

Selective oxidation of AlGaAs for confinement in III-V photonic devices

Guilhem Almuneau, Stéphane Calvez,
Gaël Lafleur, Chantal Fontaine, Alexandre Arnoult,
Antoine Monmayrant, Henri Camon, Olivier Gauthier-Lafaye

LAAS-CNRS, Toulouse - France

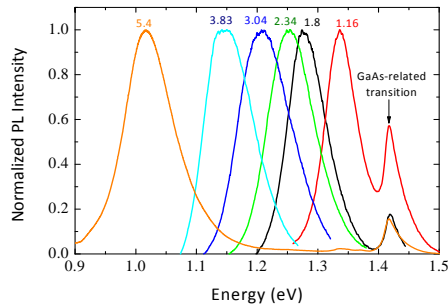
16th NAMIS workshop, VTT Technical Research center, Oulu, Finland, June 18-20, 2018

Photonics team : Research activities

More efficient systems

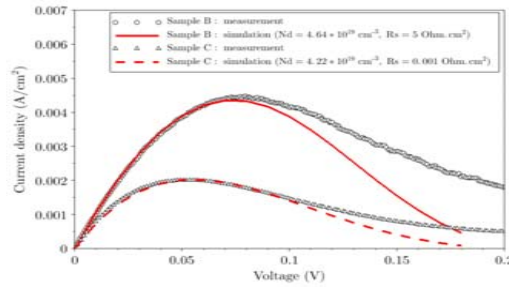
C. Fontaine, G. Almuneau

New III-V epitaxial materials (Sb, N, Bi)



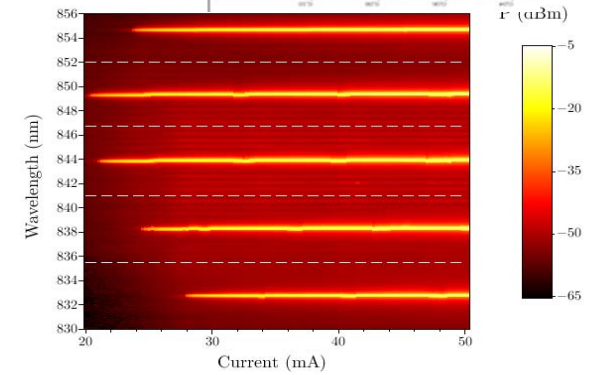
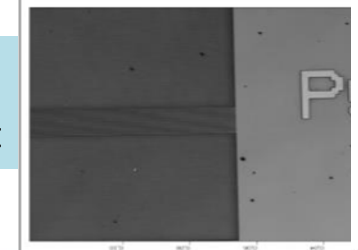
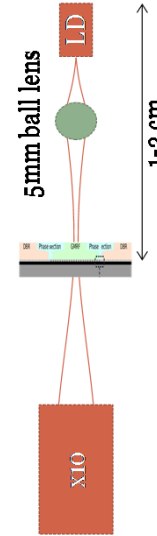
Coll. LPCNO / INSA

High perfs tunnel junctions for high efficiency photovoltaics (EMRP Solcell, coll. LNE)



Simpler systems

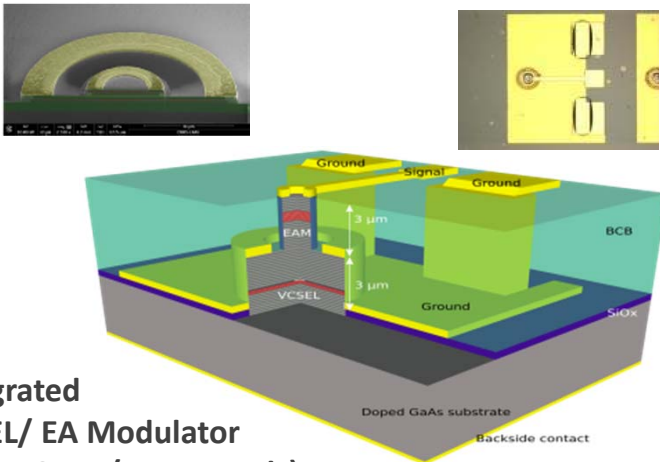
O. Gauthier-Lafaye, A. Monmayrant



External cavity laser diodes with GMRF (coll. CNES)

Multifunctional systems

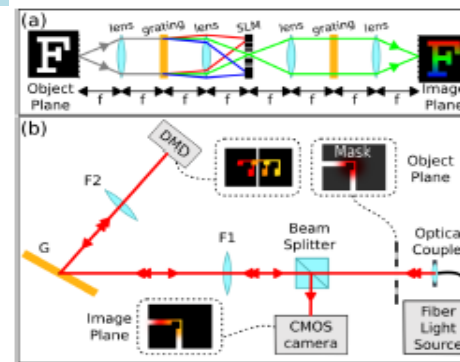
G. Almuneau, O. Gauthier-L., S. Calvez



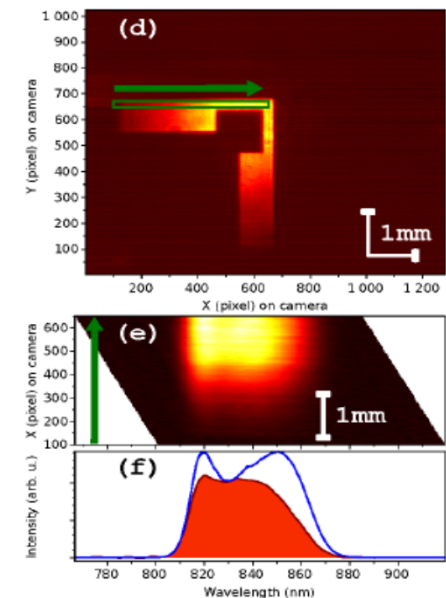
Integrated VCSEL/ EA Modulator (Coll. TONA / VUBrussels)

Smarter systems

A. Monmayrant



Hyperspectral smart imager for compressed sensing (Coll. Robotics team)



The micro and nanotechnologies platform

> An infrastructure/know-how to support micro- and nanotechnology-related projects

- Optics/Photonics
- Micro/Nano-electronics
- Bioelectronics, Biosystems, Biophysics
- Micro/Nano-devices and Systems



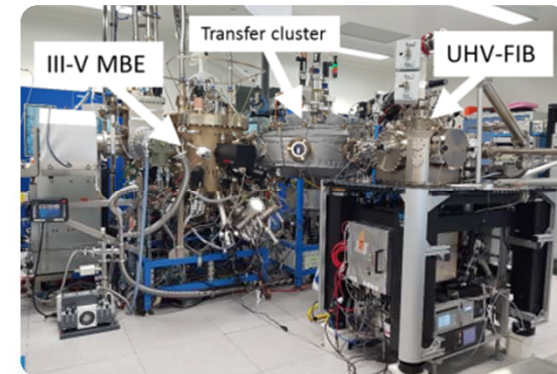
■ The platform

- 2500 m² with 1500m² clean room
- 180-200 regular users
- 140 projects/year (half exogenous)
- 1,2M€ operational budget average
- 35 M€ equivalent new equipment



TEAM technical staff

- 35-40 engineers, technicians
- Expertise, management, maintenance, development of
 - Infrastructure
 - Equipments
 - Processes
- Technological processes
 - Direct support
 - Formation
 - Management
 - Dissemination



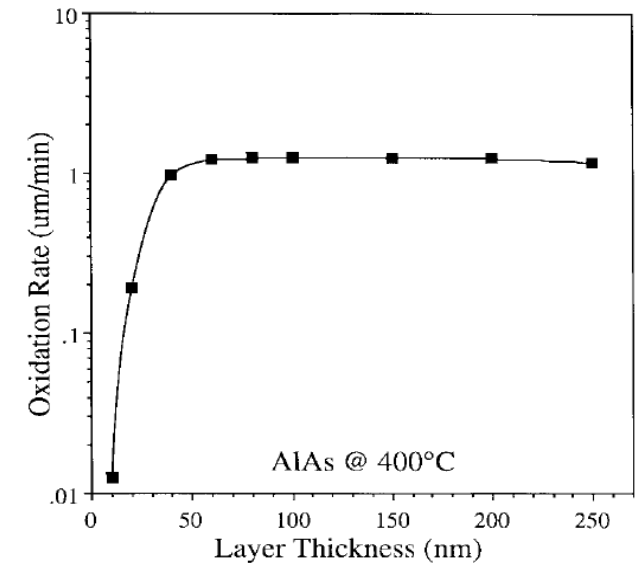
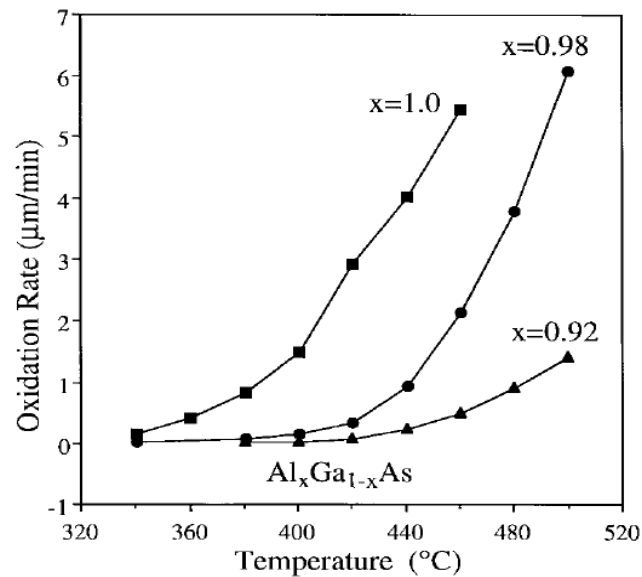
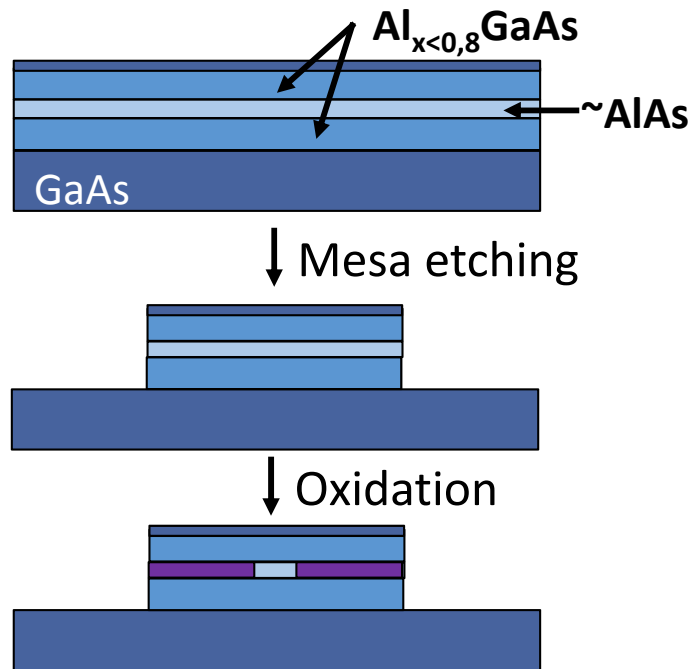
P r o f i l o m e t r y	UV lithography	Ink jet	Thermal/UV nano replication	J o u l e s e f f e c t
	X RIE Electroplating	DRIE	Diffusion SCD CMP	
	D Wafer bonding	A Pick and place	P RTP Dicing Descuming	
	LPCVD Chemistry	F M	E gun PVD S Ebeam lithography	
	Laser lithography	V D	Flip chip P D	
Roll lamination	FIB Stripping	Optical microscopy ICP plasma		
M Annealing	ALD	S Projection lithography	Wire bonding	
B Sputtering	Screen printing	E lithography	Si anisotropic etching	
E FTIR Redistribution	M Ion implantation	Ellipsometry		

Member of national and inter-regional networks

- Introduction
 - The III-V semiconductor oxidation process
 - AlO_x-based photonic devices
- Oxidation system with optical in-situ monitoring
- Modelling oxidation as a predictive tool
- III-V oxidation process : New potentialities for photonic devices
- Conclusions

III-V oxidation: the basics

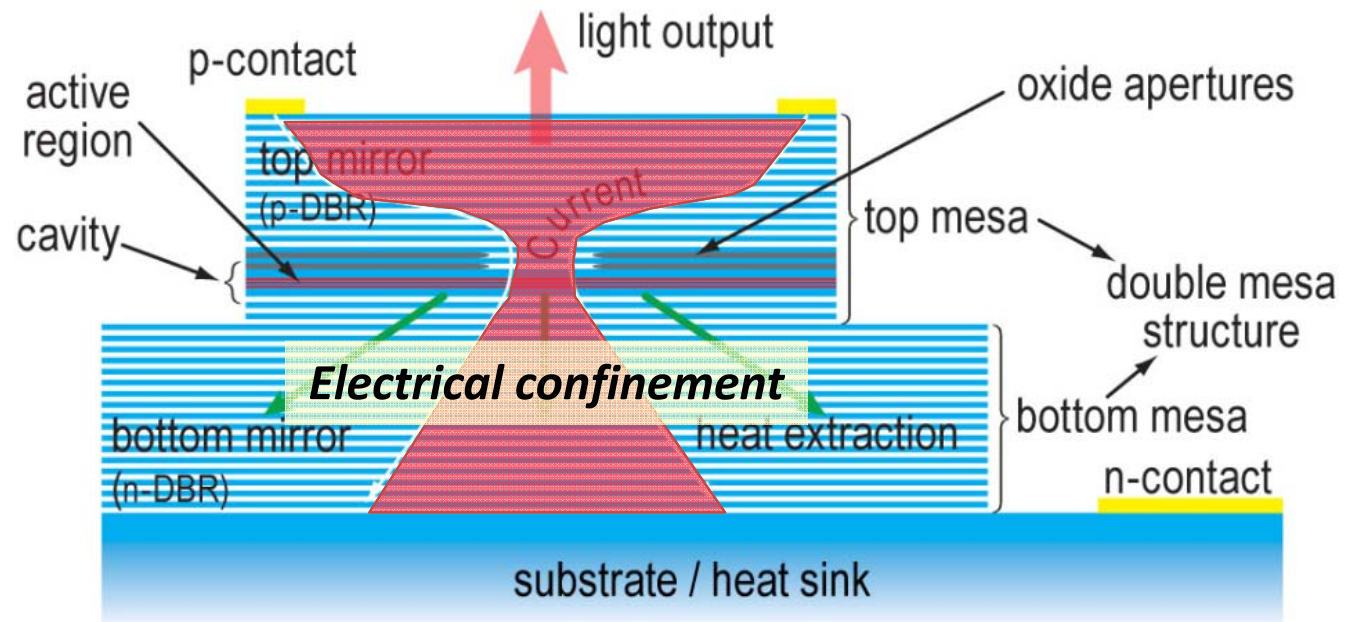
- Process which converts
 - A high Al-containing semiconductor into an insulator
 - A high-index ($n \sim 2.9$) into a low-index material ($n \sim 1.6$)
 - Lateral oxidation from the sidewalls of an etched mesa
 - 5 to 12% volumic contraction



K.D. Choquette et al., *JSTQE*, **3**, 916 (1997)

- **Contrasts between AlGaAs and AlOx properties:**
 - **Electrical conductivity (Semiconductor/dielectric)**
 - **Refractive index** ($n_{\text{AlGaAs}}=3$ / $n_{\text{AlOx}}=1.6$)

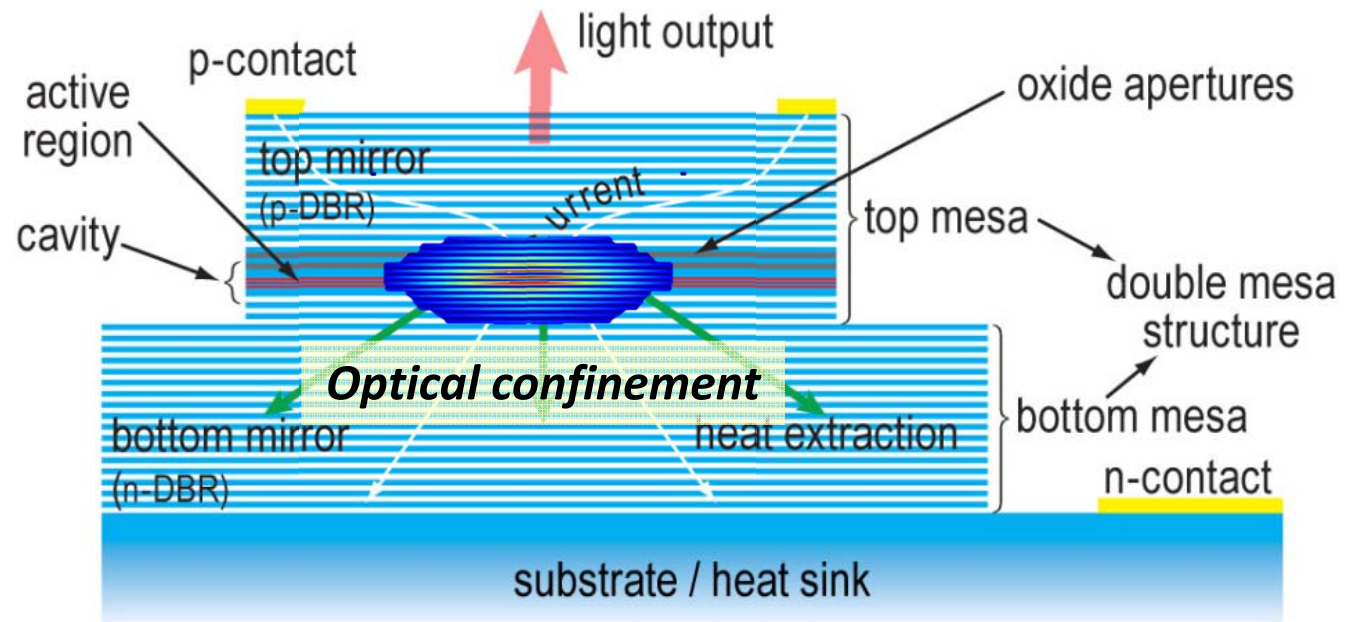
Example: VCSEL



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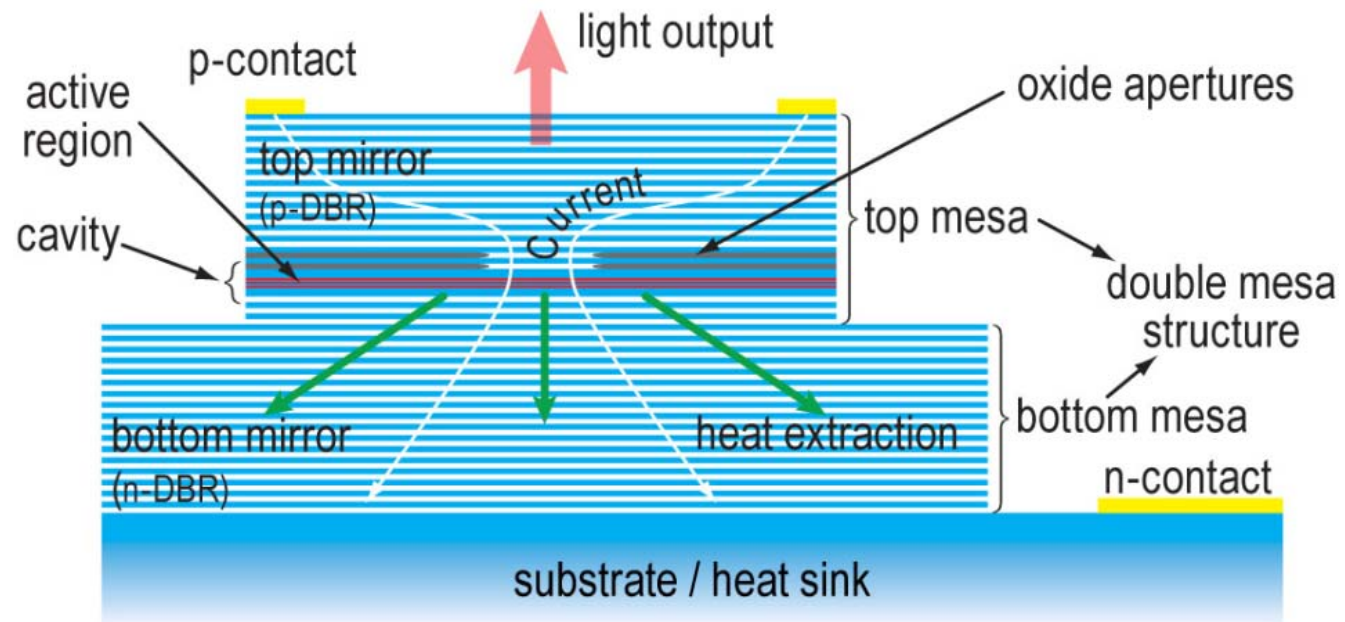
Example: VCSEL



➤ Contrasts between AlGaAs and AlOx:

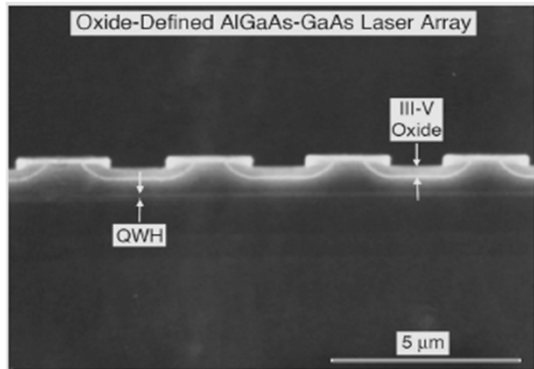
- Electrical conductivity (Semiconductor/dielectric)
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Example: VCSEL



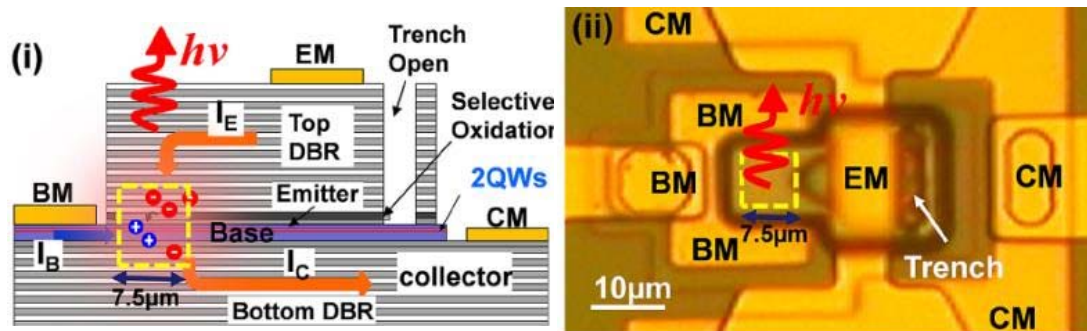
- Controls the pumped/emitting active zones
- Overlap between optical mode and amplified gain
- Strong benefits in laser sources in terms of performances

Edge Emitting lasers



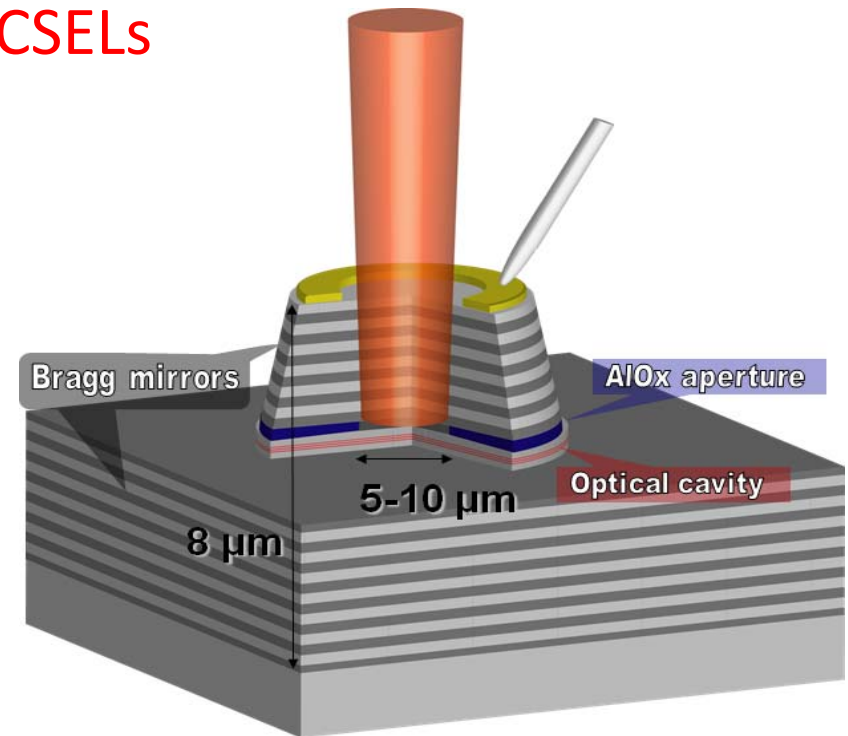
J.M. Dallesasse et al., *APL*, **58**, 834 (1991)

Transistor lasers



M.K. Wu et al., *APL*, **103**, 011104 (2013)

VCSELs

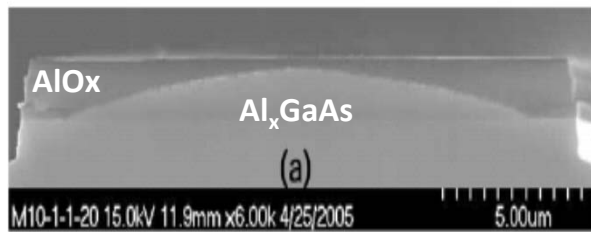


D.L. Huffaker et al., *APL*, **65**, 97 (1994)

J.M. Dallesasse, *proc. IEEE*, **101**, 2234 (2013)

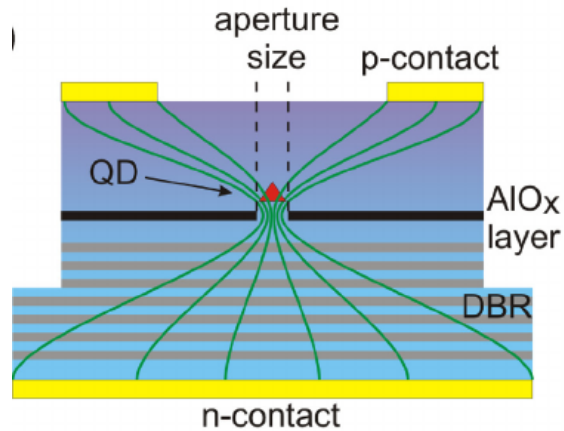
III-V oxidation: Applications

Microlenses



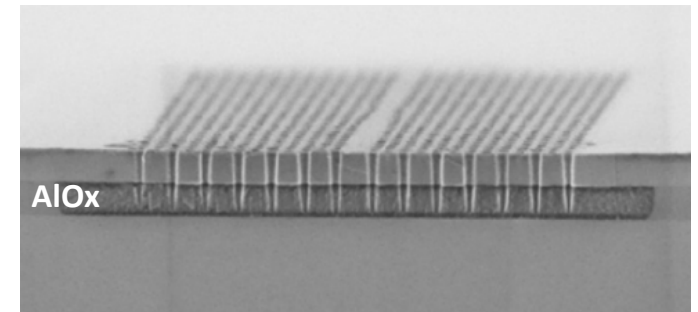
K.S. Chang et al., *PTL* (2006)

Stressor for QD growth



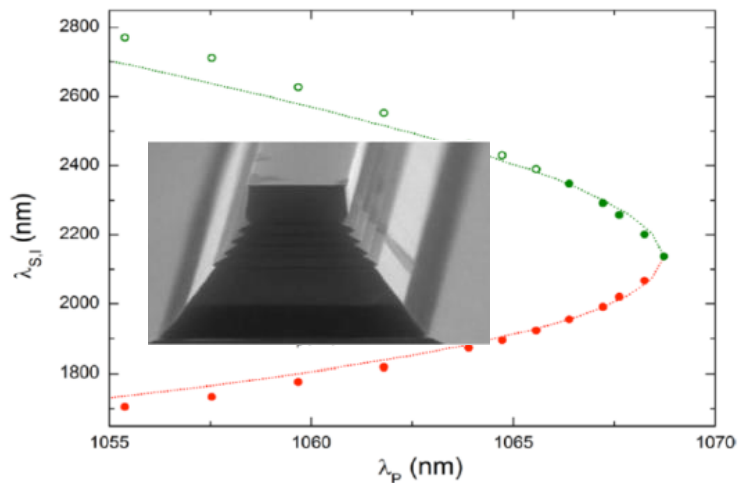
A. Strittmatter et al., *APL* (2012)

Photonic crystal



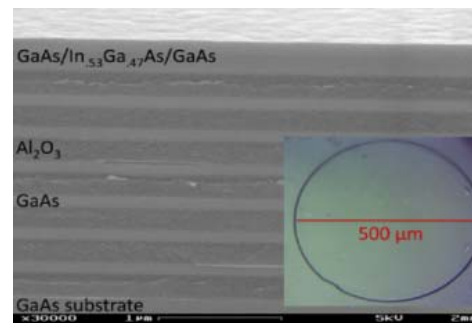
K. Welna et al., *Photon & Nanost.*, (2013)

NLO waveguides, OPO



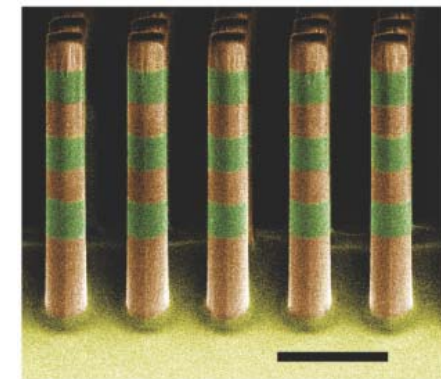
M. Savanier et al., *APL* (2013)

SESAMs



Nabanja et al., *JAP* (2013)

Metamaterials, Nanoantennas



S. Liu et al., *Adv. Opt. Mat.* (2016)

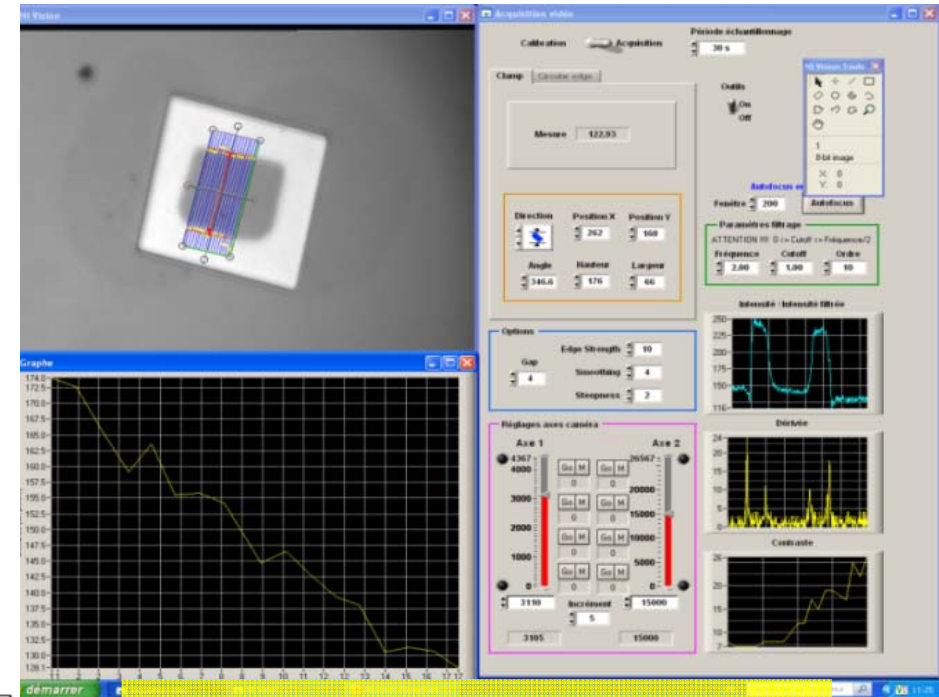
Oxidation furnace with in-situ monitoring

Oxidation furnace with in-situ monitoring

Cooperation between
AET & LAAS CNRS

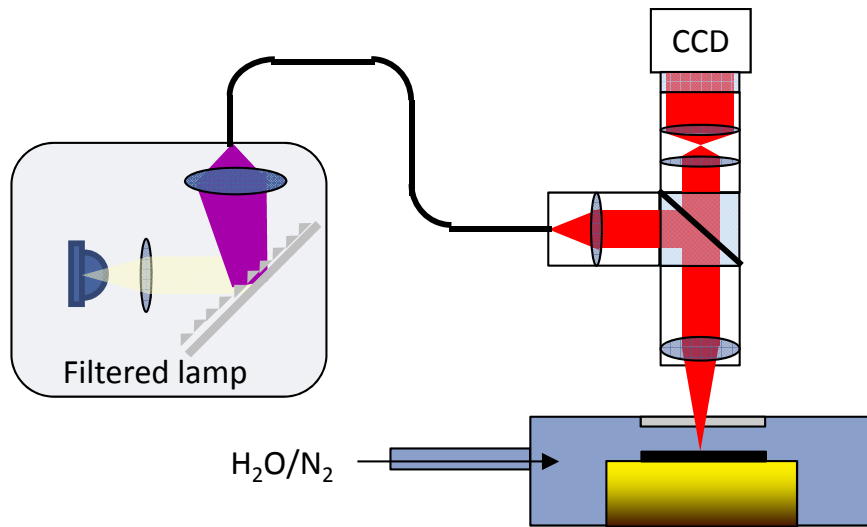


in-situ optical real-time monitoring
for highly reproducible process



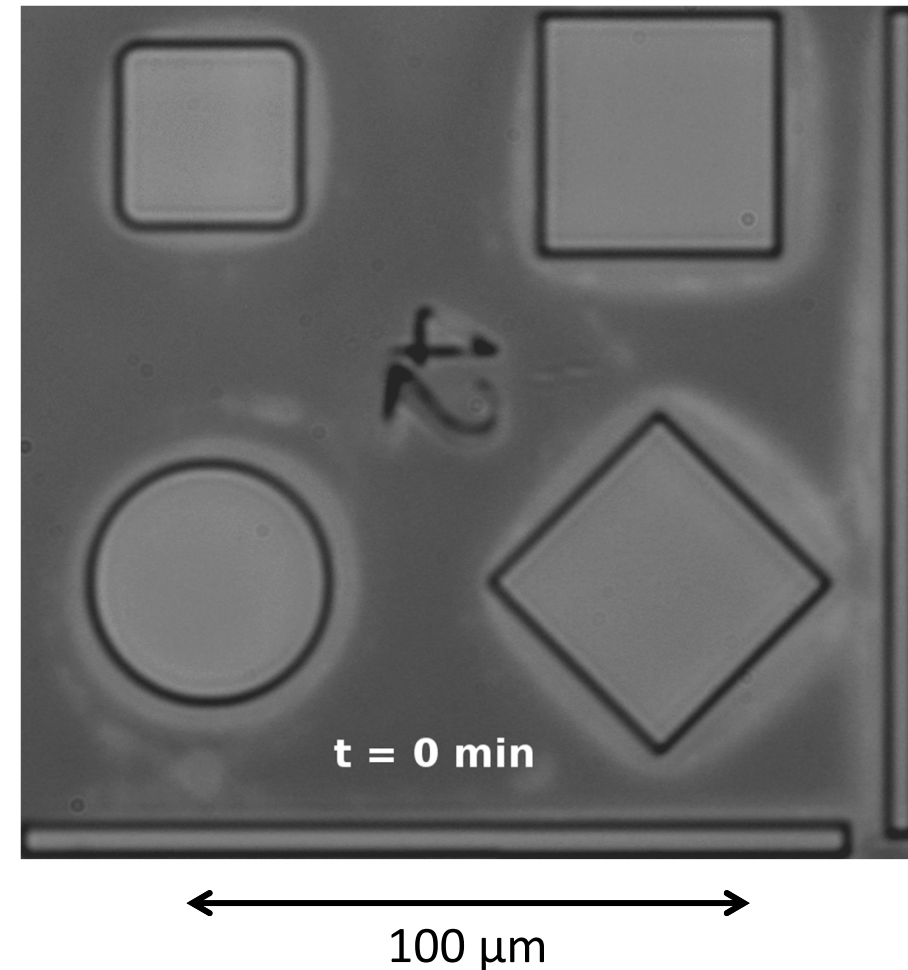
Automated control by image processing
(License LAAS-CNRS)

- Up to 6'' wafers
- Excellent uniformity & reproducibility
- In-situ monitoring with $\sim 1 \mu\text{m}$ resolution
- **Commercialized by AET Technologies: high volume VCSEL production**

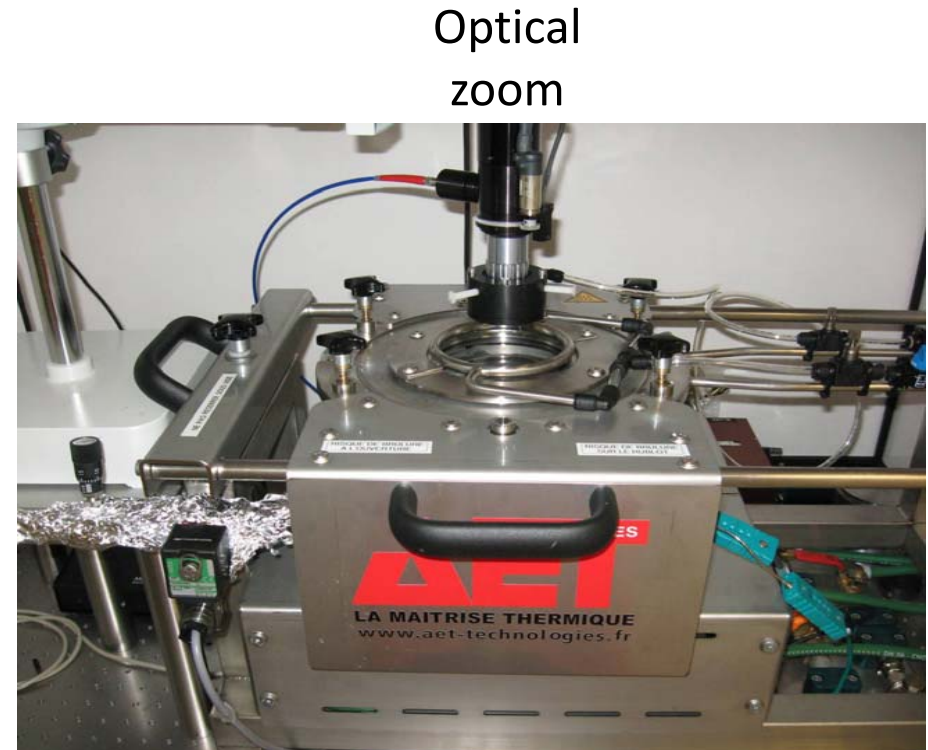
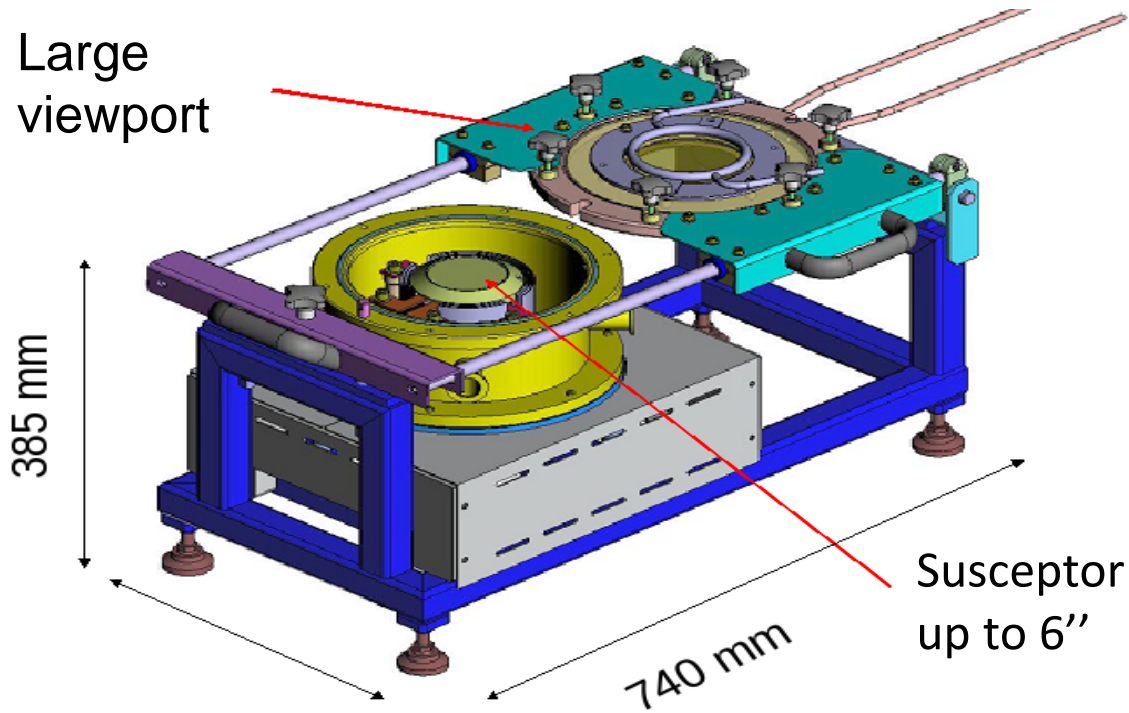


Almuneau et al, Sem. Sc. & Technol, 23, 105021 (2008)

- Tunable filtered white lamp illumination
- CCD detection
- Useful spectral range 700-950nm :
Semi-transparent window for AlGaAs and DBRs



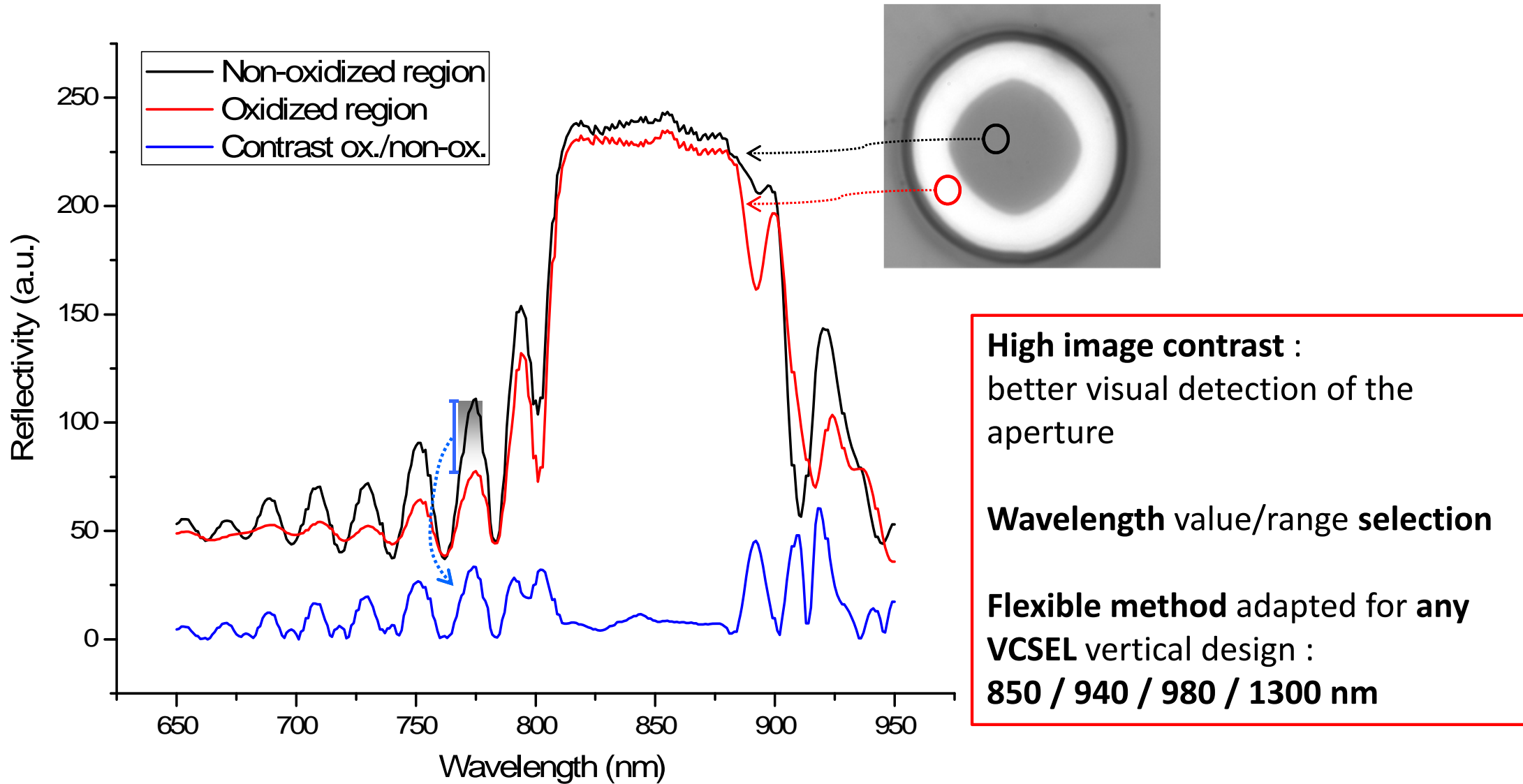
Oxidation system with optical monitoring



1st prototype installed at LAAS (2007)

- Uniform heating system (Typ. range : 400-500 °C)
- Controlled gas/liquid flows by Mass Flow Controllers
- Mechanical vibrations proofing

Principle : Wavelength-selective imaging



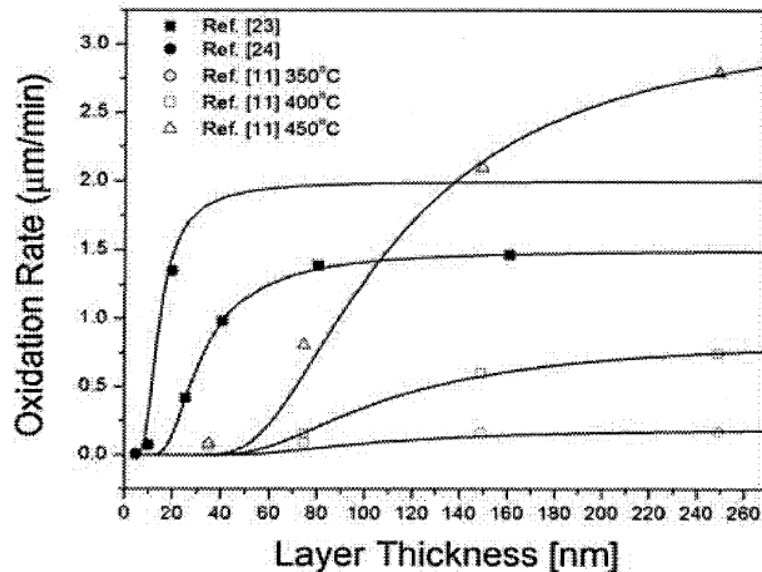
AlGaAs oxidation kinetics modelling*

** PhD thesis : Gaël LAFLEUR (2013-2016)*

Oxidation process modelling

- Extensions of Si-based (Deal & Grove, JAP, **36**, 3770 (1965)) oxidation model to include

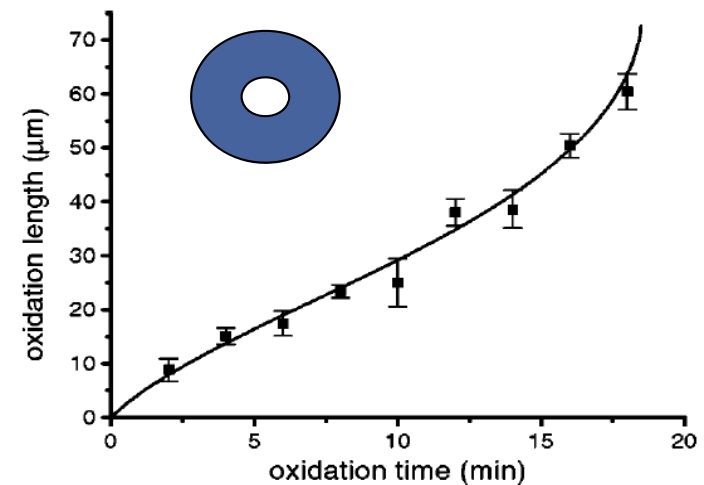
- *Thickness-dependence*



P.-C. Ku et al, *JSTQE*, **39**, 577 (2003)

- *Lateral oxidation*

(=> acceleration as surface shrinks)

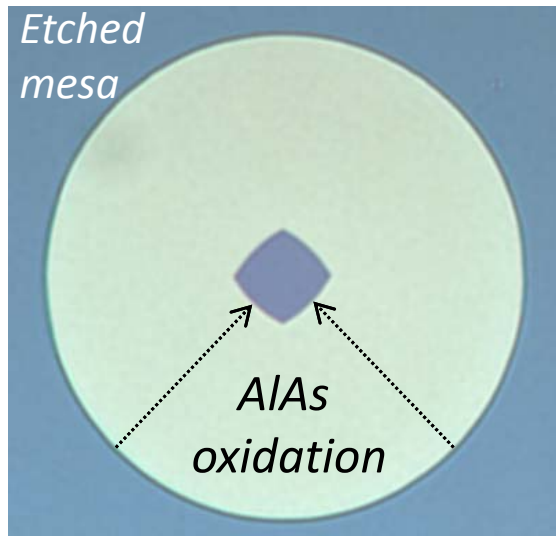


A.C. Alonzo et al, *JAP*, **84**, 6901 (1998)

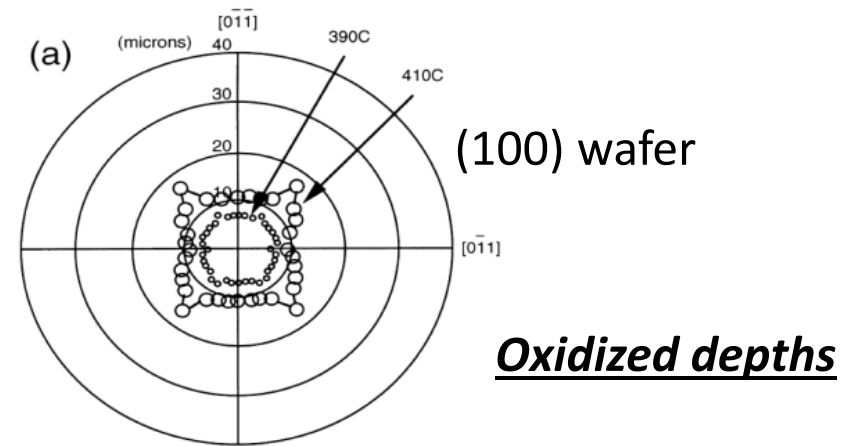
But always assumed to be isotropic !

III-V oxidation: an anisotropic process

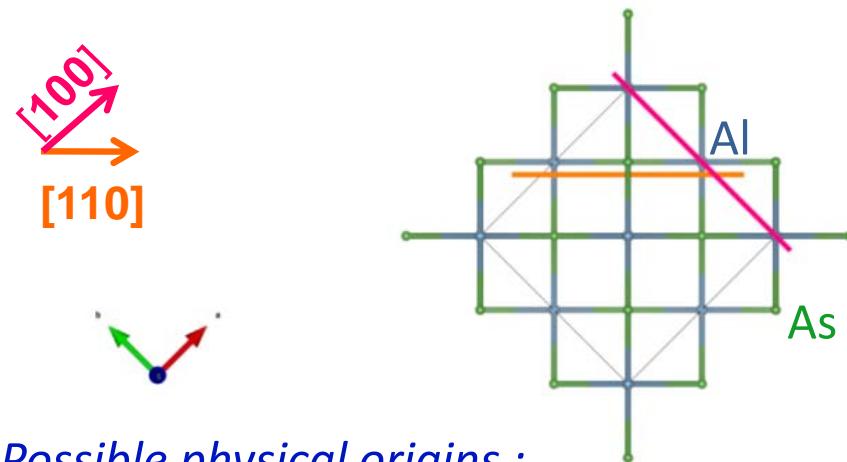
- In-plane anisotropy
 - Experimentally observed
 - Always modeled as an isotropic process
 - *(001) substrate* : Slow directions = $\langle 110 \rangle$
Fast directions = $\langle 100 \rangle$



1st observation :
Huffaker et al., APL, 65, 97 (1994)



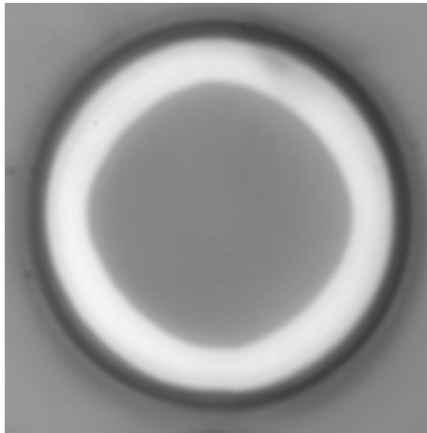
Vaccaro et al., Microelec J., 30, 387 (1999)



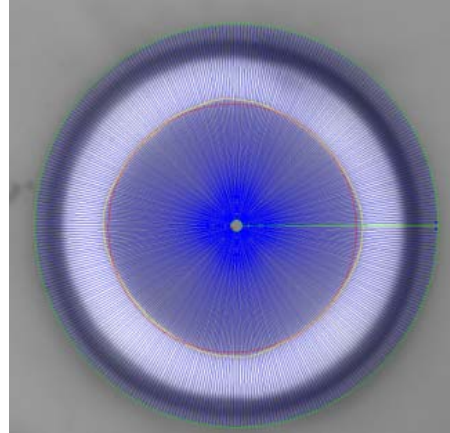
Possible physical origins :

- Different atom densities depending on crystal axis
- Chemical origin : Al / As sequencing

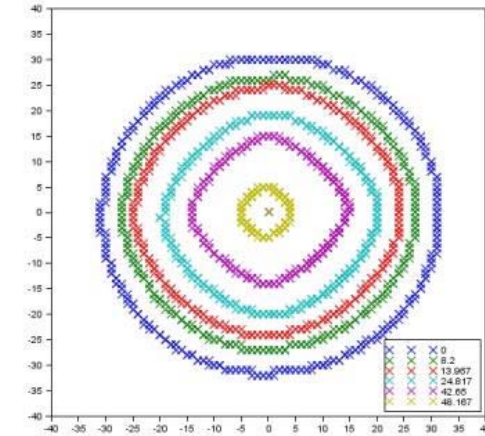
Profile data extraction



1 : Image from real-time monitoring



2 : Image edge detection

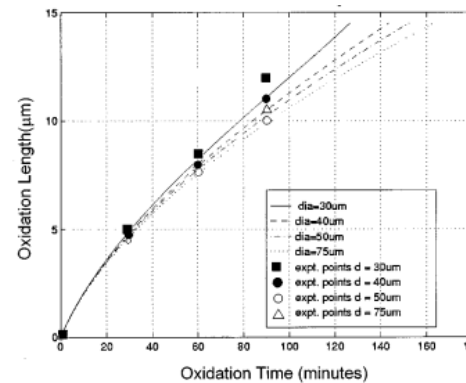


3 : Extraction of the oxidation front profile

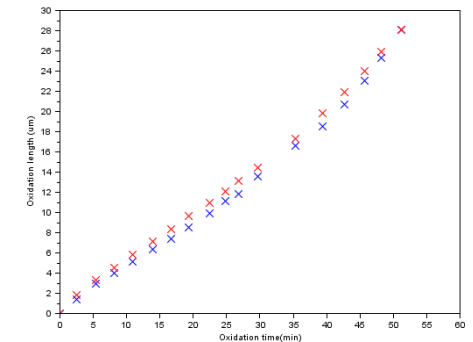
Numerous acquired profiles during one run

Influences of process conditions :

- Temperature
- Pressure
- composition de l'AlGaAs
- Initial mesa shapes



*Koley et al., JAP, 82(9),1997 :
Many repetitive runs*

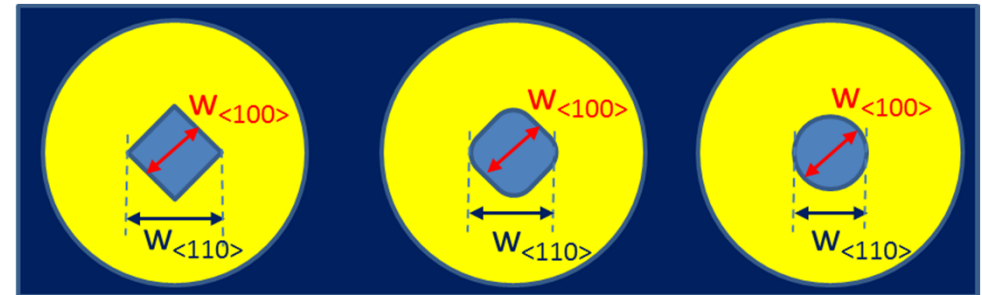


This work : only 1 run to retrieve complete kinetic

Effect of process parameters on the anisotropy

Definition of the square fraction (anisotropy):

$$s = \frac{|w_{\langle 110 \rangle} - w_{\langle 100 \rangle}|}{w_{\langle flat \rangle} \cdot (1 - \frac{1}{\sqrt{2}})}$$



$$w_{\langle 100 \rangle} = w_{\langle 110 \rangle} / \sqrt{2}$$

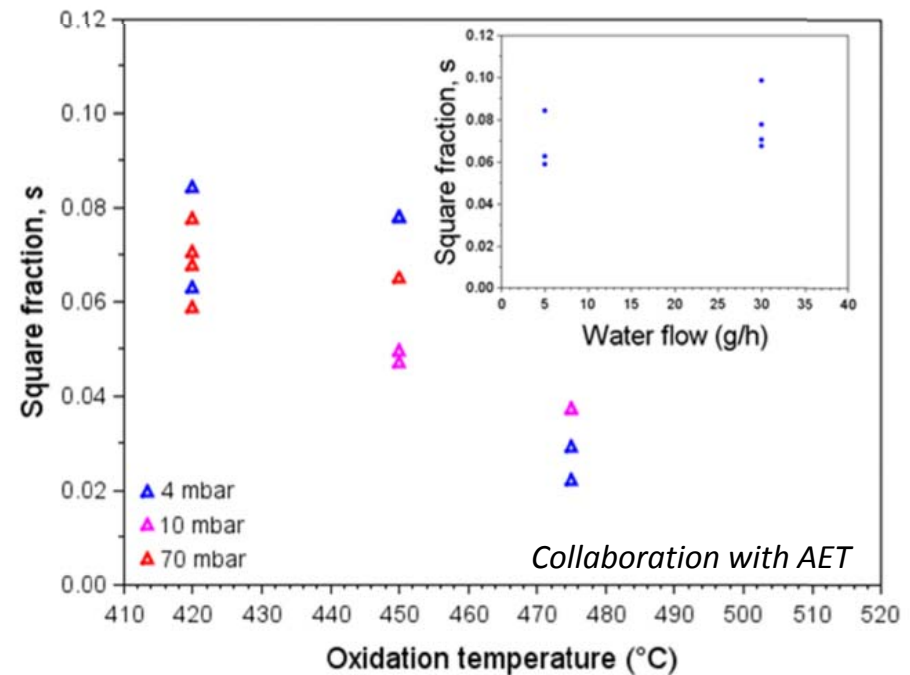
$$s = 1$$

$$0 < s < 1$$

$$w_{\langle 100 \rangle} = w_{\langle 110 \rangle}$$

$$s = 0$$

- Decreases with Ga incorporation
 - Isotropic for [Ga]>5%
- Decreases with the process temperature
- Small increase with water vapor flow
- No influence from the chamber process pressure
- *Isotropic when the oxidation is diffusion-limited*

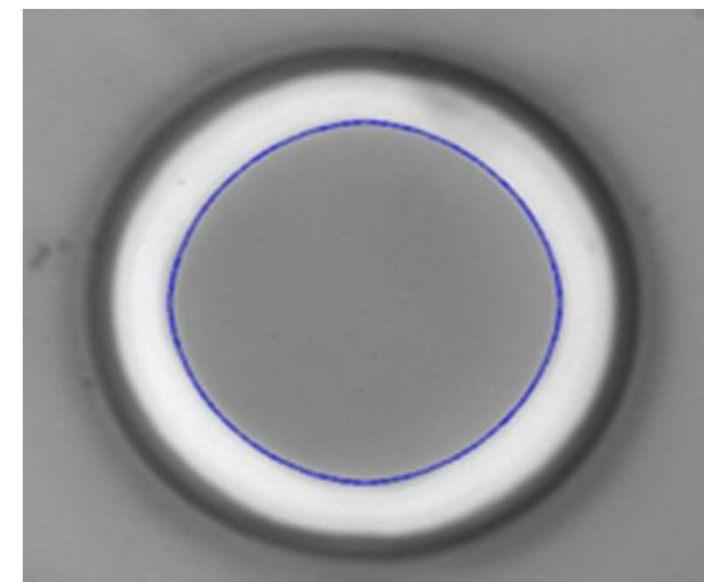
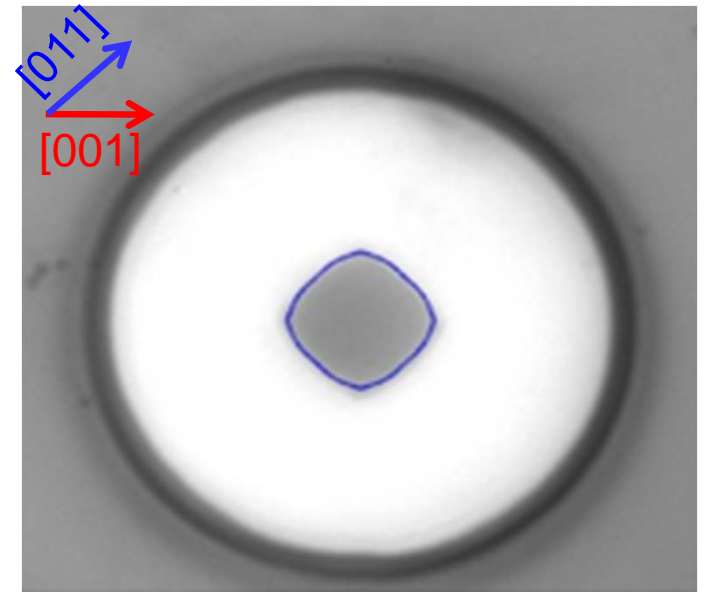
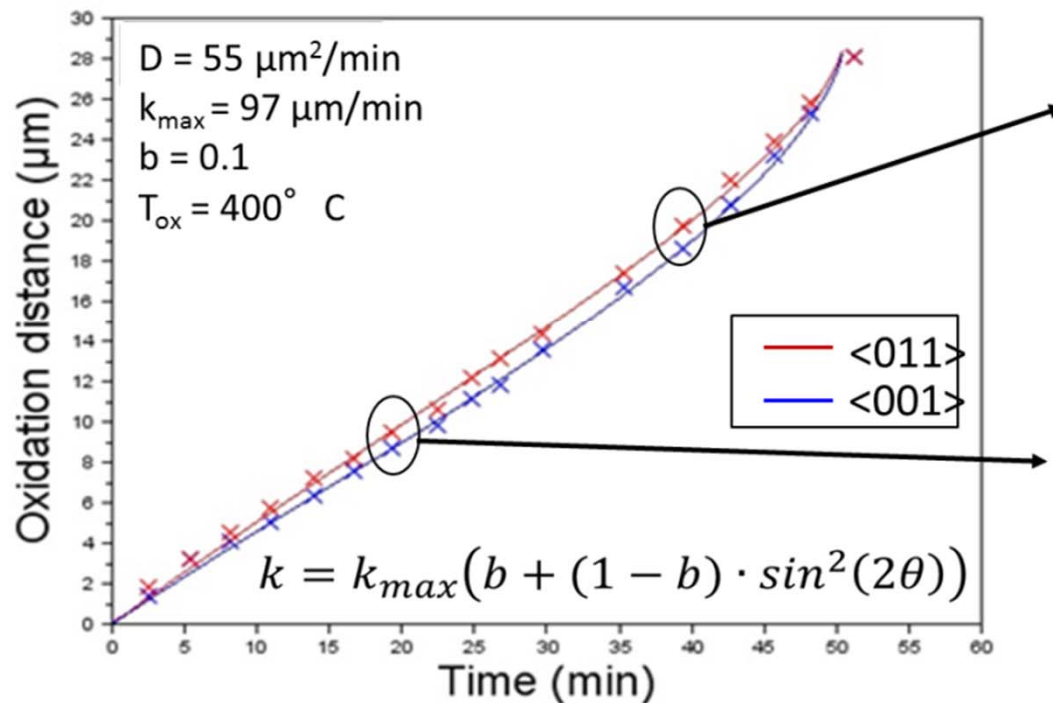


➔ **Anisotropy is correlated to chemical reactions**

G. Lafleur et al, *Optical Materials Express* (2018)

In-plane anisotropy model: Results

- Empirical model >> accurate **predictive tool** for oxidation front evolution
- Process is a combination of:
 - An **isotropic diffusion** of oxydants and by-products
 - An **anisotropic chemical reactions**



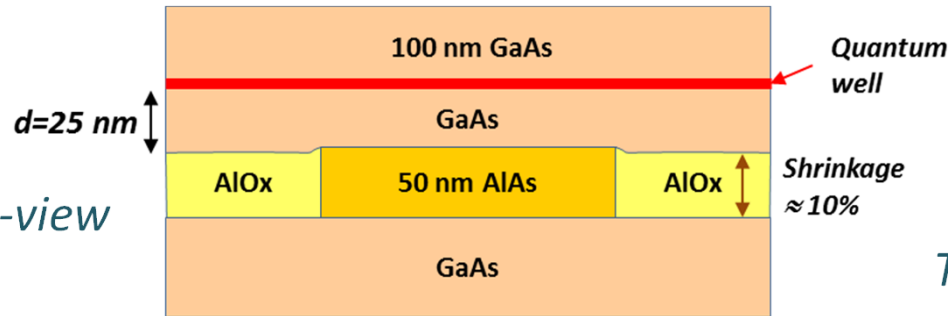
S. Calvez et al, Optical Materials Express (2018)

III-V oxidation process :

New potentialities for photonic devices

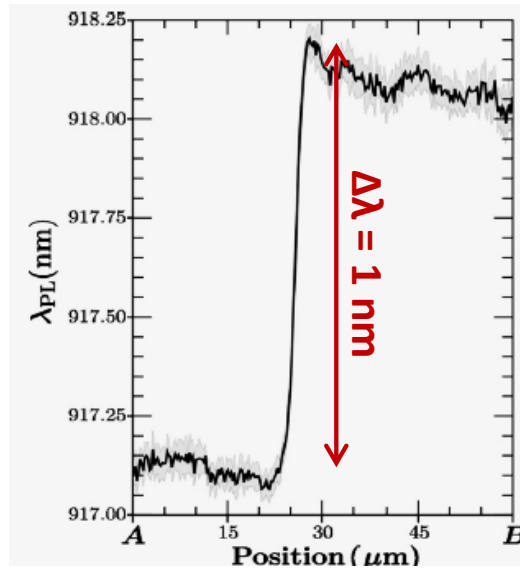
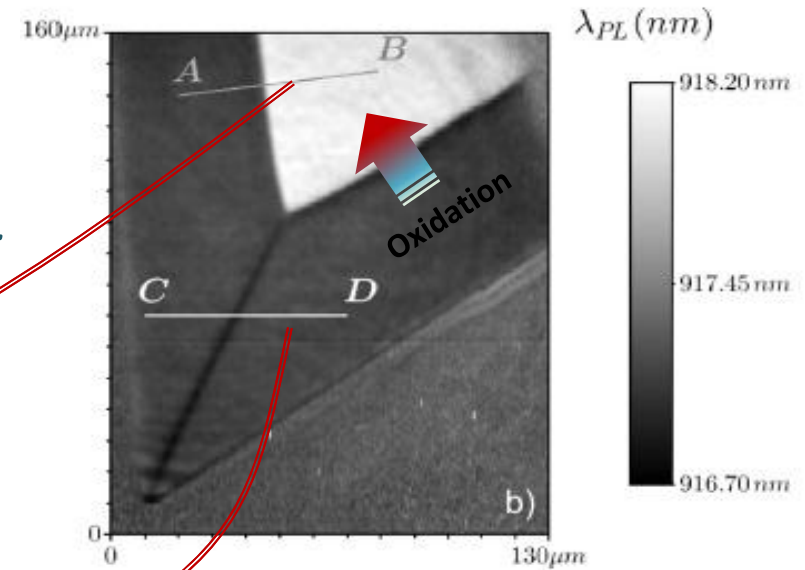
Strain induced by the oxidation of AIAs

Cross-view

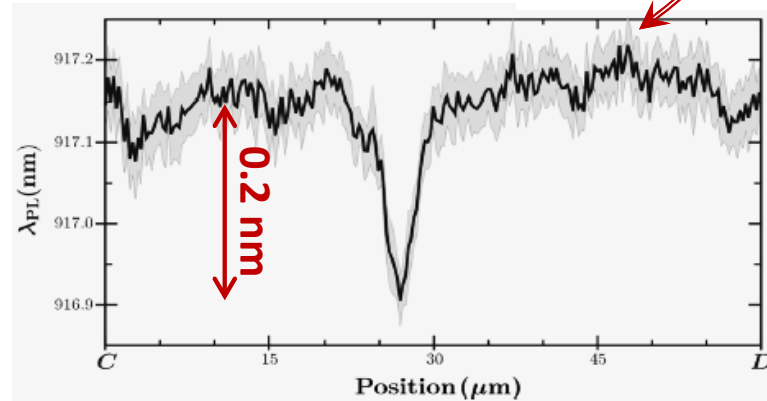


Top-view :

Spectral imaging of λ_{QW}



λ_{QW} across the oxidation front (AB section)

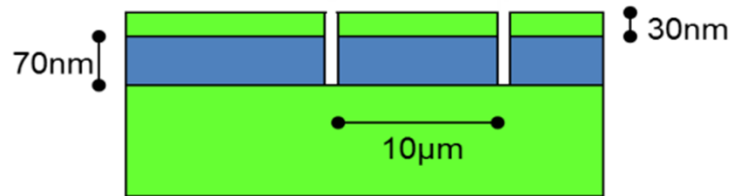
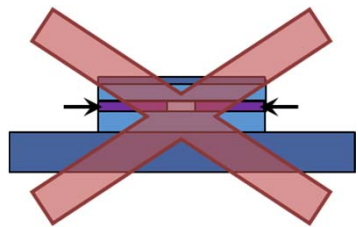


λ_{QW} across the coalescence of oxidation fronts (CD)

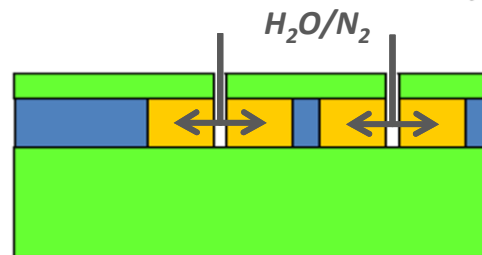
- QW PL : Strain-induced wavelength shift
- Confirmed by FEM calculations
- Embedded strain to be considered in AlOx-based devices

F. Chouchane et al, APL, vol. 98, 2011

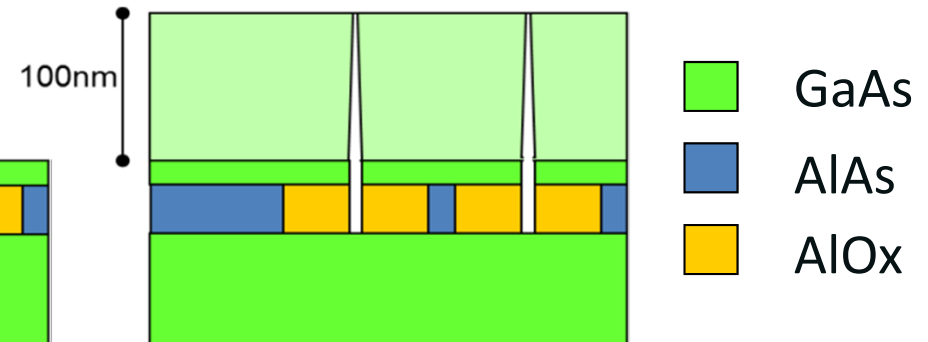
Planar oxidation with epitaxial regrowth



Etching holes
with submicronic sizes



Radial oxidation around
the etched holes

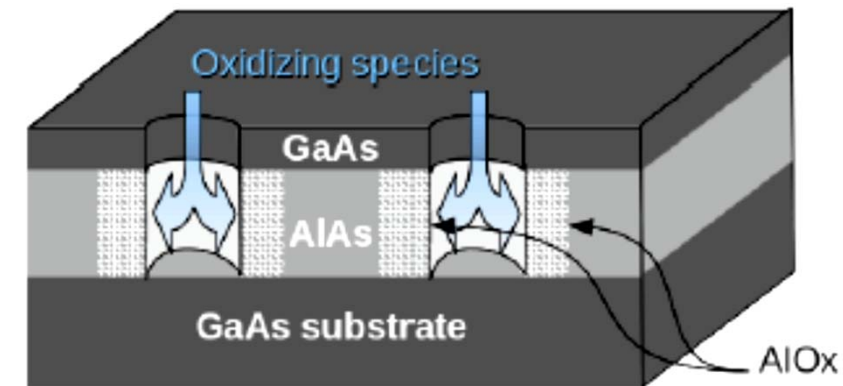


Epitaxial regrowth by MBE



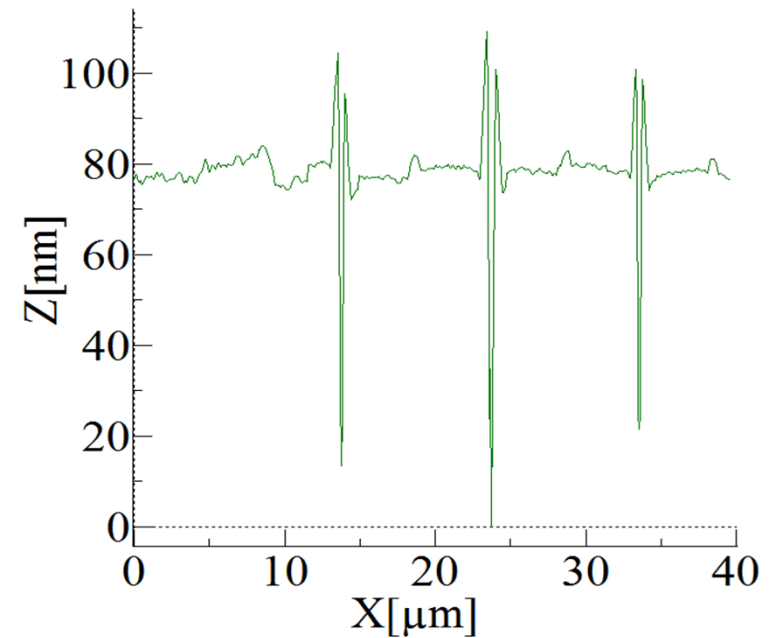
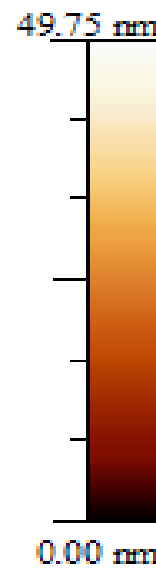
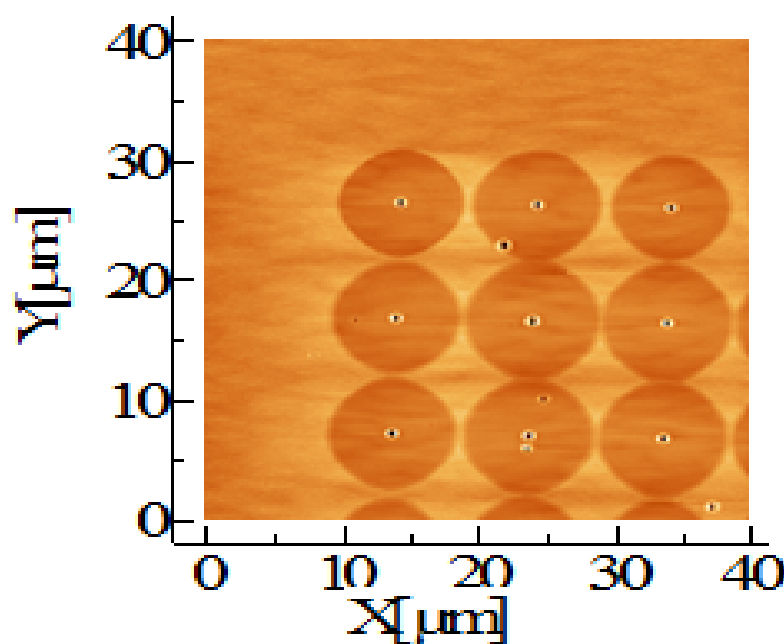
➤ Advantages of surface driven oxidation

- Keeps the surface planarity
- Free engineering of oxide shapes
- Buried patterned layer by epitaxial regrowth
- Applications: complex confinement schemes, integrated device arrays



Epitaxial regrowth on buried oxide patterns

1. Oxide removal by Hydrogen plasma at low temperature (400-500°C)
2. Epitaxial regrowth



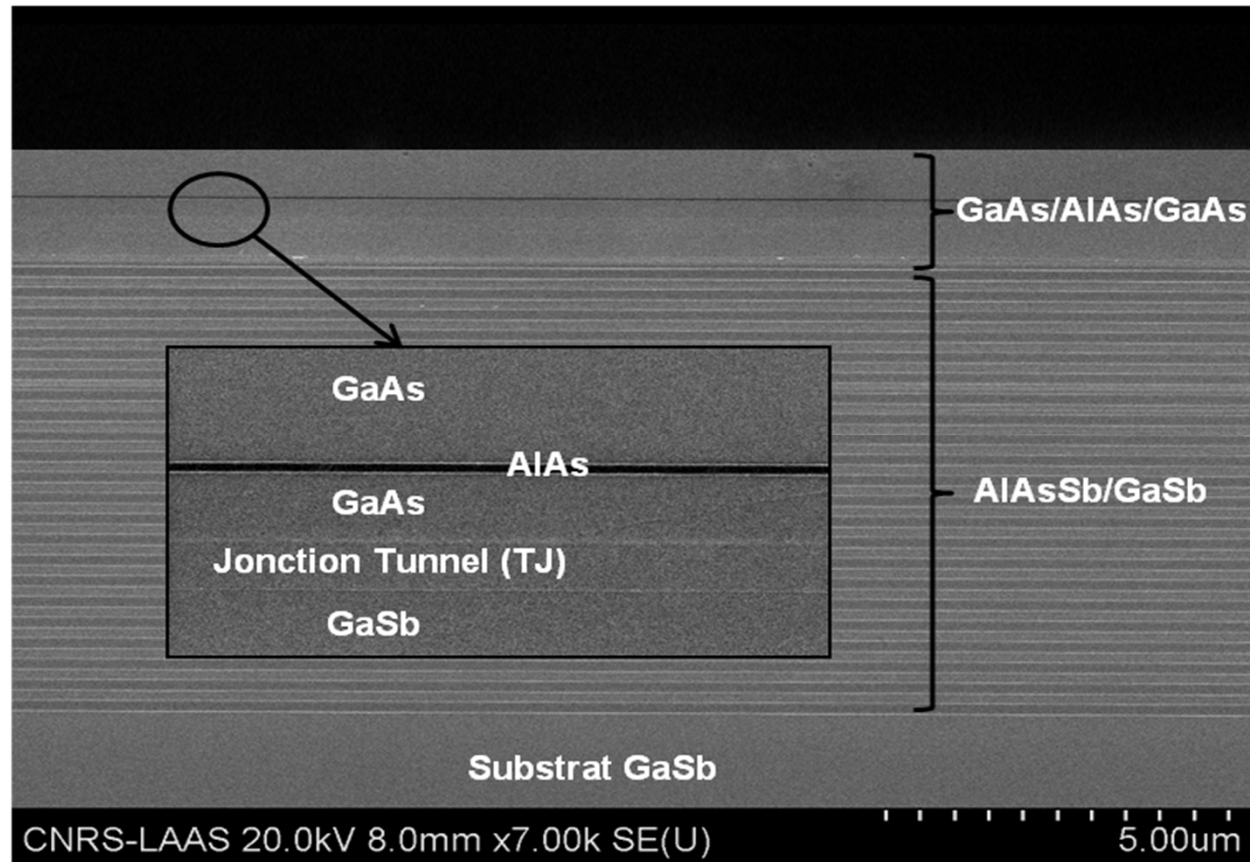
- ✓ Low roughness after 100nm regrown GaAs both on original and oxidized structure
- ✓ Good photoluminescence properties of the regrown material

Patent LAAS-CNRS : Planar oxidation method for producing a localized buried insulator (WO 2006082322)

III-V oxidation process :

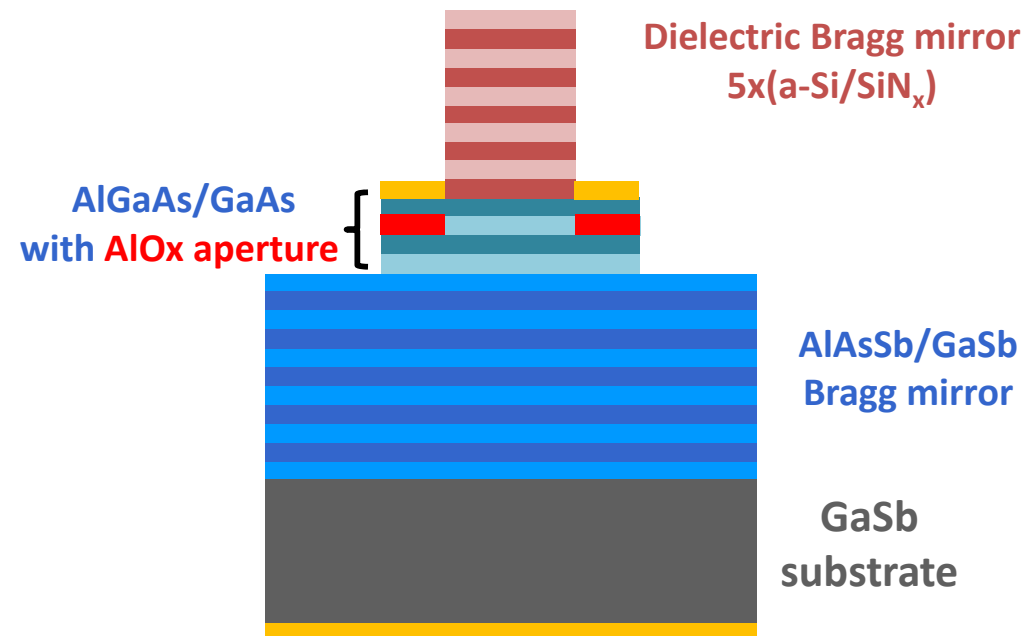
Application to other III-V systems (than AlGaAs)

Metamorphic epitaxial growth of III-As on III-Sb



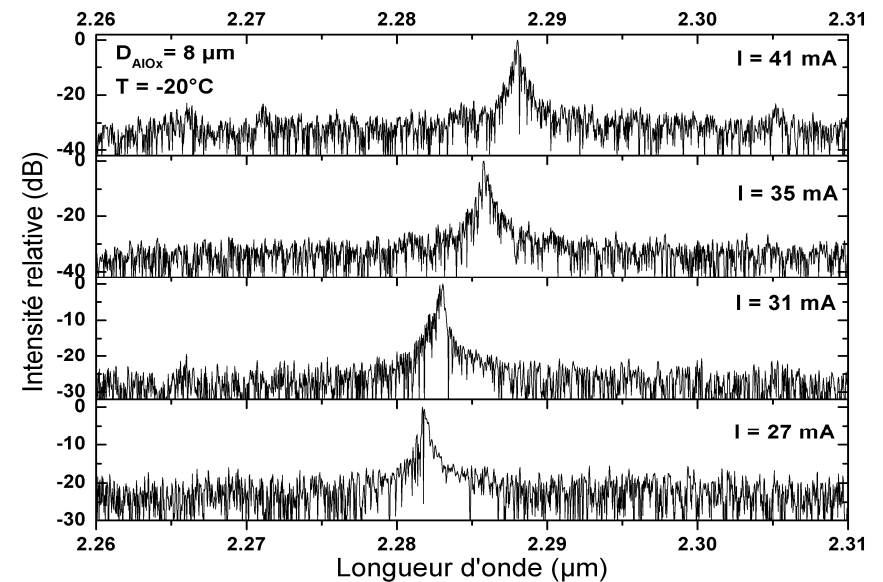
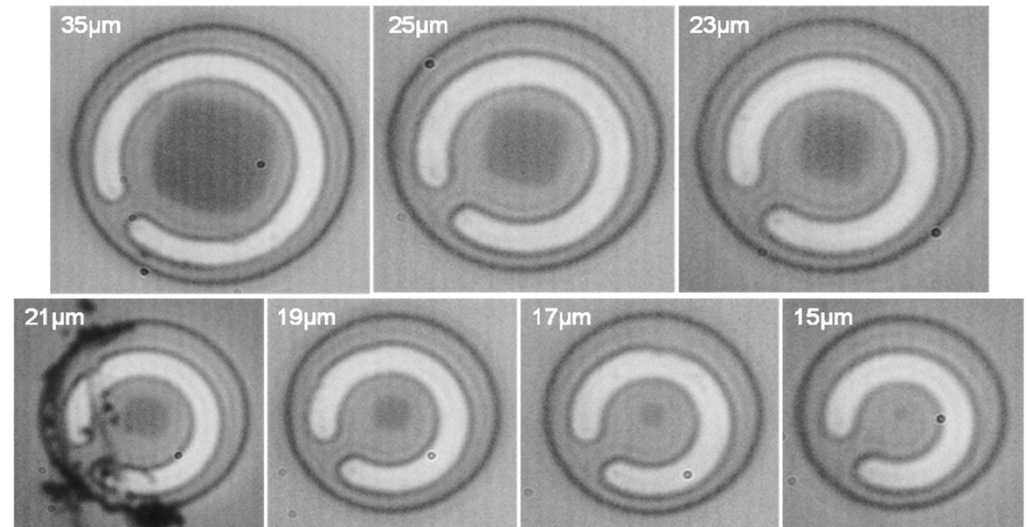
- Tunnel junction at the GaAs/GaSb interface
- Good crystalline quality of metamorphic GaAs/AlAs/GaAs layers
- Fully relaxed with laterally with dislocations released laterally

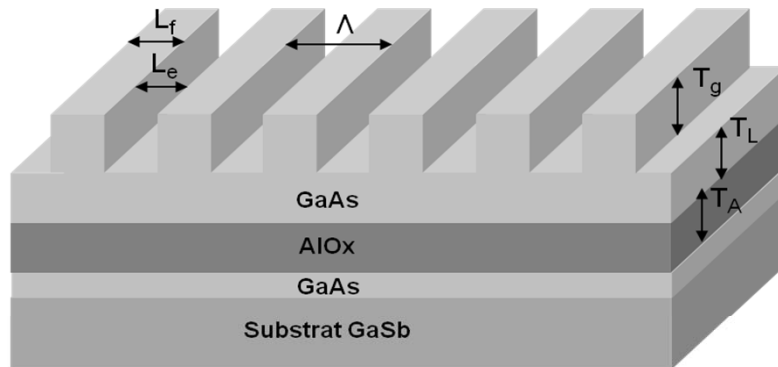
Oxide confined Mid-IR Sb-VCSEL



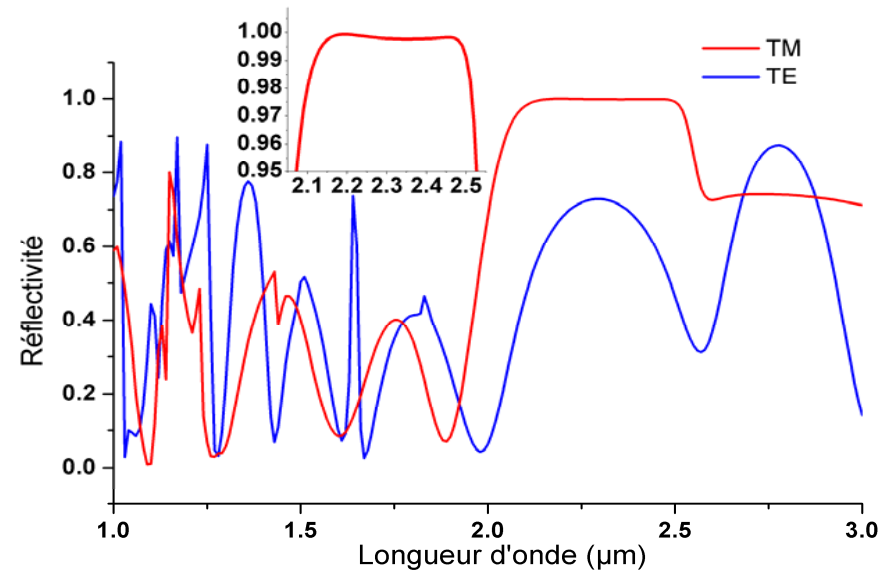
- ✓ confinement by selective oxidation of metamorphic AlAs layer
- ✓ 1st demonstration on GaSb vertical structure

Y. Laaroussi, et al., Electron. Lett. 48:1616 (2012)





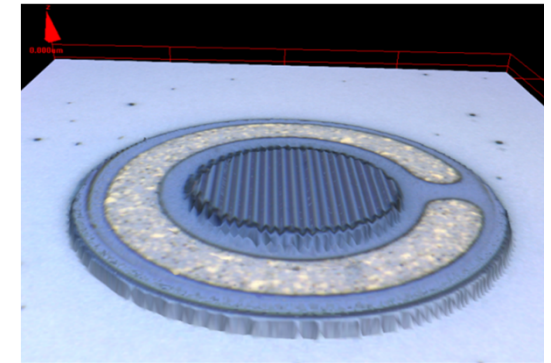
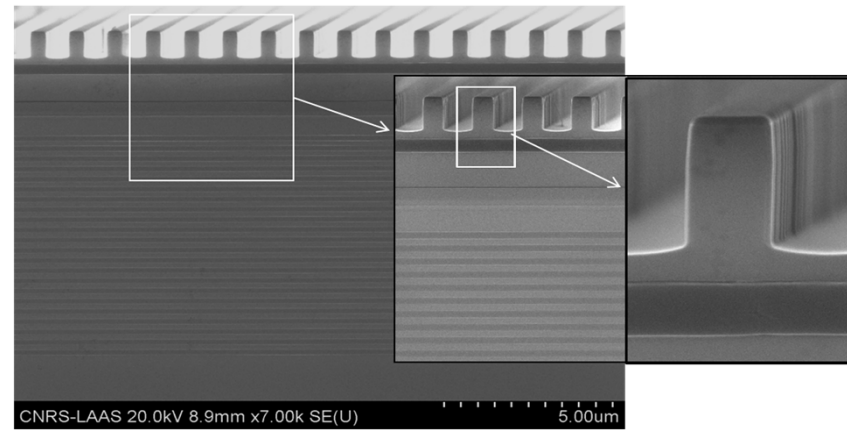
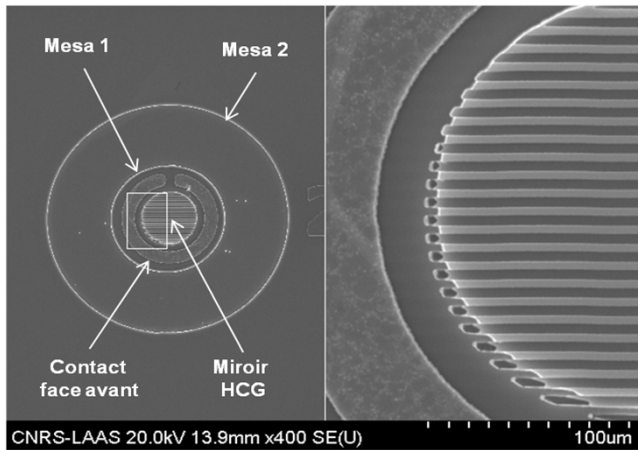
Fully monolithic approach



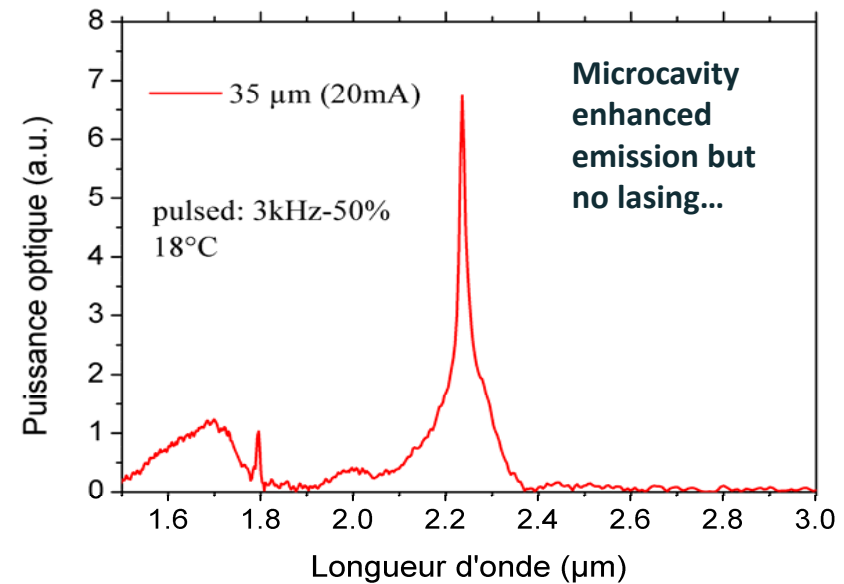
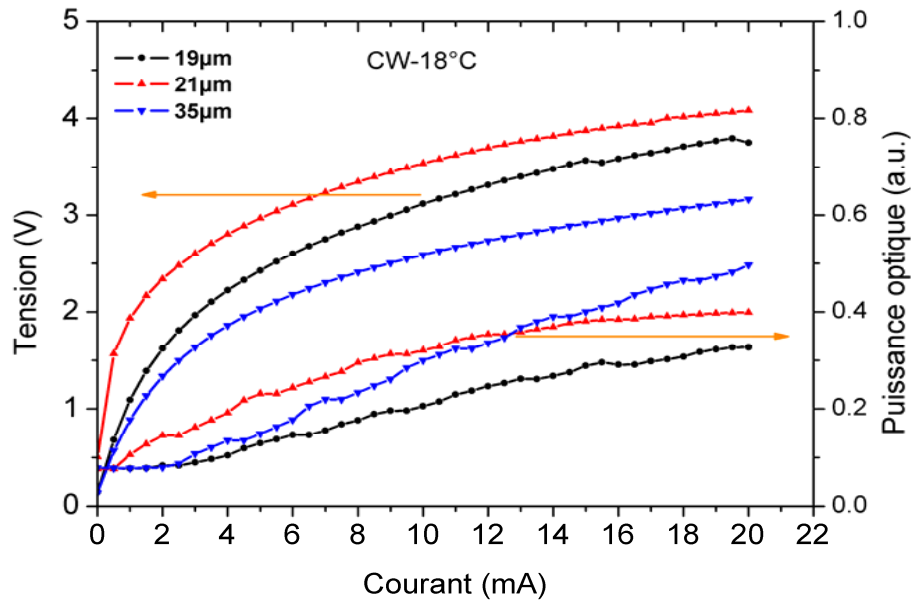
	Optimum	Tolerances for $R_{TM} > 99.5\%$
T_g	0.713 μm	0.682 $\mu\text{m} < T_g < 0.773 \mu\text{m}$
FF	0.484	0.403 $< FF < 0.548$
T_A	0.355 μm	0.255 $\mu\text{m} < T_A < 0.499 \mu\text{m}$
Λ	1.145 μm	1.038 $\mu\text{m} < \Lambda < 1.206 \mu\text{m}$
T_L	0.249 μm	0.215 $\mu\text{m} < T_L < 0.301 \mu\text{m}$
L_e	0.591 μm	0.382 $\mu\text{m} < L_e < 0.629 \mu\text{m}$
L_f	0.554 μm	0.487 $\mu\text{m} < L_f < 0.649 \mu\text{m}$
λ_0	2.309 μm	
$\Delta\lambda$	369 nm	
$\Delta\lambda/\lambda_0$	16 %	

- High reflectivity $> 99.5\%$
- Selectable in polarization
- Very wide stopband $> 350 \text{ nm} !$
- Use of optimization methods
 - *large tolerance for the fabrication*

Mid-Infrared HCG-VCSEL



Confocal microscope



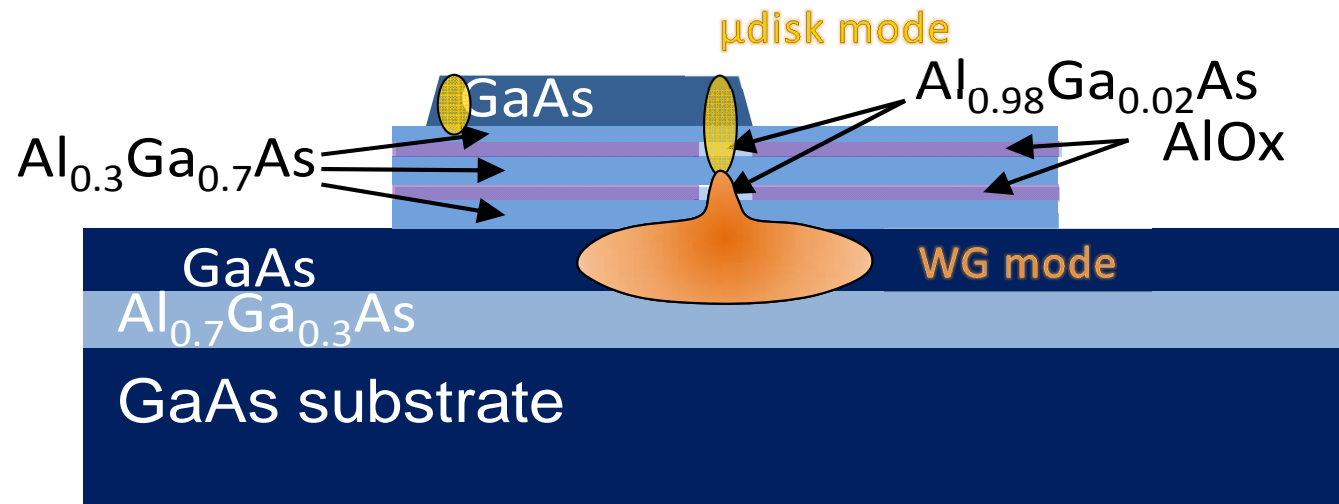
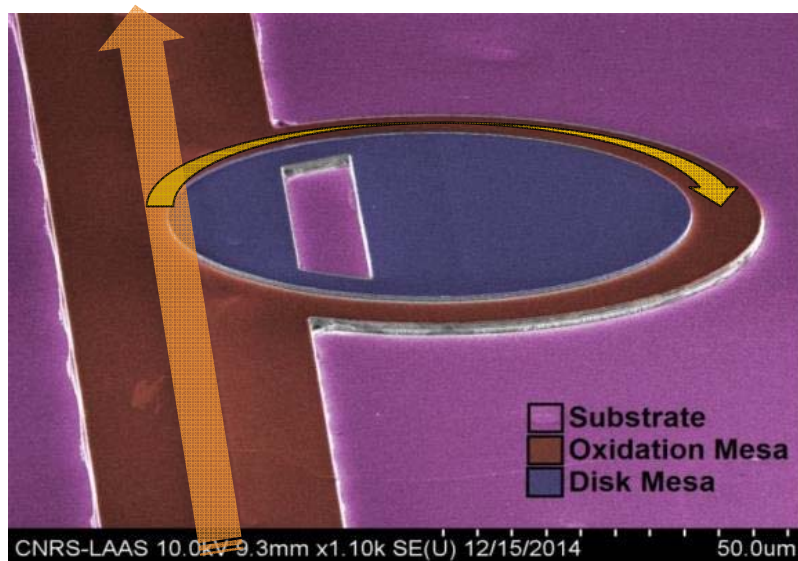
AlGaAs Metamorphic layers onto GaSb structure : oxide aperture + low index layer in HCG

Y. Laaroussi et al., *Optical Materials Express*, 3(10) :1576–1585, 2013.

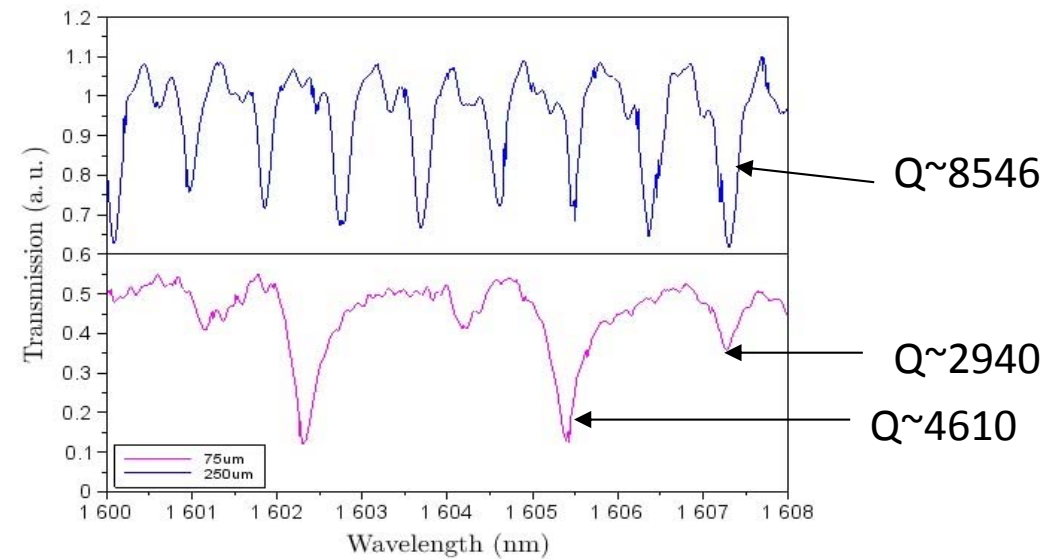
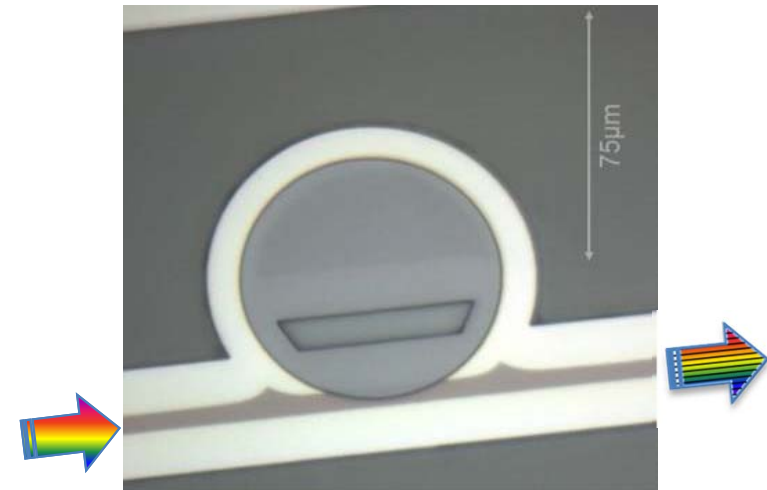
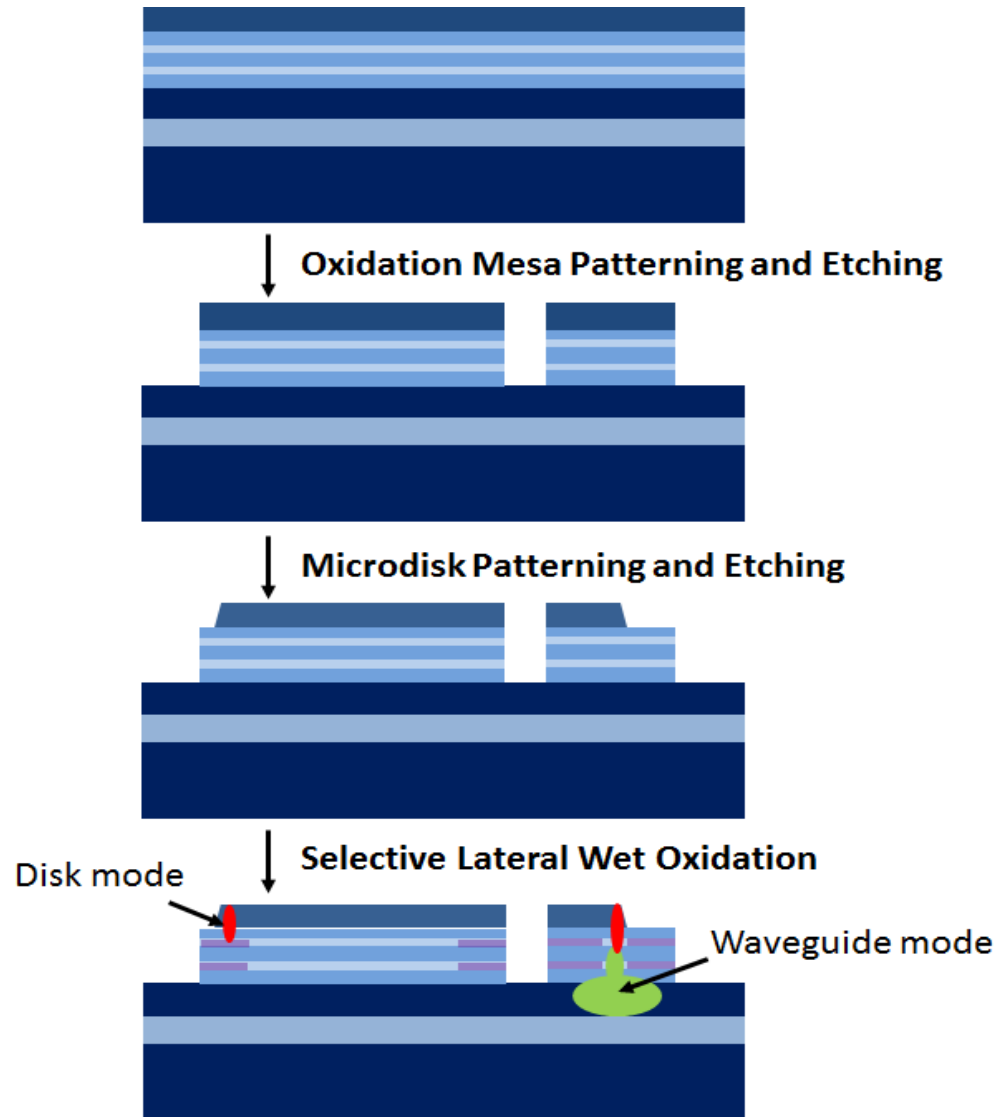
AlOx-based waveguide and couplers for non-linear optics on GaAs platform

Integrated waveguides/resonators for NLO

- Vertical integration
- Oxide confined buried III-V waveguide
- Top-down single-side processing
- No planarisation required
- Compatible with active waveguides /laser source



AlOx-confined waveguides / microdisk

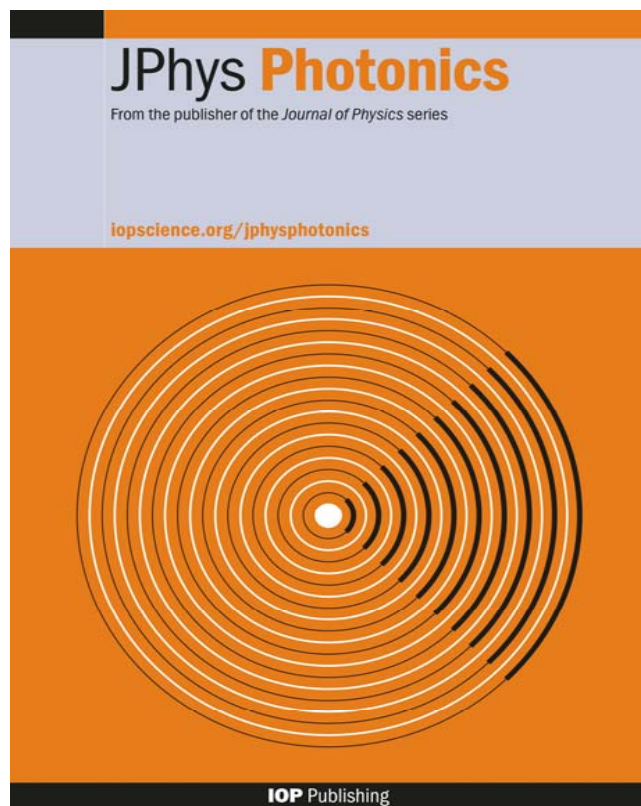


S. Calvez et al, *PTL*, **27**, 982 (2015)

- Developed furnace with in-situ monitoring
 - >> *Reliable and high-performance fab tool for R&D and VCSEL mass-production*
- Introduced a refined model of the III-V oxidation process with in-plane anisotropy
 - >> **More accurate oxide front prediction**
- Developments of AlOx process
 - >> **Characterization of embedded-strain around AlOx/AIAs interfaces**
 - >> **Planar oxidation through lithographic step and epitaxial regrowth**
 - >> **Oxide confinement for other material platform : GaSb for IR applications**
 - >> **AlOx-based HCG mirror for MIR-VCSELs**
- New vertically-coupled microdisks for non-linear optics applications
 - >> **Integrated approach for combining active gain region + non-linear functionalities**

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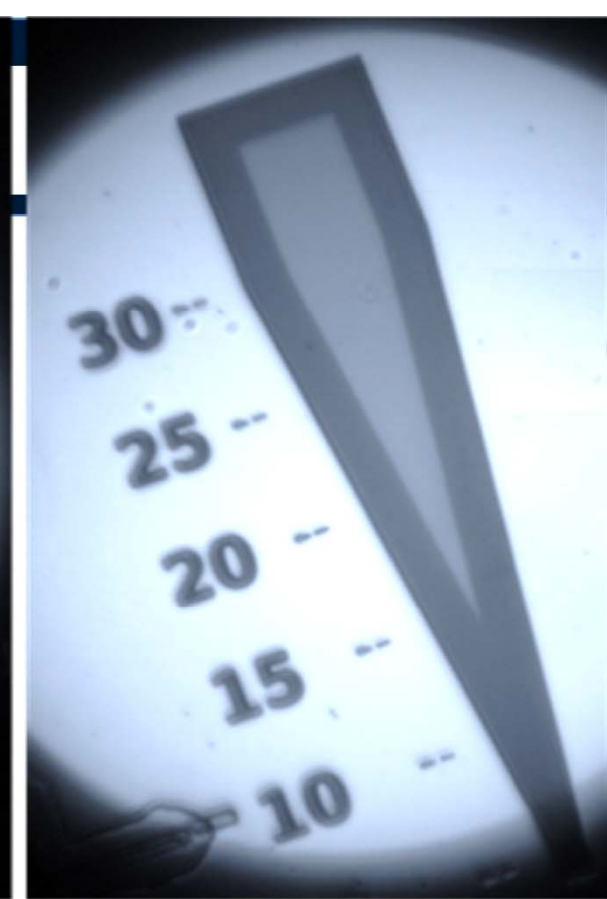
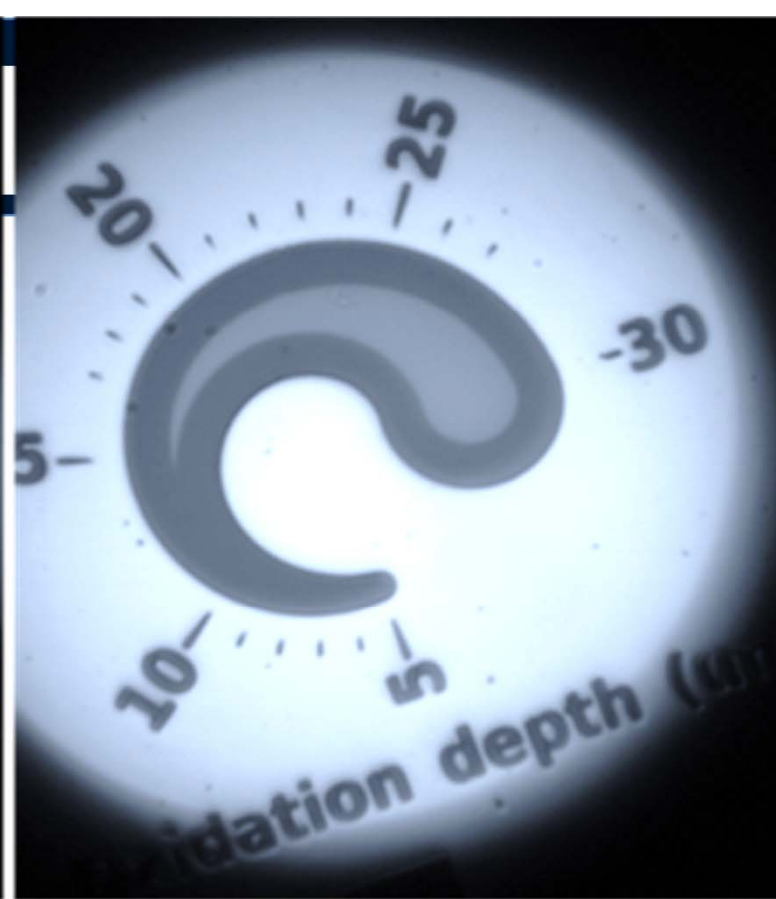
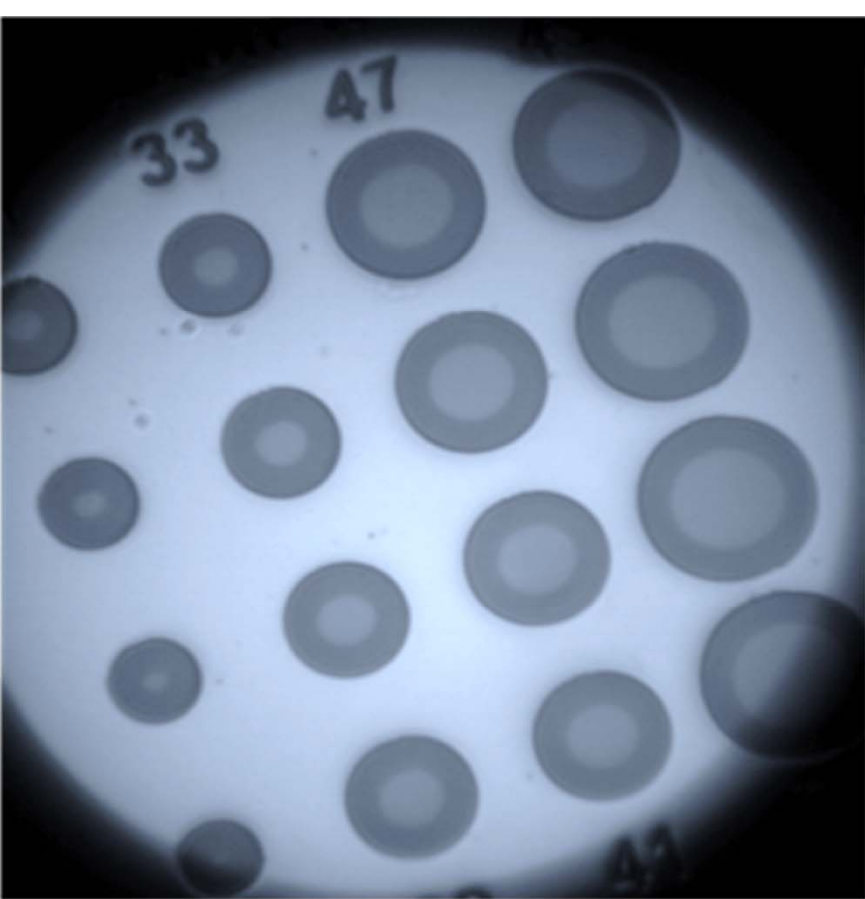
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