

Suivi in-situ de dépôts CVD de SiON

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Fédération Fermat, Journée MATAPP 2024

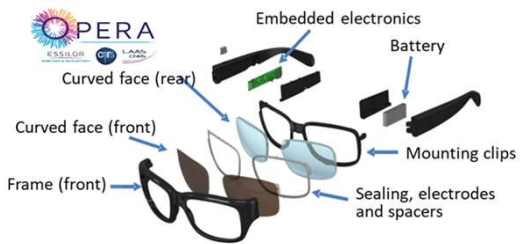
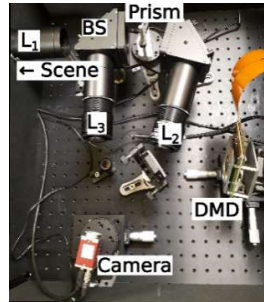
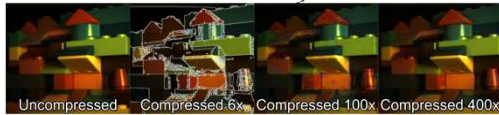
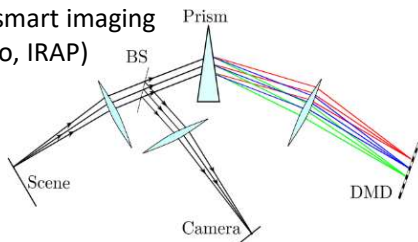
14/5/2024, 15:40-16:10

- Introduction
- Suivi en réflectométrie/spectroscopie d'émission optique (OES)
- Exemples d'application
- Conclusion

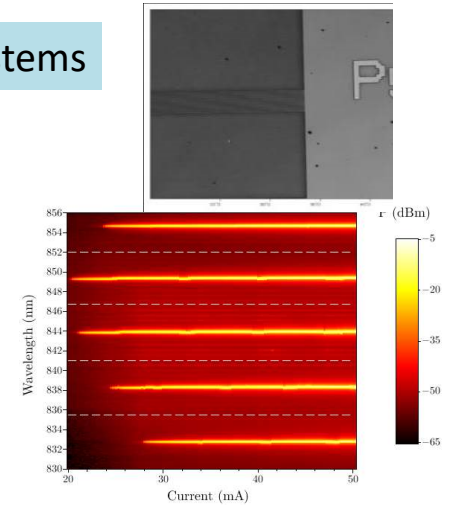
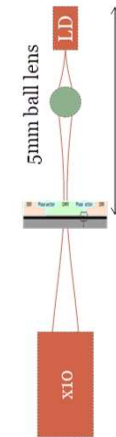
Contexte: Recherche @ « LAAS Photo »

Smarter systems

Hyperspectral smart imaging
(coll. RIS, Photo, IRAP)

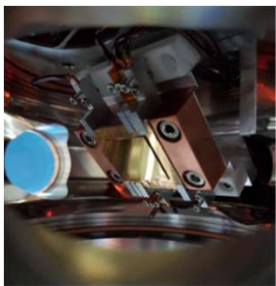


Simpler systems

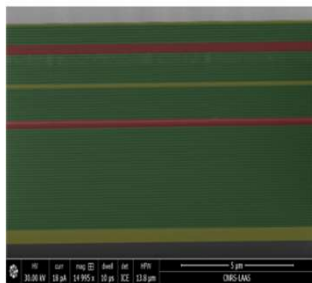


External-cavity laser diodes with grating filters (coll. CNES/Innoptics)

Multi-functional systems



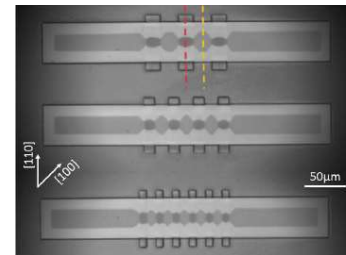
Cold atom chip



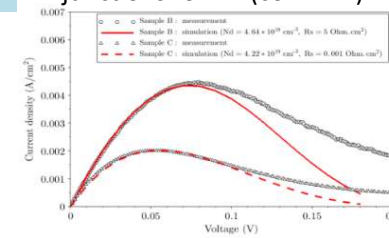
SEM crossview of a EAM-VCSEL

More efficient systems

III-V Oxide confinement engineering

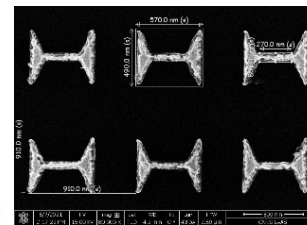


Low resistance GaAs tunnel junctions for PV (coll. LNE)



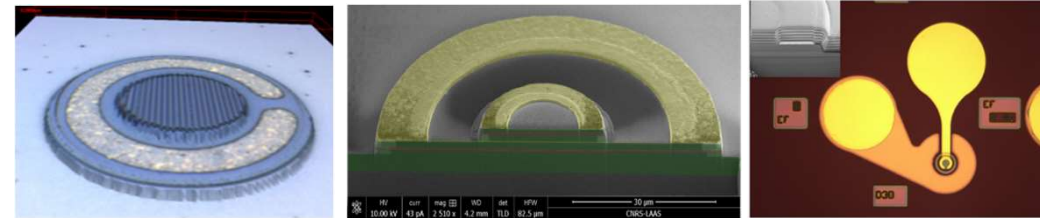
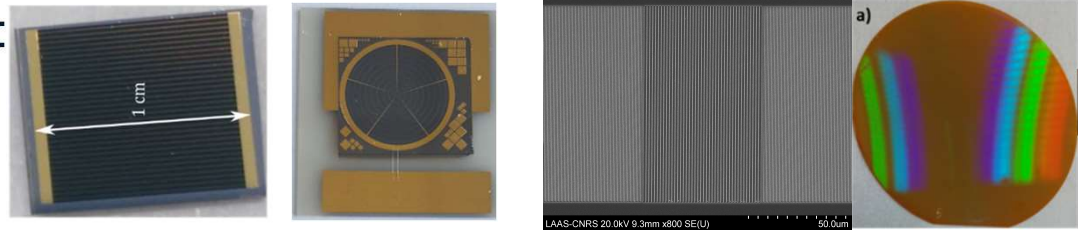
GaAs Tunnel Junction

Thermo-optic antennae



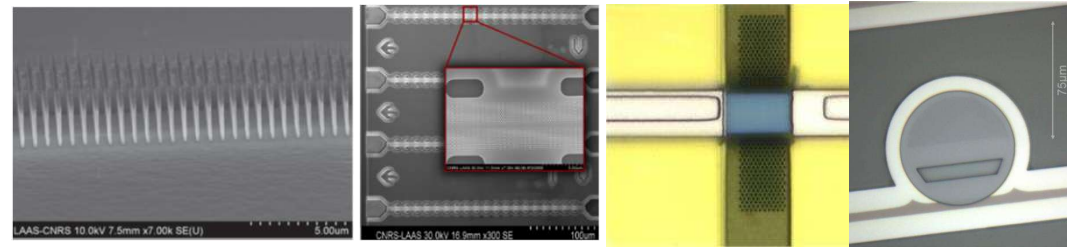
> LAAS PHOTONICS TEAM cleanroom activity:

- Photonics device fabrication
 - Process flow design & Process step optimization
 - Meso-scale mix & match integration
 - Hybrid/ novel material integration
- Custom “intelligent” equipments
 - Non-contact in-situ real-time sensors
 - Automated and controlled processes
 - Process physics
 - MBE/ III-V-oxidation furnace/ PECVD / Etch tool

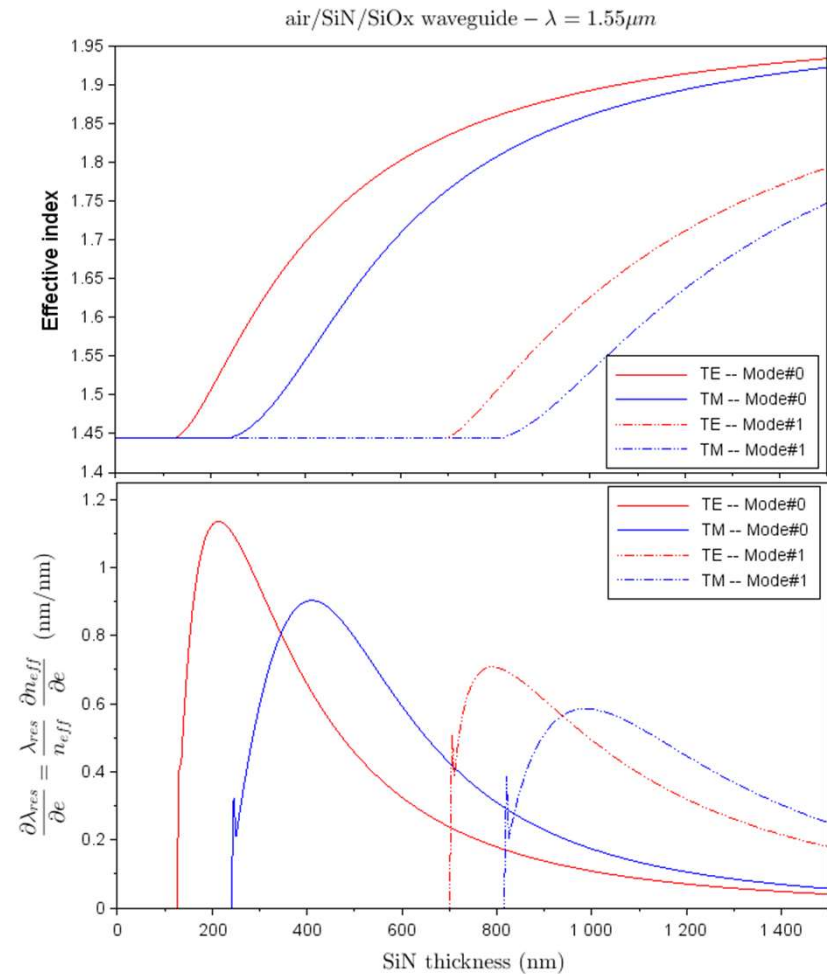
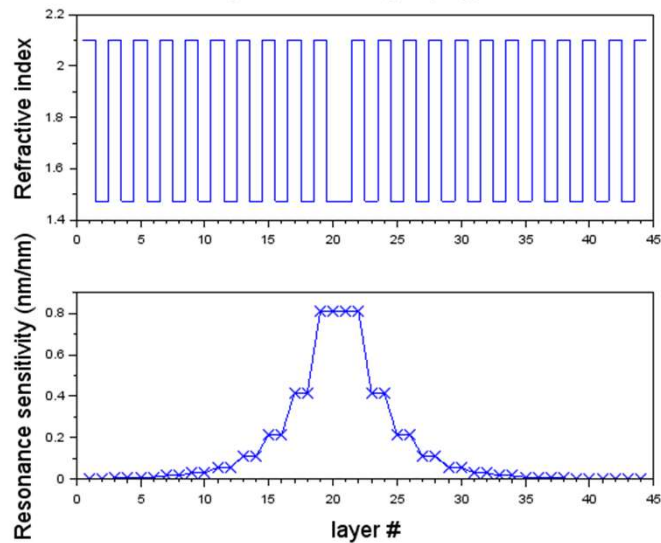
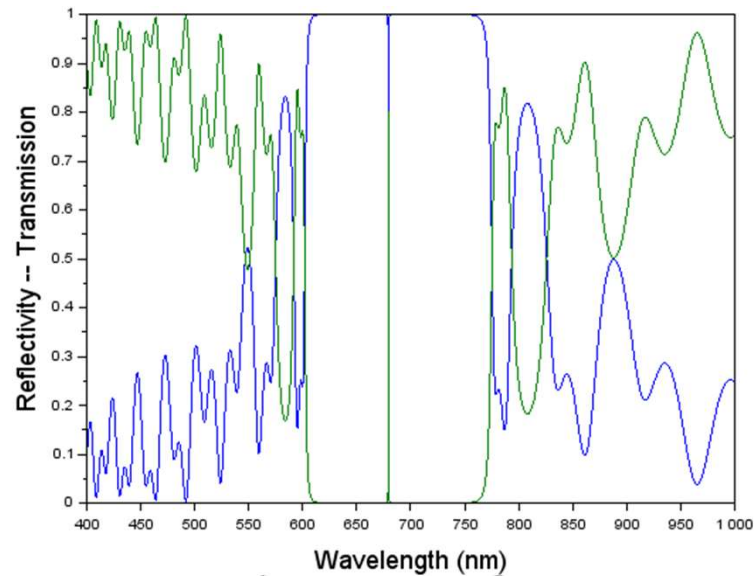


> LAAS clean-room

- 1500m² class 1000 clean-room
- Si and III-V complete processing lines
- 30-people TEAM/clean room staff
- Micro-/nano Lithography :
 - e-beam --- nanoimprint
 - UV contact -- step & repeat
 - Laser writing (mask fab. (Heidelberg), 2D/3D)
- Etching : F- and Cl-based ICP/RIE
- Customized specific equipment (RIBER MBE) :
 - 412 (4”) machine
 - C21DZ cluster with cryo-epitaxy (mid 2024)



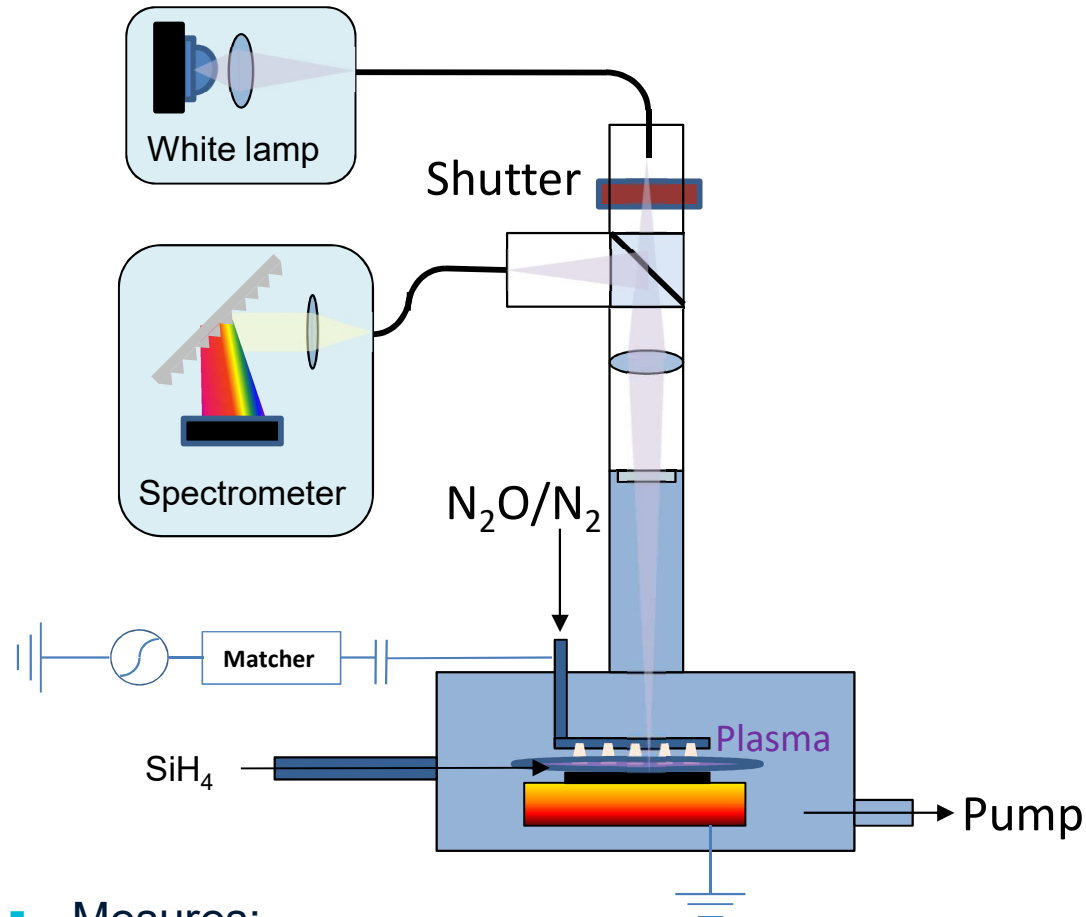
Introduction



Contrôle des épaisseurs/indices de réfraction requis à 0,1 à 1% près

Suivi in-situ sur PECVD

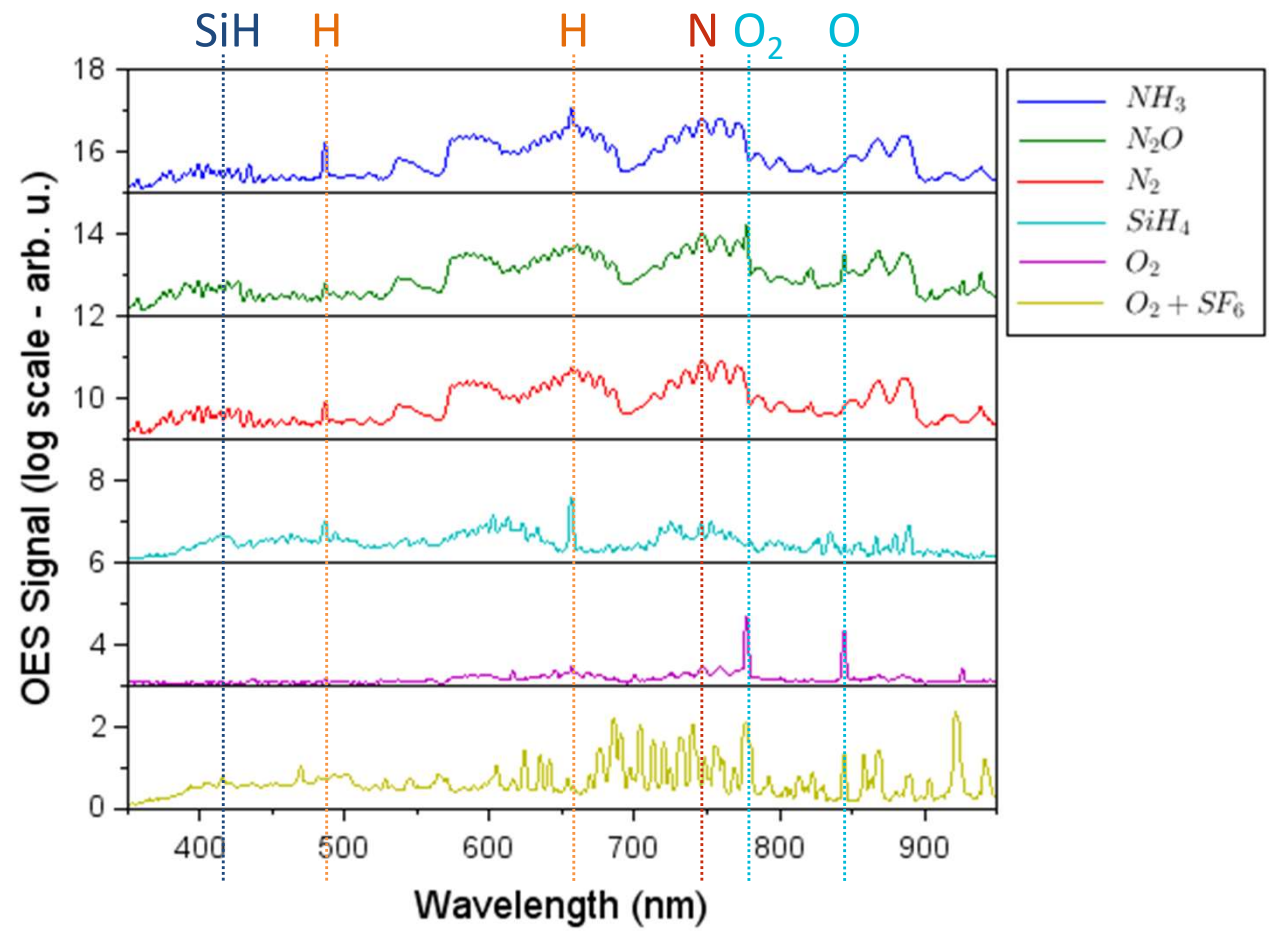
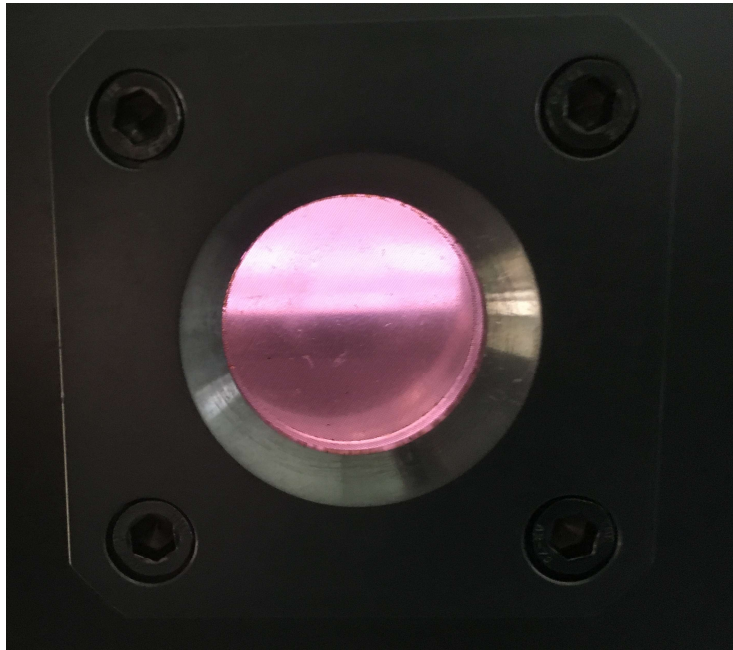
> Réflectométrie/Spectrométrie d'émission optique



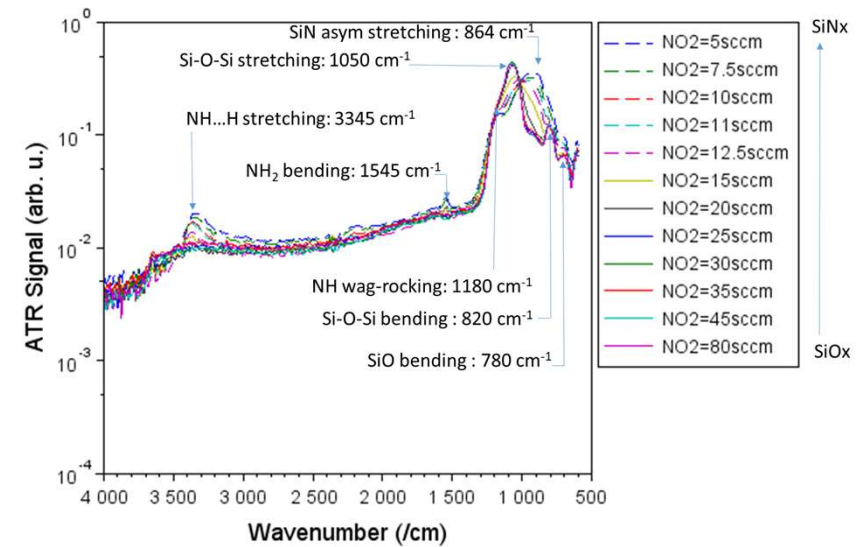
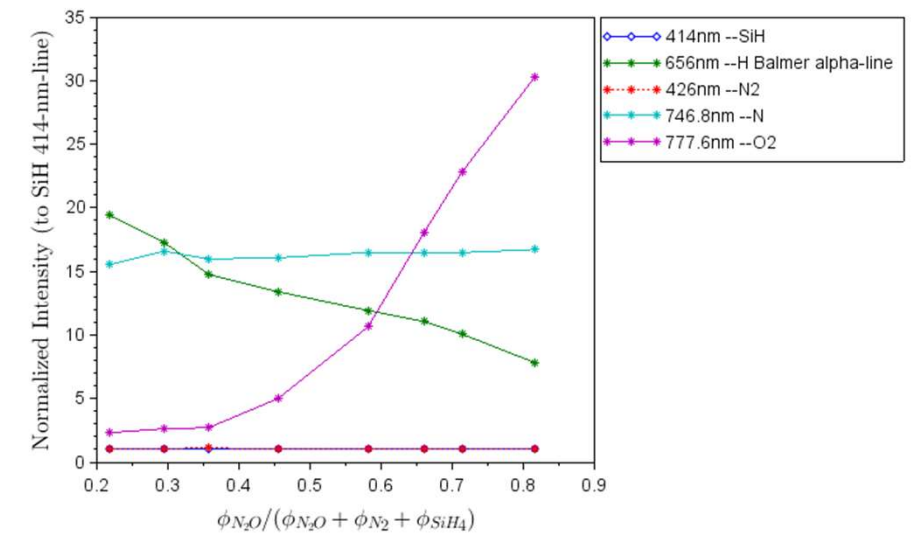
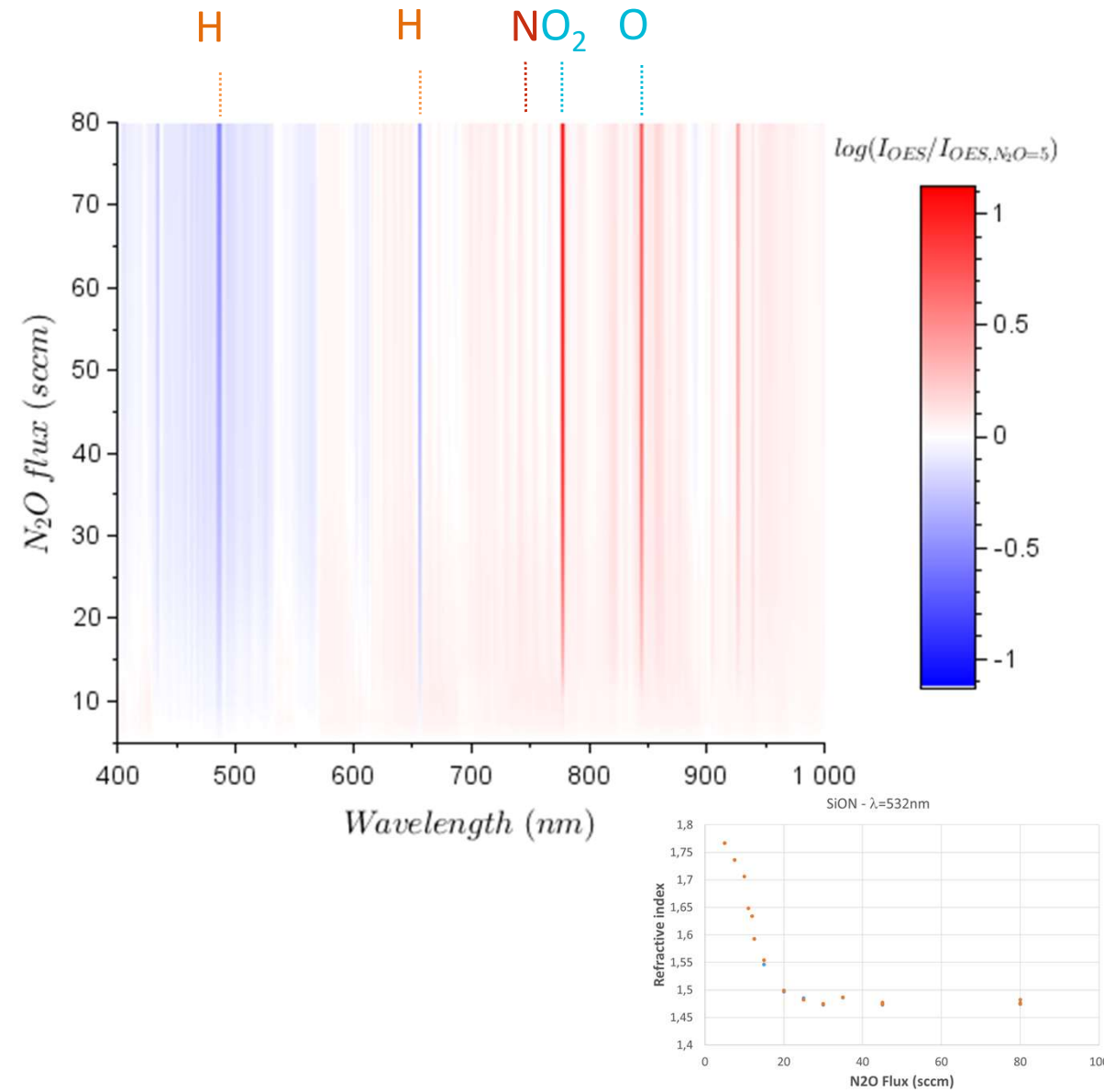
■ Mesures:

- Obturateur fermé : Spectrométrie d'émission optique (OES) du plasma --- $S_{\text{OFF}} = I_{\text{OES}}$
- Obturateur ouvert : Réflectométrie + OES --- $S_{\text{ON}} = I_{\text{OES}} + R I_{\text{lamp}}$

OES : Exemples



OES : Exemple: dépôts SiON



✓ OES permet de suivre la composition

Réflectométrie: les bases

$$R(t) = \frac{R_\infty - 2\sqrt{R_\infty R_i} e^{-\gamma t} \cos(\delta t - \sigma - \varphi) + R_i e^{-2\gamma t}}{1 - 2\sqrt{R_\infty R_i} e^{-\gamma t} \cos(\delta t - \sigma + \varphi) + R_\infty R_i e^{-2\gamma t}} \cong R_\infty - 2\sqrt{R_\infty R_i} (1 - R_\infty) e^{-\gamma t} \cos(\delta t - \sigma)$$

$$R_\infty = |r_\infty|^2 = \frac{(1-n)^2 + k^2}{(1+n)^2 + k^2},$$

$$\varphi = \tan^{-1} \left(\frac{2k}{n^2 + k^2 - 1} \right),$$

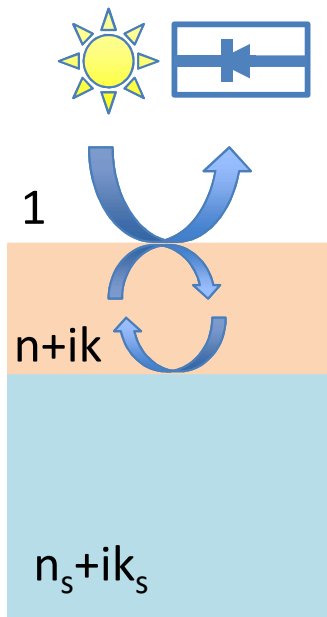
$$R_i = |r_i|^2 = |\sqrt{R_i} e^{i\sigma}|^2 = \frac{(n-n_s)^2 + (k-k_s)^2}{(n+n_s)^2 + (k+k_s)^2},$$

$$\sigma = \tan^{-1} \left(\frac{2(nk_s - n_s k)}{n^2 - n_s^2 + k^2 - k_s^2} \right),$$

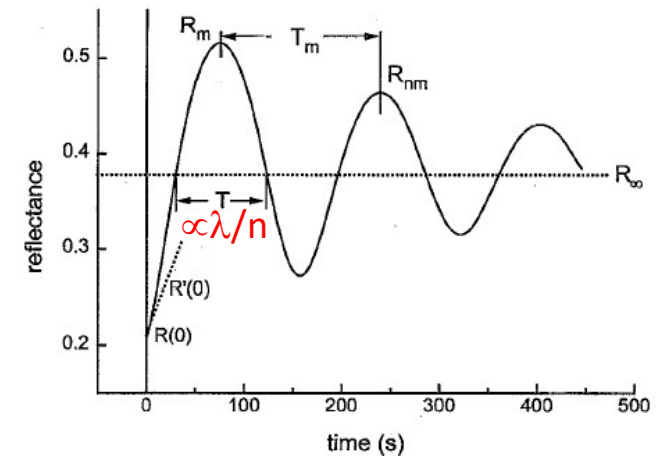
$$\gamma = 4\pi k G / \lambda,$$

$$\delta = 4\pi n G / \lambda.$$

G: growth rate



R



W.G. Breiland et al, *J. Appl. Phys.*, **78** (11), 6726 (1995)

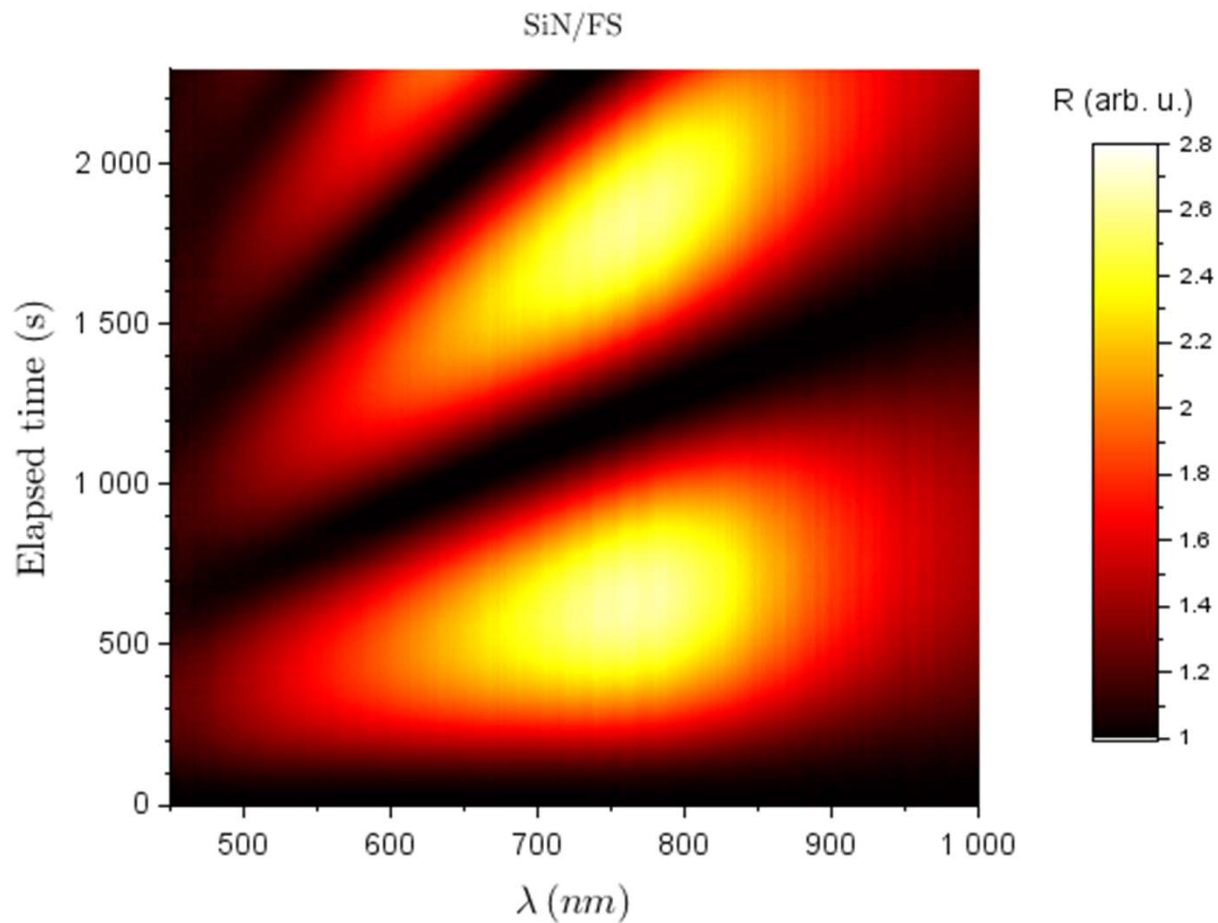
Paramètres à extraire: n, k, G, σ, ϕ



Substrat opaque !

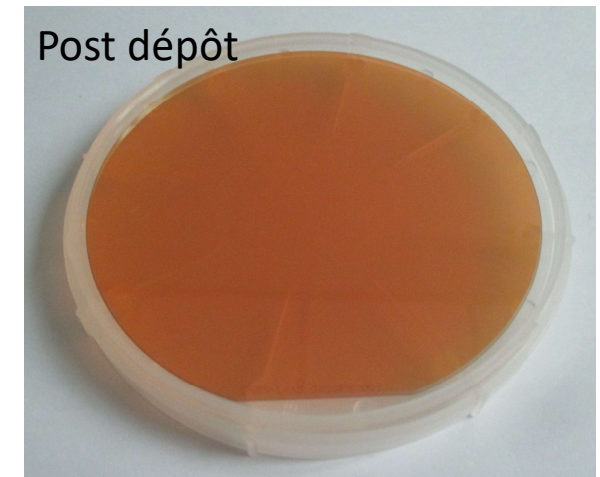
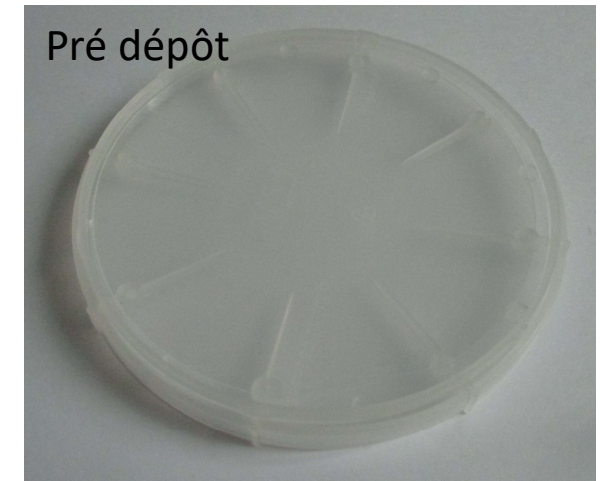
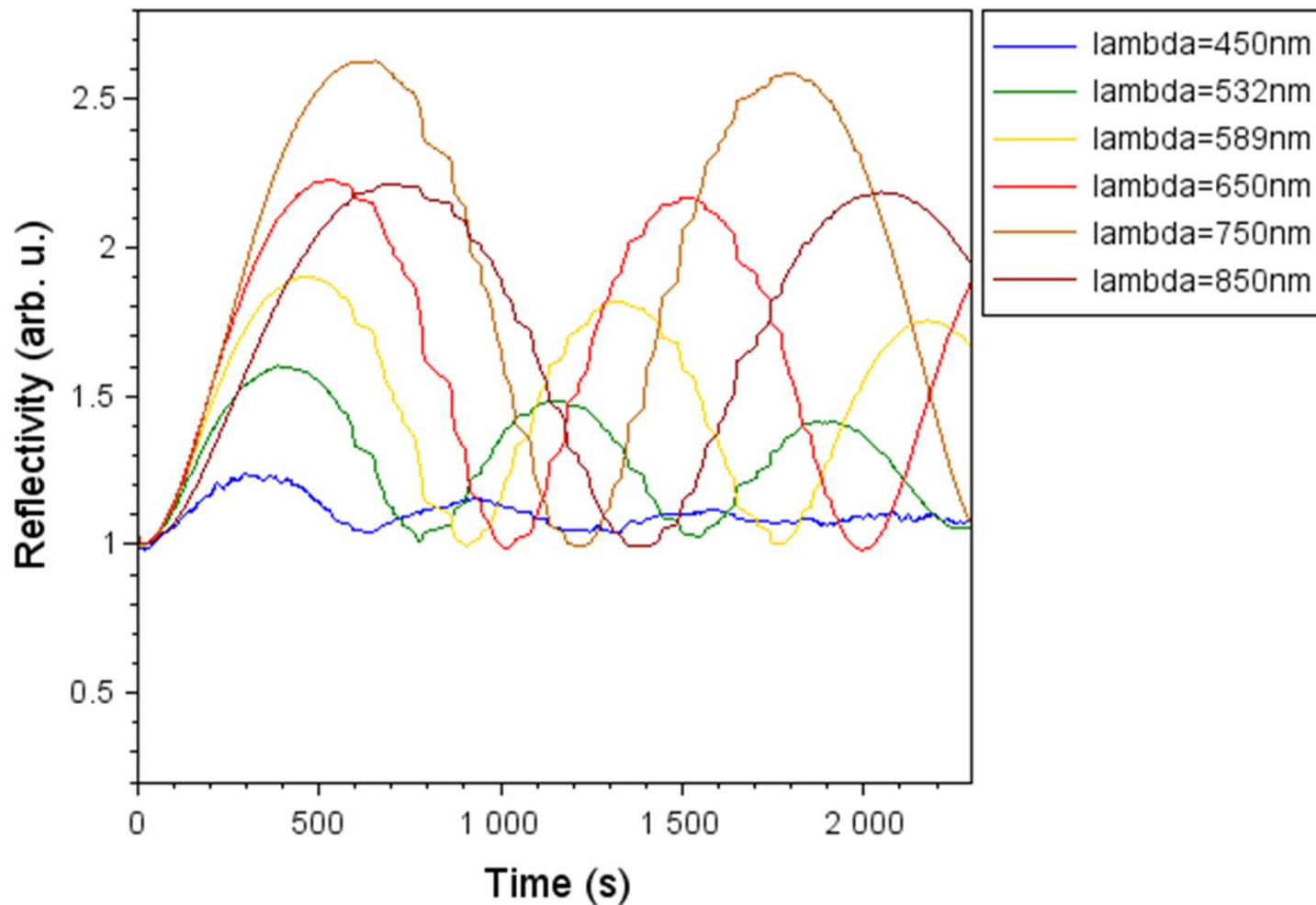
Réflectométrie: Exemple

> Mesures brutes sur un dépôt SiN/FS



Oscillations de périodicité croissante avec la longueur d'onde

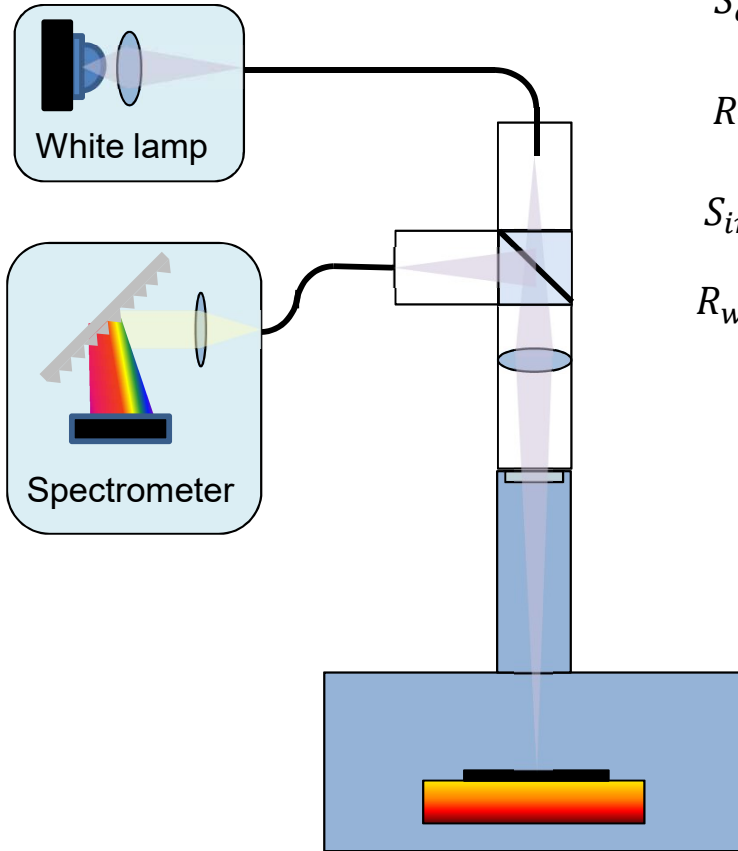
Réfectométrie: Exemple



Oscillations amorties aux courtes longueurs d'onde ($\lambda < 600\text{nm}$)

n et k extraction ?

Réflectométrie: Calibration



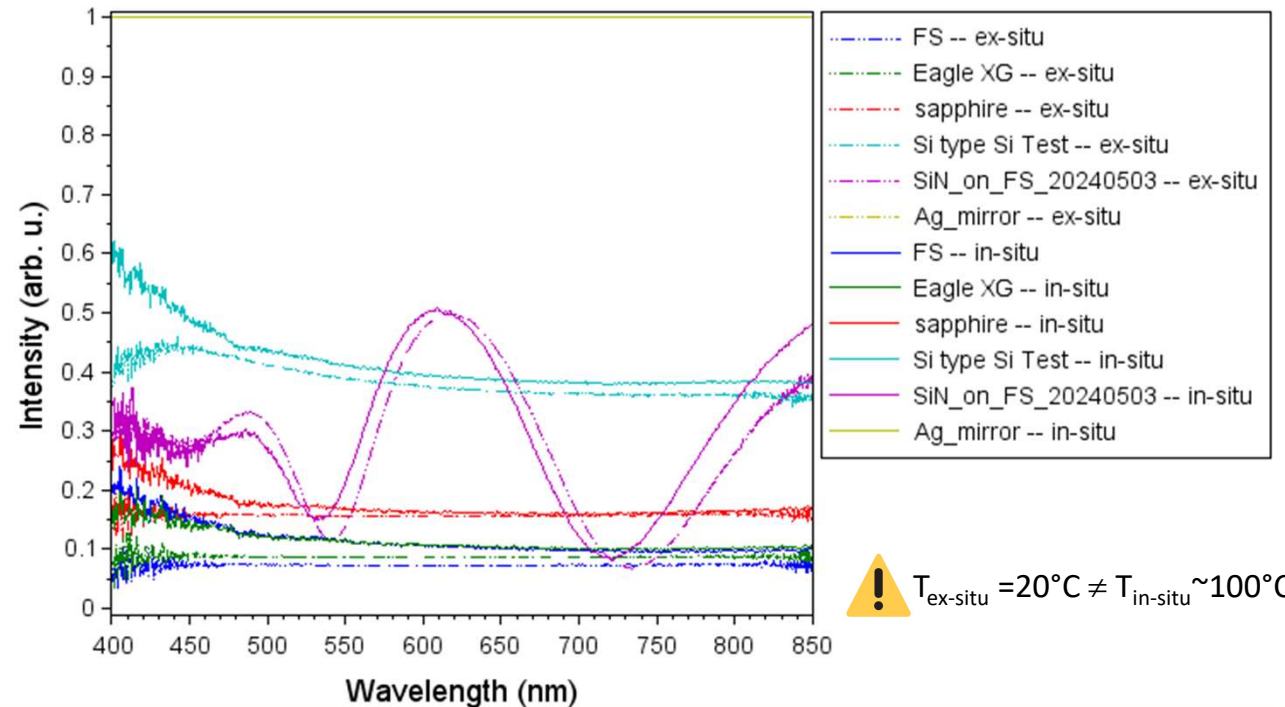
$$S_{ex-situ} = S_{bckg} + T_{obs} \cdot R \cdot S_{lamp}$$

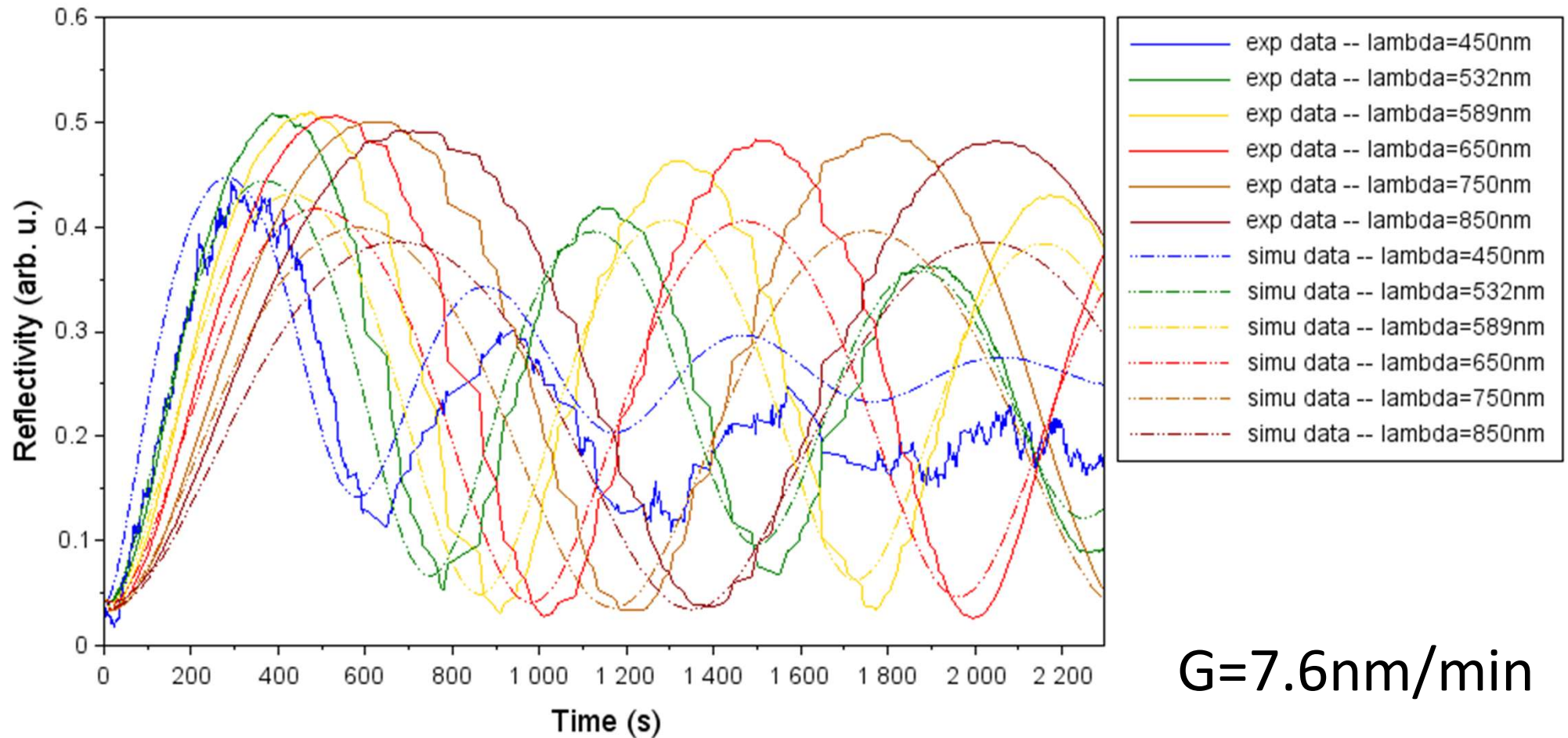
$$R_{wafer,ex-si} = R_{ref} \frac{S_{wafer} - S_{bckg}}{S_{ref} - S_{bckg}}$$

$$S_{in-si} = S_{bckg} + T_{obs} \cdot (R_{hublot} + T_{hublot}^2 \cdot R) \cdot S_{lamp}$$

$$R_{wafer,in-situ} = R_{ref} \frac{S_{wafer} - S_{hublot}}{S_{ref} - S_{hublot}} \text{ avec } S_{hublot} = S_{bckg} + T_{obs} \cdot R_{hublot} \cdot S_{lamp}$$

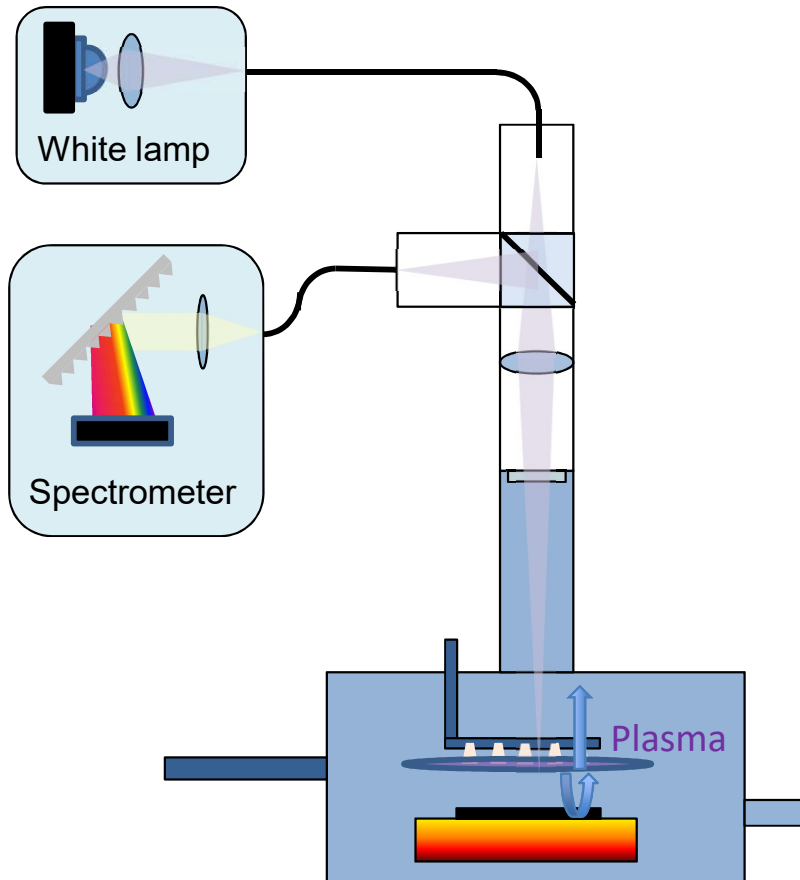
Calibration





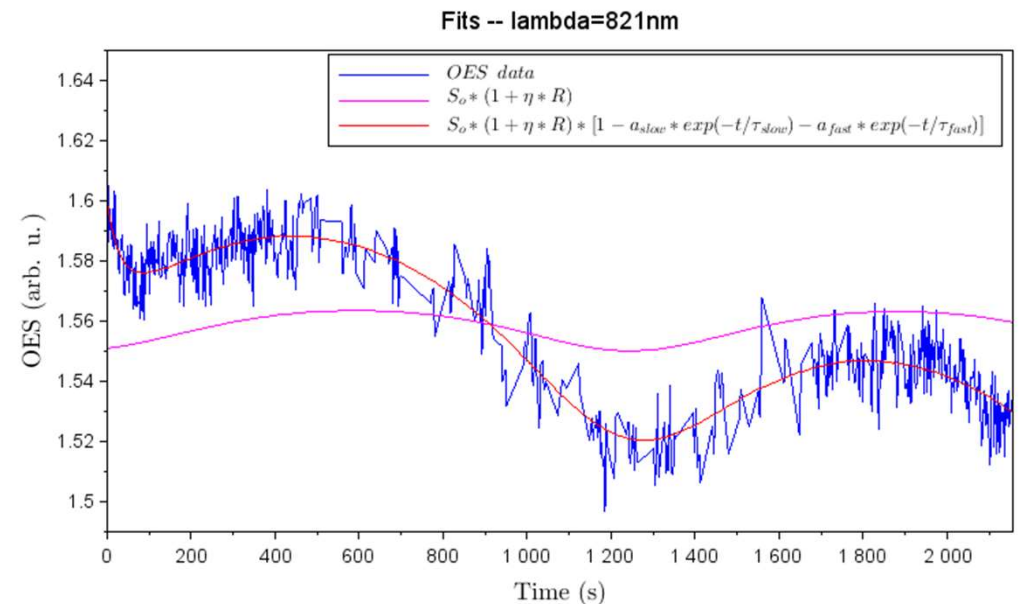
- ✓ $R_{\text{extracted}} (T \sim 100^\circ\text{C}) \sim R_{\text{simulated}} \text{ (based on ellipso data @ } T=25^\circ\text{C)}$
- ✗ (Par proxy), $n_{\text{extracted}} \sim n_{\text{ellipso}}$ mais $k_{\text{extracted}} > \sim k_{\text{ellipso}}$

OES en dynamique



$$S_{OES}(t) = S_{bckg} + T_{obs} \cdot S_{emit}(t) \cdot (1 + \eta \cdot R_{wafer}(t))$$

Conditions fixes et stables $\Rightarrow S_{emit}(t) = S_{emit}(t = 0)$



$$S_{emit}(t) = S_{emit}(t = 0) \cdot (1 - a_{fast} \cdot e^{-t/\tau_{fast}} - a_{slow} \cdot e^{-t/\tau_{slow}})$$

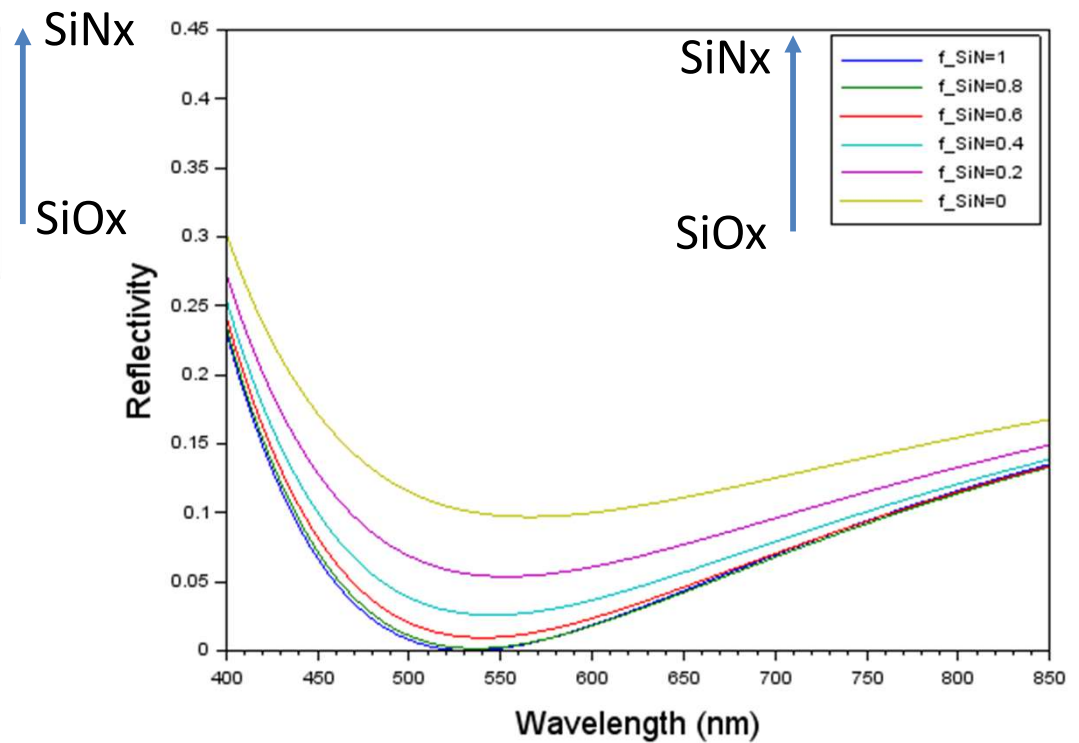
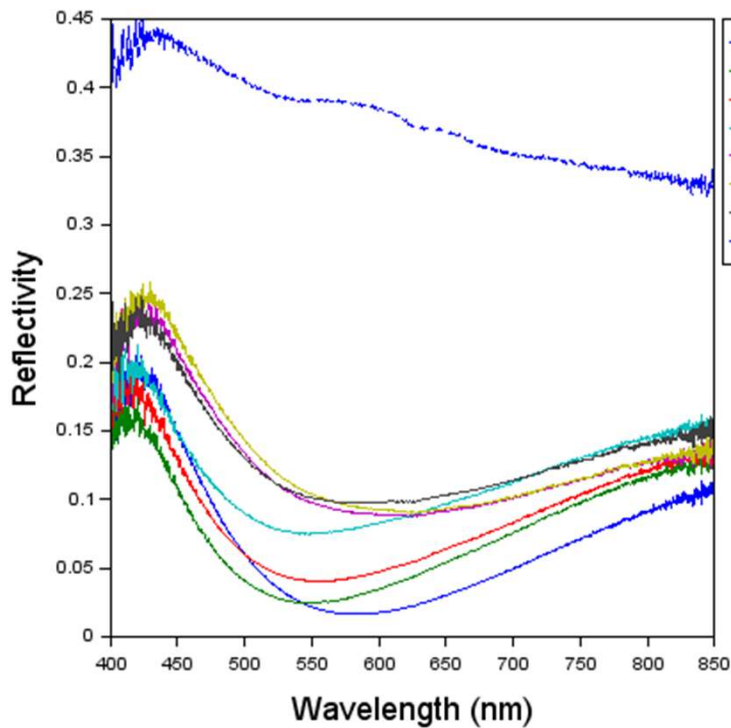
avec $\tau_{fast} \sim 27s$ $\tau_{slow} \sim 2000s$

Stabilisation des flux et plasma

Impact du dépôt sur la capacité de l'ICP ?

Applications: Anti-reflet mono-couche

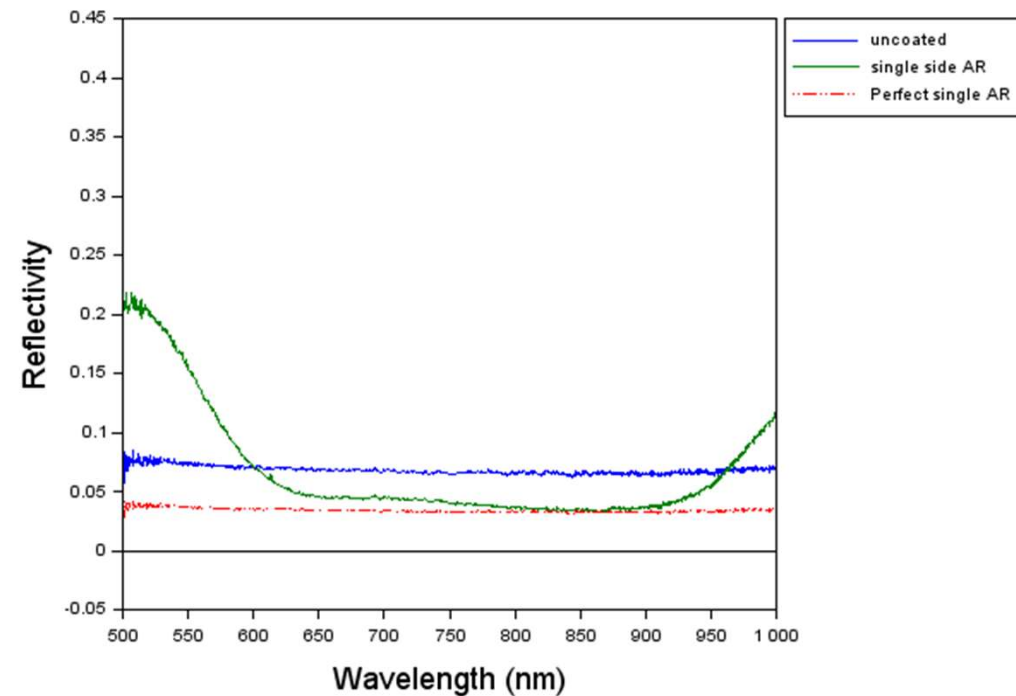
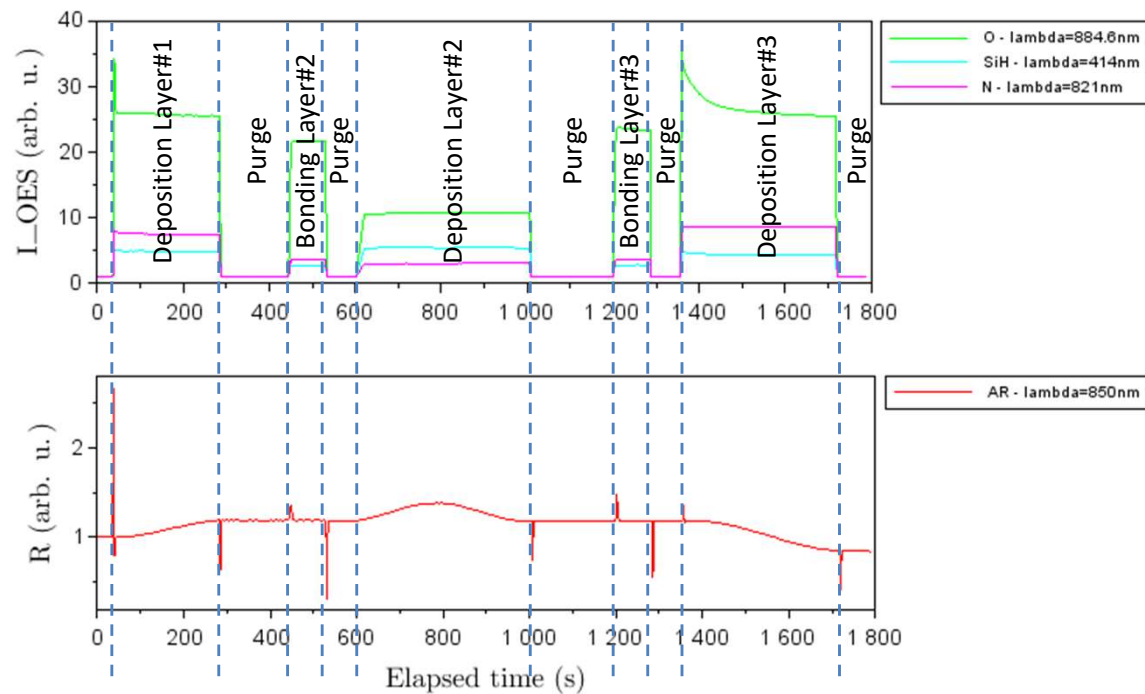
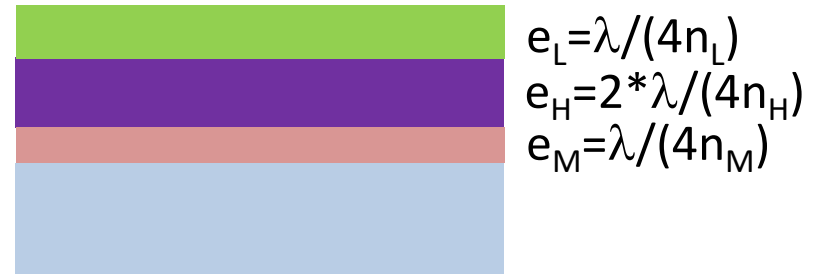
- > Design : $e = \lambda / (4n)$
- > Optimum $n = \sqrt{n_{subs}} \sim 2n_{SiNx}$



- ✓ Atténuation de la réflectivité
- ✗ Léger décalage spectral à relier au bruit/délai dans la détection des minima

Applications: Anti-reflet tri-couche

Anti-reflet tri-couche à $\lambda=850\text{nm}$ sur verre



Applications: Miroir à $\lambda=1550\text{nm}$

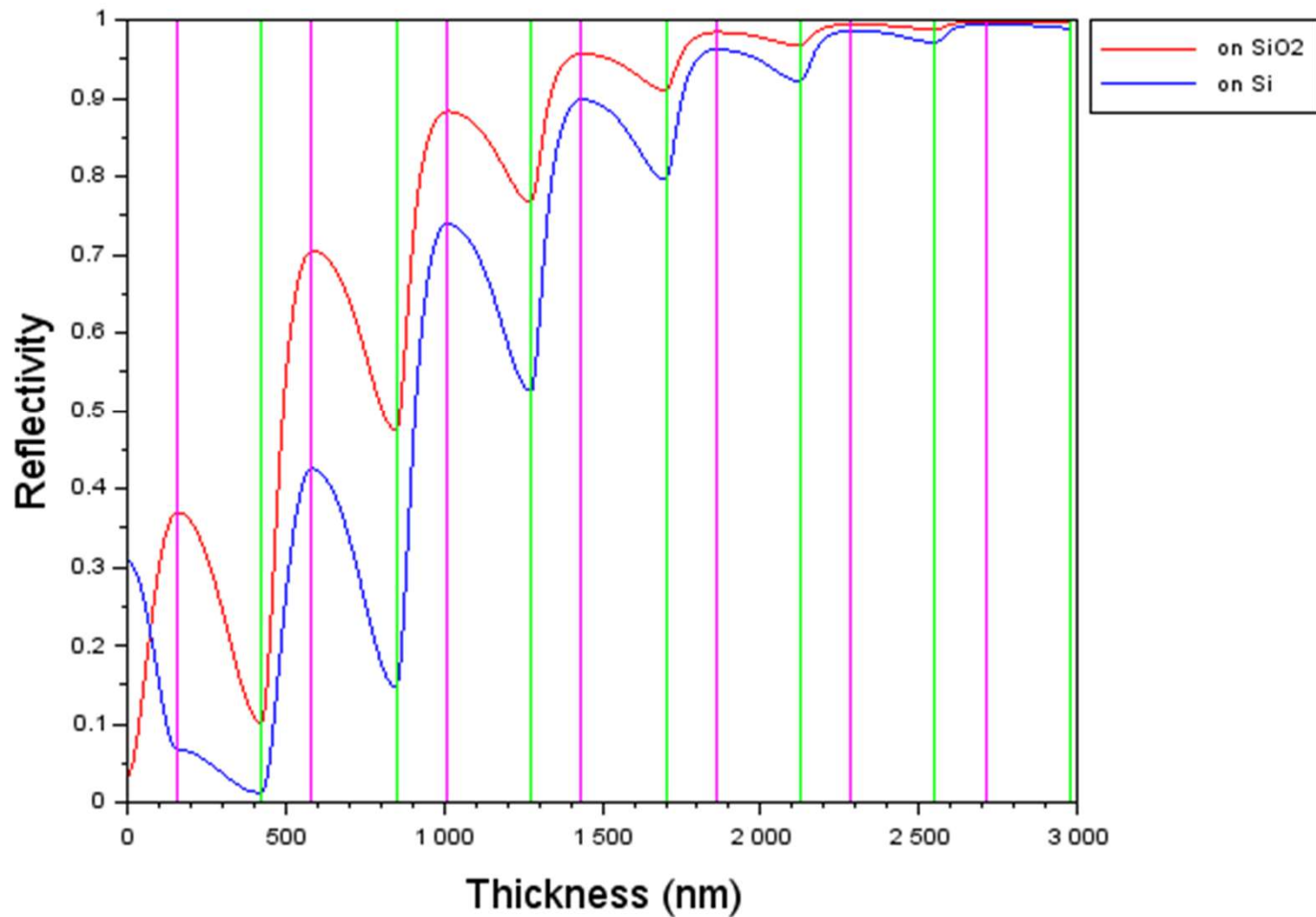
Design



$$e_L = \lambda / (4n_L)$$

$$e_H = \lambda / (4n_H)$$

air/(SiO2/SiN)⁷ stack -- lambda=1550nm

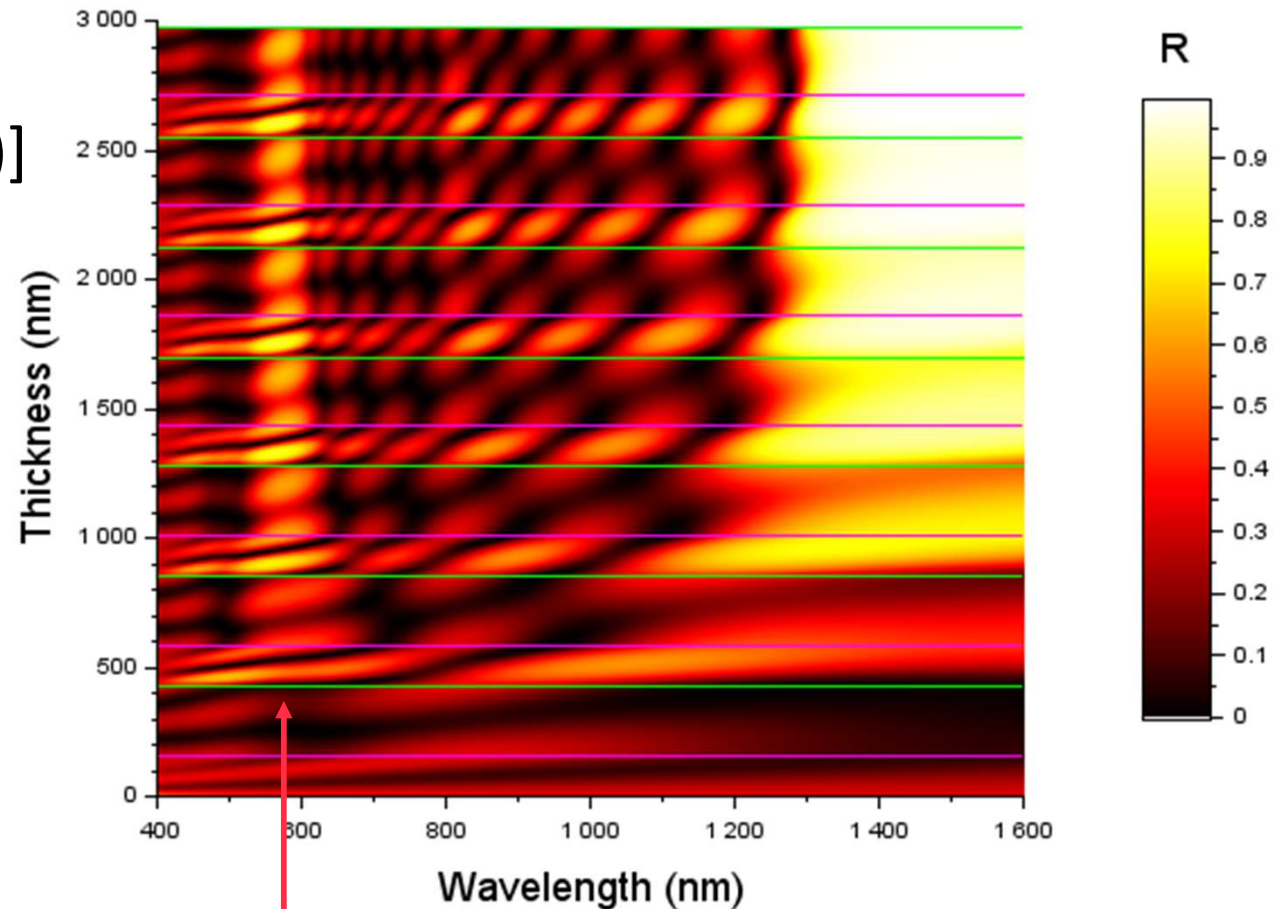


Applications: Miroir à $\lambda=1550\text{nm}$

- > Pb: Suivi n'est possible que pour $\lambda \in [400, 1100\text{nm}]$

$$e = \lambda / (4n_{\lambda}) = m * [(\lambda/m) / (4n_{\lambda/m})]$$

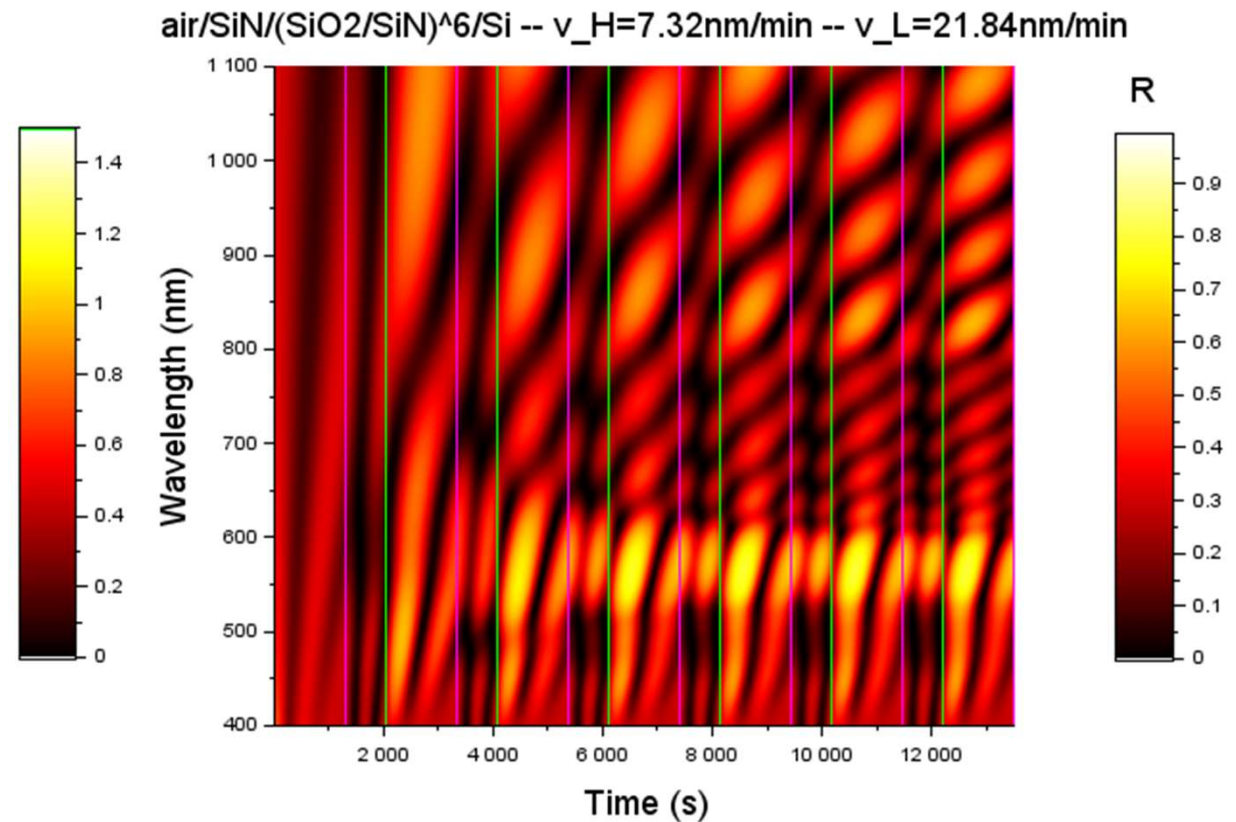
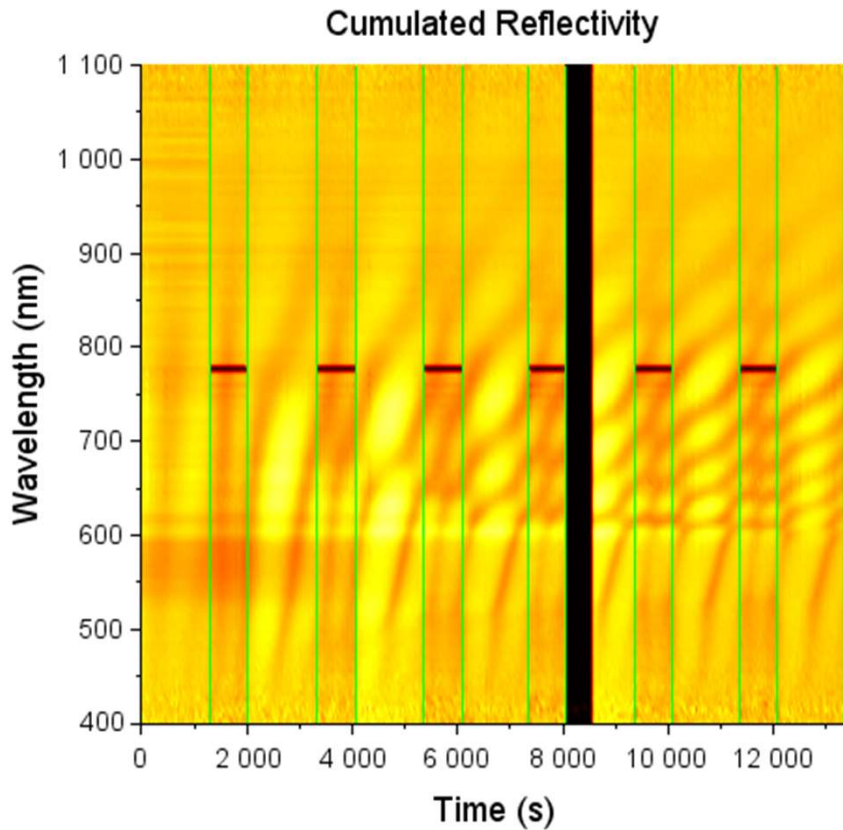
si $n_{\lambda} \sim \text{constante}$



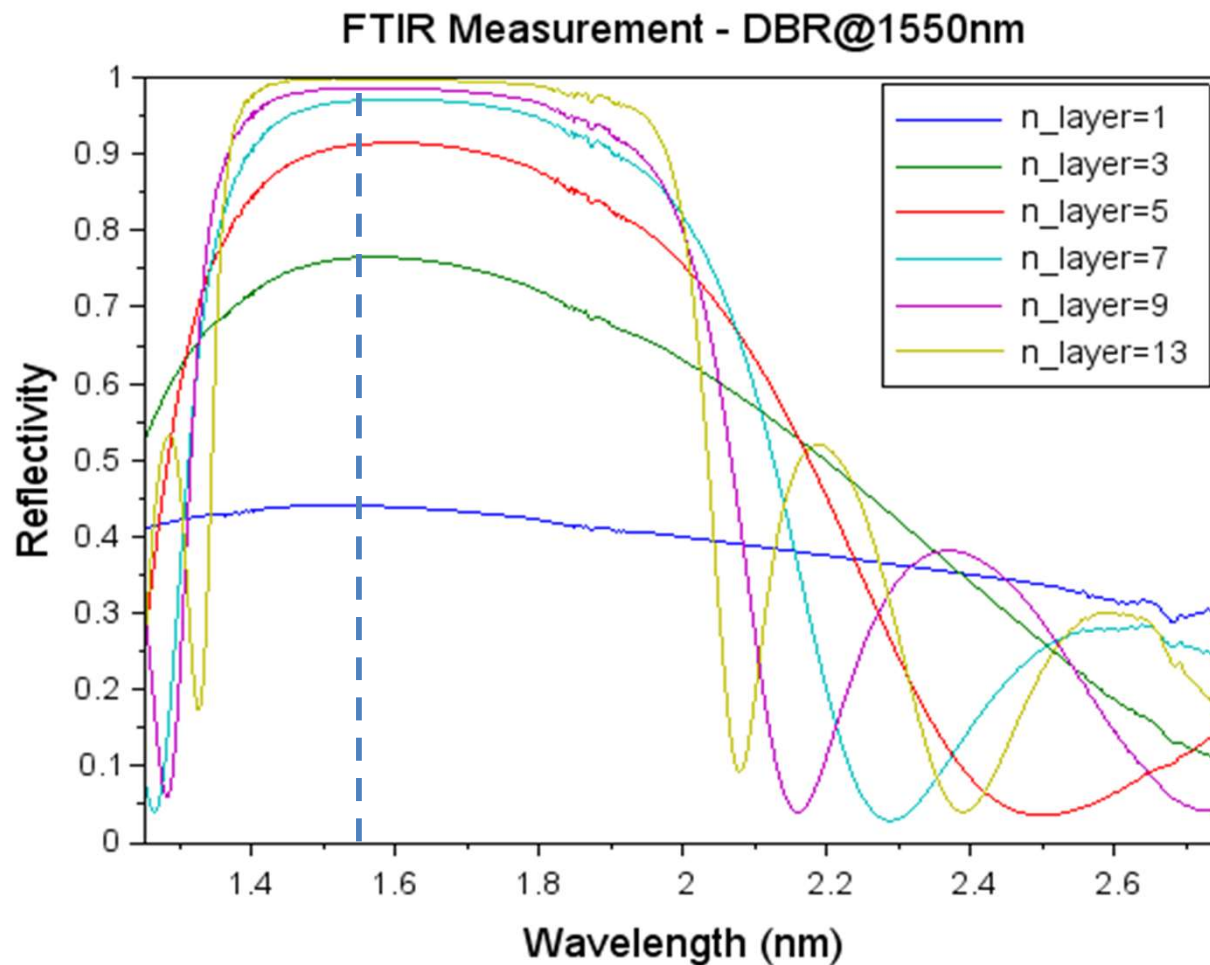
$$\lambda_{\text{suivi}} = 570\text{nm} \sim \lambda/3 = 516\text{nm}$$

Applications: Miroir à $\lambda=1550\text{nm}$

Miroir DBR à 1550nm sur Si



Applications: Miroir à $\lambda=1550\text{nm}$



- ✓ Miroir $R > 99\%$ @1550nm
- ✗ Léger décalage spectral lié aux indices de réfraction pris à 25°C (et pas 100°C)

> OES

- ✓ Indication sur la composition
- ✗ Lien indirect entre composition du plasma et celle des couches
- > Evolution temporelle
 - ✓ Dépendance bi-exponentielle observée
 - ✗ Physique sous-jacente à confirmer

> Réflectométrie

- ✓ Méthode de calibration validée
- ✓ Extraction de n, k, G en cours
- ✓ Empilements multi-couches avec réalisés avec contrôle
- ✓ Suivi et arrêt sur détection de minima de réflectivité
- ✗ Réduction de bruit sur la détection de minima