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für Höchstfrequenztechnik

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Interplay of screening and band gap renormalization effects in near UV InGaN light emitting diodes

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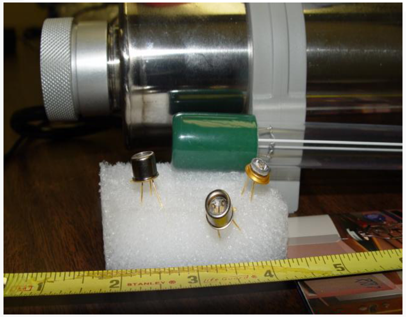
Outline

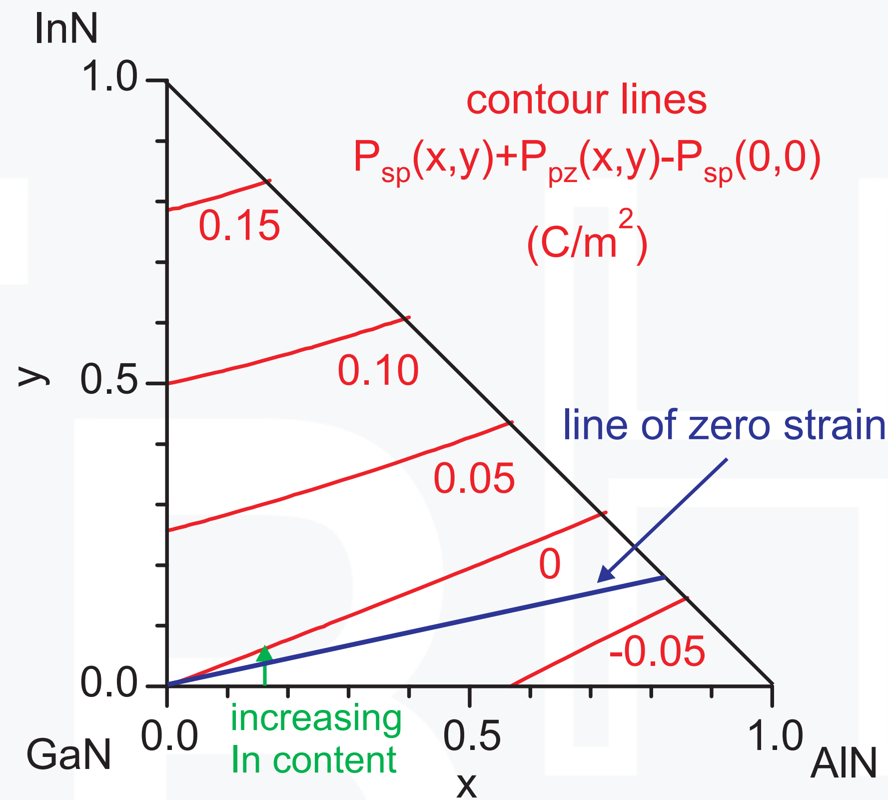
- introduction into near UV LEDs
- theoretical model
- calculated band profiles and luminescence peak wavelengths for different barrier compositions of near UV MQW active region
- fabrication of near UV LEDs and experimental setup
- measured luminescence spectra and peak wavelength dependence
- conclusions

Introduction



- many applications for UV light sources but conventional mercury lamps bulky, expensive, toxic
  $\Longrightarrow$ need for LEDs based on (Al,In,Ga)N
- nitrides grown along c-axis suffer from spontaneous and piezoelectric polarization
- active region of conventional visible LEDs:
  - compressively strained InGaN QWs separated by InGaN barriers, where difference of indium contents $> 5\%$
  - strong piezoelectric polarization effects
- active region of near UV LEDs:
  - indium content in QW $< 3\%$
    $\Longrightarrow$ aluminum containing barriers needed for sufficient carrier confinement
  - additional spontaneous polarization effects

Polarization of c-plane $Al_xIn_yGa_{1-x-y}N/GaN$



zero total polarization discontinuity to (In)GaN achievable by adding small amount of In to AlGaN $\Longrightarrow$ 'polarization matching'

Theoretical model*

Schrödinger equation: $8\times 8\ \boldsymbol{k}\cdot\boldsymbol{p}$ Hamiltonian taking into account 3 uppermost valence bands and lowest conduction band, doubly degenerated

$$\mathbf{H}\left(E_{\mathrm{c}}^{*}, E_{\mathrm{v}}^{*}, \boldsymbol{k}_{||}, \frac{d}{dz}\right)\Psi_n(\boldsymbol{k}_{||}, z) = E_n(\boldsymbol{k}_{||})\Psi_n(\boldsymbol{k}_{||}, z)$$

renormalization of bulk band edges

$$E_{\mathrm{c}}^{*} = E_{\mathrm{c}} - e\phi_{\mathrm{H}} - \frac{1}{2}V_{\mathrm{xc}}\left(\frac{n+p}{2}\right)$$
$$E_{\mathrm{v}}^{*} = E_{\mathrm{v}} - e\phi_{\mathrm{H}} + \frac{1}{2}V_{\mathrm{xc}}\left(\frac{n+p}{2}\right)$$

V_{xc} exchange–correlation potential in local density approximation

ϕ_{H} Hartree potential from Poisson equation

$$-\varepsilon_0 \mathrm{div}\,\left(\varepsilon_{\mathrm{r}}\,\mathrm{grad}\,\phi_{\mathrm{H}}\right) = e(p - n + N_{\mathrm{D}}^{+} - N_{\mathrm{A}}^{-}) - \mathrm{div}\,\left(\boldsymbol{P}_{\mathrm{sp}} + \boldsymbol{P}_{\mathrm{pz}}\right)$$

luminescence: free carrier theory with sech–type of broadening

* H. Wenzel, Opt. Quant. Electron. 38, 953, 2006

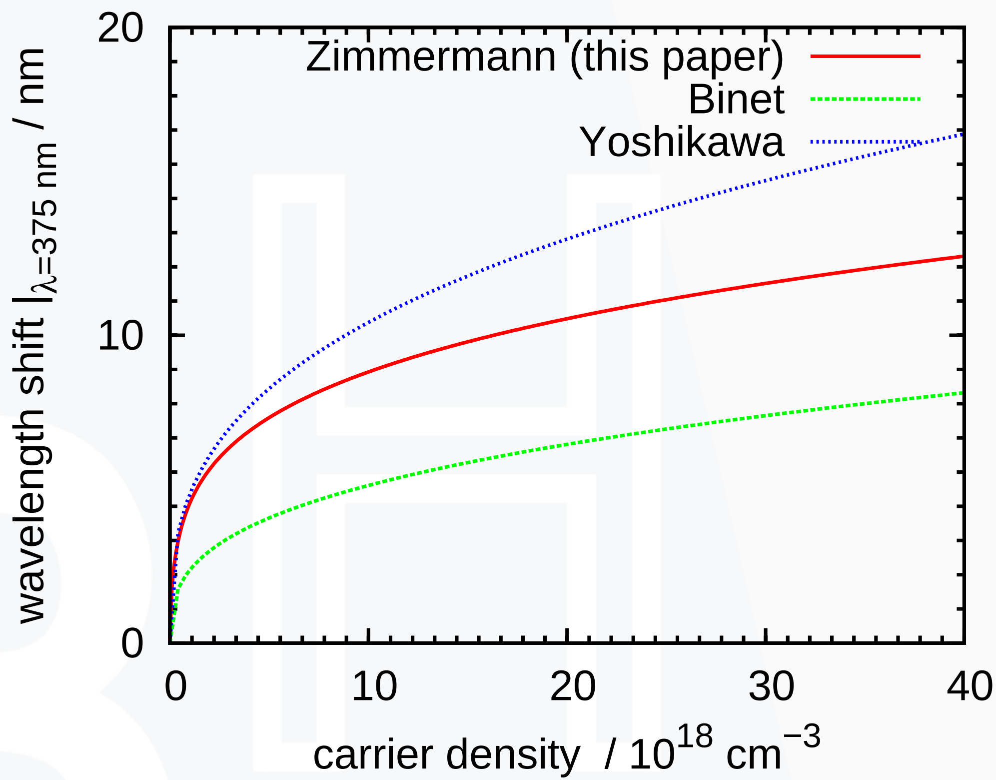
Band gap renormalization (BGR) $\Delta E_{\mathbf{g}} = -V_{\mathbf{xc}}$

$V_{\mathrm{xc}} = \zeta N^{1/3}$ (exchange only)

Binet:
$\zeta = 2.1 \times 10^{-8}$ eVcm

Yoshikawa:
$\zeta = 4.27 \times 10^{-8}$ eVcm

≈ 10 nm 'red' shift of band gap wavelength due to BGR at $\lambda = 375$ nm

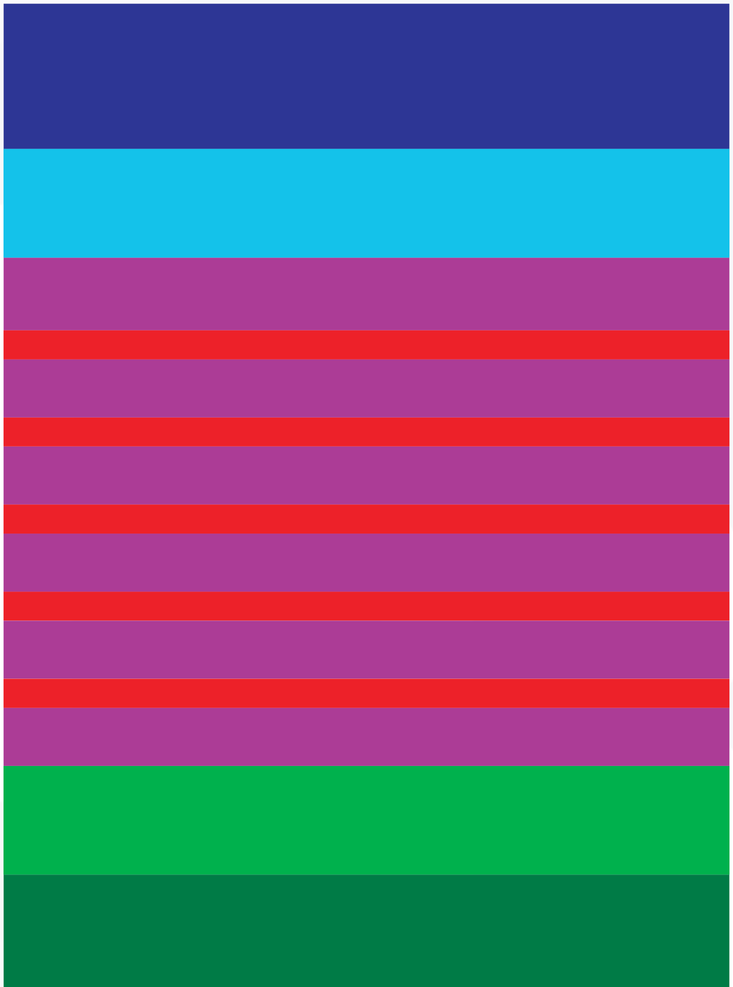


R. Zimmermann, Many-Particle Theory of Highly Excited Semiconductors, Leipzig, Germany: Teubner, 1987

F. Binet *et al.* Phys. Rev. B 60, 4715, 1999

M. Yoshikawa *et al.* J. Appl. Phys. 86, 4400, 1999

Near UV multi quantum well active region



100 nm p-GaN

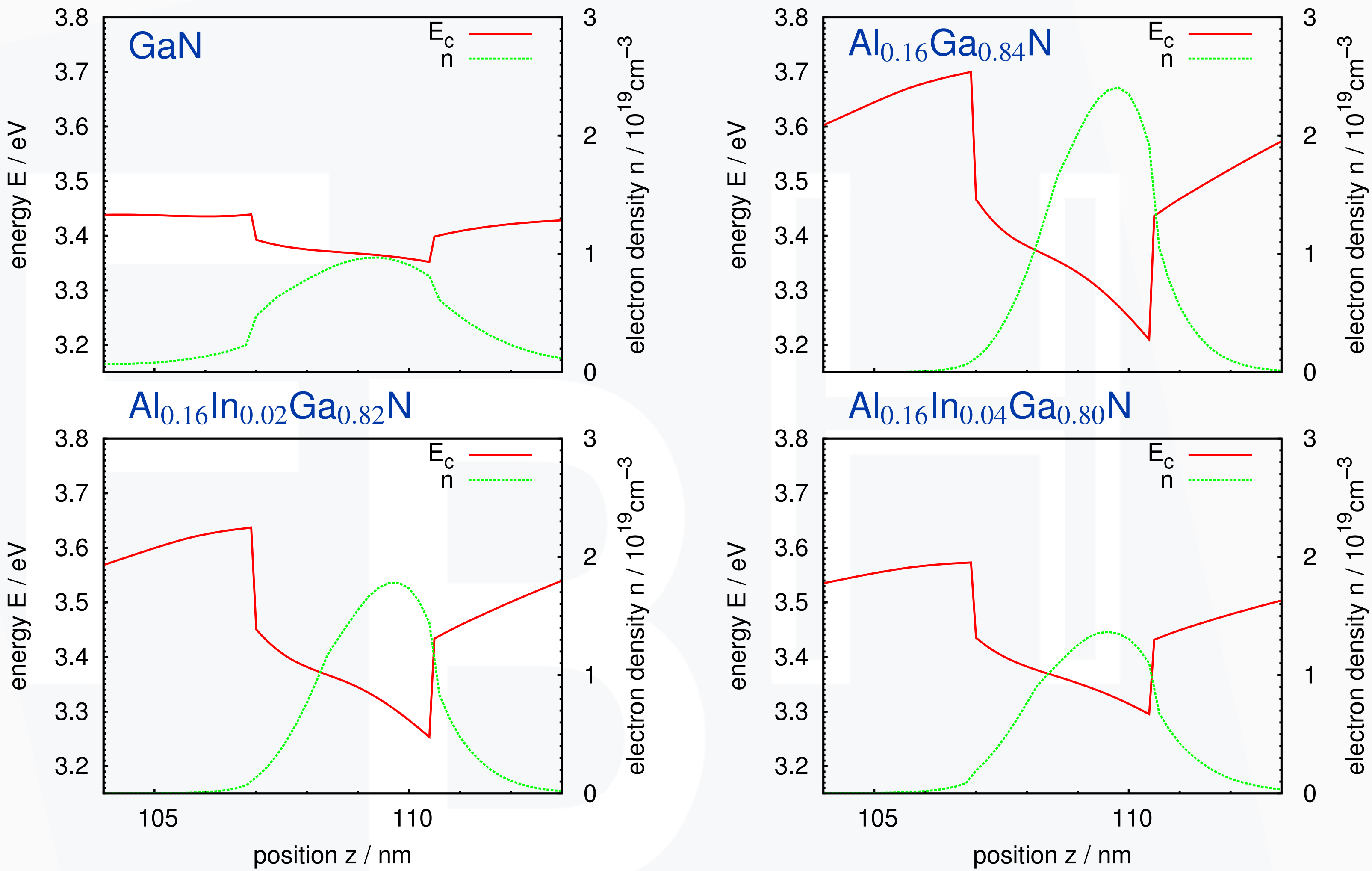
10 nm p-$Al_{0.23}Ga_{0.77}N$ electron blocking

7 nm $Al_xIn_yGa_{1-x-y}N$ barrier
3.5 nm $In_{0.02}Ga_{0.98}N$ QW
7 nm $Al_xIn_yGa_{1-x-y}N$ barrier

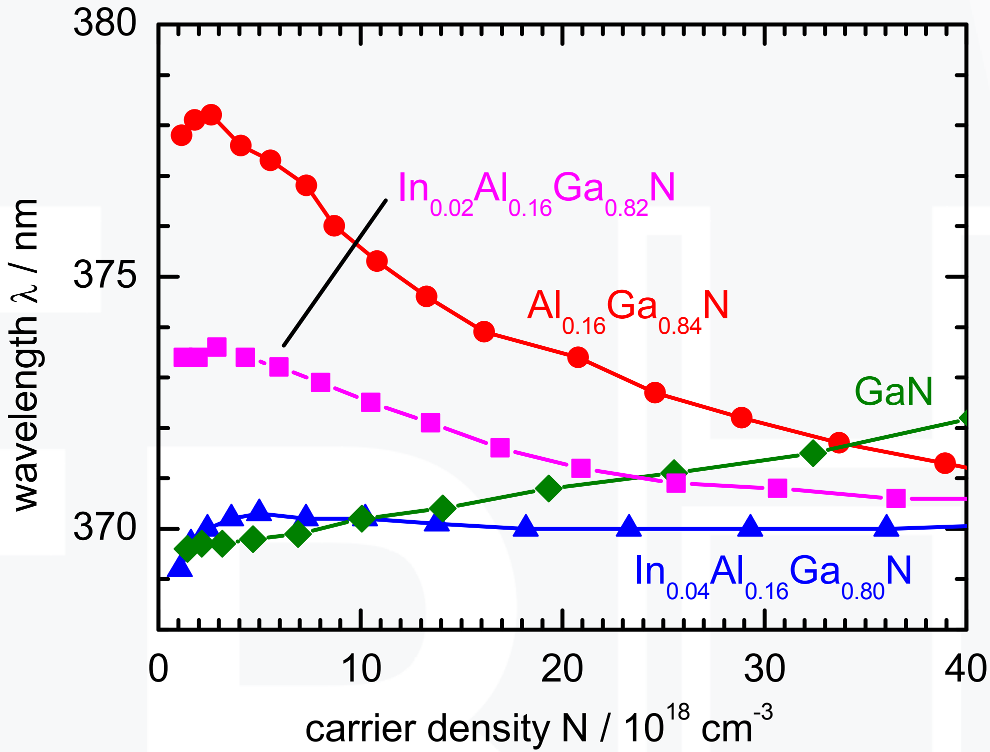
10 nm n-$Al_{0.23}Ga_{0.77}N$ hole blocking

100 nm n-GaN

Conduction band profiles at $U_F = 3.32$ V



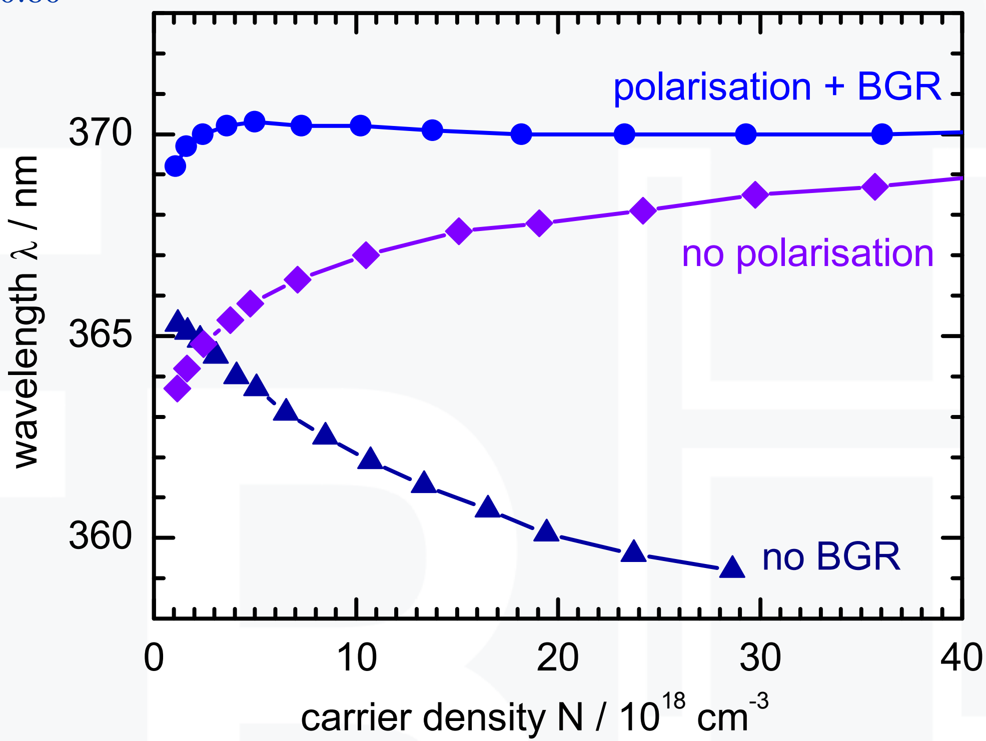
Calculated luminescence peak vs. carrier density



- GaN barriers 'red' shift of luminescence peak wavelength
- $In_xAl_{0.16}Ga_{0.84-x}N$ barriers
  $x < 0.04$ 'blue' shift of peak wavelength, decreases with increasing x
  $x = 0.04$ constant peak wavelength

Screening of polarization charges vs. BGR

$Al_{0.16}In_{0.04}Ga_{0.80}N$



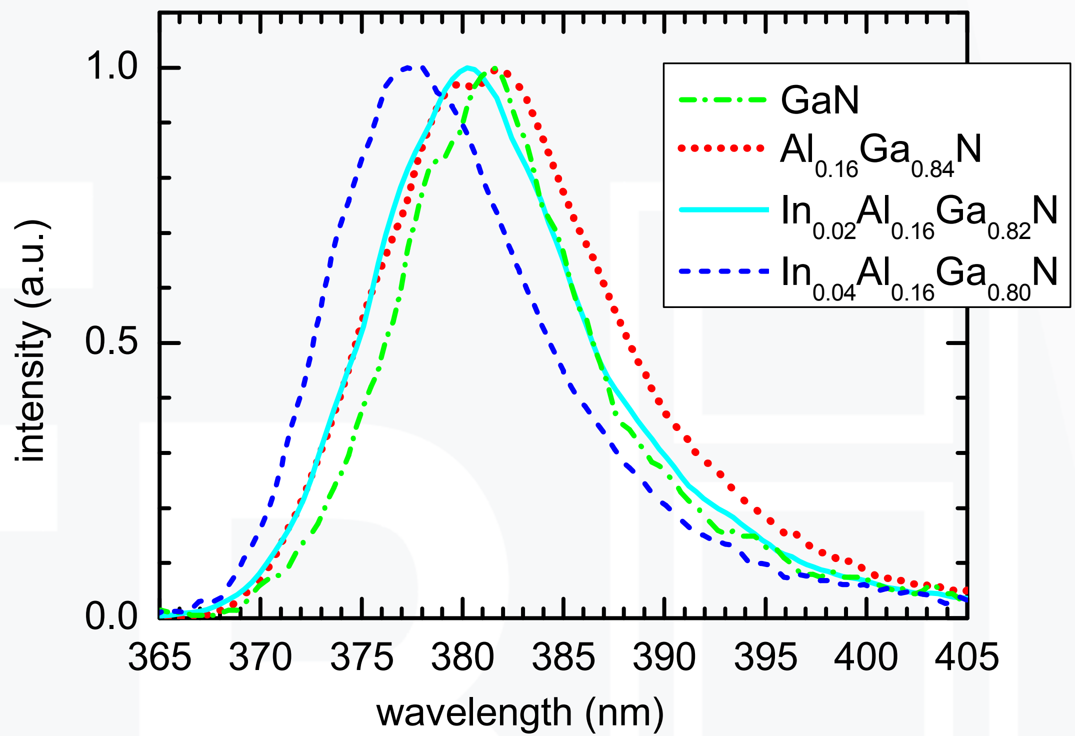
- no BGR: ‘blue’ shift due to the increasing compensation of the polarization charges by the injected charged carriers
- no polarization: ‘red’ shift due to shrinkage of the band gap

Fabrication and experimental setup

- growth by metal organic vapor phase epitaxy (MOVPE) on 2-inch (0001) sapphire substrates*
- standard LED processing technology
- $100\ \mu$m $\times$ $100\ \mu$m p-contact area
- electro luminescence measured on wafer through substrate using a calibrated Si photodetector
- pulse duration $1\ \mu$s and repetition frequency 50 Hz (duty cycle 0.00005) to avoid self-heating

* A. Knauer *et al.* Proc. SPIE 6797, 677970X-1, 2007

Measured luminescence spectra at $I = 0.26$ A



- short–wavelength slope influenced by absorption in GaN layers
- small ripples due to interference effects
- luminescence peaks determined by Gaussian fits

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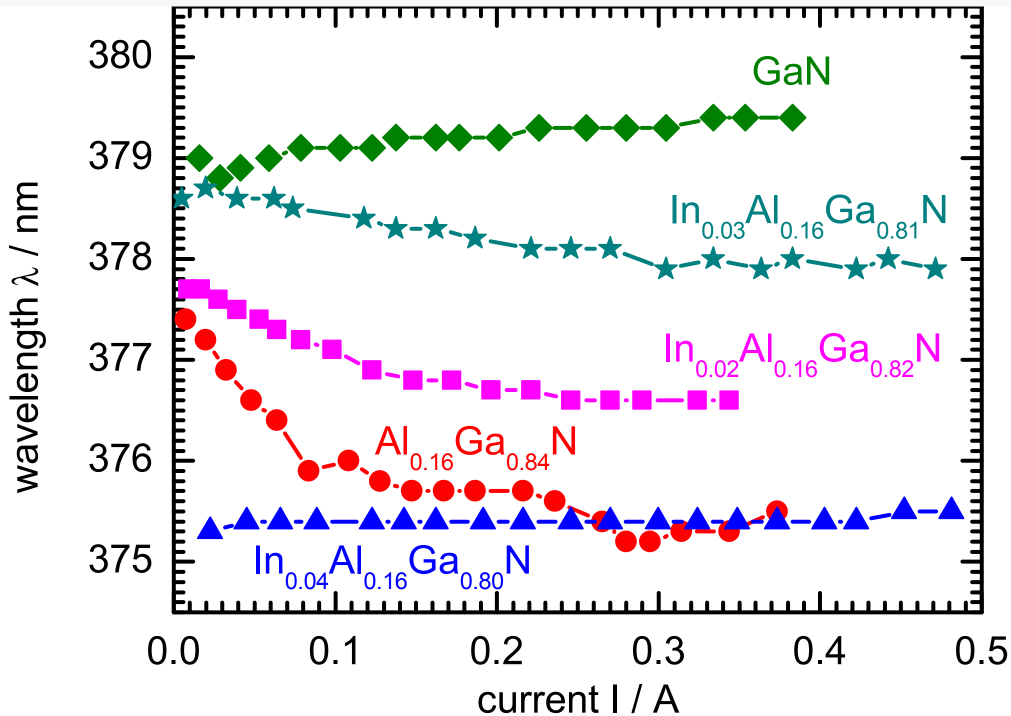
Measured peak wavelength versus injection current

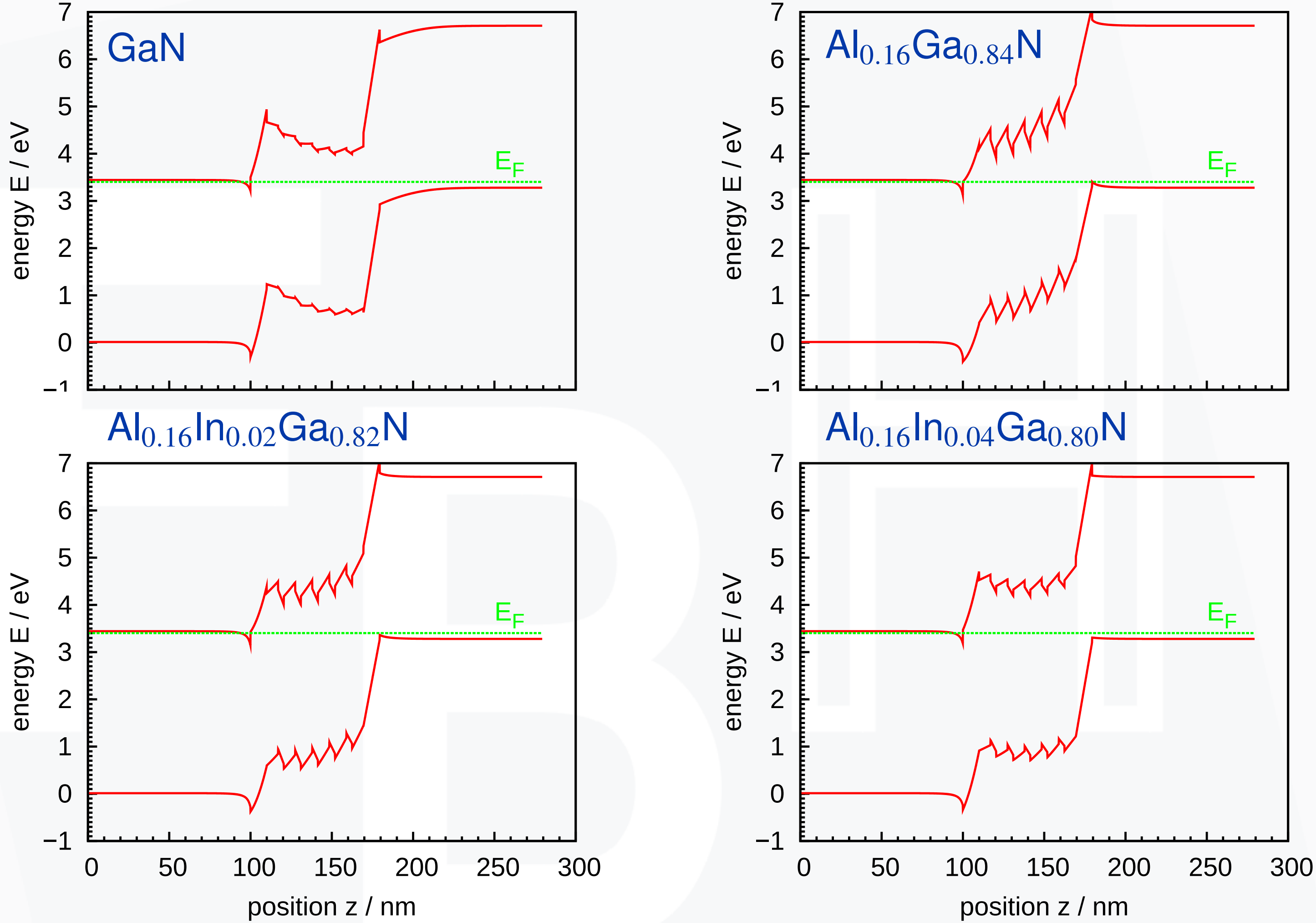


- dependence of wavelength shifts on barrier composition as simulated
- different order of peak wavelengths
- measured wavelength shifts are smaller than simulated ones

Conclusions

- dependence of luminescence properties of near UV LEDs on barrier composition investigated theoretically and experimentally
- both band gap renormalization and screening of polarization charges contribute to wavelength shifts
- good correspondence of theoretical and experimental results
- composition of the barriers and the associated strain and polarization are important parameters in LED optimization

Band profiles versus barrier composition ($U = 0$ V)



Result of simulation by APSYS (J. Piprek)

$I_{\max} = 0.5$ A, $\Delta I = 0.05$ A