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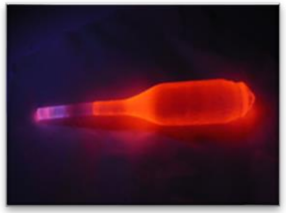

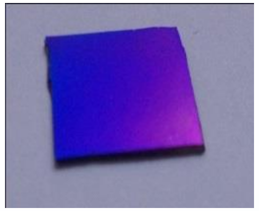

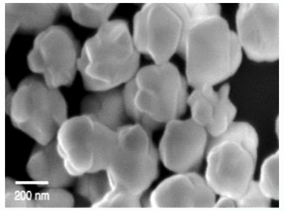

Rare-earth doped oxide thin films deposited by DLICVD for quantum technologies applications

Nao Harada, Alexandre Tallaire, Alban Ferrier, Diana Serrano, Philippe Goldner

Institut de Recherche de Chimie Paris, Chimie ParisTech, CNRS, Université PSL, Paris, France

GDR Epidox November 2021

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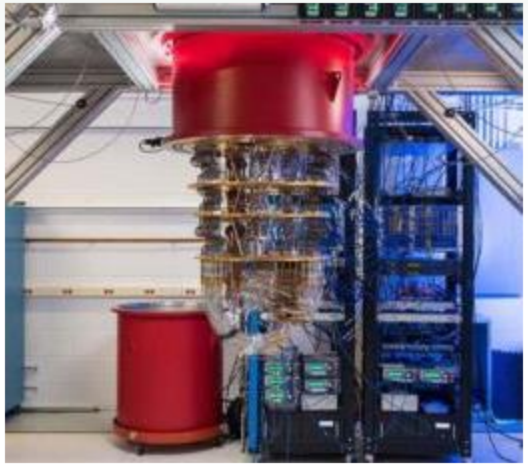
1. Introduction on quantum technologies

Quantum technologies

Quantum computing

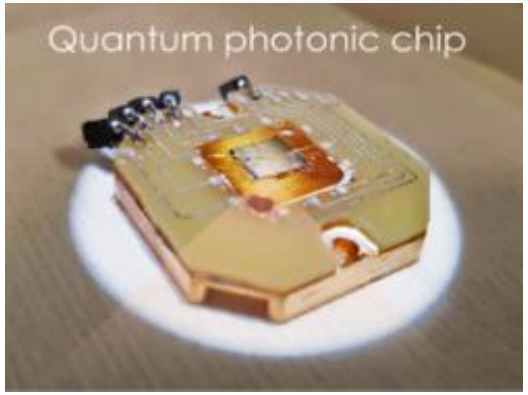


Google

Quantum cryptography

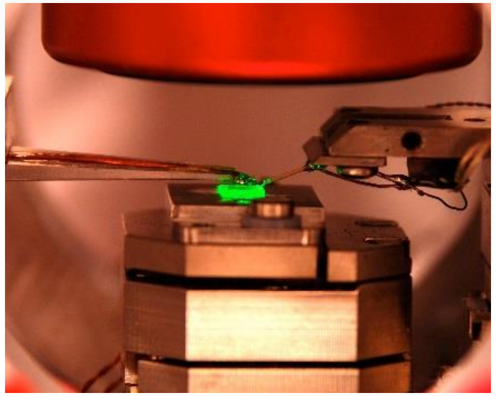
IDquantique

Quantum communications



Quandela

Quantum sensing and metrology



QNami

QUANTUM FLAGSHIP

ASTERIQS

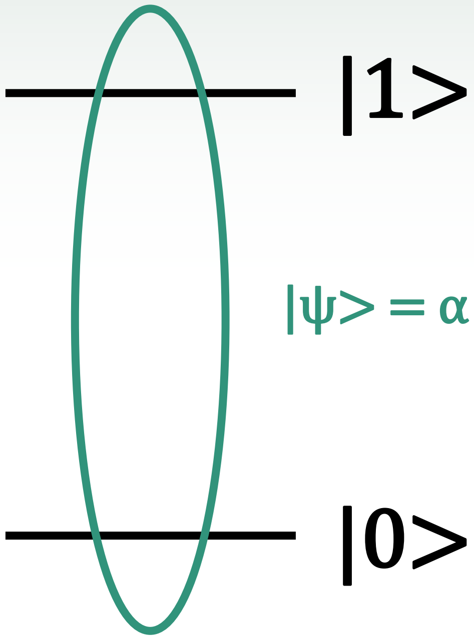
https://www.asteriqs.eu/

SQUARE

http://square.phi.kit.edu/

Need for stable qubits

Qubit

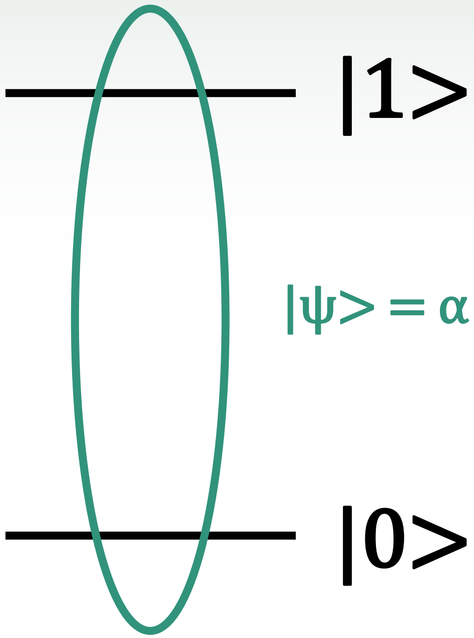


$|\psi\rangle = \alpha\,|0\rangle + \beta\,|1\rangle$

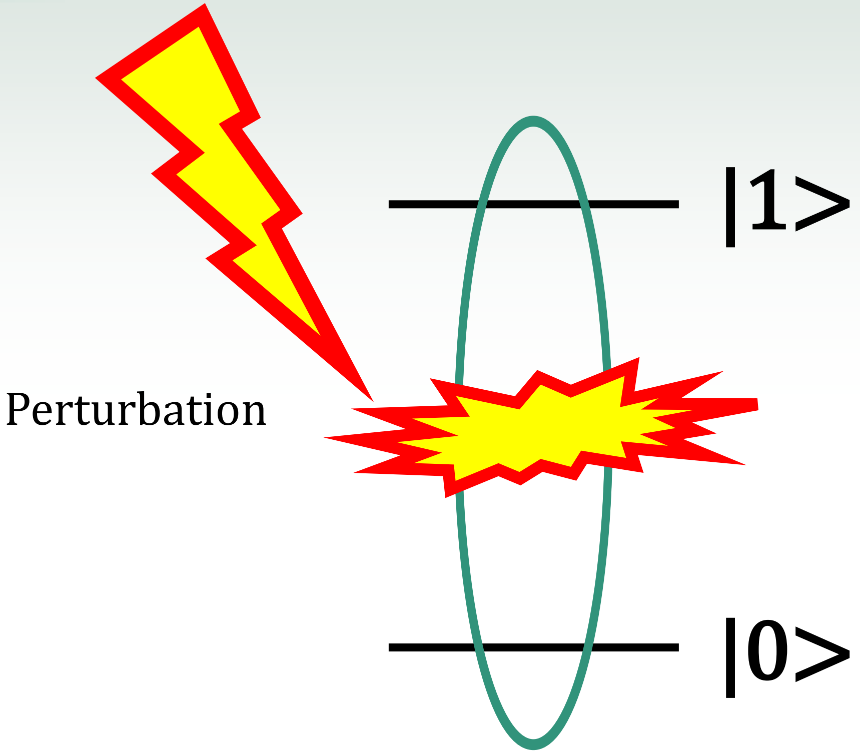
Quantum state superposition

Need for stable qubits

Qubit



$|\psi\rangle = \alpha\,|0\rangle + \beta\,|1\rangle$



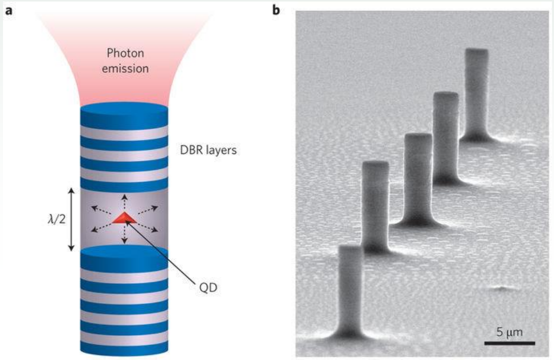
Quantum state superposition

Decoherence induced by external perturbation

Coherence time T_2

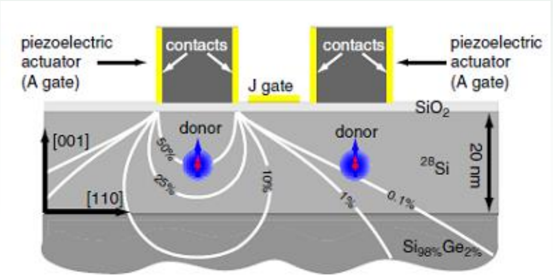
Specially engineered solid-state materials

InAs quantum dots



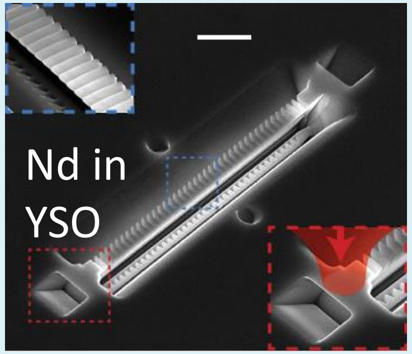
Nowak et al. Nat. Com. 2014

Single P donors in Si



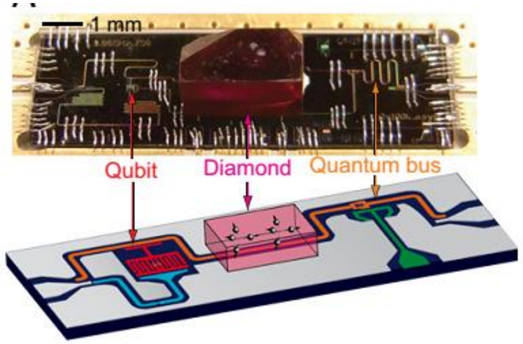
Dreher et al. PRL2011

Rare earth ions in crystals



Zhong Nat Com 2015

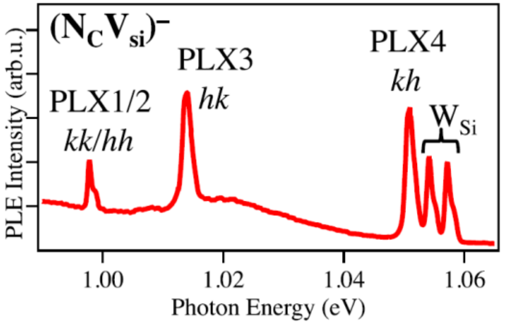
NVs in diamond



Kubo et al. PRL2010

Defects in semiconductors

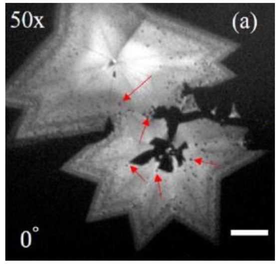
4H-SiC



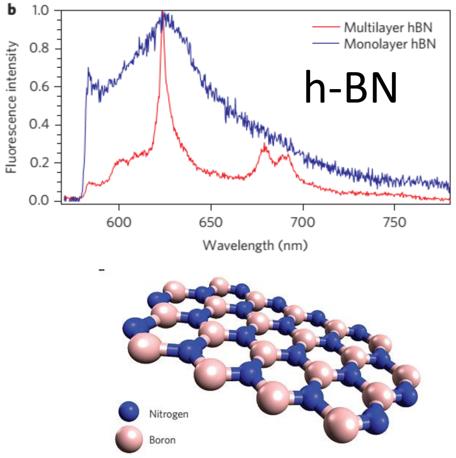
Zargaleh et al. PRB2016

2D materials

WS_2



Cao et al. 2D Mater 2017



Ahoronovich Nature Nanotech 2016

G. Zhang, Y. Cheng, J.-P. Chou, A. Gali, Material platforms for defect qubits and single-photon emitters, Applied Physics Reviews. 7 (2020) 031308.

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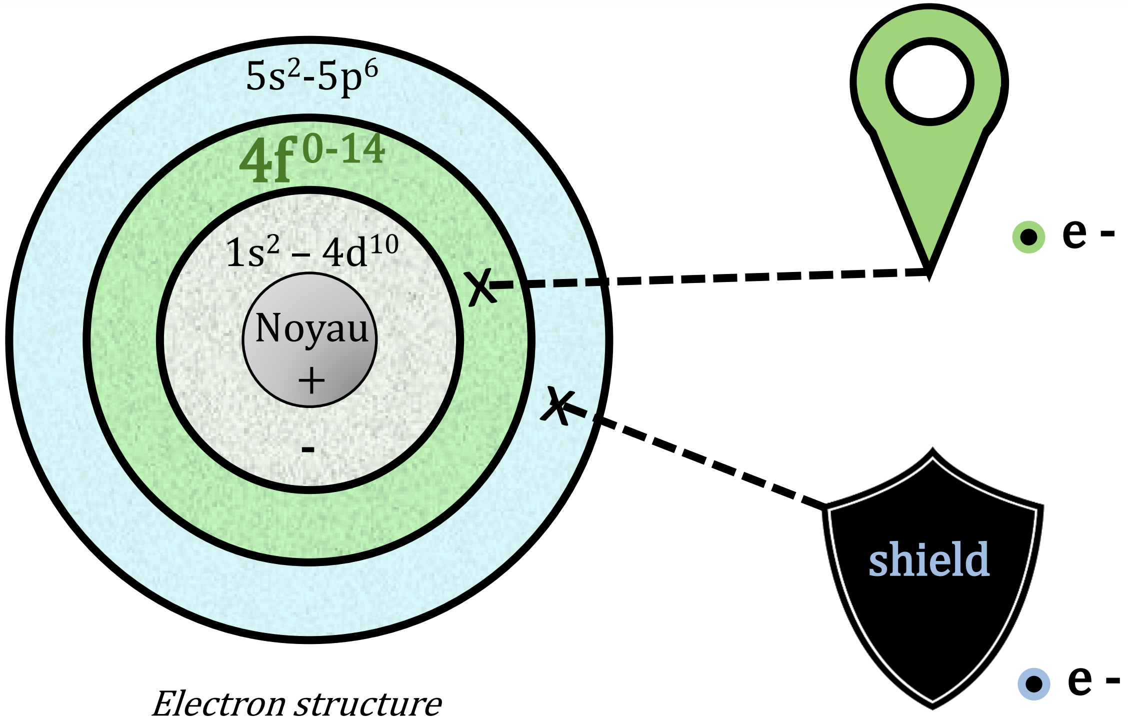
Rare-earth ions

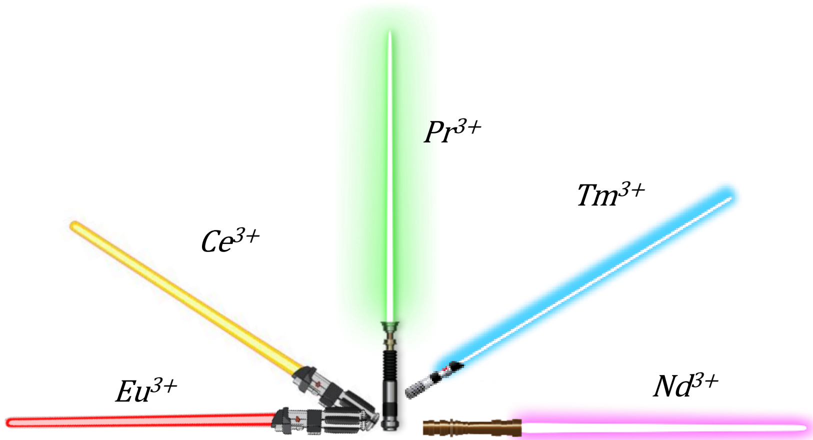
lanthane	cérium	praséodyme	néodyme	prométhium	samarium	europium	gadolnium	terbium	dysprosium	holmium	erbium	thulium	ytterbium	lutécium
57	58	59	60	61	62	63	64	65	66	67	68	69	70	71
La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
138,90547	140,116	140,90765	144,242	[144,9127]	150,36	151,964	157,25	158,92535	162,500	164,93032	167,259	168,93421	173,04	174,967

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



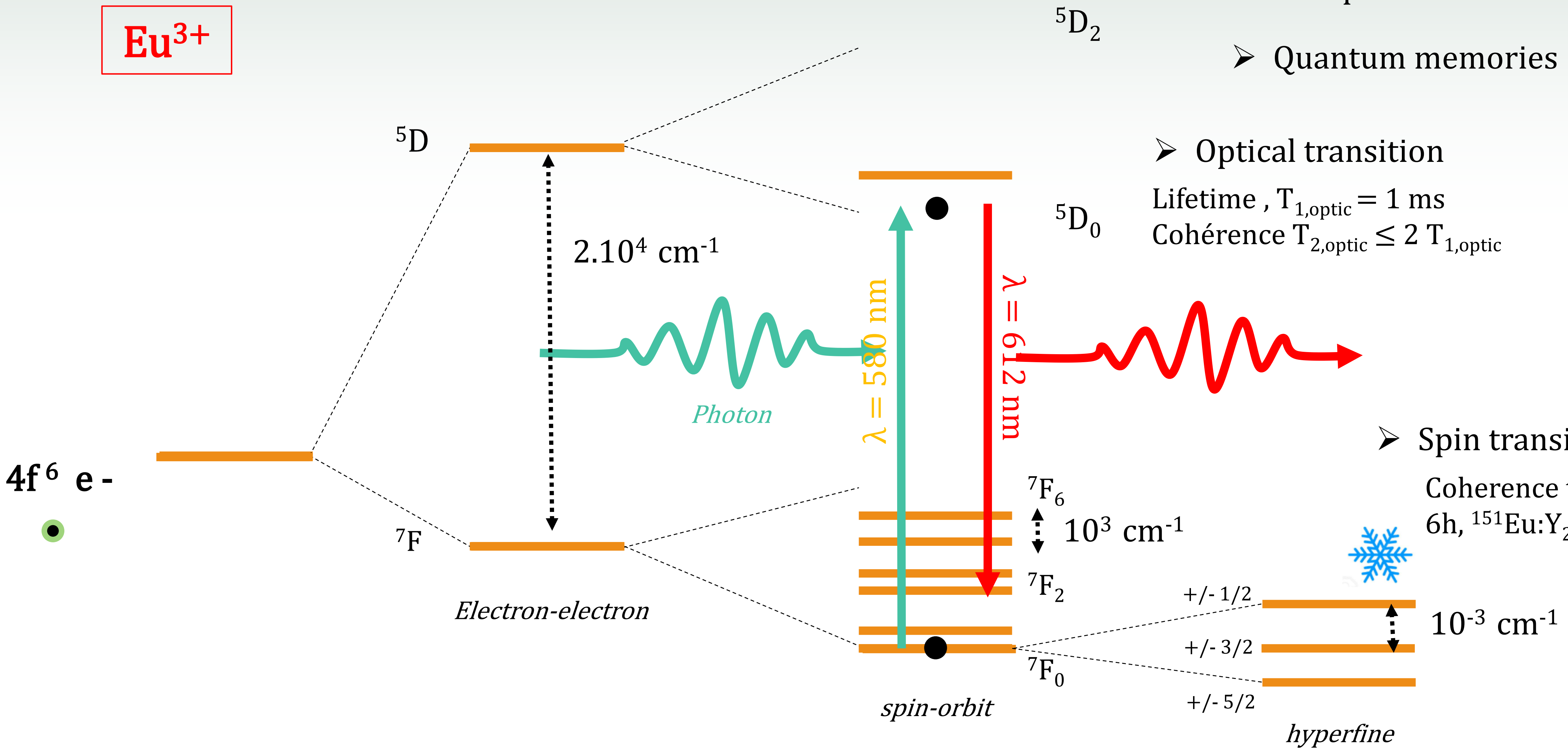
Electron structure

- Transitions involving **4f electrons**
- Screening by orbitals: $5s^2\ 5p^6$
- Narrow optical lines



Rare-earth ions

- MW-photon interface
- Quantum memories



- Optical transition

Lifetime , $T_{1,optic} = 1$ ms

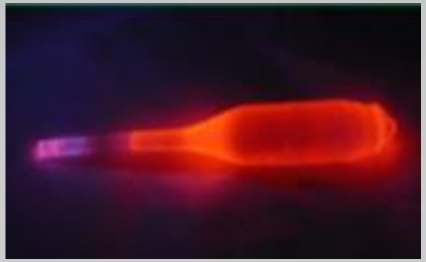
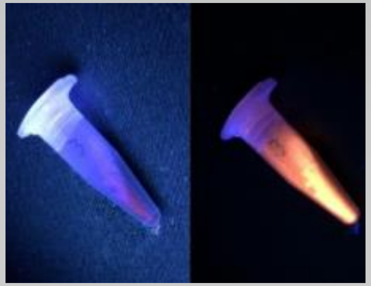
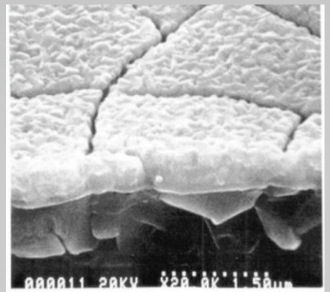
Cohérence $T_{2,optic} \leq 2\ T_{1,optic}$

- Spin transition

Coherence time $T_{2,spin}$ = 6h, $^{151}Eu:Y_2SiO_5$

Material systems available

$Eu^{3+} : Y_2O_3$ — cm — Size — nm

Photo	 Single crystal (YSO)	 Nano-particles	 CVD film 2µm	 ALD film 100nm
Homog. Linew.	600 Hz	56 kHz	12 MHz	/
Optical T_2	510 µs	5,67 µs	0,027 µs	/
Coherence	++	+	- -	- -
Integrability	- -	-	++	++

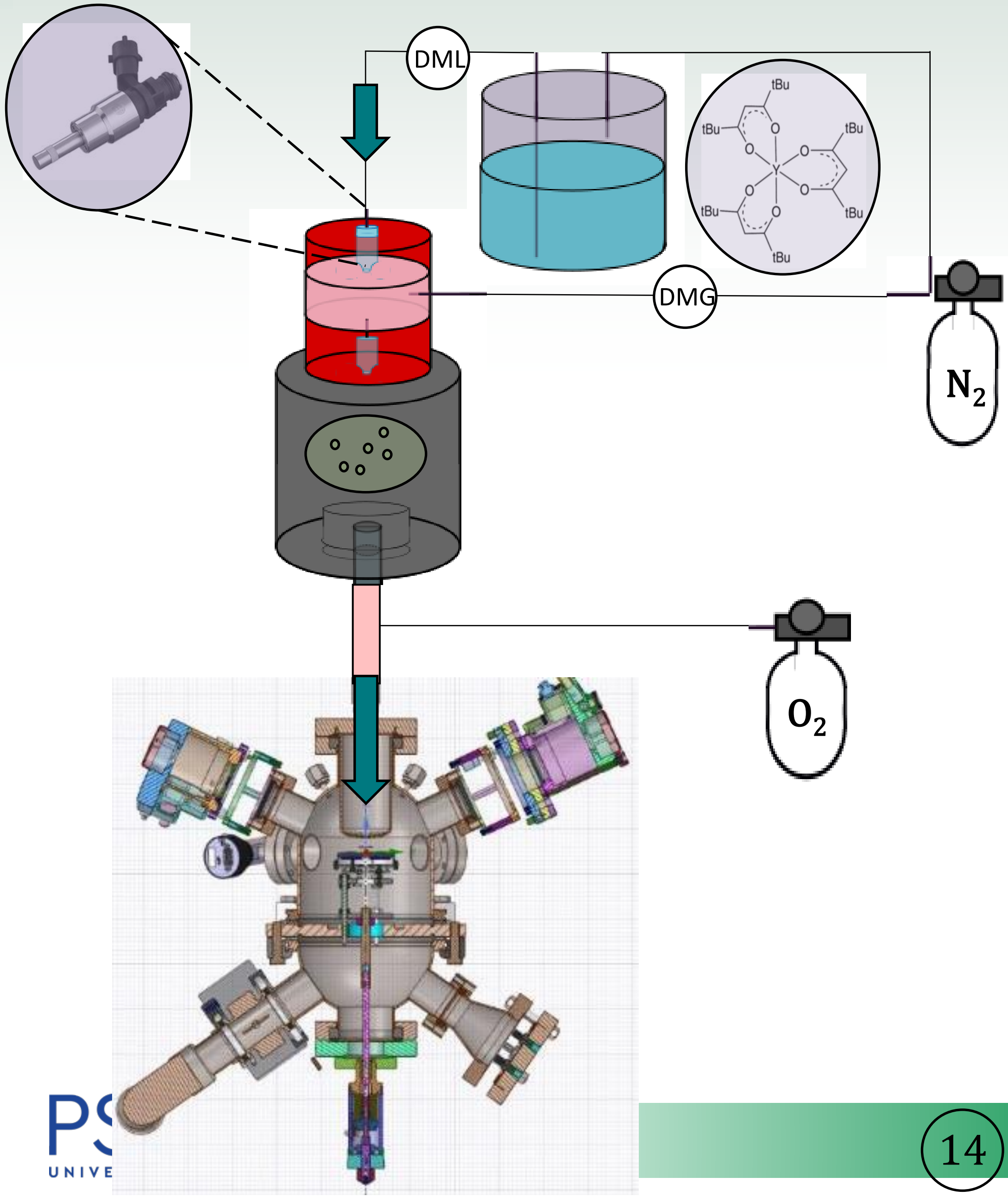
Challenge: evaluate and optimize coherent optical properties of rare-earth in CVD thin films

T. Zhong, P. Goldner, Emerging rare-earth doped material platforms for quantum nanophotonics, Nanophotonics. 8 (2019) 2003–2015.

2. Thin oxide films by direct liquid injection CVD

DLI-CVD technique

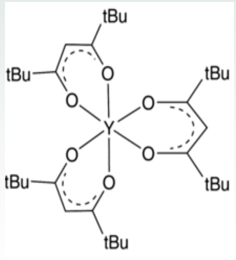
$Eu:Y_2O_3$

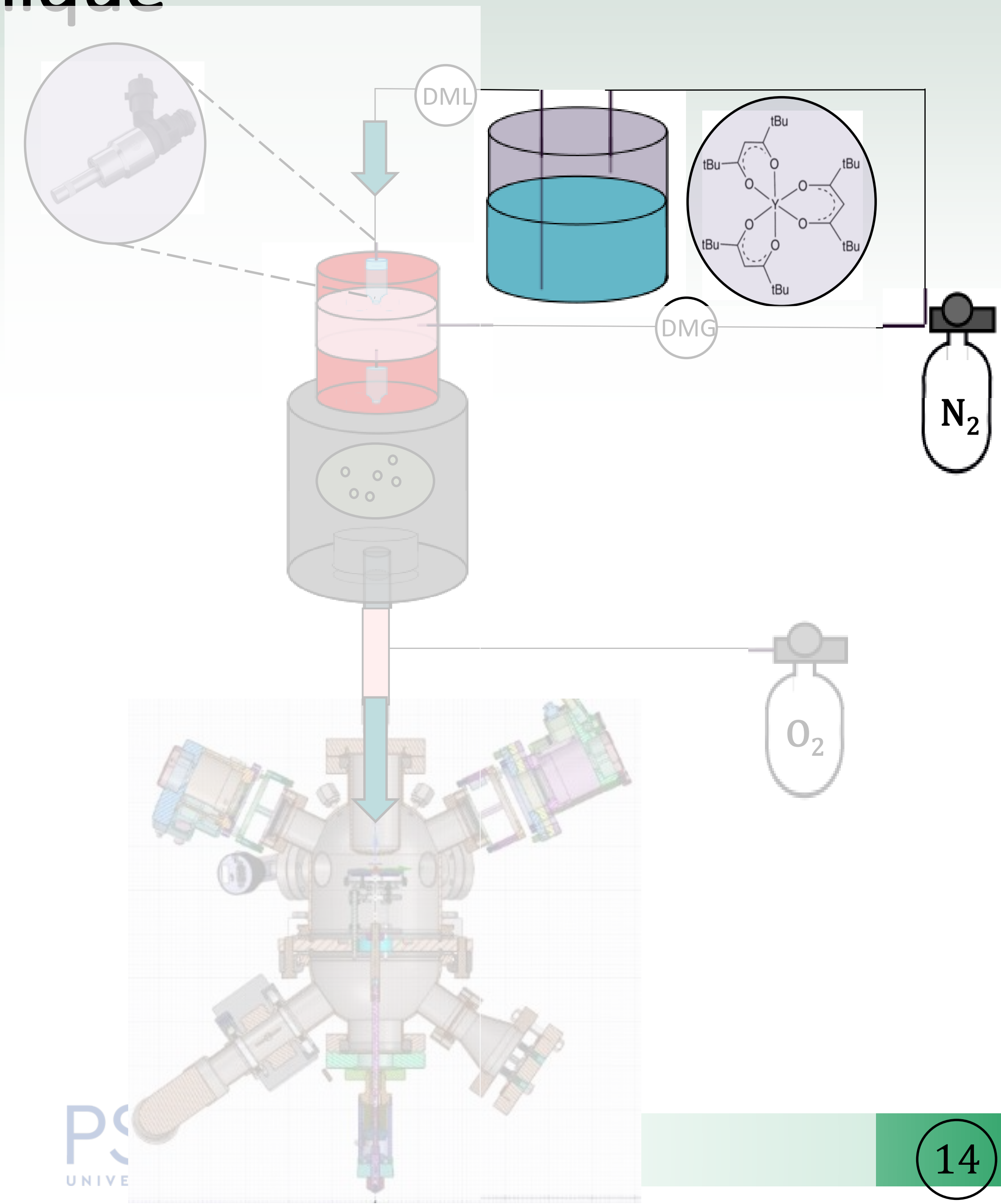


DLI-CVD technique

Eu:Y_2O_3

- B-diketonate Y or Eu(thd)$_3$

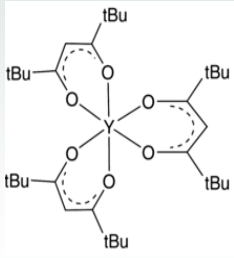




DLI-CVD technique

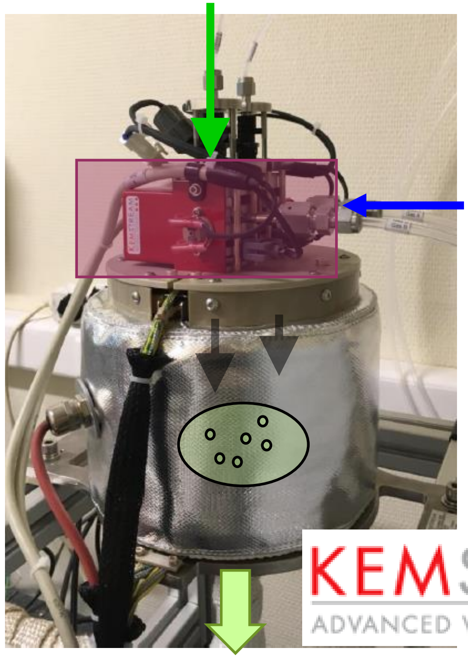
$Eu:Y_2O_3$

- B-diketonate Y or $Eu(thd)_3$



Liquid

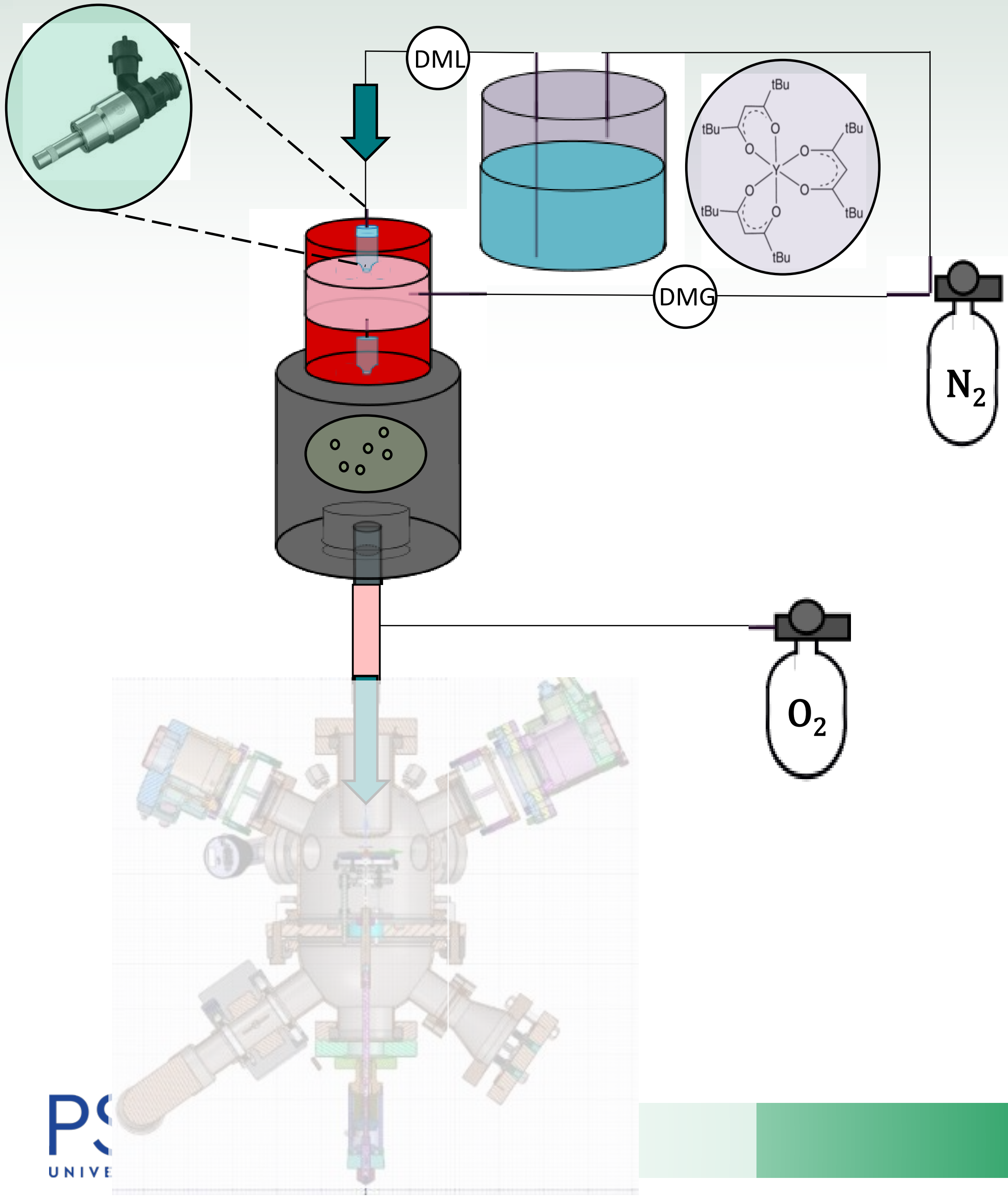
Injection



Gas

Vaporisation @ **200 °C**

KEMSTREAM ADVANCED VAPORIZERS



V. Astié, C. Millon, J. M. Decams, A. Bartasyte, Direct liquid injection chemical vapor deposition, Chemical Vapor Deposition for Nanotechnology, IntechOpen, 2019 pp. 2–23.

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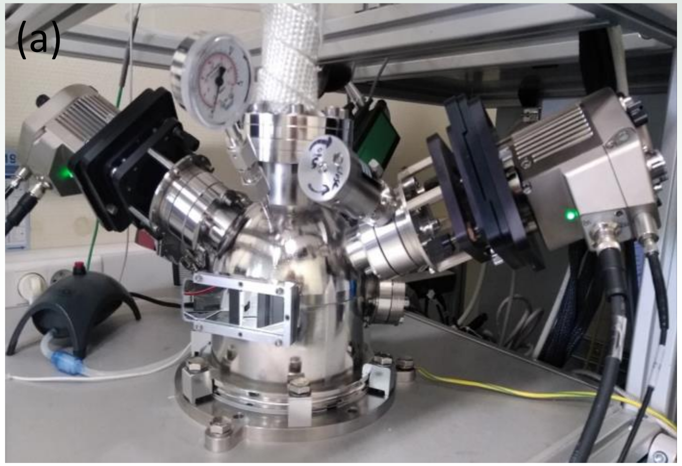
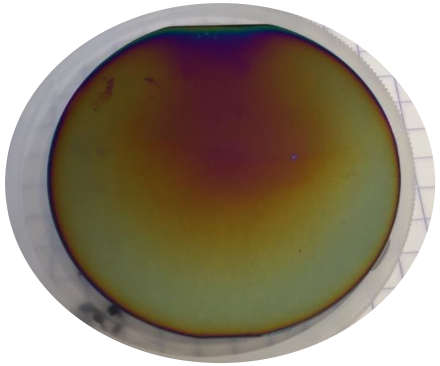
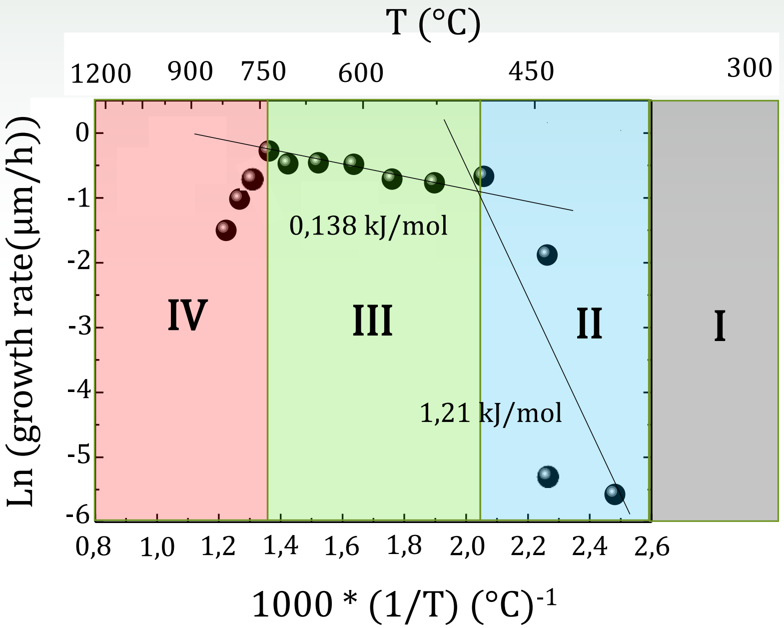
Growth of thin $Eu:Y_2O_3$ films



DLI-CVD reactor with in-situ ellipsometer

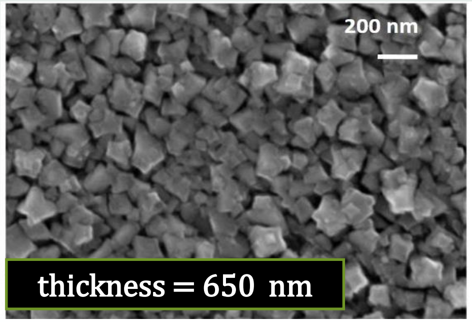


2 inch Si (111) wafers

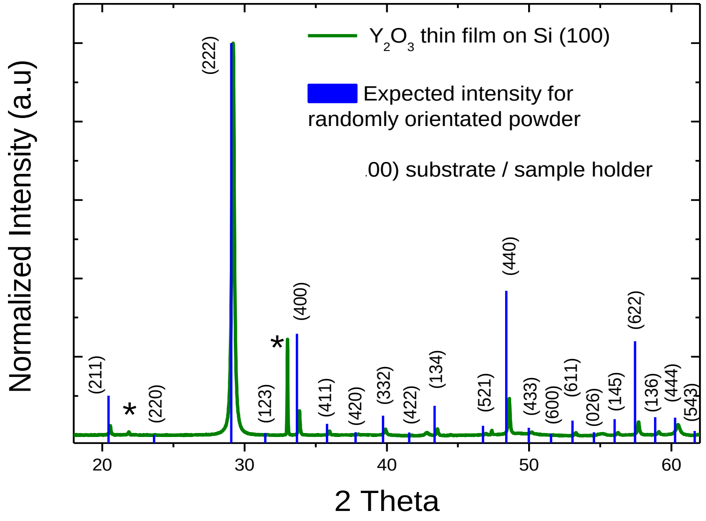


Growth kinetics

N. Harada et al. Chemically vapor deposited Eu3+:Y2O3 thin films as a material platform for quantum technologies, Journal of Applied Physics. 128 (2020) 055304



Polycrystalline on Si



Highly (111) textured

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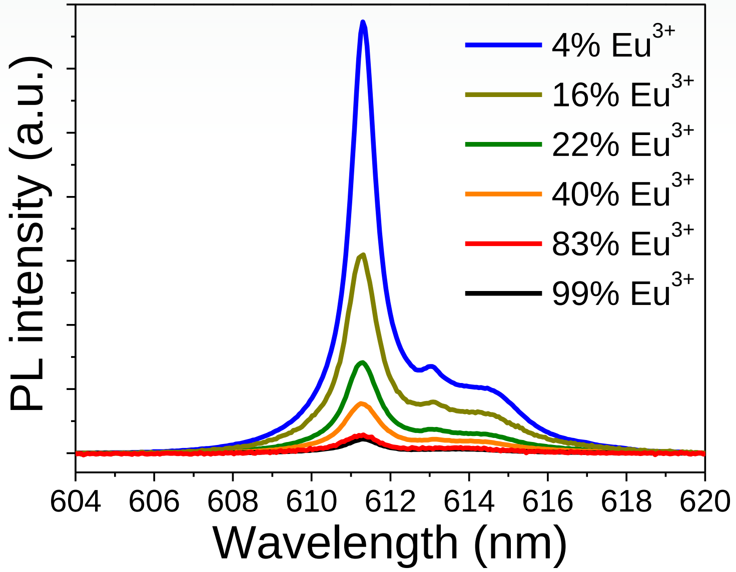
3. Assessment of optical properties using advanced spectroscopy

Optical properties

PL emission

$\lambda_{excitation} = 532$ nm



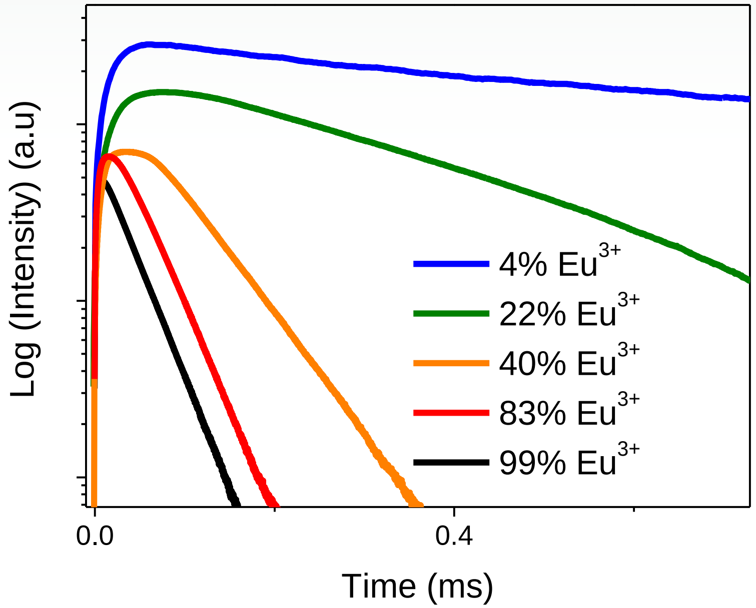
Successful doping 0-99%

PL drops above 6%

(concentration quenching)

Decay rate

$\lambda_{excitation} = 465$ nm



Optical T_1 = 1 ms

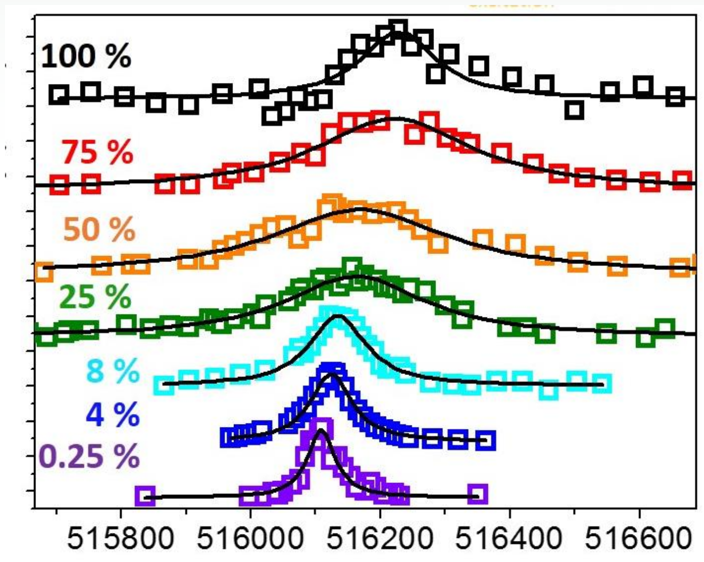
Comparable to bulk

Decrease with doping

Inhomogeneous broadening

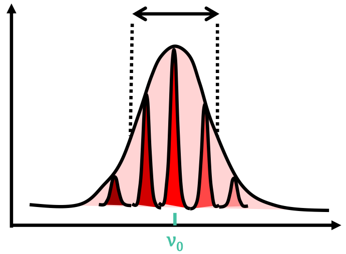
@ 12K

$\lambda_{excitation} \sim 580.88$ nm

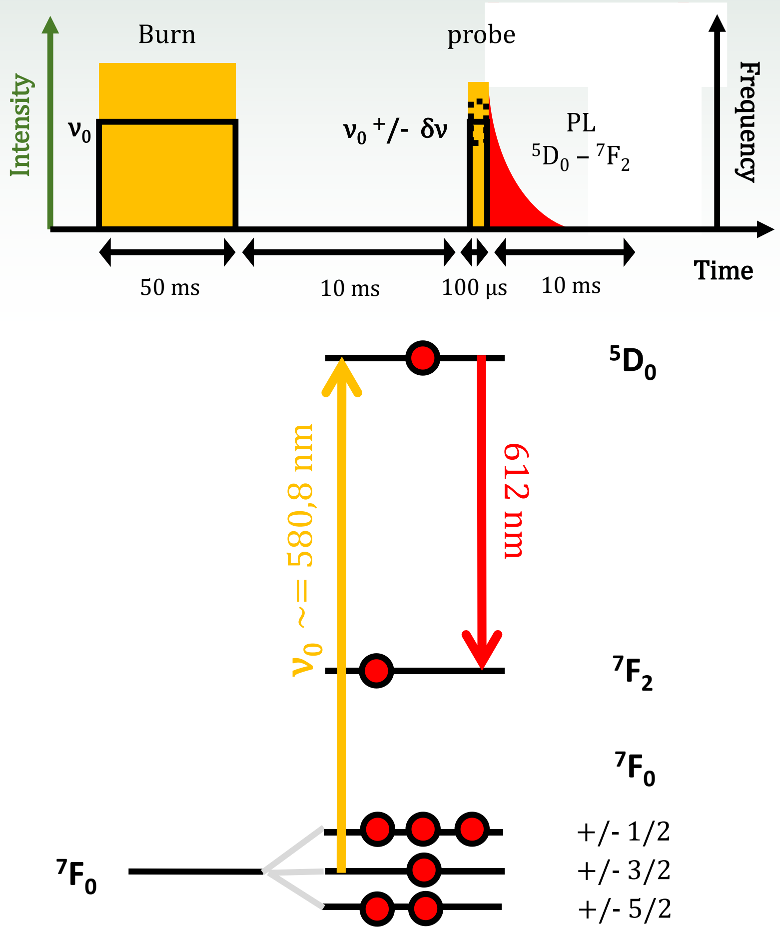


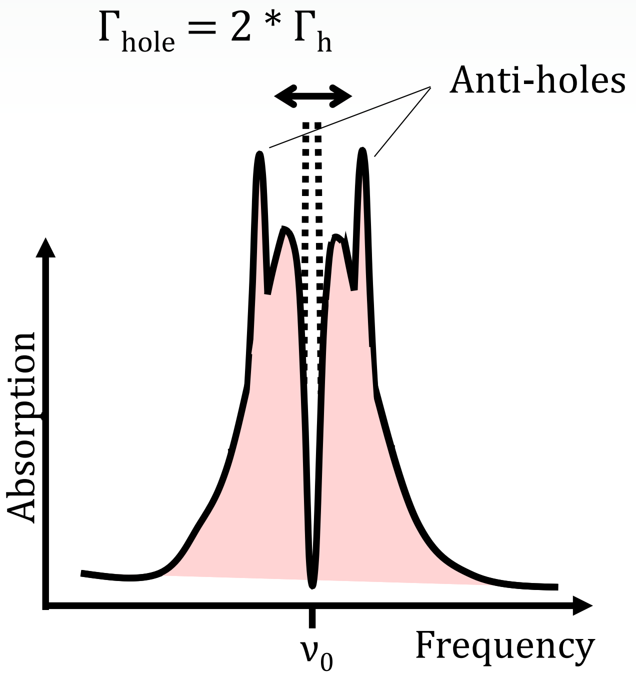
$\Gamma_{inh} = 50$ GHz @2%

10x that of bulk



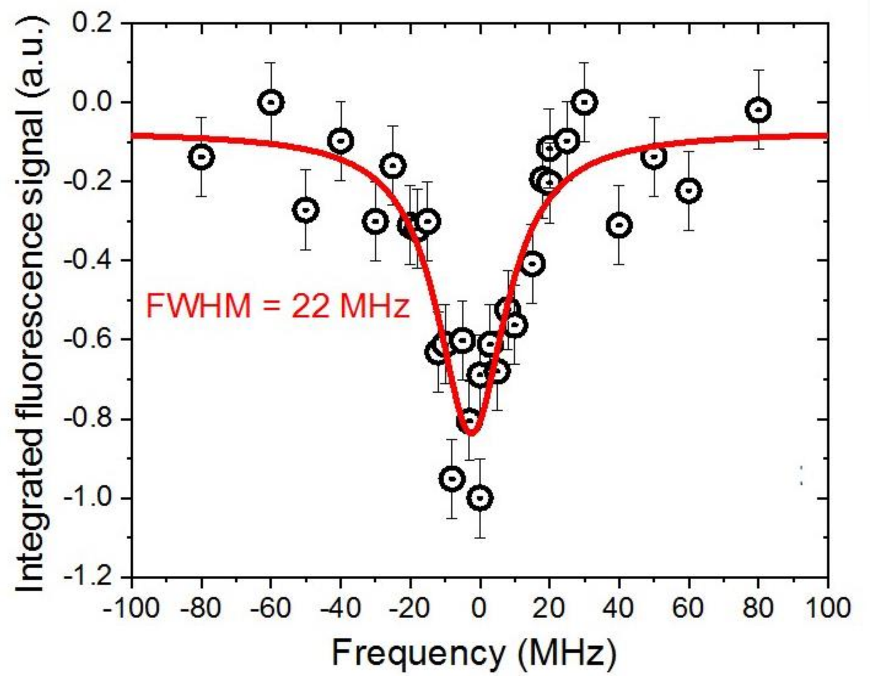
Spectral hole burning





Working principle of SHB

SHB for a 200nm $Eu:Y_2O_3$ thin film on Si @3K



Γ_h = 11MHz @2%

1000X higher than bulk

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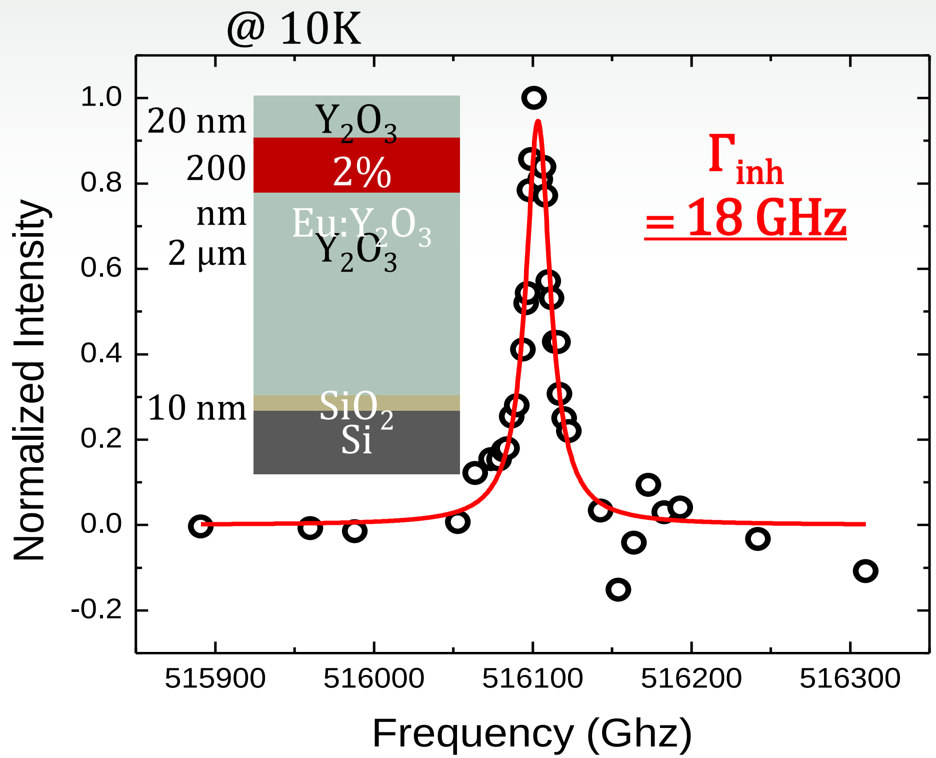
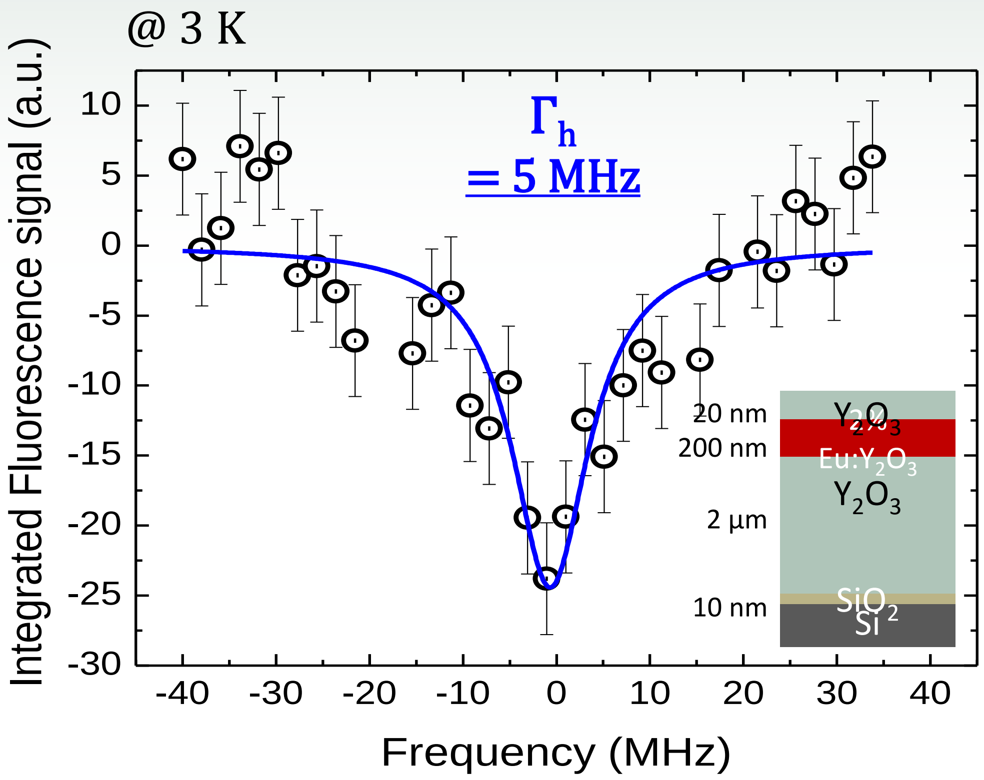
SHB on optimized thin film

Thicker multilayer with 1000°C annealing





Improvement by a factor of 2 of both inhomogeneous and homogeneous linewidth.
However still relatively broad compared to bulk and nanoparticles → more efforts needed

N. Harada et al. Controlling the interfacial reactions and environment of rare-earth ions in thin oxide films towards wafer-scalable quantum technologies, Mater. Adv. (2021).

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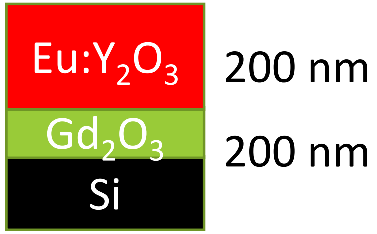
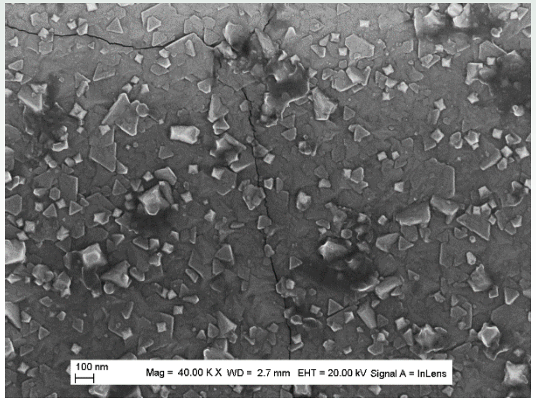
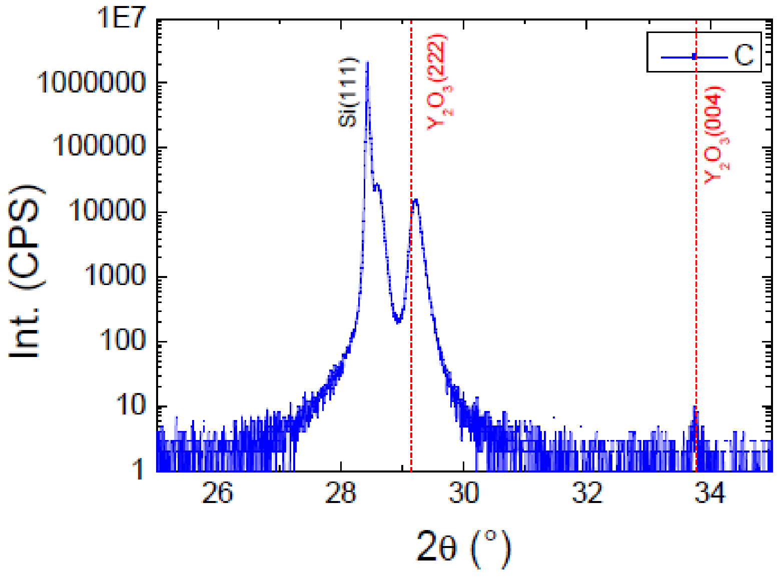
Perspective: towards epitaxial layers

Growth on a commercial **epitaxial MBE template** (Gd2O3/Si)

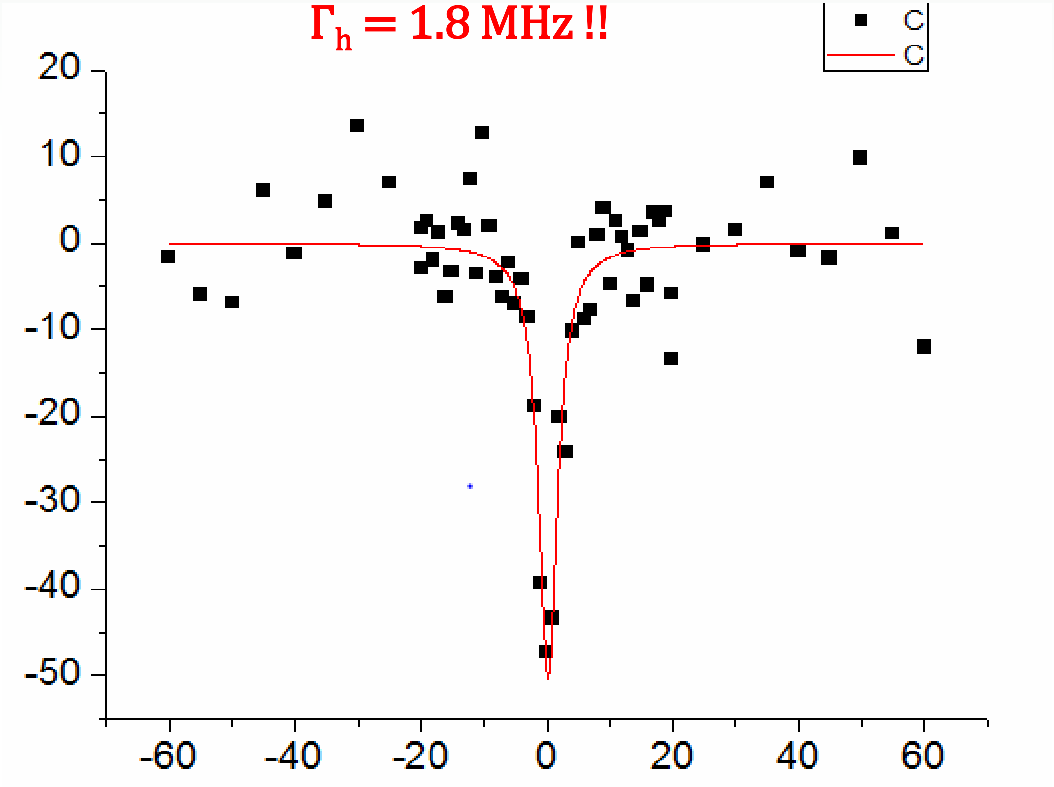






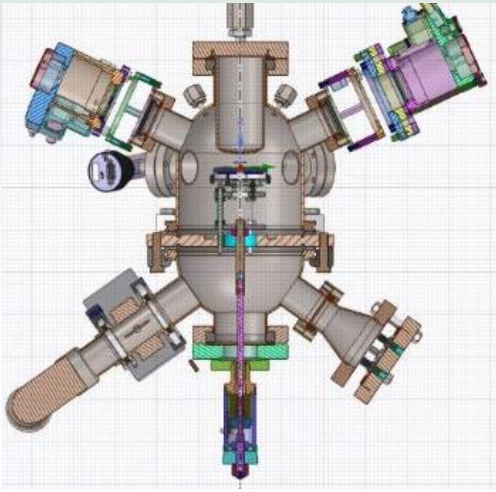
Collab. INL (R. Bachelet)

SHB measurement



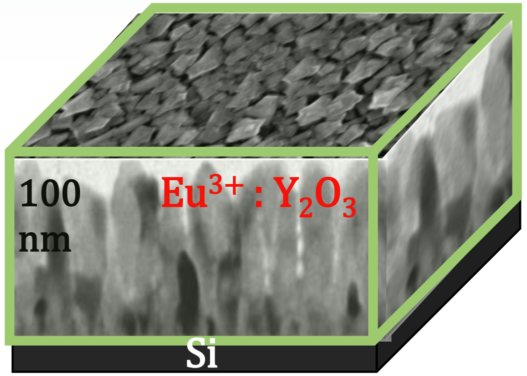
Very encouraging!

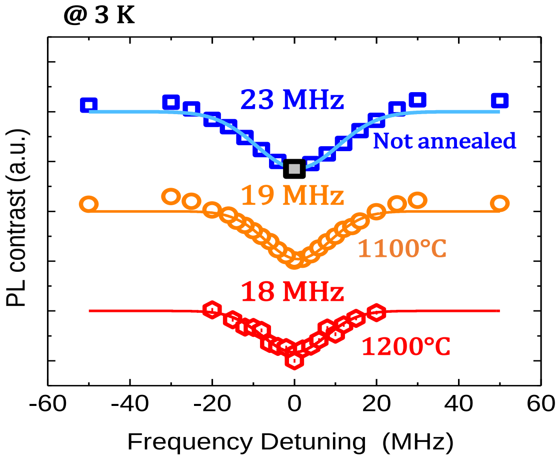
Conclusion



Development of a new and versatile DLI-CVD process for RE-Y_2O_3 thin films

Synthesis of Eu:Y_2O_3 on Si with (111) texture and in a wide doping range





Assessment of optical properties within the context of quantum technologies → homogeneous linewidth of 1-5 MHz

A new potential platform for QTs with improved integrability

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Our team @IRCP: Crystals and quantum state dynamics

Nao Harada

THANKS FOR YOUR ATTENTION!

Funding

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Scalable Rare Earth Ion QUAntum Computing Nodes

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