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Interdiffused MOCVD-Grown InGaAsN and InGaAsP Quantum Dots:
Getting P and N into the MOCVD-InGaAs QDs

Ronald A. Arif [(a)], Nam-Heon Kim [(b)], Luke J. Mawst [(b)], and Nelson Tansu [(a),†]

[(a)] Center for Optical Technologies, Department of Electrical and Computer Engineering, Lehigh University

[(a)] Reed Center for Photonics, Department of Electrical and Computer Engineering, University of Wisconsin-Madison

[†]Email: Tansu@Lehigh.Edu

Latest News on QD Lasers

Leading Groups:
MBE: UT-Austin, TU-Berlin, Fujitsu Lab, Univ of New Mexico, SUNY-Albany
MOCVD: Univ of Tokyo, Fujitsu Lab, TU-Berlin, Univ of New Mexico

Common Features:
Controllable Chirp (+, -, 0 chirp)
Extremely Broad Band → Good for SOA, disadvantage for lasers
Low J_{th} (for some of the best devices) → *Only* UT-Austin and TU-Berlin
Potential for realizing high T_0 lasers

Common Challenges:
Difficult to push to longer λ (λ > 1300-nm)
Large Inhomogeneous broadening → from Size distribution of QDs
Low Max Modulation Speed
Slow Relaxation of Carriers from the Excited to the Ground State
Difficult to Achieve Ground State Lasing
Etc...

MBE- vs MOCVD-Grown InGaAs QD Lasers on GaAs

MBE-Grown QD Lasers (Pyramidal QDs)

- **980 nm Edge Emitters for Pump Laser by MBE**
  - B. Sumpf et al : CW 6.3 W at 15°C [1]
- **1.3 μm Edge Emitters and VCSELs by MBE**
  - O. B. Shchekin, et al : J_{th} = 100 A/cm², λ = 1.31 μm [2]
  - A. R. Kovsh et al : λ = 1.26-1.28 μm, J_{th} = 40 A/cm² [3]
  - N. Ledentsov et al : λ = 1.3 μm, Output power up to 0.8 mW [4]
  - V. Tokranov, et al : J_{th} = 40 A/cm² (L_{cav}=5150-μm), λ = 1.22 μm [5]
- **1460 nm Edge Emitters by MBE**
  - N. Ledentsov, et. al. : J_{th} = 2.3 kA/cm², λ = 1.46 μm [6]

980-nm ← MBE → 1500-nm

MOCVD-Grown QD Lasers (Pancake-like QDs)

- R. L. Sellin et al : λ = 1.14 μm, J_{th} = 110 A/cm², 3 stacked QD [7]
- J. Tatebayashi et al : λ = 1.18 μm, J_{th} = 147 A/cm² (HR/HR), 3 stacked QD [8]
- I. N. Kaiander et al : λ = 1.24 μm, J_{th} = 200 A/cm², 10 stacked QD [9]

1100-nm ← MOCVD → 1200-nm

1 Elect. Letters, vol. 39, p. 2003
2 Appl. Phys. Lett., vol. 80 (18), May 2002.
3 J. Cryst. Growth, vol. 251, p.729, 2003
4 Physica E, vol. 13, p.871, 2002
5 Appl. Phys. Lett., vol. 83 (5), August 2003.
6 Electron. Lett., vol. 39 (15), August 2003.
7 Appl. Phys.Lett., vol. 78, p.1207, 2001
8 Electron. Lett., vol. 39 (15), July 2003.
9 Appl. Phys.Lett., vol. 84, p.2992, 2004

Why Trying to Get *P* and *N* into *MOCVD*-InGaAs QD?

MOCVD-Grown QD Lasers (Pancake-like QDs)

Challenges:

- 'Natural' wavelength of MOCVD-grown InAs QD on GaAs ~ 1.15-1.18 μm
- MOCVD-growth related QD structure
  → Pancake-like QDs → additional challenges to achieve ground state lasing
- Difficult to change the QD size for effective wavelength tuning

1100-nm ← MOCVD → 1200-nm

P- and N-Based Intermixing into InGaAs QDs

- P-incorporation allow blue shift → Interdiffused InGaAsP QDs
  → Interdiffusion or Neutral Impurity Implantation
- N-incorporation allow red shift → Interdiffused InGaAsP QDs
  → Interdiffusion or Neutral Impurity Implantation
- Allow blue-shift and red-shift for MOCVD-grown InGaAs QDs (980-1500 nm)

980-nm ← P- or N-Based Interdiffused QDs → 1500-nm

Interdiffused InGaAsP QDs | Interdiffused InGaAsN QDs

How To Form In(Ga)AsN QDs ?

Epitaxy:

InAsN QDs or InGaAsN QDs on GaAs or InGaAs
→ **Utilizing conventional SK Growth**
TBA and U-DMHy → V-precursors

InAs +highly-strained InGaAsN
→ **Prior to QD formation: InAs + InGaAsN layers**
→ **After QD formation: InGaAsN QDs**

N-QWI:

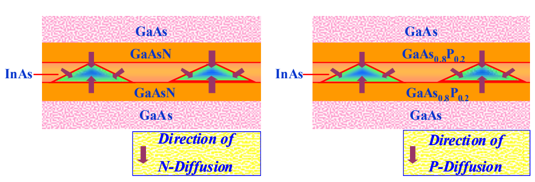
N-Implantation into In(Ga)As QDs
→ **In(Ga)As QDs embedded inside GaAs matrix**

N-diffusion into In(Ga)As QDs
→ **In(Ga)As QDs embedded inside (In)GaAsN matrix**

N- and P-Interdiffusion into InGaAs QDs

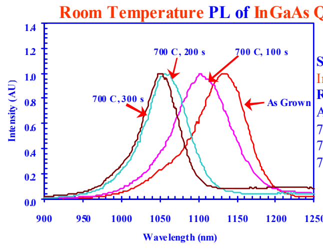
Methods:

- MOCVD-grown InAs QD sandwiched by 1) GaAsN or 2) GaAsP barrier
- Incorporation of 1) N or 2) P into the dot by interdiffusion

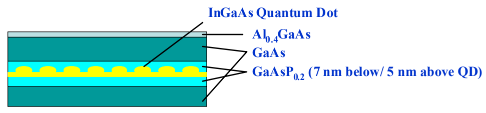


Other Potential Technique: Neutral Impurity Implantation

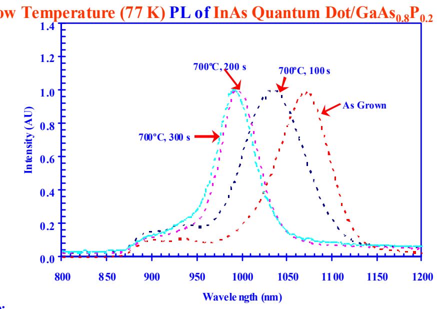
Room Temperature PL of InGaAs Quantum Dot/$GaAs_{0.8}P_{0.2}$ on GaAs



Sample:
InAs Quantum Dot/$GaAs_{0.8}P_{0.2}$ on GaAs
Results:
As-grown λ_{peak}: 1.136 μm, FWHM: 73.17 meV
700 C, 100 s: λ_{peak}: 1.1 μm, FWHM: 86.248 meV
700 C, 200 s: λ_{peak}: 1.058 μm, FWHM: 73.25 meV
700 C, 300 s: λ_{peak}: 1.052 μm, FWHM: 65.11 meV

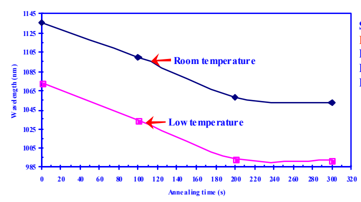


Low Temperature (77 K) PL of InAs Quantum Dot/$GaAs_{0.8}P_{0.2}$ on GaAs



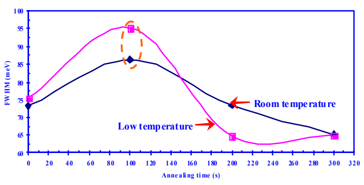
Sample:
InAs Quantum Dot/$GaAs_{0.8}P_{0.2}$ on GaAs
Results:
As-grown λ_{peak}: 1.073 μm, FWHM: 75.5 meV
700 C, 100 s: λ_{peak}: 1.034 μm, FWHM: 95.29 meV
700 C, 200 s: λ_{peak}: 0.994 μm, FWHM: 64.76 meV
700 C, 300 s: λ_{peak}: 0.992 μm, FWHM: 65.02 meV

Wavelength and FWHM shifts of Interdiffused InGaAsP QDs

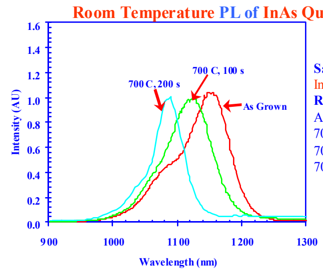


Sample:
InAs Quantum Dot/$GaAs_{0.8}P_{0.2}$ on GaAs
Results:
Room temperature lambda shift: 84 nm
Low temperature lambda shift: 81 nm

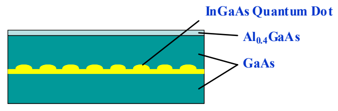
Sample:
InAs Quantum Dot/$GaAs_{0.8}P_{0.2}$ on GaAs
Results:
Room temperature FWHM shift: 8.06 meV
Low temperature FWHM shift: 10.48 meV



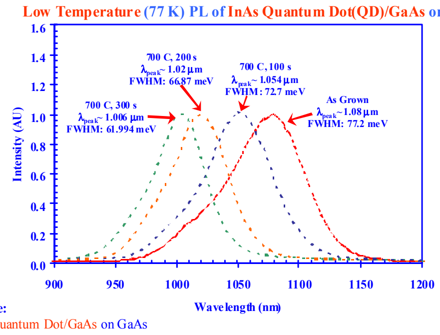
Room Temperature PL of InAs Quantum Dot(QD)/GaAs on GaAs



Sample:
InAs Quantum Dot/GaAs on GaAs
Results:
As-grown λ_{peak}: 1.154 μm, FWHM: 82.1 meV
700 C, 100 s: λ_{peak}: 1.125 μm, FWHM: 81.4 meV
700 C, 200 s: λ_{peak}: 1.09 μm, FWHM: 52.84 meV
700 C, 300 s: very noisy

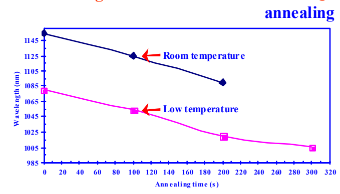


Low Temperature (77 K) PL of InAs Quantum Dot(QD)/GaAs on GaAs



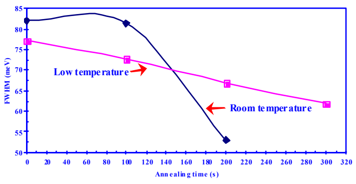
Sample:
InAs Quantum Dot/GaAs on GaAs
Results:
As-grown λ_{peak}: 1.08 μm, FWHM: 77.2 meV
700 C, 100 s: λ_{peak}: 1.054 μm, FWHM: 72.7 meV
700 C, 200 s: λ_{peak}: 1.02 μm, FWHM: 66.87 meV
700 C, 300 s: λ_{peak}: 1.006 μm, FWHM: 61.994 meV

Wavelength and FWHM shifts of InAs Quantum Dot/GaAs on GaAs due to annealing



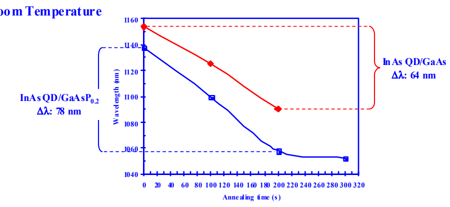
Sample:
InAs Quantum Dot/GaAs on GaAs
Results:
Room temperature lambda shift: 64 nm
Low temperature lambda shift: 74 nm

Sample:
InAs Quantum Dot/GaAs on GaAs
Results:
Room temperature FWHM shift: 29.26 meV
Low temperature FWHM shift: 15.206 meV

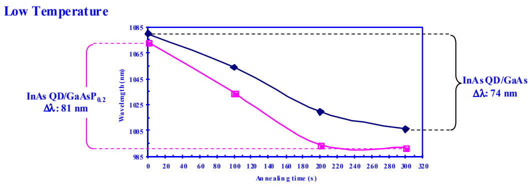


PL peaks comparison of InAs QD/GaAs and InAs QD/$GaAsP_{0.2}$ on GaAs

Room Temperature



Low Temperature



Summary

- Shorter emission in InAs QDs with GaAsP (compared with InAs QDs with GaAs):
  → Larger barrier, higher confinement energy
- Larger PL shifts in InAs QDs with GaAsP (compared with InAs QDs with GaAs):
  → Possible incorporation of P into InAs QDs,
  → Need to verify these by additional experiments
- Decreasing FWHM with annealing on both types of samples

Future Plans on Interdiffused SbN-Based QWs

Intermixing for InGaAs QDs with GaAsN and GaAsP Barriers
P-Incorporation, N-Incorporation } Interdiffused InGaAs***P*** and InGaAs***N*** QDs

Fabrication of Interdiffused QD Laser Devices
Interdiffused InGaAsP QDs, Interdiffused InGaAsN QDs } Broad-Area Edge-Emitting Lasers

Interdiffused InGaAsSbN QW Lasers
Investigate the interdiffusion process in InGaAsSb-InGaAsN QWs
Interdiffused InGaAsSbN QW Edge-Emitting Laser Devices