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High throughput fabrication of Fabry-Pérot type cavities for strong coupling experiments using maskless grayscale UV lithography.

Siim Pikker, PhD

Tartu
20.09.2025

The people

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Nanostructured physics lab + Laboratory of Thin Film Technology

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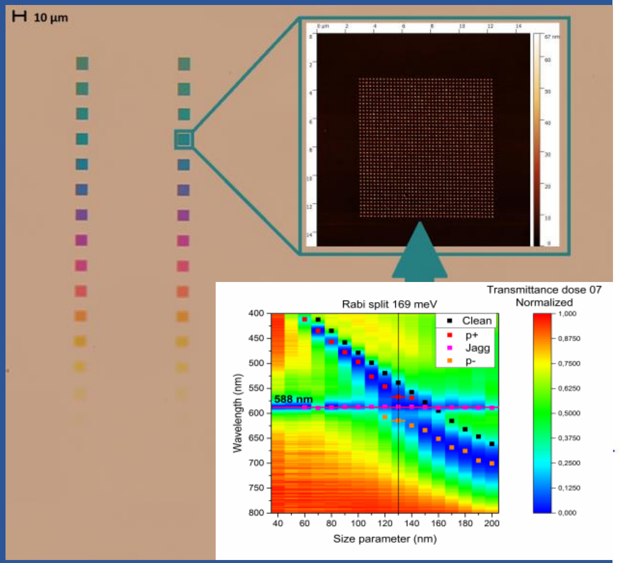
My background

Micro- and nanostructures for optics, plasmonics, polaritonics, design, simulation, fabrication and characterization, SERS, MEF etc.

https://doi.org/10.1063/5.0037896 , https://www.science.org/doi/10.1126/sciadv.aap8978



Article | Open access | Published: 04 August 2024

Thermal disorder prevents the suppression of ultra-fast photochemistry in the strong light-matter coupling regime

Arpan Dutta, Ville Tiainen, Ilia Sokolovskii, Luís Duarte, Nemanja Markešević, Dmitry Morozov, Hassan Qureshi, Siim Pikker, Gerrit Groenhof & J. Jussi Toppari

Nature Communications 15, Article number: 6600 (2024) | Cite this article

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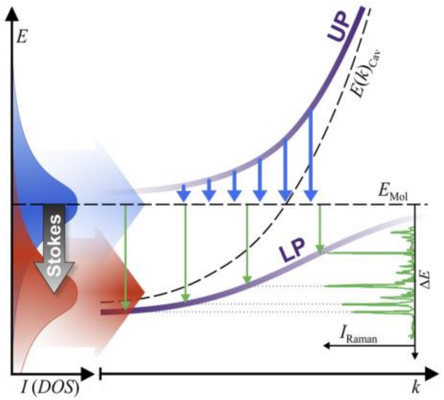
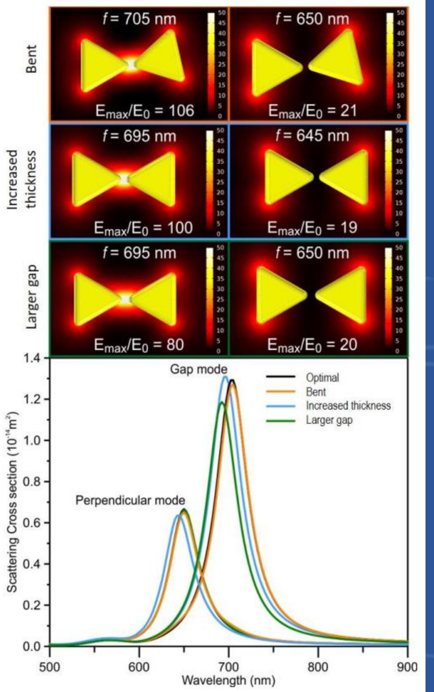
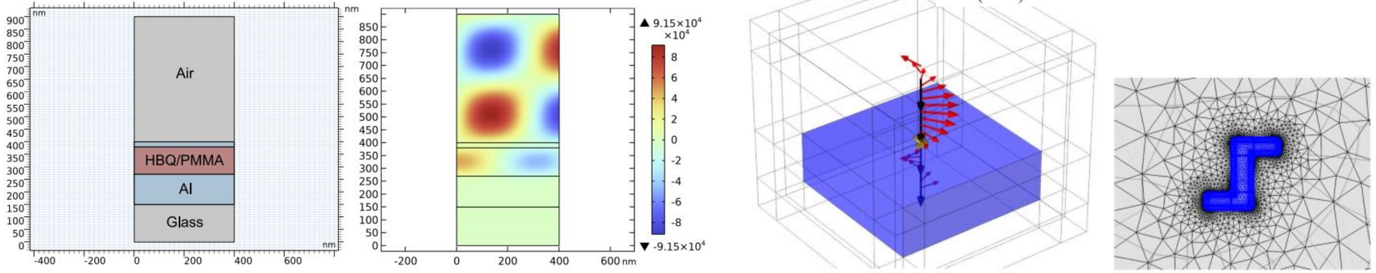






Strong coupling and polaritons

Polaritons are hybrid particles resulting from strong coupling electromagnetic waves (photons) to on electric dipole-carrying excitation.

Examples:

EM field + oscillating electrons at metal surface = surface plasmon polaritons
EM field + exciton (electron- hole pair) = exciton polariton
EM field + phonons = phonon polariton
Plasmon + exciton = plexciton
…

Strong coupling and polaritons

Low-threshold coherent light sources / polariton lasers — polariton condensation in organic dye microcavities can produce coherent emission with much lower thresholds than conventional photon lasers, enabling energy-efficient, compact coherent light sources. https://www.nature.com/articles/s41598-017-06125-y , DOI: 10.1126/sciadv.1600666 , https://doi.org/10.1364/OPTICA.6.001124

Next-generation displays & ultra-pure emitters — strong light–matter coupling in dye cavities gives extremely narrow, tunable emission and high color purity that can be exploited for brighter, more color-accurate displays and micro-LED alternatives. https://www.nature.com/articles/s41566-023-01164-6

Enhanced energy transfer & long-range excitation transport — polaritons delocalize excitations over many molecules, enabling long-range, ultrafast energy transfer and potentially improved charge/exciton collection in photovoltaics or light-harvesting assemblies. DOI: 10.1039/C8SC01043A

Polaritonic chemistry — control of chemical reactivity and pathways — coupling molecular electronic (or vibrational) transitions to cavity modes can modify reaction rates, energy landscapes, and branching ratios; dye systems offer convenient chemical functionality to explore cavity-modified chemistry. https://www.nature.com/articles/s41467-024-50532-5 , doi: 10.1039/c8sc01043a

… Ultrafast nonlinear optics & switching and Topological & quantum photonic devices

Strong coupling and polaritons

3594 | Nanoscale, 2018, 10, 3593–3605

Table 1 Overview of strongly coupled systems known to date

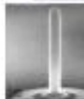
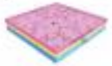
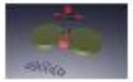
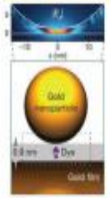
Typical parameters					Wave-number, eV (nm)	Q	$V, \left(\frac{\lambda}{n}\right)^3$	$\hbar\kappa$, meV	$\hbar\gamma$, meV	$\hbar\Omega_R$, meV	Ref.
Coupling to the cavity field	Ensemble of oscillators in a cavity	Vibrational strong coupling		An ~2 μm layer of polyvinyl acetate is sandwiched between 10 nm Au mirrors on a Ge substrate.[36]	0.1–0.6 (2×10^3–10×10^3	50–100	~10^3	15–20	5–8	5–30	36–41
		Electronic strong coupling		Semiconductor cavity. A monolayer of molybdenum disulphide sandwiched between two SiO_2 layers to form the cavity layer, which is placed between SiO_2/Si_3N_4 distributed Bragg reflector (DBR) mirrors. Reprinted with permission from ref. 16. Copyright (2015) Nature Publishing Group.	1.7–2.5 (500–700)	100–1000	~10^3	5–10	30–240	40–300	16–23
				Optical cavity. Thin films of cyanine dye forming J-aggregates placed in a micro-cavity formed by two silver layers.[7]	1.7–2.5 (500–700)	30–100	~10^3	15–25	30–200	300–1000	7, 24–28
	Single oscillator in a cavity			Optical cavity. The experiment employs the $6S_{\frac{1}{2}}, F = 4 \rightarrow 6P_{\frac{3}{2}}, F' = 5'$ transition of the $D2$ line in trapped Cs at a temperature of ~200 μK. Reprinted with permission from ref. 47. Copyright (2004) American Physical Society.	1.45–1.6 (780–850)	4.4×10^7–1×10^{10}	15–30	~10^{-6}	~10^{-6}	~3×10^{-4}	46 and 47
				Photonic crystal. A single quantum dot coupled to the mode of a photonic crystal.[13] Reprinted with permission from ref. 10. Copyright (2006) Nature Publishing Group.	1–1.6 (750–1200)	7×10^3–12×10^3	0.02–1.2	150×10^{-3}–300×10^{-3}	70×10^{-3}–140×10^{-3}	150×10^{-3}–400×10^{-3}	13, 48, 51–53
				Micropillar. A single $In_{0.3}Ga_{0.7}As$ dot in a micropillar cavity 1.5 μm in diameter. Reprinted with permission from ref. 14. Copyright (2007) Nature Publishing Group.			0.1–0.5				14 and 54
				Microdisks. The strong coupling regime between a GaAs quantum dot and the mode of a microdisk cavity. Reprinted with permission from ref. 15. Copyright (2005) American Physical Society.			2–8				15
Coupling to the field of a plasmonic cavity	Ensemble of excitons			Arrays of nanovoids or holes of nano-structured metal covered with an excitonic layer. Surface plasmon polaritons strongly coupled to J-aggregates of cyanine dyes. Adapted with permission from ref. 29, 55 and 56. Copyright (2006) American Physical Society and Copyright (2016) John Wiley and Sons.	1.79 (693)–1.91 (649)	7–16	10^{-5}–10^{-6}	120–270	50–120	100–400	29, 30, 55 and 56
				Strong coupling between surface plasmons localized within isolated gold nanodisk dimers[31] or silver nanoprisms[11] and J-aggregate excitons of cyanine dye (TDBC) placed into the gap between the nanoparticles. Reprinted with permission from ref. 31. Copyright (2013) American Chemical Society.							11 and 31

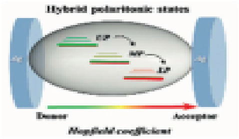
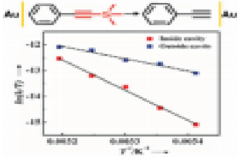
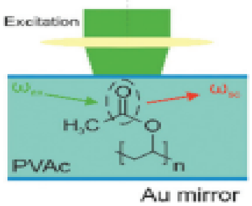
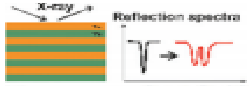
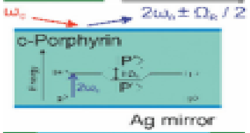
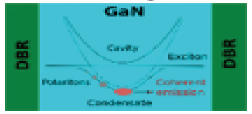
Table 1 *(Contd.)*

Typical parameters				Wave-number, eV (nm)
	With a single emitter		J-aggregate cyanine dye molecules placed into the gap between a gold nanocube and an Au surface[32] and WSe_2 layers embedded into the space between the gold sphere and Au substrate.[33] Reprinted with permission from ref. 32. Copyright (2017) American Chemical Society.	
			Methylene blue molecules in the gap between gold nanoparticles (40–60 nm) and a mirror (a 70 nm-thick gold film) underneath (the nanoparticle-on-mirror geometry). Reprinted with permission from ref. 34. Copyright (2016) Nature Publishing Group.	
			A single CdSe/ZnS quantum dot placed in the gap between two silver bowties.[35]	

https://doi.org/10.1039/C7NR06917K

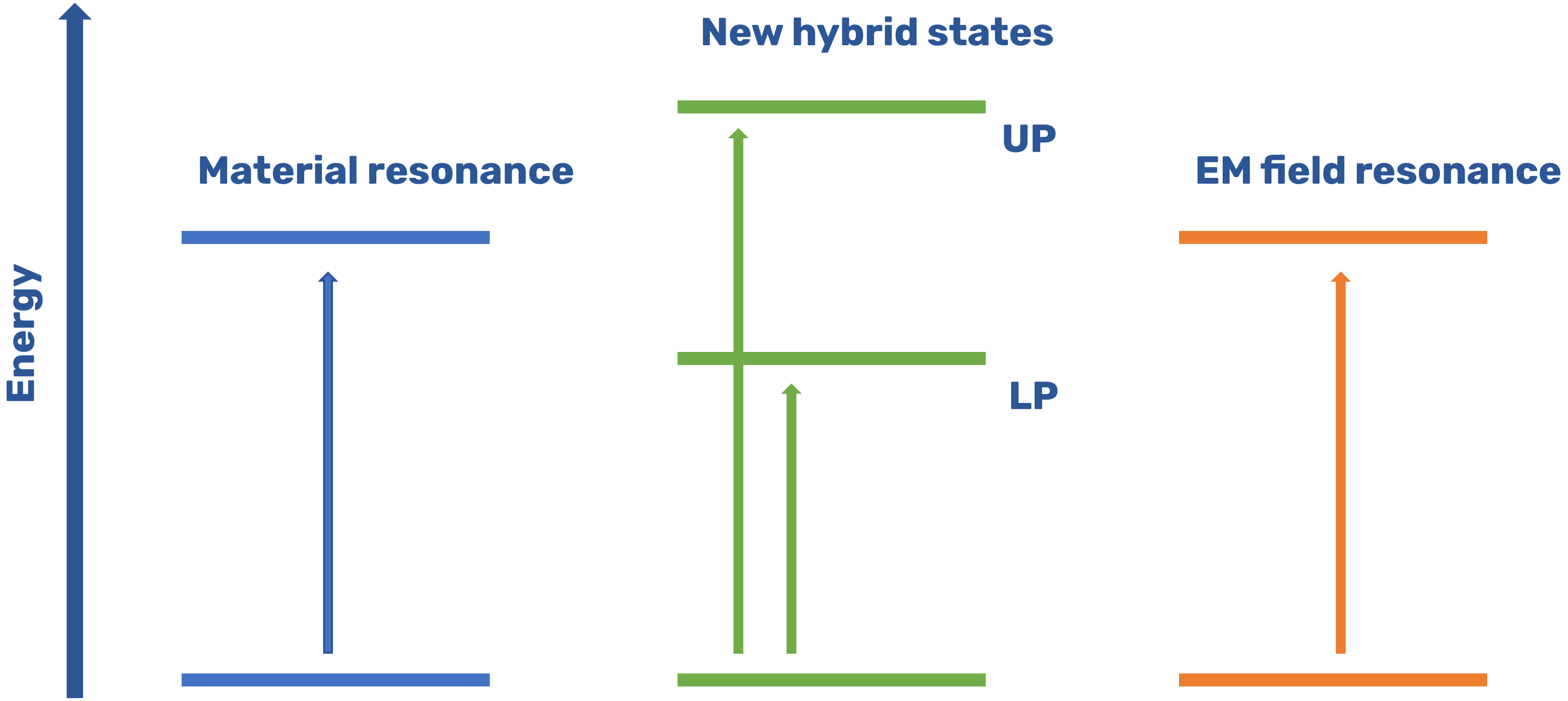
Strong coupling and polaritons

Table 2 Effects of strong coupling known to date

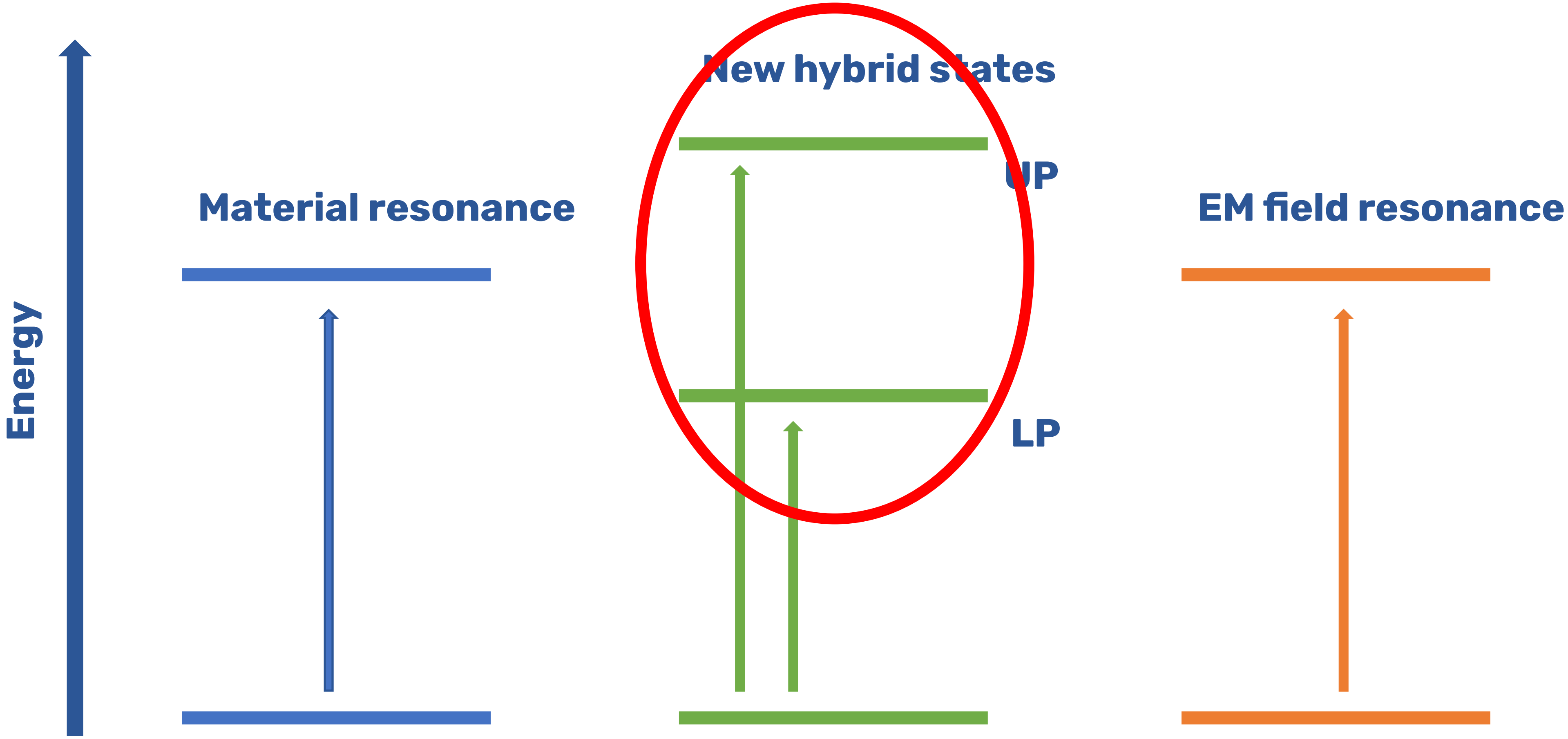
Rabi splitting		Experimental implementation	Parameters of strong coupling
Enhancing nonradiative energy transfer and energy transfer between separated entangled molecules		A donor–acceptor system (J-aggregates of TDBC and BRK as the donor (D) and acceptor (A), respectively) embedded between two Ag mirrors[4] and a similar system with the exception of the spatial separation of D and A.[69]	$\hbar\Omega_D$ = 277 meV; $\hbar\Omega_A$ = 150–200 meV
Modifying the chemical reaction rate		PTA + TBAF in a flow Fabry–Perot cavity form ZnSe windows coated with a 10 nm Au layer. Reprinted with permission from ref. 5. Copyright (2016) John Wiley and Sons.	$\hbar\Omega_R$ = 12 meV
Enhancing conductivity		PDI2EH-CN2 spin-coated on a nanohole array of an Al structure.	$\hbar\Omega_R$ = 0.7 eV
Enhanced Raman scattering		A polyvinyl acetate layer between two Ag mirrors.	$\hbar\Omega_R$ = 215 meV
Strong collective X-ray–nucleus interaction		A multilayer of ^{56}Fe and ^{57}Fe sandwiched between two Ta layers.[74]	$\hbar\Omega$ = 37 neV
High-harmonic generation		SHG: A layer with crystal c-porphyrin nanofibres between two silver mirrors. THG: A similar system with the exception of the polymethine layer.[76]	$\hbar\Omega_2$ = 510 meV; $\hbar\Omega_3$ = 707 meV
Bose–Einstein condensation and coherent emission		A bulk GaN microcavity with bottom 35-period $Al_{0.85}In_{0.15}N/Al_{0.2}Ga_{0.8}N$ and top 10-period SiO_2/Si_3N_4 distributed Bragg reflectors at room temperature.	$\hbar\Omega_R$ = 28 meV

https://doi.org/10.1039/C7NR06917K

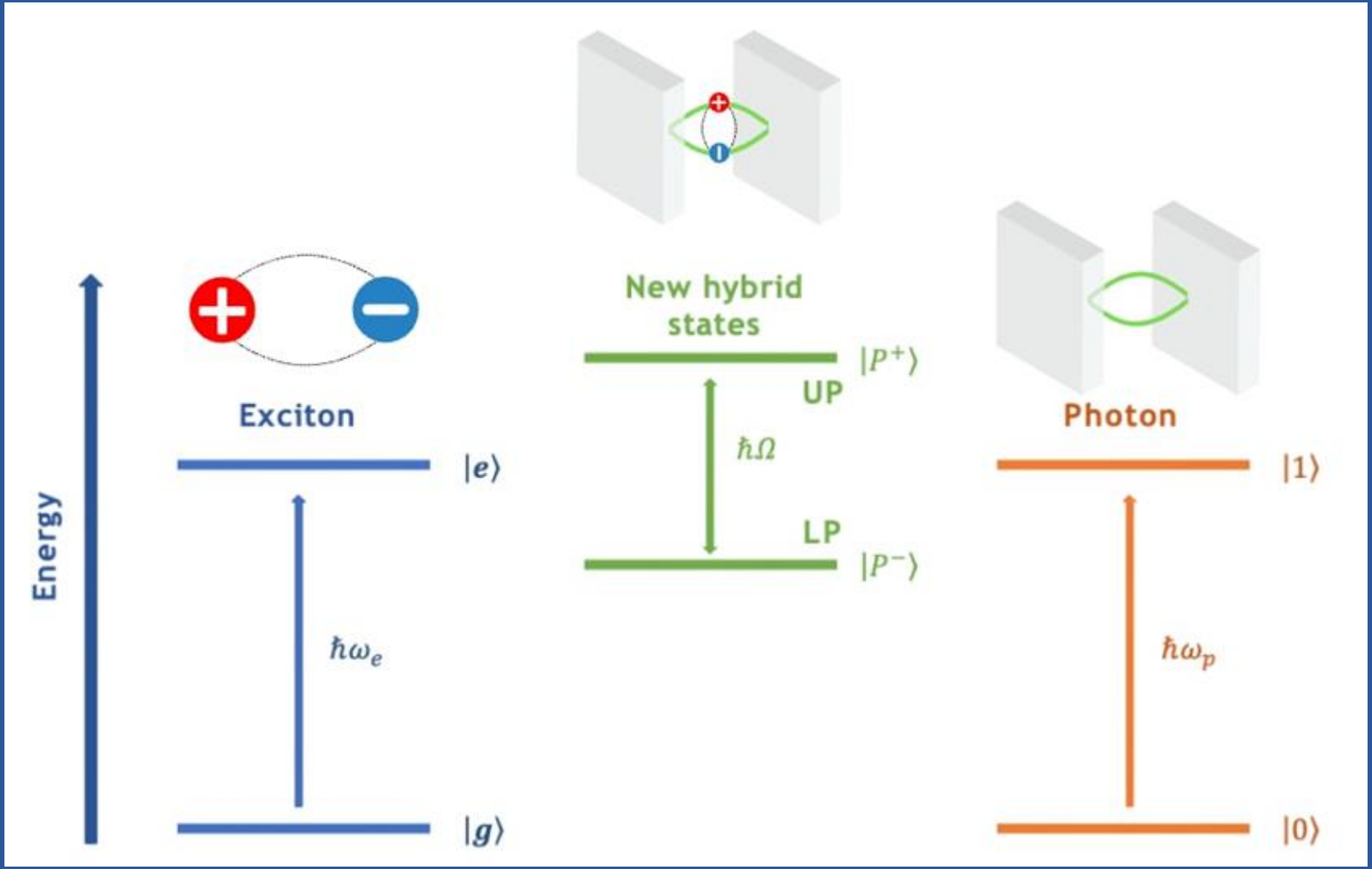
Strong coupling and polaritons



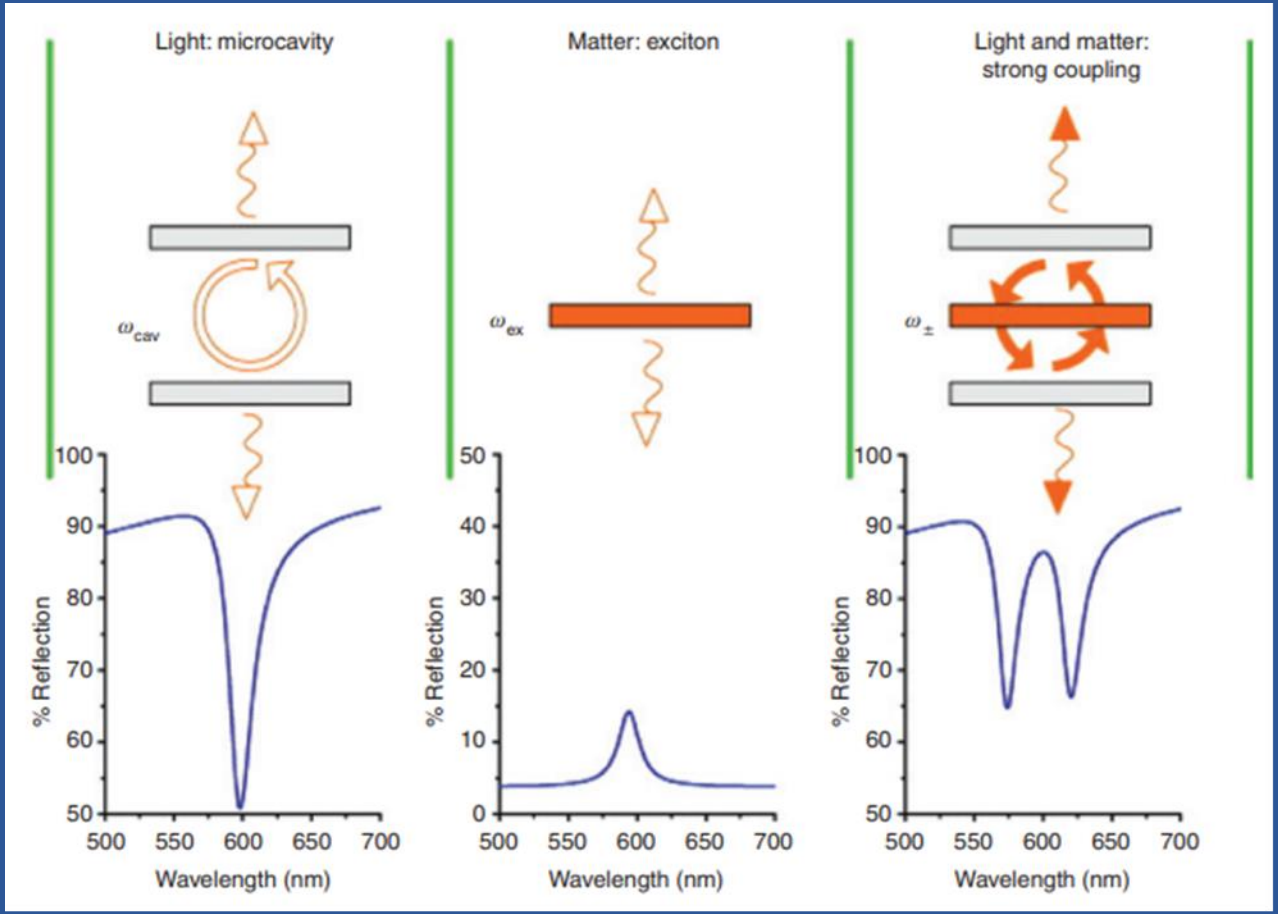
Why couple strongly?

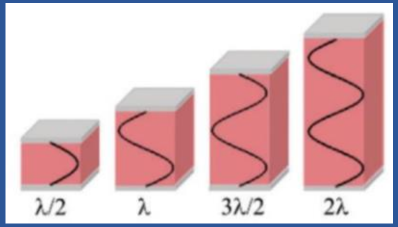


Strong coupling and polaritons



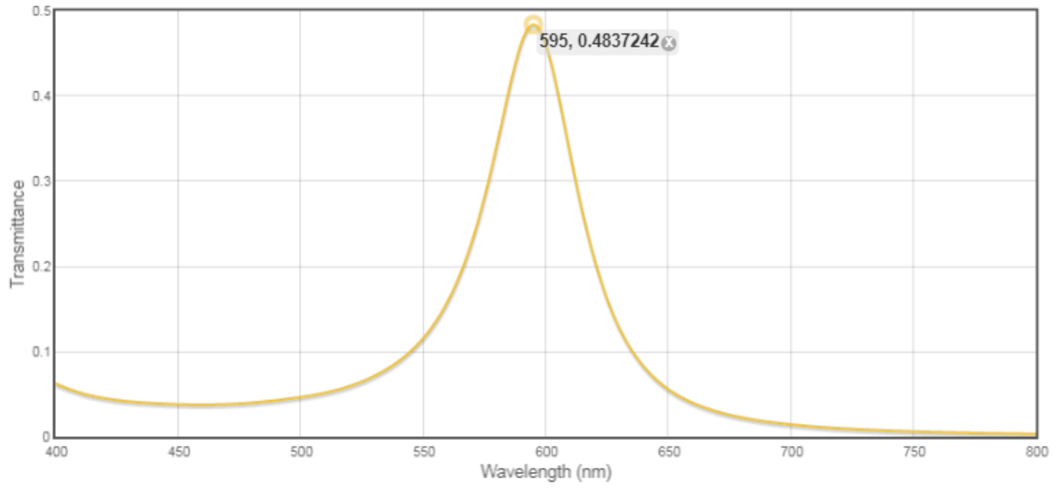
Strong coupling and polaritons





DOI 10.1515/nanoph-2017-0059

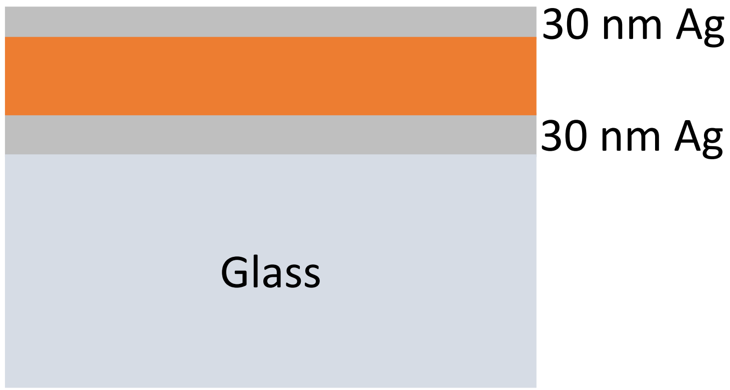
Strong coupling in cavities



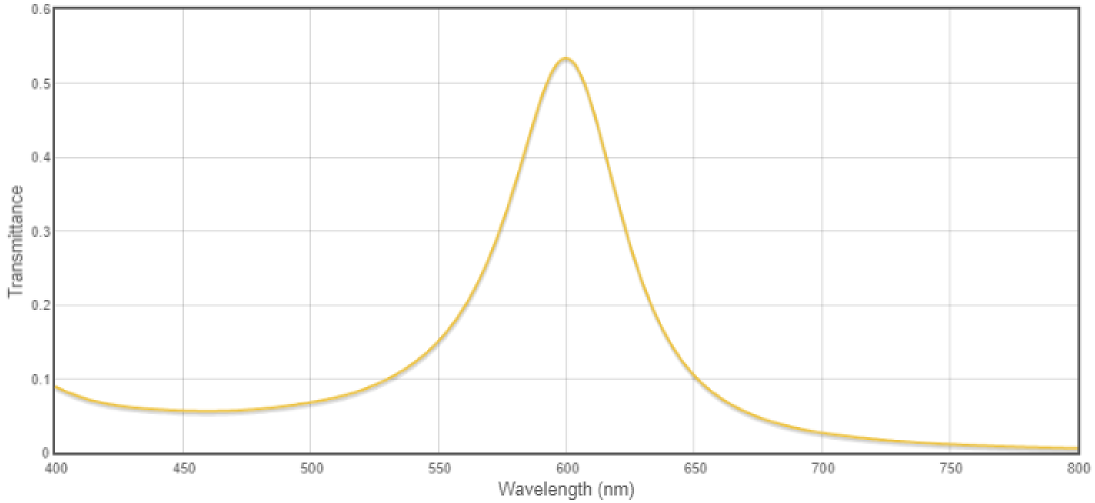
Plot start: 400 nm Plot end: 800 nm Data point spacing: 1 nm

Angle of incidence: 0 degrees Polarization: s p mixed

Layer #	Material	Thickness nm
Medium	Air	
1	Ag	30 nm
2	Acrylic	145 nm
3	Ag	30 nm
4	BK7	1000000 nm
Substrate	Air	



Strong coupling in cavities



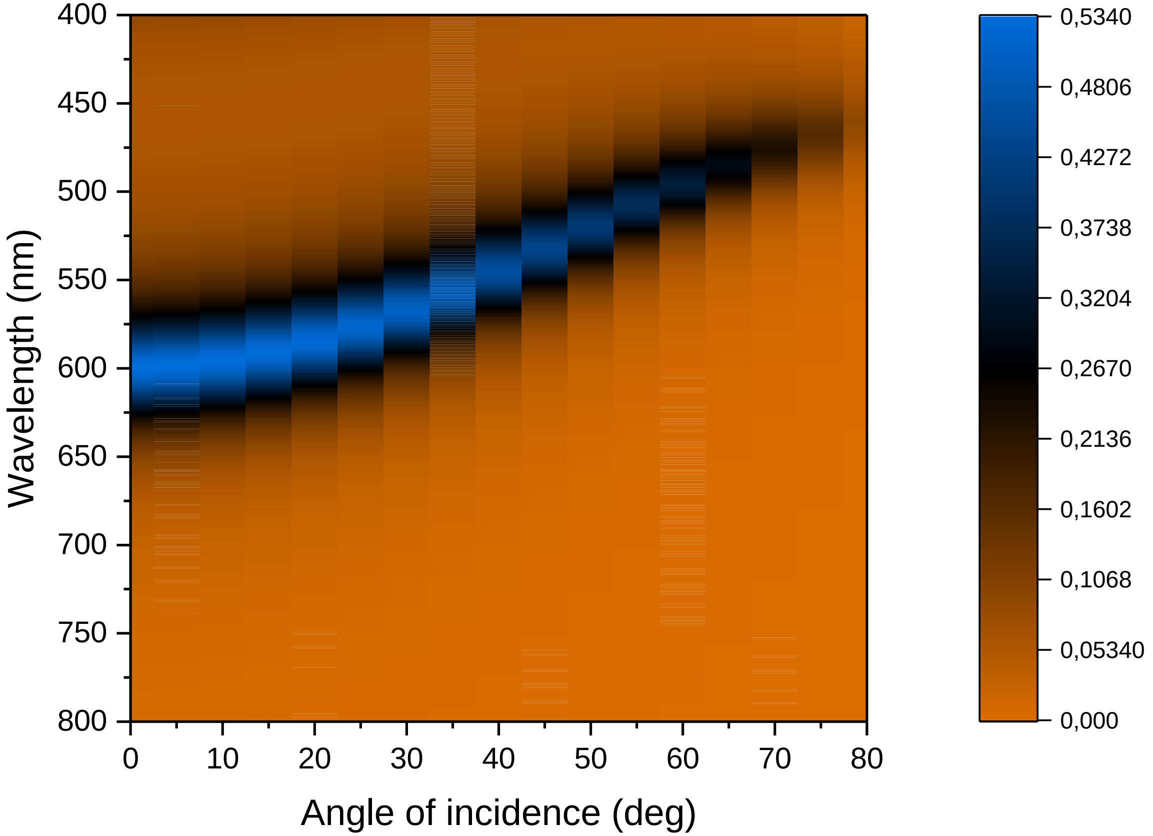
Plot start: 400 nm Plot end: 800 nm Data point spacing: 1 nm

Angle of incidence: 0 degrees Polarization: s p mixed

Layer #	Material	Thickness (nm)
Medium	Air	
1	Ag	27 nm
2	Acrylic	145 nm
3	Ag	27 nm
4	BK7	1000000 nm
Substrate	Air	

Simulated empty cavity S-pol transmittance

27nm Ag / 145nm Acrylic / 27nm Ag / 1mm BK7 glass



Measurement systems

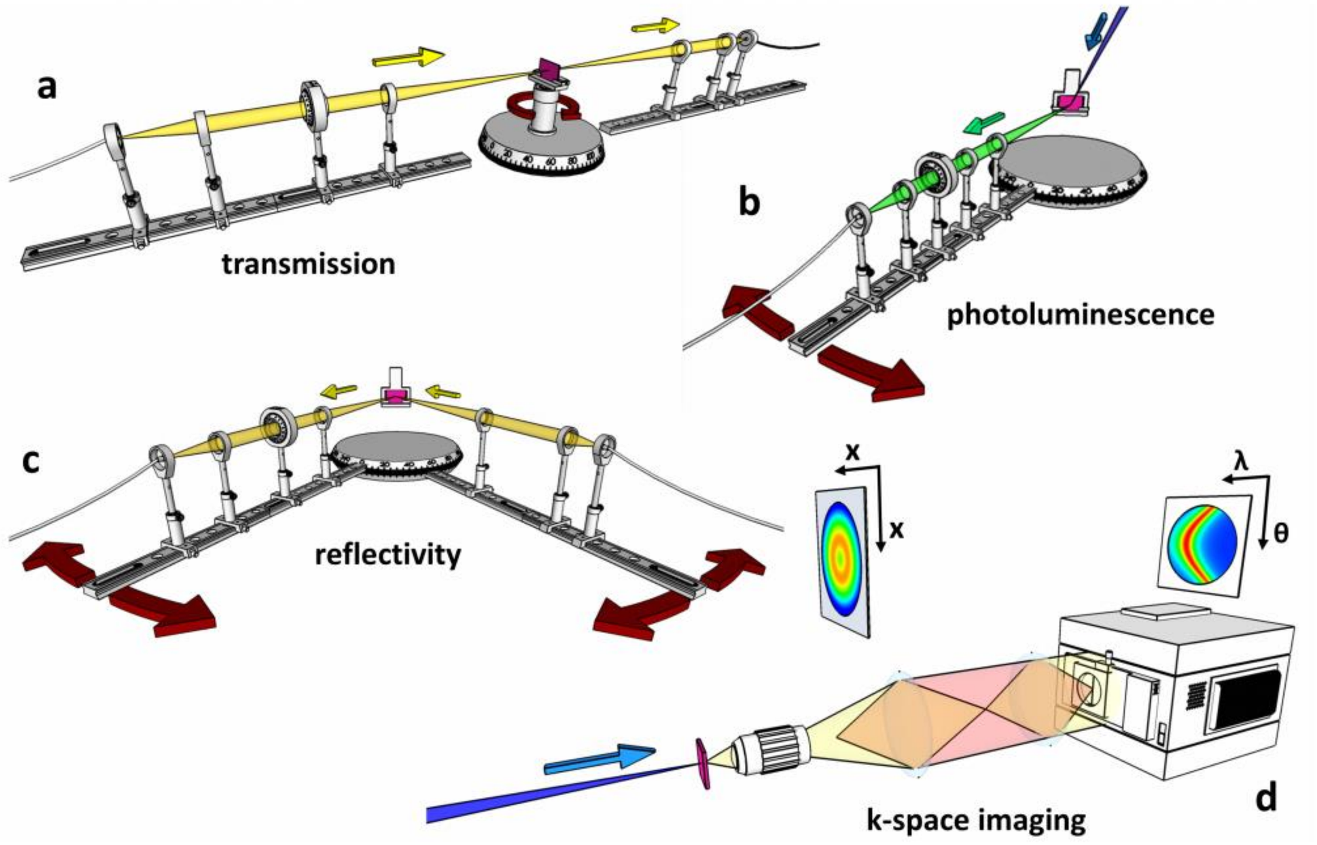
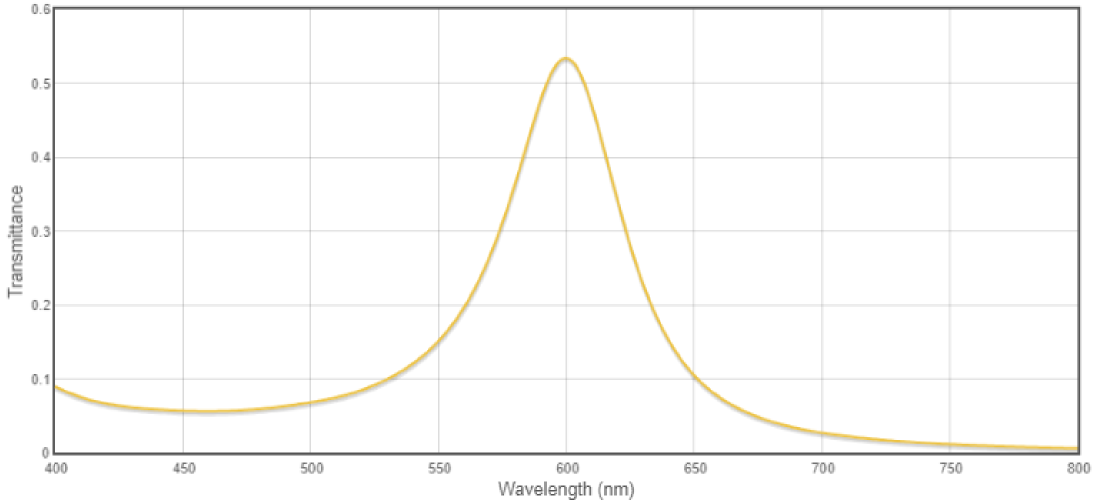


Fig. 1.4 Commonly used angular-dependent experiments for characterising strongly coupled planar microcavity structures. (a) transmission. (b) photoluminescence (c) reflectivity (d) k-space imaging.

https://doi.org/10.1007/978-3-319-16580-6_11

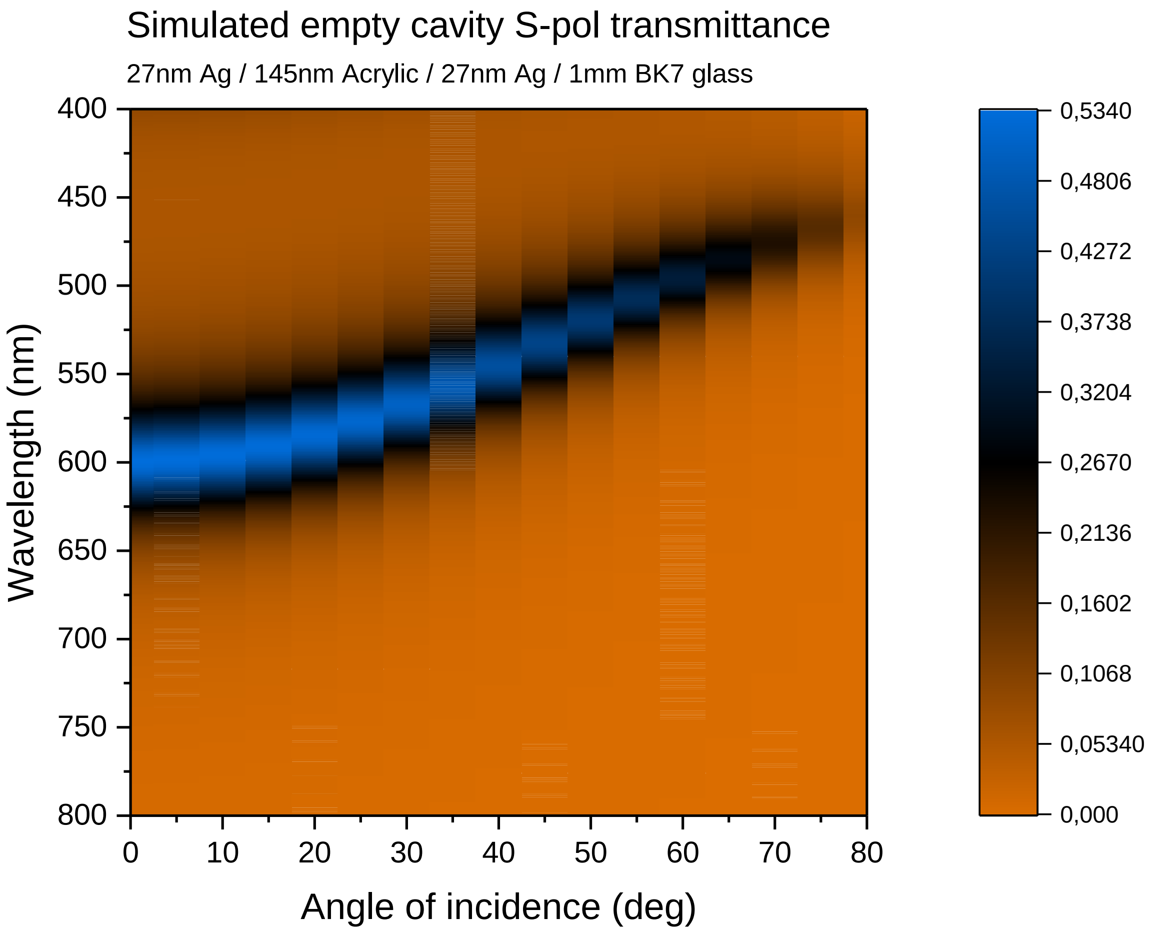
Strong coupling in cavities



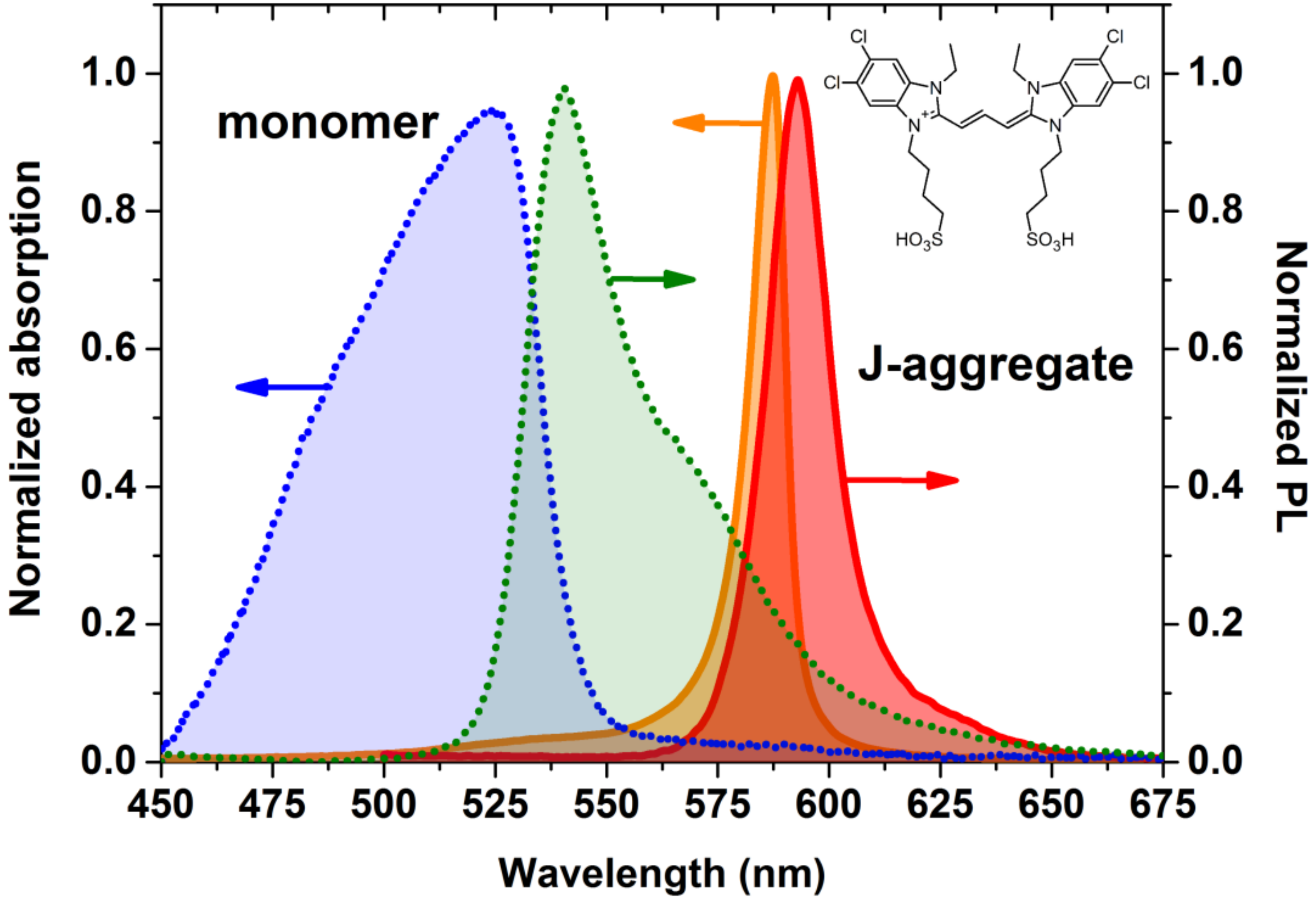
Plot start: 400 nm Plot end: 800 nm Data point spacing: 1 nm

Angle of incidence: 0 degrees Polarization: s p mixed

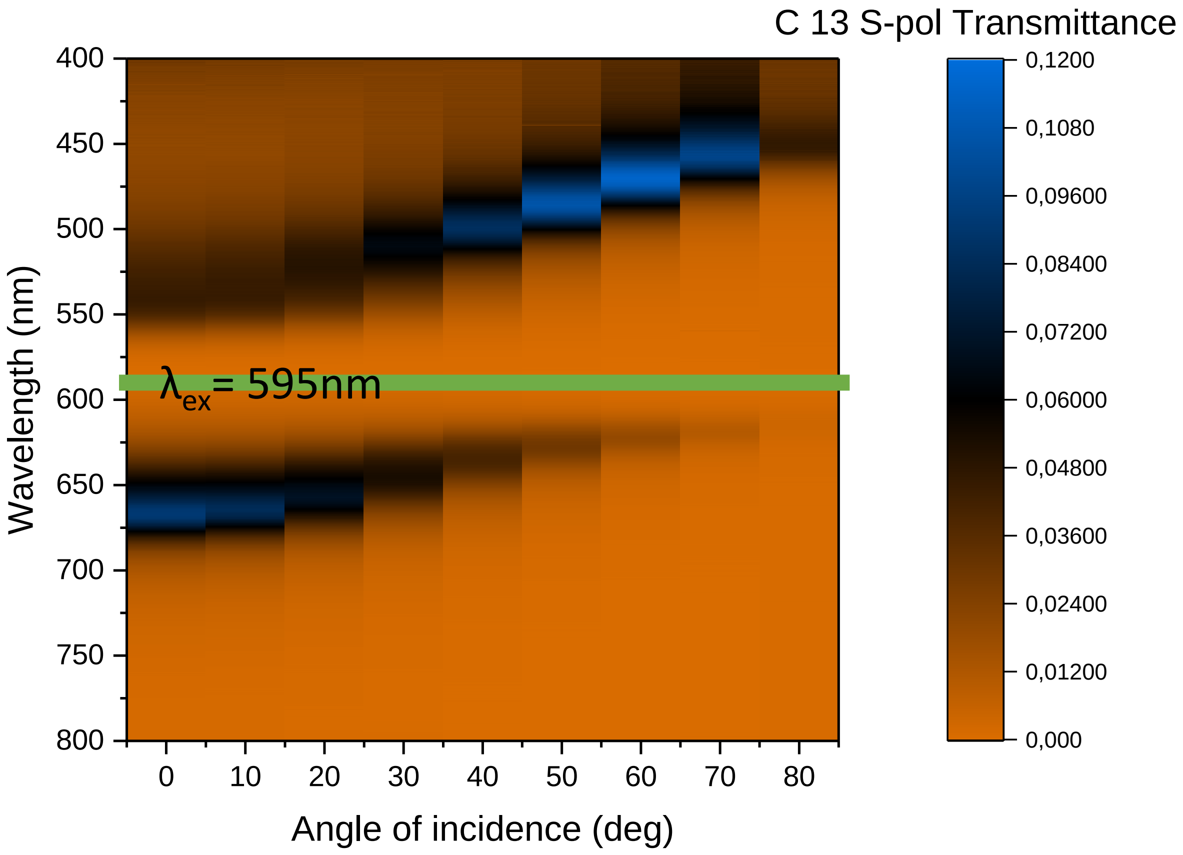
Layer #	Material	Thickness nm
Medium	Air	
1	Ag	27 nm
2	Acrylic	145 nm
3	Ag	27 nm
4	BK7	1000000 nm
Substrate	Air	

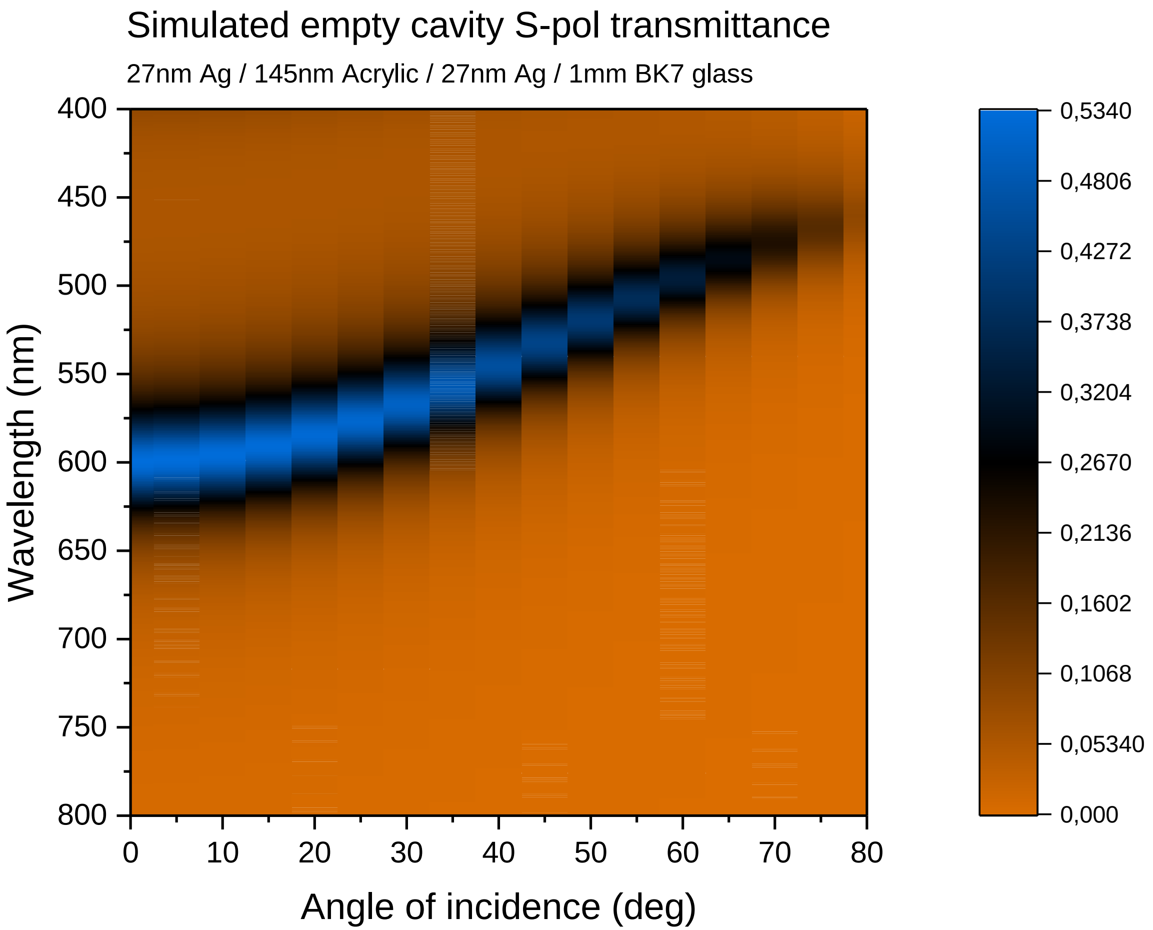


Strong coupling in cavities

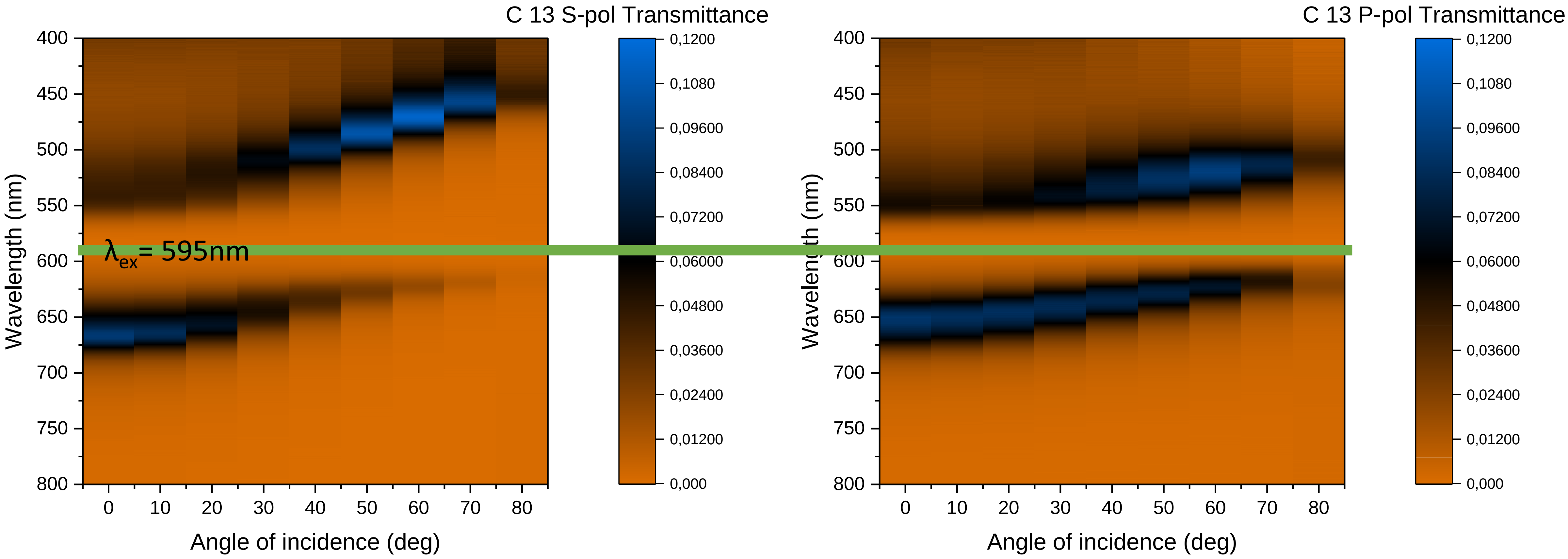


Strong coupling in cavities





Strong coupling in cavities



Strong coupling in cavities

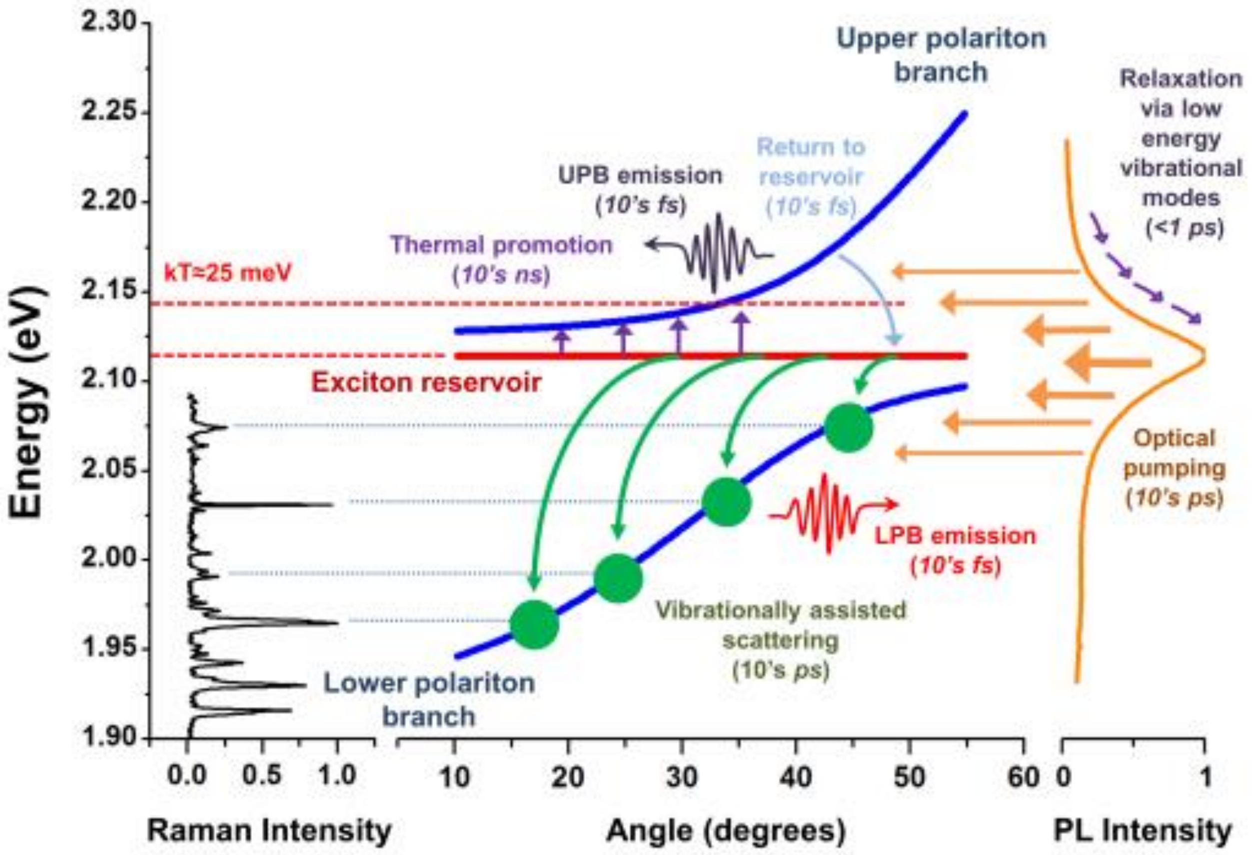


Fig. 1.11 Schematic of the important processes involved in populating the polariton branch states.

Lidzey, D. G., & Coles, D. M. (2015). Strong Coupling in Organic and Hybrid-Semiconductor Microcavity Structures. In D. Comoretto (Ed.), *Organic and Hybrid Photonic Crystals* (pp. 243–273). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-16580-6_11

Measurement systems

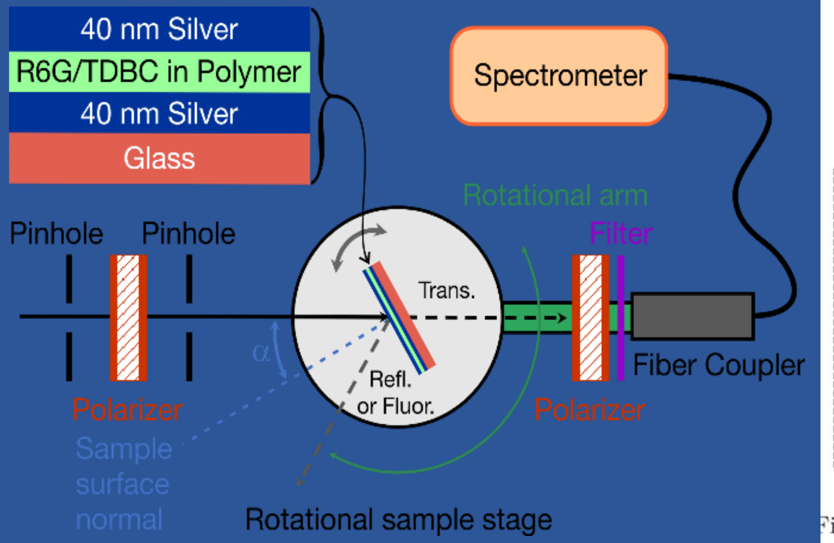


Figure 1: Schematics of the experimental measurement setup and the sample structure

Hulkko, E.; Pikker, S.; Tiainen, V.; Tichauer, R. H.; Groenhof, G.; Toppari, J. J.; (2021). Effect of molecular Stokes shift on polariton dynamics. The Journal of Chemical Physics, 154, 154303–154303. DOI: 10.1063/5.0037896.

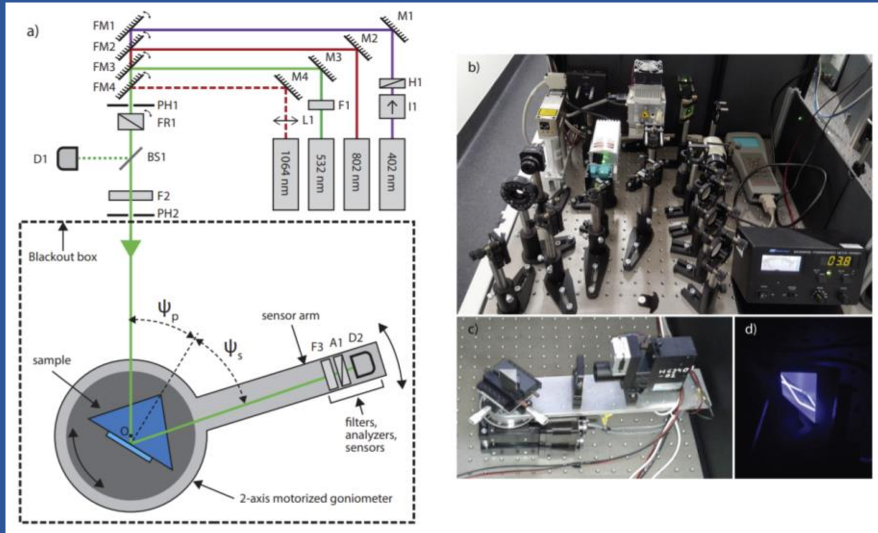
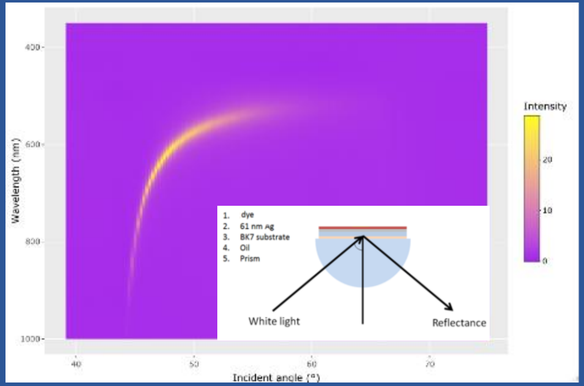
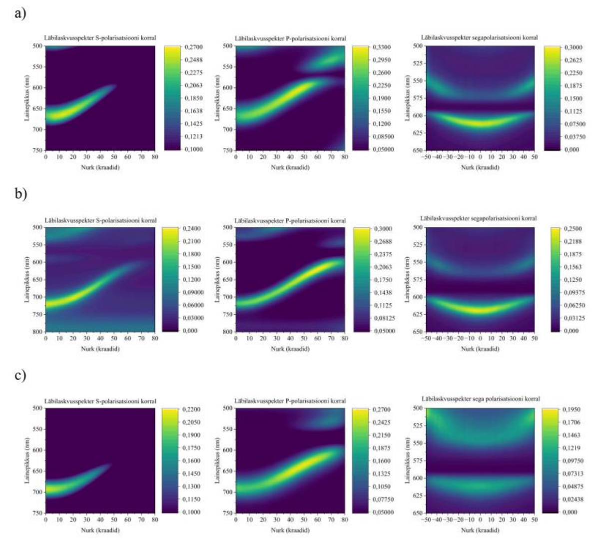


Figure 3.5: The schematic of the goniometric setup (a) and the pictures of the lasers (b), goniometer with lock-in detection system (c) and N-SF11 prism under illumination of violet laser. [II]

Enhanced spontaneous parametric down-conversion in plasmonic and dielectric structures (Ardi Loot); University of Tartu; 2018



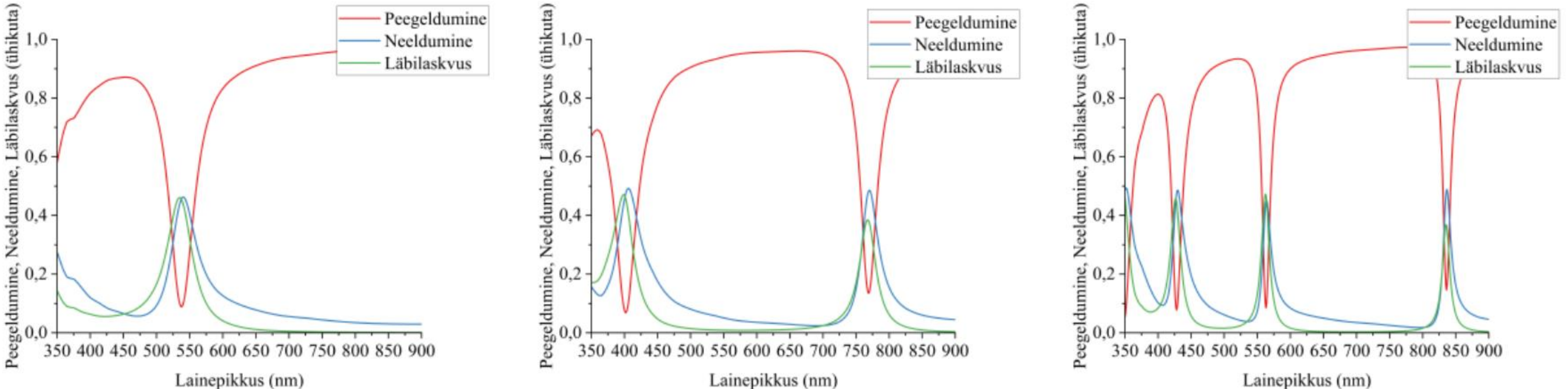
Fabrication, characterization and application of Fabry-Pérot type resonators in the study of strong coupled systems (Elizaveta Dmitrijeva); University of Tartu; 2024



The Problem and what did we do?

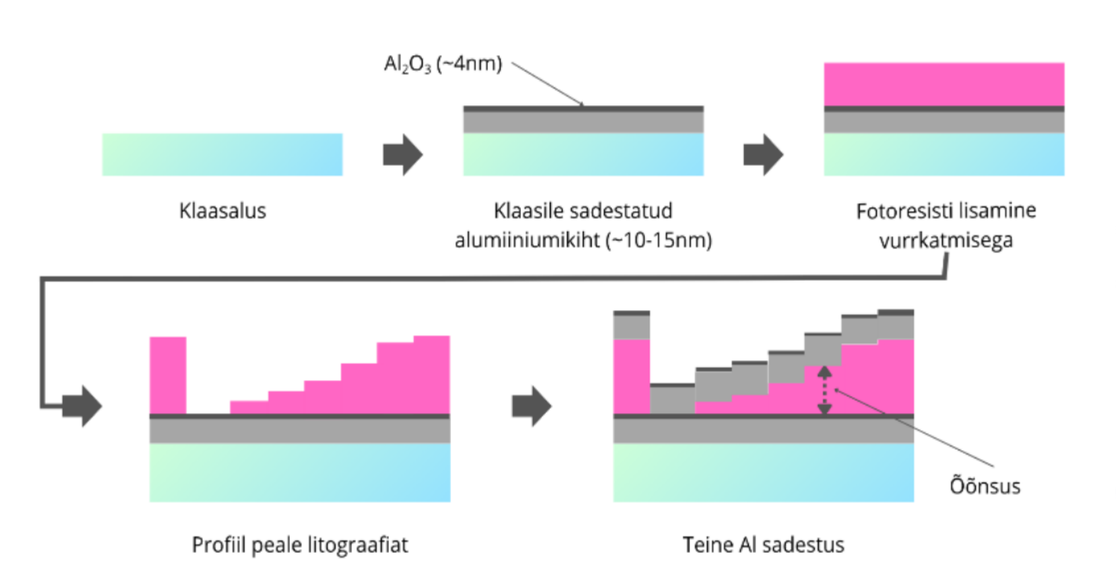
Cavity fabrication = mirror on substrate + spin coating + top mirror

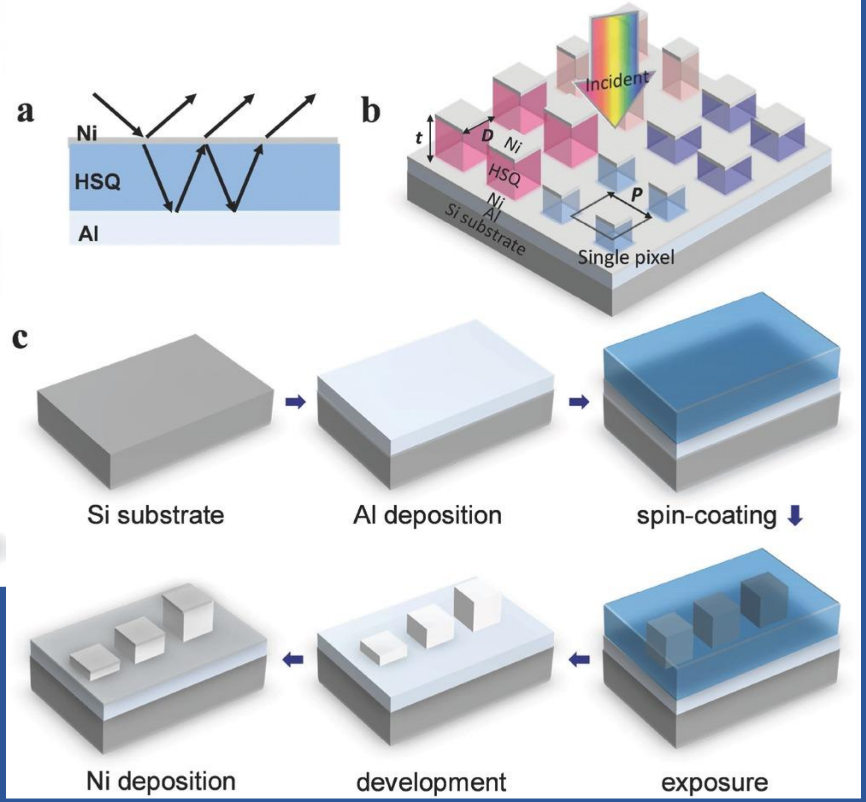
… if you are fast and setup allows ca 1h+1h+1h=**3h** for one cavity
When wrong then what? → ANOTHER 3h for 1 sample
Why not many different cavities on 1 sample at once?



The Problem and what did we do?

Why not many different cavities on 1 sample at once?

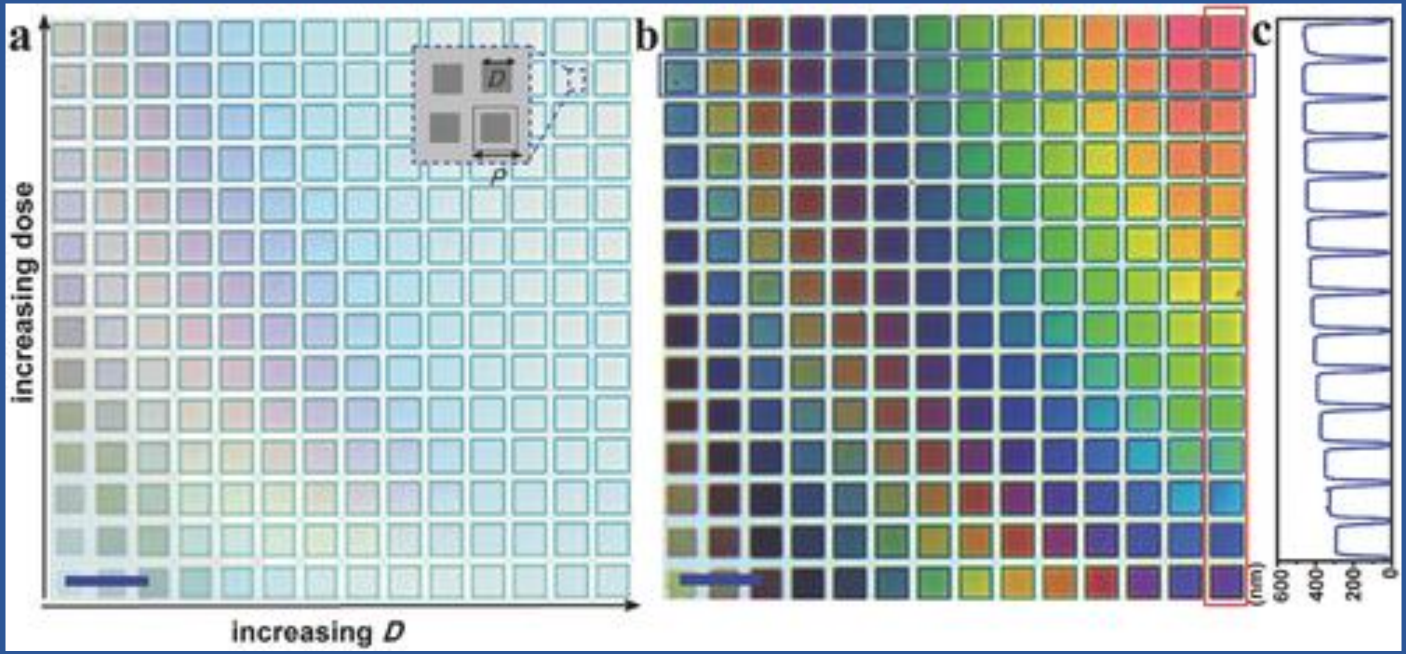


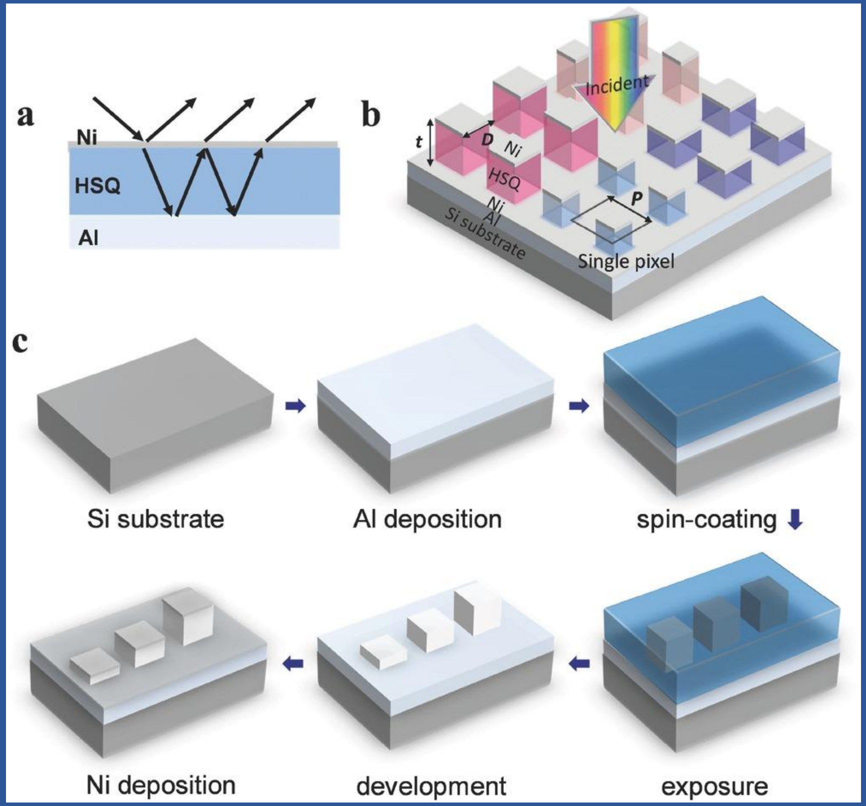


https://doi.org/10.1002/adom.201700029

The Problem and what did we do?

Not done for highly doped photoresist material !





https://doi.org/10.1002/adom.201700029

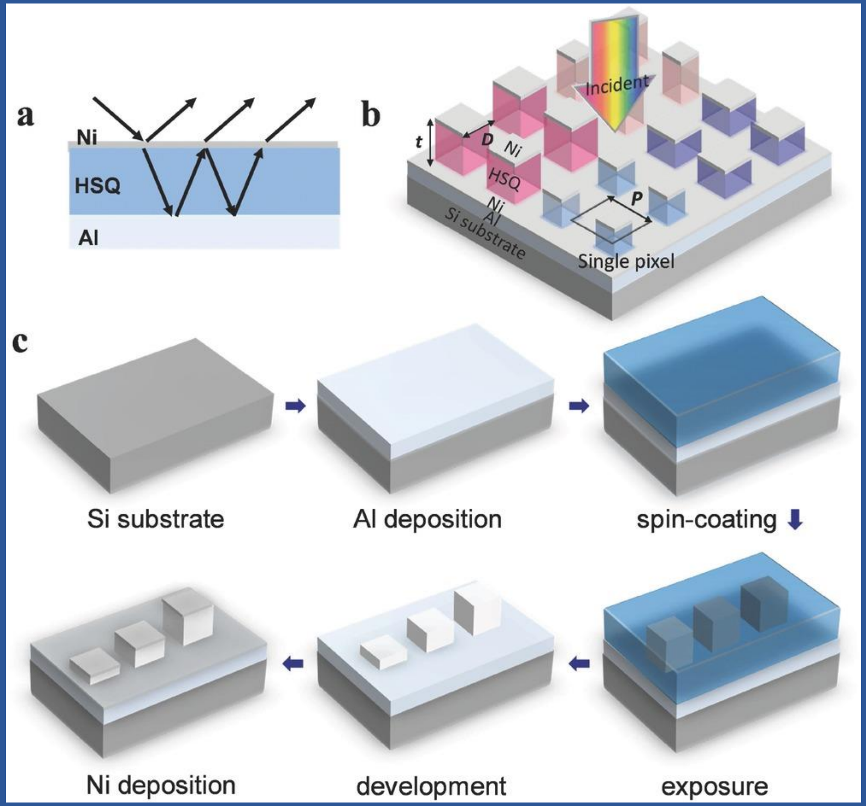
The Problem and what did we do?

Not done for highly doped photoresist material !

Why?

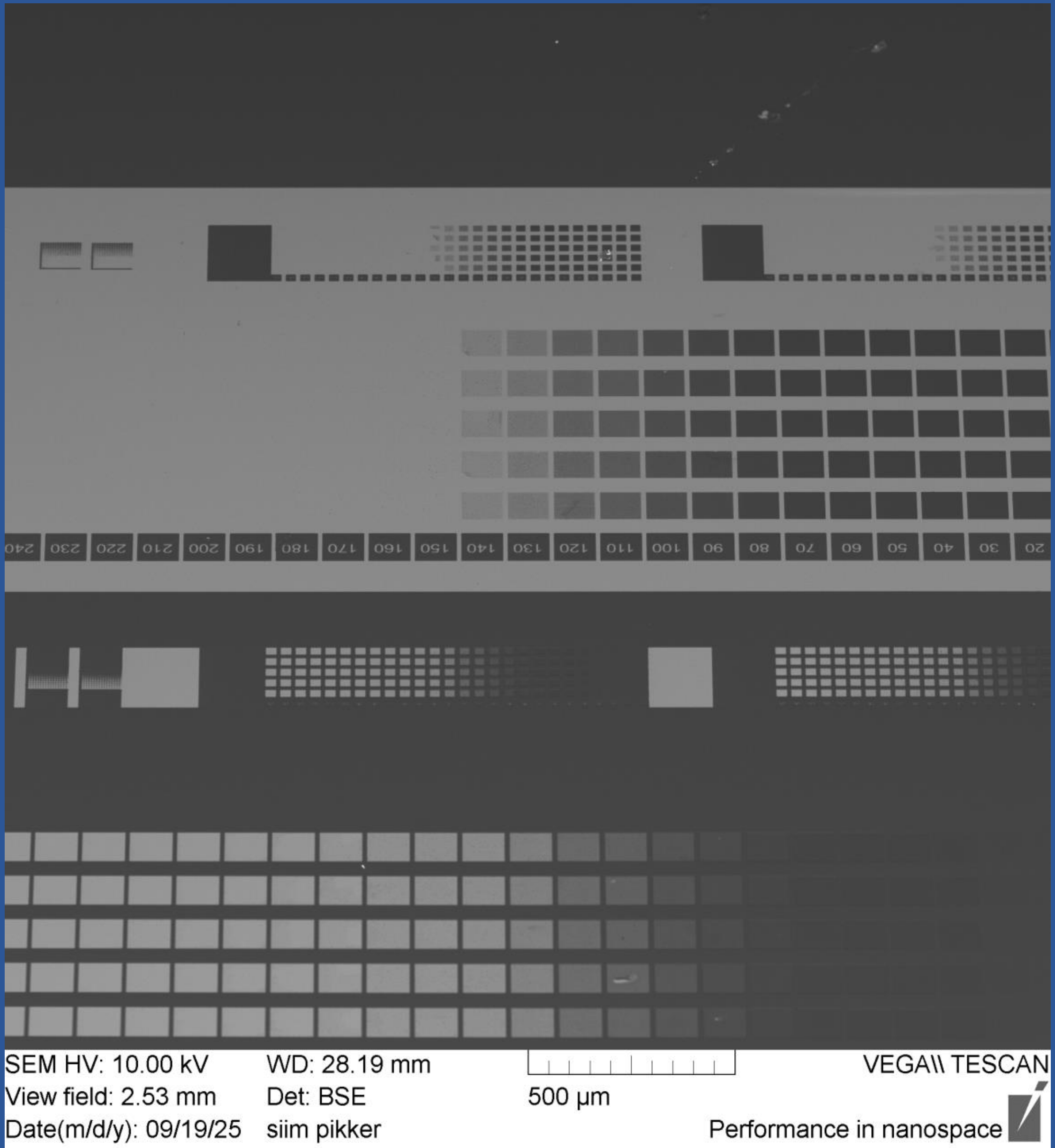
High dye concentration → 1 to 15% dye in polymer
Solubility problems
Film quality issues
Reduced photoresist performance
…

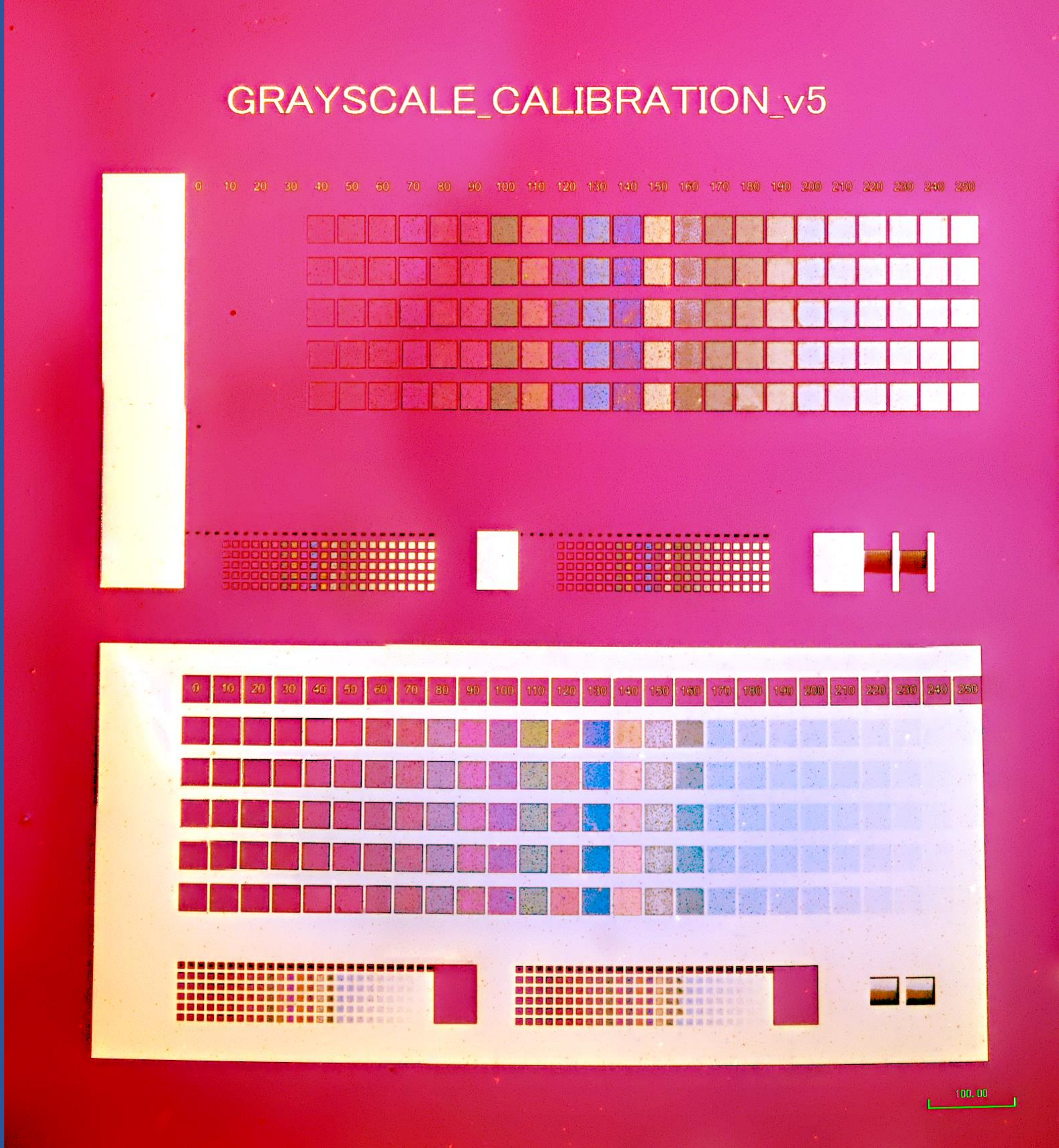
Dyes make it more difficult!



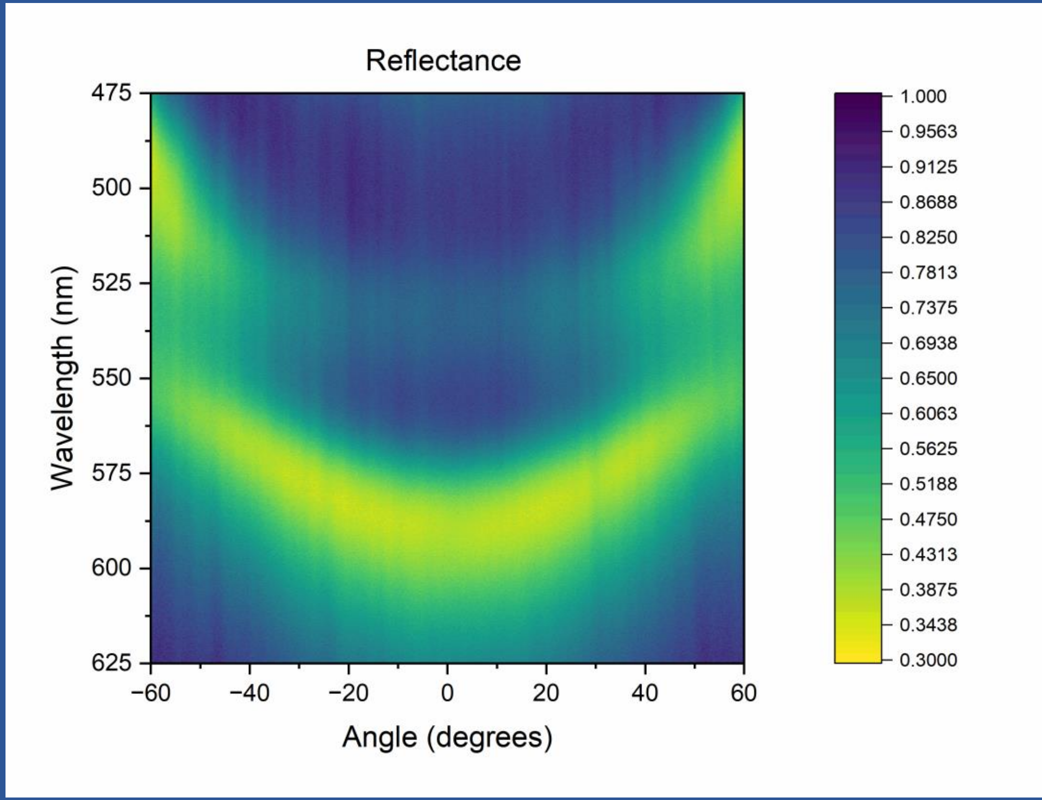
https://doi.org/10.1002/adom.201700029

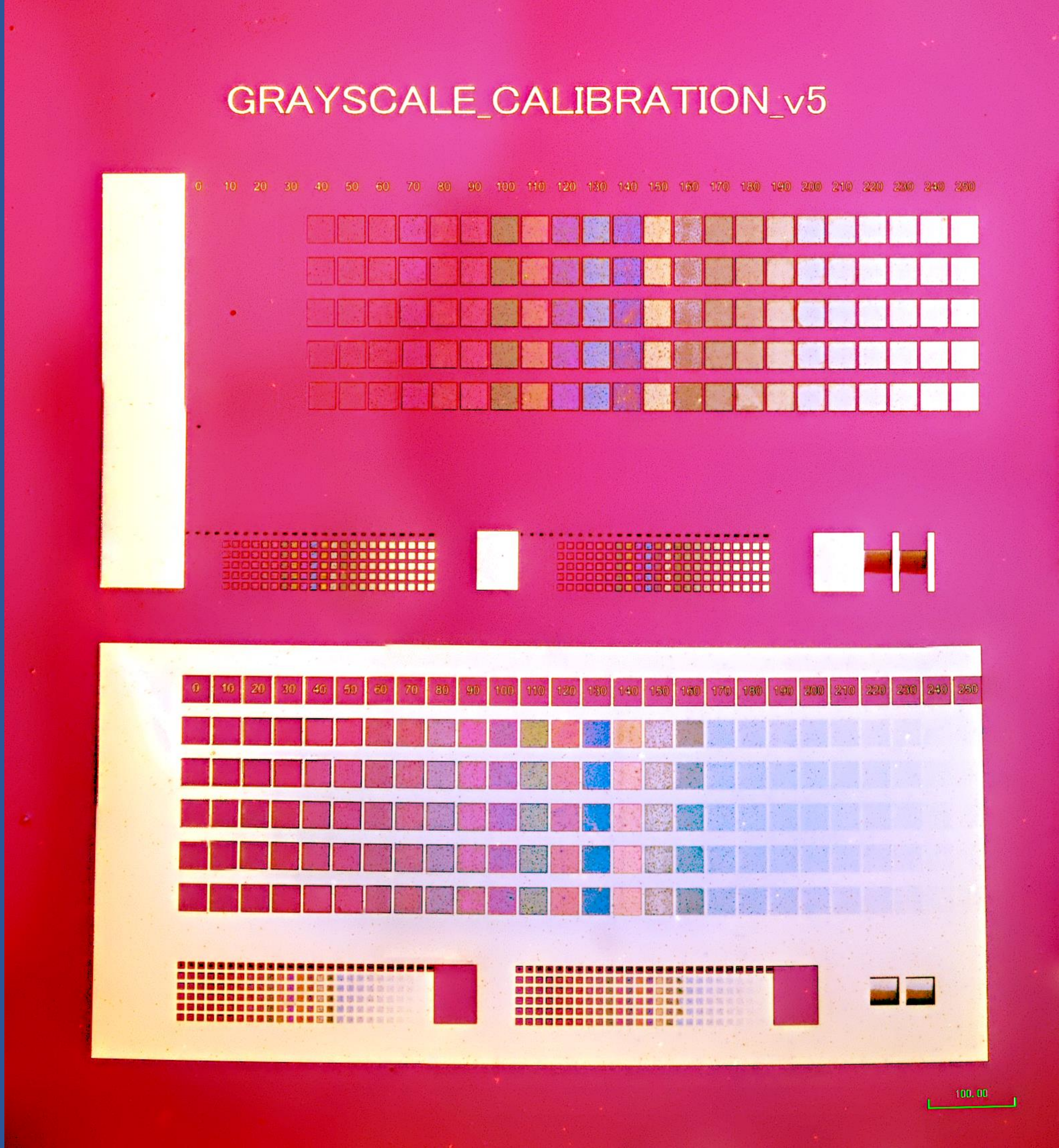
Difficult is not impossible!





Difficult is not impossible!





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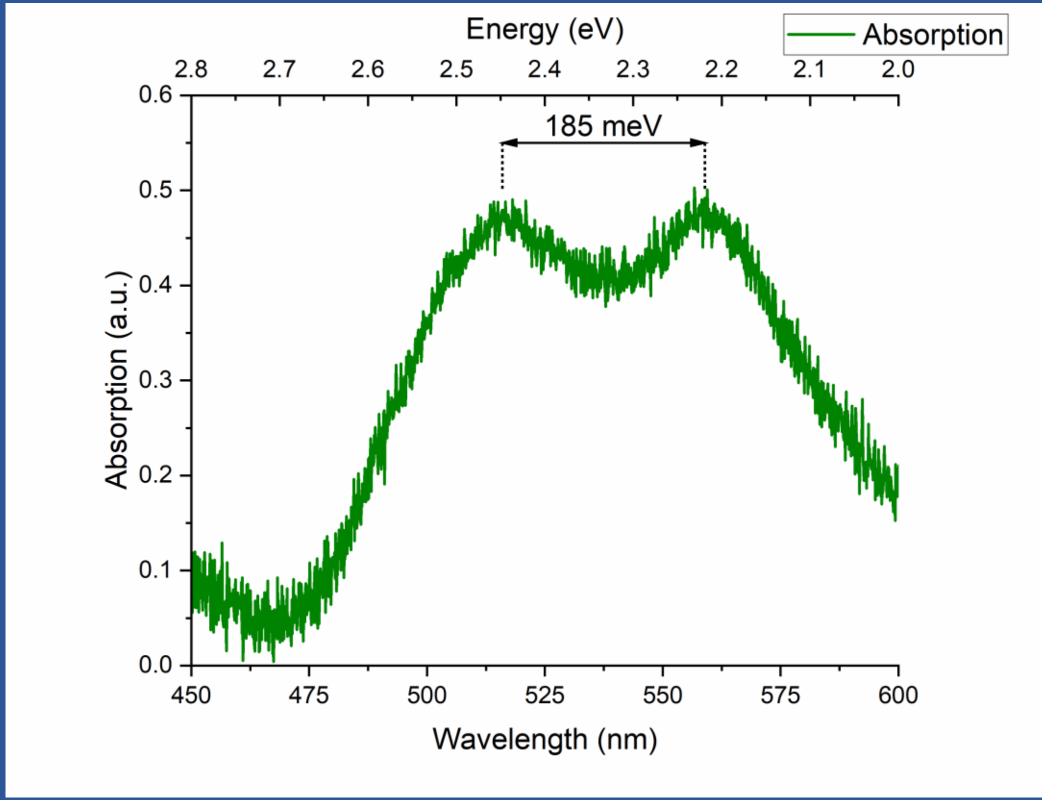

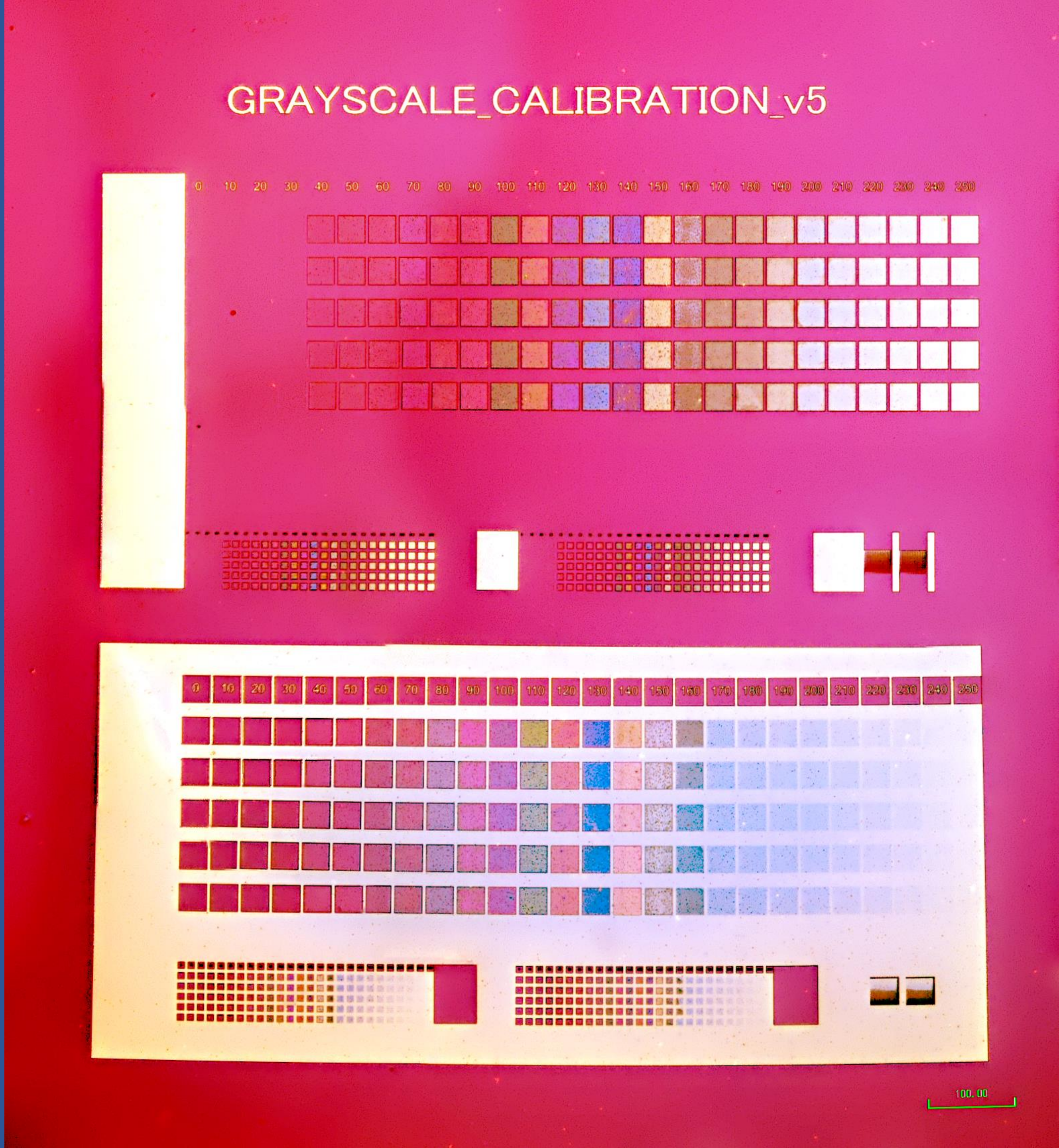

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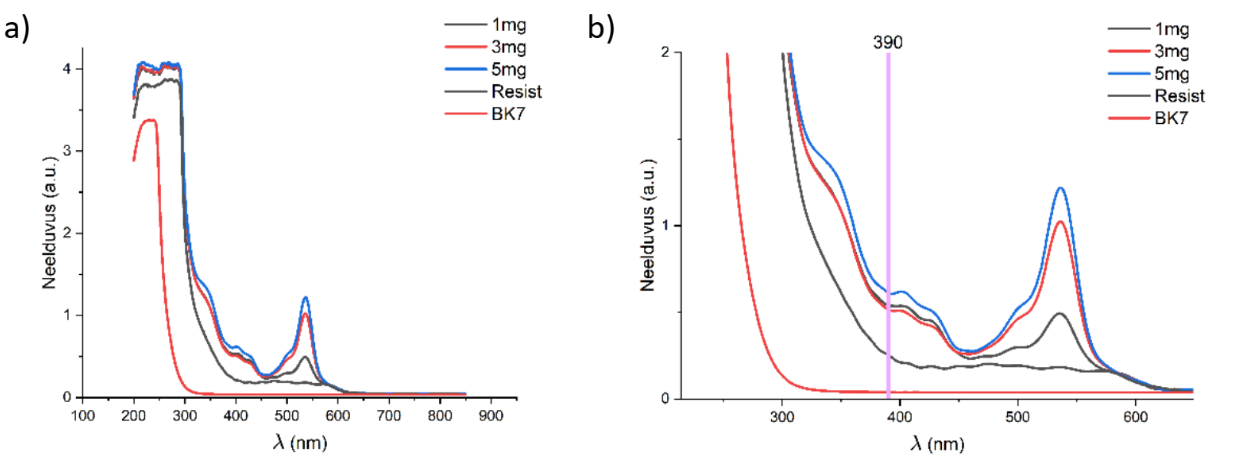

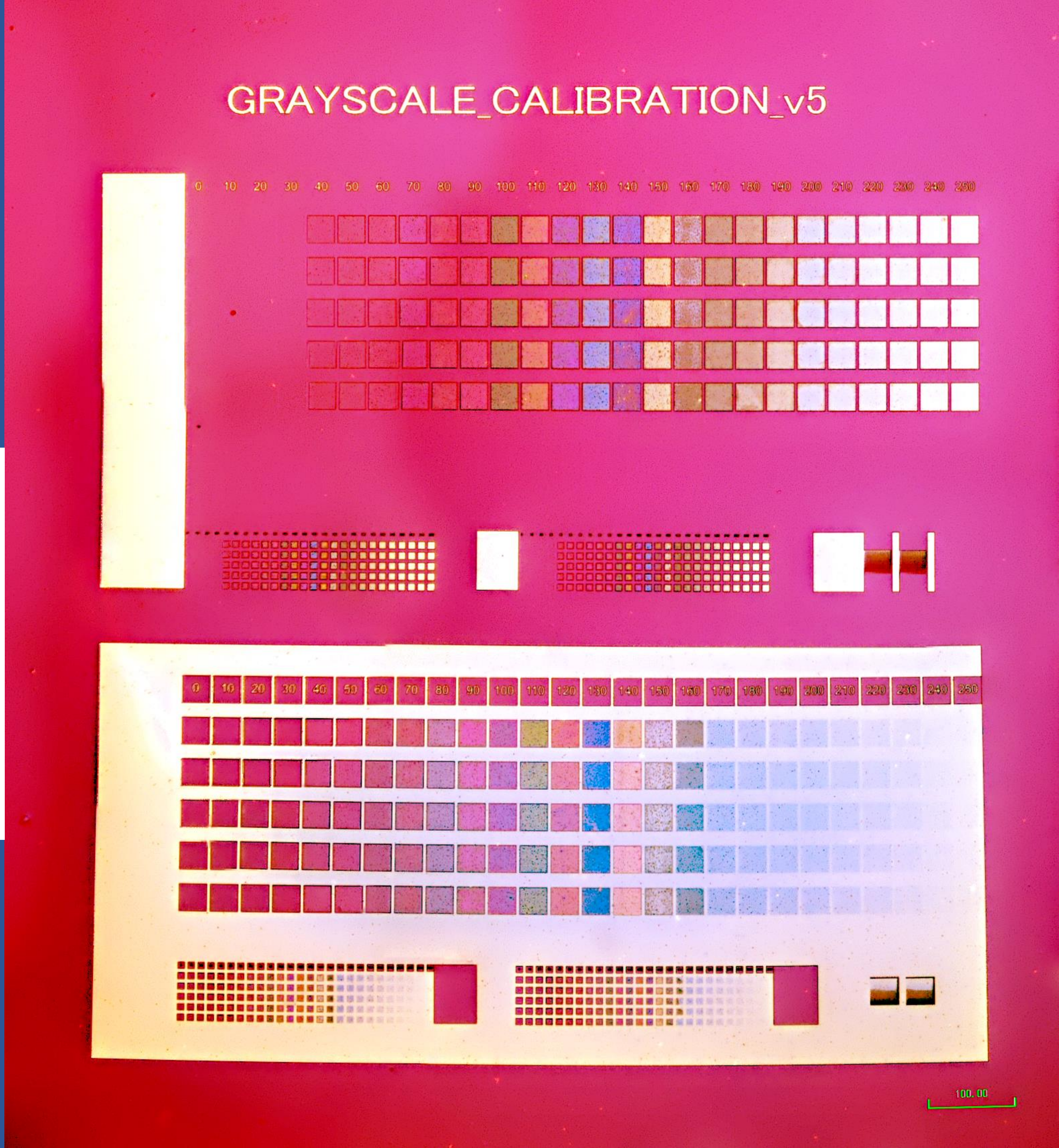

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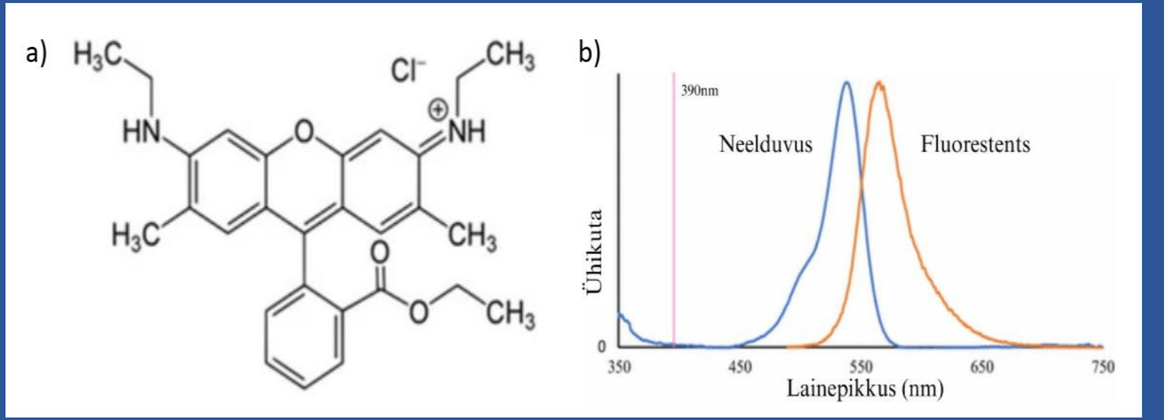

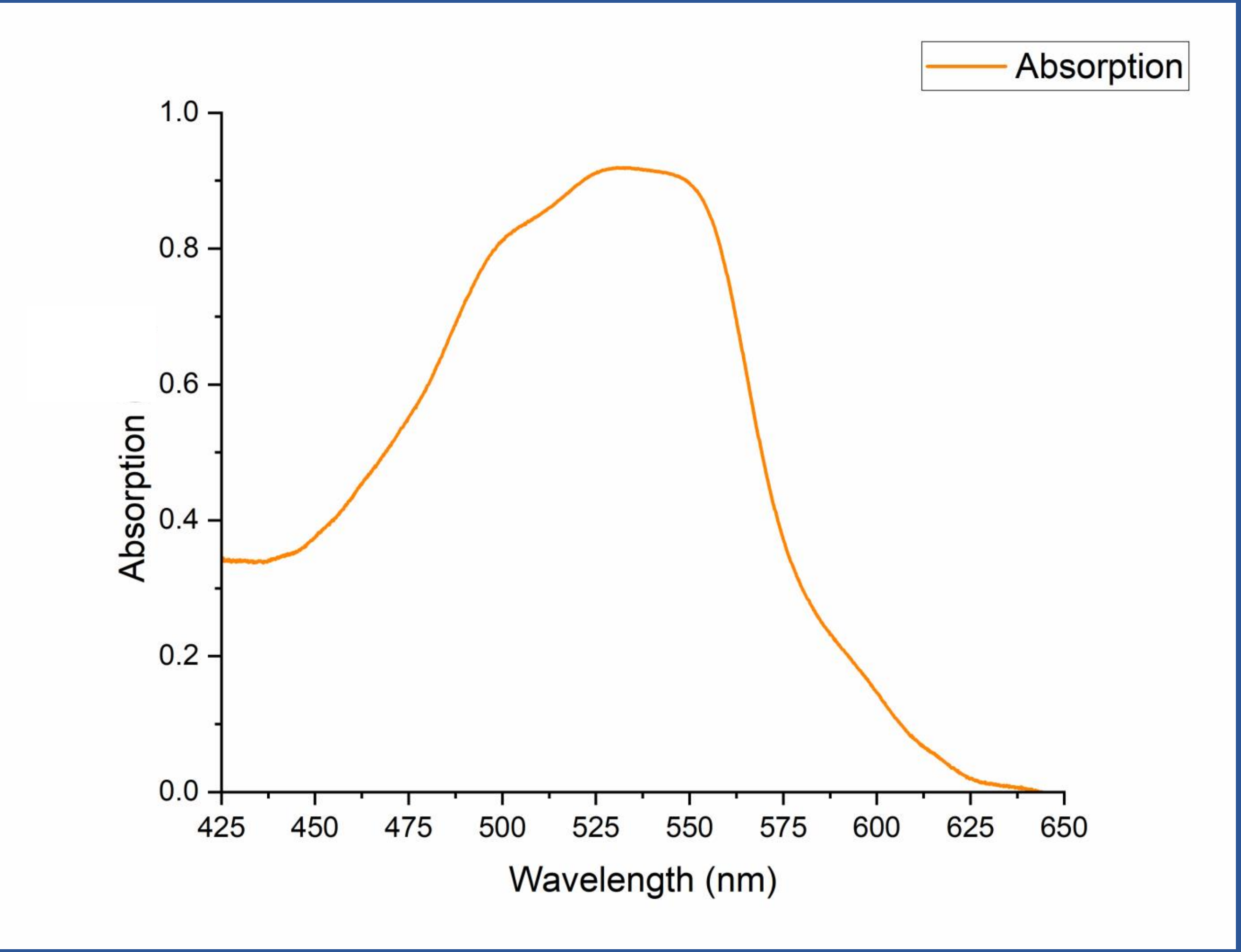

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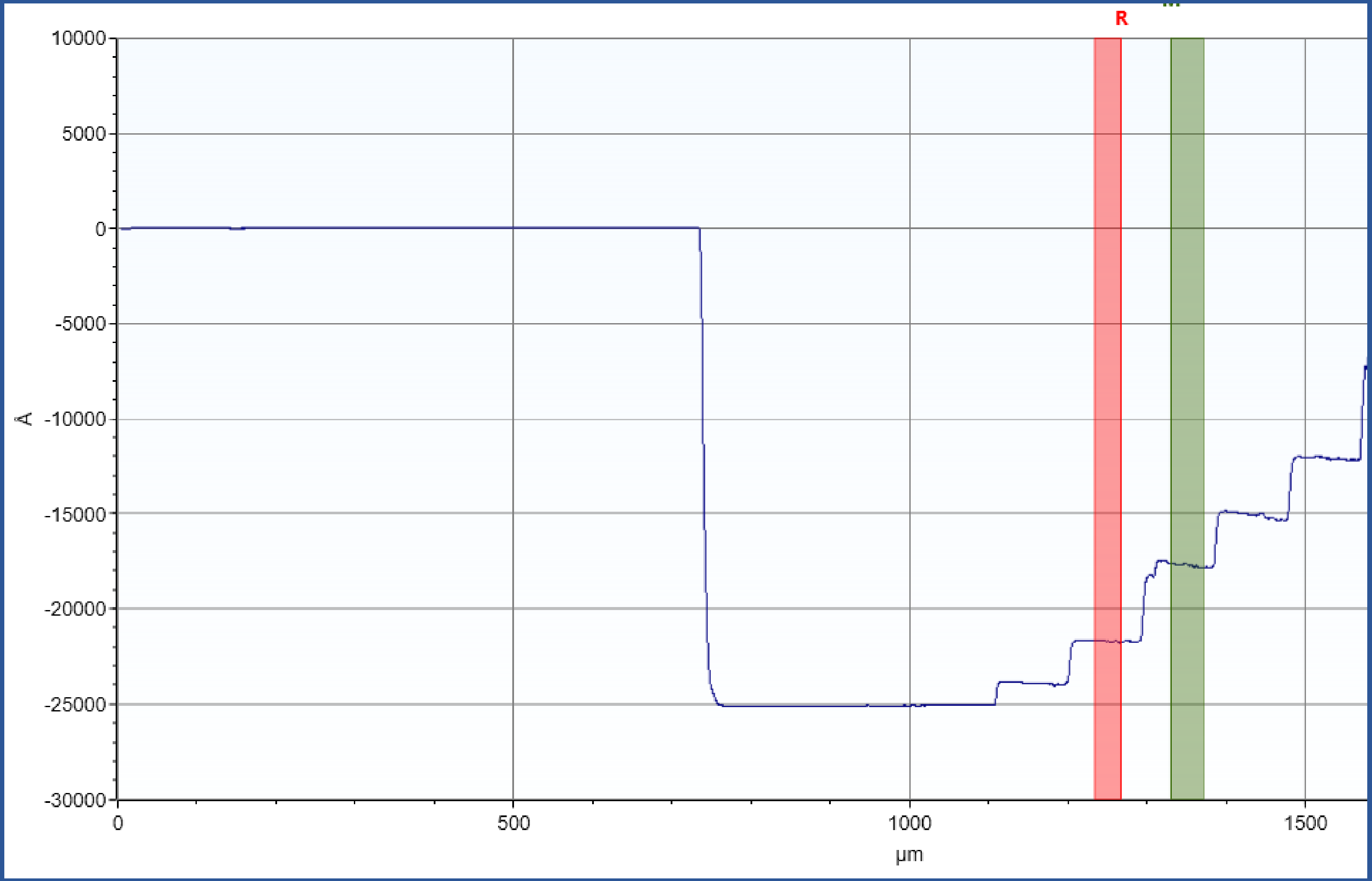

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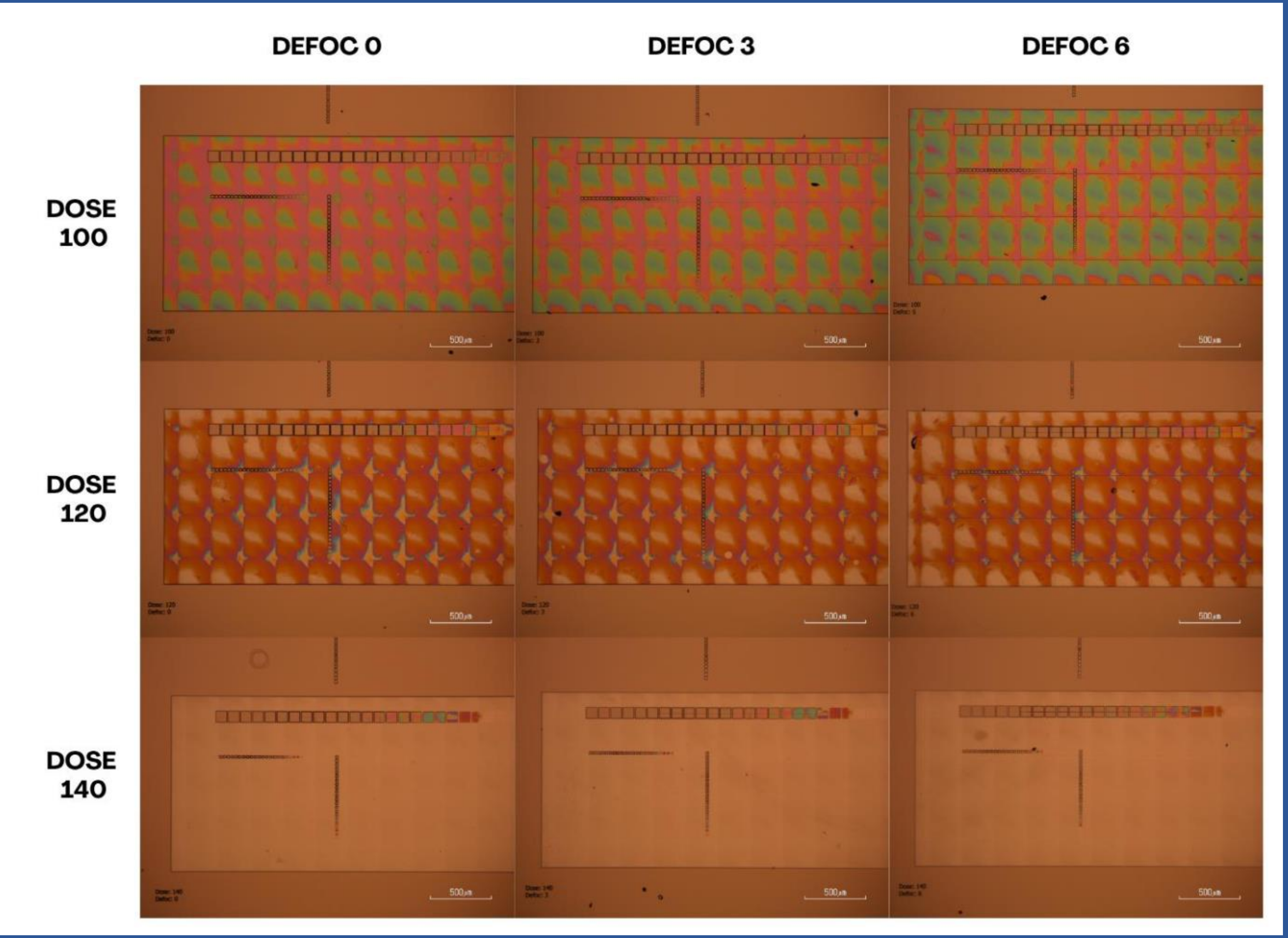

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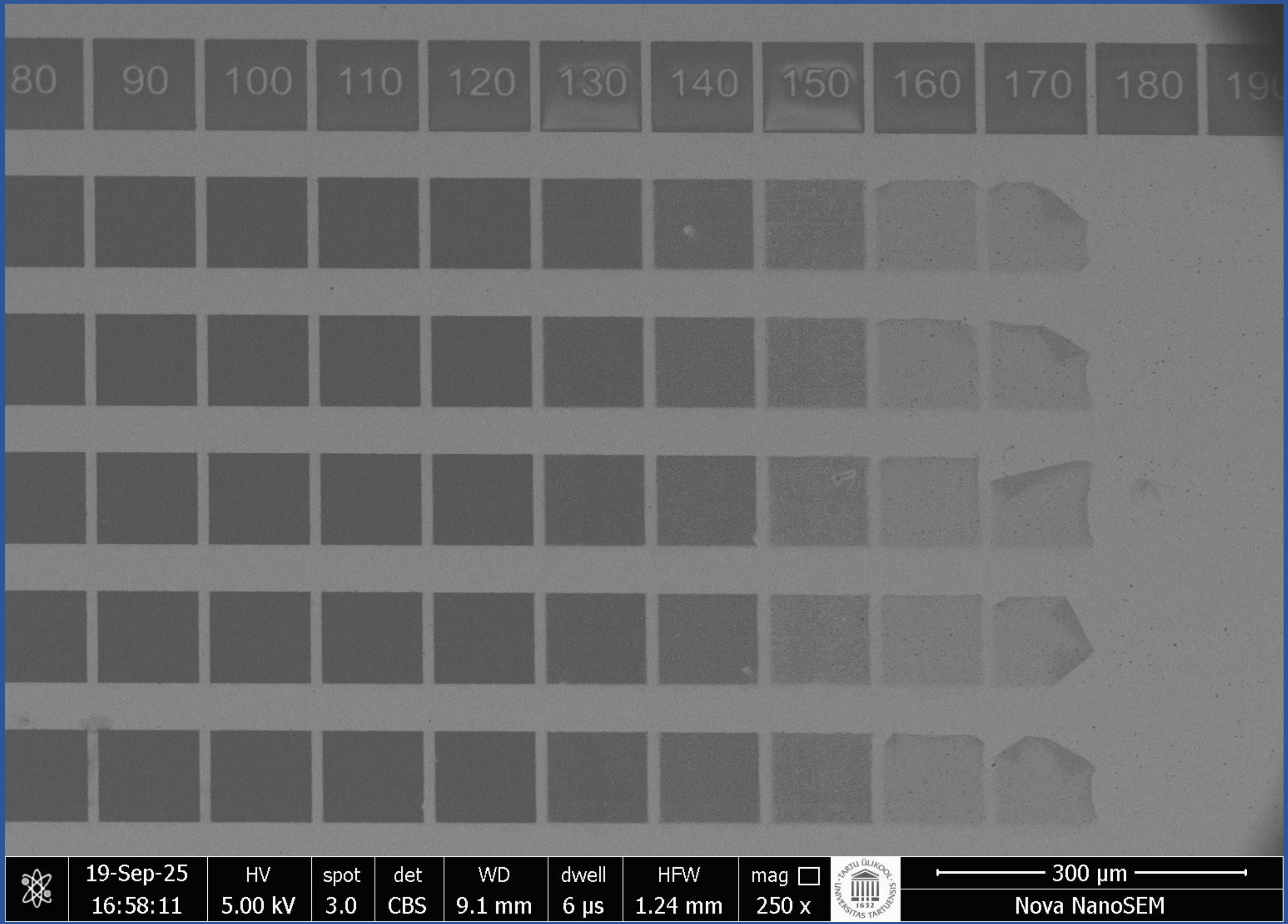

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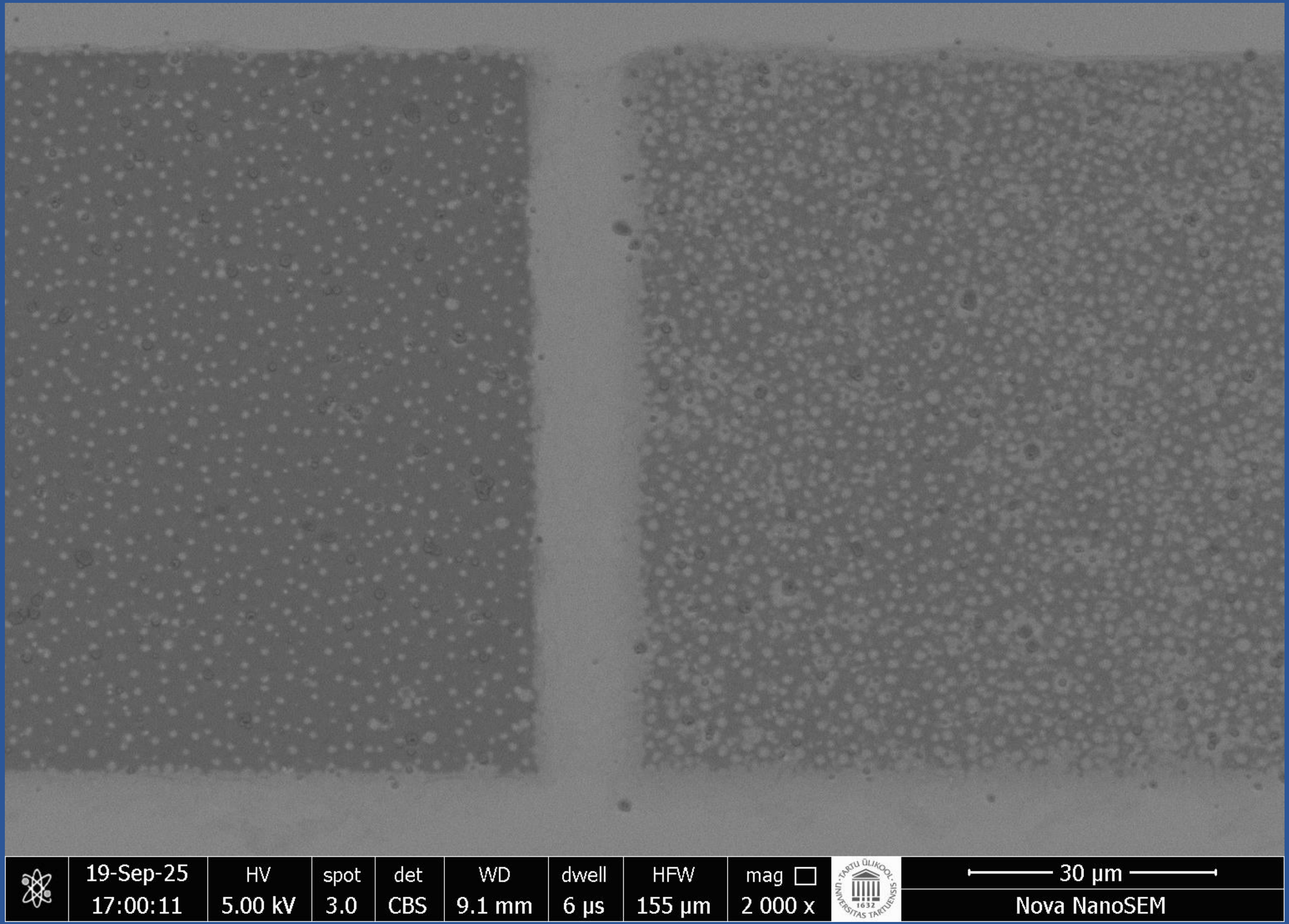

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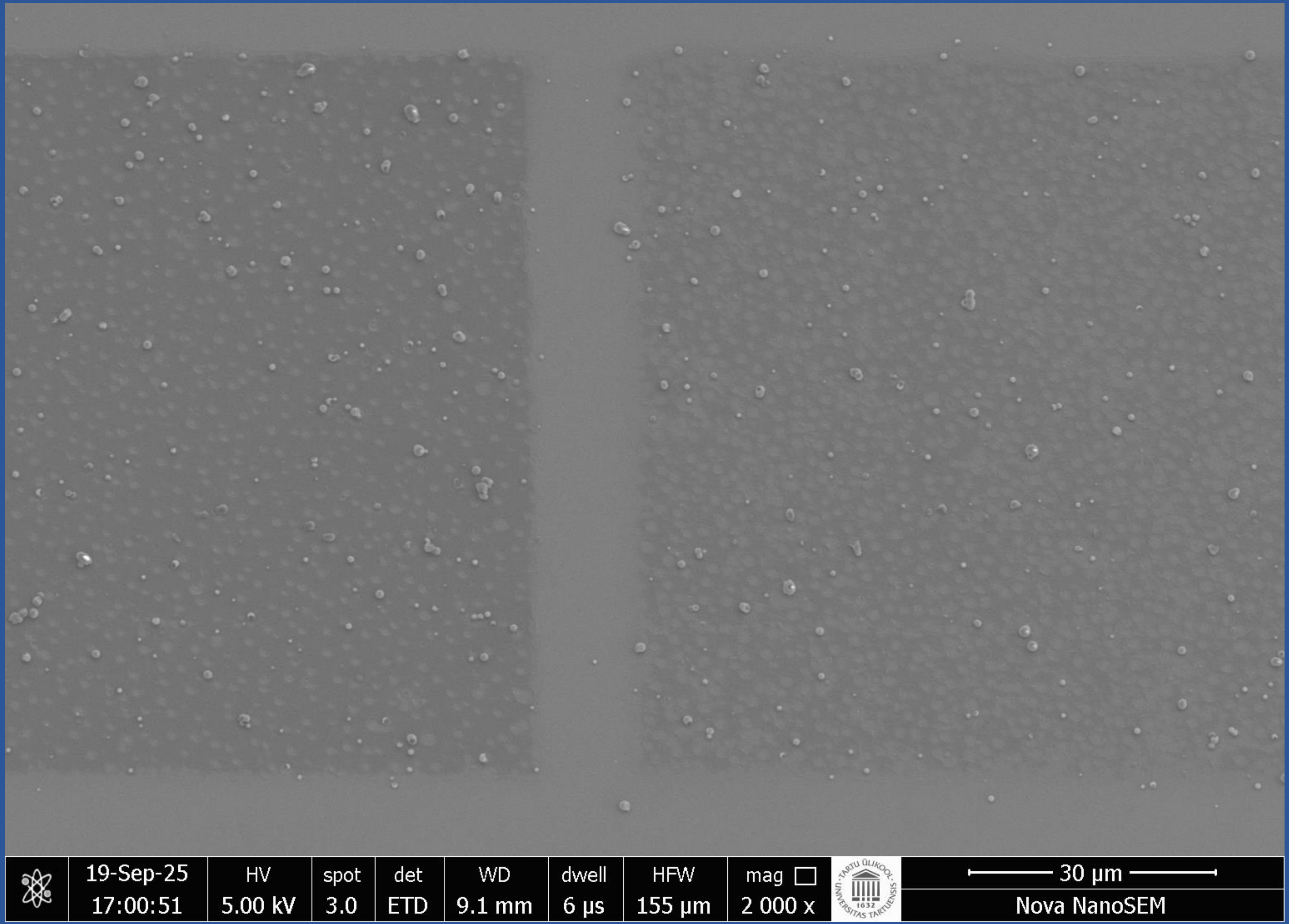

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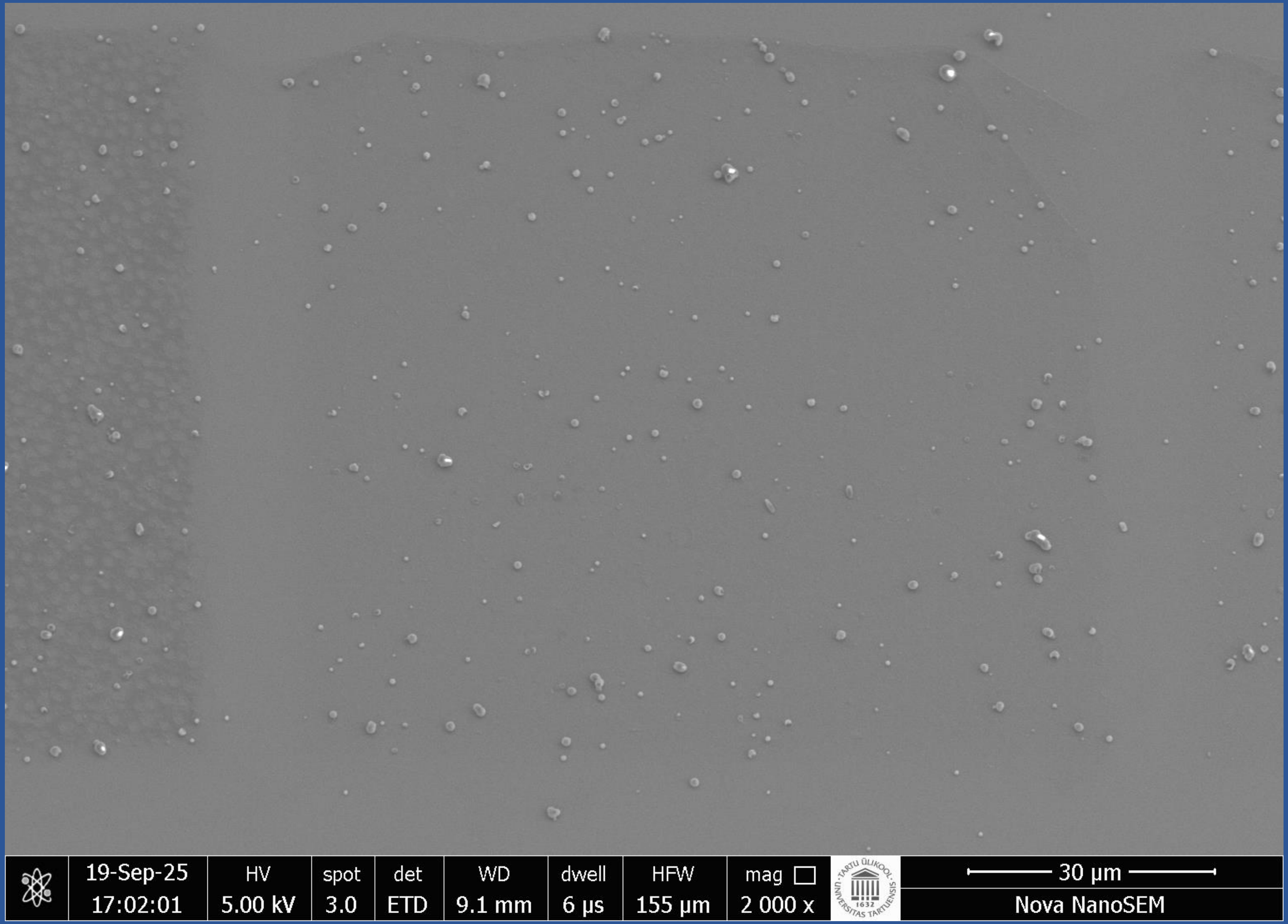

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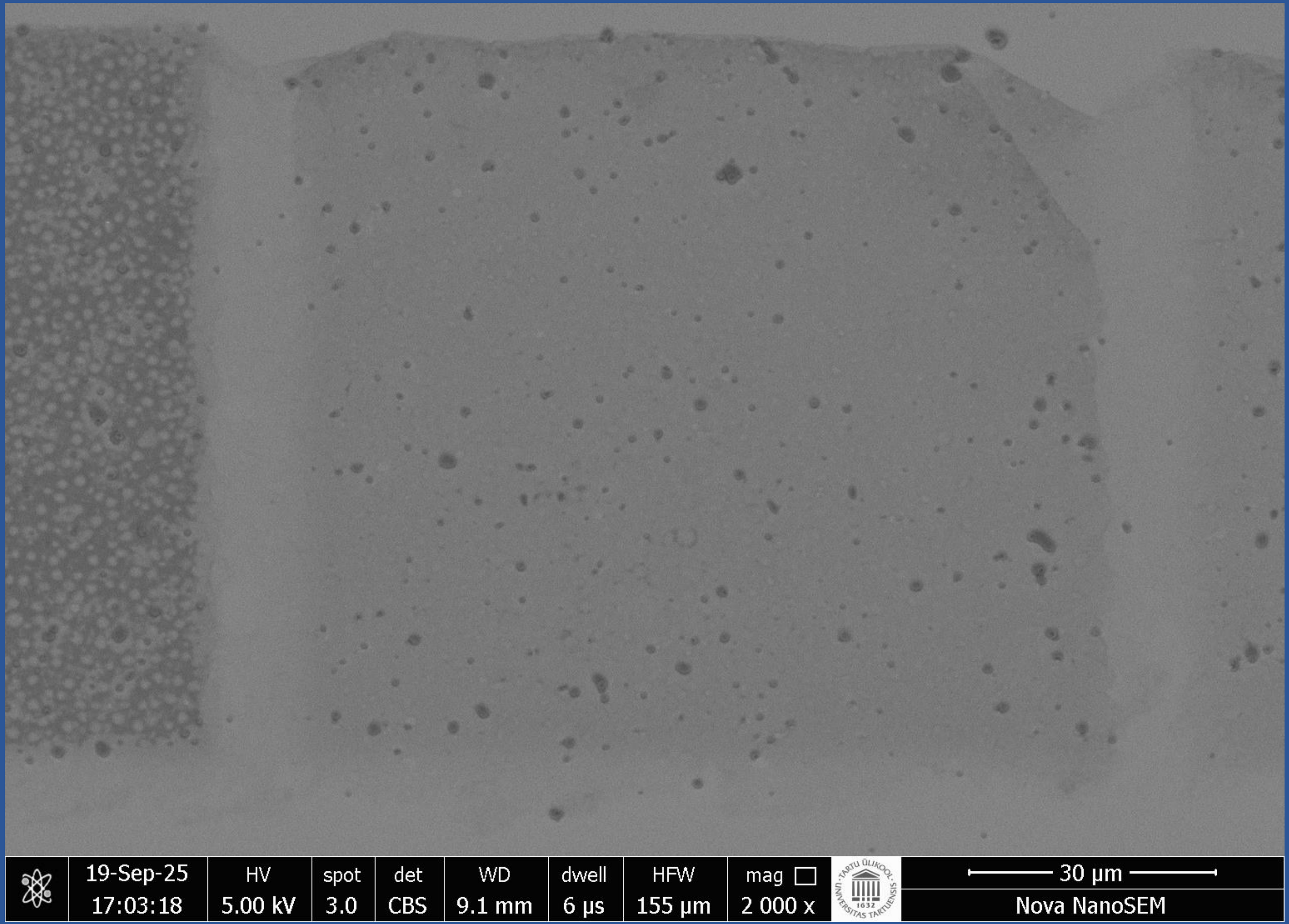

Publication soon!

nature

… be prepared! ☺

Ackwnolegments

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Ackwnolegments

Thank you!

Täname!

Thank you!