In-situ metrology during growth of novel nitride-based semiconductor Bragg mirrors

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Distributed Bragg mirrors

- Alternating layers of different refractive index
- Tunable reflectivity, central wavelength, and bandwidth
- Key elements in micro-resonators
Nitride-based Bragg-reflectors

Challenges:

- Mismatch of optimal growth windows
- Lattice mismatch
- Conduction band offsets
- Polarization fields
In-situ monitoring of DBR growth

Curvature

Reflectance at:
- 950 nm
- 633 nm
- 405 nm

Light source
Mirror
Detector

Wafer

True temperature

LayTec EpiCurve® TT AR
AlInN/GaN DBR

XSEM of AlInN/GaN DBR

- Lattice-matched growth on GaN for $x_{\text{In}} \sim 17\%$
- $\Delta n/n \sim 7.5 \%$, bandwidth $> 20$ nm
- Maximum reflectivity values above 99 % possible
Mismatch of optimum growth window

- Steep temperature ramps required
- Very long growth times

45x AlInN/GaN DBR

Temperature (°C)

Time (h)
Evolution of DBR reflectivity

Spectral evolution

Single transients

- Characteristic pattern at each wavelength
Prediction of stopband position

\[ \Delta d_{Layer1} = +1 \text{ nm} \]

Weak sensitivity within stopband
Faster dynamics away from stopband
Experimental

Stopband @ 341 nm

Stopband @ 356 nm

Stopband @ 375 nm

Stopband @ 382 nm
Simulation of full DBR growth
GaN - refractive index at high temperatures
Refractive index of AlInN – in-situ

- Reflectivity
- Measurement
- Simulation
- Time (min)
- Reflectivity

n = 2.185
950 nm

n = 2.233
633 nm

r = 0.0368 nm/s

n = 2.368
405 nm

➢ Refractive index fitted using LayTec EpiNet simulation tool.
DBR structure by Ge doping of GaN (strain-free growth)

- $\Delta n/n \approx 2.0\%$, bandwidth $\sim 5$ nm
- Narrow-band reflector
Homoepitaxial DBR mirrors

Refractive index change by doping

- Burstein-Moss-effect
  - Blue shift of absorption edge with free carrier concentration
  - Change of refractive index

E. Burstein, Phys. Rev. 93, 632 (1954)

- Strain-free, conductive layers
- Similar growth conditions
Change of the excitonic transition energy

- Bandgap renormalization
- Burstein-Moss-shift

Significant ($\Delta E_g > 250$ meV) bandgap shift for $[n] \sim 10^{20}$ cm$^{-3}$.

Ge-doping superior over Si-doping in MOVPE.

>2% refractive index change across visible spectrum

R>90% for 60 layer pairs
In-situ calibration of doping level

- Increase of refractive index contrast with doping concentration
- Oscillation amplitude probes free carrier concentration
Drift of Ge incorporation

- Strong initial change within 10-15 min
- Long-term drift over hours
Improved modelling

Adjustment of GaN:Ge n-k values with increasing growth time
LED with GaN/GaN:Ge DBR

T = 300 K

EL-intensity (a. u.)
Wavelength (nm)

T = RT

EL-Intensity (arb. units)
Energy (eV)

Current (mA)
Forward voltage (V)

EL-intensity (a. u.)
Wavelength (nm)

T = RT
EL-Intensity (arb. units)
Energy (eV)

68 µA
86 mA
Summary

- In-situ metrology for growth of lattice-matched AlInN/GaN and GaN:Ge/GaN DBRs
- Reflectivity oscillations as sensitive fingerprint of DBR stopband position
- Strength of amplitude oscillations proportional to Ge doping level
- High-temperature n,k-database for GaN as basis for in-situ analysis of AlInN and GaN:Ge