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Interdiffused (In)GaAsSbN Quantum Wells on GaAs for 1300-1550 nm Lasers: Theory and Experiment

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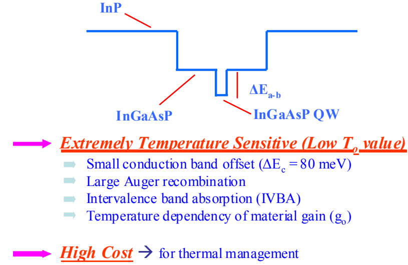
Conventional 1300-1550 nm Lasers by InGaAsP/InP QW



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 performance
- Lack of Materials for DBRs on InP-based VCSELs

Approaches for 1300-1550 nm Lasers on GaAs

Type-I QWs/QDs
- InGaAsN QWs [1-3] → Excellent 1300-nm Lasers [1-3]
  - Difficult to push to 1550-nm
- In(Ga)As QDs [4] → Excellent 1300-nm Lasers
  - Large strain limits the max λ
- InGaAsSbN QWs [5,6] → Promising MBE results [5], but challenging by MOCVD

Type-II QWs
- GaAsSb-InGaAs type II QWs [7] → Highly-strained & reduced electron-hole overlap
- Dilute-Nitride Type-II QWs [8] → Allow emission up to 1600-nm[8,9]
  - Promising, but still at early stage of development

1. N. Tansu, N. J. Kirsch, and L. J. Mawst, Appl. Phys. Lett., vol. 81(14), September 2002.
2. D. A.Livshits, A. Yu. Egorov, and H. Riechert, Electron. Lett., 36(16), pp. 1381-1382, 2000.
3. T. Takeuchi, Y.-L. Chang, M. Leary, A. Tandon, H.-C. Luan, D. P. Bour, S. W. Corzine, R. Twist, and M. R. Tan, IEEE LEOS 2001 Post-Deadline Session, San Diego, USA, Nov. 2001.
4. O. B. Shchekin and D. G. Deppe, Appl. Phys. Lett., vol. 80(18), pp. 3277-3279, May 2002.
5. S. Bank, V. Gambin, M. A. Wistey, H. Yuen, J. S. Harris, Jr., IEEE J. Quantum. Electron., vol. 40(6), pp. 656-664, 2004.
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7. P. Dowd, W. Braun, D. J. Smith, C. M. Ryu, C.-Z. Guo, S. L. Chen, U. Koelle, S. R. Johnson, and Y.-H. Zhang, Appl. Phys. Lett., 75 (9), pp. 1267-1269, 1999.
8. N. Tansu, and L. J. Mawst, IEEE J. Quantum. Electron., vol. 39 (10), October 2003.
9. J. R. Meyer, I. Vurgaftmann, L. J. Mawst, and N. Tansu, SPIE Photonic West 2005.

What Can InGaAsSbN QW Offer ?

- **Extremely Large dg/dn[1] ~ 1.06 x 10^{-15} cm^{-2}**
  - → dg/dn (InGaAsSbN) ~ 15-20 x dg/dn (InGaAsP)

$$\omega_{3dB}^2 \cong 1.55^2 \frac{1}{2\cdot\pi}\cdot\frac{1}{V}\cdot\frac{1}{h\nu}\cdot\frac{c}{N_{eff}}\cdot\frac{\alpha_m+\alpha_i}{\alpha_m}\cdot\frac{\partial g}{\partial n}\cdot\left(1+\frac{\tau_{DC}}{\tau_e}\right)^{-1} P_0$$

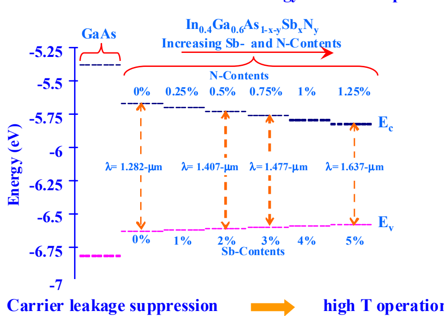
- **Improved Electron and Holes Confinement**
  - → Leading to reduced $1/\tau_{e_electron}$ & $1/\tau_{e_holes}$ [2]
  - → Improved η_{inj_th} at high temperature [2]

$$\eta_{_inj_th} = \frac{1}{\left[1+\frac{\tau_{bw}}{\tau_b}\cdot\left(1+\frac{\tau_{QW_total}}{\tau_e}\right)\right]}$$

Suitable for high-ω_{3dB} and high-T devices

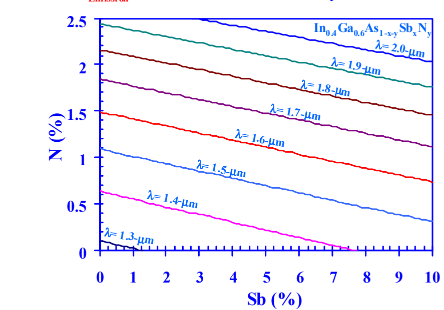
1. H. Shimizu, K. Kumada, S. Uchiyama, A. Kasukawa, Electron. Lett., Vol 37(1), January 2001
2. N. Tansu, and L. J. Mawst, Journal of Applied Physics, February 15th 2005.

InGaAsSbN on GaAs - Energy Band Lineup



Carrier leakage suppression → high T operation

Constant $\lambda_{Emission}$ Contour Plot of Strained-Layer InGaAsSbN on GaAs



→ InGaAsSbN / GaAs Analysis with *only* Strain Consideration

→ λ ~ 1550 nm → $In_{0.4}Ga_{0.6}As_{0.9375}Sb_{0.05}N_{0.0125}$

Methods to achieve InGaAsSbN QWs

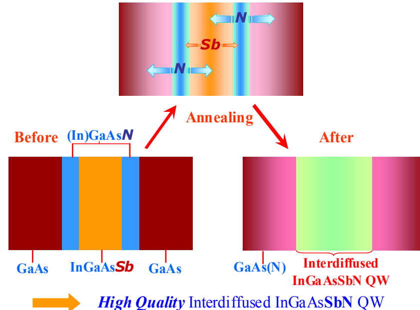
MBE
- Delivers promising results:
  - J_{th} = 1.06 kA/cm^2, L_{cav} = 2450 μm, λ= 1.498 μm[1]

MOCVD
- **Challenging** simultaneous incorporation of Sb- and N-species into InGaAs
- **Optimized** [V]/[III] growth requirement:
  - InGaAsN ~ 180 – 200 (with [DMHy]/[AsH_3] = 20 – 25)[2]
  - InGaAsSb ~ 3[3,4]

Our Novel Approach
- MOCVD epitaxy + interdiffusion process → Interdiffused InGaAsSbN QW
- *Individual optimization* of InGaAsN and InGaAsSb MOCVD growth

1. Seth Bank, Mark A. Wistey, Homan B. Yuen, Lynford L. Goddard, Vincenzo Lordi and James S. Harris, Jr., IEEE. J. Quantum Electron., vol. 40 (6), pp. 656-664, June 2004.
2. N. Tansu, N. J. Kirsch, and L. J. Mawst, Appl. Phys. Lett., vol. 81(14), September 2002.
3. J.G. Cederberg, M.J. Hafich, R.M. Biefield, M. Palmisiano, J. Cryst. Growth, vol. 248, pp. 289-295, 2003
4. H. C. Kuo, H. H. Yao, Y. S. Chang, M. Y. Tsai, S. C. Wang, L. H. Laih, Proc. of the 12th Int. Conf. – Metalorganic Vapor Phase Epitaxy (IC-MOVPE XII) 2004, Lahaina, Hawaii, USA, 2004.

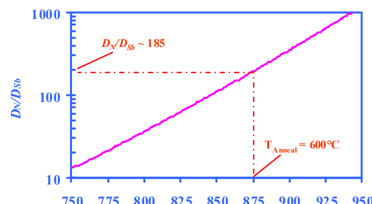
Schematics of MOCVD + Interdiffusion Process[1]



→ **High Quality** Interdiffused InGaAsSbN QW

1. R. A. Arif, and N. Tansu, "Interdiffused InGaAsSbN Quantum Wells on GaAs for 1300-1550 nm Lasers," Proc. of the SPIE Photonics West 2005, Novel Optoelectronics Devices, San Jose, CA, Jan 2005.

Ratio of N- and Sb-Diffusion Constants in GaAs Lattice



At T_{Anneal}=600°C:
- D_{Sb} = 5.3 × 10^{-18} cm^2/s, D_N = 9.84 × 10^{-16} cm^2/s [1,2]
- D_{In} ~ D_{Ga} ~ 10^{-20} cm^2/s [3]

1. V.V. Chaldyshev, N.A. Bert, G. Musikhin, A.A. Suvorova, V.V. Preobrazhenskii, M.A. Putyato, B.R. Semyagin, P. Werner, and U. Gosele, Appl. Phys. Lett., vol. 79(9), pp. 1294-1296, August 2001.
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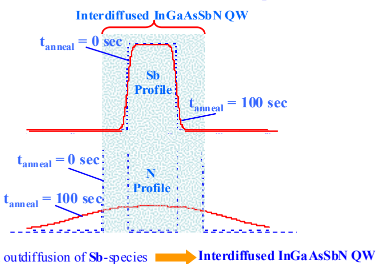
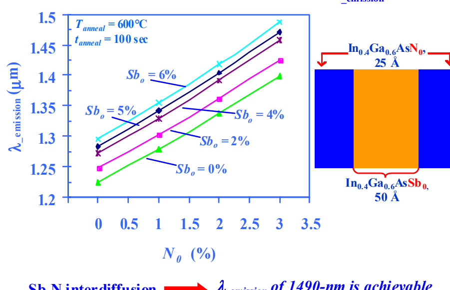
Concentration Profile of Sb and N-species



Minimum outdiffusion of Sb-species → Interdiffused InGaAsSbN QW

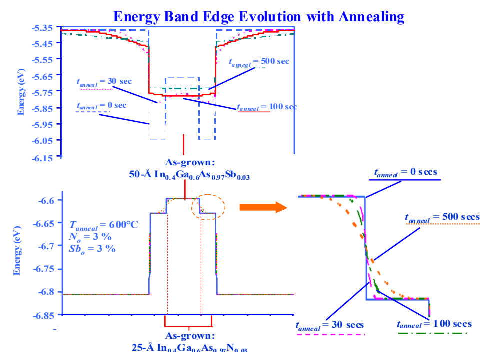
1. R. A. Arif, and N. Tansu, "Interdiffused InGaAsSbN Quantum Wells on GaAs for 1300-1550 nm Lasers," Proc. of the SPIE Photonics West 2005, Novel Optoelectronics Devices XIII, San Jose, CA, Jan 2005.

Effects of Sb- and N-Content on $\lambda_{_emission}$



Sb-N interdiffusion → *$\lambda_{emission}$ of 1490-nm is achievable*

Energy Band Edge Evolution with Annealing



Optimization of Structures for Long $\lambda_{_emission}$ ~ 1550 nm

Factors to Consider and Their Desirable Features:

- **InGaAsSb/InGaAsN layer thicknesses**:
  - → *thicker QW for lower quantized energy*
  - → *thinner InGaAsSb for higher N incorporation in the well center*
- **Initial Sb/N content in the InGaAsSb/InGaAsN layers**:
  - → *higher Sb_0- and N_0-content for lower E_g*
  - → *N is more dominant in extending $\lambda_{_emission}$*
- **In-content in the InGaAsSb/InGaAsN layers**:
  - → *higher In-content for lower E_g to begin with*
- **Annealing time**
- **Annealing temperature**

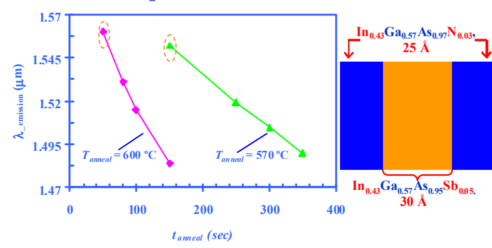
} *right combination of t_{anneal} and T_{anneal} for a particular QW thickness for maximum N incorporation in the well center*

Optimization of Structures for Long $\lambda_{_emission}$ ~ 1500 nm (cont'd)

Practical Limitations:

- **Too high Sb-content and too thick QWs**:
  - → *too high of a strain and low N incorporation in the well center*
- **Too high In-content in InGaAsN layers:**
  - → *difficult to grow with sufficiently high initial N-content, N_o*
- **For good annealing process control:**
  - → *t_{anneal} cannot be too short*

$\lambda_{_emission}$ of the Optimized Structure



Estimated from **optimized** proposed structure:

- **-1.552 μm** for t_{anneal} = 150 sec, T_{anneal} = 570°C
- **-1.56 μm** for t_{anneal} = 50 sec, T_{anneal} = 600°C

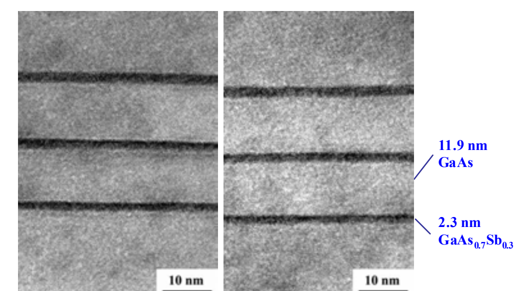
Experimental Work: Investigation of Sb-N Interdiffusion

Objective:
- To realize high quality SbN-based QW by MOCVD + interdiffusion
- To understand the fundamental materials parameters, i.e., D_{Sb} and D_N in GaAs

Methods:
1. GaAsSb QW on GaAs and GaAsN QW on GaAs.
2. GaAsSb-GaAsN QW on GaAs → *Interdiffused* GaAsSbN QWs
3. InGaAsSb-GaAsN QW on GaAs → *Interdiffused* InGaAsSbN QWs

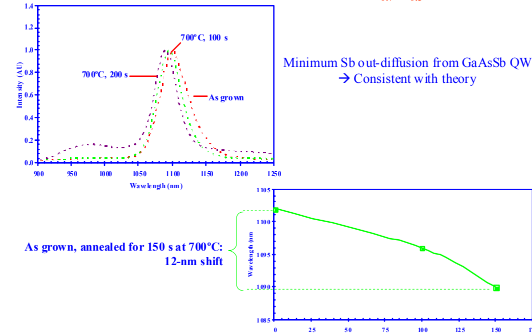
Sets of Experimental Studies:
- Rapid Thermal Annealing (RTA) to study interdiffusion of Sb and N in GaAs
- Photoluminescence measurement
- Correlation with numerical model to extract D_{Sb} and D_N in GaAs
- TEM, SIMS and XRD to gain insight into structure and materials composition

TEM result of $GaAs_{0.7}Sb_{0.3}$ MQWs on GaAs: As-grown



- TEM Analysis Indicates Sharp Interfaces for GaAsSb and GaAs

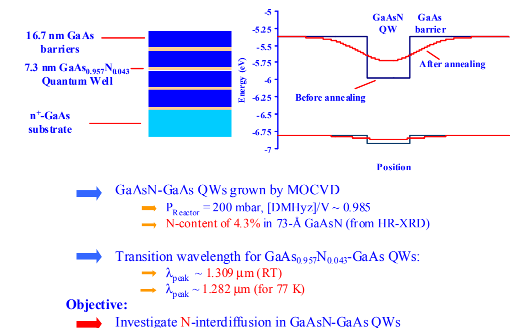
Low Temperature PL of Interdiffused $GaAs_{0.7}Sb_{0.3}$ QWs



Minimum Sb out-diffusion from GaAsSb QW → Consistent with theory

As grown, annealed for 150 s at 700°C: 12-nm shift

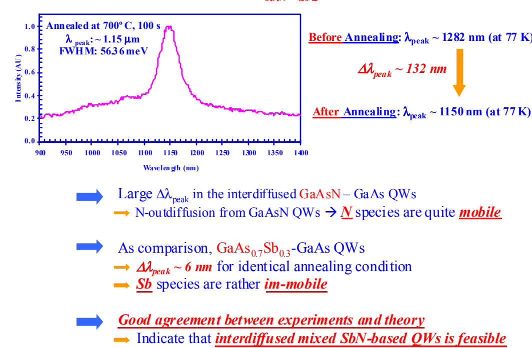
N-Interdiffusion in GaAsN-GaAs Quantum Wells



- GaAsN-GaAs QWs grown by MOCVD
  - $P_{Reactor}$ = 200 mbar, [DMHyz]/V ~ 0.985
  - N-content of 4.3% in 73-Å GaAsN (from HR-XRD)
- Transition wavelength for $GaAs_{0.957}N_{0.043}$-GaAs QWs:
  - λ_{peak} ~ 1.309 μm (RT)
  - λ_{peak} ~ 1.282 μm (for 77 K)

Objective:
- Investigate N-interdiffusion in GaAsN-GaAs QWs

N-Interdiffusion in $GaAs_{0.957}N_{0.043}$-GaAs Quantum Wells



Before Annealing: λ_{peak} ~ 1282 nm (at 77 K)

$\Delta\lambda_{peak}$ ~ 132 nm

After Annealing: λ_{peak} ~ 1150 nm (at 77 K)

- Large $\Delta\lambda_{peak}$ in the interdiffused GaAsN – GaAs QWs
  - N-outdiffusion from GaAsN QWs → **N** species are quite ***mobile***
- As comparison, $GaAs_{0.7}Sb_{0.3}$-GaAs QWs
  - *$\Delta\lambda_{peak}$ ~ 6 nm* for identical annealing condition
  - **Sb** species are rather ***im-mobile***
- ***Good agreement between experiments and theory***
  - Indicate that ***interdiffused mixed SbN-based QWs is feasible***

Summary

Interdiffused InGaAsSbN QWs for 1300-1550-nm

- **Novel** method $\lambda_{_emission}$ in the 1500-nm regime on GaAs is proposed:
  - combination of **MOCVD growth** and **interdiffusion** process
  - based on **established** growth methods of **InGaAsN**[1] and **InGaAsSb**[2,3]
  - an **excellent** alternative (due to its **simplicity**) to the existing approach
  - potentially feasible method based on encouraging experimental results

Future Plans

***Strain-Compensated* Interdiffused GaAsSbN QW Lasers**
- → Theoretical and experimental studies to investigate the interdiffusion process in (In)GaAsSb-GaAsN QWs
- → Interdiffused (In)GaAsSbN QW Edge-Emitting Laser Devices

Interdiffused InGaAsSbN QW Lasers

Investigate the interdiffusion process in InGaAsSb-InGaAsN QWs

Interdiffused InGaAsSbN QW Edge-Emitting Laser Devices

1. N. Tansu, N. J. Kirsch, and L. J. Mawst, Appl. Phys. Lett., vol. 81(14), September 2002.
2. J.G. Cederberg, M.J. Hafich, R.M. Biefield, M. Palmisiano, J. Cryst. Growth, vol. 248, pp. 289-295, 2003.
3. H. C. Kuo, H. H. Yao, Y. S. Chang, M. Y. Tsai, S. C. Wang, L. H. Laih, Proc. of the 12th Int. Conf. – Metalorganic Vapor Phase Epitaxy (IC-MOVPE XII) 2004, Lahaina, Hawaii, USA, 2004.