlin:

H.K. Cho, J. Glaab, S. Hagedorn, K. Hilbrich, A. Knauer, T. Kolbe, N. Lobo-Ploch, A. Mogilatenko, C. Netzel, J. Rass, J. Ruschel, S. Walde, S. Einfeldt, M. Weyers

Collaborations:

- M. C. Meinke, L. Busch, J. Schleusener (**Charité - UM Berlin, Germany**)
- A. Kramer, P. Zwicker (**University of Greifswald Medical School, Germany**)
- H. Miyake (**Mie University, Japan**)

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Page 50

50