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Threshold and gain measurements of AlGaN-based UVC lasers & Temperature dependent electroluminescence spectroscopy on AlGaN-based 235nm far-UVC LEDs with different active region growth temperatures

Markus Blonski & Paula Vierck | Institute of Solid State Physics

Technische Universität Berlin

Schwellen- und Gewinnmessungen bei AlGaN-basierten UVC Lasern
&
Temperaturabhängige Elektrolumineszenz-spektroskopie an 235 nm AlGaN UVC LEDs mit variabler Wachstumstemperatur der aktiven Zone

Markus Blonski & Paula Vierck | Institute of Solid State Physics

LED Bändermodell

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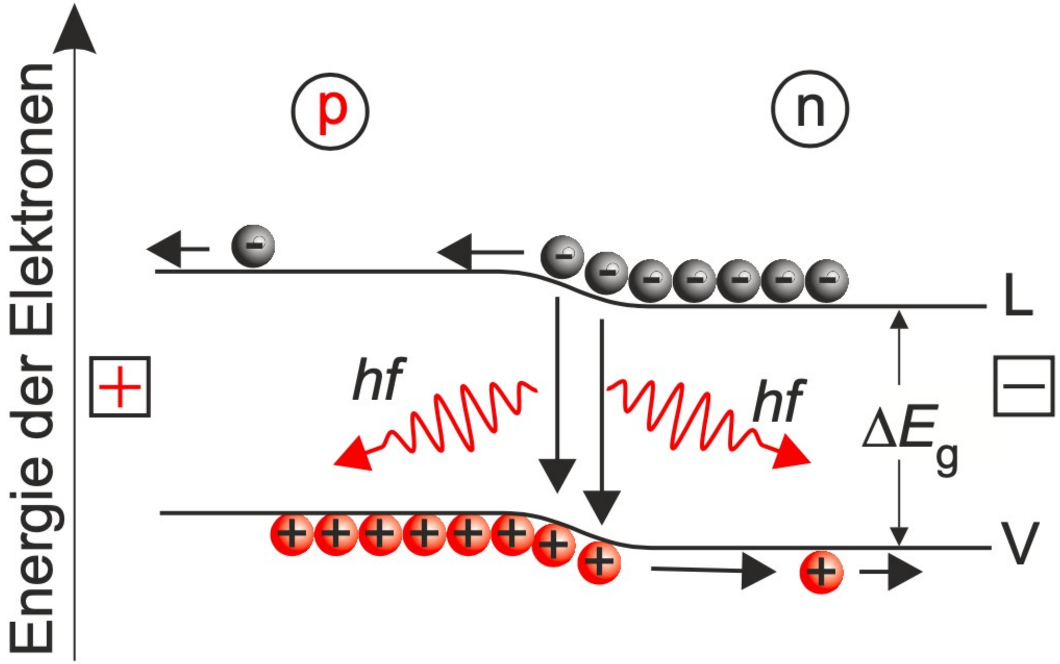
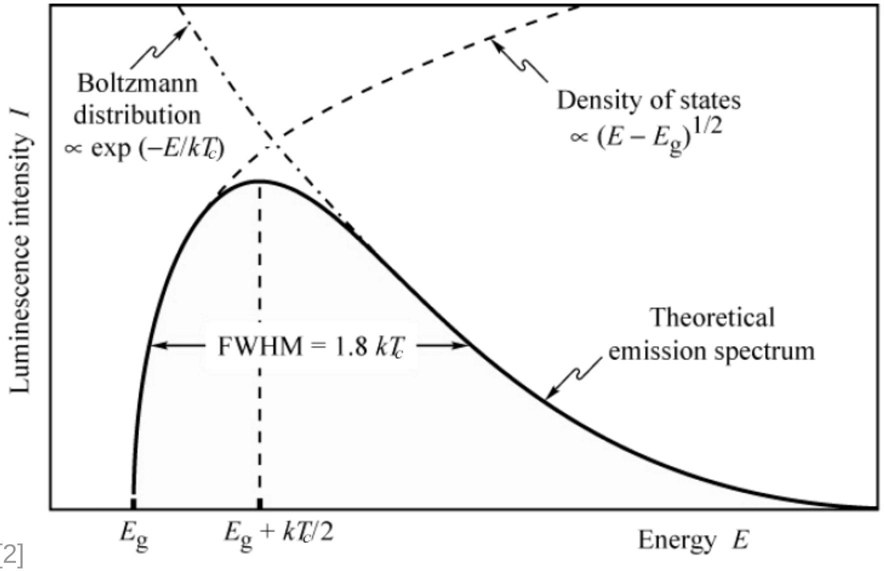


[1]



[2]

[1] *Das Neue Physikalische Grundpraktikum,* Eichler, Kronfeldt, Sahm
[2] https://www.researchgate.net/figure/Theoretical-light-emitting-diode-spectrum-as-a-product-of-the-density-of-energy-states_fig34_268054048

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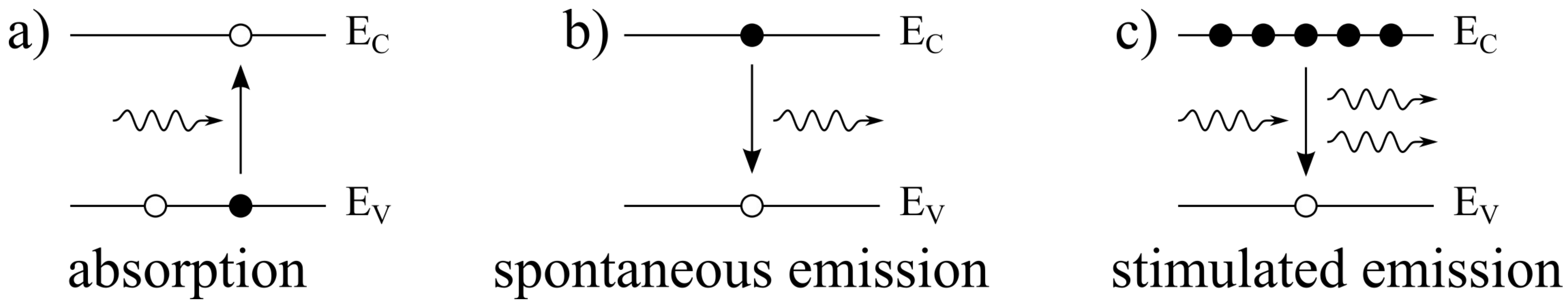
Photon-Elektron-Wechselwirkung



[1]

[1] *Das Neue Physikalische Grundpraktikum,* Eichler, Kronfeldt, Sahm

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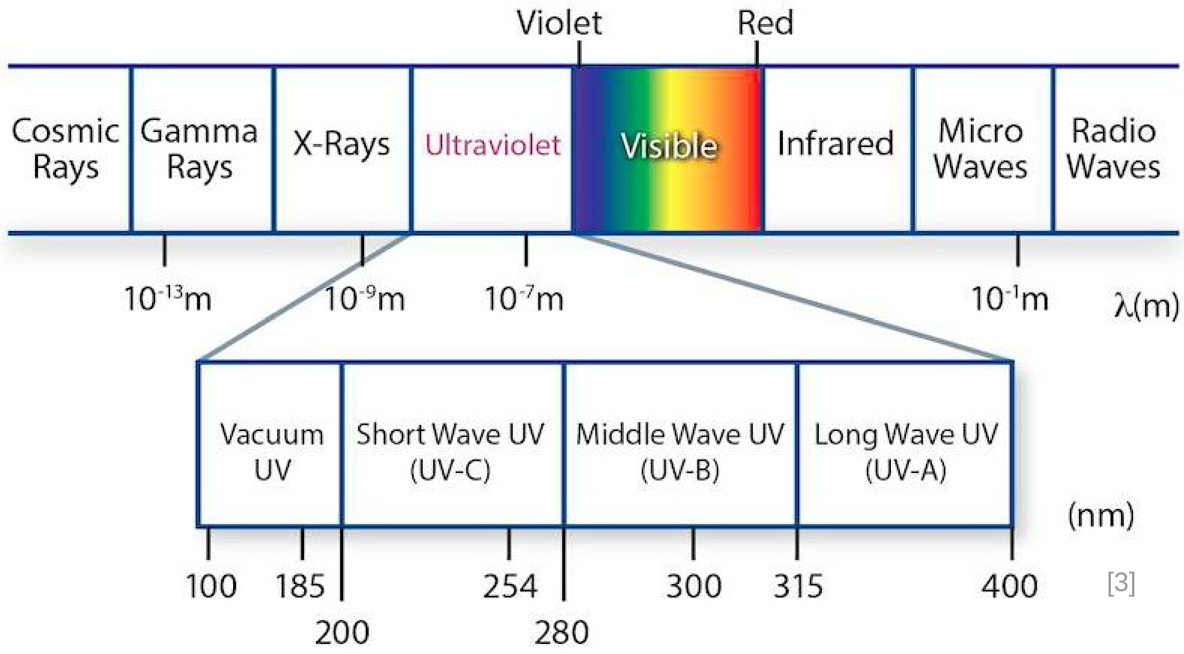
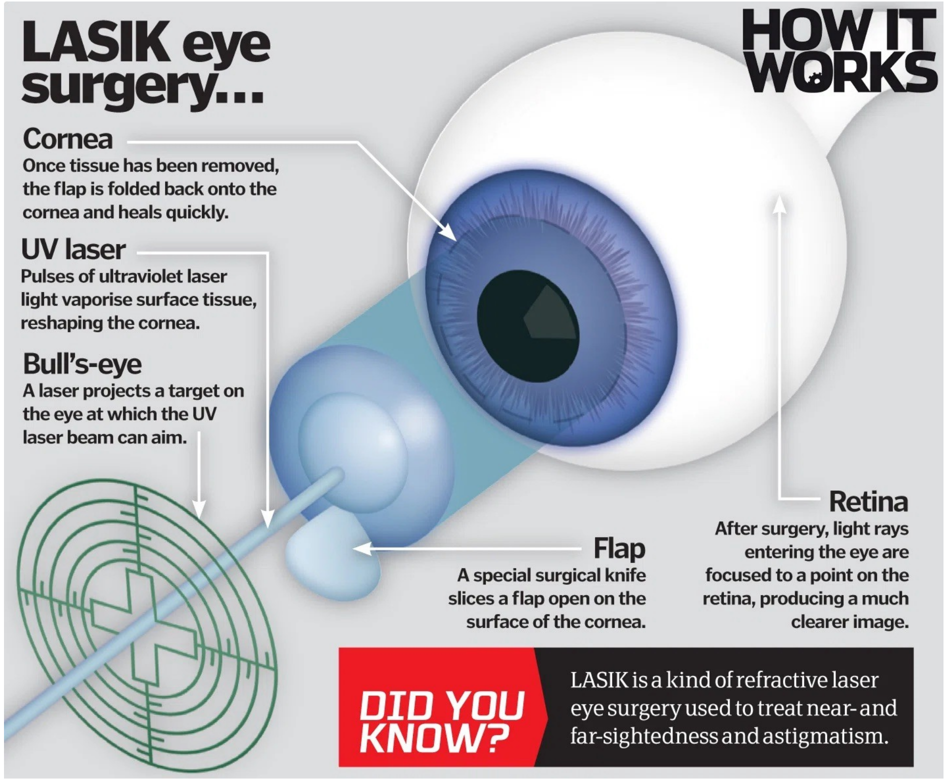
UV-Spektrum



[3]

[3] https://www.uvfab.com/uv-spectrum-and-applications/

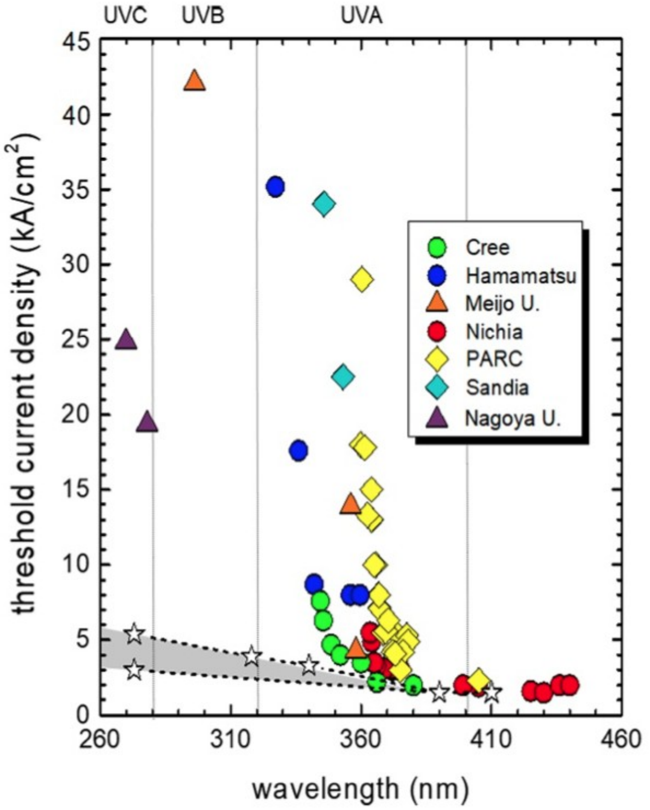
UV-C Anwendungen



[4] https://www.coherent.com/de/lasers/excimer/indystar
[5] https://www.kotte-zeller.de/origin-outdoors-trinkflasche-fairbanks-mit-uv-wasserfilter-schwarz-fuer-outdoor-zur-notversorgung
[6] https://www.howitworksdaily.com/how-does-laser-eye-surgery-work/

Motivation

[7]

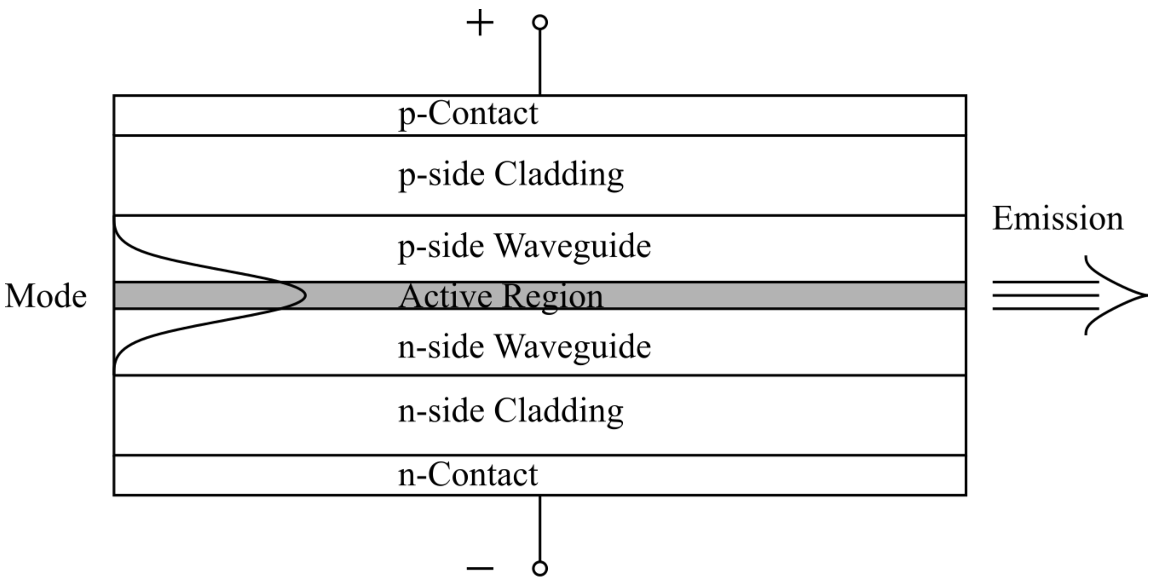


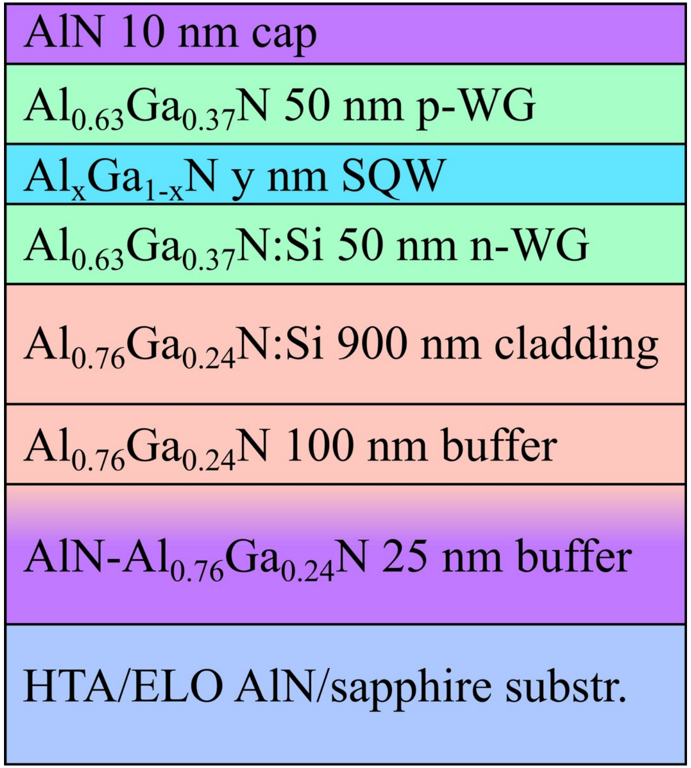
[8]

[7] https://www.coherent.com/de/lasers/excimer/indystar

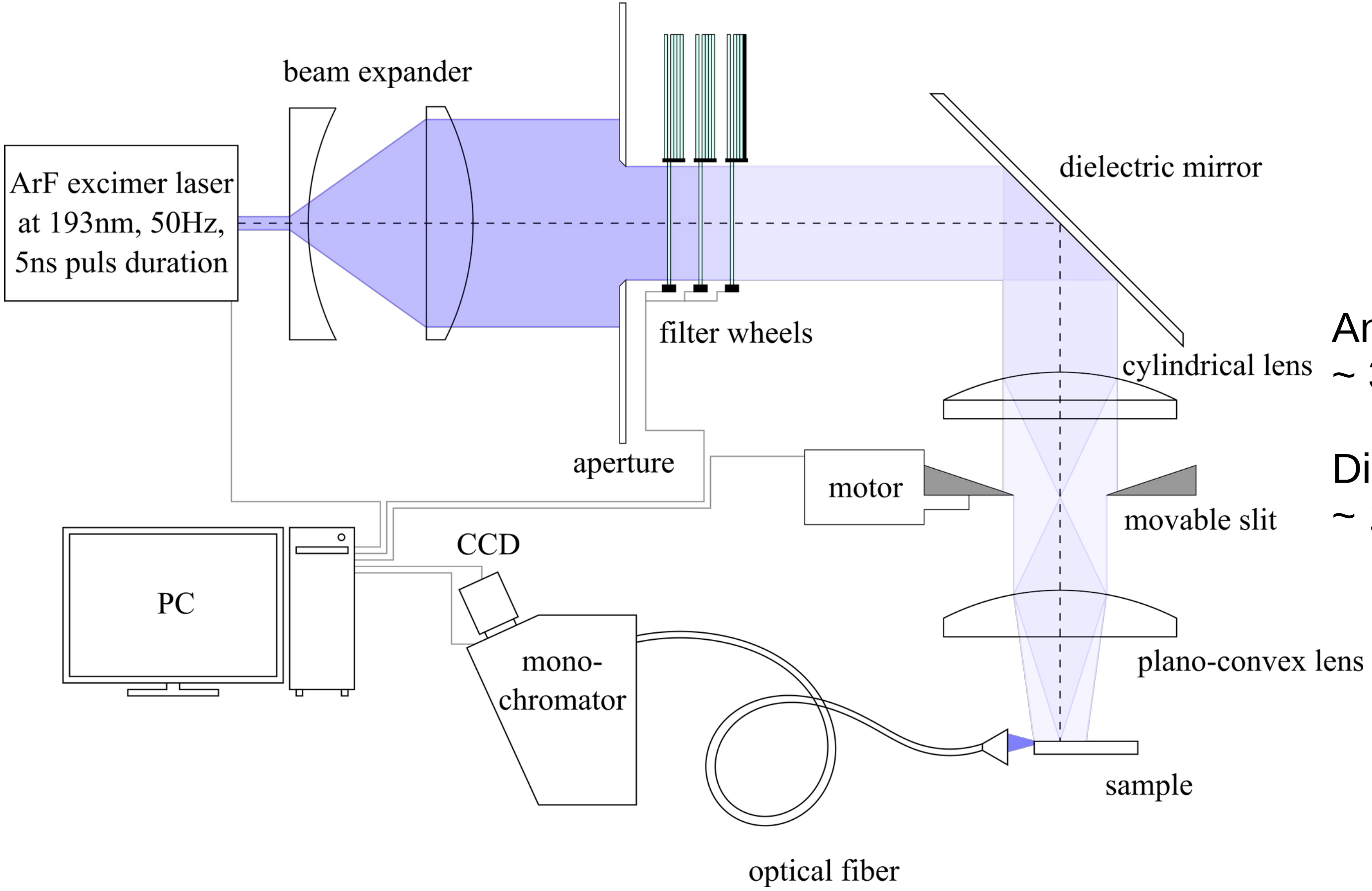
[8] Amano et. al. (2020) J. Appl. Phys., 53,503001

Edge-Emitting Lasers (EELs)





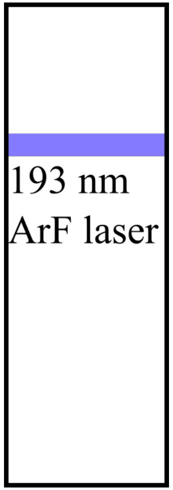
Photolumineszenzaufbau

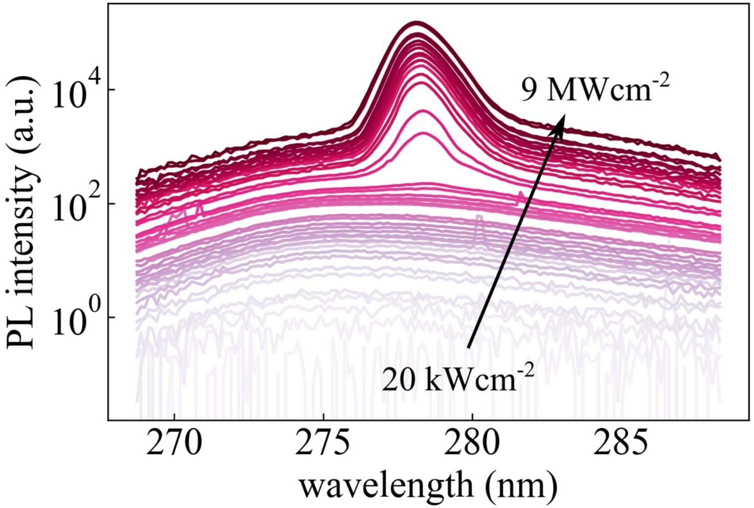


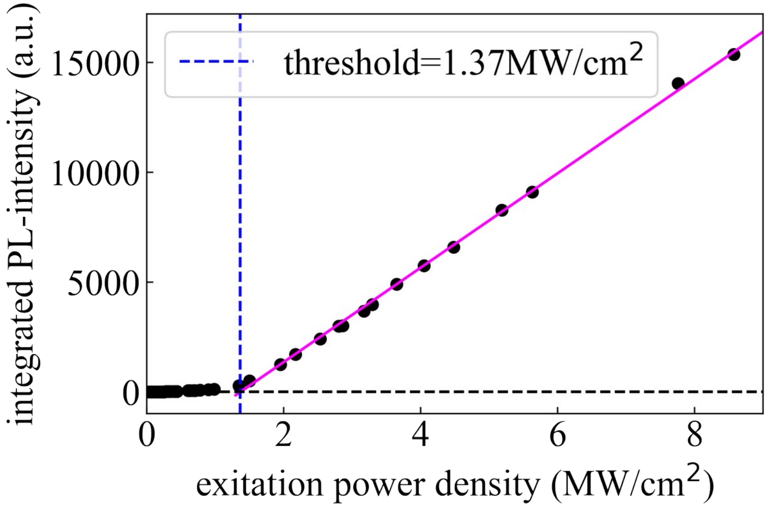
Anregungsleistungsdichte:
~ 30 $kWcm^{-2}$ - 9 $MWcm^{-2}$

Dimensionen des Leuchtstreifens:
~ 14 µm × (50 - 500) µm

Messung und Berechnung der Schwelle

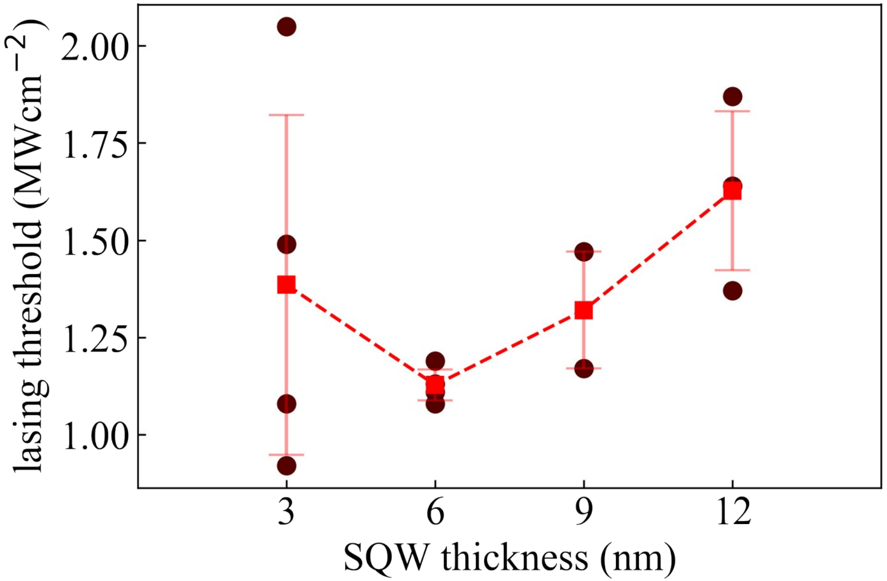


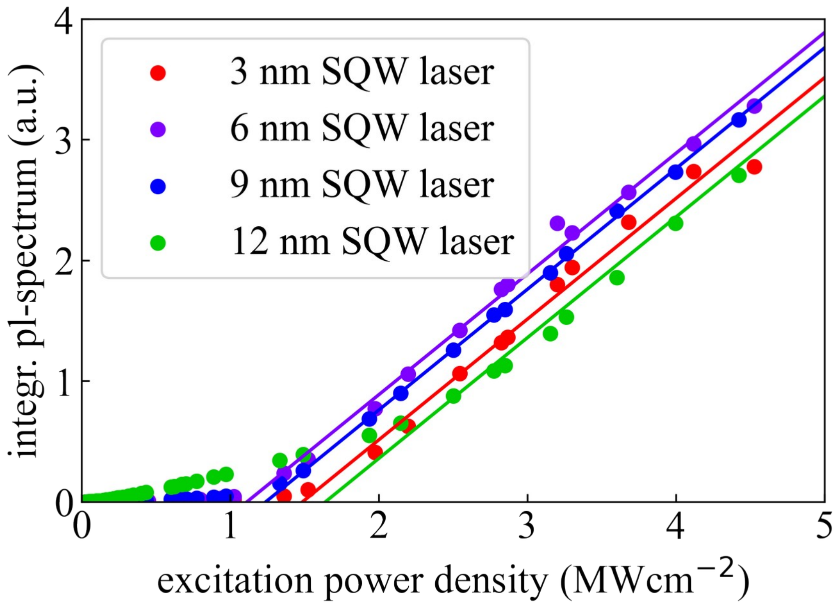




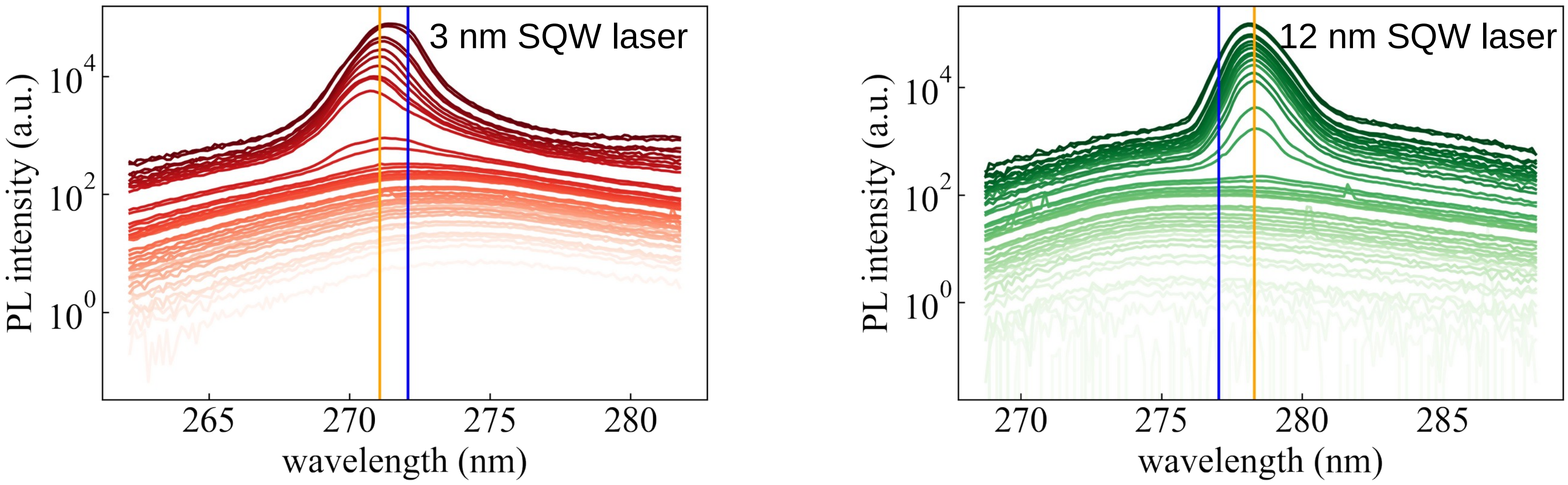
12 nm SQW laser (TS5862)

Laserschwelle





Emissionsspektren von AlGaN basierten optisch angeregten Lasern



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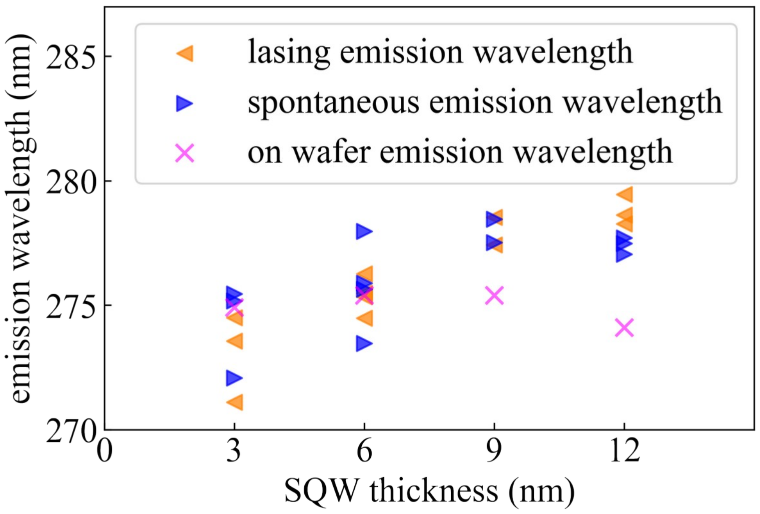
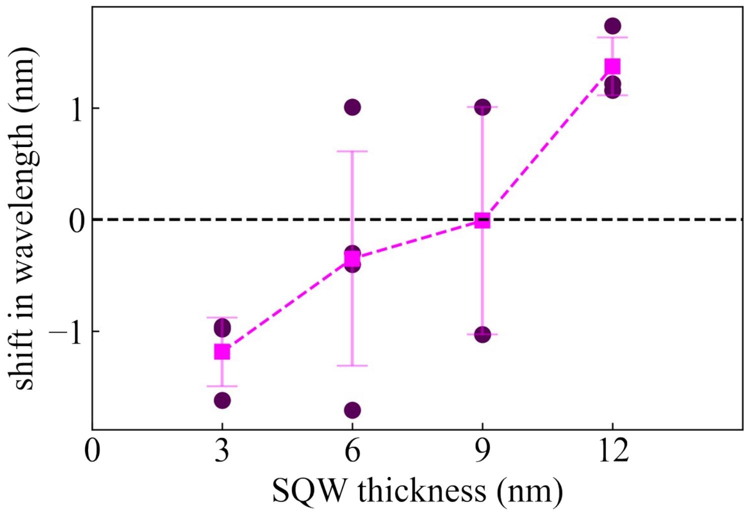
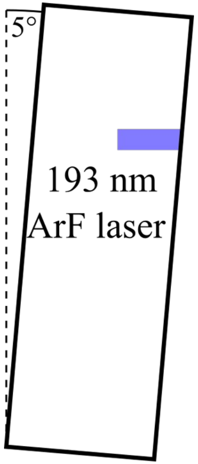
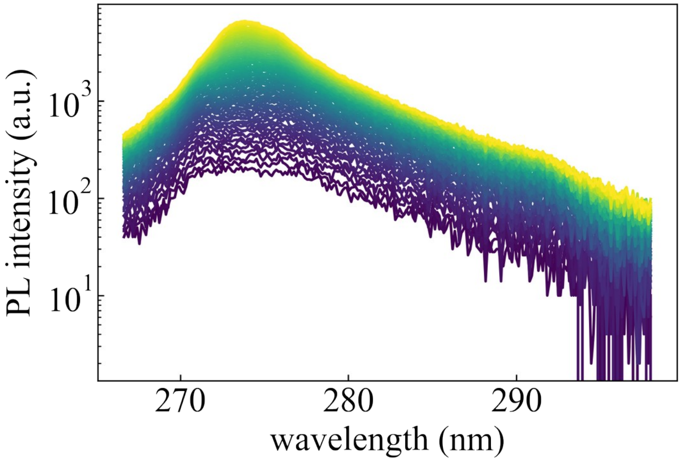
Emissionswellenlänge

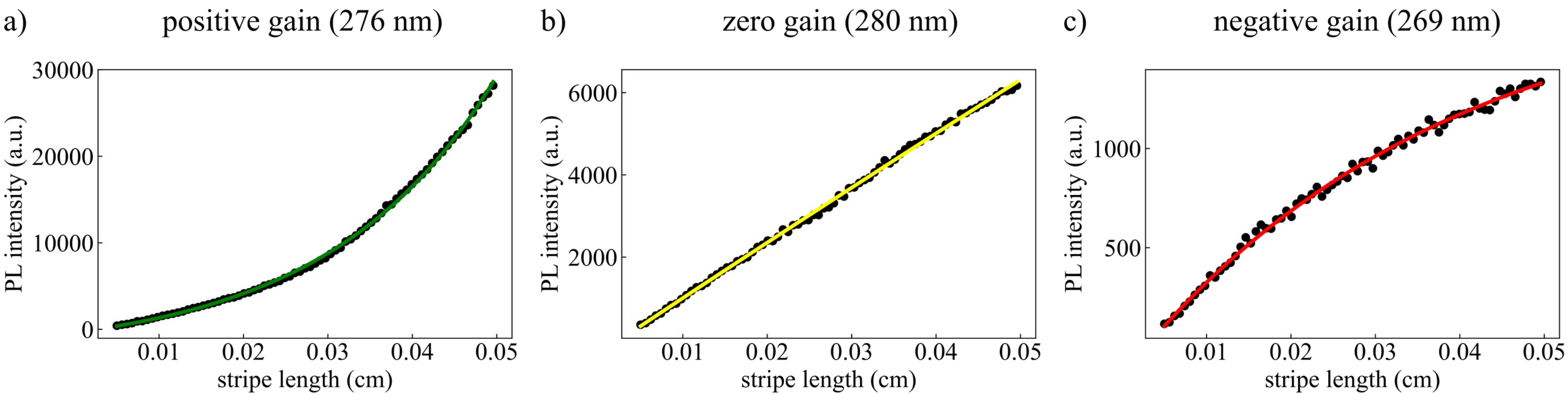




Gewinnmessung und Berechnung







6 nm SQW laser (TS5858)

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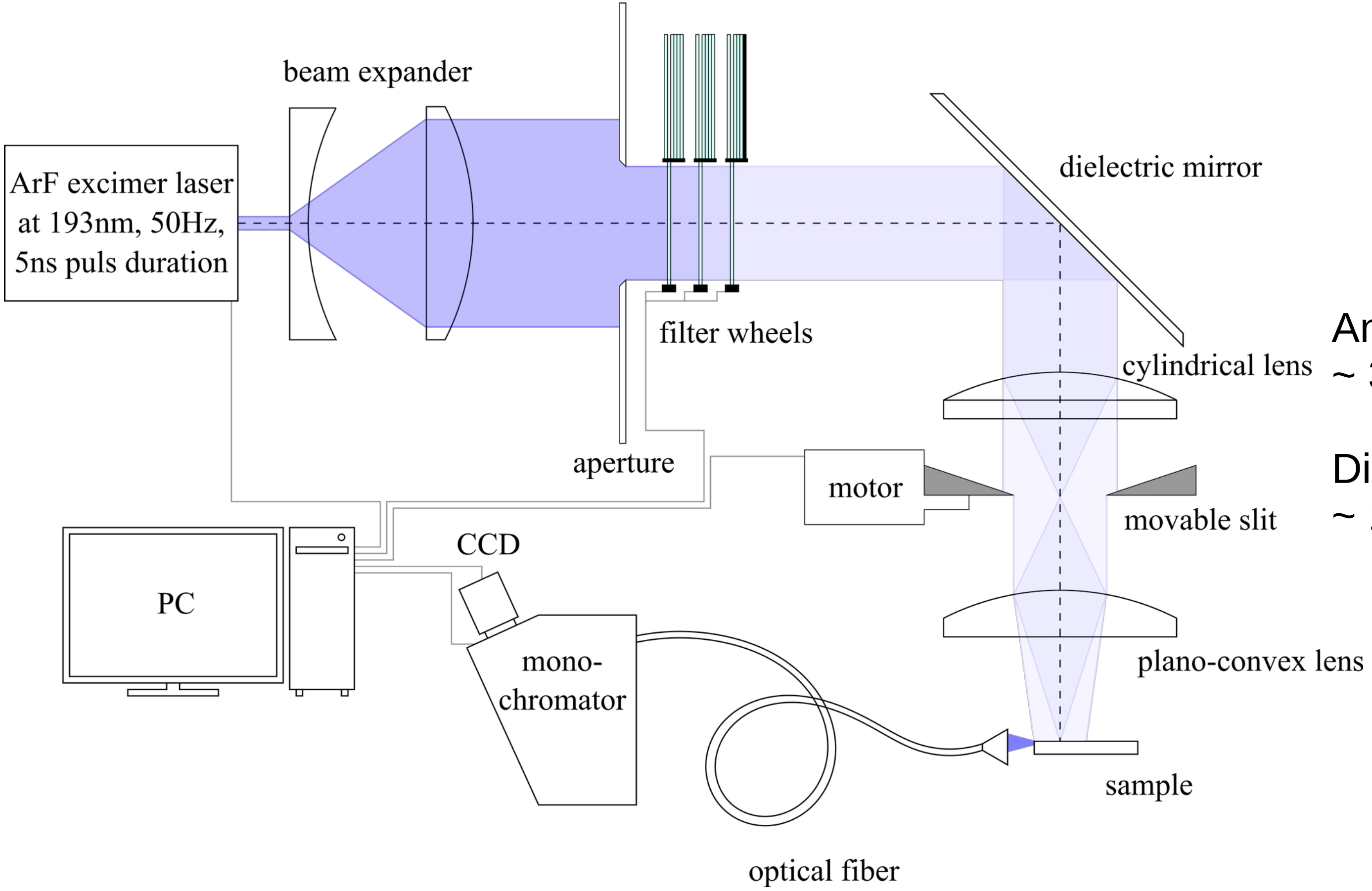
Photolumineszenzaufbau



Anregungsleistungsdichte:
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Dimensionen des Leuchtstreifens:
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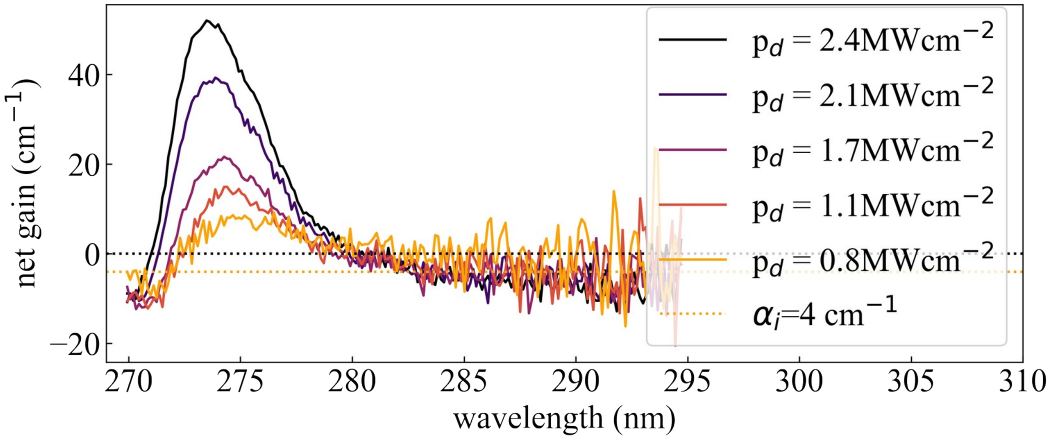
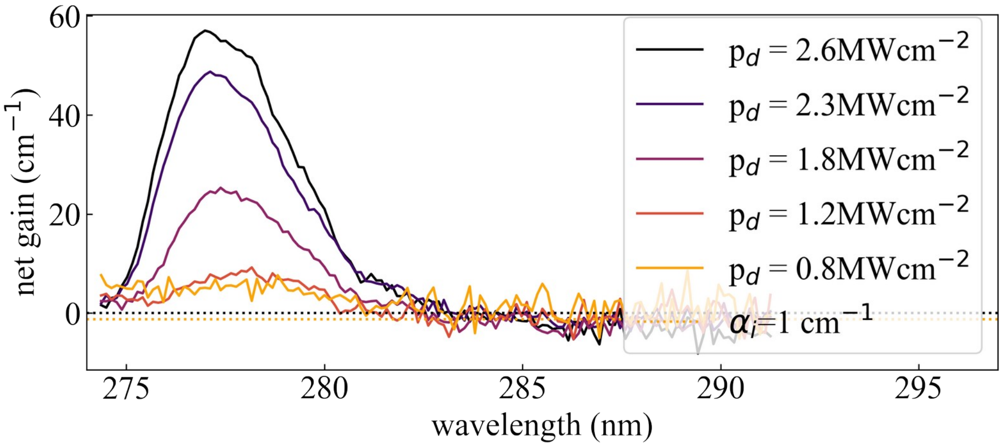
Gewinnspektren





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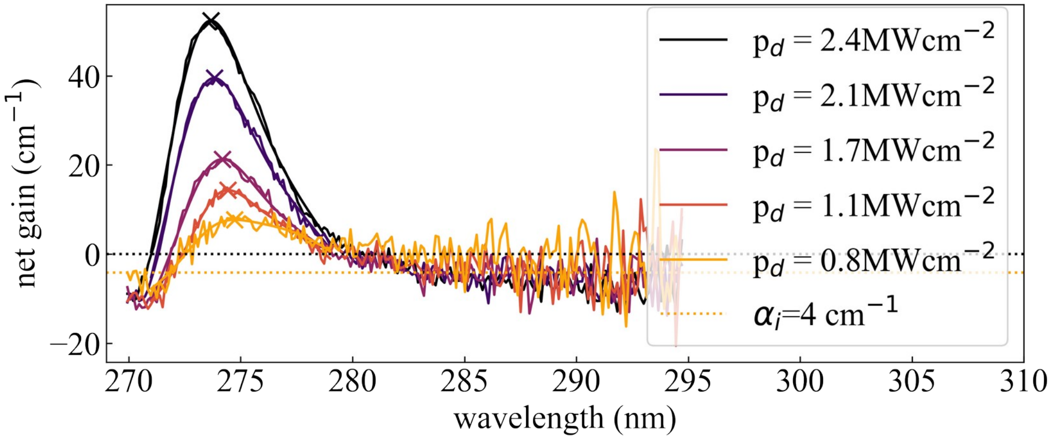
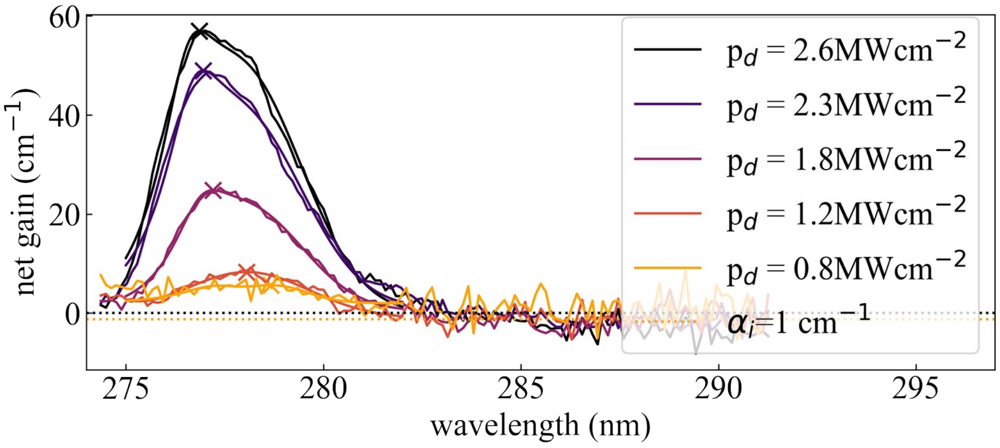
Gewinnspektren



6 nm SQW laser



12 nm SQW laser

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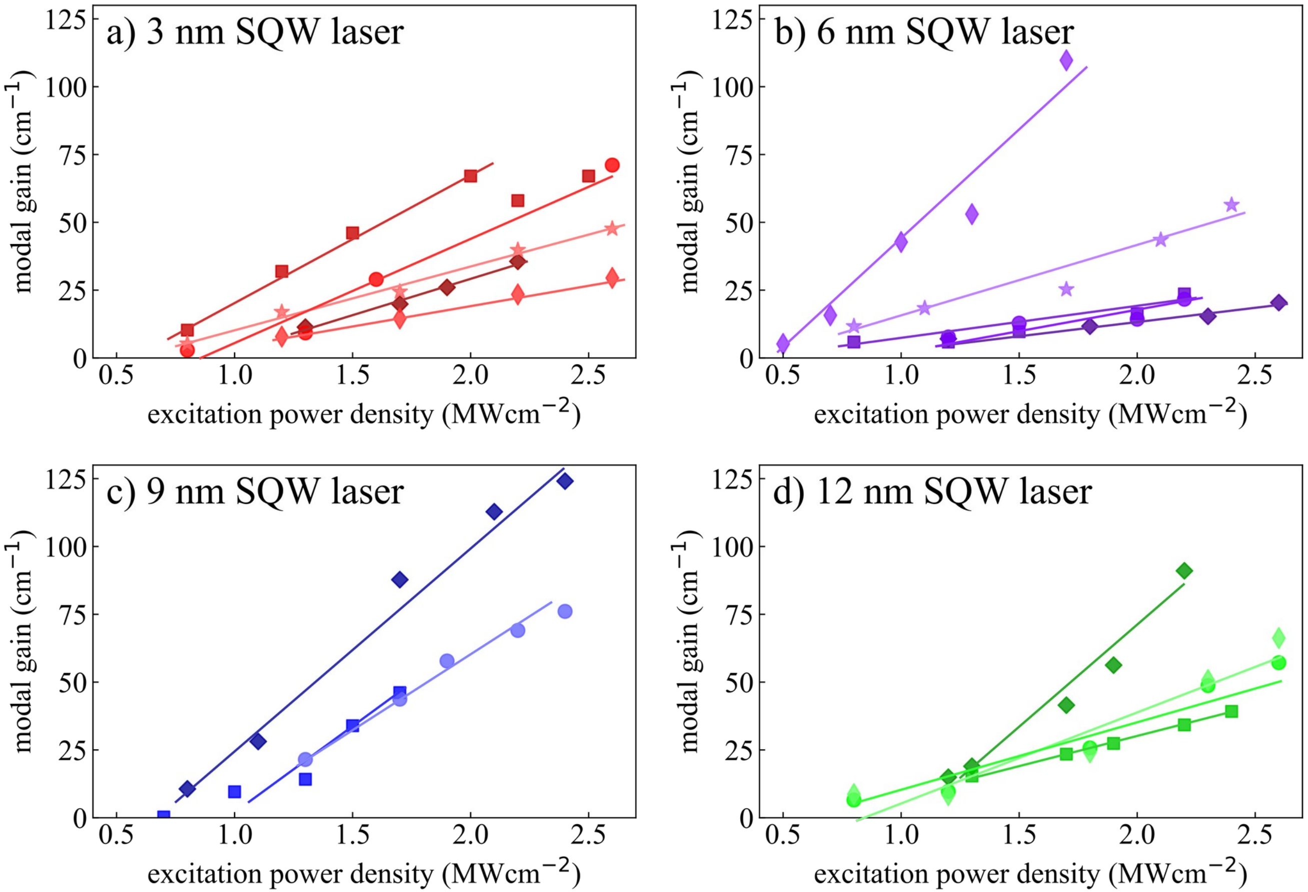
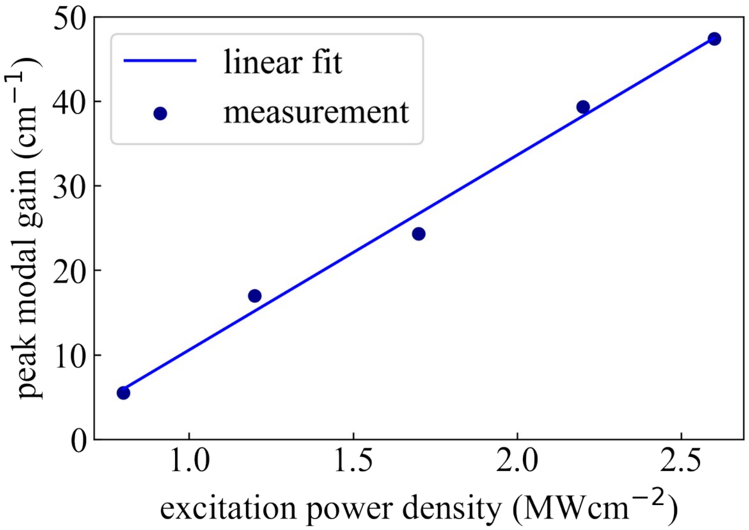
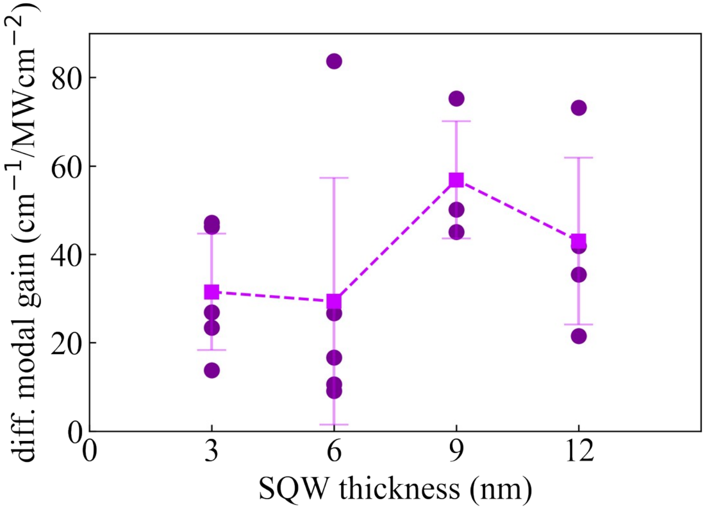
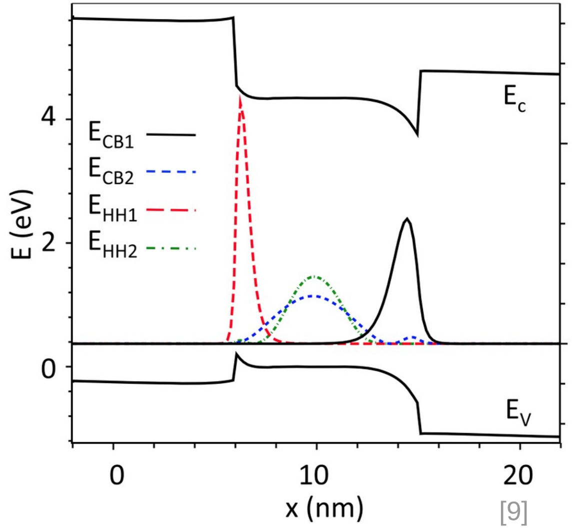
Modaler Gewinn



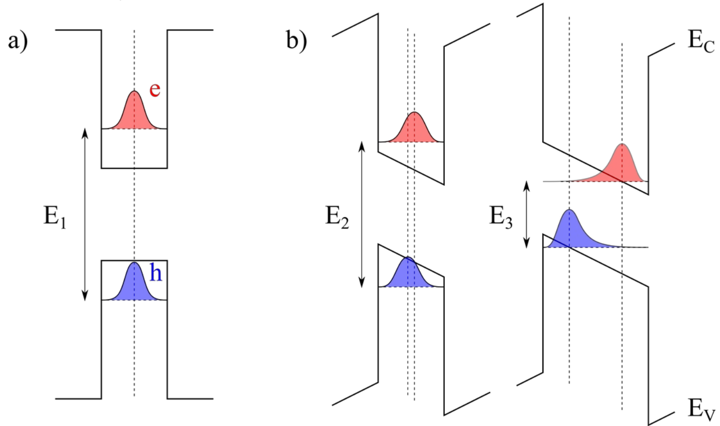
Differentieller Gewinn





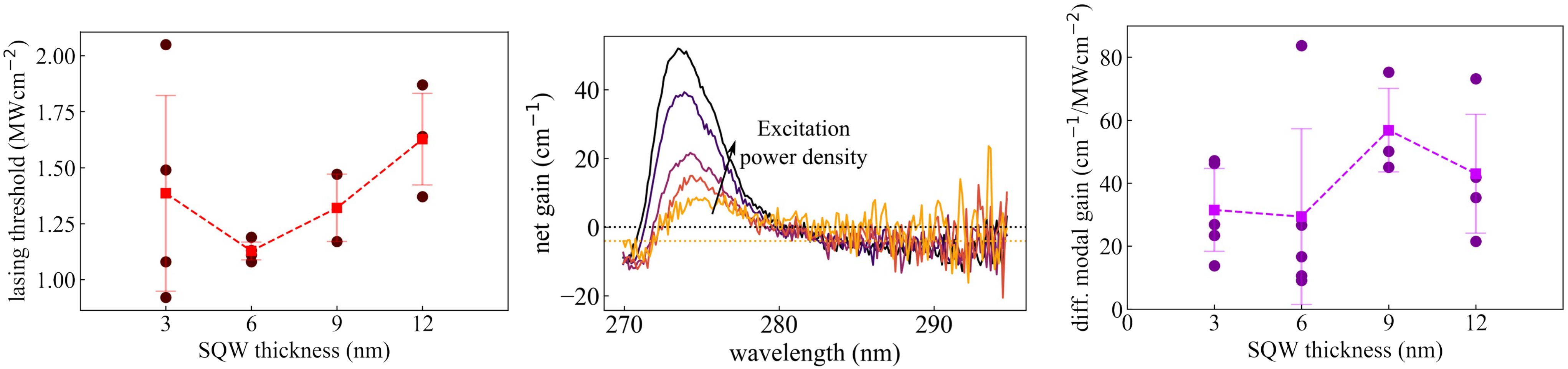


[9]



[9] B. Witzigmann et al. (2020) AIP Advances, 10,095307

Zusammenfassung und Ausblick



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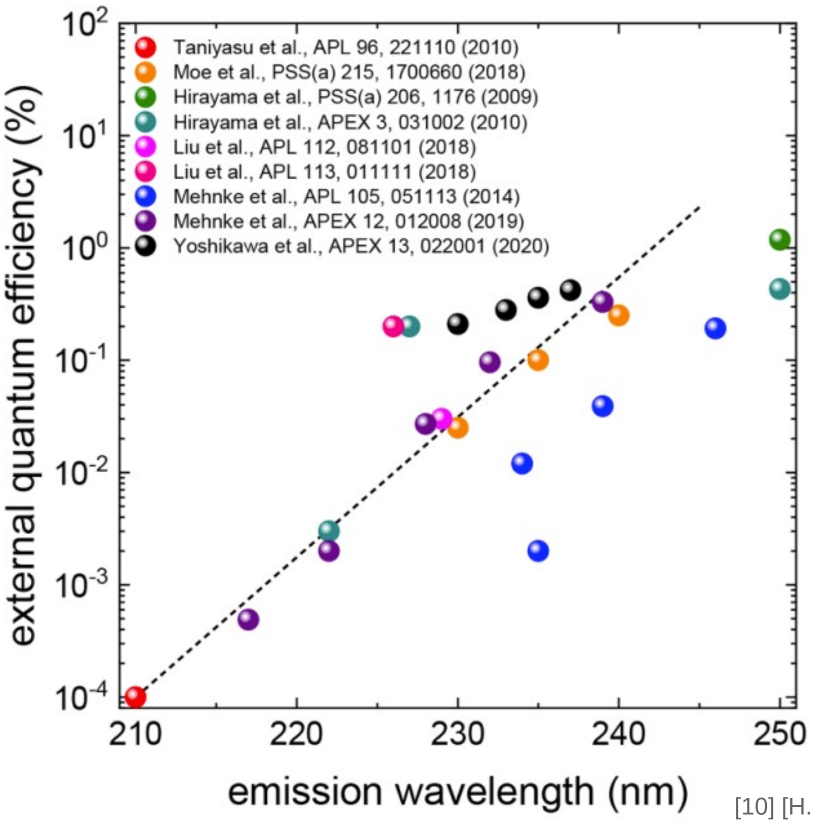
Motivation



[10]

[10] [H. Amano et al., J. Phys. D: Appl. Phys. 53 503001 (2020)]

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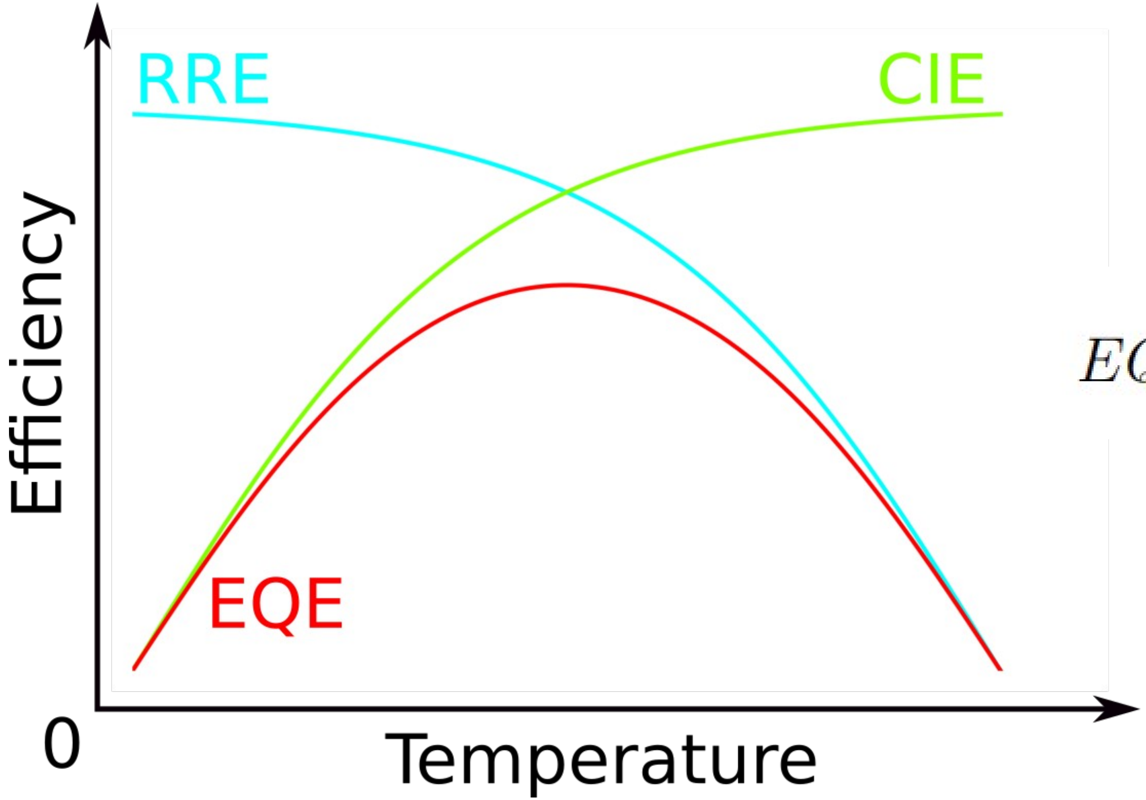
Externe Quanteneffizienz (EQE)



$$EQE = LEE \cdot CIE \cdot RRE$$

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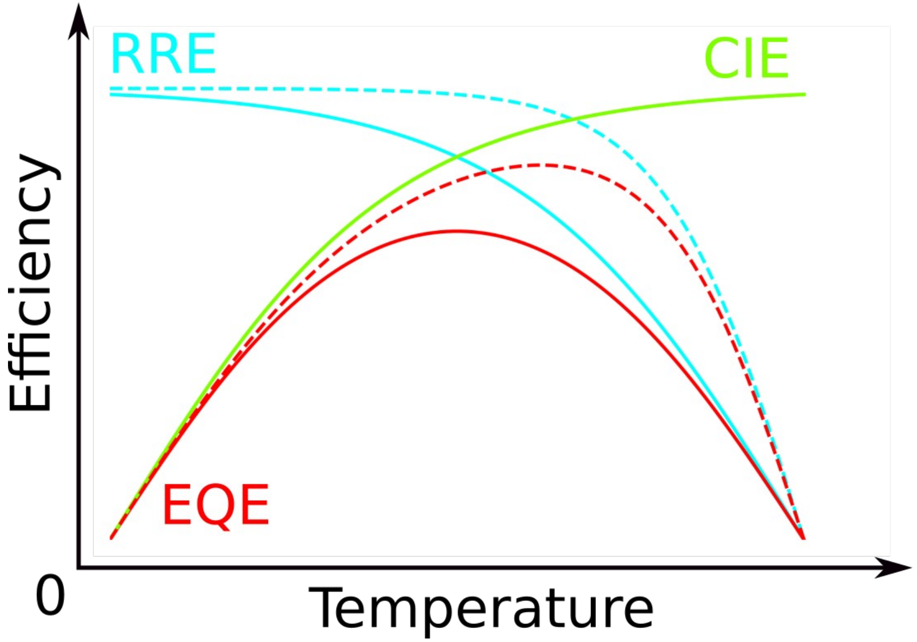
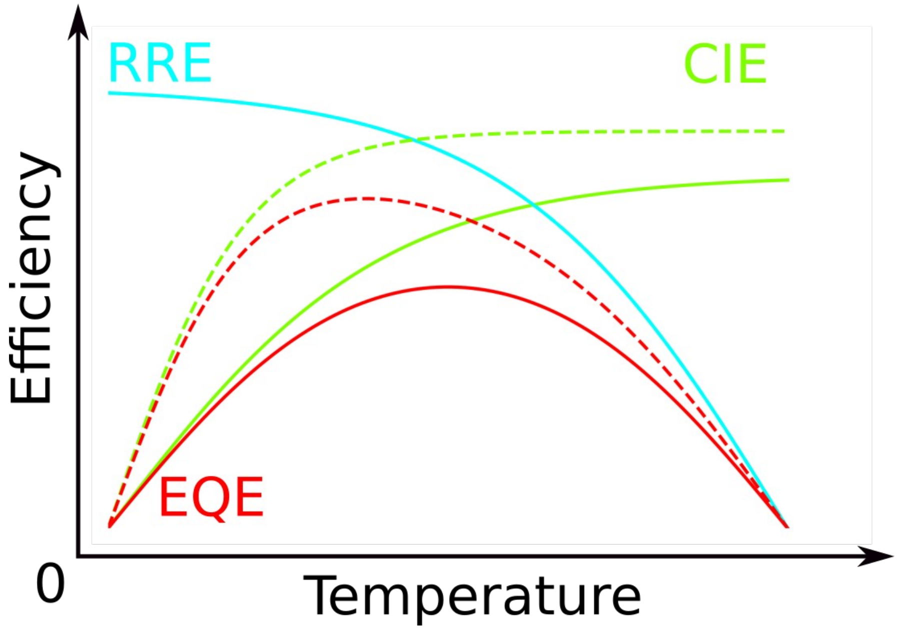
Externe Quanteneffizienz (EQE)





Elektrolumineszenzspektroskopie bei Raumtemperatur

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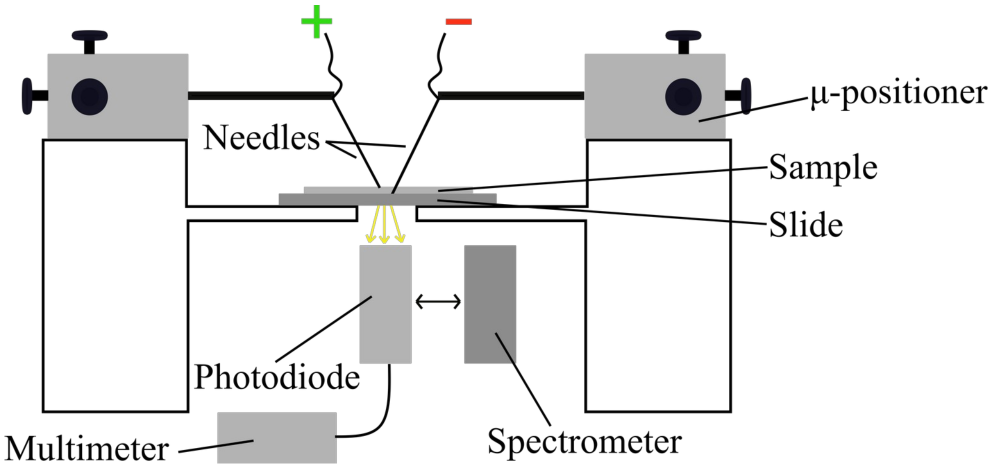

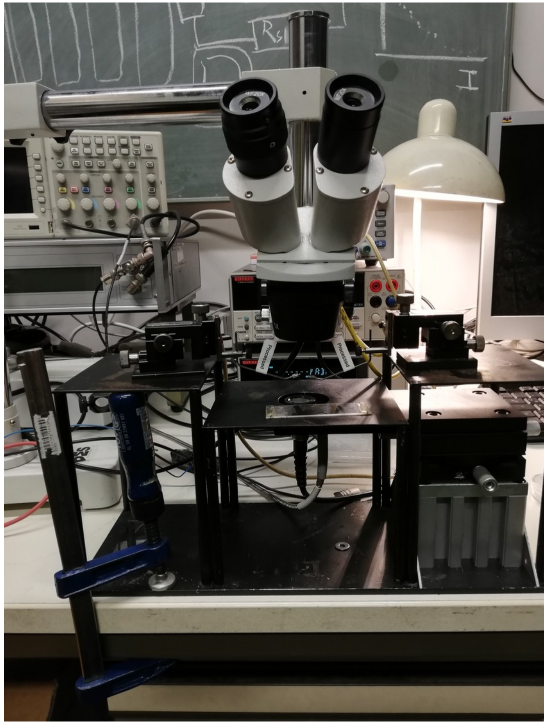

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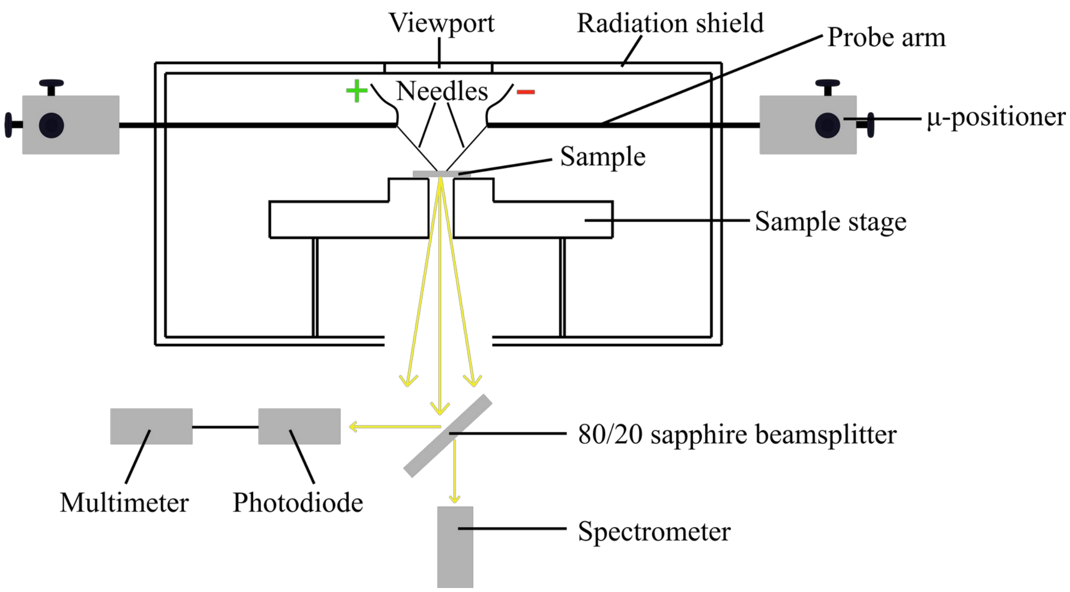
Temperaturabhängige Elektrolumineszenzspektroskopie



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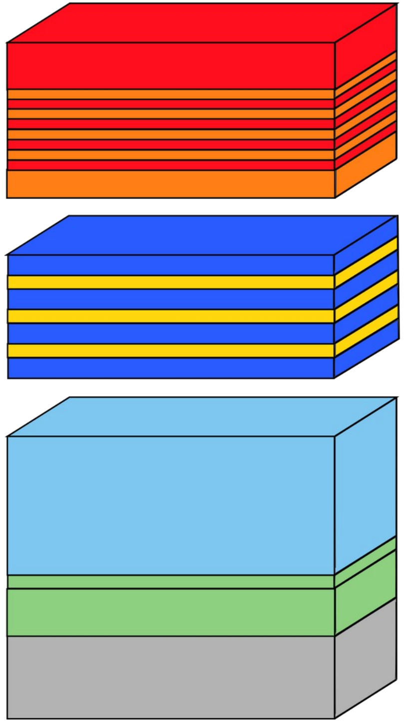
UVC LED Heterostruktur

- Sechs verschiedene Wachstumstemperaturen der aktiven Zone:
  900 °C, 935 °C, 970 °C, 1020 °C,
  1060 °C, 1100 °C

- Quadratischer p-Kontakt der Größe 0.001 cm^2



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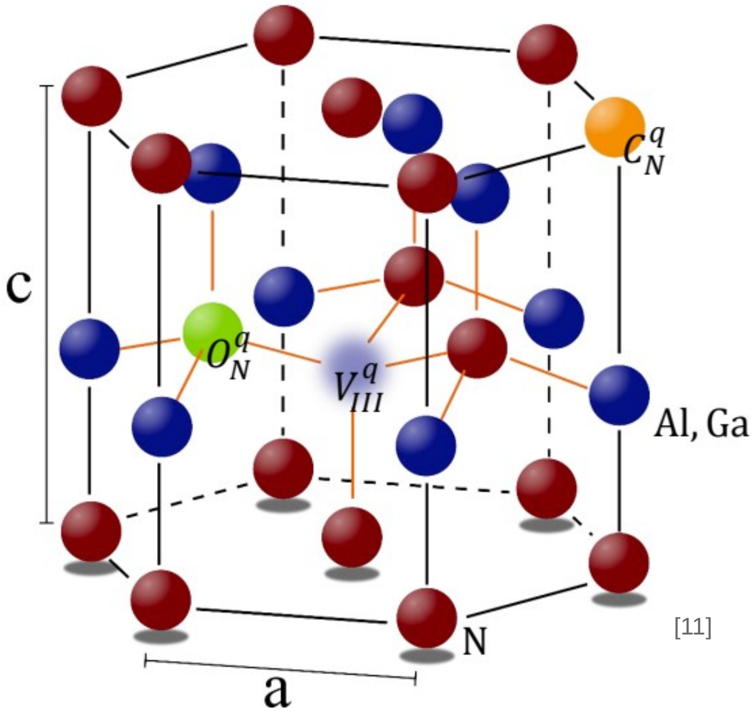
Einbindung von Punktdefekten



[11]

[11] [Image: M. Schilling, TU Berlin]

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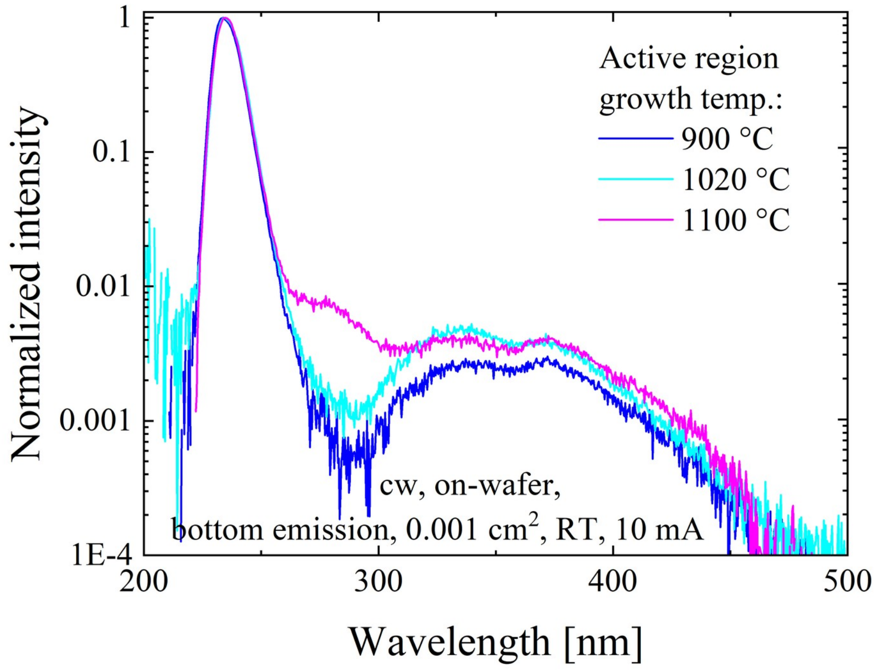
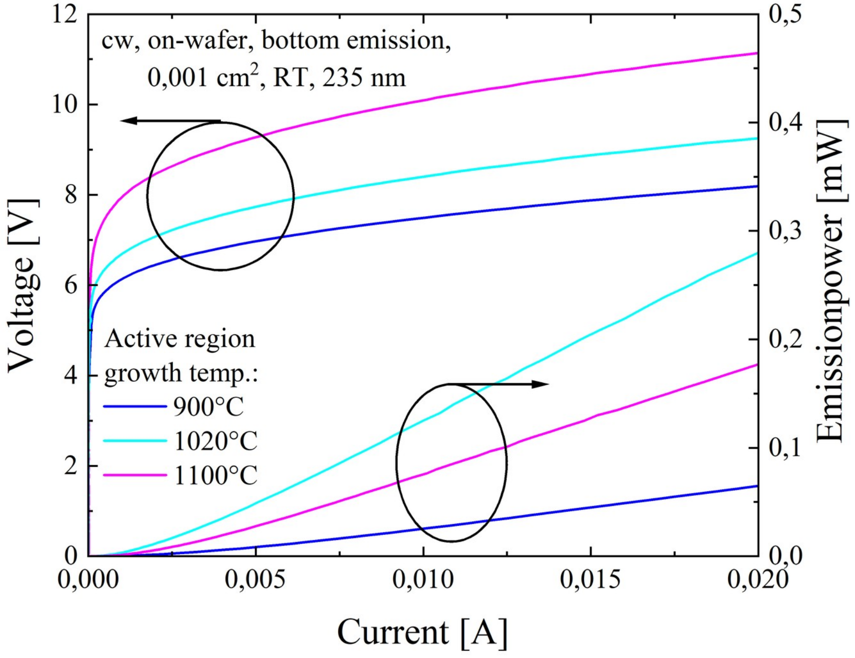
Spektren und LIVs bei Raumtemperatur

- LIV: light output power (Photostrom)- current (Strom)- Voltage (Spannungs) Kurven





Ergebnisse bei Raumtemperatur

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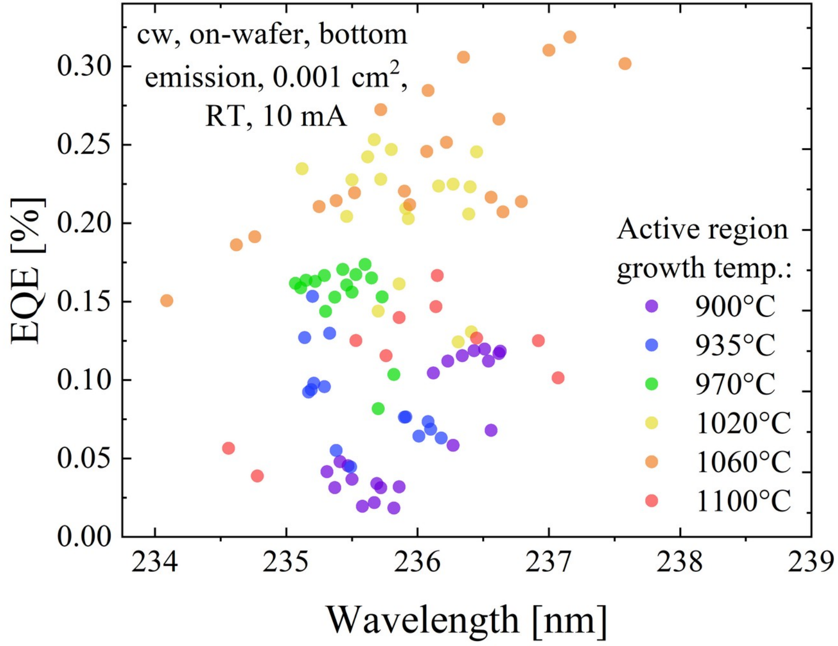
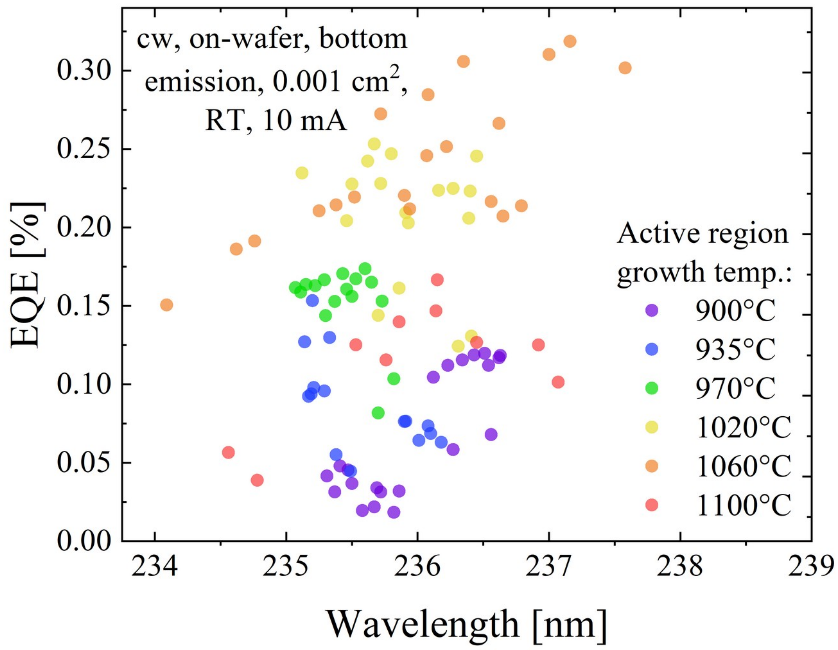
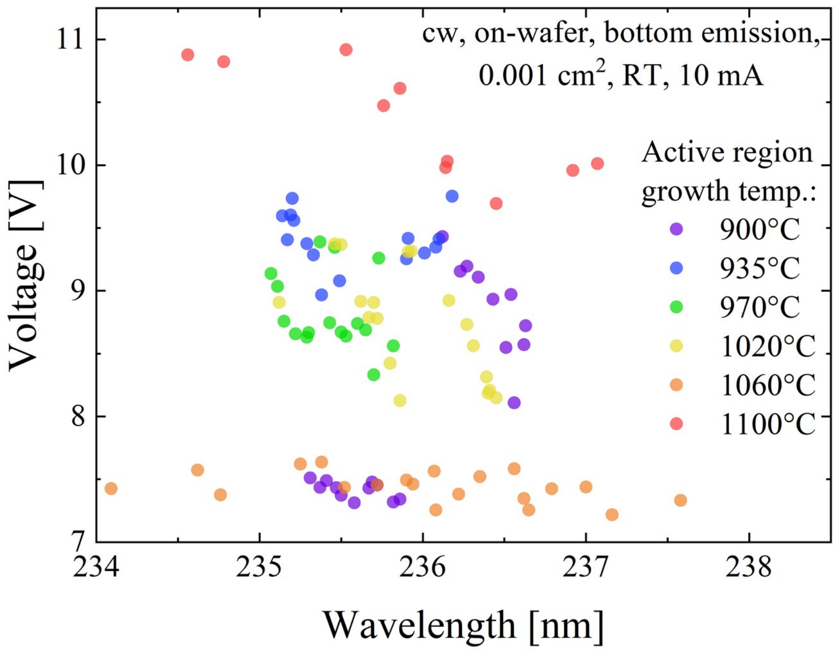


Ergebnisse bei Raumtemperatur





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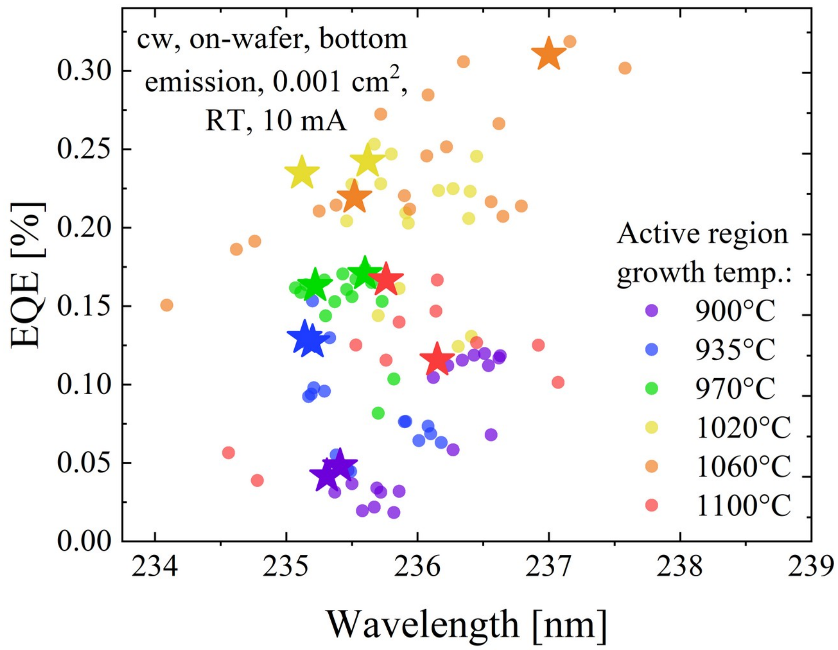
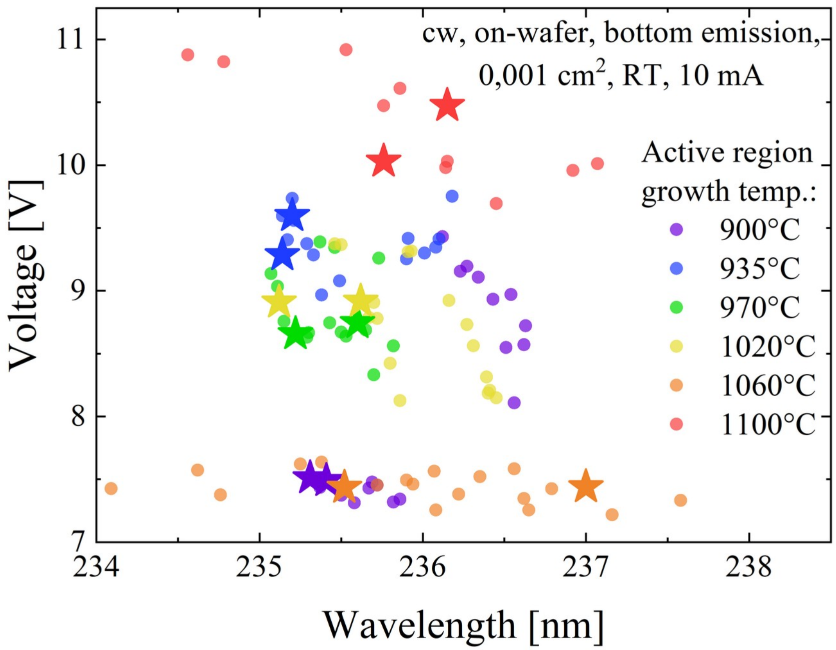
Ergebnisse bei Raumtemperatur





Temperaturabhängige Betriebsspannung bei 10 mA

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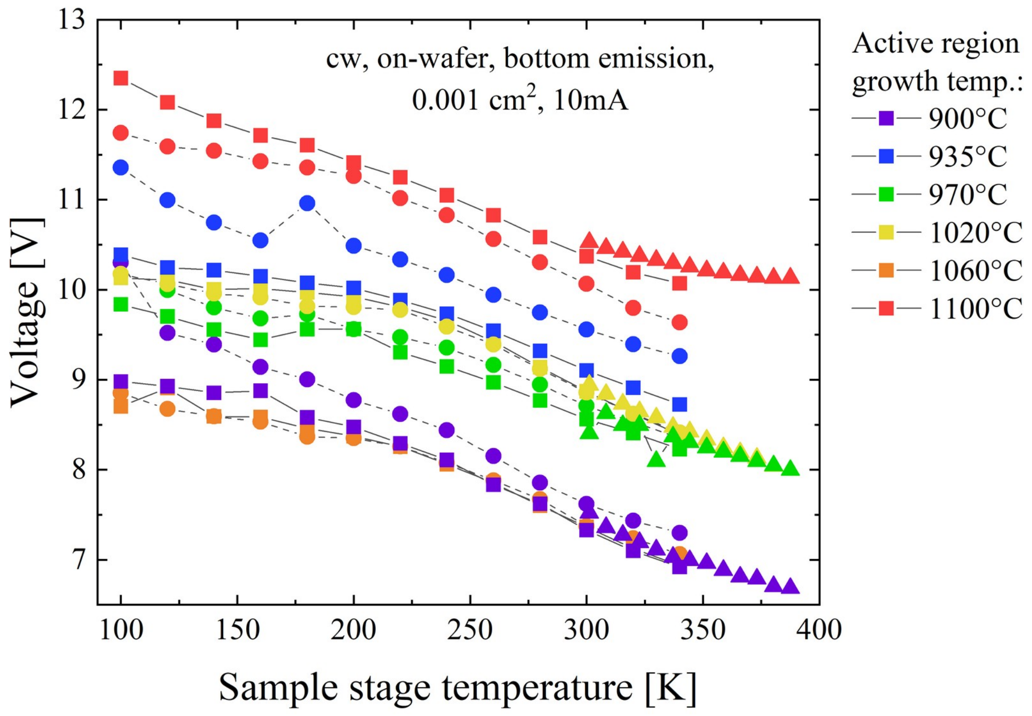

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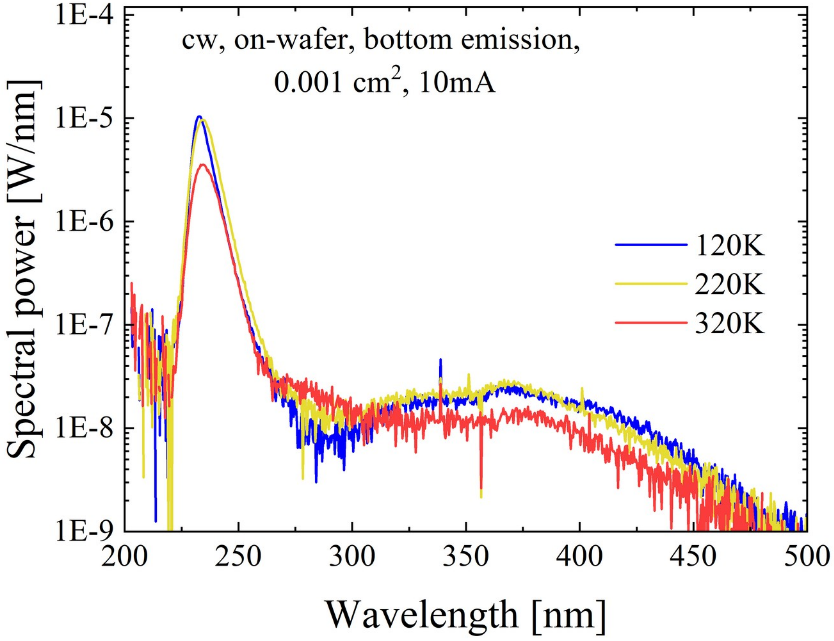
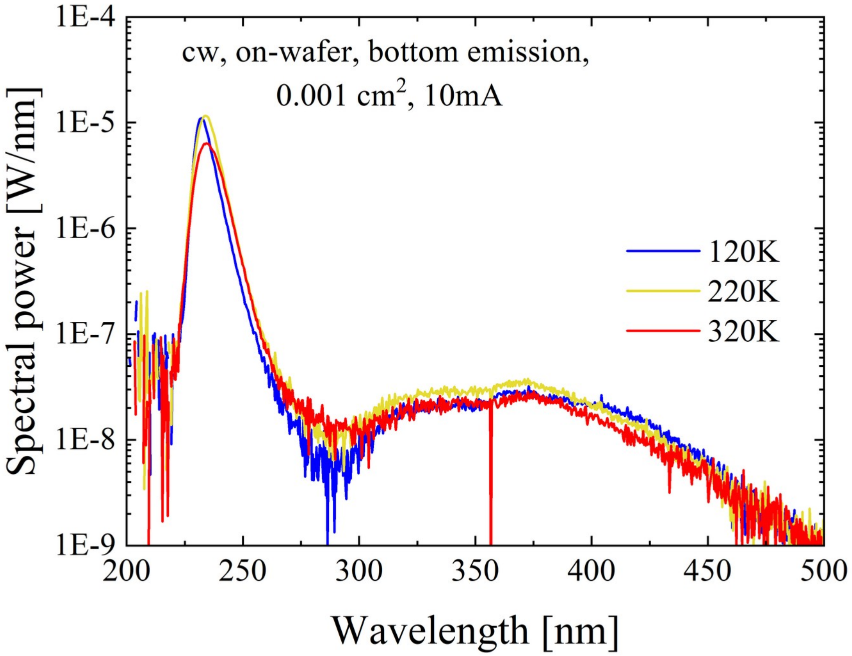
Temperaturabhängige Spektren

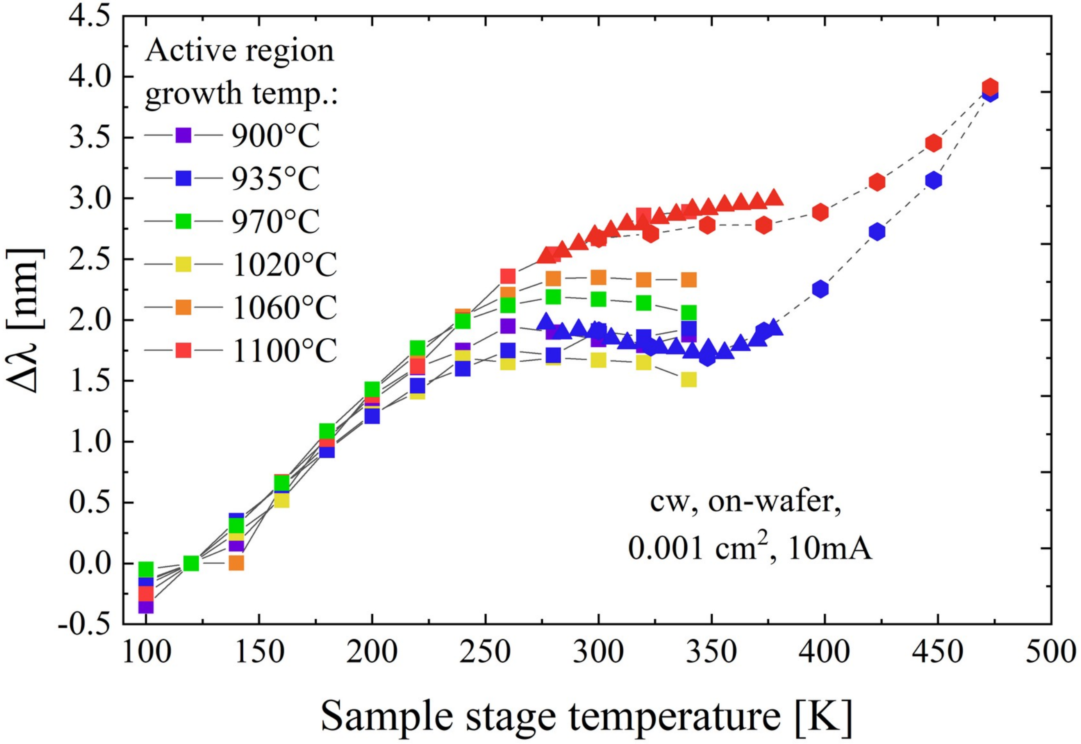
935 °C

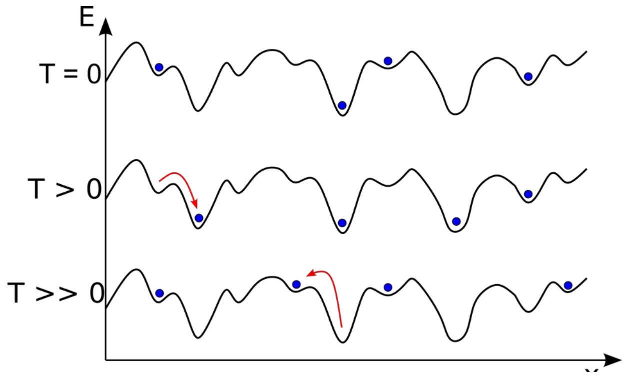


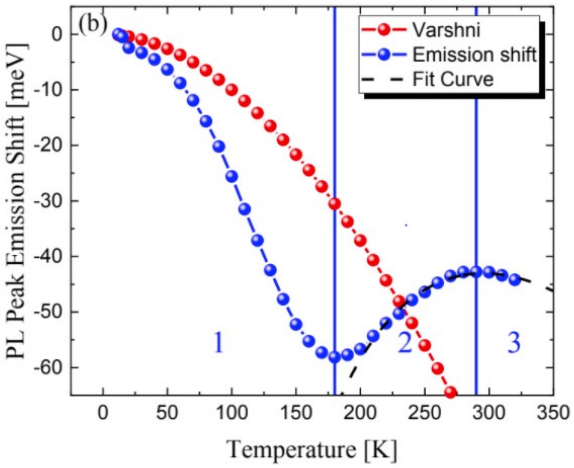
1060 °C



Temperaturabhängige Emissionswellenlänge und Lokalisationseffekte







[12]

[12] [C. Frankerl et. al., J. Phys. D: Appl. Phys. 127, 095701 (2020)]

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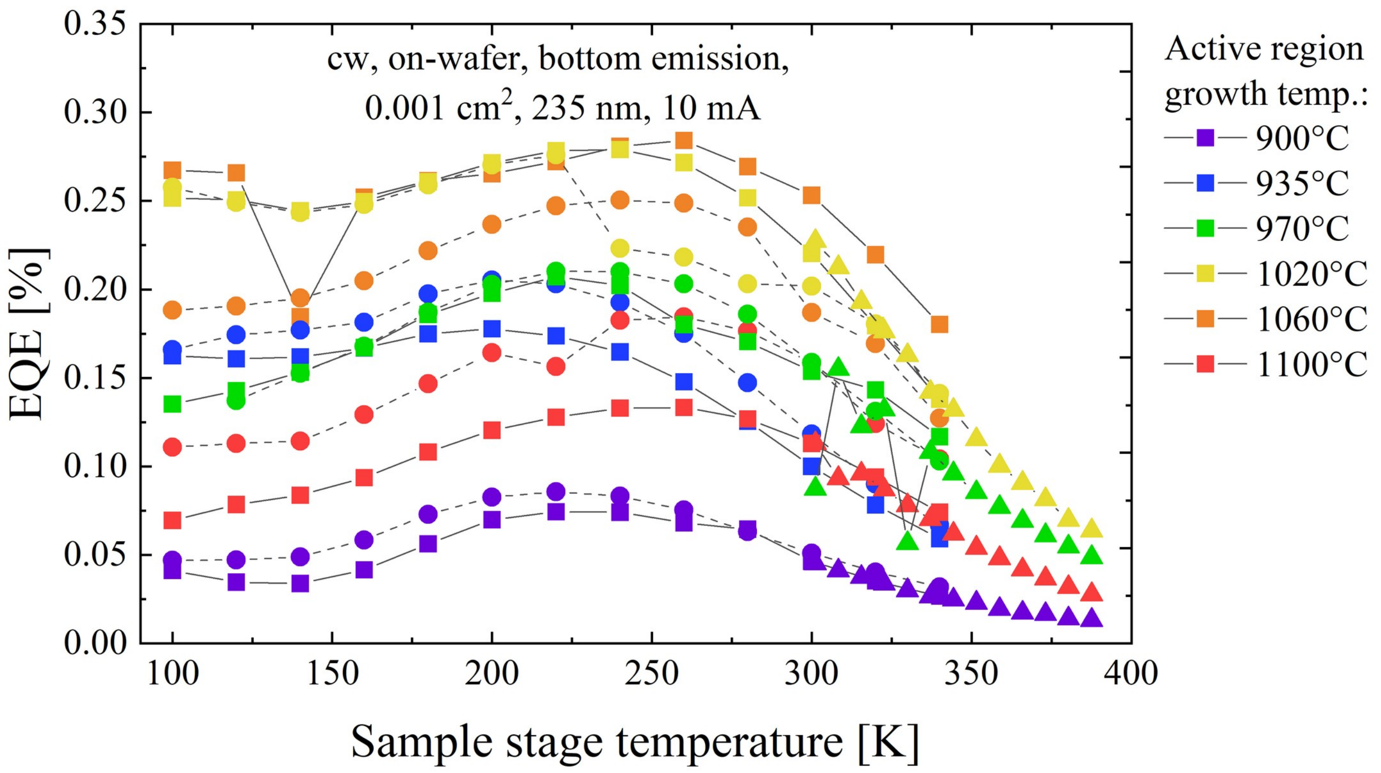
Temperaturabhängige EQE



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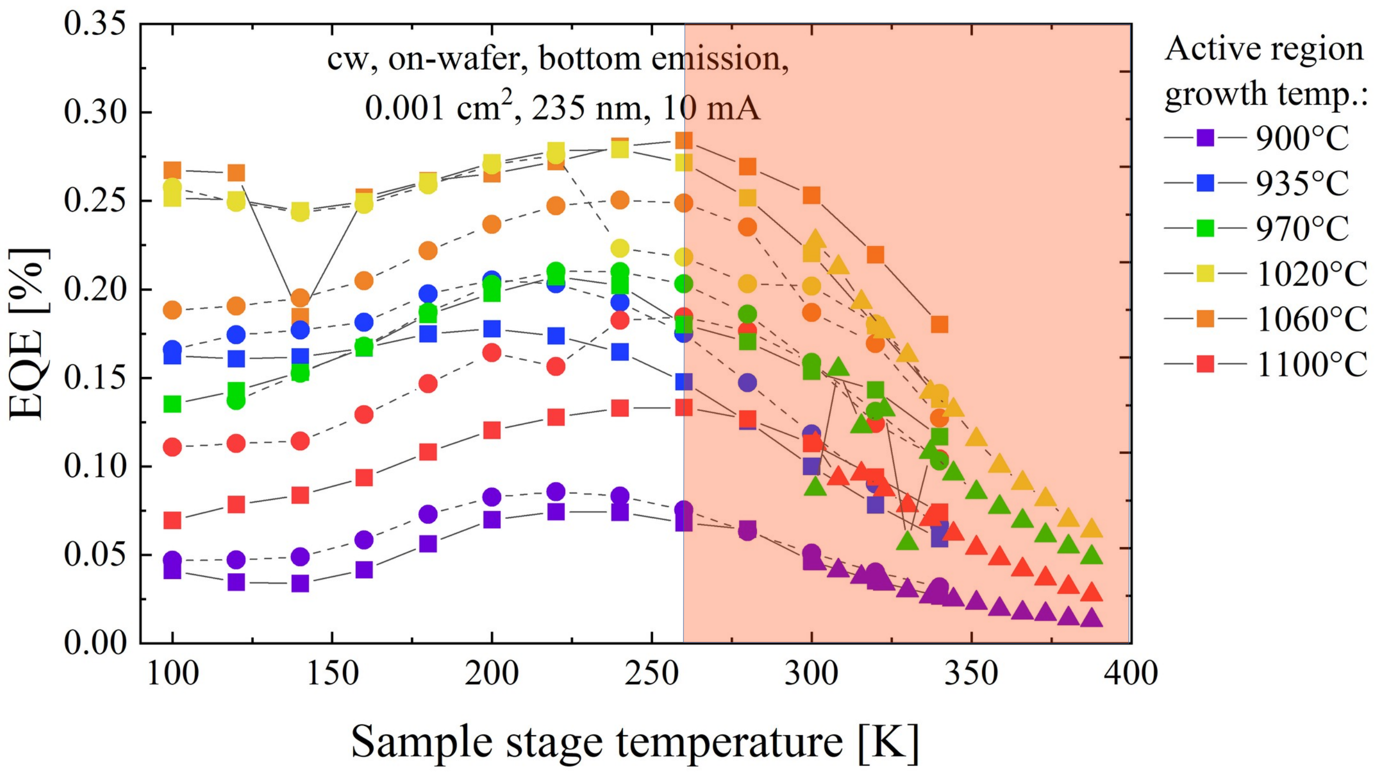
Temperaturabhängige EQE



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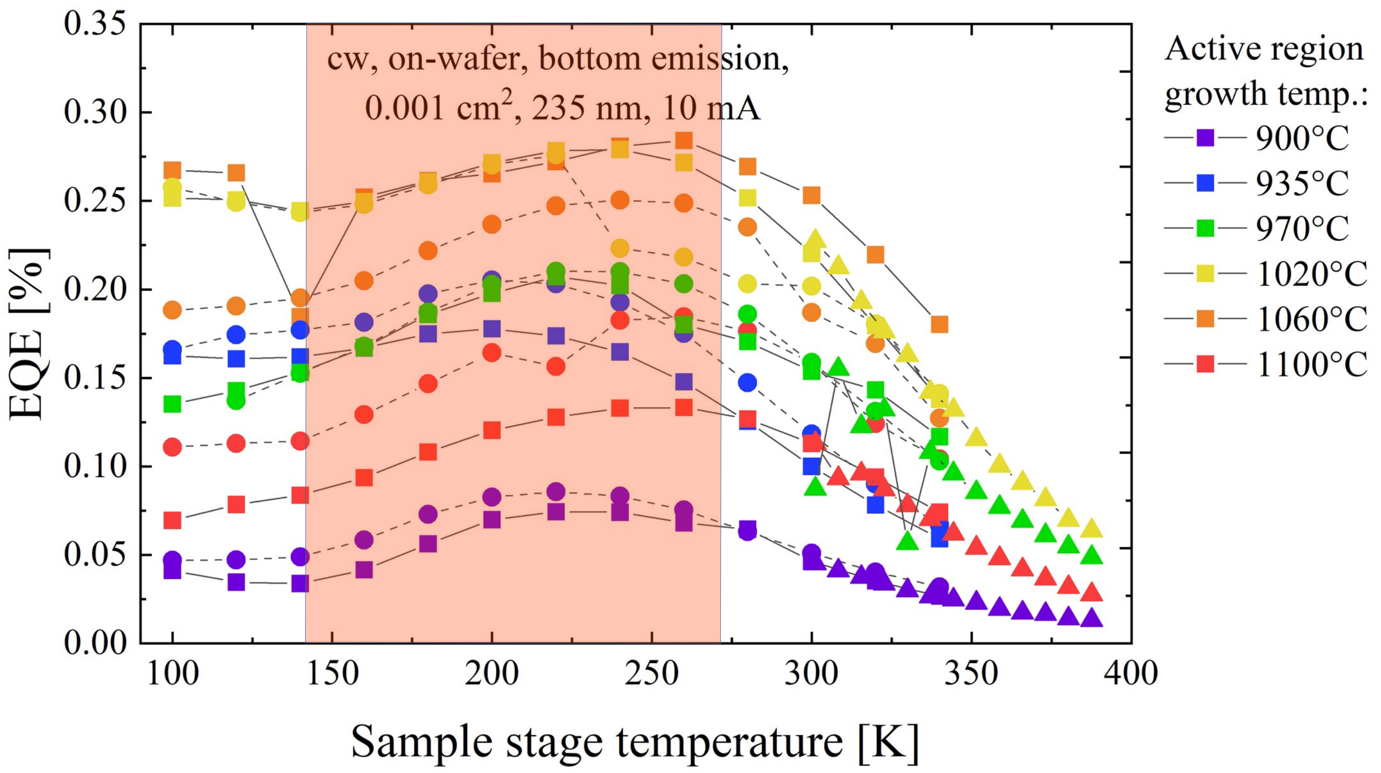

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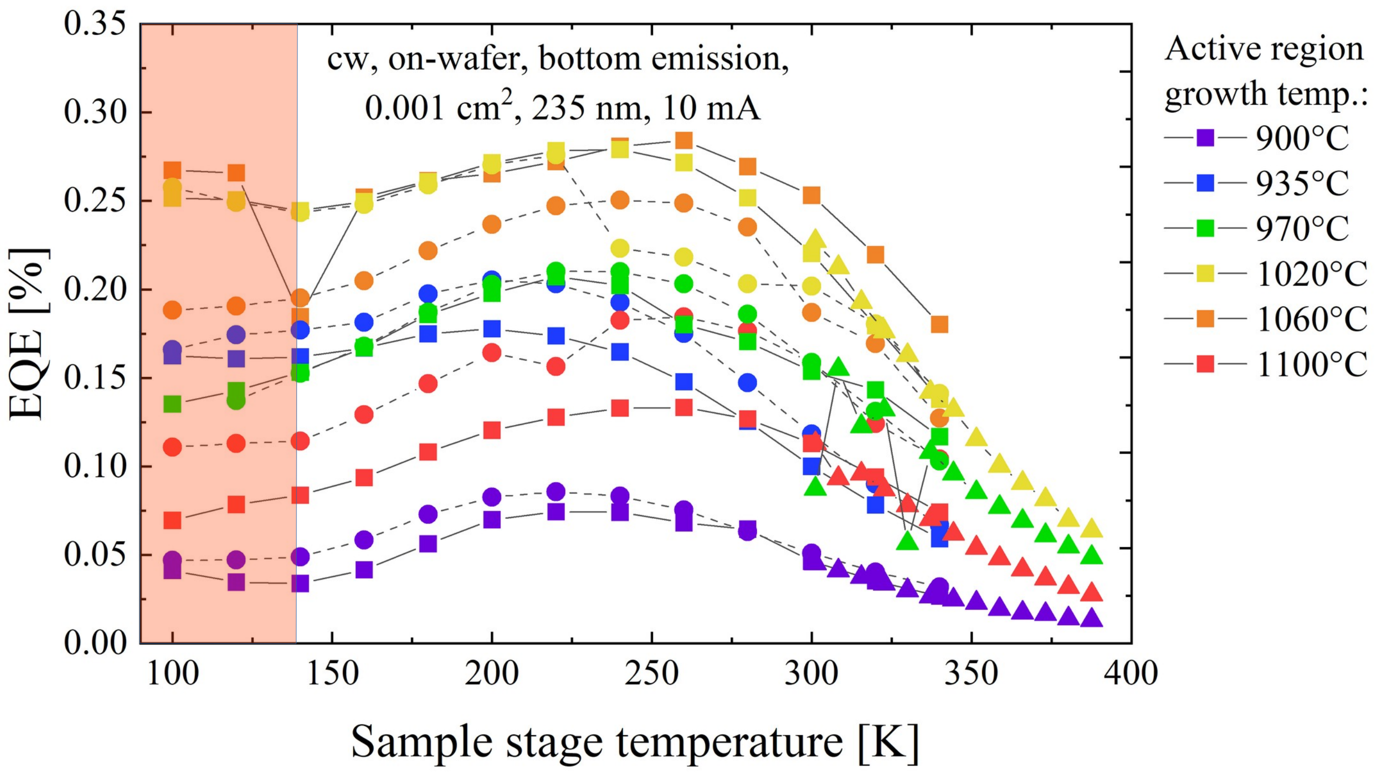
Temperaturabhängige EQE



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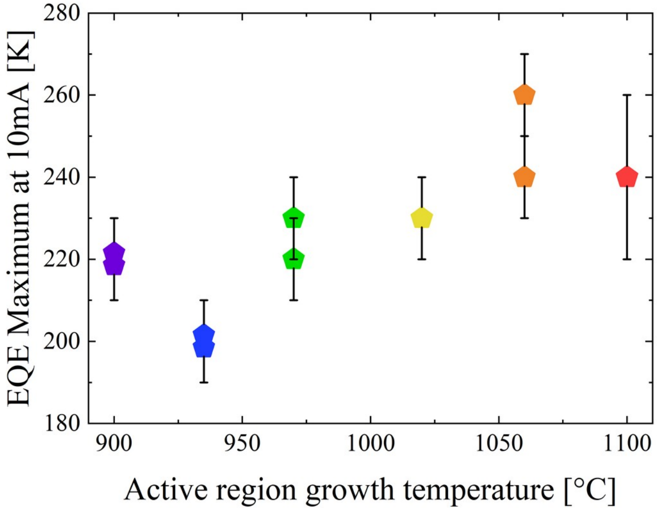
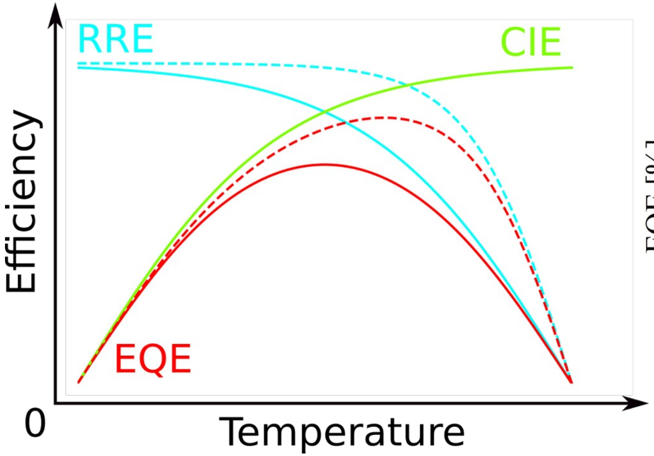
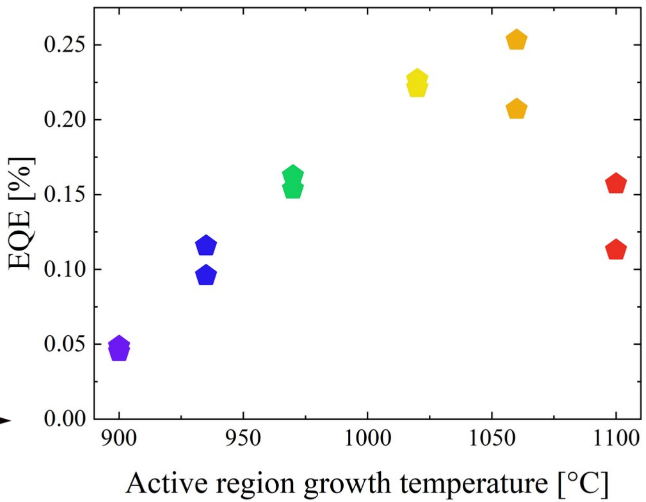
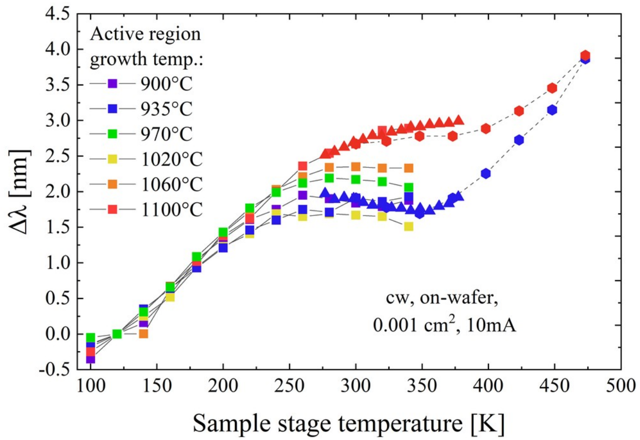
EQE Maximum

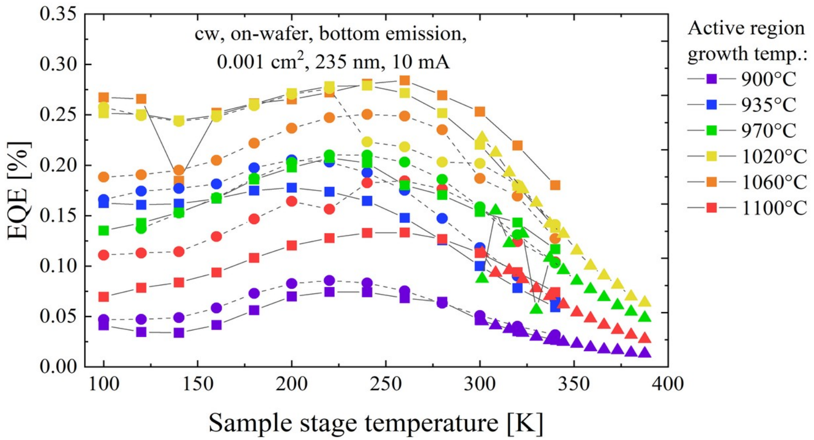


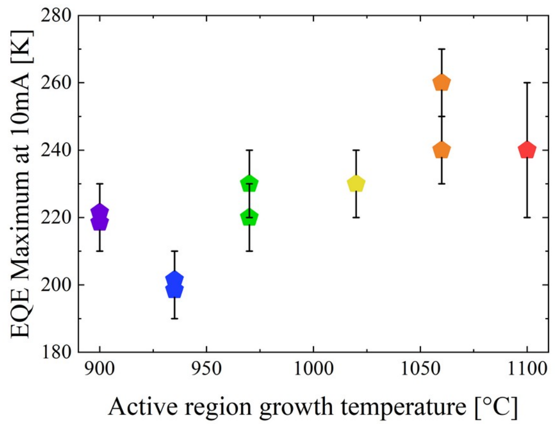




Zusammenfassung und Ausblick







Danke für eure Aufmerksamkeit!

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Backup Slides Markus

Quantum well width

- Non-zero polarization, band bending
- Reduction of electron and wavefunctions overlap (QCSE)
- Overlap defines matrix element

$$|M_T|^2 \equiv |\langle u_c|\hat{e}\cdot p|u_v\rangle|^2 |\langle F_2|F_1\rangle|^2$$

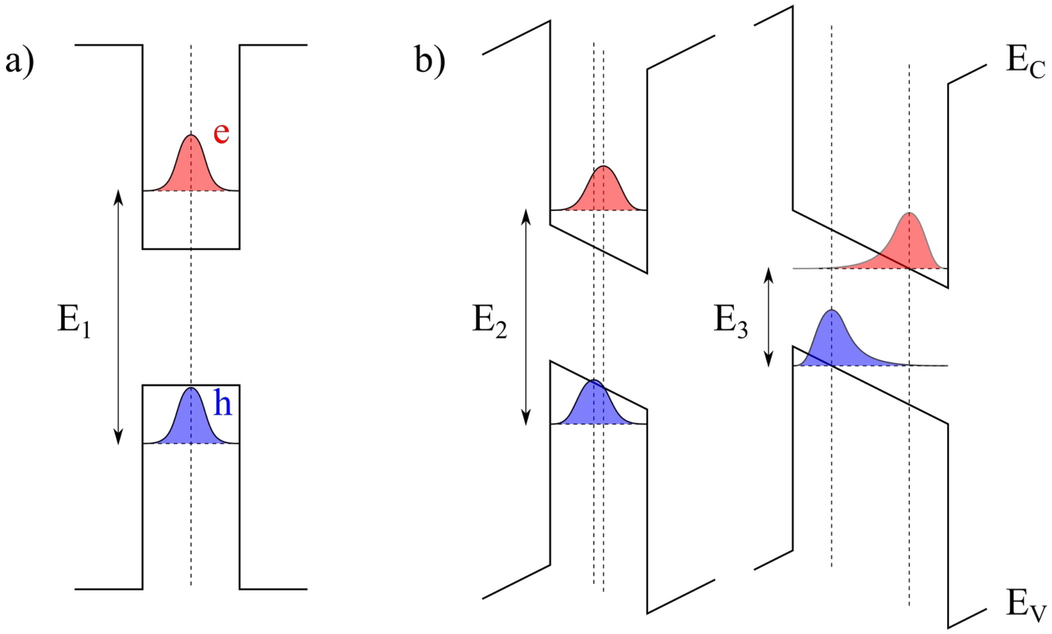
- gain dependent on matrix element

$$g_{21} \propto |M_T|^2 \rho_r(E_{21}) \cdot (f_2 - f_1)$$

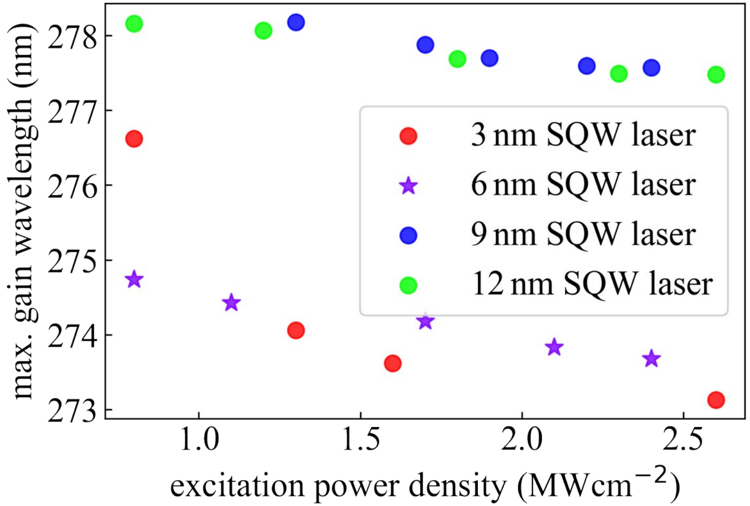
(Fermi's golden rule)

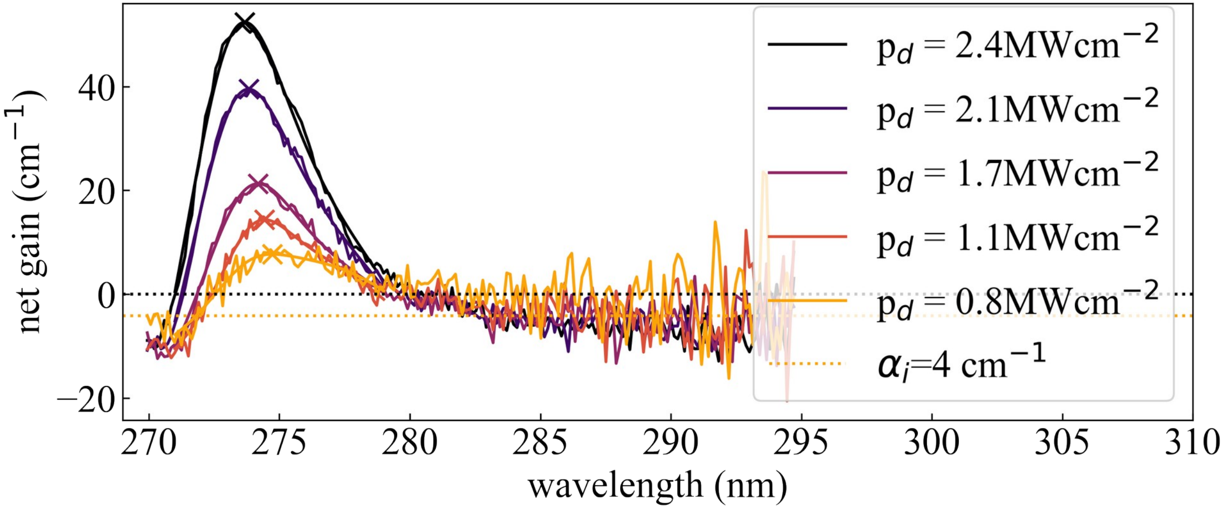
- wider well reduces overlap

➔ lower achievable gain



Maximum gain wavelength





- Blue-shift with increasing excitation power density due to band filling
- Shift more pronounced on lasers with narrower SQWs
- Limited blue-shift rate due to non-resonant pumping → high carrier density in the barriers screening the fields in the in the SQW

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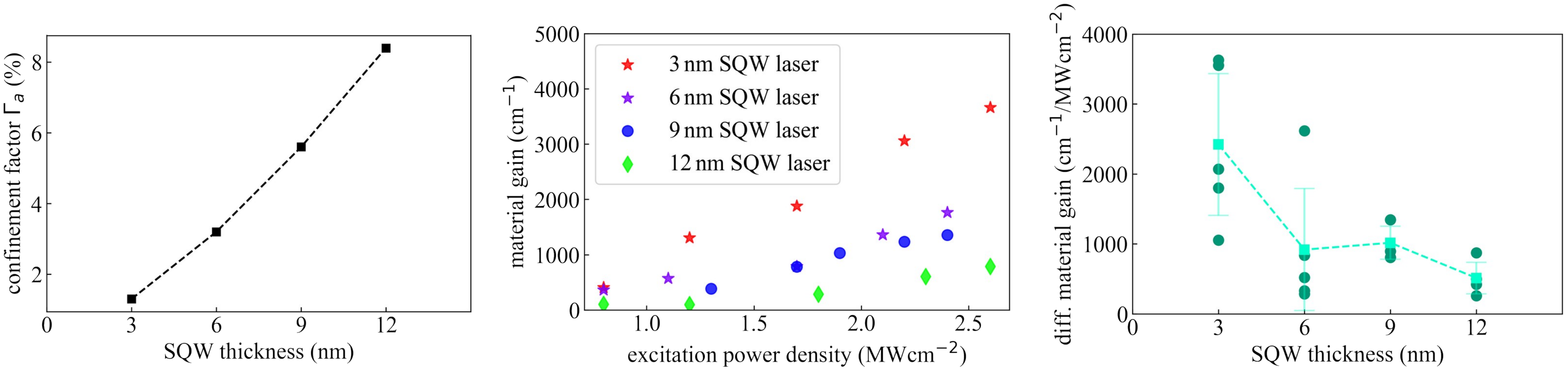
Material gain

- Confinement factor defined by overlap between optical mode and active region
- Material gain: $$g_{mat} = \frac{g_{mod}}{\Gamma_a} = \frac{g_{net} + \alpha_i}{\Gamma_a}$$
- material gain and differential material gain mirror confinement factor



SiLENSe simulation by G.Cardinali

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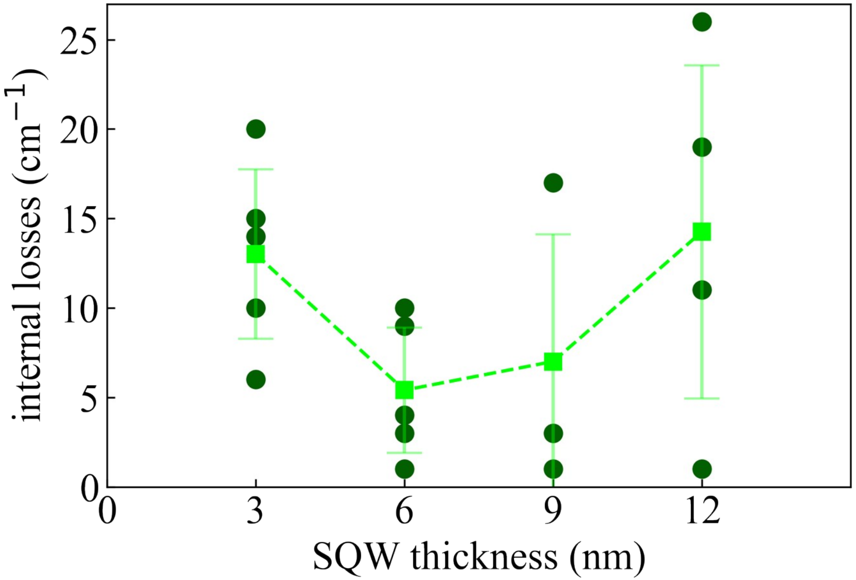
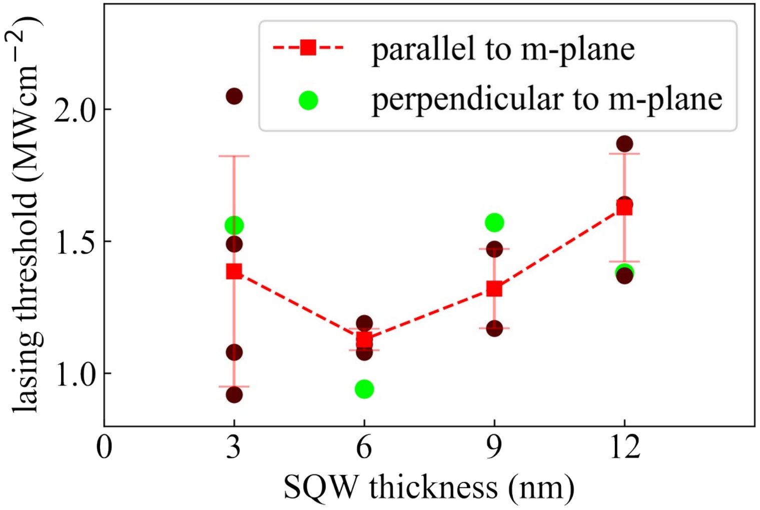
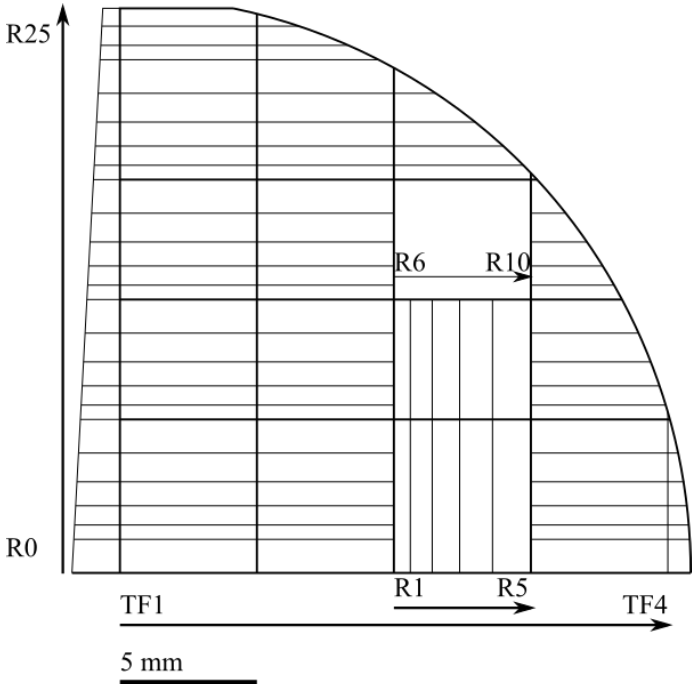
Internal losses



- Internal losses comparable on different lasers
- Trend follows the threshold power density
- Scattering in losses attributed to lateral variation of epitaxial structure

Influence of facet orientation

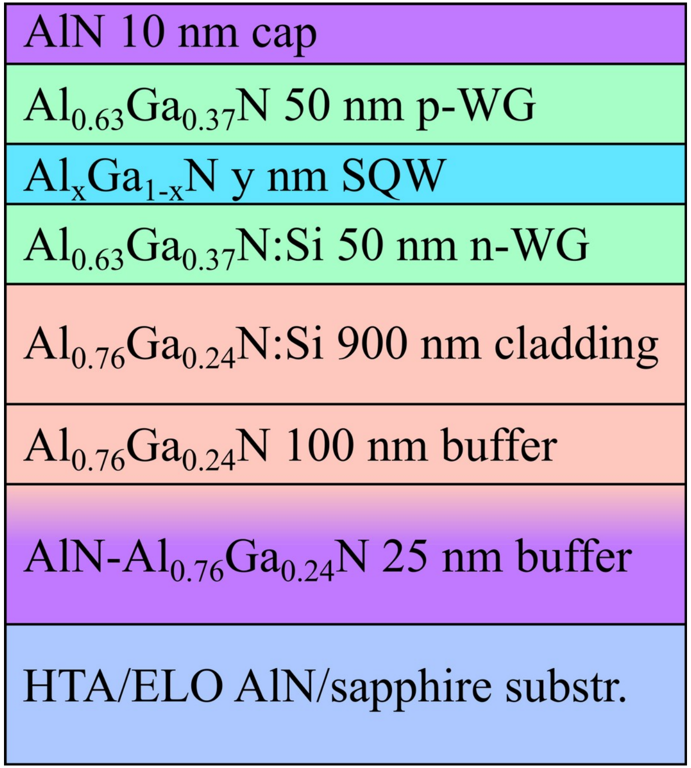




- Laser bars with different orientations
- Dependent on m-plane, a-plane and ELO stripes
- no apparent change in threshold

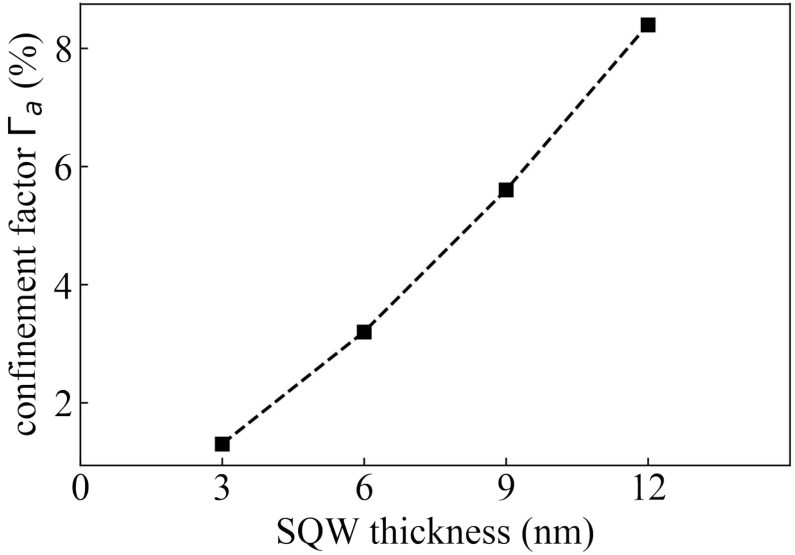
Edge-Emitting Lasers (EELs)

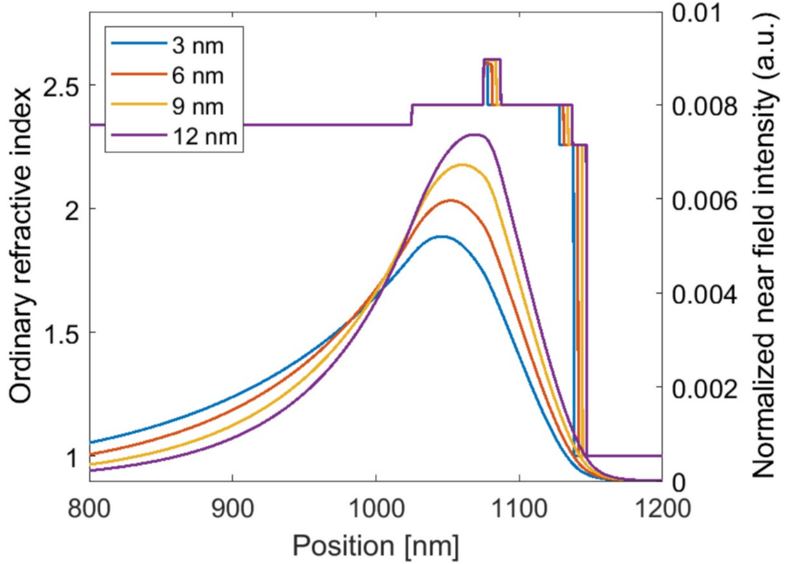
- Laser cleaved facets acting as semi-transparent resonator mirrors
- Constructive interference on light (cavity modes)
- Emission wavelength defined by the mode, for which gain is higher than losses
- Emission through the edge
- Cavity length of EELs can be easily varied
- Elliptical output beam



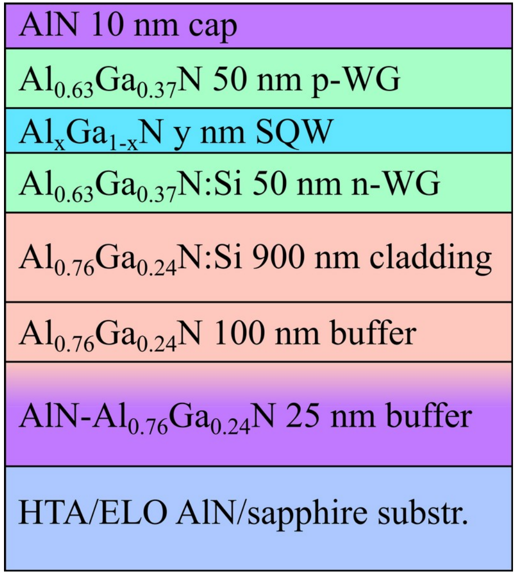
Optical Gain

- Material gain defined by Fermi's golden rule $g_{mat} \propto |M_T|^2 \rho_r(E_{21}) \cdot (f_2 - f_1)$
- Modal gain: $g_{mod} = \Gamma \cdot g_{mat}$ with confinement factor Γ
- Net gain is measured and includes losses: $g_{net} = g_{mod} + \alpha_i$



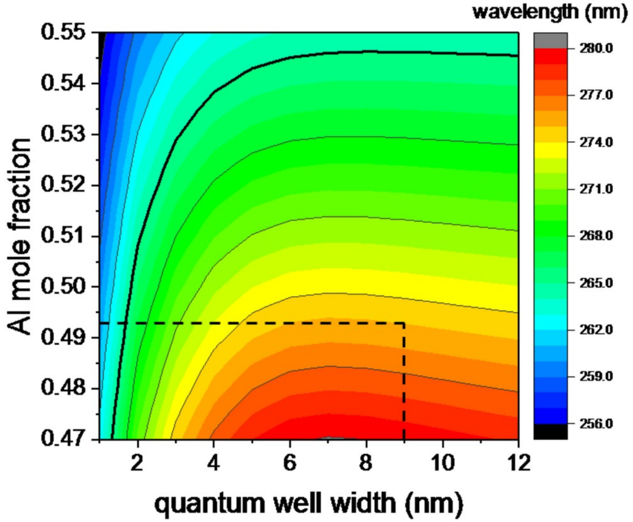


Laser structure

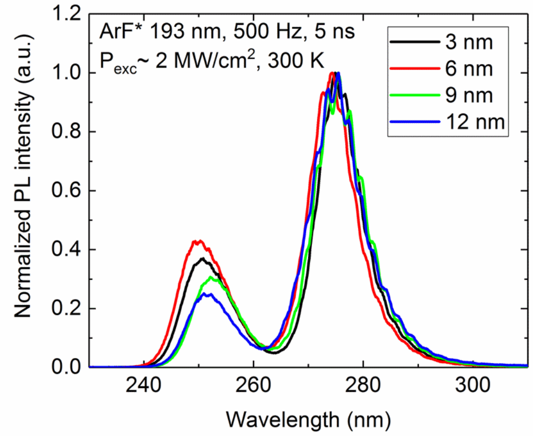


TS number	x	y
5873	0.438	3
5858	0.446	6
5877	0.433	9
5862	0.429	12

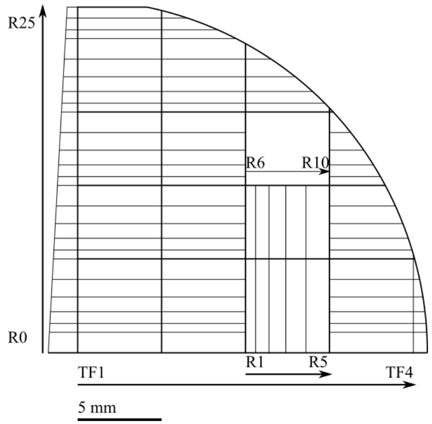
- AlGaN-based optically-pumped lasers with SQW active region (3 nm, 6 nm, 9 nm, 12 nm)
- Al molar fraction in SQW calibrated to emit at 275 nm at 2 MW/cm^2
- Laser scribing into single laser bars



Simulation by M. Guttmann



Measurements by G. Cardinali



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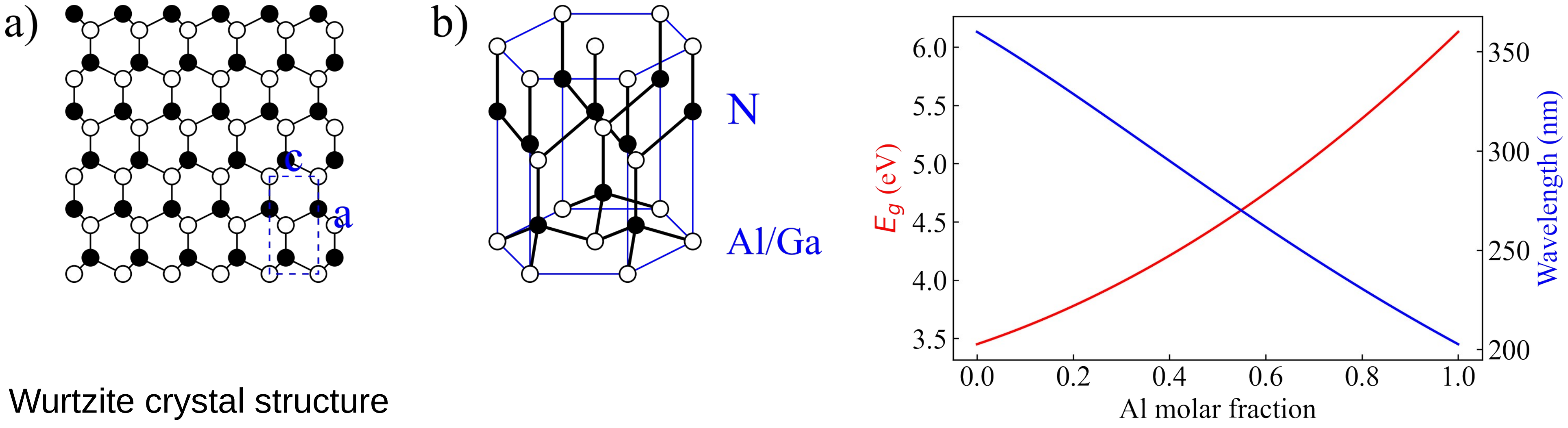
AlGaN material system



- Wurtzite crystal structure
- AlGaN energy bandgap dependent on Al molar fraction, is calculated by Vegard's law

- Non-zero net dipole moment (spontaneous polarization)
- Growth of strained layers with different lattice constants causes piezoelectric polarization

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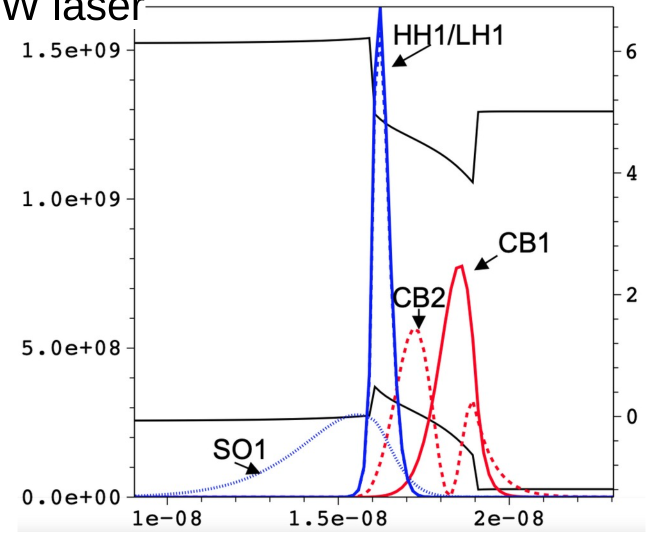
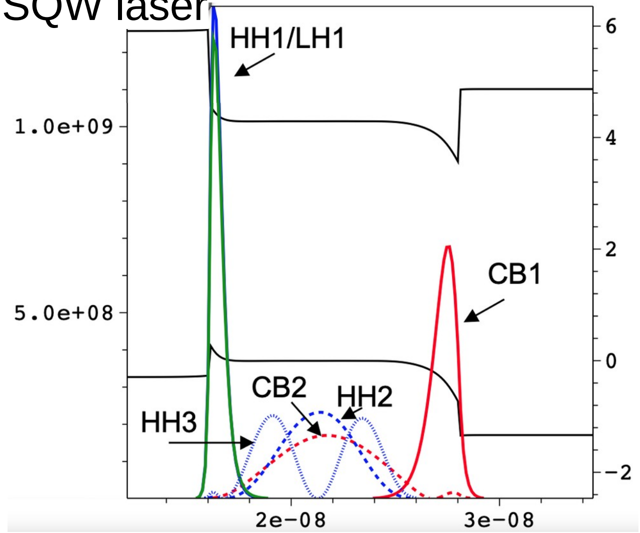
k•p simulations

- Simulations by B. Witzigmann
- Polarization fields screening by fundamental states for thicker QWs

3 nm SQW laser

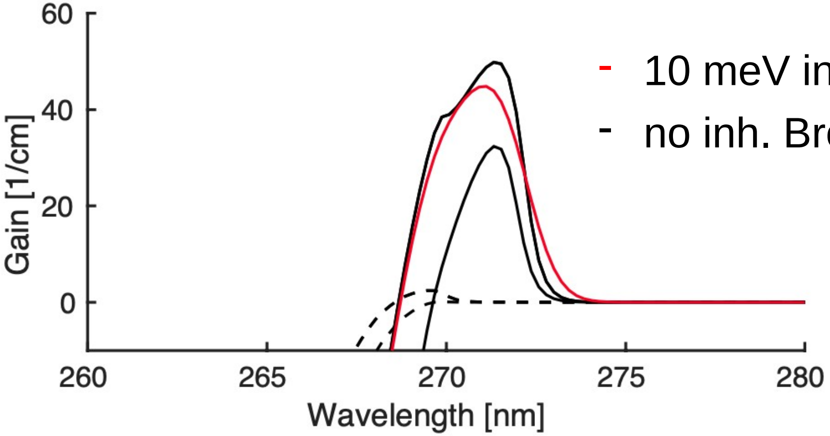


12 nm SQW laser

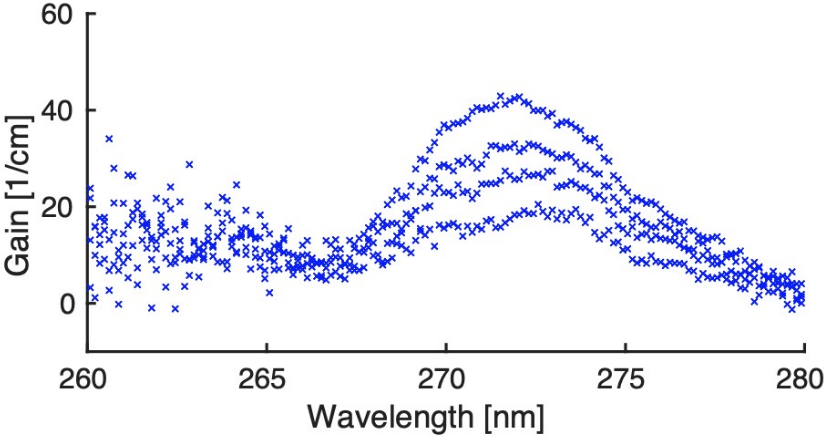


Simulations by B. Witzigmann

Gain Simulation 3nm

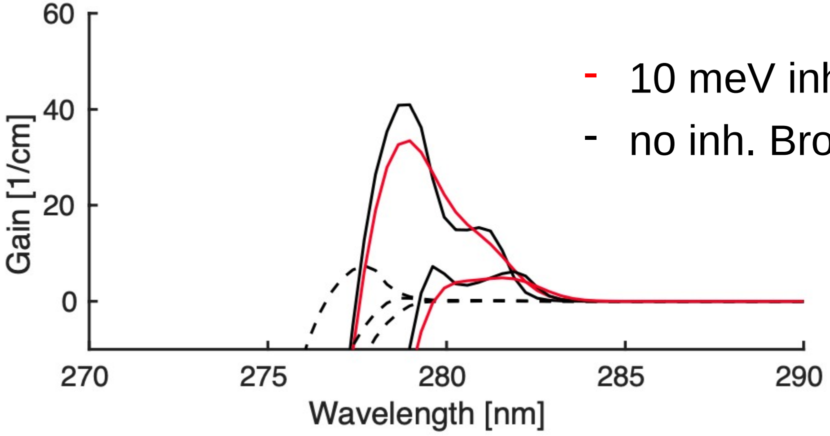


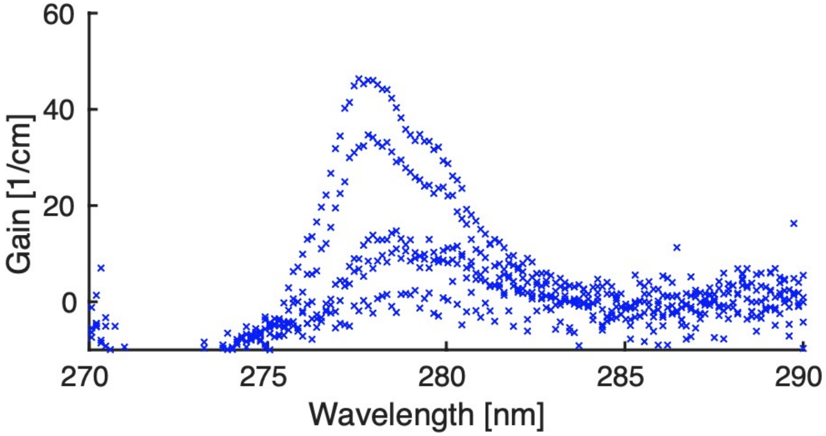
- 10 meV inh. broadening
- no inh. Broadening



- Simulation by B. Witzigmann
- Screened Hartee-Fock approximation (5 meV state broadening)
- Reduced polarization charges
- Main transitions:
  - → <e1|h1> and <e1|h2>

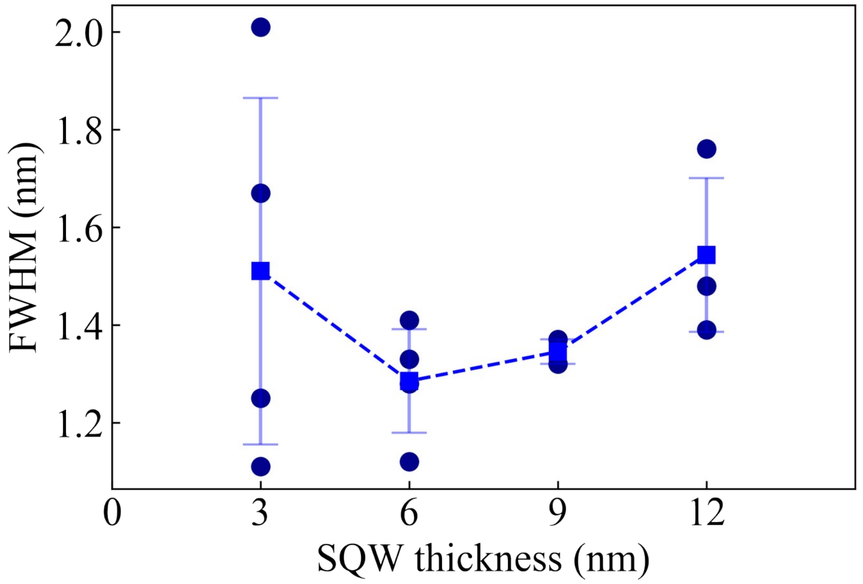
Gain Simulation 12nm





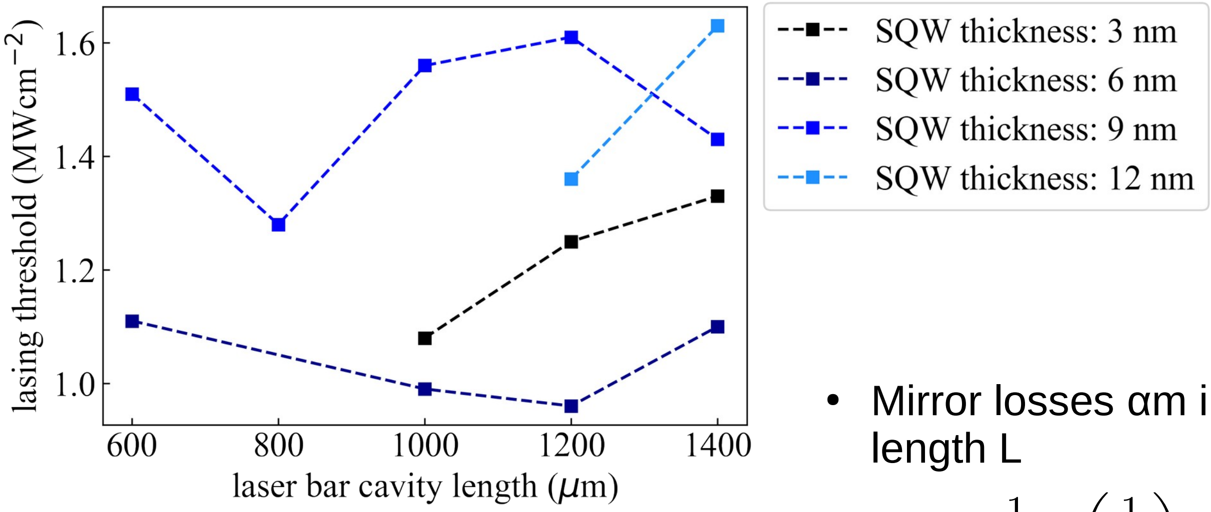
- Simulation by B. Witzigmann
- Screened Hartee-Fock approximation (5 meV state broadening)
- Reduced polarization charges
- Main transitions:
  - → <e1|h2> and <e2|h3>

Full width at half maximum (FWHM)



- Determined by gaussian fit of emission peaks
- FWHM below 2 nm for all samples

Influence of cavity length

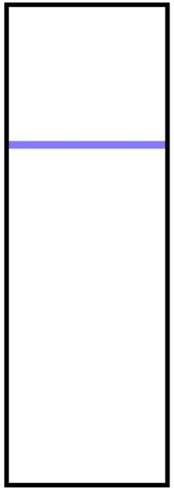


- Mirror losses αm increase with decreasing cavity length L

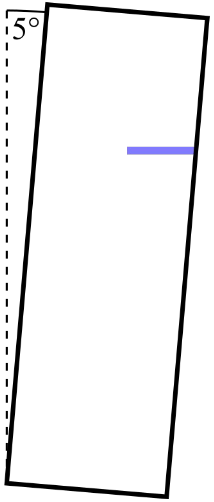
$$\alpha_m = \frac{1}{L}\ln\left(\frac{1}{R}\right)$$

- Higher losses for gain to overcome should increase threshold with decreasing cavity length
- Trend not noticeable

a)



b)



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Measurements

- Power series
- Lasing threshold measurements:
  - Spectra for various excitation power densities
  - Full cavity pumped, stripe perpendicular to edge (a)
- Variable stripe length method:
  - Spectra taken for several stripe lengths (50 µm - 500 µm)
  - Repeated for few excitation power densities
  - Sample at an angle to avoid resonance (b)

Backup Slides Paula

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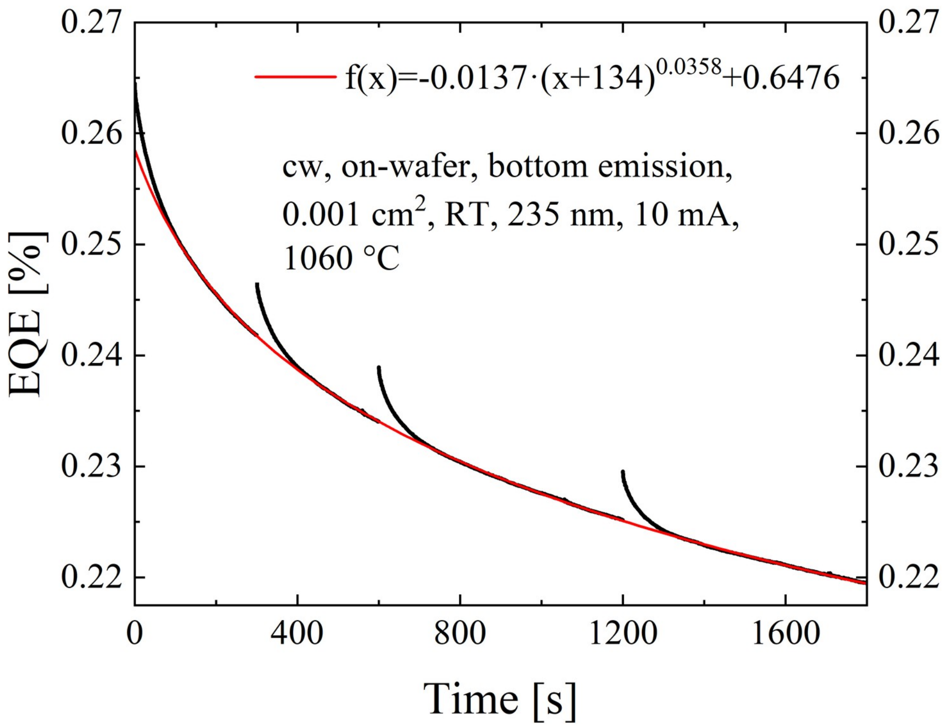
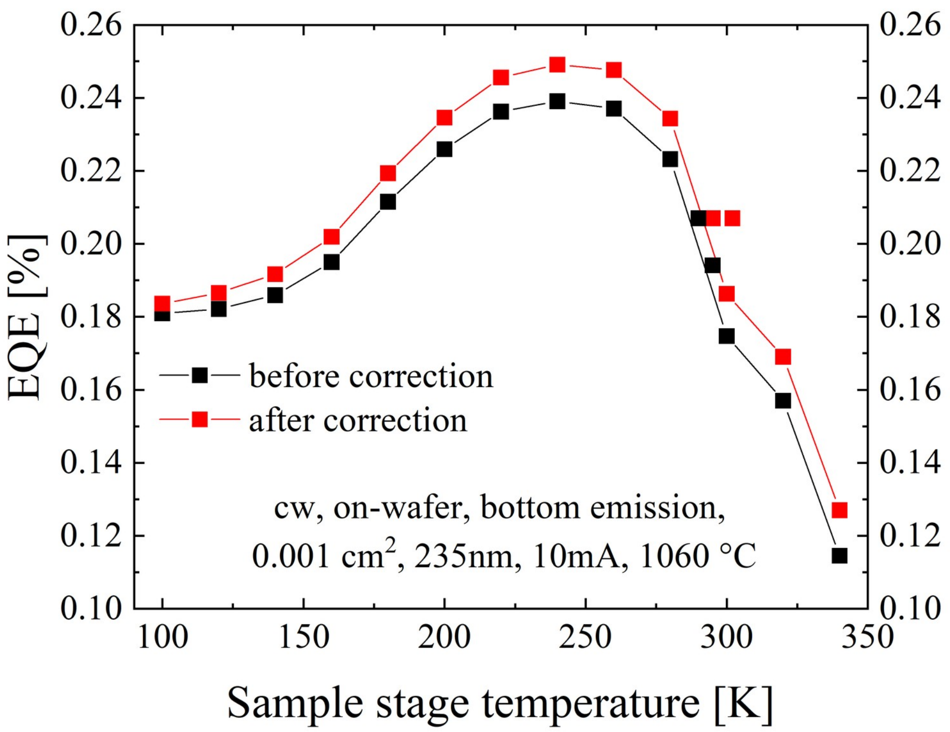
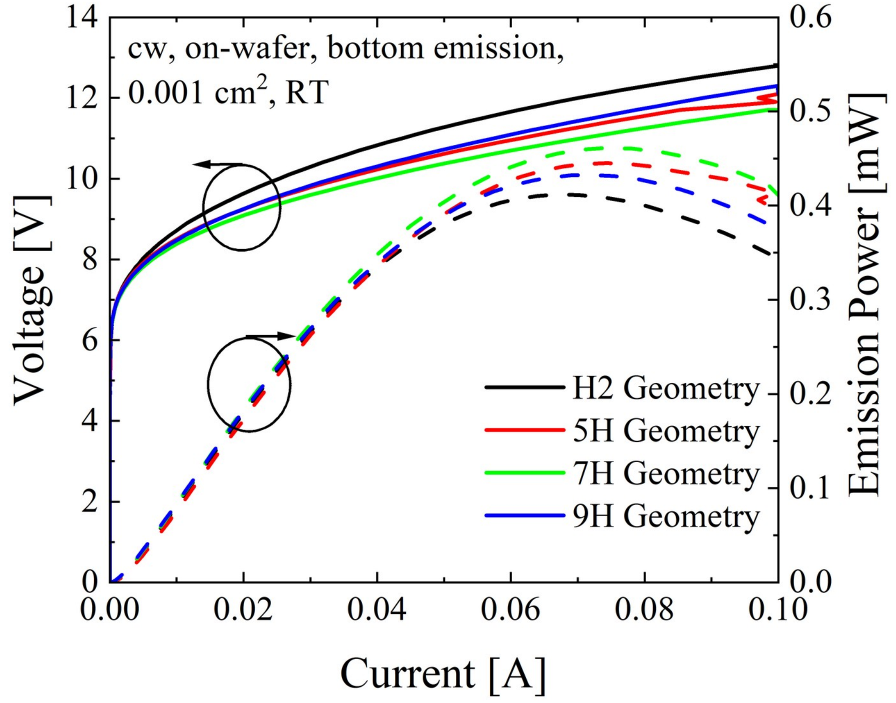
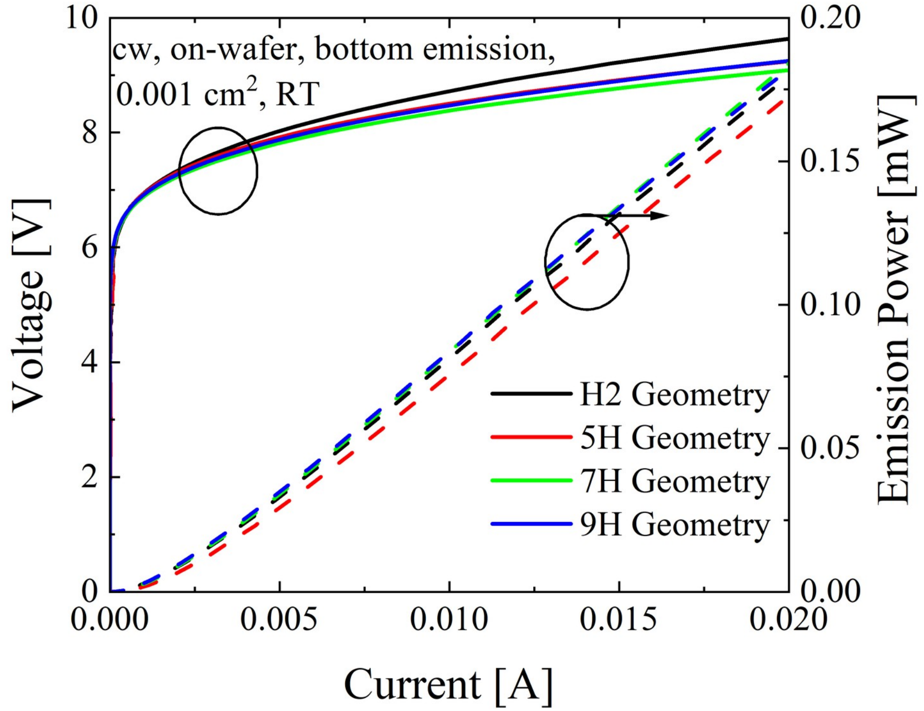
Alterungseffekte





Kontaktgeometrie





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Struktur

Layer	x [%]	d [nm]	Doping	Remarks
GaN:Mg	0	300	2%	Cap
14x ($Al_xGa_{1-x}N$:Mg / $Al_yGa_{1-y}N$:Mg)	80/70	25 (0.9/0.9)	5E-3/4.4E-3	p-SPSL
AlGaN	100	6	-	EBL
AlGaN	83.5	5	-	last barrier
2 x AlGaN(:Si)	83.5	5	2.02E-4	barriers
3 x AlGaN	70	1	-	QW
AlGaN:Si	83.5	40	4.02E-4	first barrier
AlGaN:Si	87	2200	1E-4	n-side buffer
AlGaN	87	100	-	Buffer
AlN-AlGaN transition	100→87	25	-	Buffer transition
AlN	100	400	-	Smooth buffer
HTA ELO-tmpl.			-	

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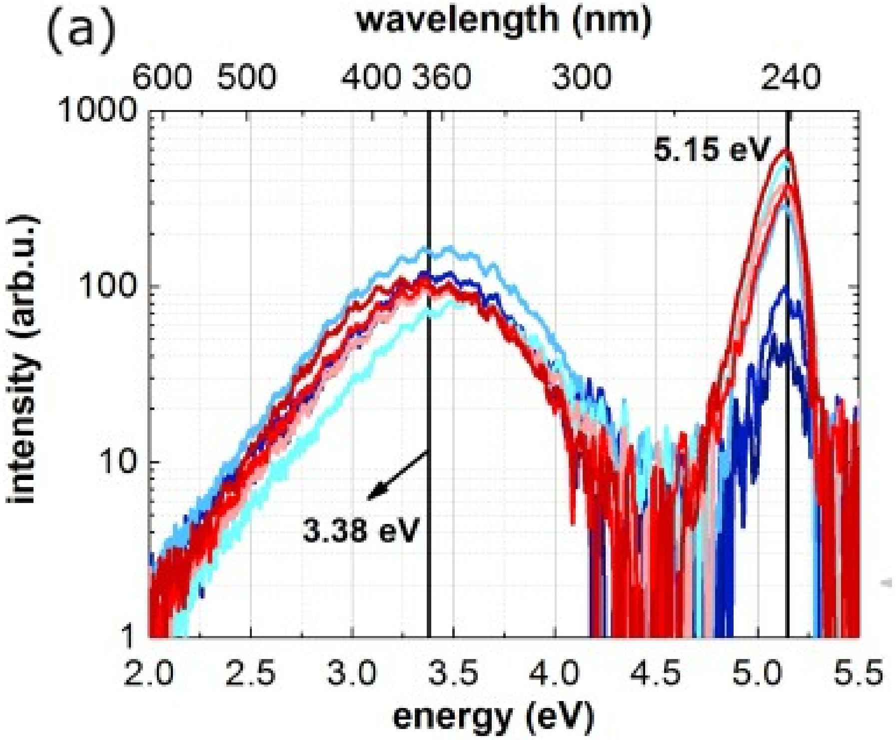
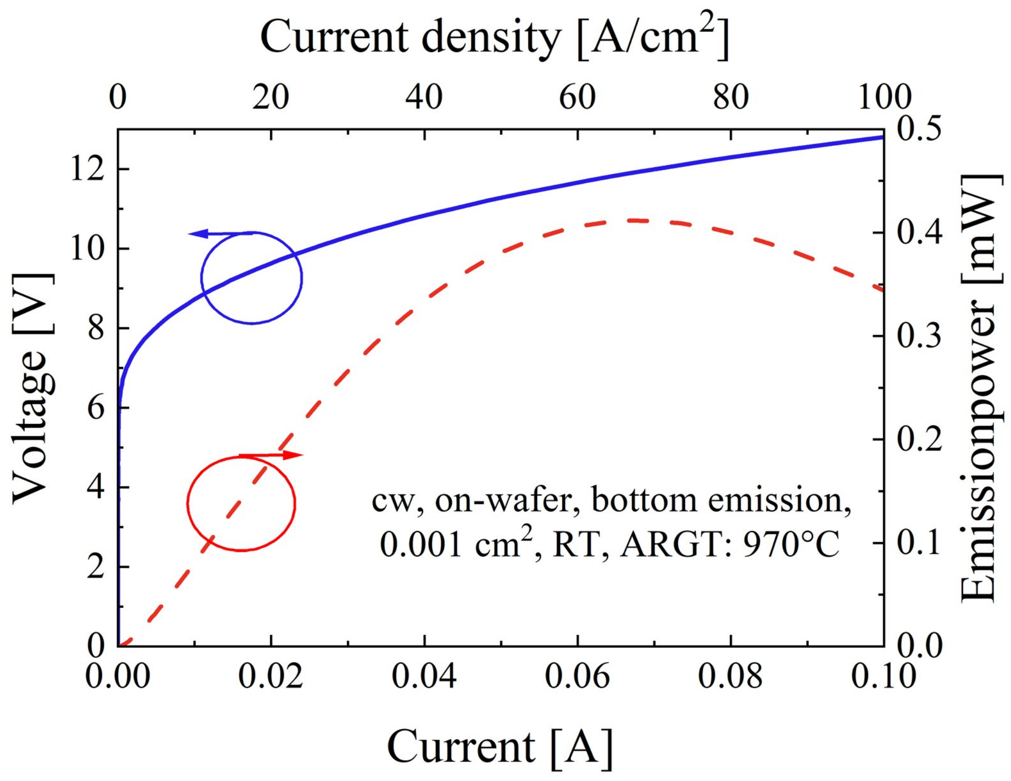
PL Measurements

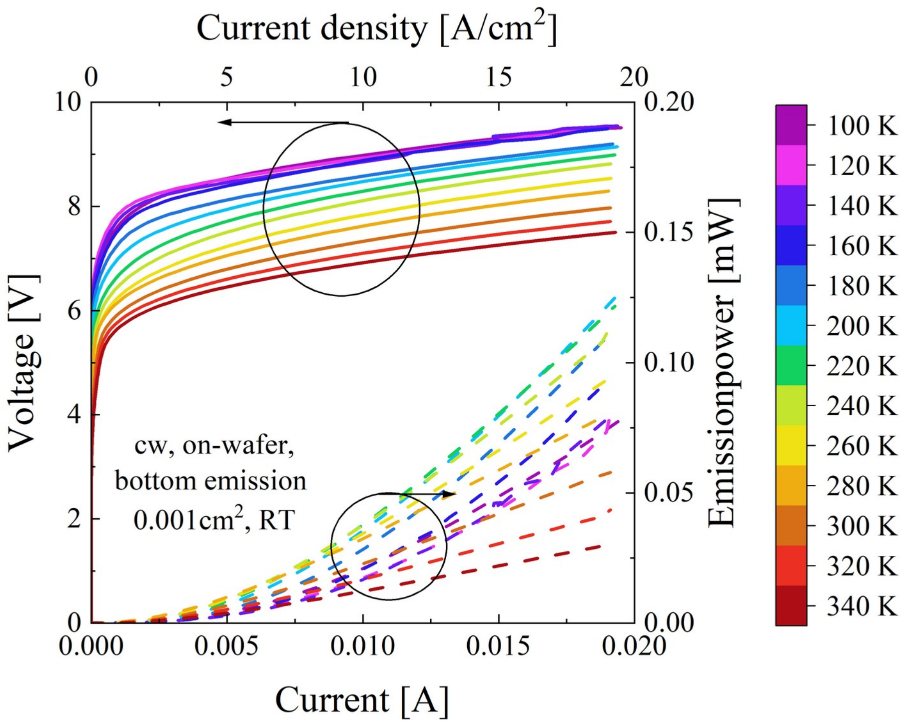


LIV bis 100 mA

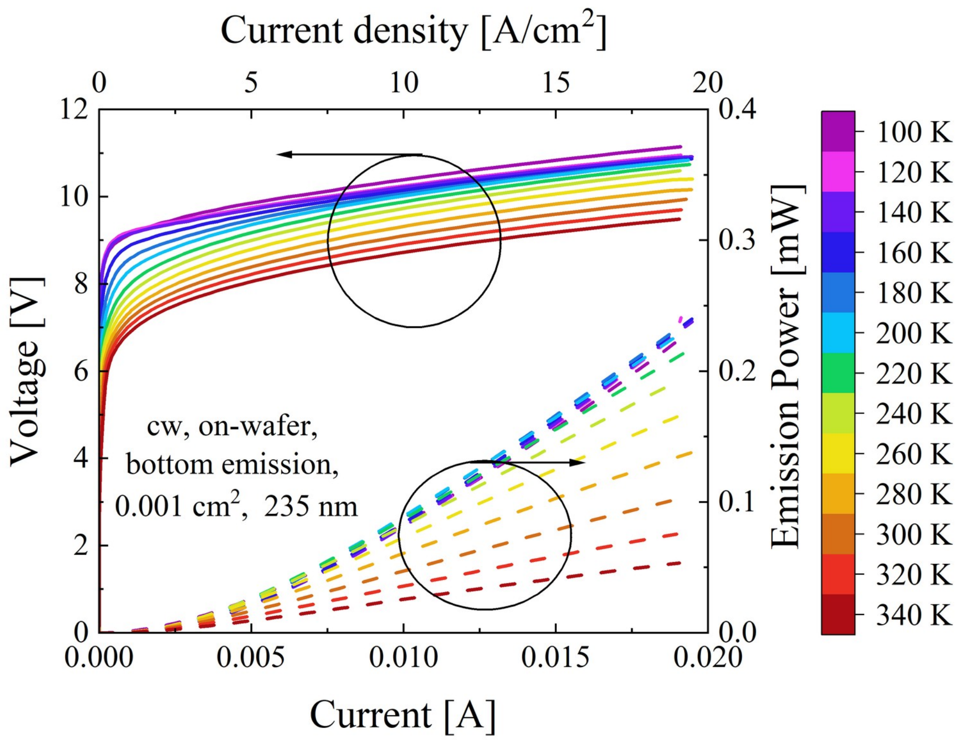


LIV Kurven

900 °C:

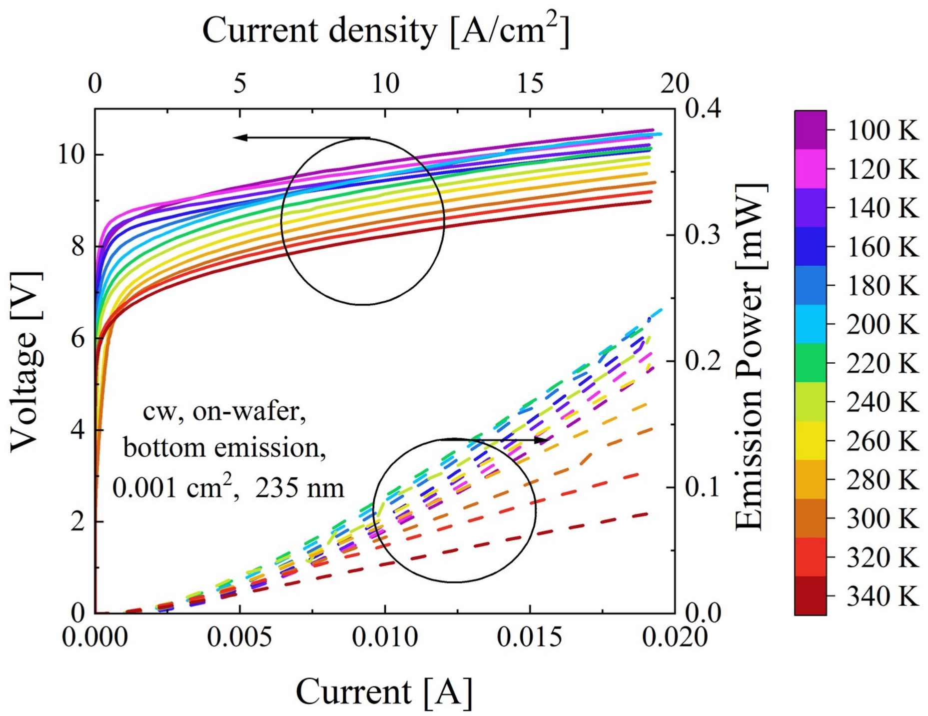


935 °C:

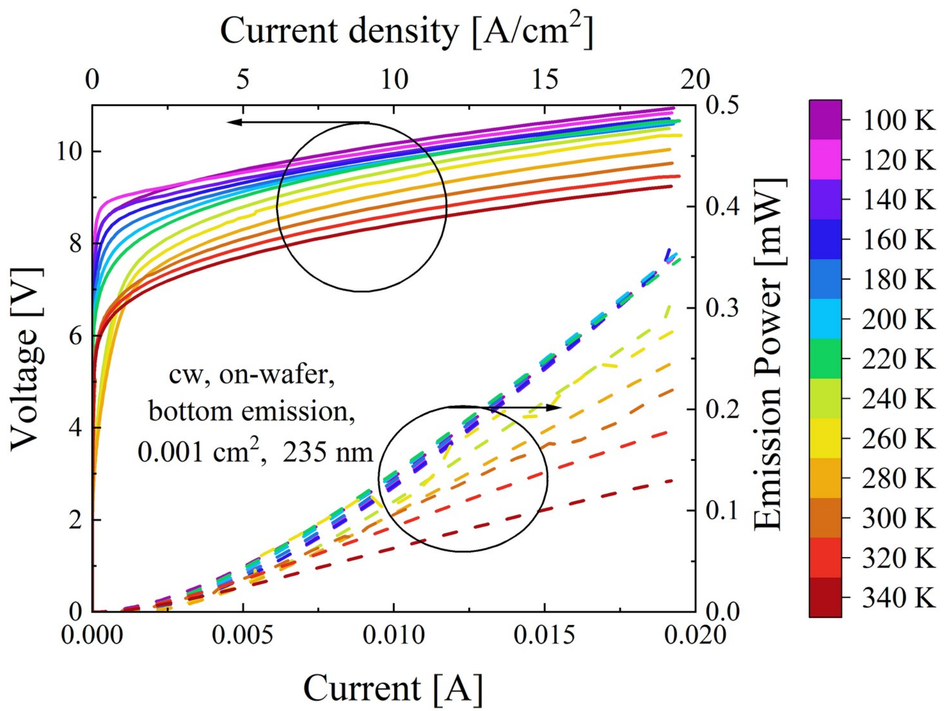


LIV Kurven

970 °C:

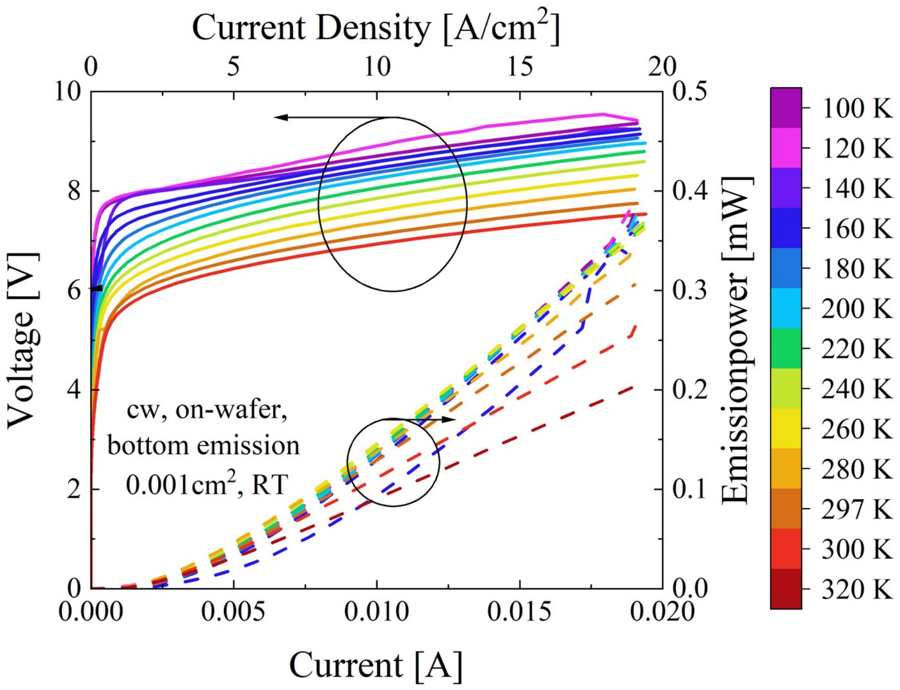


1020 °C:

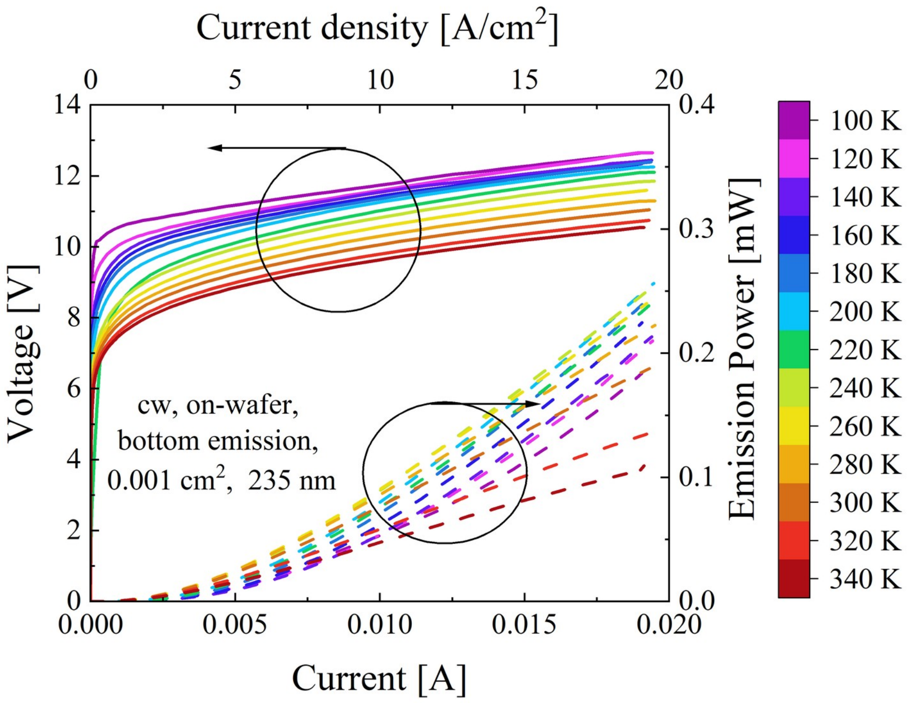


LIV Kurven

1060 °C:



1100 °C:



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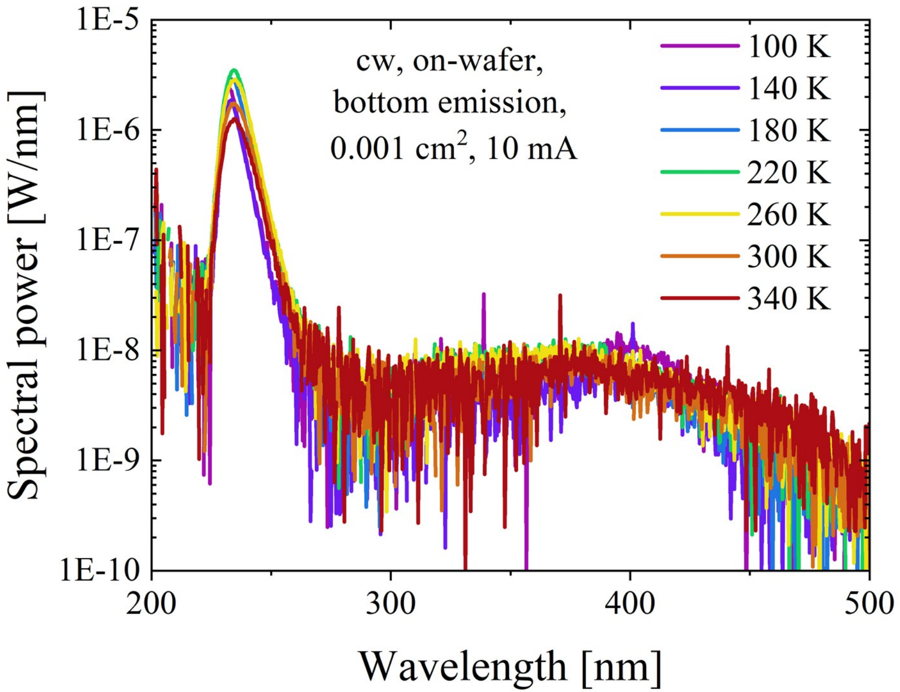
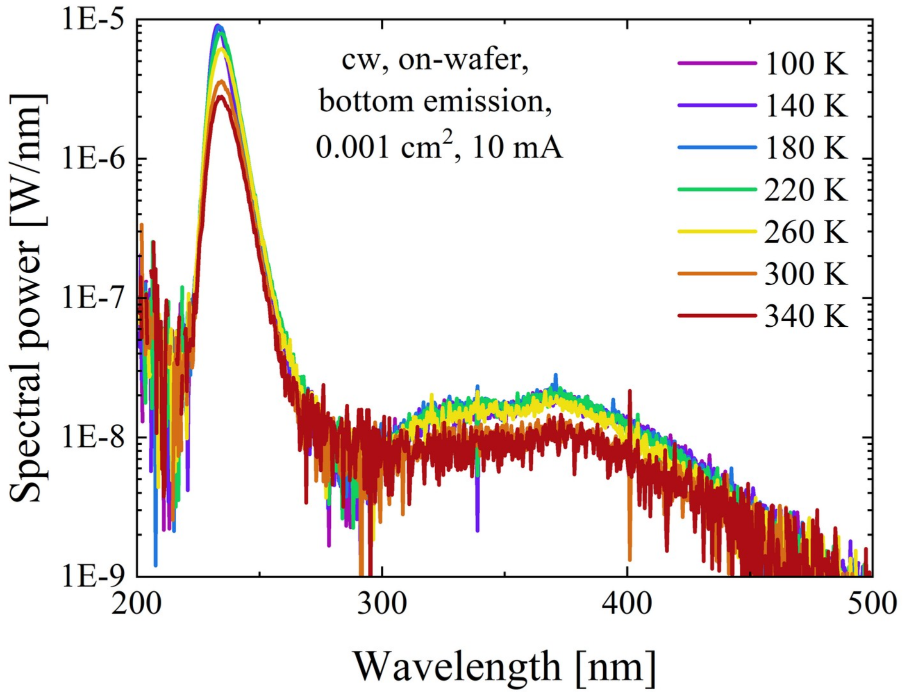
Spektren

900 °C:



935 °C:



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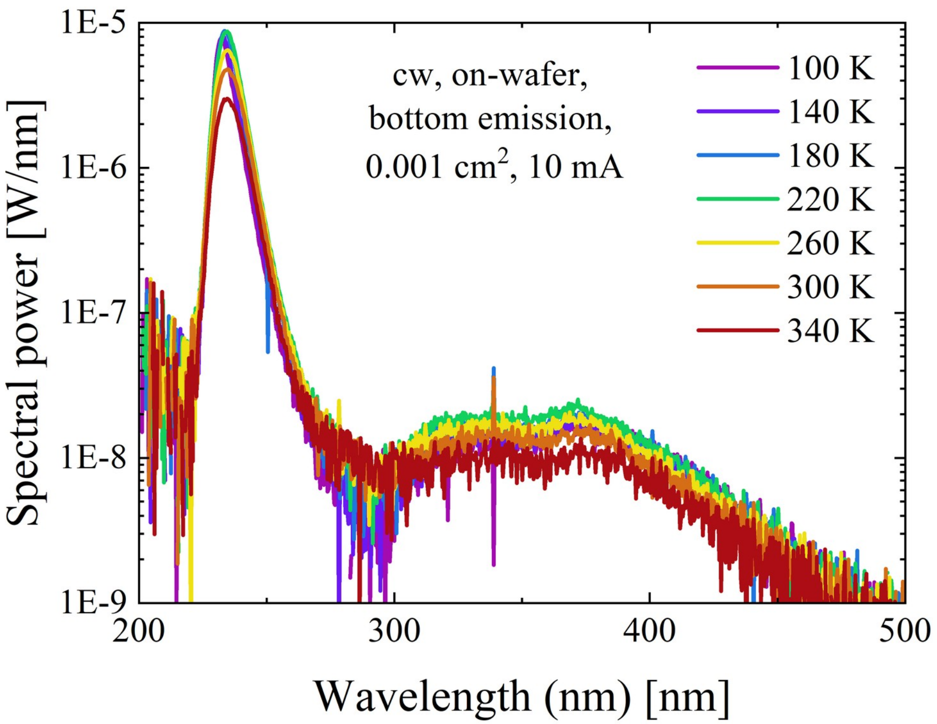
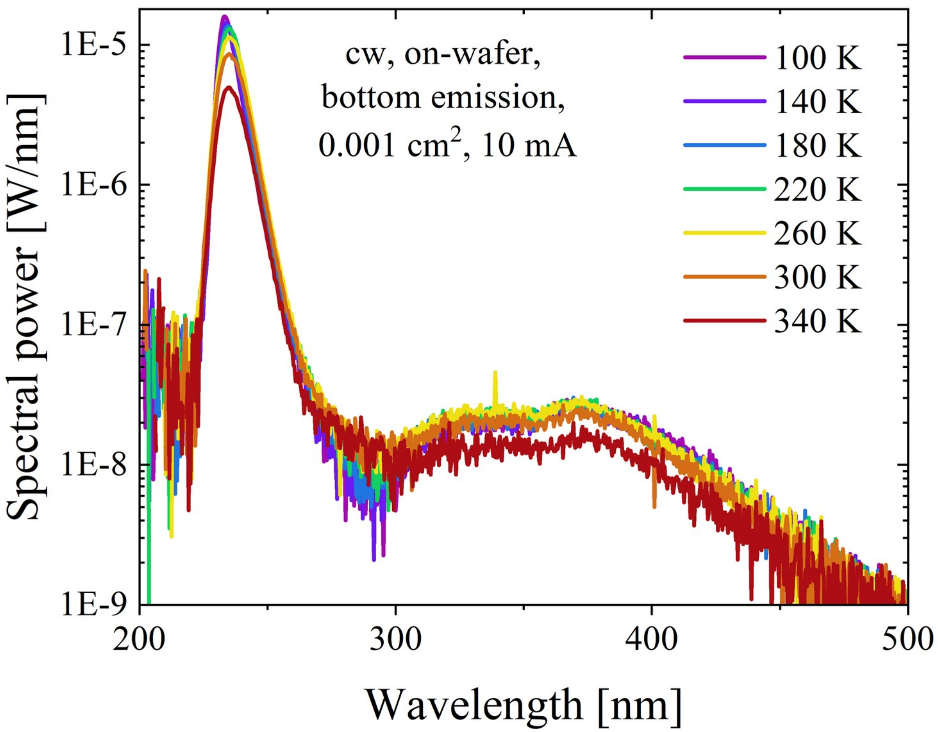
Spektren

970 °C:



1020 °C:



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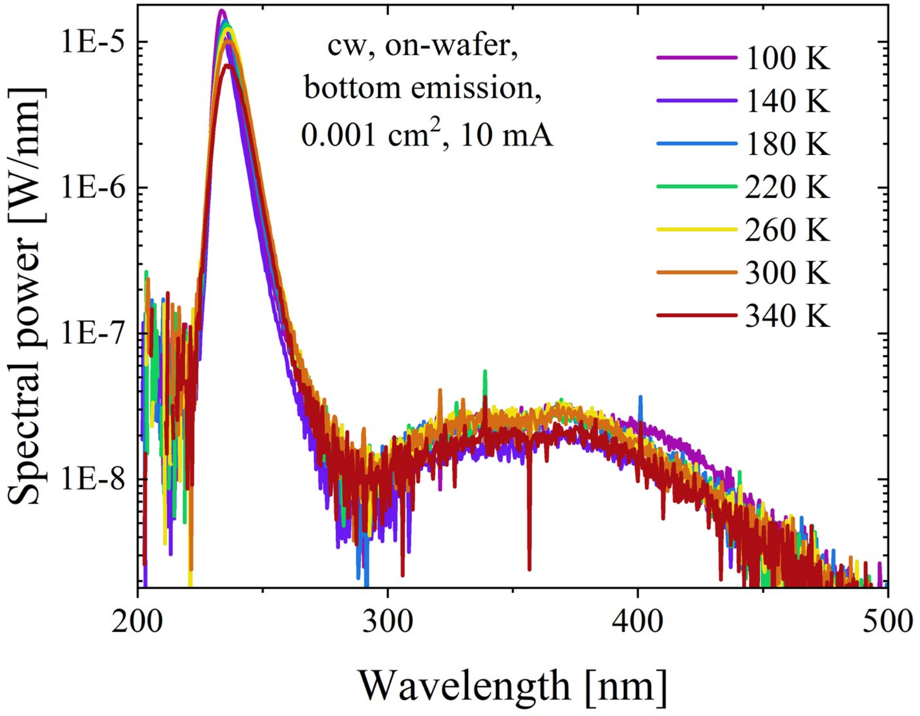
Spektren

1060 °C:



1100 °C: