Thermometry and Biomedical Applications from Fluorescent Nanodiamond Particles

Universidad de Sonora

WORKSHOP ON MEDICAL AND HIGH ENERGY PHYSICS AT SONORA, MEXICO

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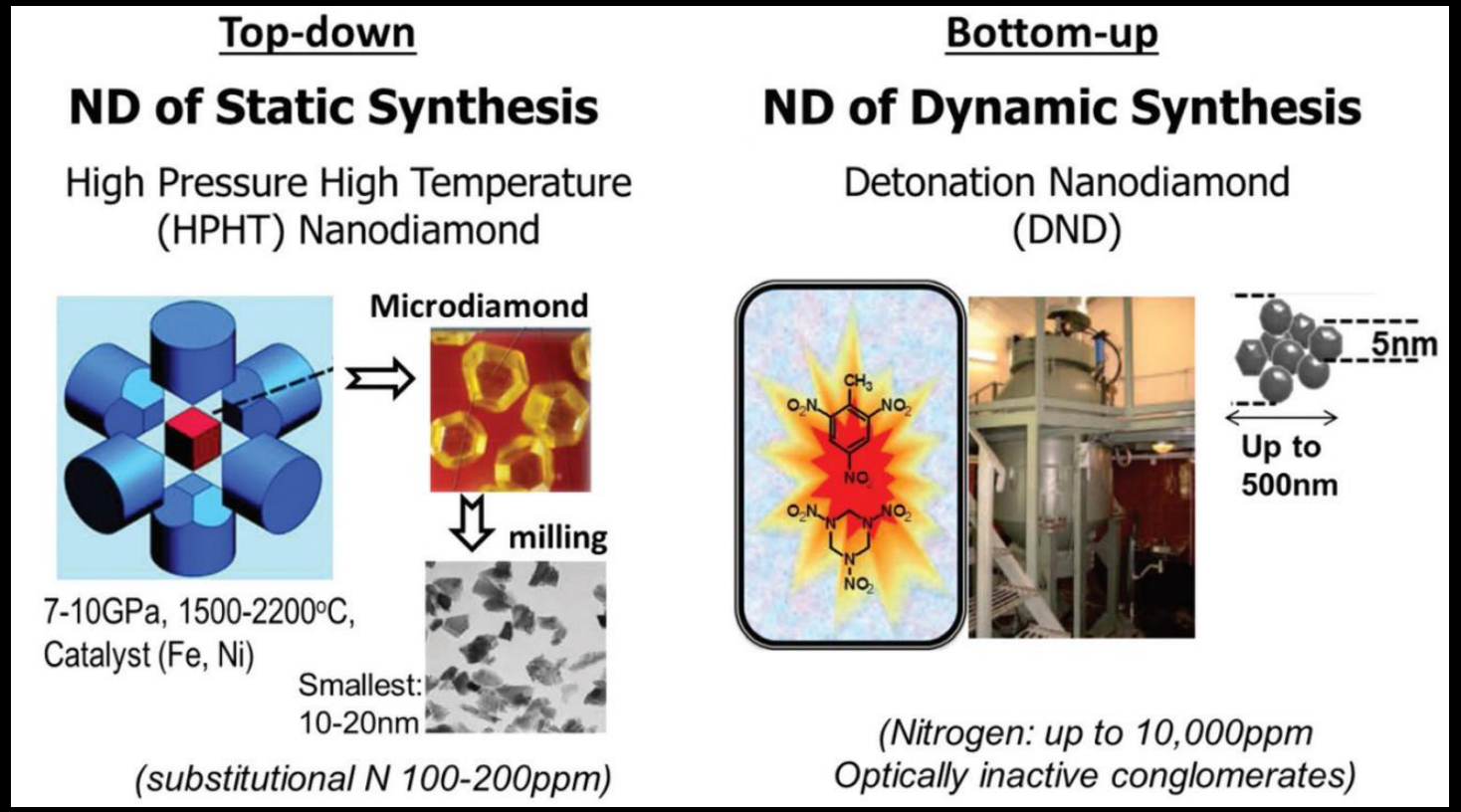
CONAHCYT

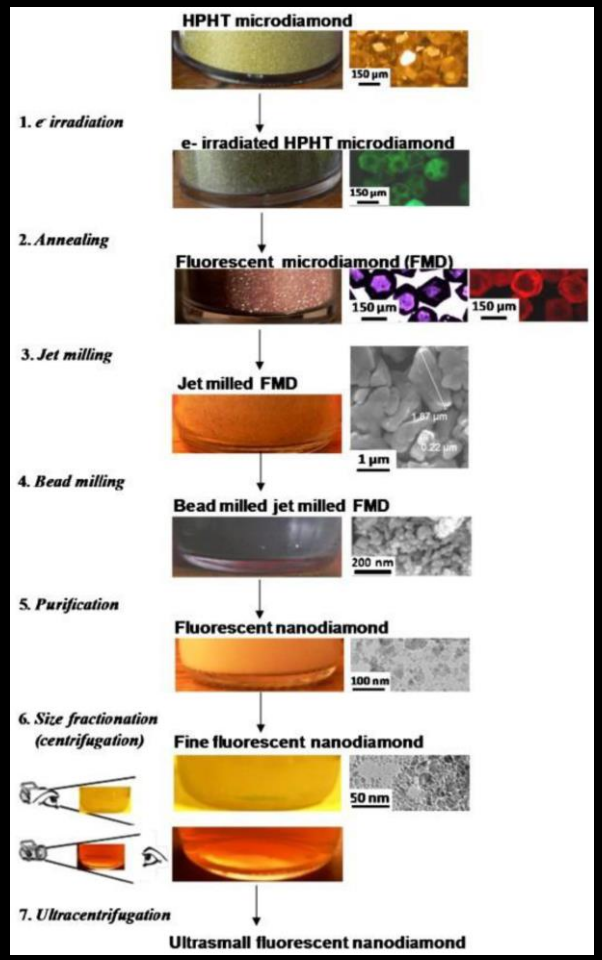
CONSEJO NACIONAL DE HUMANIDADES CIENCIAS Y TECNOLOGÍAS

Outline

- Nanodiamonds as promising nanostructures with temperature sensing capabilities.
- Thermometric characterization with different sample sizes.
- Advances in highly sensitive fluorescence thermometry.
- Concentration effect in fluorescence emission.

Production of nanodiamonds





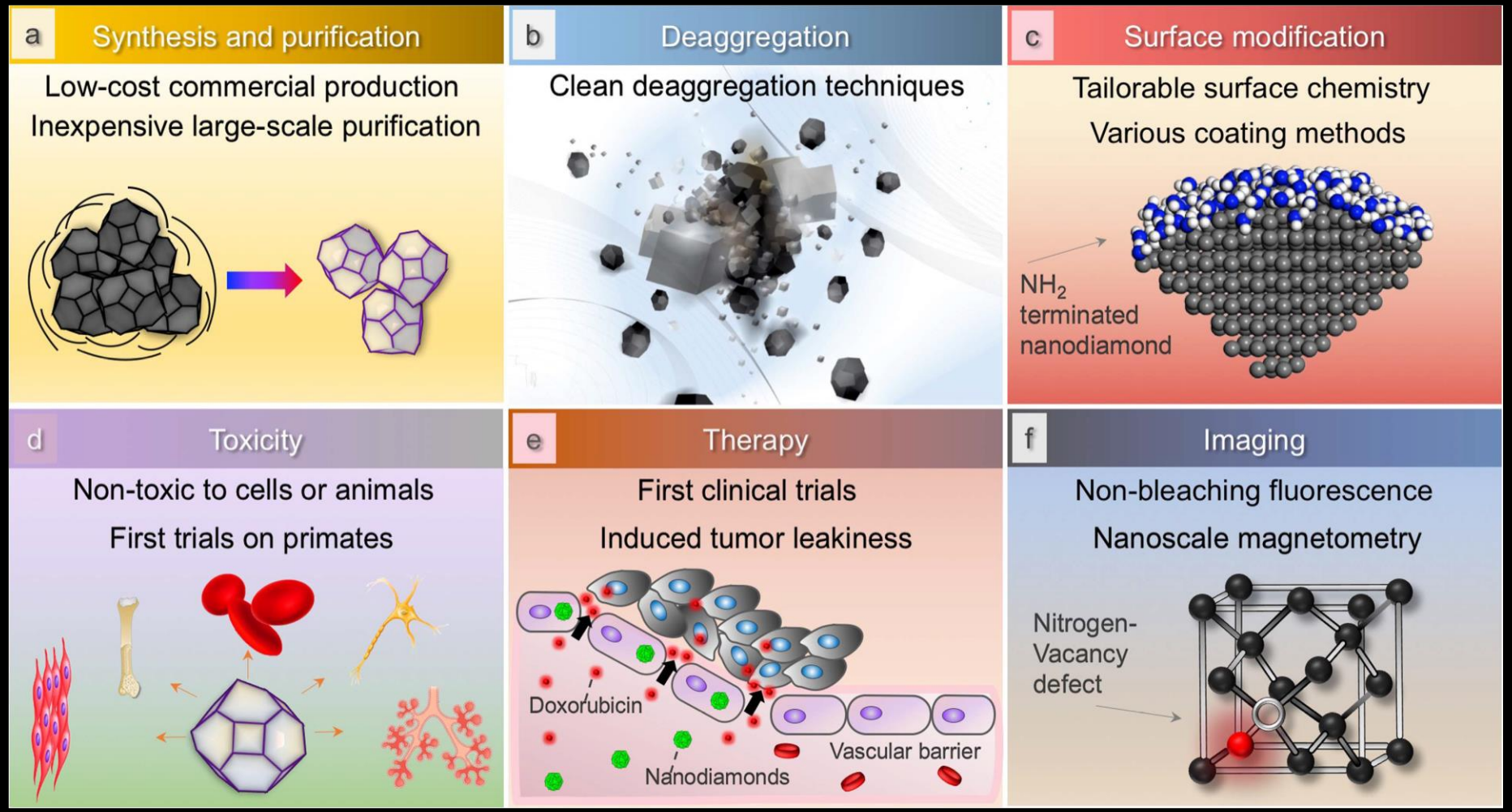
CVD, laser ablation, PECVD…

Strict protocol of production, impurity doping and activation, purification, fractionation, …

REF: Shenderova, O. A. & McGuire, G. E. Science and engineering of nanodiamond particle surfaces for biological applications (Review). Biointerphases 10, 030802 (2015).

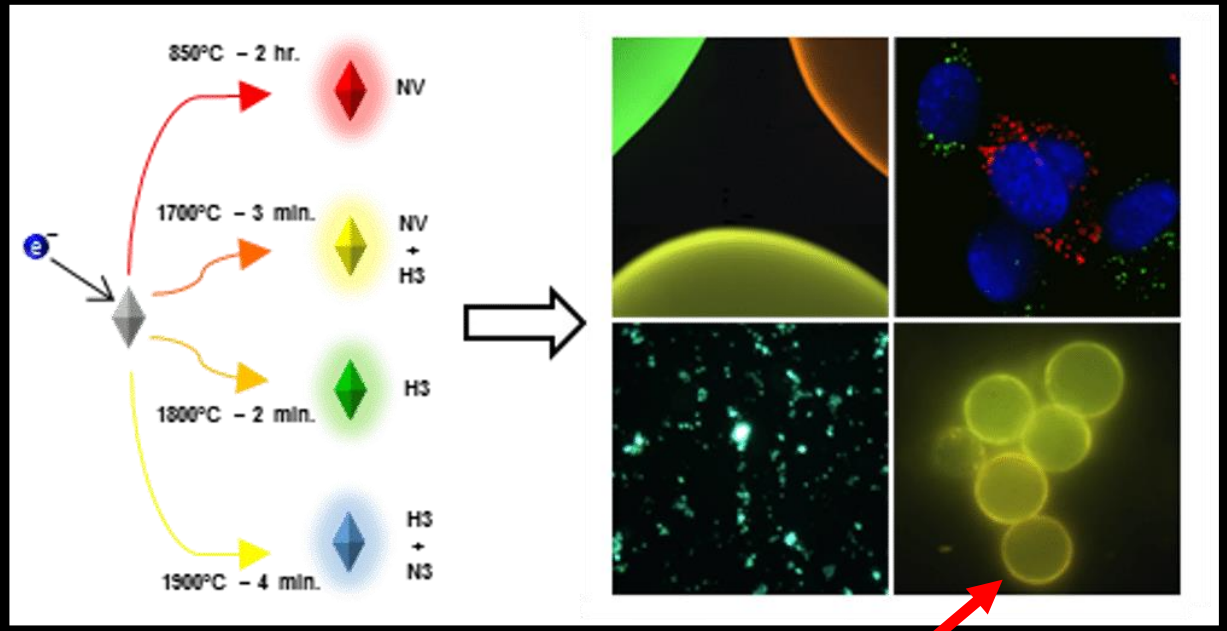
REF: Basso, L., Cazzanelli, M., Orlandi, M. & Miotello, A. Nanodiamonds: Synthesis and Application in Sensing, Catalysis, and the Possible Connection with Some Processes Occurring in Space. Appl. Sci. 10, 4094 (2020).

Key properties of fluorescent nanodiamonds

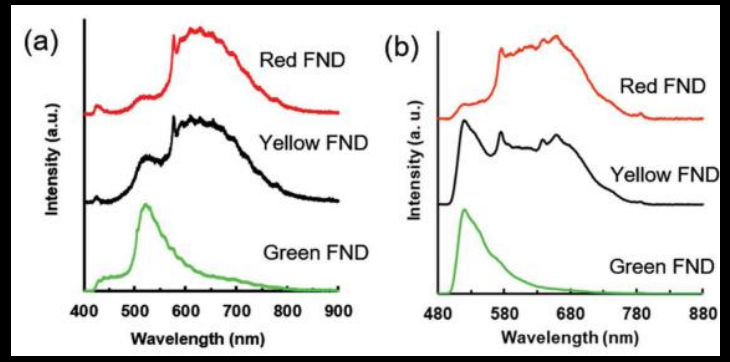


REF: Turcheniuk, K. & Mochalin, V. N. Biomedical applications of nanodiamond (Review). Nanotechnology 28, 252001 (2017).

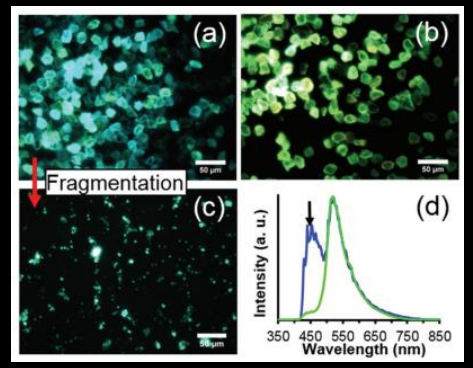
Nanodiamonds as fluorescent dyes for cellular tracking

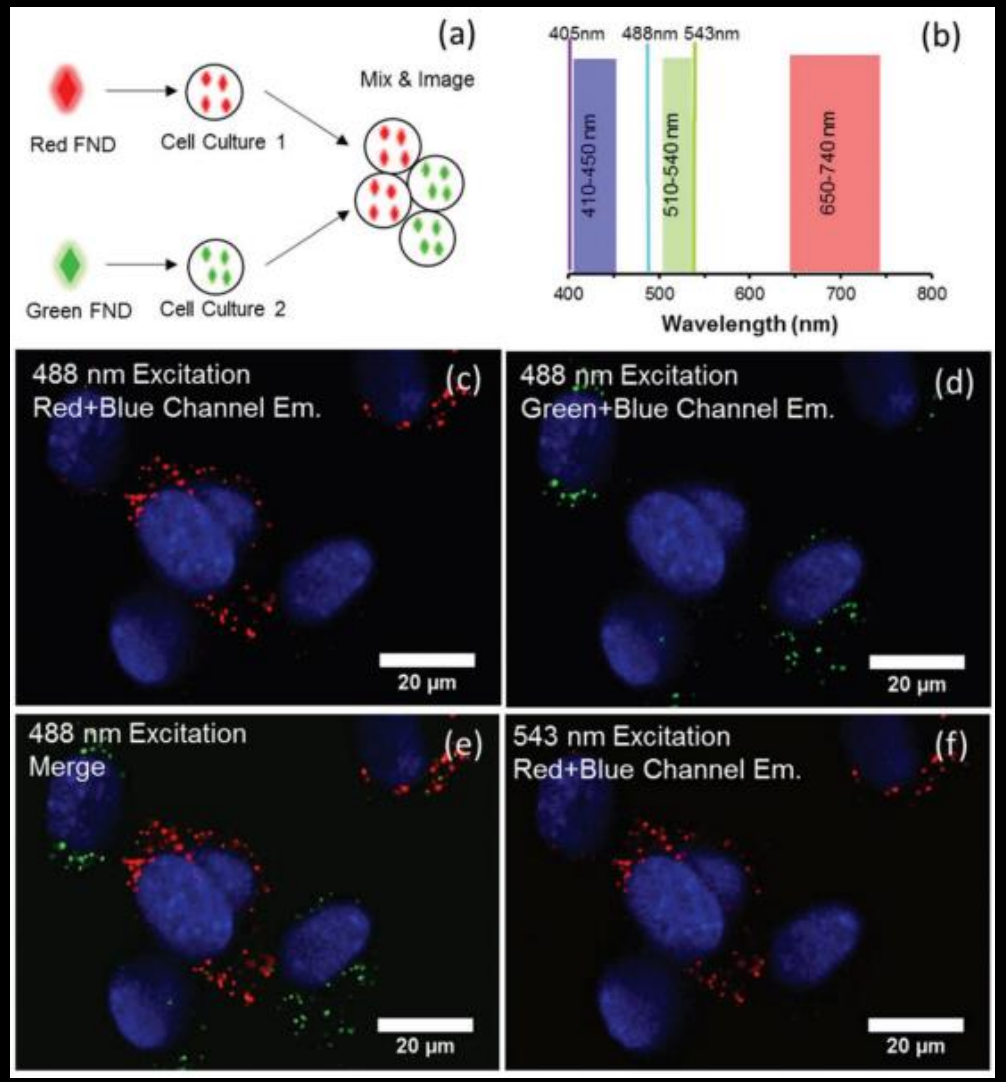


15.3 µm silica bead coated with FNDs



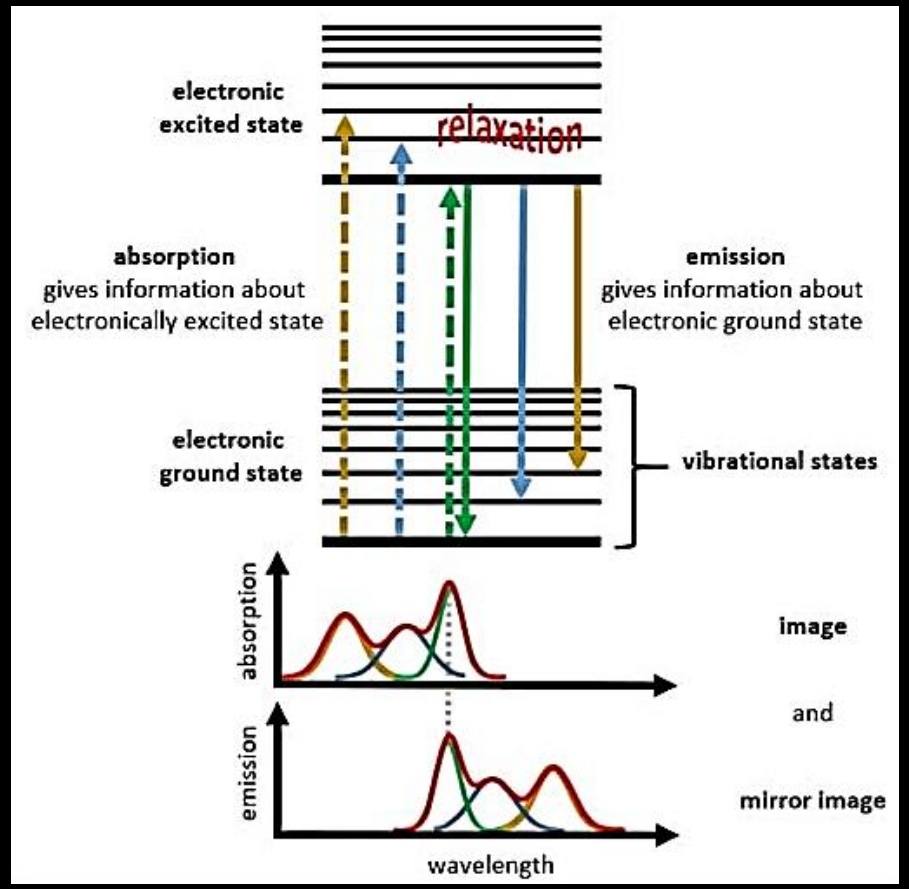
365 nm and 470 nm excitation



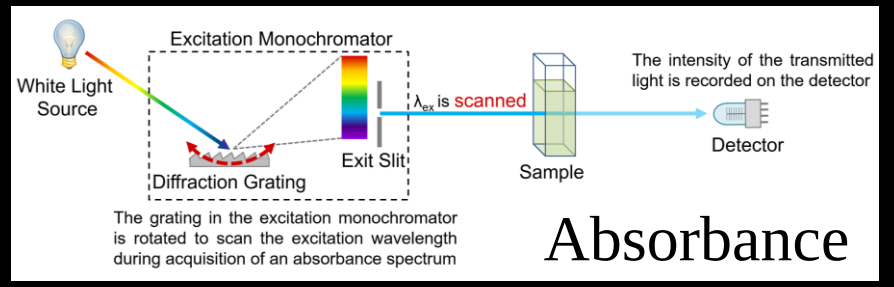


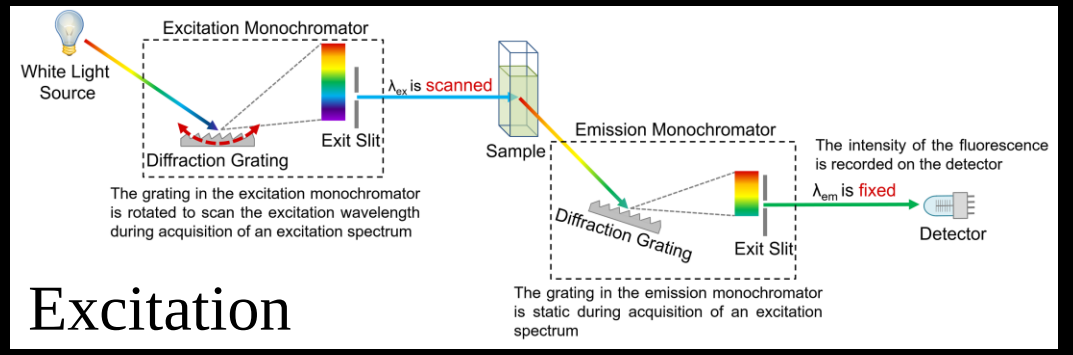
REF: Nunn, N. et al. Brilliant blue, green, yellow, and red fluorescent diamond particles: synthesis, characterization, and multiplex imaging demonstrations. Nanoscale 11, 11584–11595 (2019).

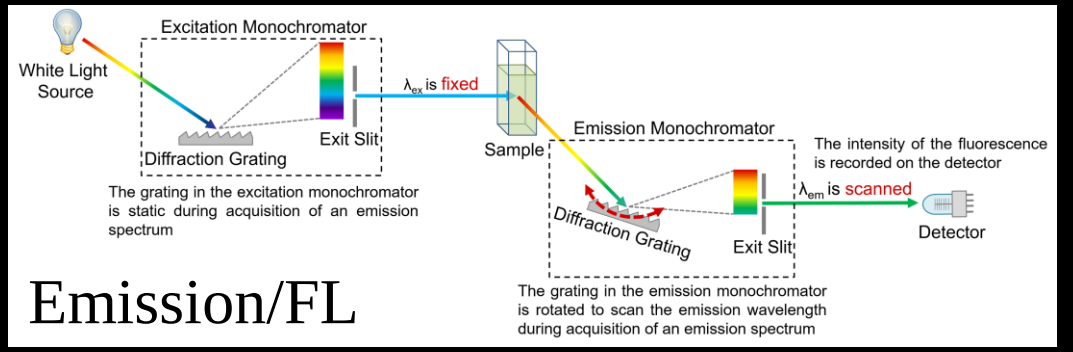
Fluorescence spectroscopy



REF: https://www.agilent.com/en/support/molecular-spectroscopy/fluorescence-spectroscopy/what-is-fluorescence-spectroscopy-faqs

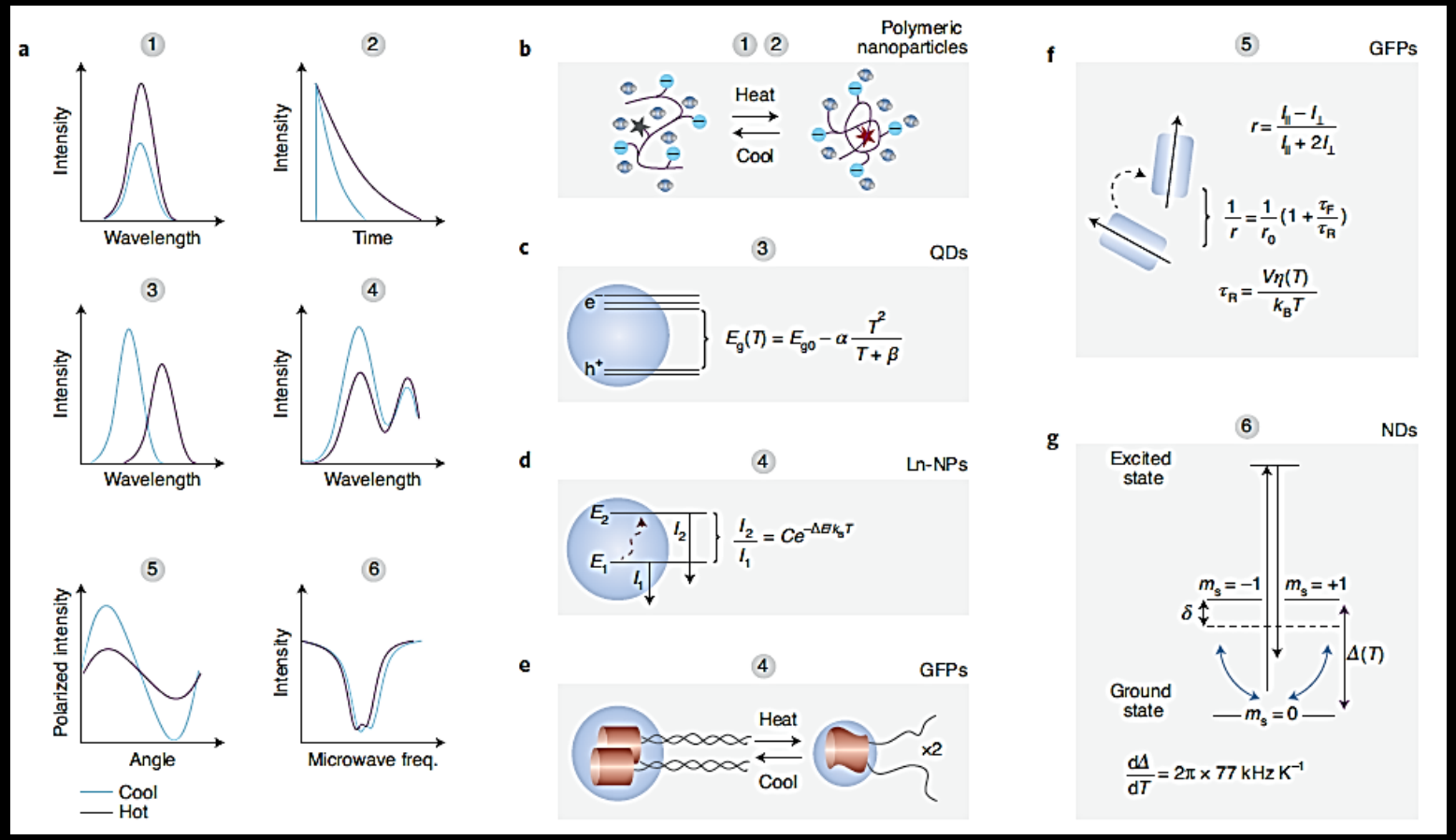




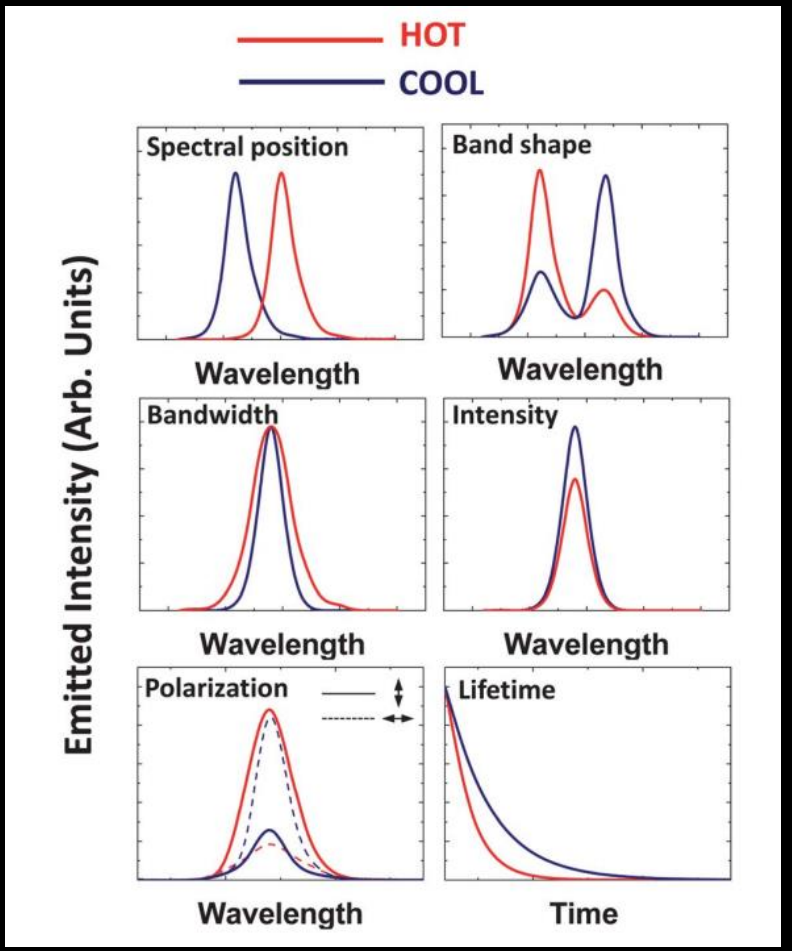


REF: https://www.edinst.com/blog/what-are-absorption-excitation-and-emission-spectra/

Luminescence nanothermometry strategies

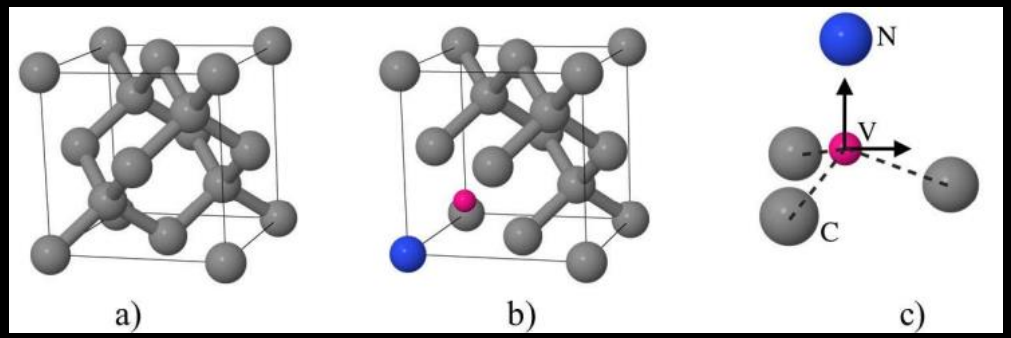


REF: Zhou, J., del Rosal, B., Jaque, D., Uchiyama, S. & Jin, D. Advances and challenges for fluorescence nanothermometry. Nat. Methods 17, 967–980 (2020).

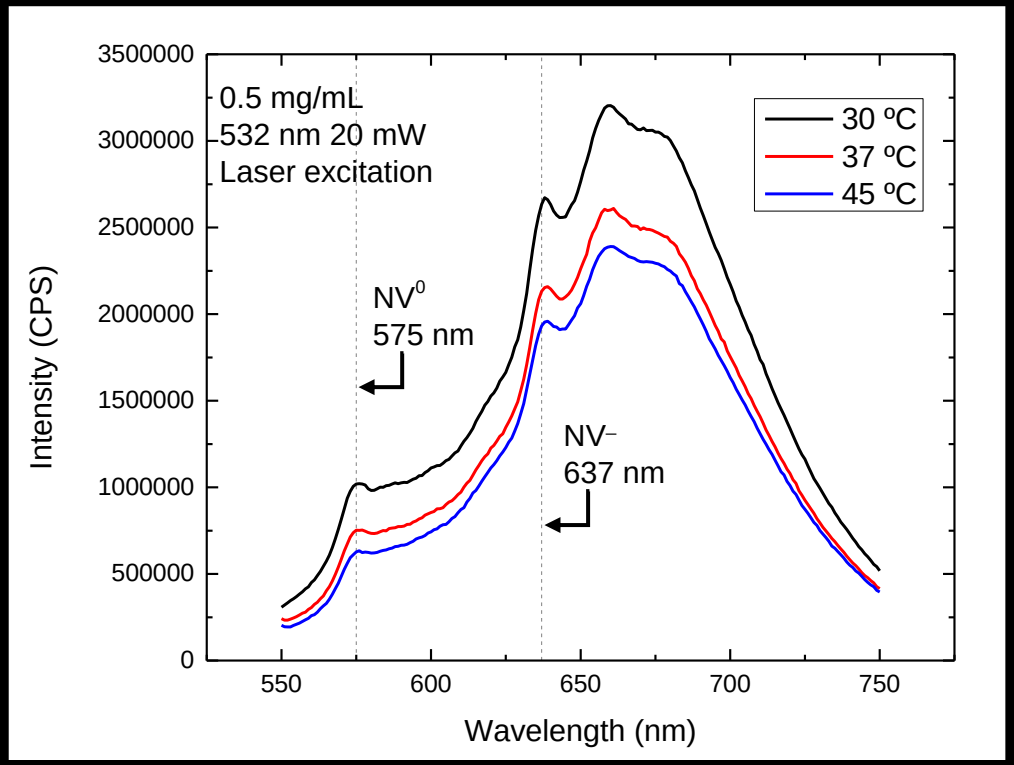


REF: Jaque, D. & Vetrone, F. Luminescence nanothermometry. Nanoscale 4, 4301–4326 (2012).

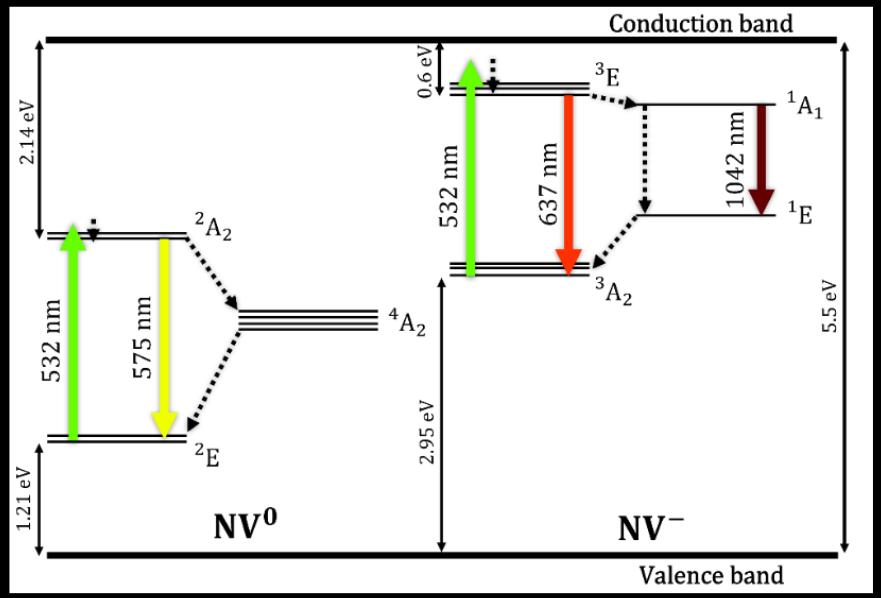
The nitrogen-vacancy (NV) color center



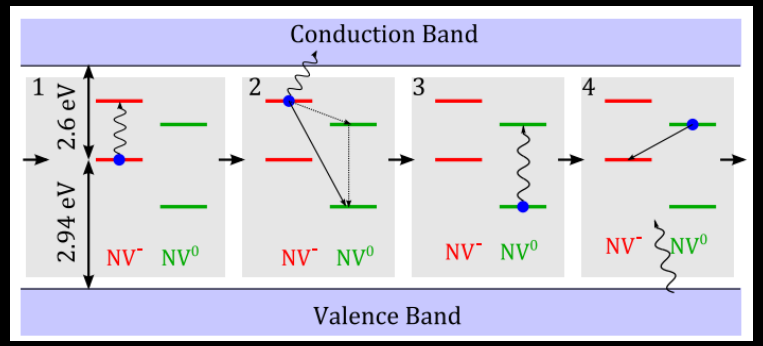
Other: SiV, GeV, PbV, NVN, N3, …



Intensity quenching associated with temperture



Two electronic structures



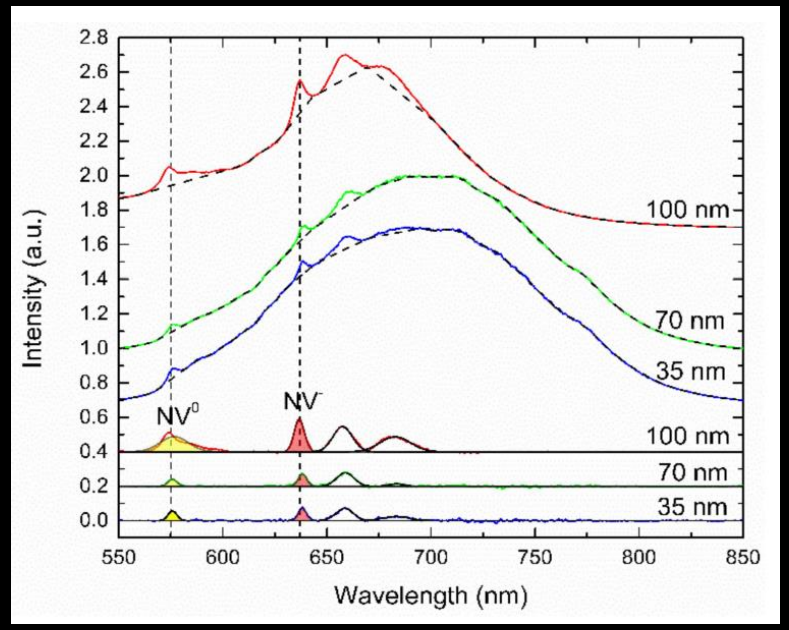
REF: Aslam, N., Waldherr, G., Neumann, P., Jelezko, F. & Wrachtrup, J. Photo-induced ionization dynamics of the nitrogen vacancy defect in diamond investigated by single-shot charge state detection. New J. Phys. 15, 013064 (2013).

Nanodiamonds thermometric characterization

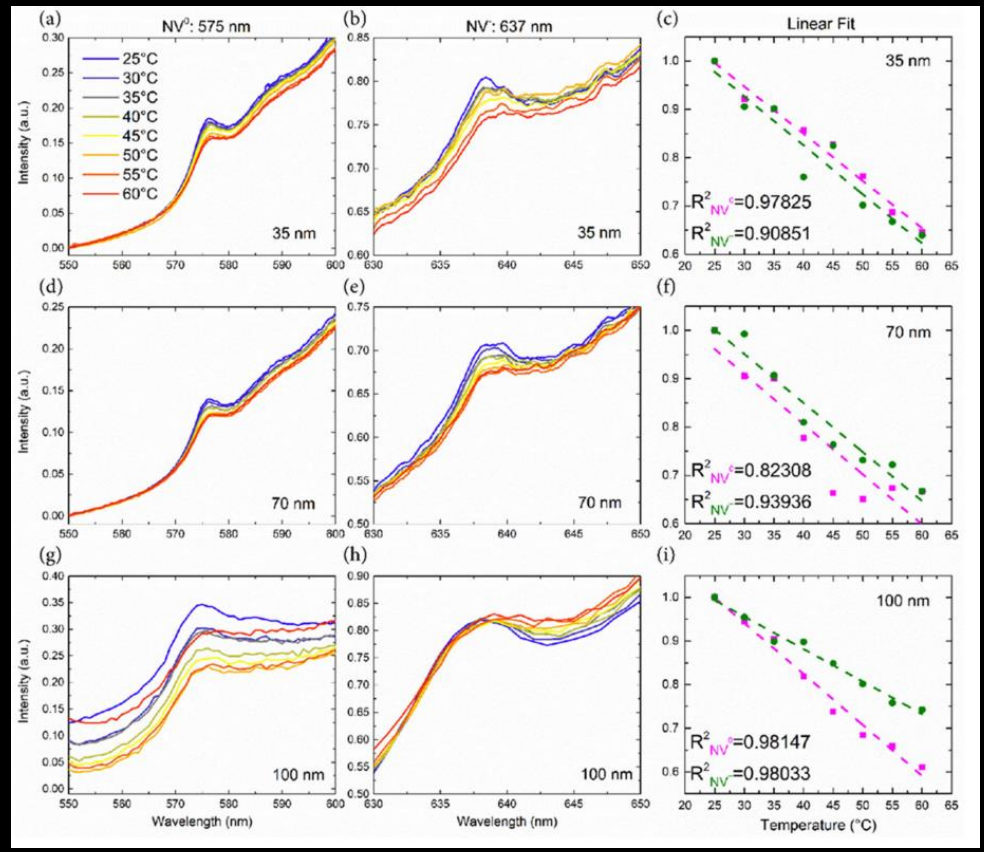
Fluorescence intensity quenching in three different sized nanodiamonds with NV color centers:

Table 1. Sigma Aldrich's nanodiamonds specifications.

Part Number	Concentration	NV Centres/Particle	Size
900172-5 mL	1 mg/mL	≤4	35 nm
798169-5 mL	1 mg/mL	>300	70 nm
900174-5 mL	1 mg/mL	>900	100 nm



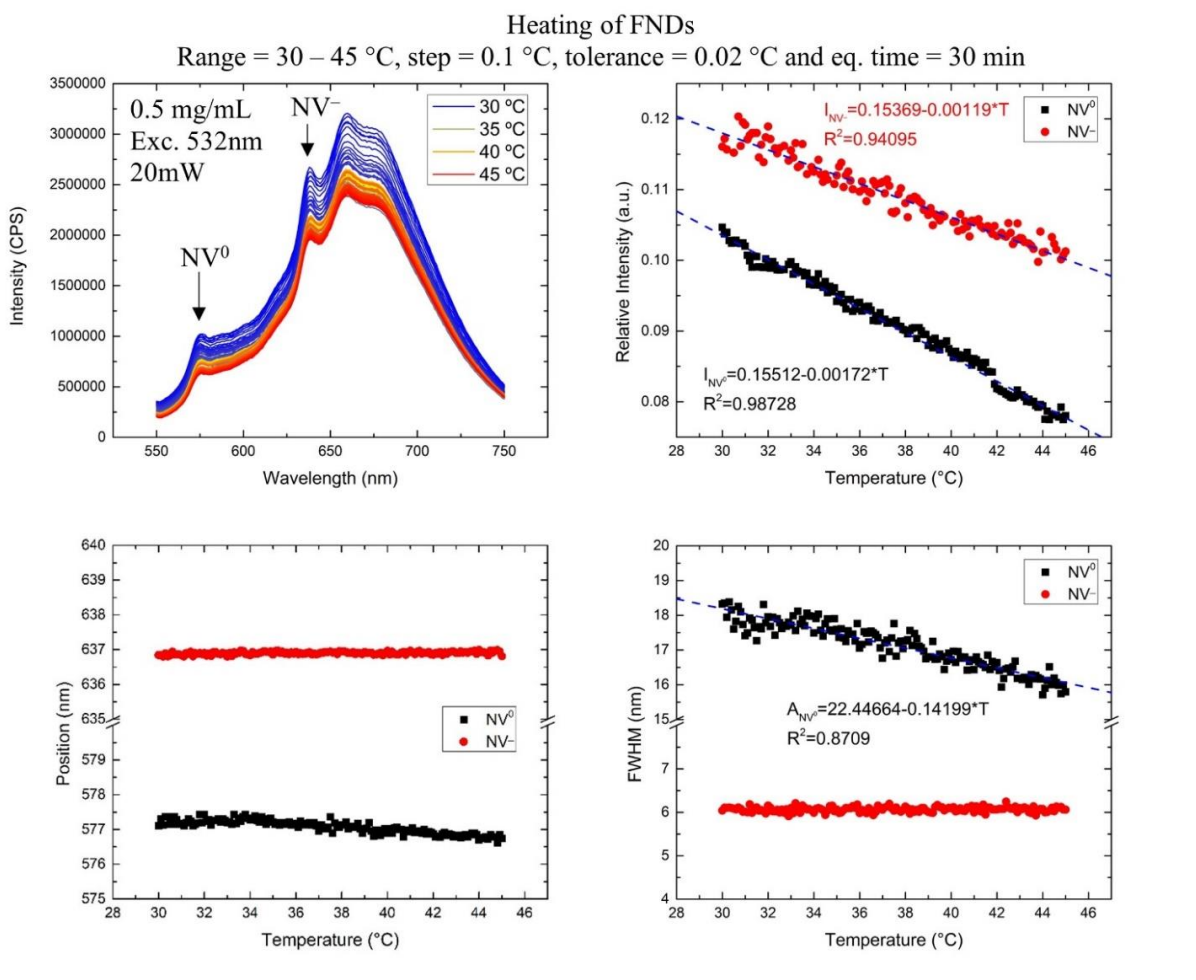
- ✓ Neutral and negative charge state thermometry.
- ✓ Relative sensitivity values were calculated 4-6 %/ºC.
- ✓ Average uncertainty values yielded 1.3 ºC.
- ✓ 100 nm size – best linear representation.

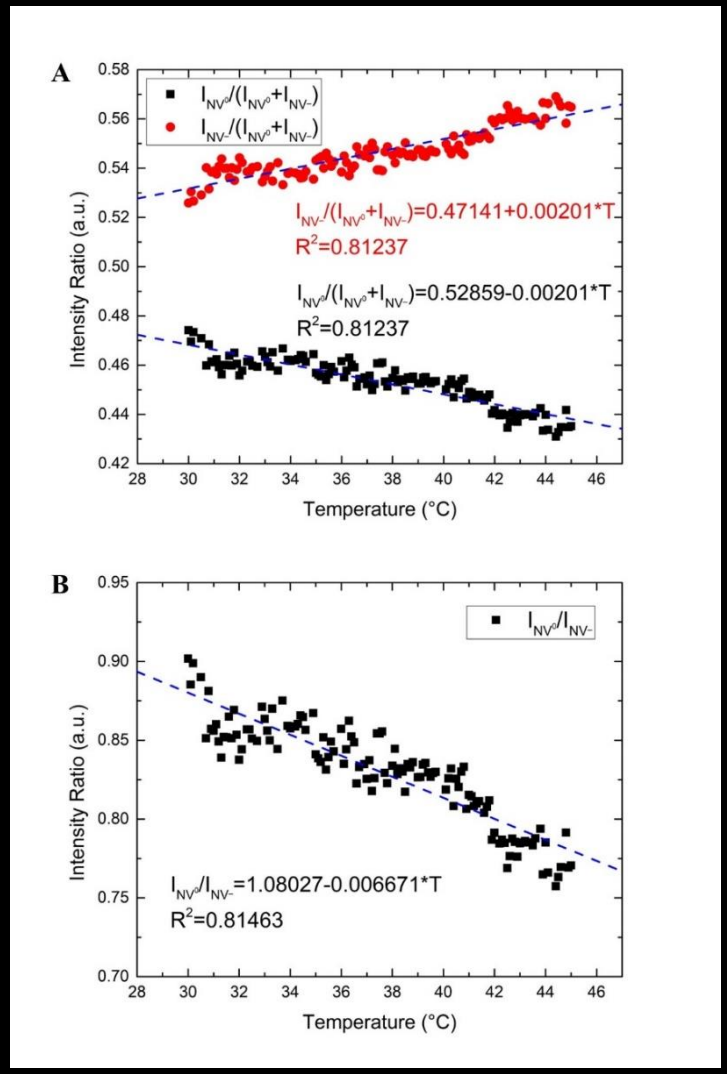


REF: Pedroza-Montero, F. *et al.* Thermometric Characterization of Fluorescent Nanodiamonds Suitable for Biomedical Applications. *Appl. Sci.* **11**, (2021).

Normalize[0,1] -> BaselineSub -> GaussianFit[575,637] -> Relative intensity values

Highly precise fluorescence–based temperature sensing





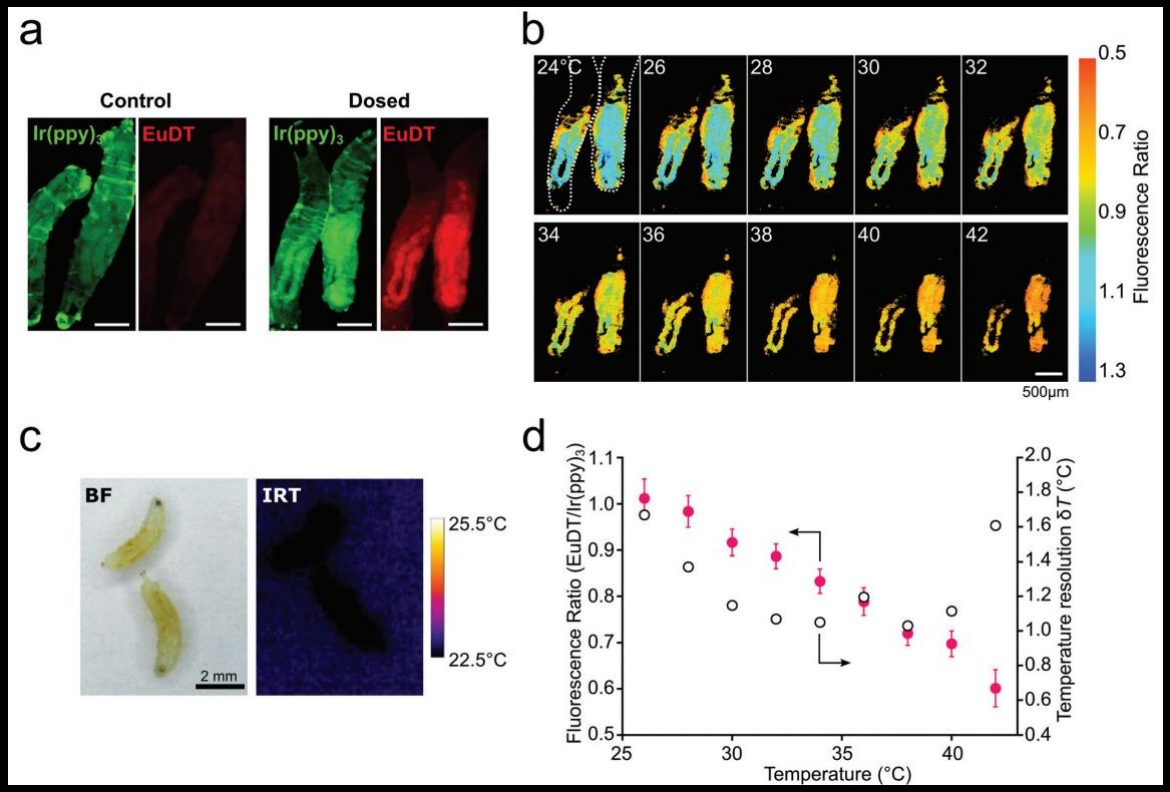
Normalize[0,1] -> BaselineSub -> GaussianFit[575,637] -> Relative intensity values

REF: Pedroza-Montero, F. *et al.* Commercial nanodiamonds for highly precise fluorescence–based temperature sensing. *Appl. Phys. Lett.* **Under Review**, (2024).

Highly precise fluorescence–based temperature sensing

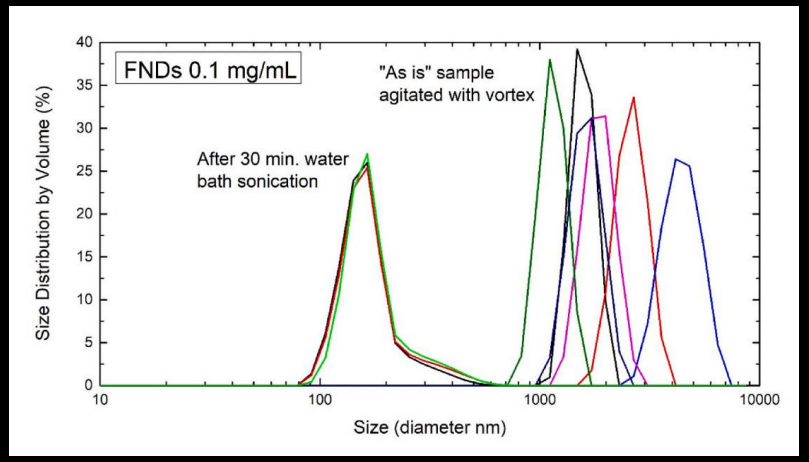
REF: Pedroza-Montero, F. *et al.* Commercial nanodiamonds for highly precise fluorescence–based temperature sensing. *Appl. Phys. Lett.* **Under Review**, (2024).

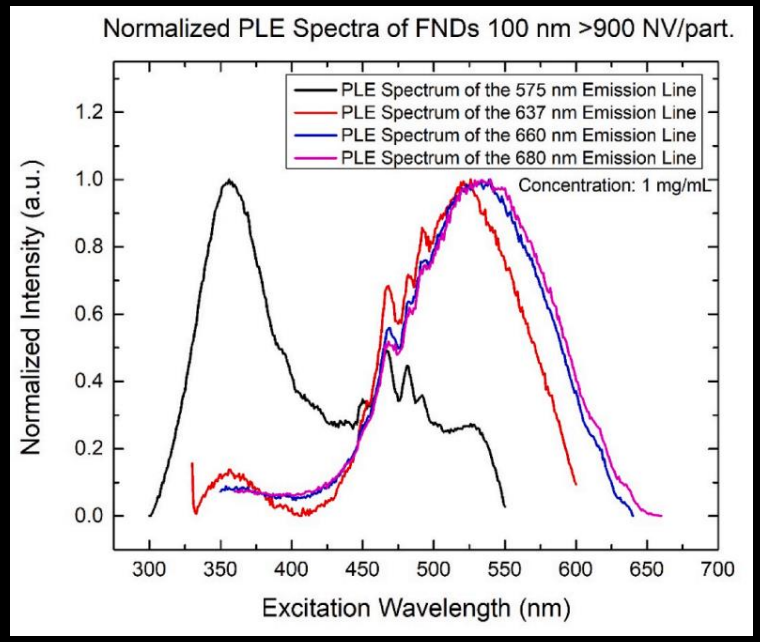
Term (units)	I_{NV^0}	I_{NV^-}	A_{NV^0}	$\frac{I_{NV^0}}{I_{NV^0}+I_{NV^-}}$	$\frac{I_{NV^-}}{I_{NV^0}+I_{NV^-}}$	$\frac{I_{NV^0}}{I_{NV^-}}$
S_a (a.u./ºC)	* 0.000373	* 0.000635	0.123895 (nm/ºC)	0.001540	0.001540	0.005163
S_r (%/ºC)	0.456716	0.579934	0.721555	* 0.339479	* 0.282022	0.621194
ϵ (ºC)	* 0.412884	* 0.861714	1.313149	1.754283	1.754283	1.741153

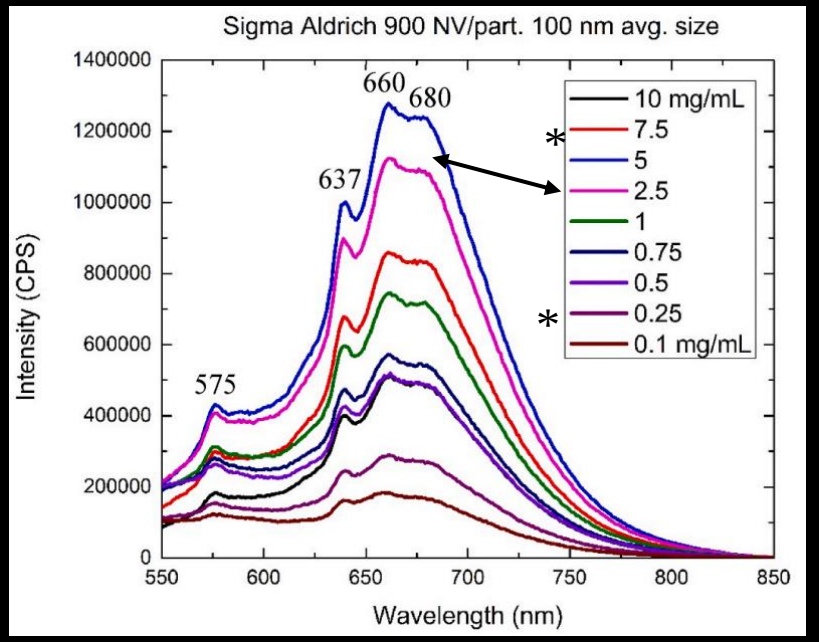


REF: Arai, S. *et al.* Micro-thermography in millimeter-scale animals by using orally-dosed fluorescent nanoparticle thermosensors. *The Analyst* **140**, 7534–7539 (2015).

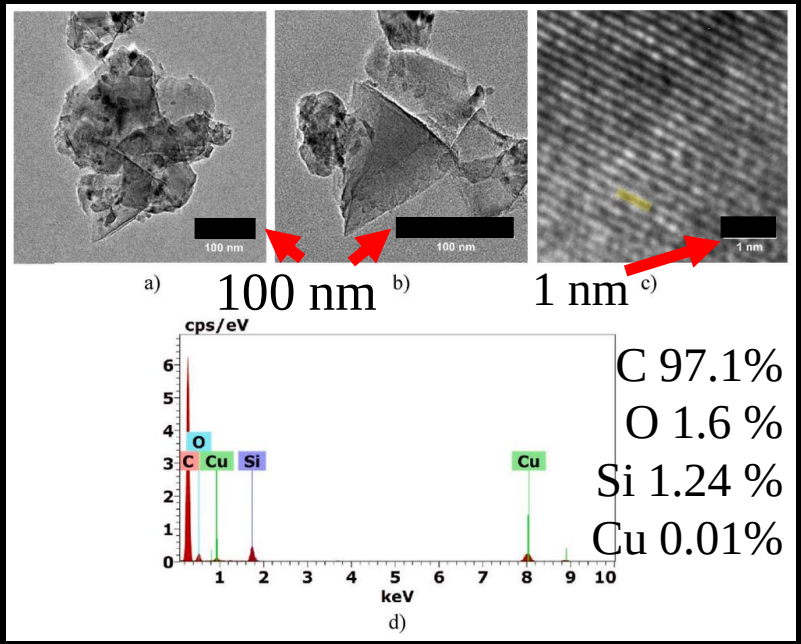
Concentration effect in fluorescence emission in 900174-5mL







PLE and PL



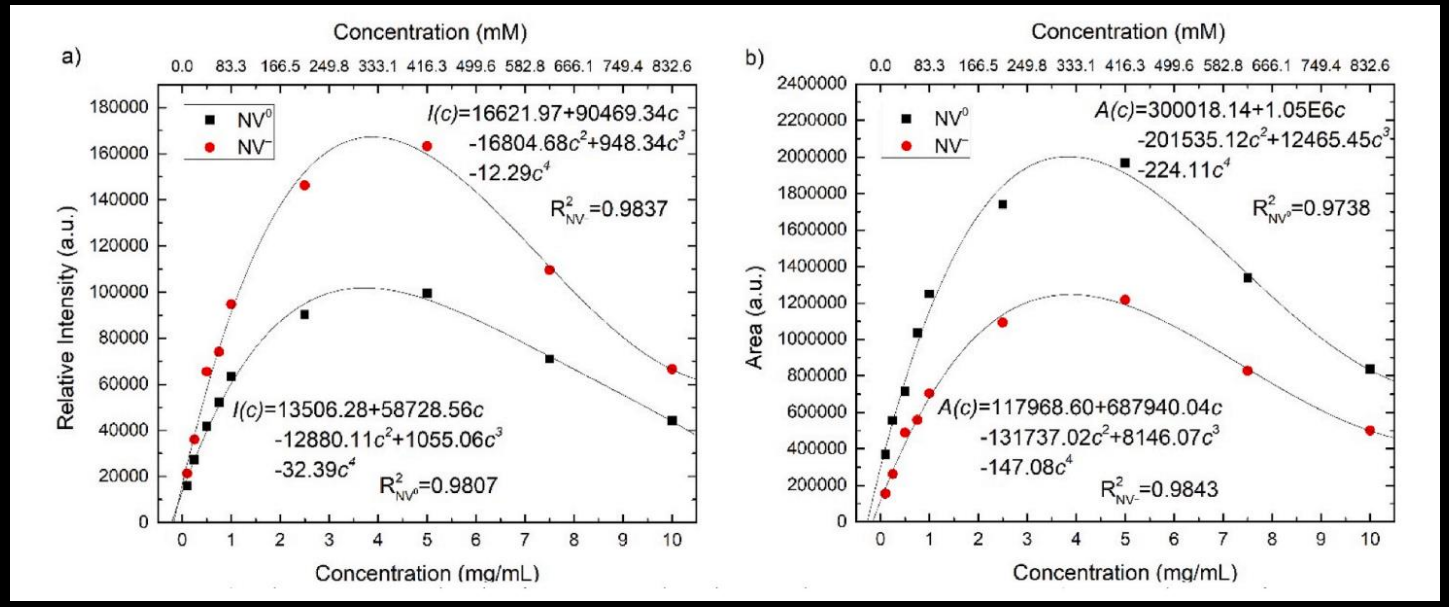
DLS, TEM and FTIR (not shown)

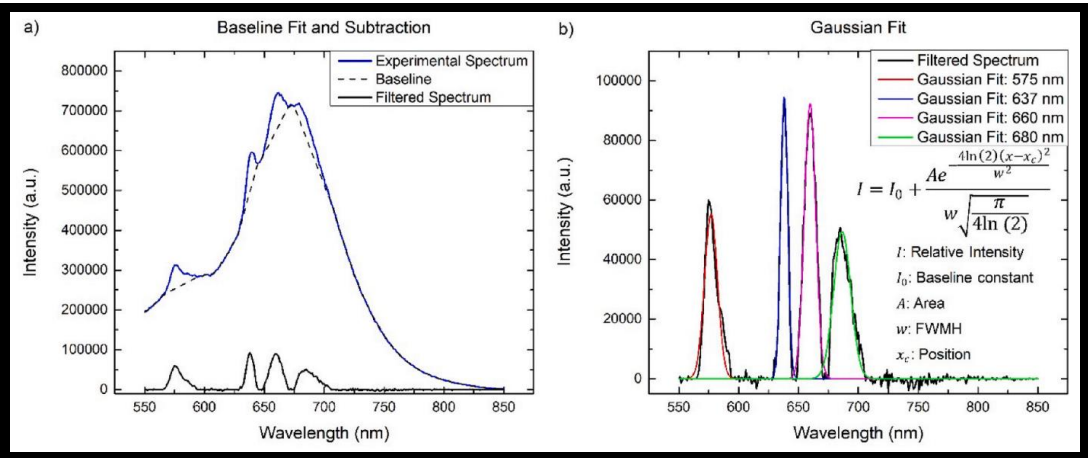
Table 1
Summary of photoluminescence excitation and emission spectra of FNDs associated to NV^0, NV^-, PSB1 and PSB2 bands.

Photoluminescence excitation spectrum				Photoluminescence emission spectrum
Fixed emission wavelength (nm)				Fixed excitation wavelength (nm)
575 (NV^0)	637 (NV^-)	660 (PSB1)	680 (PSB2)	532
356	356	450	450	575 (NV^0)
450	450	467	467	637 (NV^-)
467	467	481	481	660 (PSB1)
481	481	492	492	680 (PSB2)
492	492	534	534	
	523			

REF: Pedroza-Montero, F. A. et al. Study of fluorescent nanodiamonds concentrations in aqueous solutions for biological applications. Opt. Mater. 140, 113872 (2023).

Concentration effect in fluorescence emission in 900174-5mL





BaselineSub -> GaussianFit[575,637] -> Intensity values

REF: Pedroza-Montero, F. A. et al. Study of fluorescent nanodiamonds concentrations in aqueous solutions for biological applications. Opt. Mater. 140, 113872 (2023).

Conclusions

- Nanodiamonds with NV color centers exhibit highly temperature sensitive fluorescence properties.
- NV emission was found to decrease linearly within 25-60 ºC (three sizes) and 30-45 ºC (100 nm).
- Their use in fluorescence microscopy for cell monitoring could provide of thermally-resolved images of biological events.
- The use of relative intensity measurements provided sub-1 ºC uncertainties.

Thank you.