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Hybrid CVD-MBE Er:Y_2O_3 thin films for on-chip quantum technologies

Anna Blin

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Workshop OSEPI - 17/05/2024

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Introduction

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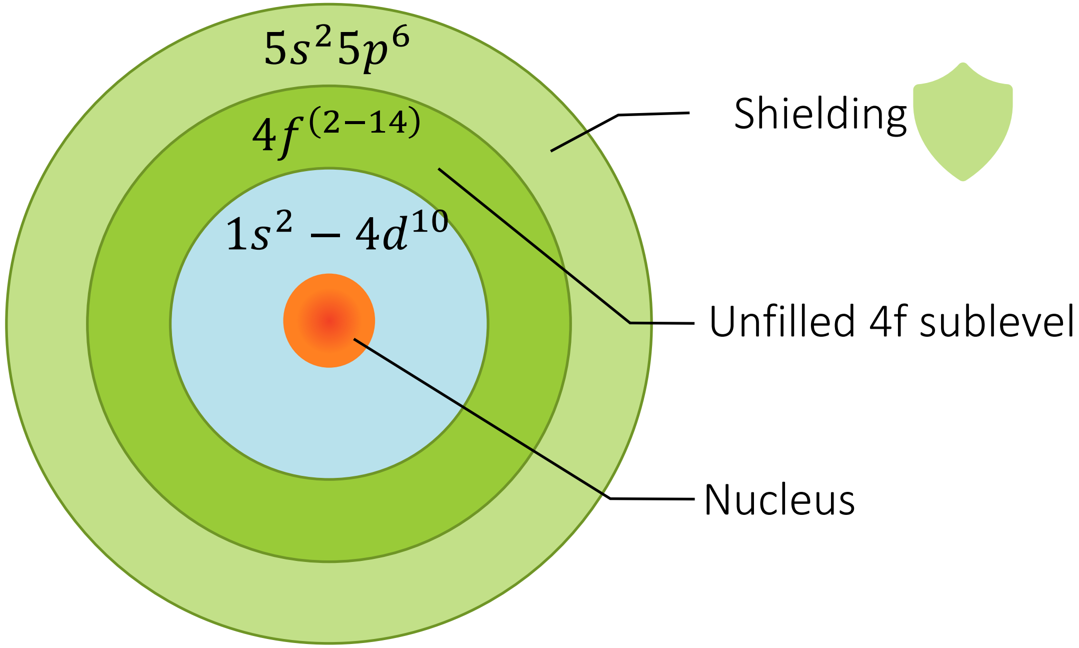
Introduction

The rare-earth ions

The lanthanides– [Ln]

57	58	59	60	61	62	63	64	65	66	67	68	69	70	71
La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Lanthanum	Cerium	Praseodymium	Neodymium	Promethium	Samarium	Europium	Gadolinium	Terbium	Dysprosium	Holmium	Erbium	Thulium	Ytterbium	Lutetium
	140	141	144		150	152	157	159	162.5	165	167	169	173	175

- Lanthanide ions [Ln^{3+}] : $1s^2\,2s^2\,2p^6\,3s^2\,3p^6\,4s^2\,3d^{10}\,4p^6\,5s^2\,4d^{10}\,5p^6\,\mathbf{4f^n}$

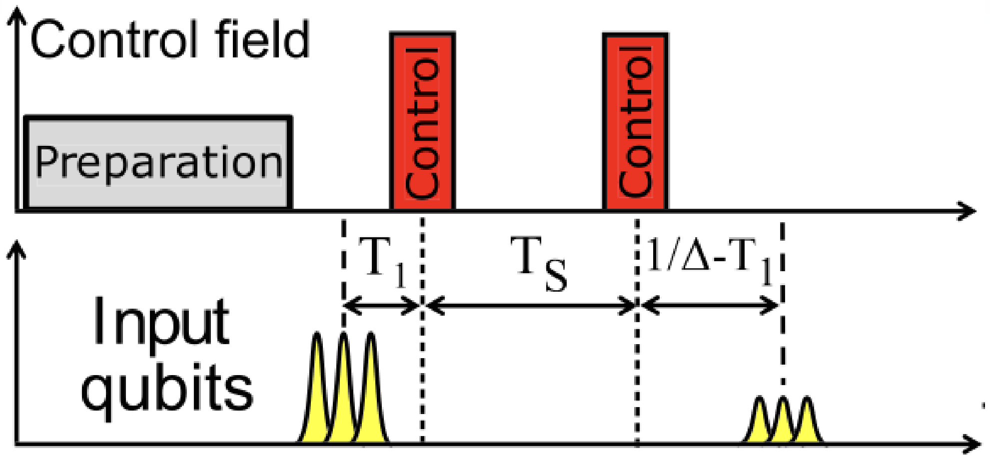


Rare earth Lanthanide ion [Ln^{3+}] *atomic structure*

- Shielding by the electron of the $5s^2$ and $5p^6$ sublevels
- Narrow transitions, almost unaffected by the crystal environment
- Long optical and spin coherence time at low temperature

Introduction

The rare-earth ions for quantum applications : quantum memories



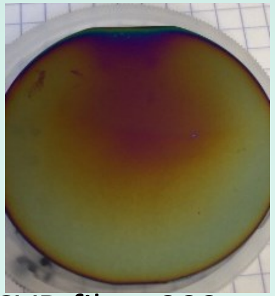
- Businger et al., *Non-classical correlations over 1250 modes between telecom photons and 979-nm photons stored in $^{171}Yb^{3+}:Y_2SiO_5$,Nat. Commun. 13, 6438 (2022)*
- Askarani et al., *Long-Lived Solid-State Optical Memory for High-Rate Quantum Repeaters, Phys. Rev. Lett. 127(22), 220502 (2021).*
- Kutluer et al. *Time Entanglement between a Photon and a Spin Wave in a Multimode Solid-State Quantum Memory*, Phys. Rev. Lett. 123 (2019)
- Zhong et al. *Nanophotonic rare-earth quantum memory with optically controlled retrieval*, Science 357 (2015)
- Heinze et al., *Stopped light and image storage by electromagnetically induced transparency up to the regime of one minute*, Phys. Rev. Lett. 111 (3), (2013)

Introduction

Quantum applications

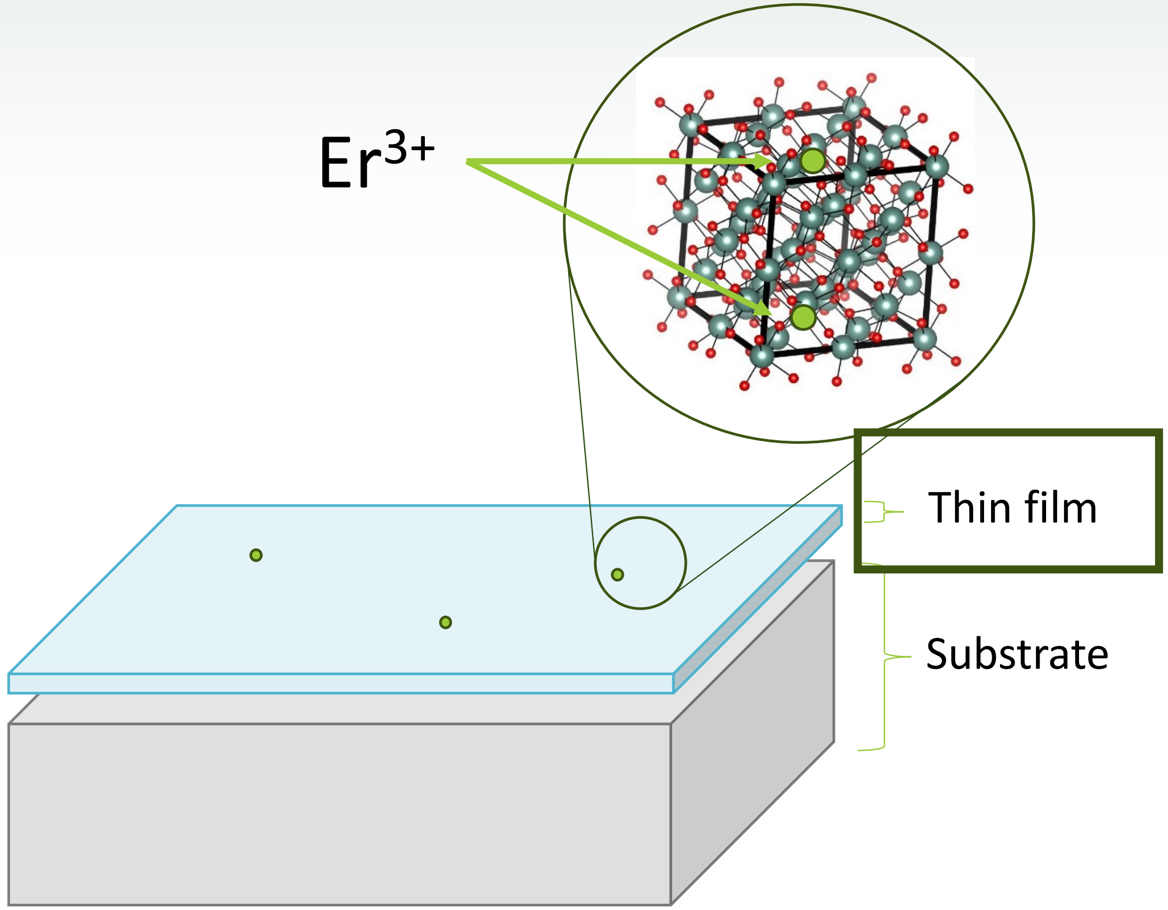
Size

cm ← nm

System	Bulk material (YSO)	Nano-particules (Y_2O_3)	Thin films (Y_2O_3)
	 Monocristal (under UV lamp)	 NPs (100 nm) (under UV lamp)	 DLI-CVD films 200 nm on Si
RE doping	0,3 %Eu	0,3 %Eu	2 %Eu
Inhomogeneous linewidth	5 GHz	11 GHz	90 GHz
Homogeneous linewidth	600 Hz	56 kHz	12 MHz
-	-	-	-
Optical T_2	510 µs	5,67 µs	0,027 µs
References	G. P. Flinn et al. , *Phys. Rev. B*, **49**, 5821 (1994)	S. Liu et al. , *ACS Nano*, **14**, 9953–9962 (2020)	G. A. West & K. W. Beeson, *J. Mater. Res.* , **5**, 1573–1580 (1990)

Introduction

Material



Thin films:

- Grown by **Direct Liquid Injection CVD**
- Possible integration : resonators, waveguides
- Research to optimize coherence properties

Y_2O_3 :

- Chemical compatibility with RE
- Binary compound
- IR transparency
- Long coherence time possible (spin and optical)

Er^{3+} :

- Emission wavelength in the telecom C-band
- Paramagnetic with an electronic spin
- Substitution of Y: two possible sites C_2 and C_{3i}

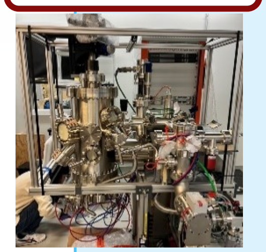
Different substrates and their impact on epitaxy

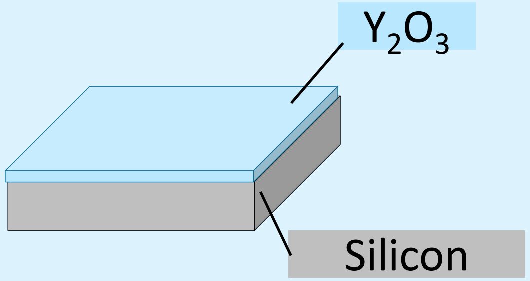
Silicon :

- Si(100)
- Si(111)

- Commercially available ✓
- Possible to remove the substrate from the film ✓
- Direct epitaxial growth of Y_2O_3 very difficult ✗

MBE template :

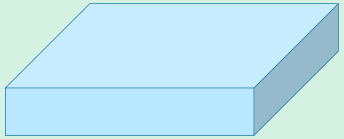




- Interface more favorable for epitaxy ✓
- Possible to remove the substrate from the film ✓

Oxides :

- Sapphire
- Quartz
- YSZ (Yttria Stabilized Zirconia)



- Interface more favorable for epitaxy ✓
- Difficult substrate removal ✗

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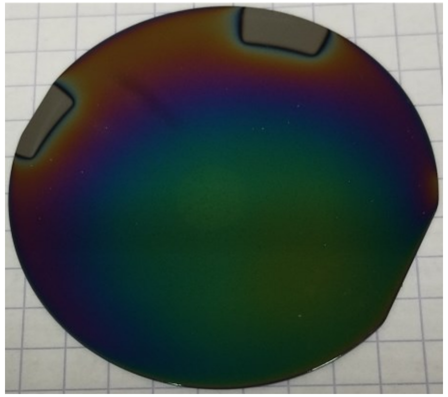
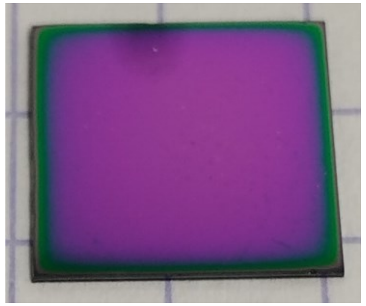
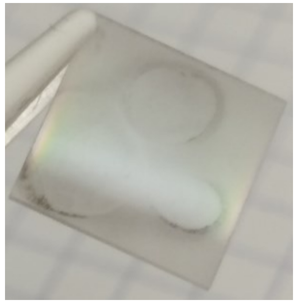
Results



Er^{3+} : Y_2O_3 on Si(100)



Er^{3+} : Y_2O_3 on MBE template



Er^{3+} : Y_2O_3 on YSZ

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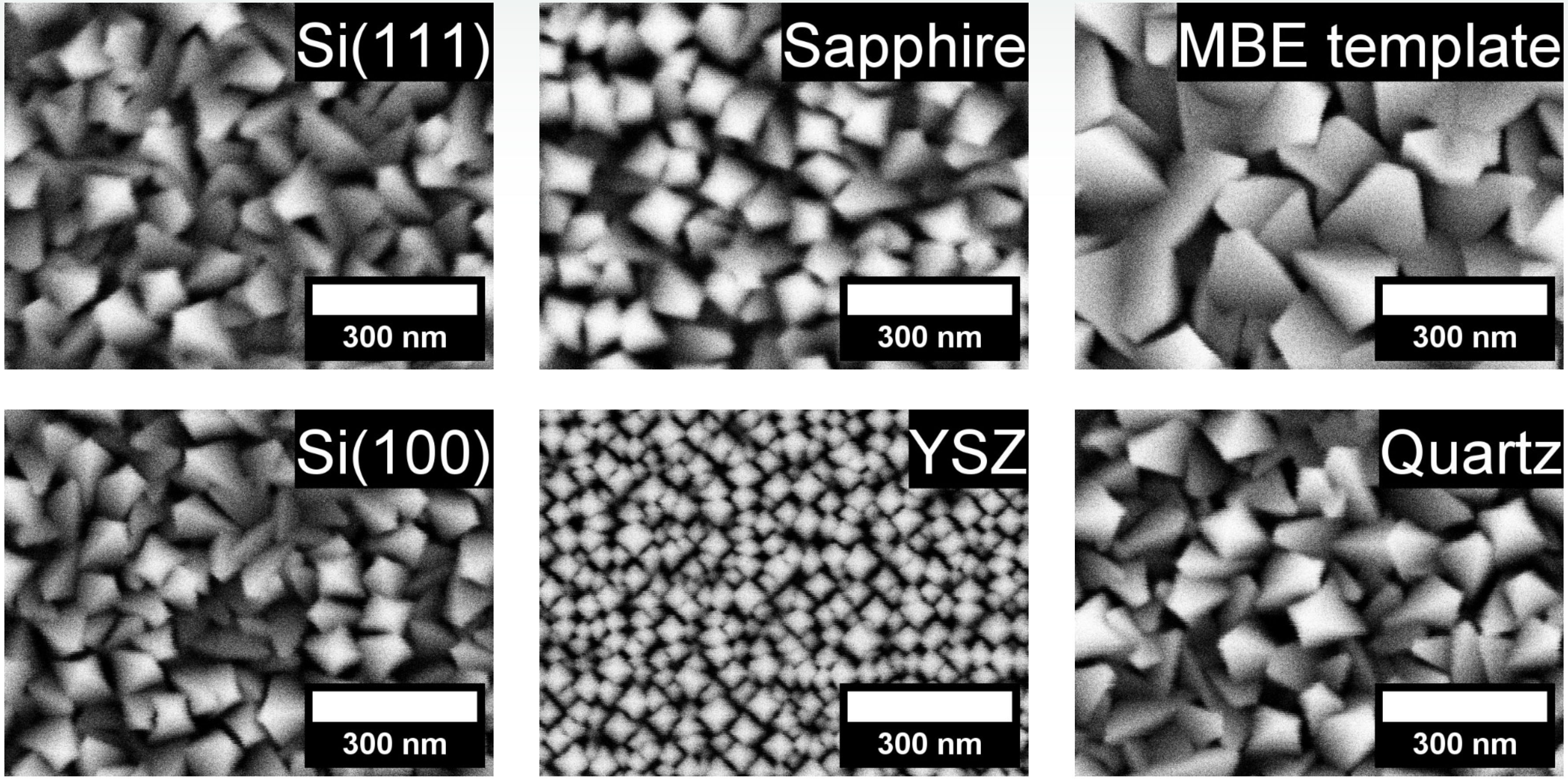
Results

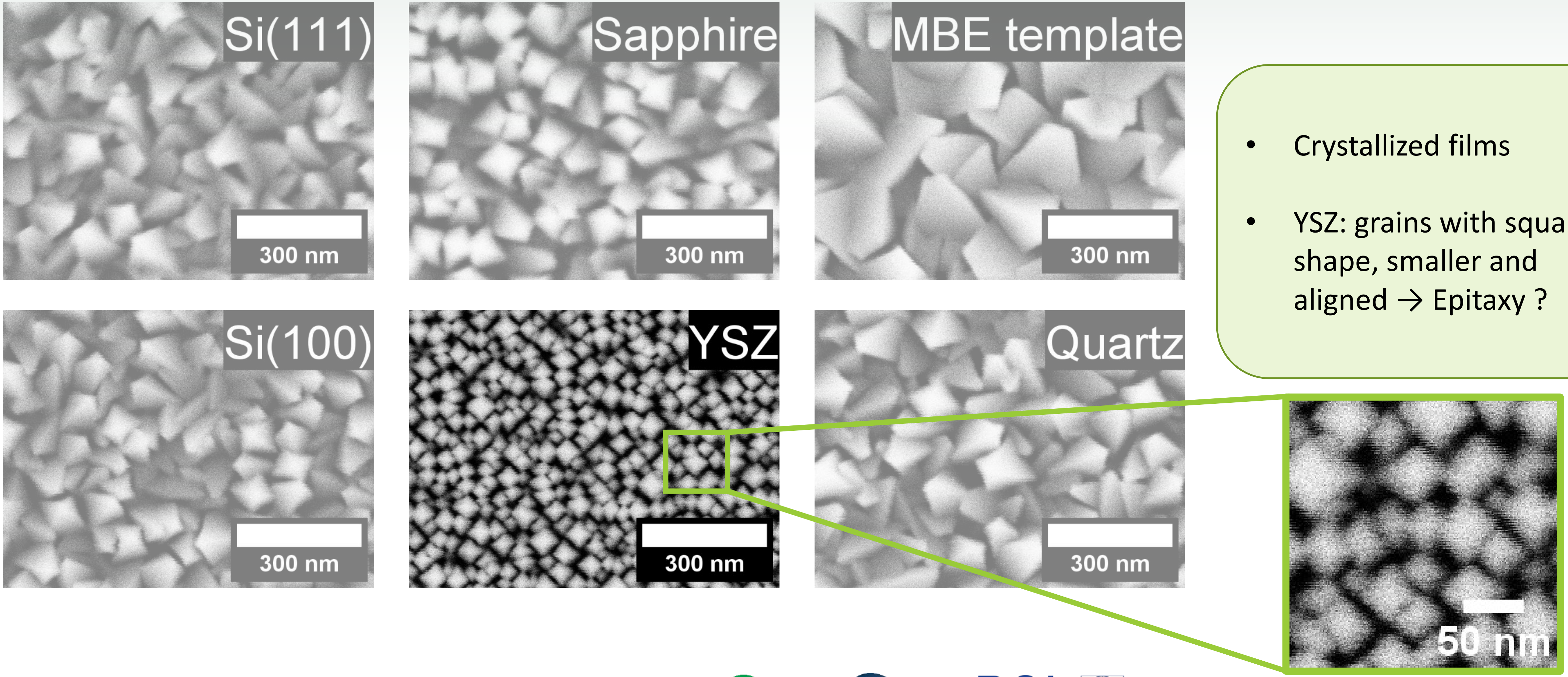
Morphological properties: SEM images



- Crystallized films

Results

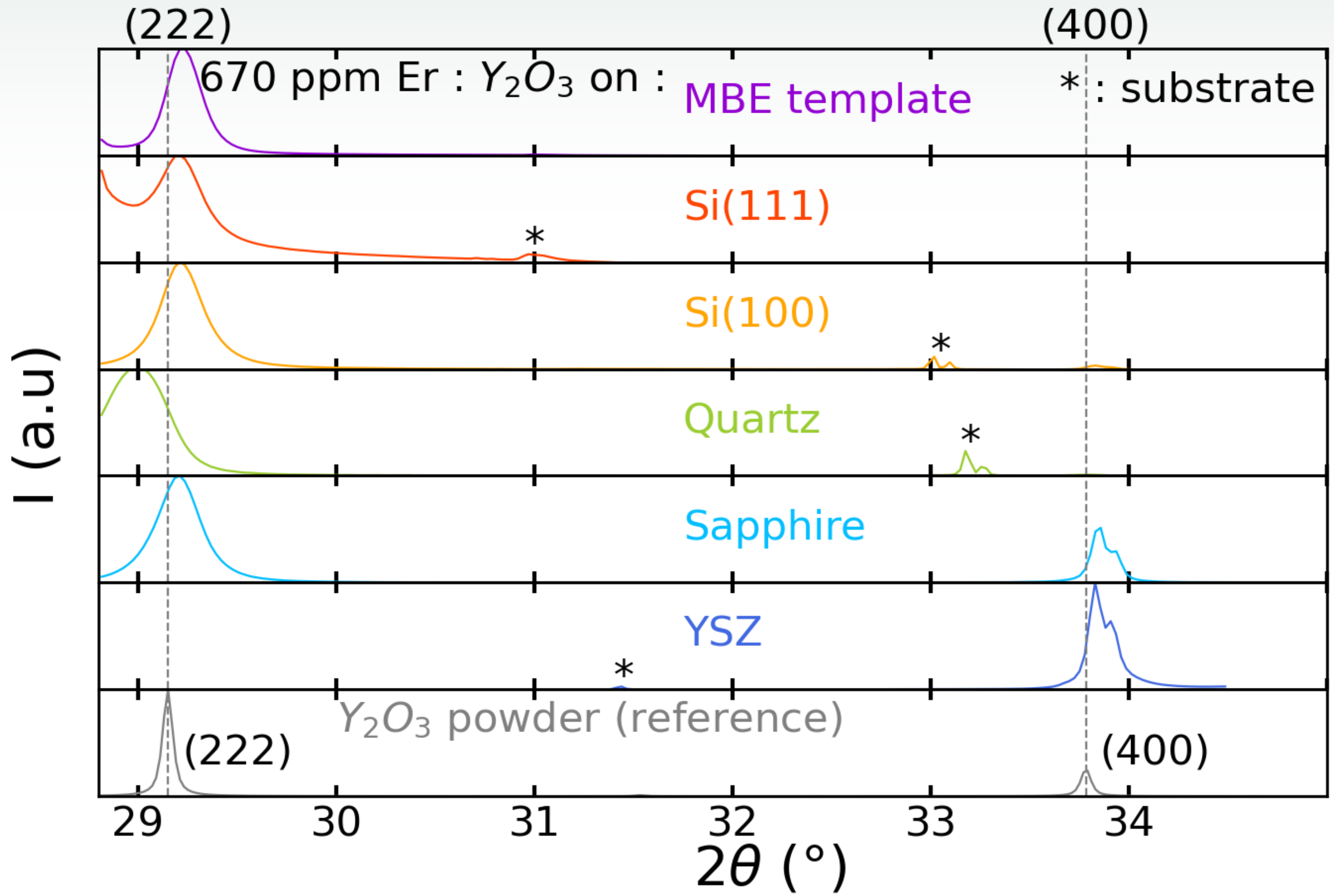
Morphological properties: SEM images



- Crystallized films
- YSZ: grains with square shape, smaller and aligned → Epitaxy ?

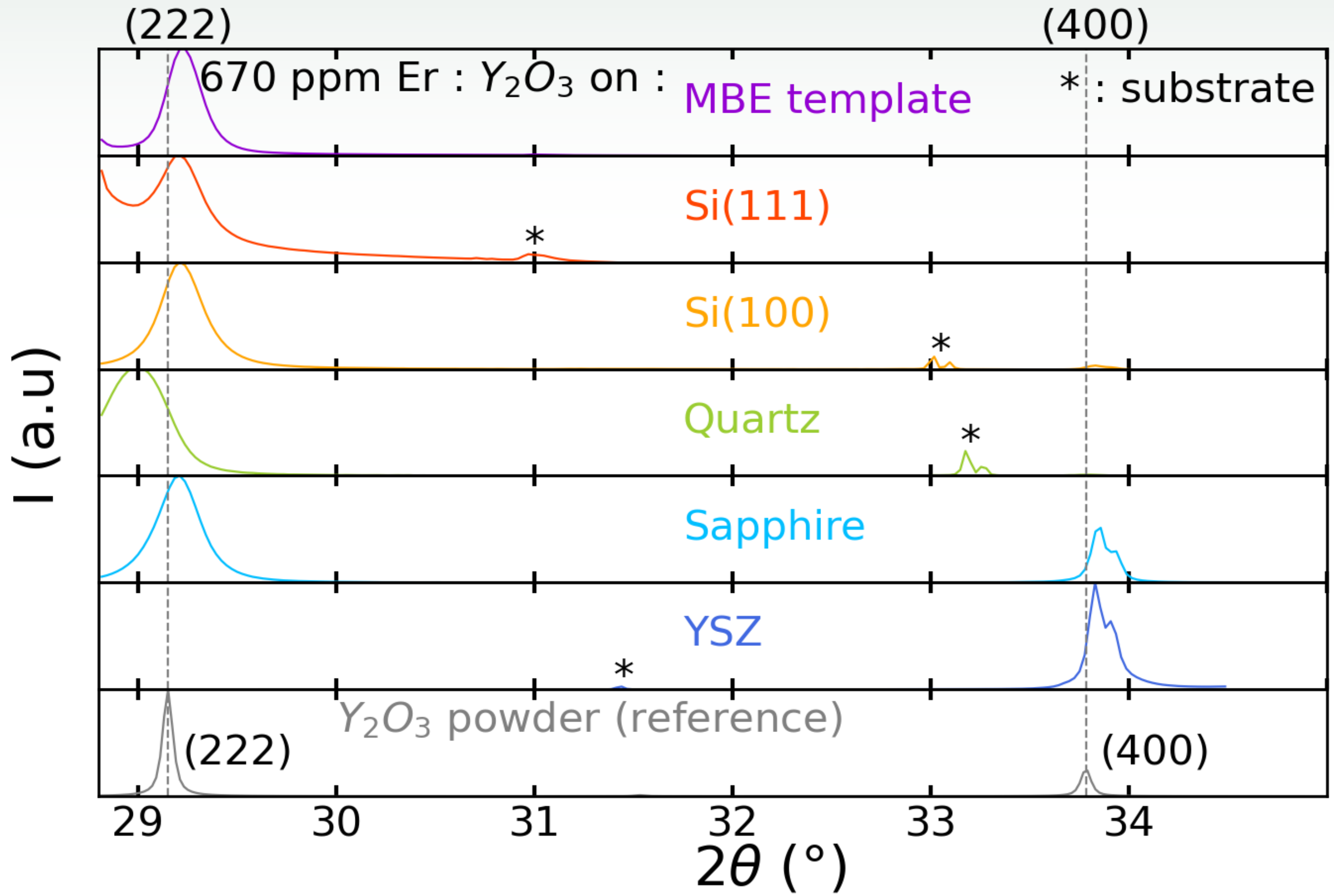
Results

Structural properties: X-ray diffraction



Results

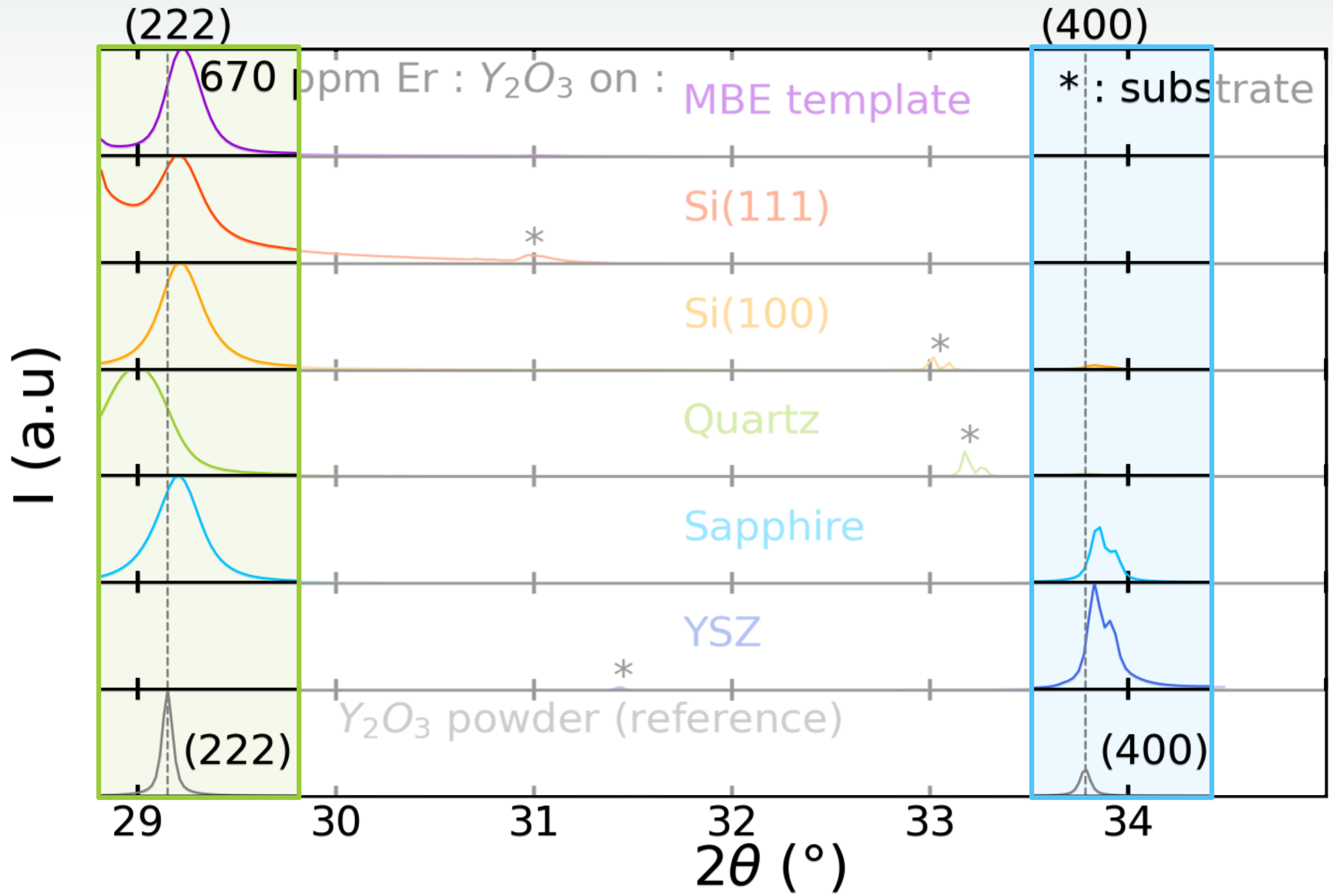
Structural properties: X-ray diffraction

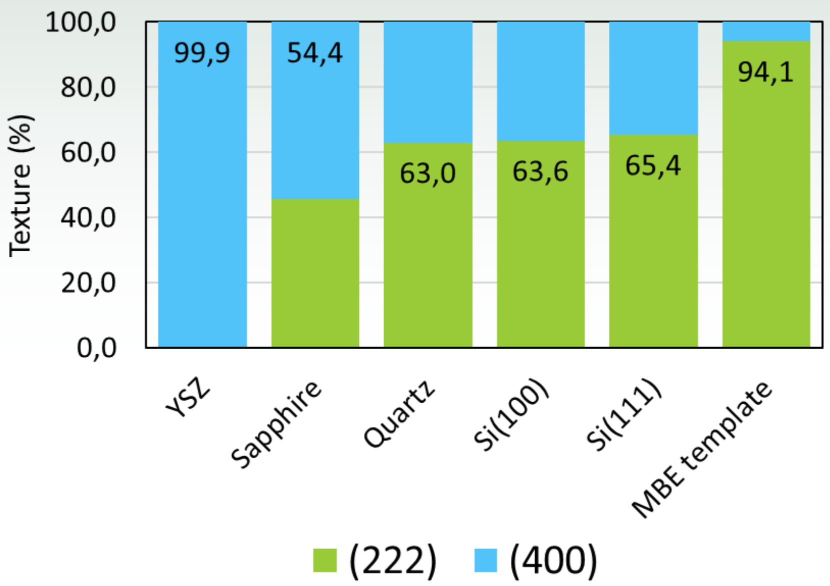


- (222) and (400) peak size varies with **substrate**

Results

Structural properties: X-ray diffraction





$$\%_{texture} = 100 \times \left(1 - \frac{\left(\frac{I_{400}}{I_{222}}\right)}{\left(\frac{I_{400}}{I_{222}}\right)_{powder}} \right)$$

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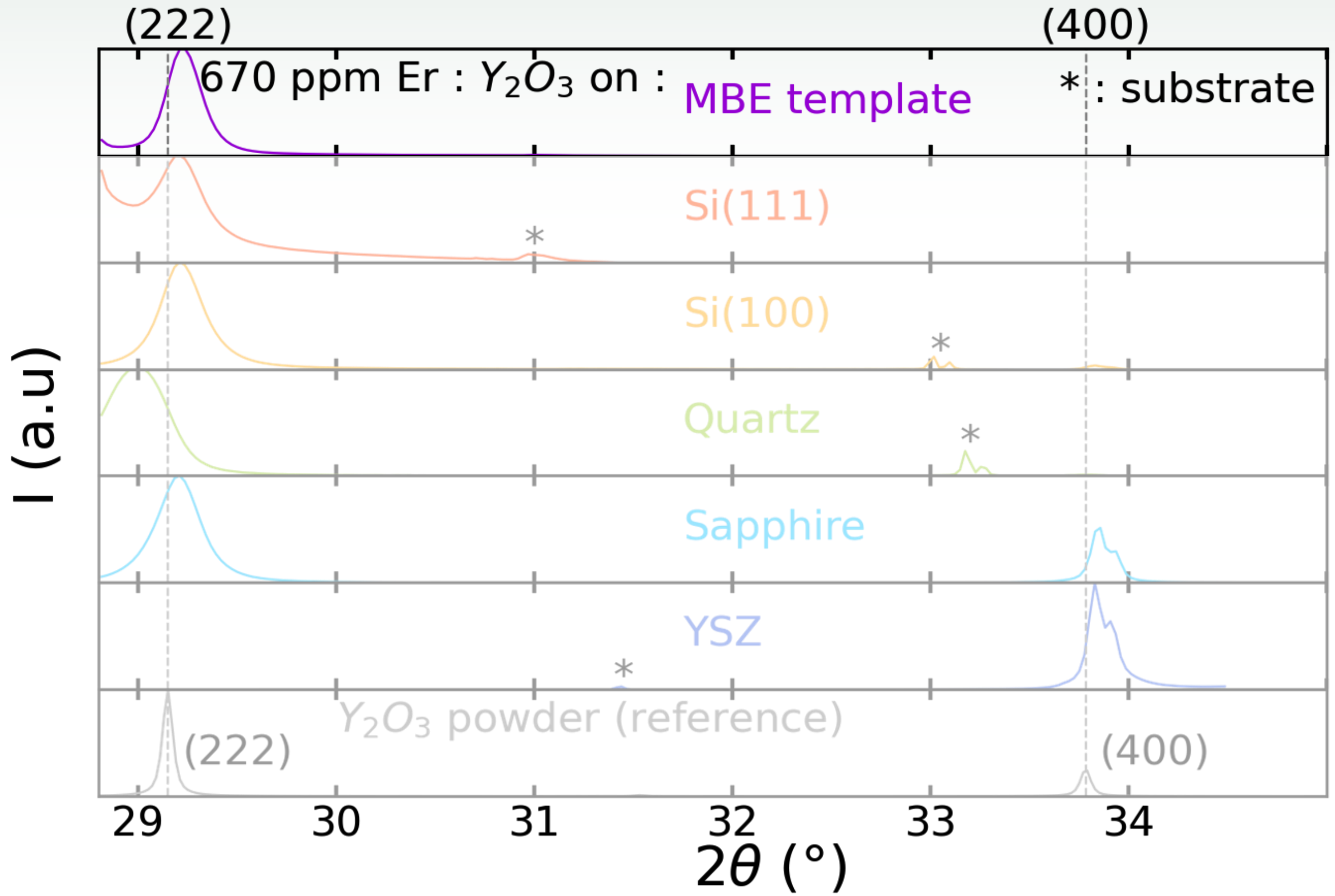
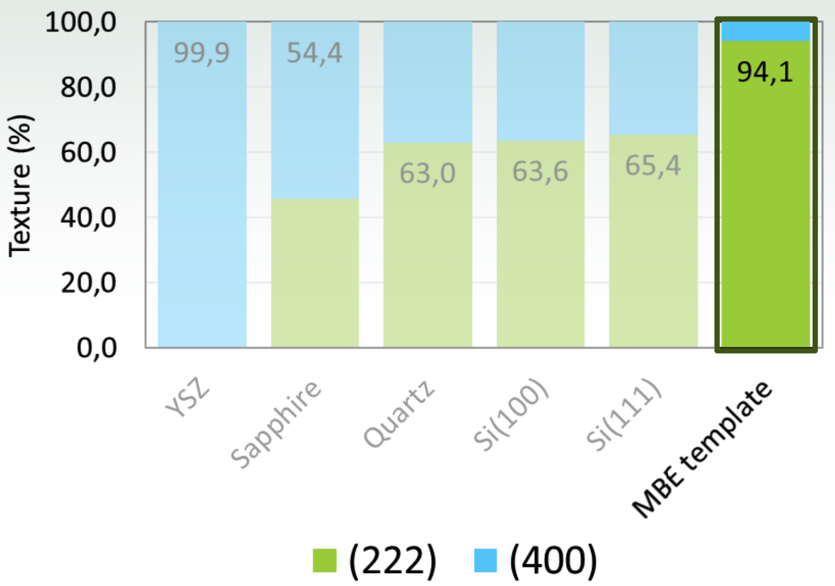
Results

Structural properties: X-ray diffraction

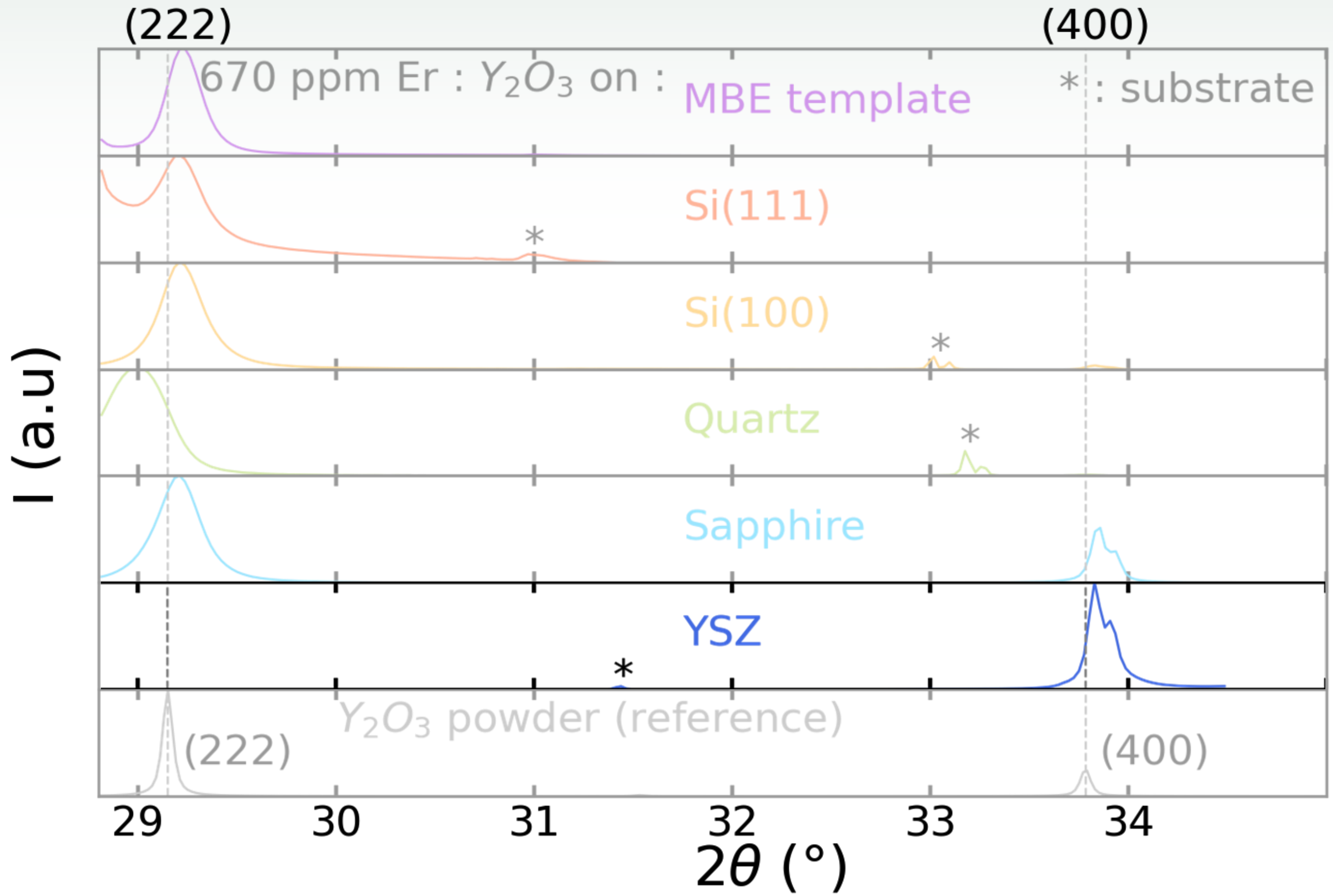


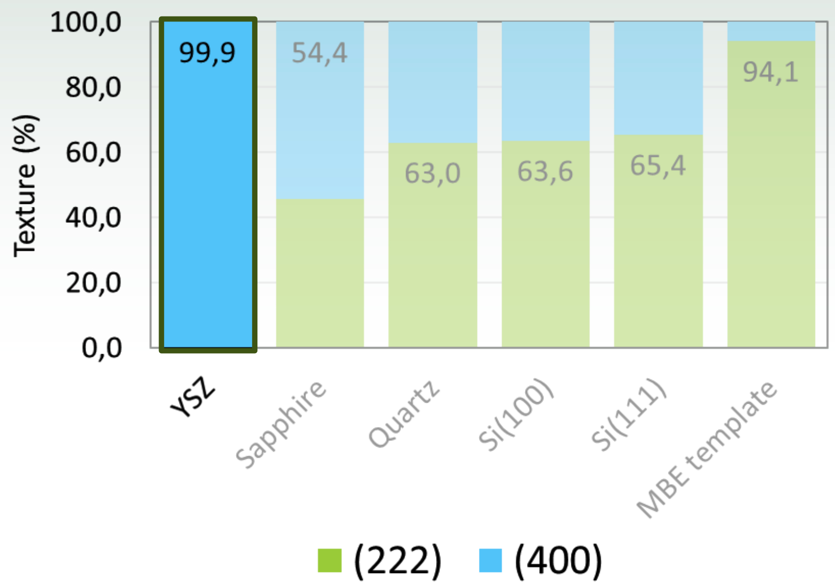


- (222) and (400) peak size varies with **substrate**
- Increase of preferential orientation with **MBE template**

Results

Structural properties: X-ray diffraction





- (222) and (400) peak size varies with **substrate**
- Increase of preferential orientation with **MBE template**
- **YSZ**: orientation almost 100 % → Epitaxy ?

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Results

Optical properties

Results

Optical properties: Photoluminescence spectra

$$\mathcal{H} = H_{IL} + \boxed{H_{CC}} + H_{Spin}$$

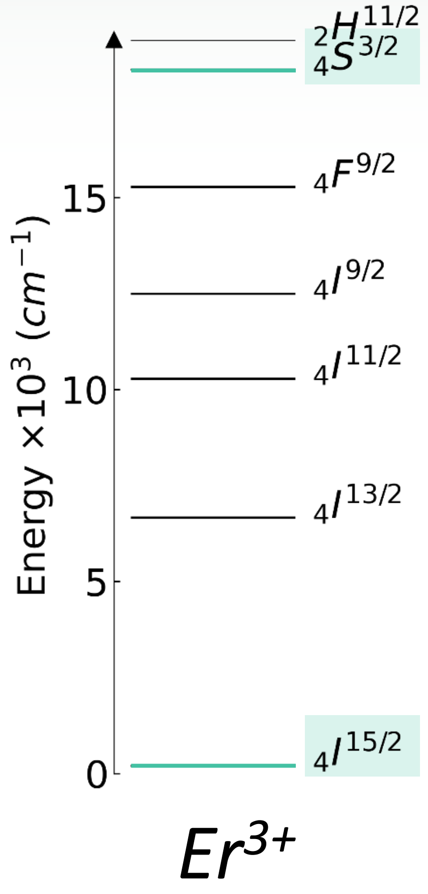
H_{IL} :	Free ion Hamiltonian
H_{CC} :	Crystal field Hamiltonian
H_{Spin} :	Spin Hamiltonian

Results

Optical properties: Photoluminescence spectra

@ 10 K

$$\mathcal{H} = H_{IL} + H_{CC} + H_{Spin}$$



Results

Optical properties: Photoluminescence spectra

@ 10 K

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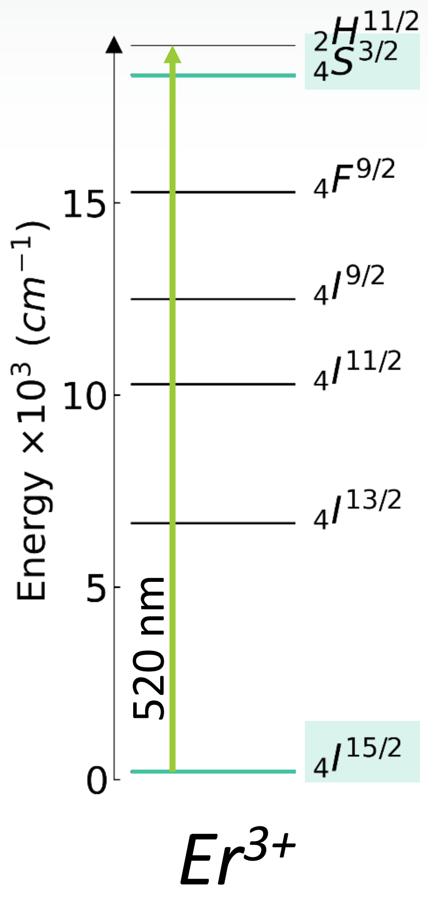

Results

Optical properties: Photoluminescence spectra

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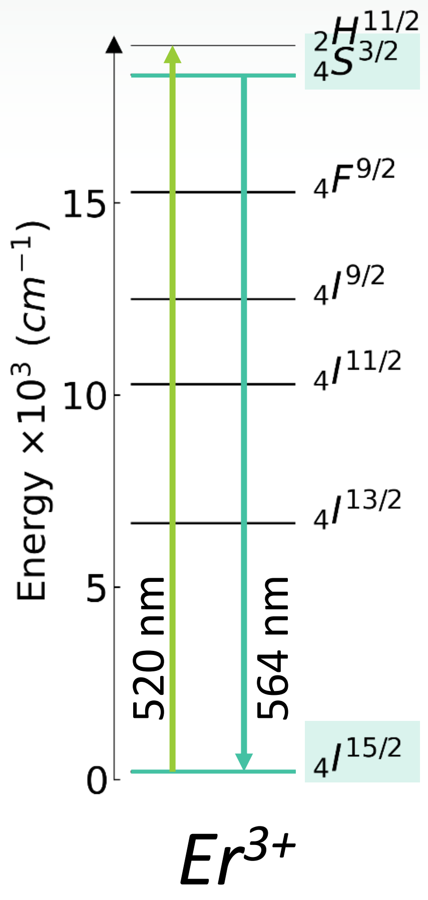
$$\mathcal{H} = H_{IL} + H_{CC} + H_{Spin}$$



Optical properties: Photoluminescence spectra

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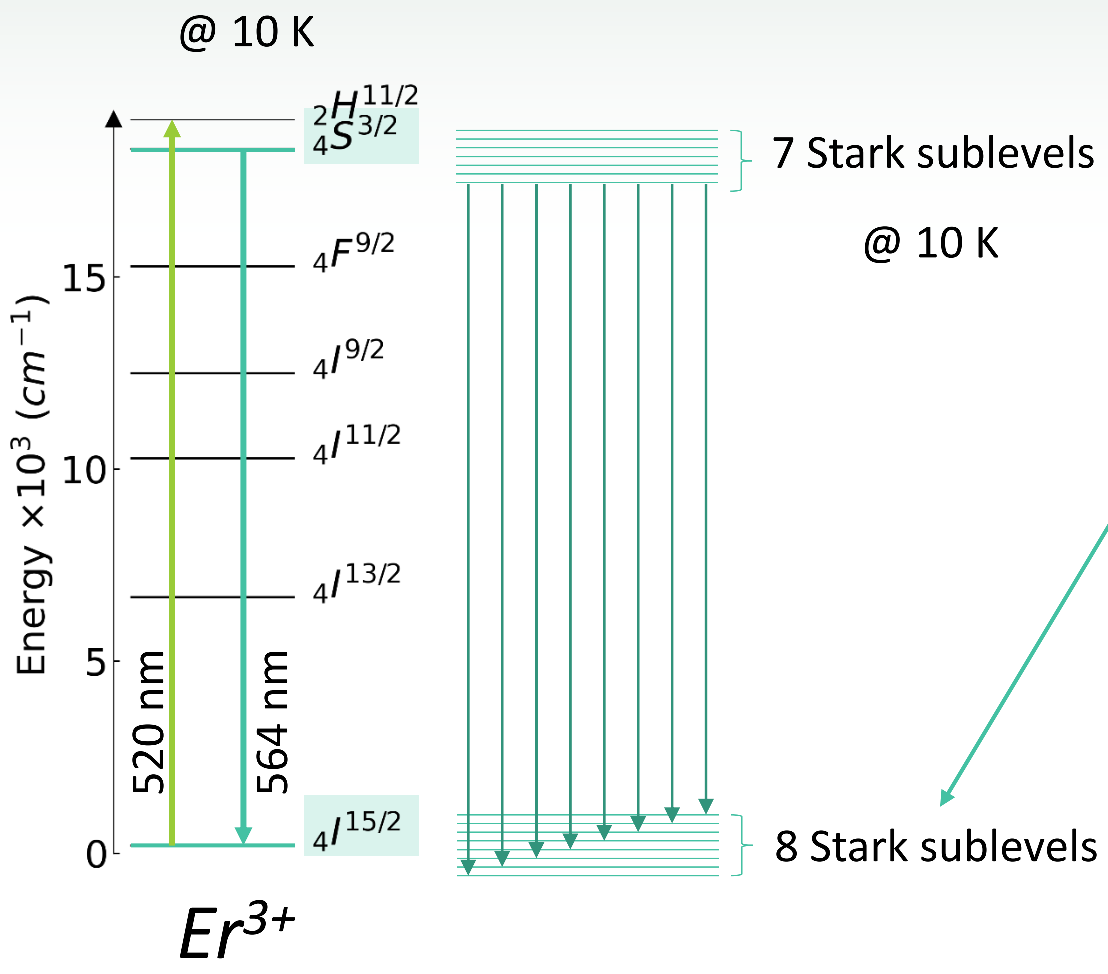

Results

Optical properties: Photoluminescence spectra

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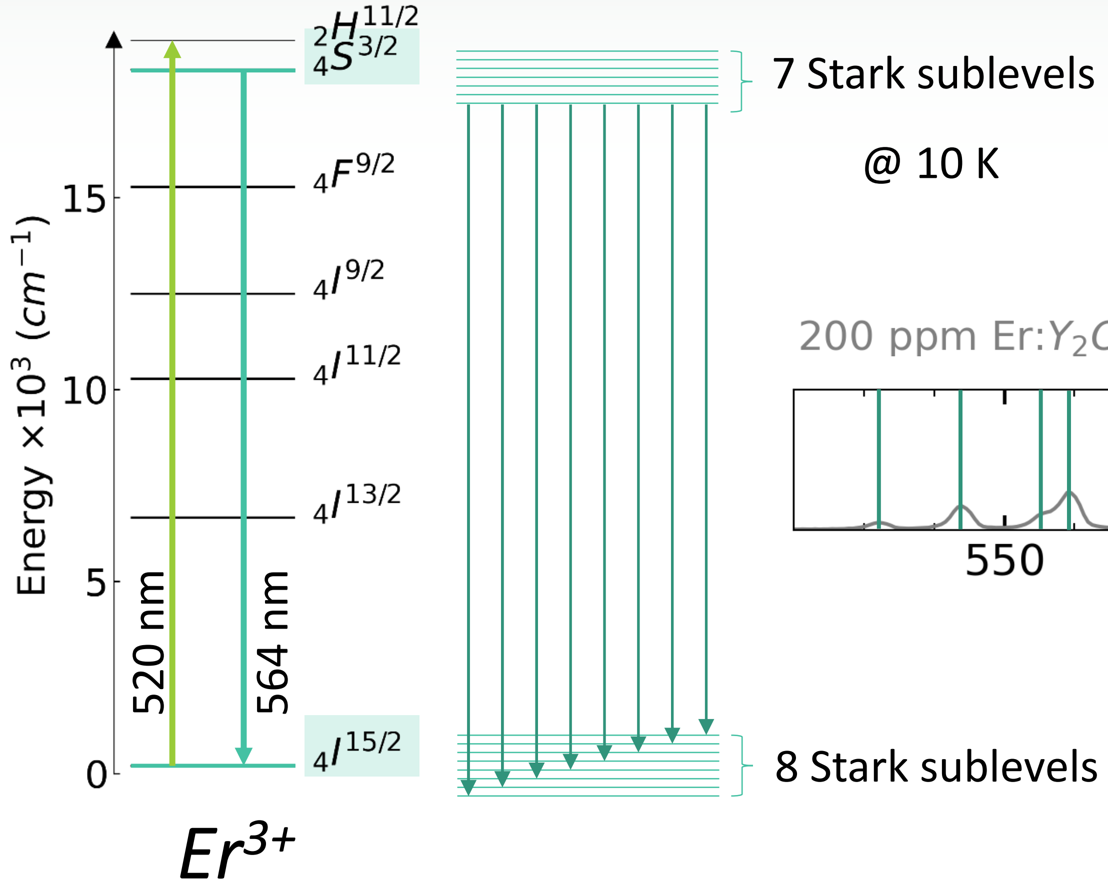
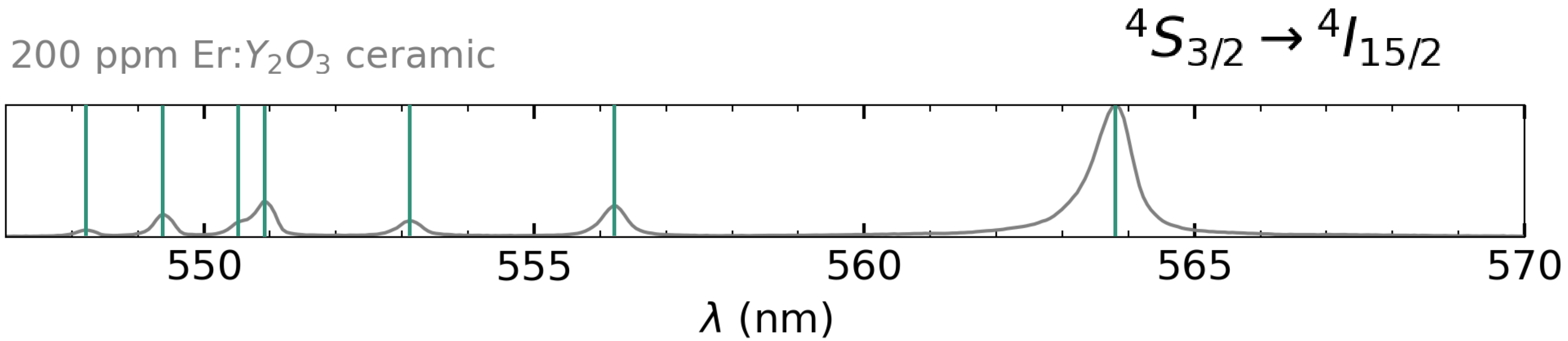
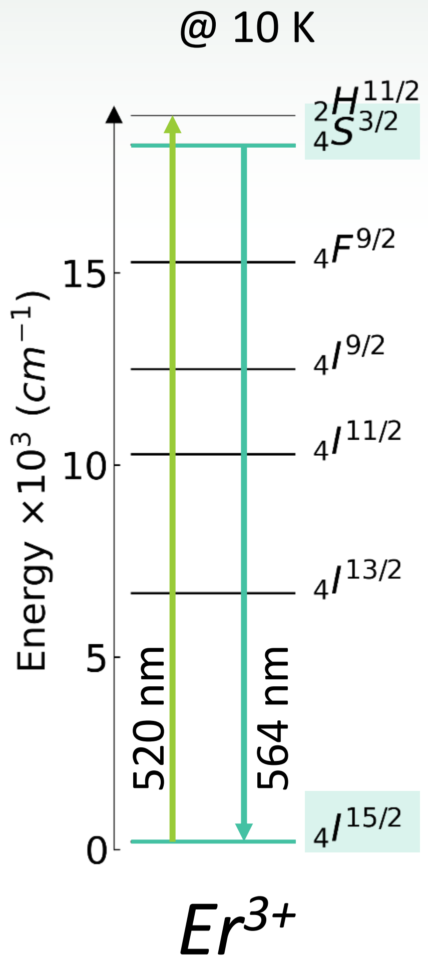


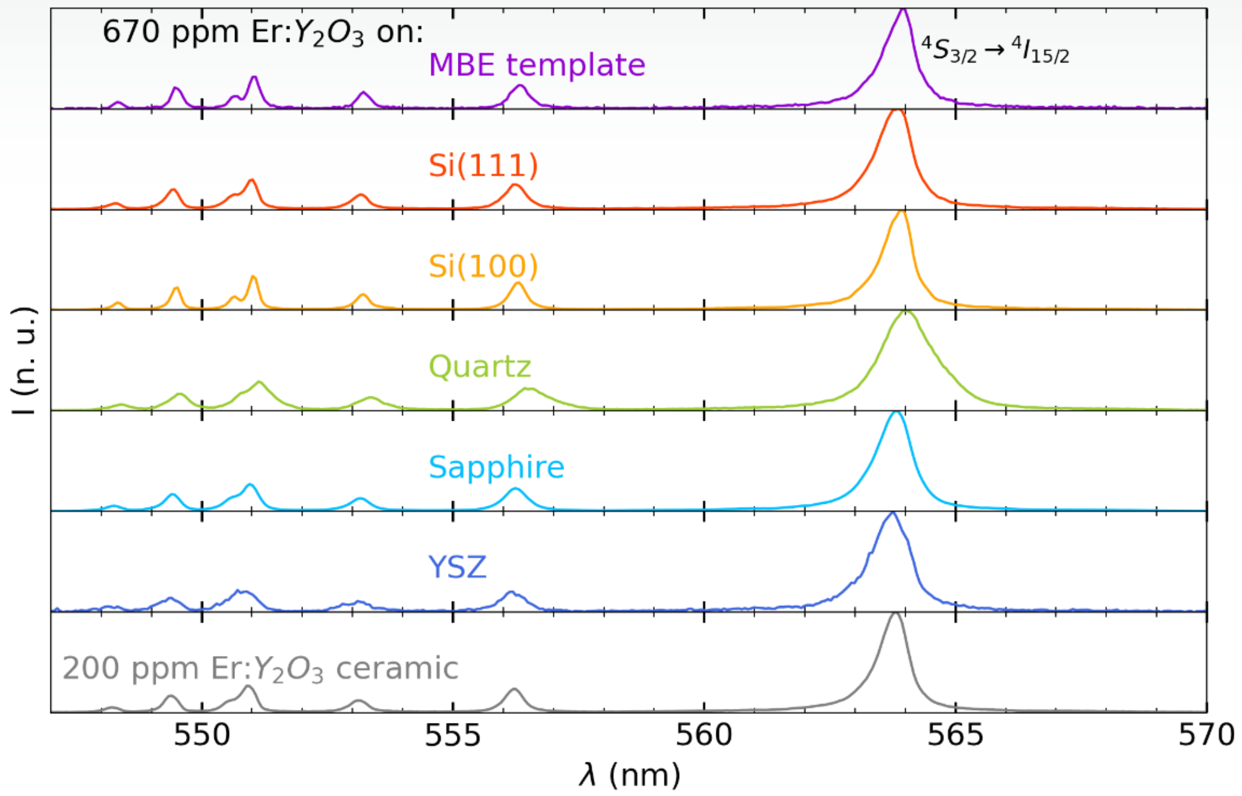
@ 10 K



Results

Optical properties: Photoluminescence spectra

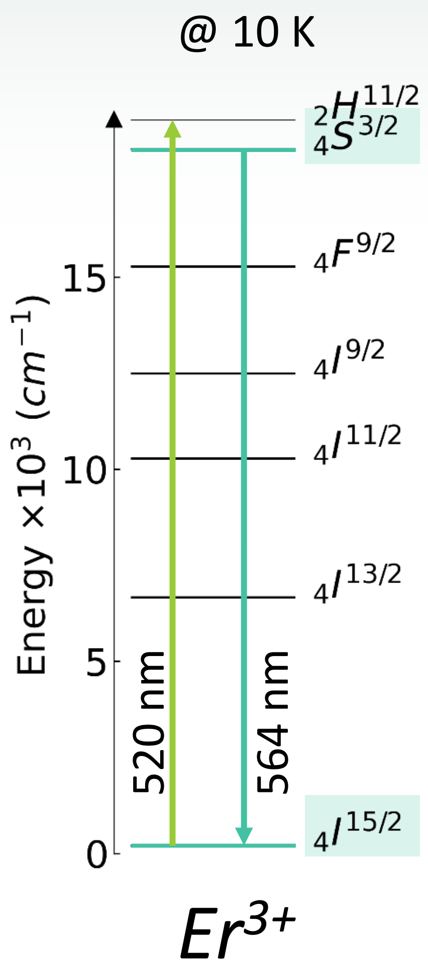


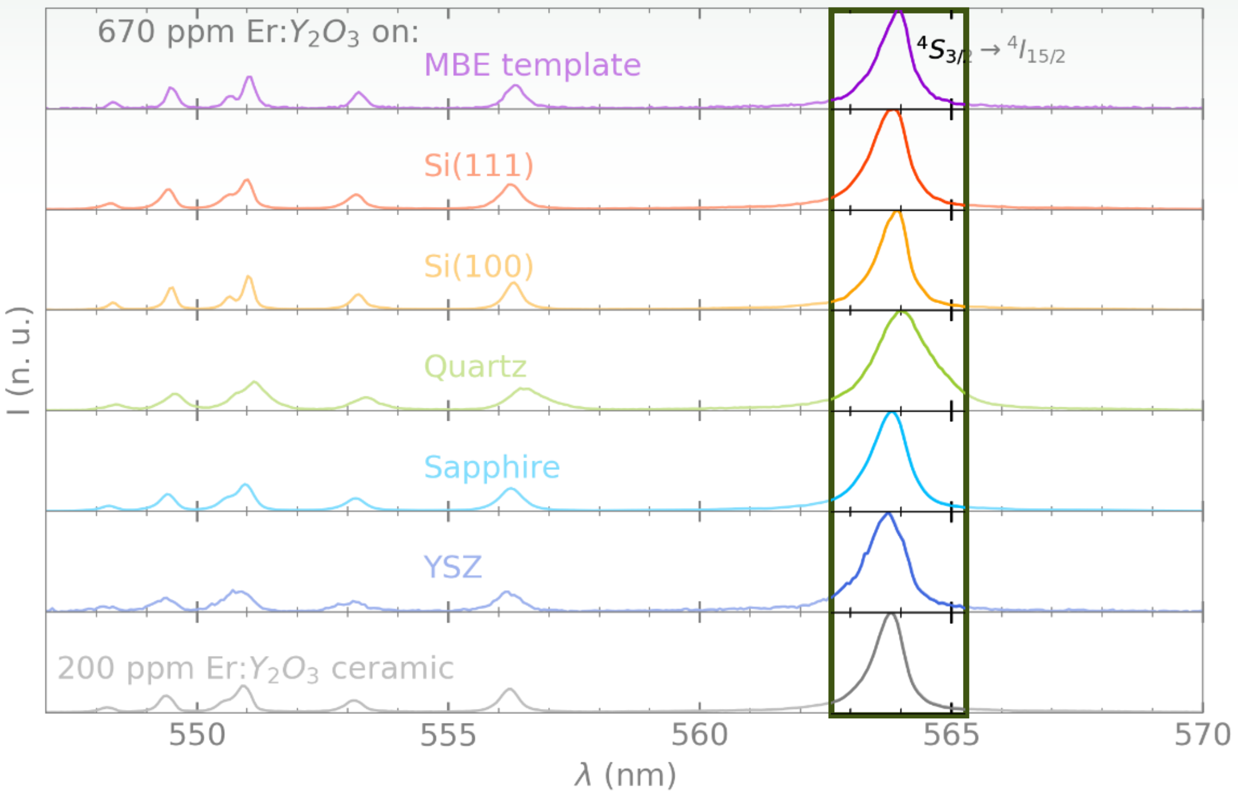


On all the substrate, the Y_2O_3 film is crystallised

Results

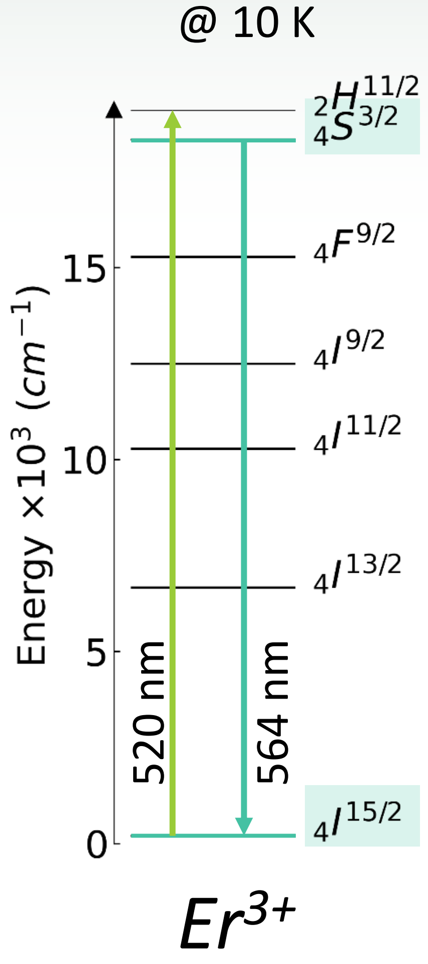
Optical properties: Decays

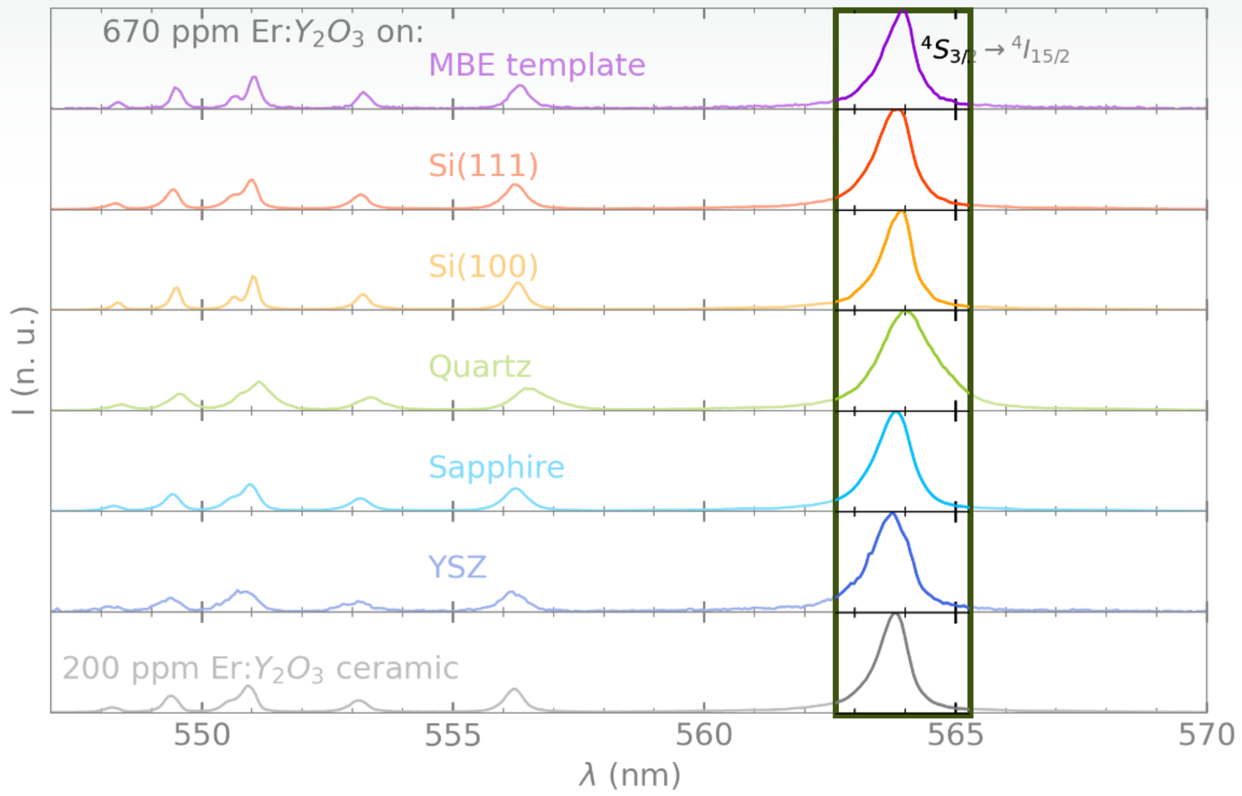




Results

Optical properties: Decays



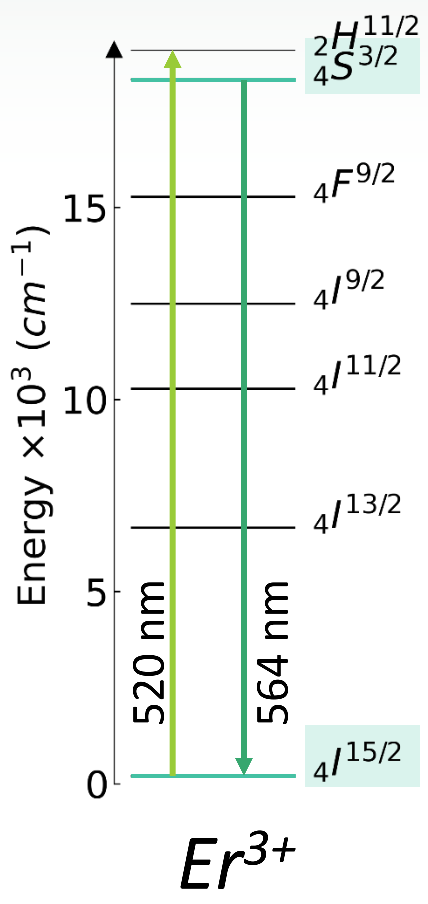


Analysis of decay **shape** and **time** gives information on RE environment

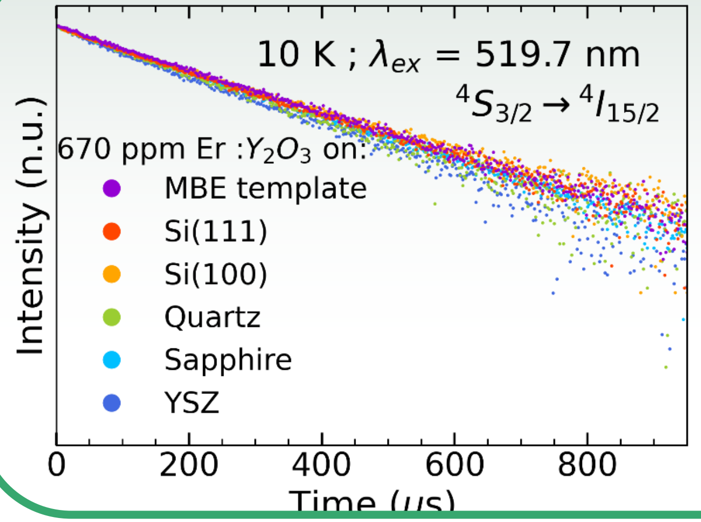
Results

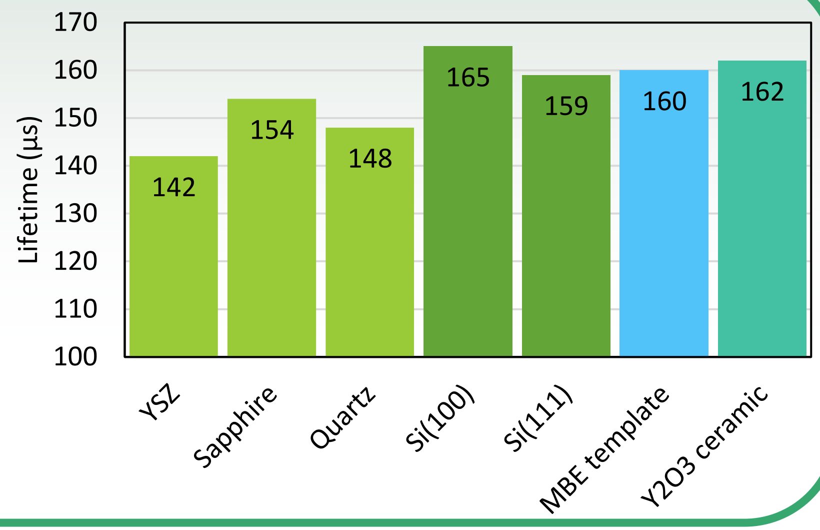
Optical properties: Decays

@ 10 K



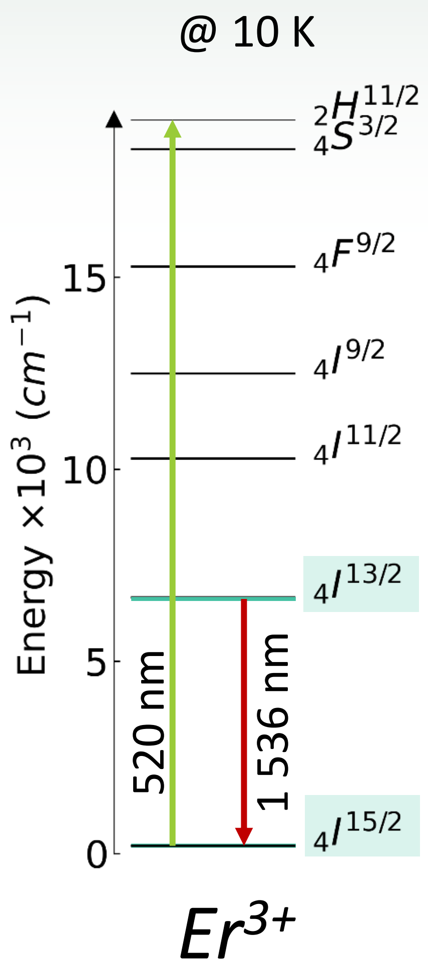
Visible

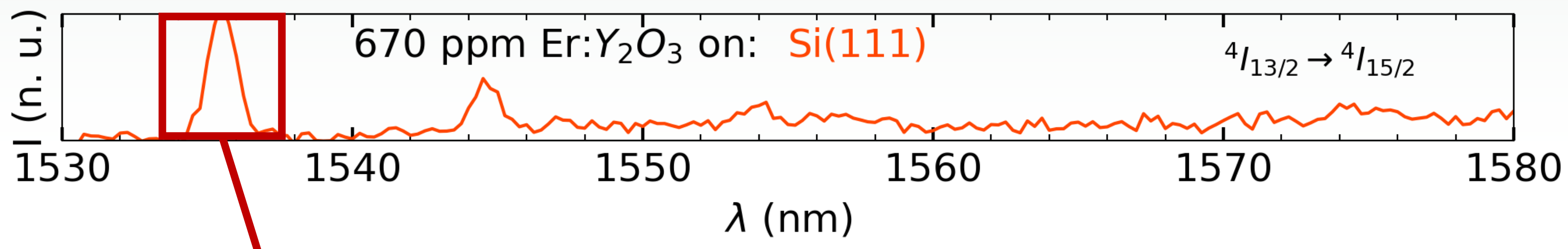




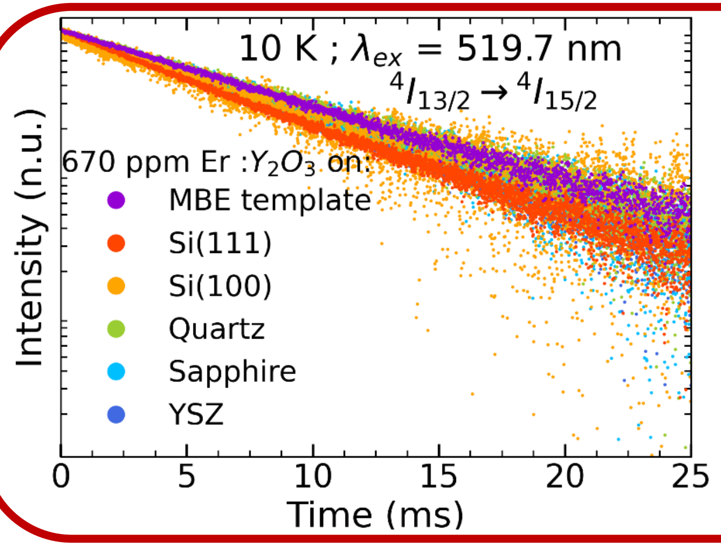
Results

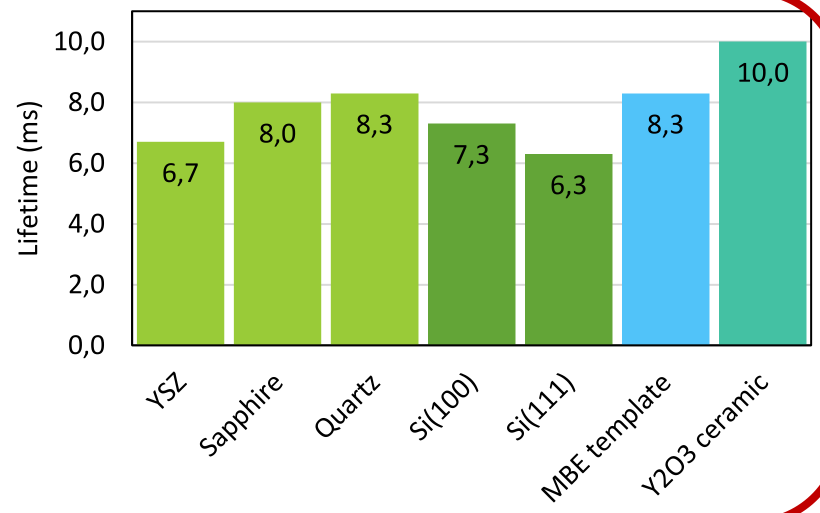
Optical properties: Decays





IR

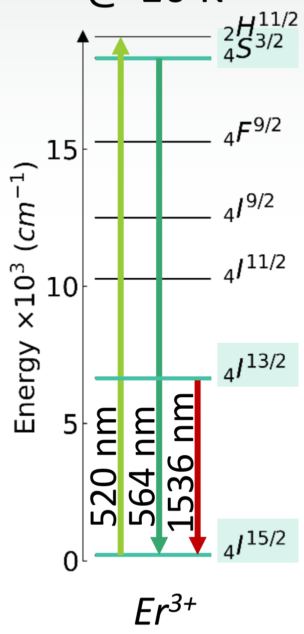




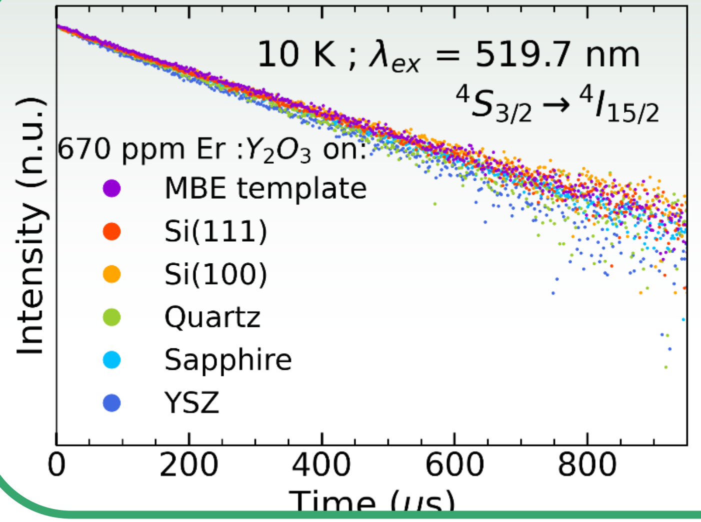
Results

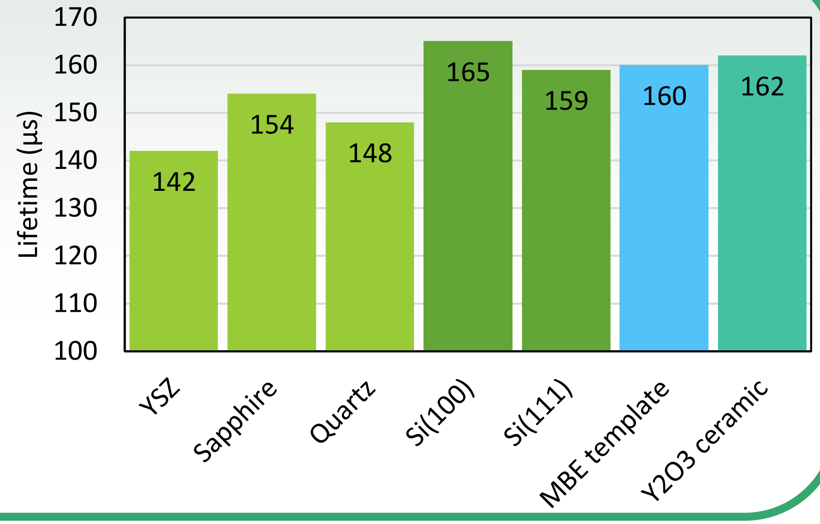
Optical properties: Decays

@ 10 K



Visible





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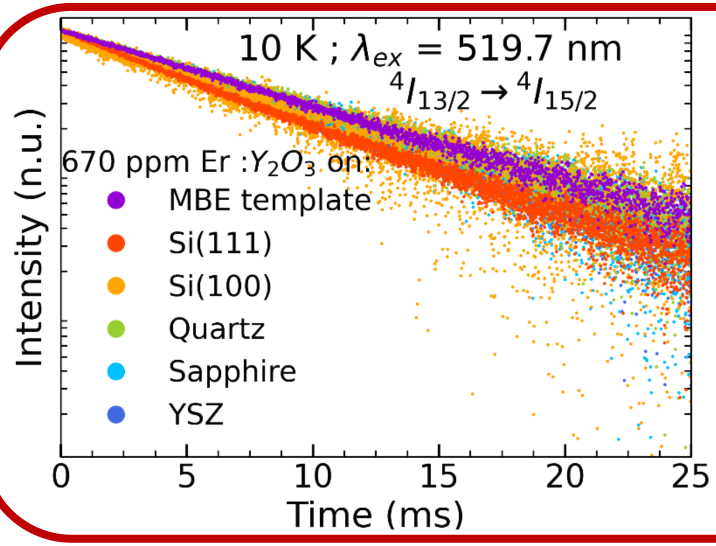

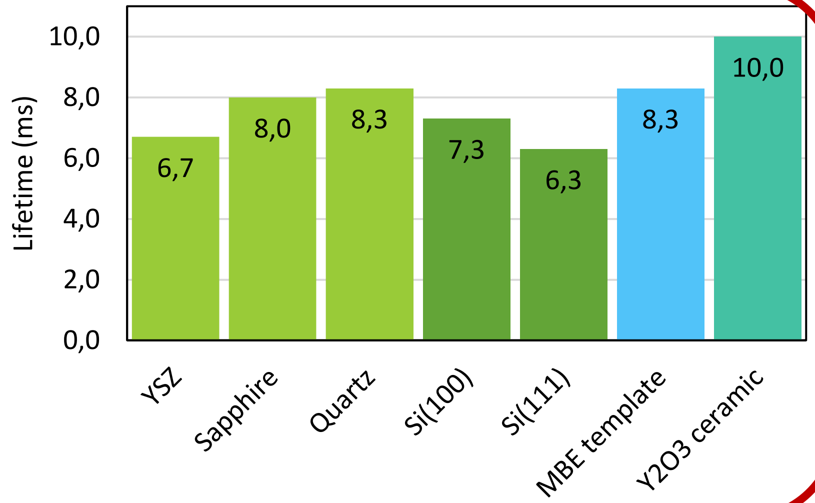

- Similar lifetimes for **all samples** and close from ceramic
- **YSZ** : shorter lifetime → smaller grains ?

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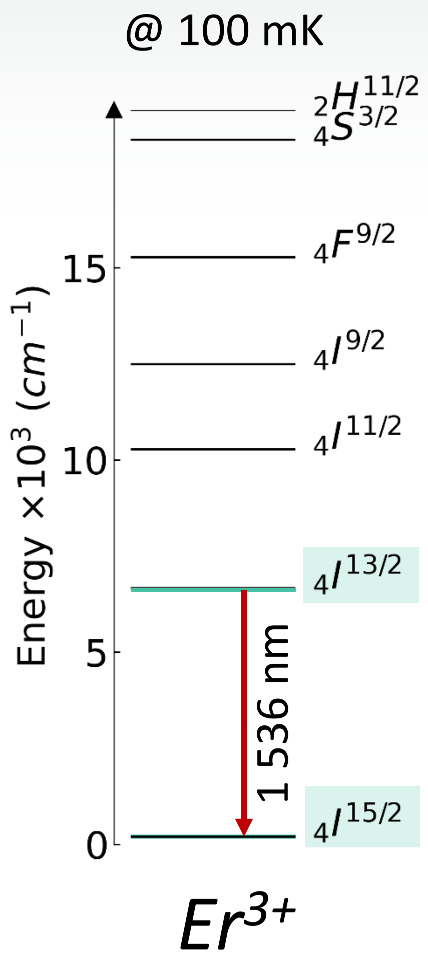
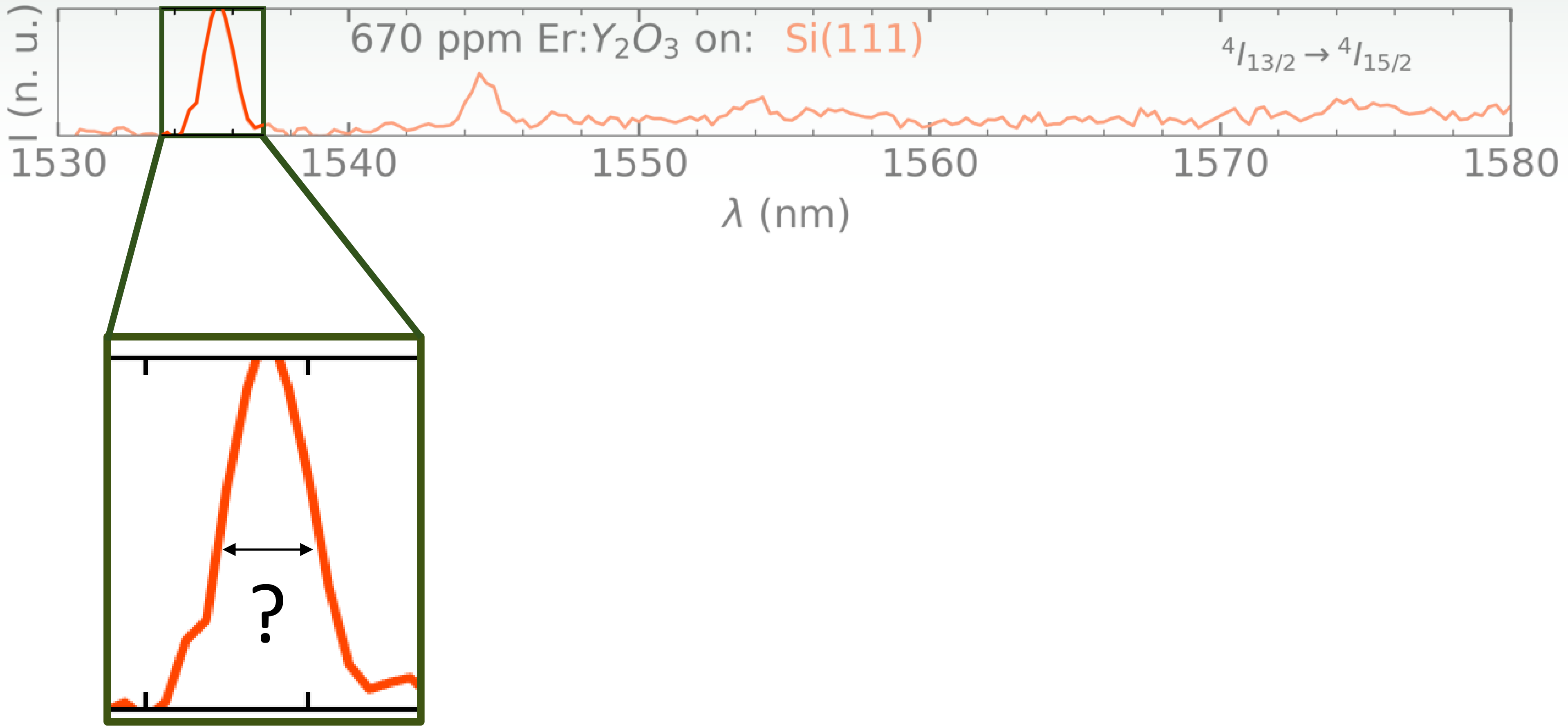
Results

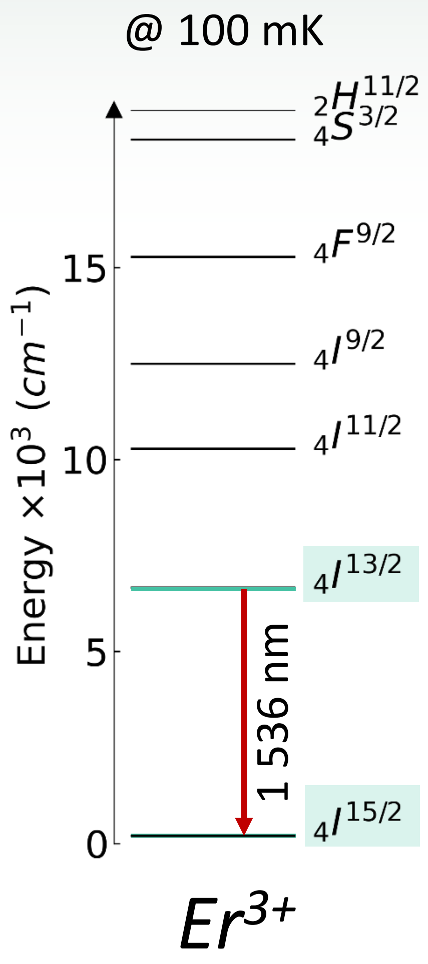
Optical properties: Inhomogeneous linewidth

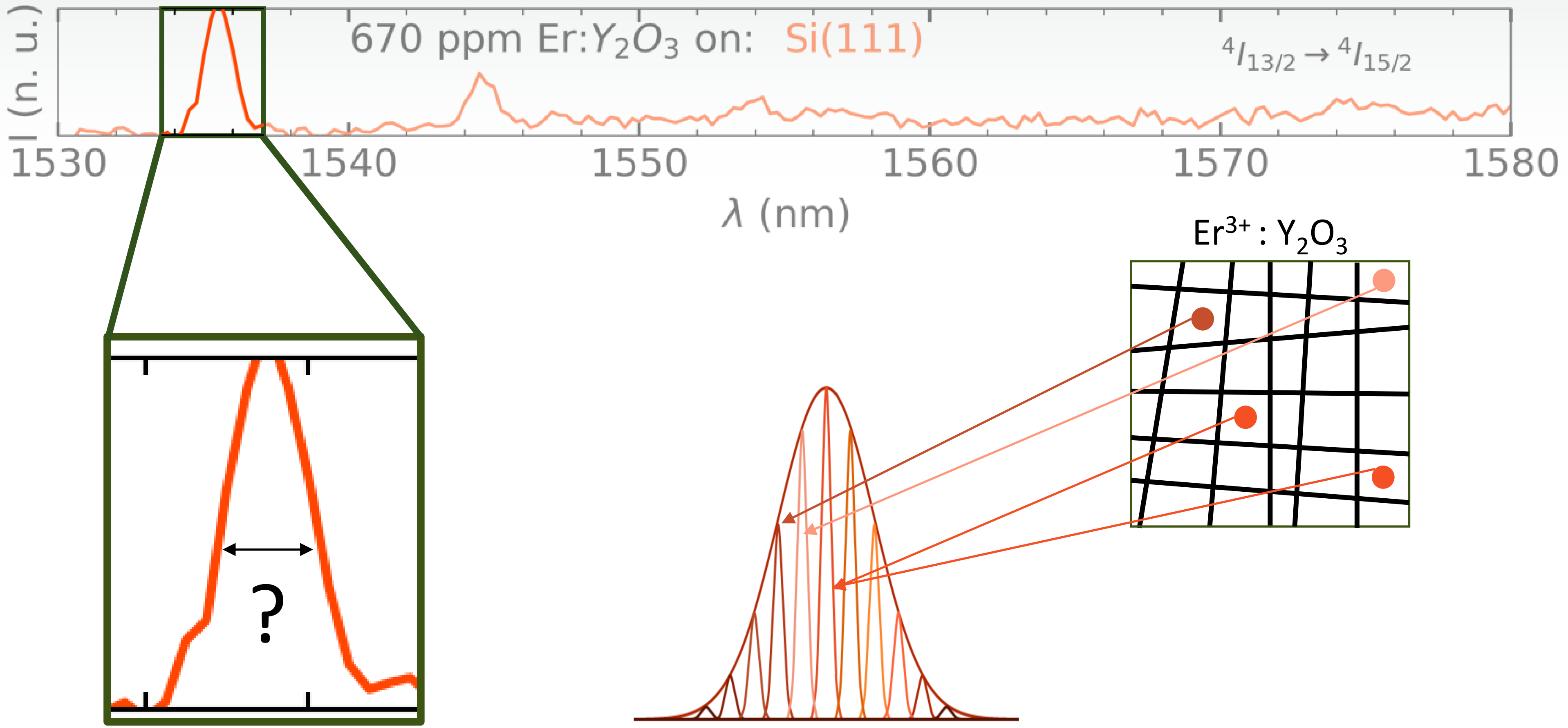




Results

Optical properties: Inhomogeneous linewidth

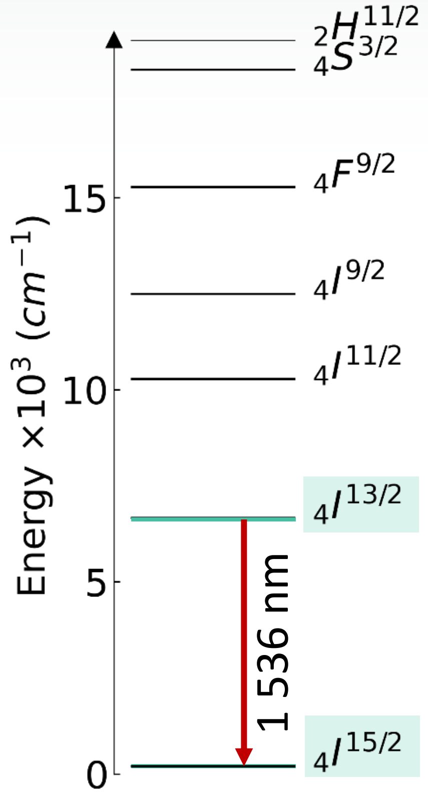




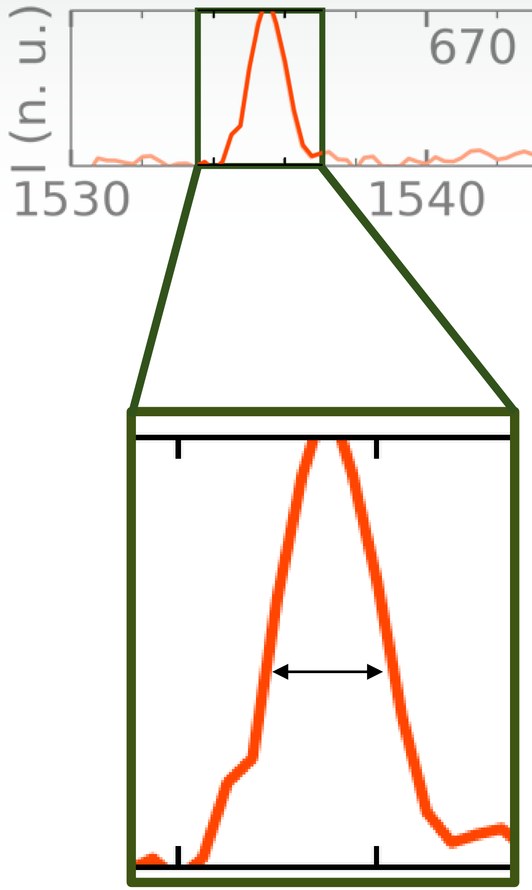
Results

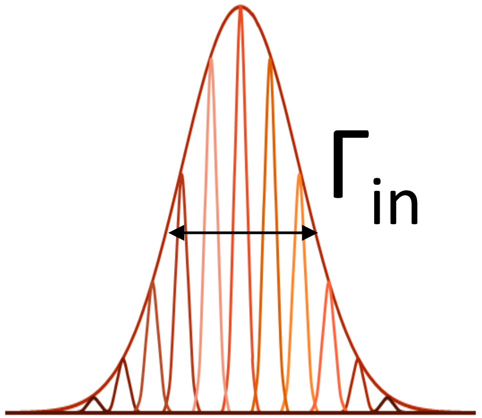
Optical properties: Inhomogeneous linewidth

@ 100 mK

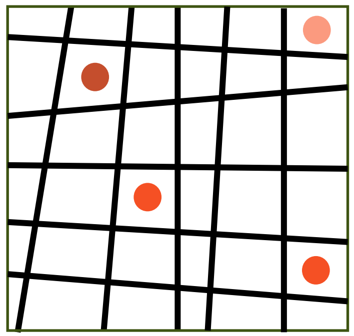


Er^{3+}



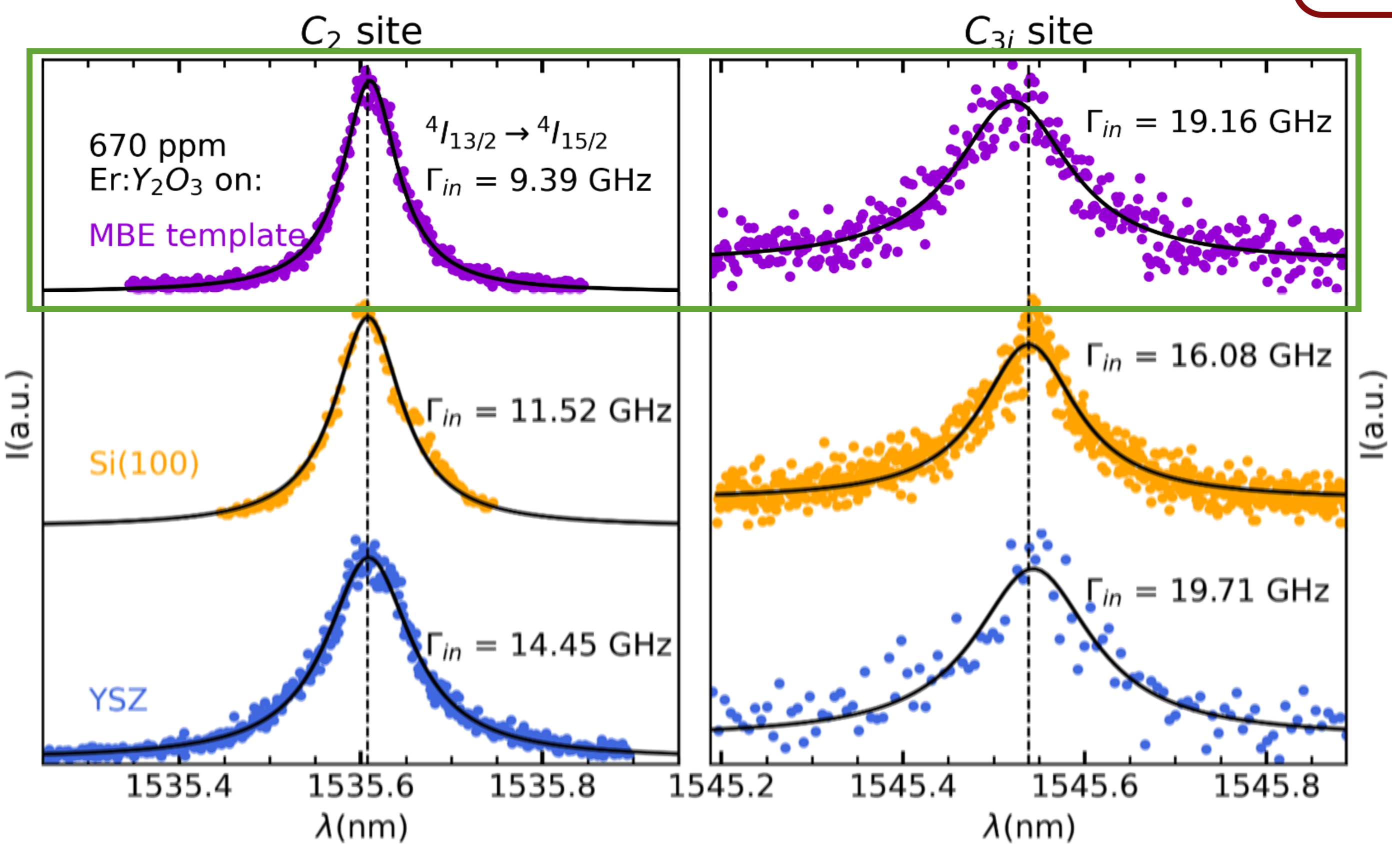


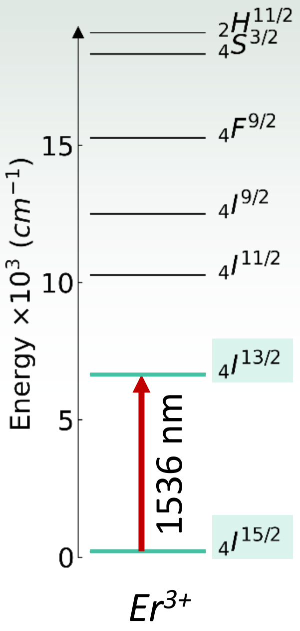
$Er^{3+} : Y_2O_3$



Results

Inhomogeneous broadening @100 mK





- Larger Γ_{in} than Er:Y_2O_3 bulk crystals (0.4 GHz) but similar to MBE Er:Y_2O_3 films (5 - 24 GHz)
- Narrowest Γ_{in} for **MBE template**

R. Fukumori et al. , *Phys. Rev. B*, **101**, 214202 (2020)
M. K. Singh et al. , *APL Mater.* , **8**, 031111 (2020)

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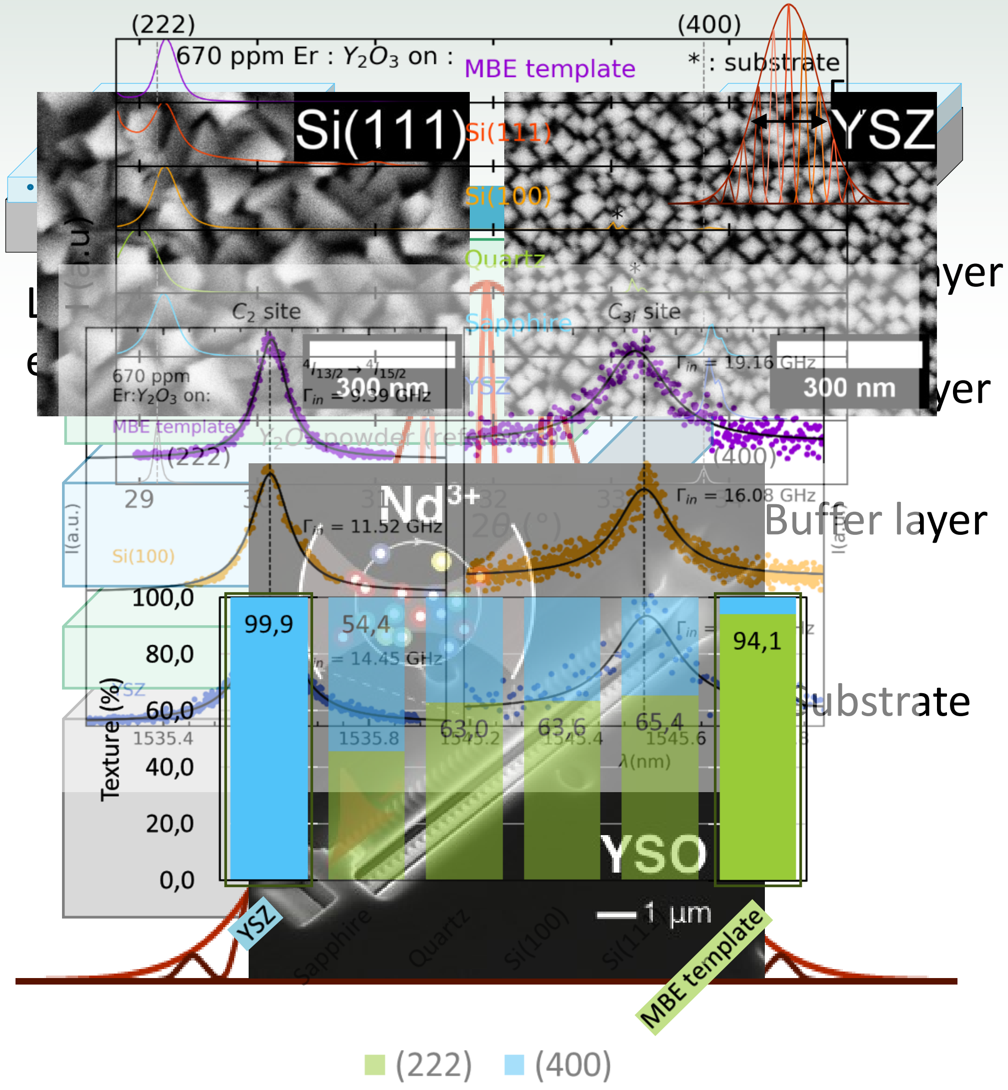
Conclusion and outlook

Conclusion and outlook

Conclusions

- Films well crystalized were grown on **all substrates**
- **YSZ** and **MBE template** espacially seem promising regarding structural and morphological properties
- Film on the **MBE template** gives a slightly **narrower** $\mathbf{\Gamma_{in}}$



Outlooks

- Measurements of the $\mathbf{\Gamma_h}$ of the most promising samples
- Develop strategies to improve crystalline quality
- **Nanostructuring** of the films to integrate them into resonators or waveguides

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Thanks for your attention !

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