Novel Approach to Efficient UV Emitters by Frequency-Doubling in Nitrides-Based Structures from Laser Diode

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Different Approaches to Efficient UV Emitters

- Nitride-based semiconductor laser diodes
  (any wavelengths)
  LED only; 1 mW, pulsed (sub-ns), broad linewidth
- All-solid-state frequency converters (any wavelengths)
  Bulky; high coherence; high powers
- Silicon UV emitters (316 nm):
  LED only
- Argon lasers
  (275 nm, 300-306 nm, 334 nm, 351 nm, 364 nm):
  Bulky; 0.01%; short lifetimes; high coherence

Potential Applications for UV Lasers

- Lighting
- Display
- Fluorescence studies
- Biosensors:
  e.g. 260-280 nm excitation wavelengths with 300-400 nm emissions for detecting micro-organisms, pollens, pollen allergens, fungal spores, organic pollutants;
  340-360 nm excitations with 400-550 nm emissions for monitoring reduced nicotinamide adenine dinucleotide (NADH) in micro-organisms

Our Novel Approach

- To use AlGaN-based multilayers as doubler to convert visible radiation from semiconductor laser diode to coherent UV beam

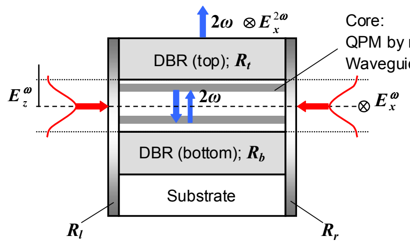
Advantages

- To take advantage of efficient visible edge-emitting lasers
- To use optical lithography, etching, and selective area re-growth to eventually fabricate monolithic current-injection UV emitters
- To avoid doping-caused problems in nitride-based emitters

Previous Work

- *Redwing, Loeber, Anderson, Tischler, Flynn (1996):*
  Optically pumped GaN-based VCSEL with emission wavelength of 363 nm using 30-period $Al_{0.40}Ga_{0.60}N/Al_{0.12}Ga_{0.88}N$ – demonstrated
- *Bhattacharyya, Iyer, Iliopoulos, Sampath, Cabalu, Moustakas, Friel (2002):*
  Reflectivity of 99% at 340 nm with bandwidth of 20 nm based on 30-period $Al_{0.43}Ga_{0.57}N/AlN$ – achieved
- *Fujita, Hasegawa, Haraguchi, Okamoto, Fukui, Nakamura (2000):*
  Second-order nonlinear optical susceptibility for GaN – measured; $d_{xzx} \approx$ 15.3-40.8 pm/V
- *Gavrilenko & Wu (2000):*
  Second-order nonlinear optical susceptibility tensor elements – calculated
- *Özgür, Webb-Wood, Everitt, Yun, Morkoç (2001):*
  Dispersion relations for $Al_xGa_{1-x}N$ – obtained

Proposed Structure



Second-Order Optical Susceptibility Tensor for Wurtzitic AlGaN Layers

$$\begin{pmatrix} P_x \\ P_y \\ P_z \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & 0 & d_{xzx} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ d_{zxx} & 0 & d_{zzz} & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} E_x^2 \\ E_y^2 \\ E_z^2 \\ 2E_zE_y \\ 2E_zE_x \\ 2E_xE_y \end{pmatrix}$$

Conversion Efficiencies

- For relatively low conversion efficiency (η ≤ 10%)

$$\eta = \frac{2R_4}{(1-R_3R_4)^2}\frac{P_{pump}}{P_s}$$

where

$$P_s = \frac{\lambda^2 n_\omega^2 n_{2\omega}(1-R_1R_2)}{8\pi^2 L\eta_0(\Delta d_{xzx})^2}\frac{d_{eff}}{d}$$

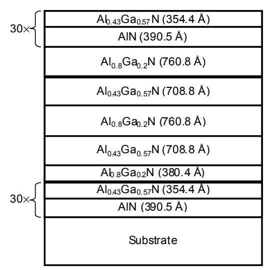
P_s – saturation power per unit waveguide width
L – waveguide length
d_{eff} – effective SHG waveguide thickness
d – physical waveguide thickness
Δd_{xzx} – difference of nonlinear coefficients between two alternating layers

Ding, Khurgin, Lee (1995)

Optimization Procedure

- Vertical cavity length:
  Too short – poor confinement for two fundamental beams
  Too long – intensities for pump beams are reduced
- Bragg reflectors:
  Bottom – highest
  Top – optimum coupling
  Maximum period of multilayers used – limited by absorption
- Introduce dielectric multilayers instead of nitride-based vertical Bragg reflectors – much higher reflectivities are achievable
- Horizontal cavity based on dielectric multilayers to increase intensities for two fundamental beams – much more sensitive

Final Structure for Efficient Generation of 340-nm Emission



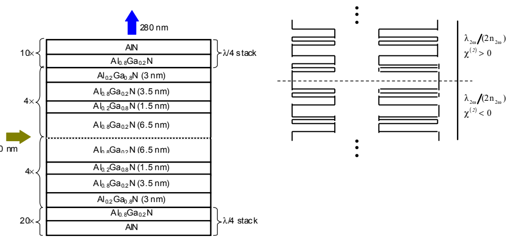
- Pump wavelength: 680 nm

Output Powers

- Surface-emitting geometry – ideal for UV generation:
  - Vertical & horizontal cavities – formed along two orthogonal axes such that they do not interfere with each other
  - Feasible for monolithic integration of doublers with edge-emitting lasers

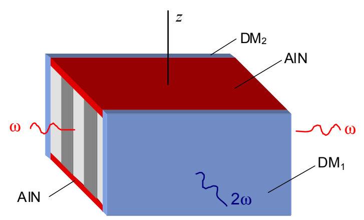
  Ding, Khurgin, Lee (1995): theory for surface-emitting SHG – developed for GaAs/AlGaAs structures
- For $Al_{0.43}Ga_{0.57}N/Al_{0.8}Ga_{0.2}N$, $\Delta d_{xzx} \approx$ 3.663 pm/V
  - CW: $R_1 = R_2 = R_3 = R_4 \approx$ 99%, $L \approx$ 1 cm, $W \approx$ 100 μm,
    $P_{UV} \approx$ 5.0 mW, $P_{pump} \approx$ 50 mW, $\eta \approx$ 10%
    As pump power is increased, conversion efficiency is also increased
  - Quasi-CW: $R_1 = R_2 \approx$ 99%, $R_3 \approx$ 14%, $R_4 \approx$ 99%, $L \approx$ 1 cm, $W \approx$ 25 μm,
    $P_{UV} \approx$ 24 W, $P_{pump} \approx$ 237 W, $\eta \approx$ 10%
    Average output power ≈ 24 mW for average pump power ≈ 237 mW

Asymmetric Coupled Quantum Wells



- Effective nonlinearity is at least one order of magnitude higher (a factor of 16)
- Switching sign of nonlinear coefficient results in enhancement of nonlinearity by a factor of at least two

Growth, Deep Etching, and Selective-Area Re-growth



- To take advantage of channel waveguide
- To achieve high-Q cavity using dielectric multilayers
- To access d_{zzz} coefficient

Conclusion

- Novel approach to coherent UV generation – proposed
- Conversion efficiency of ~ 10% – possible
- Output powers range from several mW (CW) to ~ 24 W (peak power, quasi-CW) – feasible
- This novel approach does not require p-type and n-type doping in AlGaN layers
- UV emitters after monolithic integration of doublers with edge-emitting lasers – comparable with regular semiconductor laser diodes in terms of current injection, size, and lifetime

Conclusion

- Lower pump power (a factor of 64) can be used if asymmetric coupled quantum wells (AlGaN/AlGaN- or GaN/AlGaN-based) are introduced
- Nitrides-based Bragg mirrors forming vertical cavity can be replaced by dielectric multilayers resulting in higher Q (horizontal cavity – not necessary)
- Channel waveguide (UV edge-emitter based on growth, deep etching, and selective-area re-growth, d_{zzz}) – reducing pump power by at least one order of magnitude

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