High Performance 1360-1382 nm InGaAsN Quantum Well Lasers by Metalorganic Chemical Vapor Deposition

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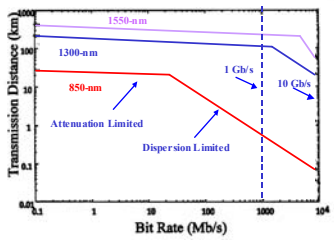
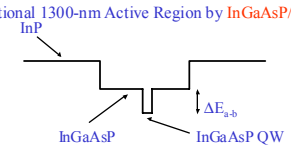


- 850 nm VCSELs → 10 Gb/s , limited up to 50-100 m
- 1.3 μm VCSELs → 10 Gb/s, up to 20-40 km

Low-Cost 1300-nm VCSELs / DFBs

→ Suitable for Metro Optical Network → **10 Gb/s at 85 ^{0}C**

Conventional 1300-nm Active Region by InGaAsP/InP QW



- ***Extremely Temperature Sensitive (Low T_o value)***
  - Small conduction band offset (ΔE_c = 80 meV)
  - Large Auger recombination
  - Intervalence band absorption (IVBA)
  - Temperature dependency of material gain (g_o)
- ***High Cost*** → for thermal management
- ***Poor InP-based VCSELs*** **Performances**
  - Lack of Materials for DBRs on InP-based VCSELs

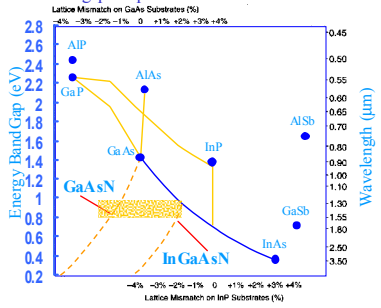
Long Wavelength Lasers on GaAs

- Less temperature sensitive lasers
  - Large band offset (ΔE_{a-b}=470 meV)
- Practical Implementation to 1.3-μm VCSELs [1]
  - High quality AlAs/GaAs DBRs on GaAs

Alternative approach :

- **InGaAsN/GaAs QW** [2,3,4,5]
- In(Ga)As/GaAs QD [6,7,8]
- GaAsSb/GaAs Type II QW [9,10]

The Bandgap Map for InGaAsN Materials [1]



(In)GaAsN QW on GaAs

→ **Excellent Candidate for Optical Communications**

→ **λ = 1300-1550 nm**

1. M. Kondow, et. al., J. Select. Quantum. Electron. 1997.

MOCVD Growth of InGaAsN-QW VCSELs

→ **MOCVD → suitable for VCSELs growth**

→ **High growth rate in MOCVD**

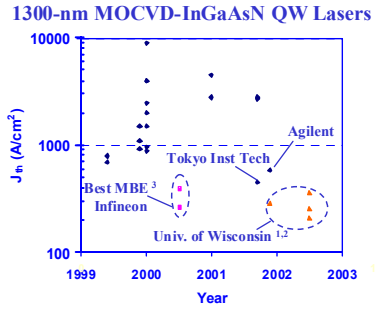
→ **Thick DBRs ~ 5-8 μm**

→ **Better control hetero-interfaces in DBRs**

→ **Compositional & Doping Control**

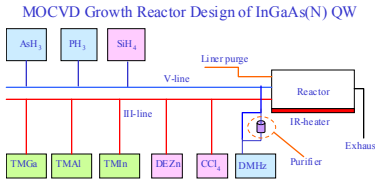
→ **Low resistive DBRs**

1300-nm MOCVD-InGaAsN QW Lasers



1. N. Tansu, and L. J. Mawst, *IEEE Photon. Technol. Lett., vol. 14(4), pp. 444-446, April 2002.*
2. *N. Tansu, N. J. Kirsch, and L. J. Mawst, Appl. Phys. Lett., vol. 81(14), September 2002.*
3. *D. A.Livshits, A. Yu. Egorov, and H. Riechert, Electron. Lett., 36, 1381 (2000).*

MOCVD Growth Reactor Design of InGaAs(N) QW



Epitaxy Challenges for MOCVD-InGaAsN QW [1]

→ **The Source for N in MOCVD**

→ **Low Purity U-DMHy**

Not Higher Purity N_2 RF-Plasma

→ **Low N-Incorporation Efficiency**

→ **Low AsH_3/III requirements**

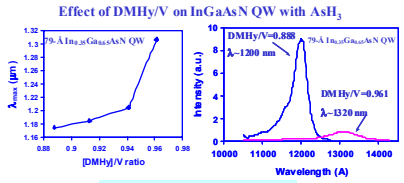
Reduced luminescence

→ **Growth Conditions – Narrow Window**

→ **Pressure, Temperature, Growth Rate**

1. *N. Tansu, and L. J. Mawst, IC-MOVPE XI 2002, Berlin, Germany, June 2002.*

Effect of DMHy/V on InGaAsN QW with AsH_3



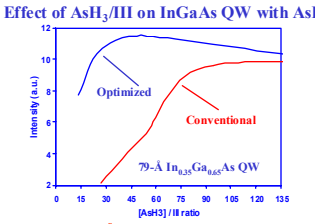
Gas : 96 % N + 4 % As

Solid : 0.8 % N + 99.2 % As

→ **DMHy/V > 0.961 for 1300-nm emission**

→ **Require [AsH_3]/III < 13.5**

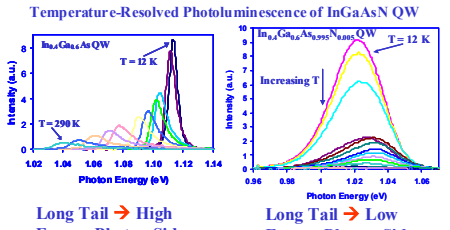
Effect of AsH_3/III on InGaAs QW with AsH_3



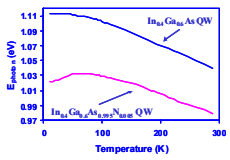
Low AsH_3/III → Reduce Optical Luminescence

Optimize your InGaAs → Optimize InGaAsN

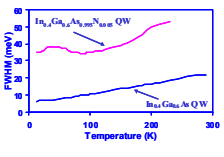
Temperature-Resolved Photoluminescence of InGaAsN QW



Long Tail → High Energy Photon Side

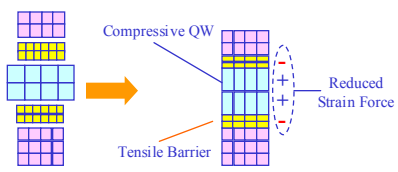


Long Tail → Low Energy Photon Side



- **Existence of Carrier Localization in InGaAsN QW → No localized State in InGaAs QW**
- **Full Localization and Delocalization → ~ 20K & 40K**

The Strain-Compensation of InGaAsN-QW Lasers

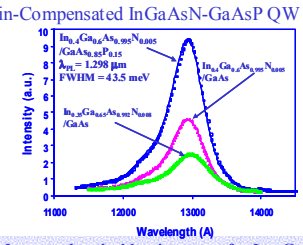


Highly-Strain InGaAsN (In ~ 40 %)

+ Tensile Barriers of GaAsP[1,2] or GaAsN[3]

1. *N. Tansu, and L. J. Mawst, IEEE Photon. Technol. Lett., vol. 13(3), March 2001.*
2. *N. Tansu, and L. J. Mawst, IEEE Photon. Technol. Lett., vol. 14(4), pp. 444-446, April 2002.*
3. N. Tansu, J. Y. Yeh, and L. J. Mawst, *Appl. Phys. Lett., submitted.* → *Experiments for GaAsN*

Strain-Compensated InGaAsN-GaAsP QW Lasers [1]



→ **Improved optical luminescence for $In_{0.4}Ga_{0.6}AsN$**

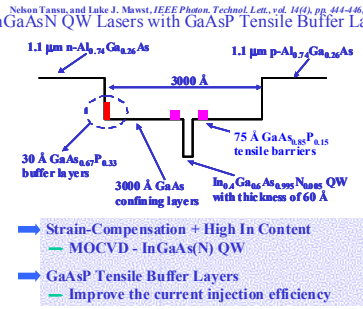
→ **Reduced N content → 1300-nm emission**

→ **GaAsP Strain Compensation on InGaAsN**

→ **Improved optical luminescence**

1. Nelson Tansu, and Luke J. Mawst, *IEEE Photon. Technol. Lett., vol. 14(4), pp. 444-446, April 2002.*

InGaAsN QW Lasers with GaAsP Tensile Buffer Layers [1]

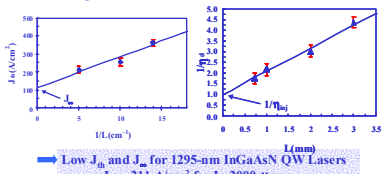


→ **Strain-Compensation + High In Content — MOCVD - InGaAs(N) QW**

→ **GaAsP Tensile Buffer Layers — Improve the current injection efficiency**

1. *N. Tansu, N. J. Kirsch, and L. J. Mawst, Appl. Phys. Lett., vol. 81(14), September 2002.*

Lasing Characteristics of InGaAsN QW Lasers [1]



→ **Low J_{th} and J_{tr} for 1295-nm InGaAsN QW Lasers**

→ **J_{th} = 211 A/cm^2 for L=2000-μm**

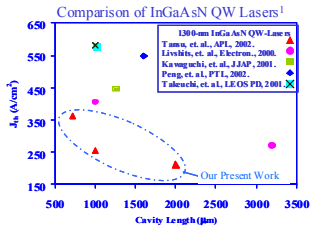
→ **J_{th} = 254 A/cm^2 for L=1000-μm**

→ **High current injection efficiency → η_{inj} ~ 97 %**

→ **GaAsP Tensile Buffer**

1. *N. Tansu, N. J. Kirsch, and L. J. Mawst, Appl. Phys. Lett., vol. 81(14), September 2002.*

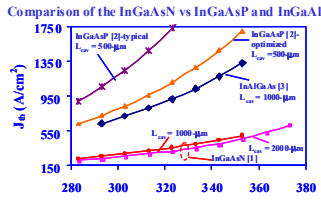
Comparison of InGaAsN QW Lasers [1]



→ Represents the best J_{th} and J_{tr} for 1300-nm InGaAsN QW lasers

1. *N. Tansu, N. J. Kirsch, and L. J. Mawst, Appl. Phys. Lett., vol. 81(14), September 2002.*

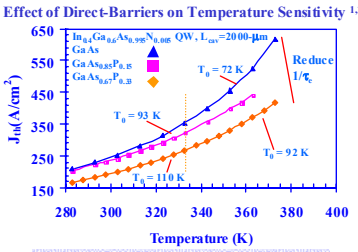
Comparison of the InGaAsN vs InGaAsP and InGaAlAs



→ InGaAsN → Extremely-low J_{th} at room and high temperature

1. *N. Tansu, A. Quandt, M. Kanskar, W. Mulhearn, and L. J. Mawst, Appl Phys. Lett., vol.83(2), July 2003.*
2. *G. L. Belenky, C.L. Reynolds, D. V. Donetsky, G. E. Shtengel, M. S. Hybertsen, M. A. Alam, G. A. Baraff, R. K. Smith, R. F. Kazarinov, J. Winn, and L. E. Smith, IEEE J. Quantum Electron., 35, 1515 (1999).*
3. *P. Sarmalainen, M. Toivonen, P. Melanen, V. Viikkinen, M. Saarinen, S. Orsila, T. Kuusisto, A. Salokatve, H. Asonen, T. Pamardis, R. Murkin, and M. Pessa, in Proc. 13th IPRM, Mo-P09, (1999).*

Effect of Direct-Barriers on Temperature Sensitivity [1,2]

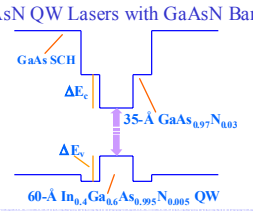


1/τ_c ↓ → Low-J_{th} at High Temperature

J_{th} (InGaAsN) → *only* 360 A/cm^2 at 90 ^{0}C

1. *N. Tansu, and L. J. Mawst, Appl. Phys. Lett., vol. 82(10), 1500, March 2003.* → *Theory*
2. *N. Tansu, J. Y. Yeh, and L. J. Mawst, IEEE Photon. Technol. Lett. (to be submitted).* → *Experiment*

InGaAsN QW Lasers with GaAsN Barriers



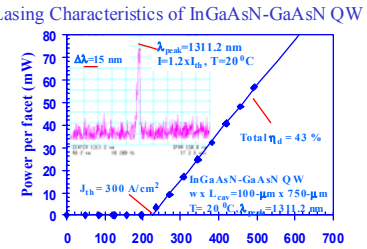
→ **Reduced ΔE_c → Longer λ_{lasing} by 20-nm**

→ **Type-II GaAsN/GaAs [1,2] → ~ 15-20 meV/%N**

→ **Larger ΔE_v to Suppress Hole-Leakage [3]**

1. J. Wu, W. Shan, W. Walukiewicz, K. M. Yu, J. W. Ager III, E. E. Haller, H. P. Xin, and C. W. Tu, *Phys Rev. B.*, vol 64, pp. 85320, August 2001.
2. T. Kitatani, M. Kondow, T. Kikawa, Y. Yazawa, M. Okai, and K. Uomi, *Jpn. J. Appl. Phys.*, Vol. 38, pp. 5003-5006, September 1999.
3. N. Tansu, J. Y. Yeh, and L. J. Mawst, Appl. Phys Lett. (submitted).

Lasing Characteristics of InGaAsN-GaAsN QW [1]

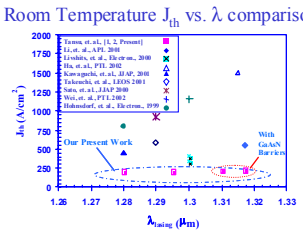


→ Extremely-low J_{th} at λ=1311-1317nm

→ J_{th} (L_{cav}=2000-μm) = 210 A/cm^2

1. *N. Tansu, J. Y. Yeh, and L. J. Mawst, Appl. Phys. Lett., (submitted).*

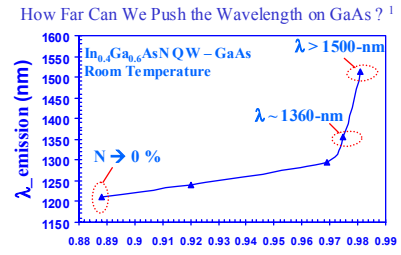
Room Temperature J_{th} vs. λ comparison



RT-J_{th} independent of λ → Identical InGaAsN QW Choice of Barriers → Affects J_{th} at high Temp

1. *N. Tansu, N. J. Kirsch, and L. J. Mawst, Appl. Phys. eLett., vol. 81(14), September 2002.*
2. N. Tansu, J. Y. Yeh, and L. J. Mawst, *Appl. Phys. Lett., (submitted).*

How Far Can We Push the Wavelength on GaAs ? [1]

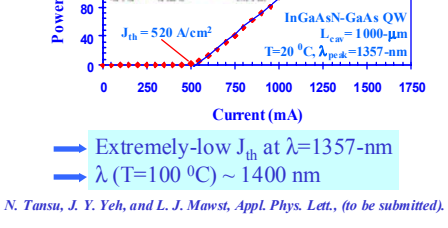


Add N into InGaAsN → λ > 1500-nm

First Realization by MOCVD with AsH_3

1. *N. Tansu, J. Y. Yeh, and L. J. Mawst, Appl. Phys. Lett., (to be submitted).*

Lasing Characteristics of $In_{0.4}Ga_{0.6}AsN$-QW [1]

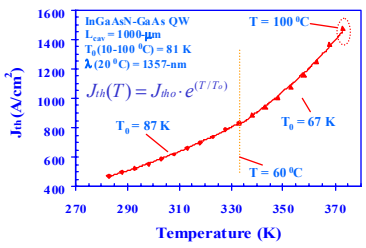


→ Extremely-low J_{th} at λ=1357-nm

→ λ (T=100 ^{0}C) ~ 1400 nm

1. *N. Tansu, J. Y. Yeh, and L. J. Mawst, Appl. Phys. Lett., (to be submitted).*

Lasing Characteristics of $In_{0.4}Ga_{0.6}AsN$-QW [1]

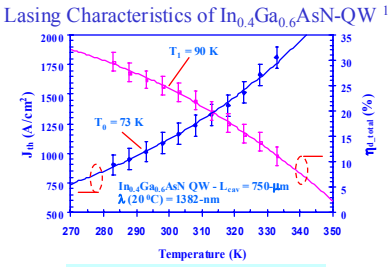


→ Reasonably-high T_o values

→ λ (T=100 ^{0}C) ~ 1400 nm

1. *N. Tansu, J. Y. Yeh, and L. J. Mawst, Appl. Phys. Lett., (to be submitted).*

Lasing Characteristics of $In_{0.4}Ga_{0.6}AsN$-QW [1]

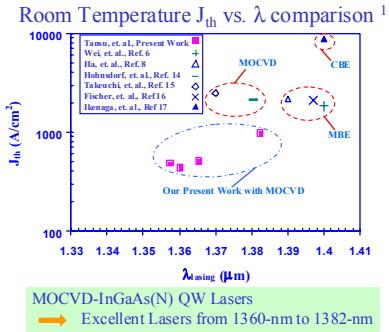


→ Reasonably-low J_{th} at λ=1382-nm

→ Very temperature-sensitive η_d

1. *N. Tansu, J. Y. Yeh, and L. J. Mawst, Appl. Phys. Lett., (submitted).*

Room Temperature J_{th} vs. λ comparison [1]



MOCVD-InGaAs(N) QW Lasers

→ Excellent Lasers from 1360-nm to 1382-nm

1. *N. Tansu, J. Y. Yeh, and L. J. Mawst, Appl. Phys. Lett., (submitted).*

Summary on InGaAsN QW Lasers

- High Performance 1170-1382-nm InGaAs(N) QW Lasers
  - → ***Record*** performances & **First-time** with MOCVD-AsH_3
  - → 1170-1233nm : J_{th} = 65-90 A/cm^2 (L=1000-μm)
  - → 1295-1317nm : J_{tr} = 79 A/cm^2 & J_{th} = 211 A/cm^2
  - → 1360-nm : J_{th} = 450 A/cm^2 (L=1500-μm)
- High-Performance CW 1300-nm InGaAsN QW Lasers
  - → J_{th} (InGaAsN-GaAs) → ***only* 610 A/cm^2 at 100 ^{0}C**
  - → The lowest-J_{th} at T = 100 ^{0}C, for ***any 1300-nm QW-Lasers***
- Suppression of Carrier Leakages in InGaAsN QW
  - → J_{th} (InGaAsN-GaAsP) → ***only* 360 A/cm^2 at 90 ^{0}C**

Acknowledgement

- **Agilent Technologies Labs, Palo Alto, CA**

Dr. Michael R. T. Tan, Dr. Dave P. Bour, Dr. Scott W. Corzine, Dr. Tetsuya Takeuchi, Dr. Ying-Lan Chang

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