Friedrich-Alexander-Universität
Technische Fakultät

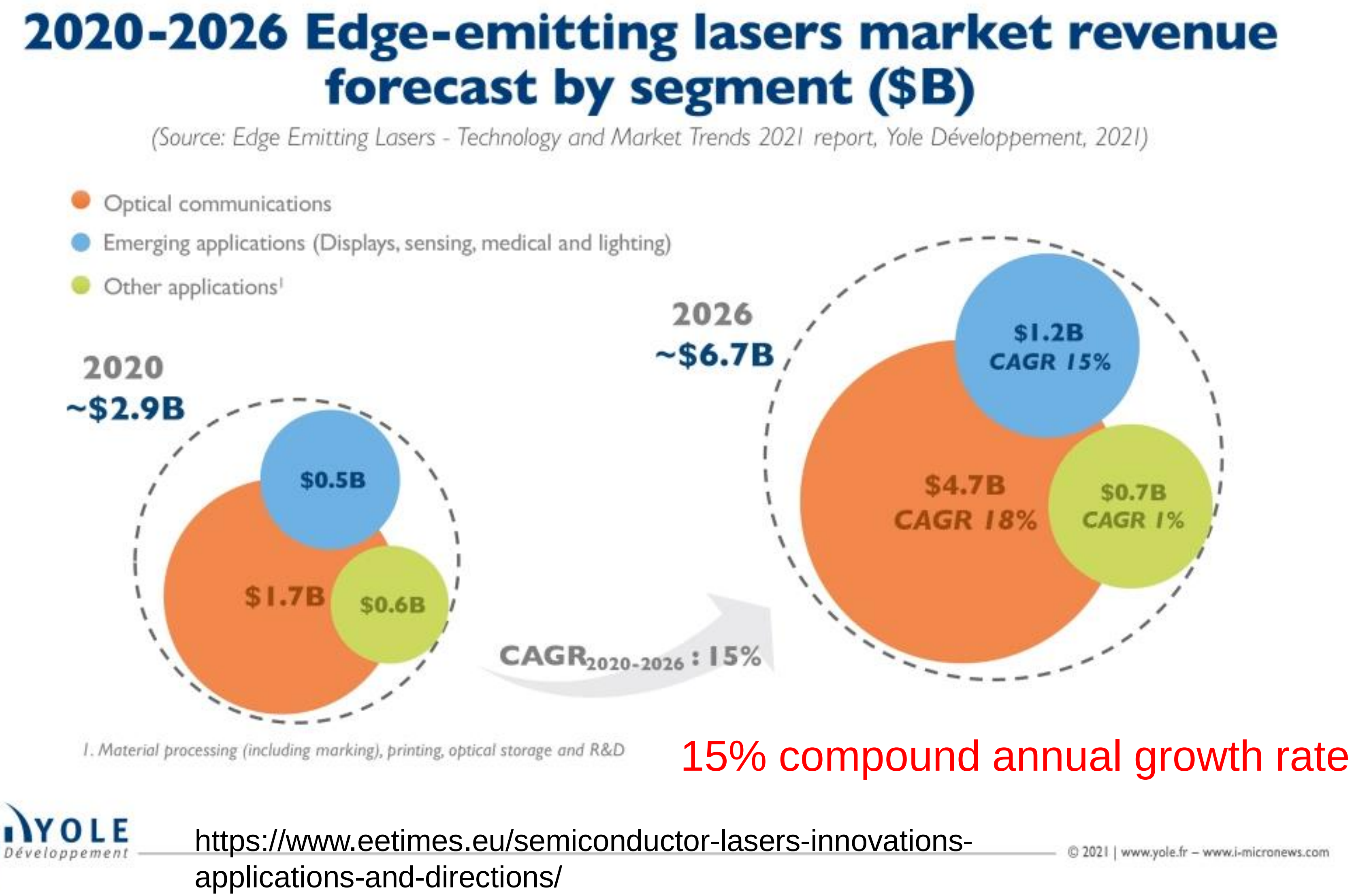
Epitaxial lead-halide-perovskite microcrystal microcavity lasers

Wolfgang Heiss

Semiconductor laser forecast

Short Summery About Solar Cells and Modules Market:

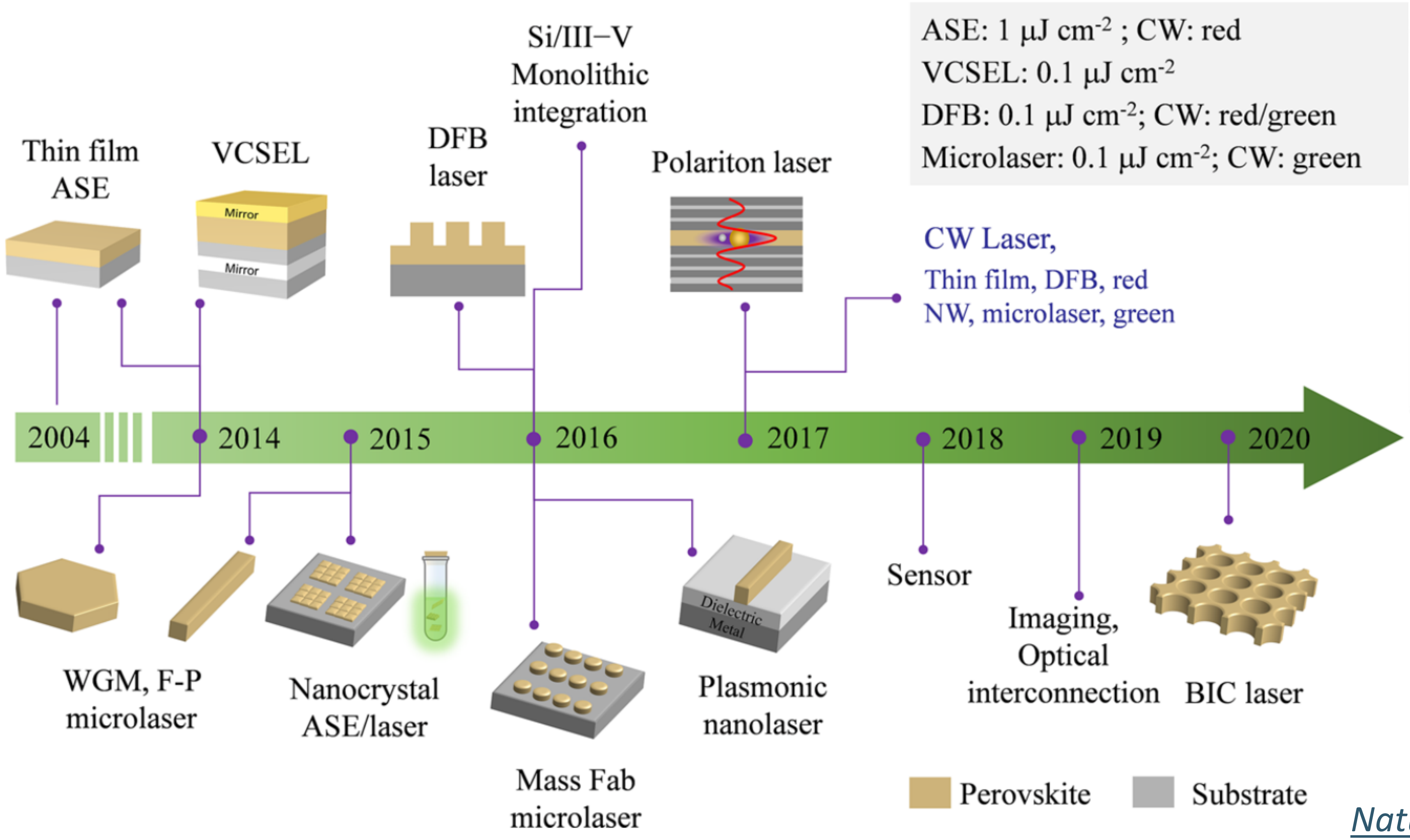
The Global Solar Cells and Modules market is anticipated to rise at a considerable rate during the forecast period, between 2024 and 2032. In 2024, the market is growing at a steady rate [CAGR of 9.2%] and with the rising adoption of strategies by key players, the market is expected to rise over the projected horizon.

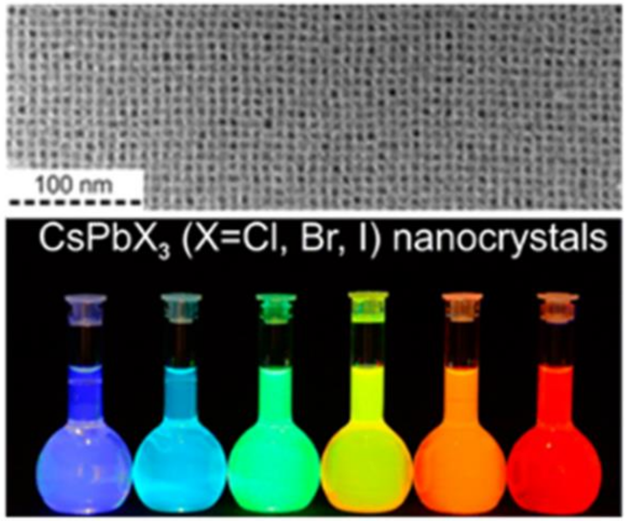


15% compound annual growth rate

https://www.eetimes.eu/semiconductor-lasers-innovations-applications-and-directions/

Perovskite lasers





Yakunin,

Protesescu,

….

Heiss,

Kovalenko

Nature Communications **6**, 8056 (2015)

Q. Zhang et al., Nano Lett. 2021, 21, 1903-1914

Contens

2022

a) Solution epitaxial lasers rivaling vapor phase deposited ones.

b) Squeezing the threshold of microcrystal microcavity laser

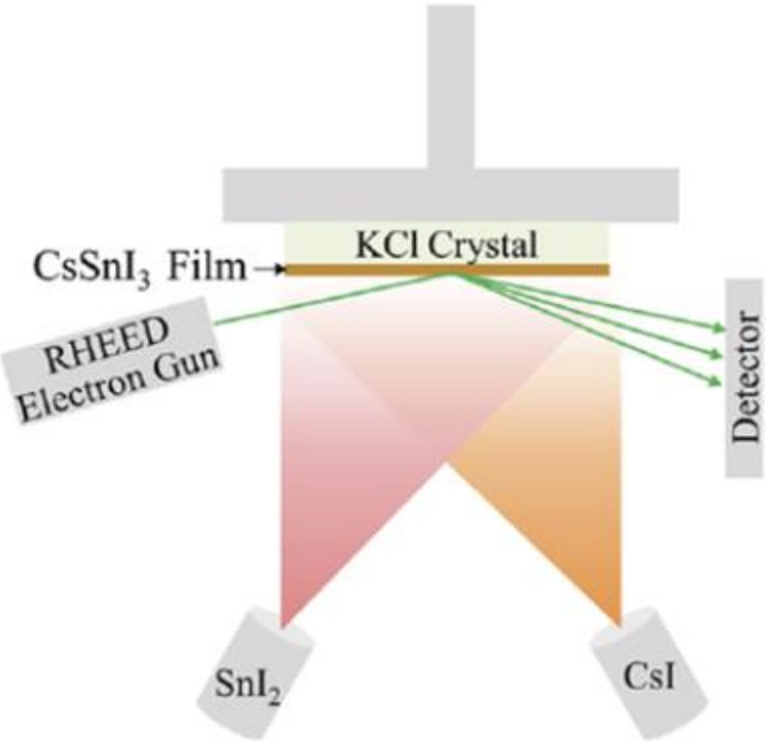
c) Surface passivation of epitaxial microstructures

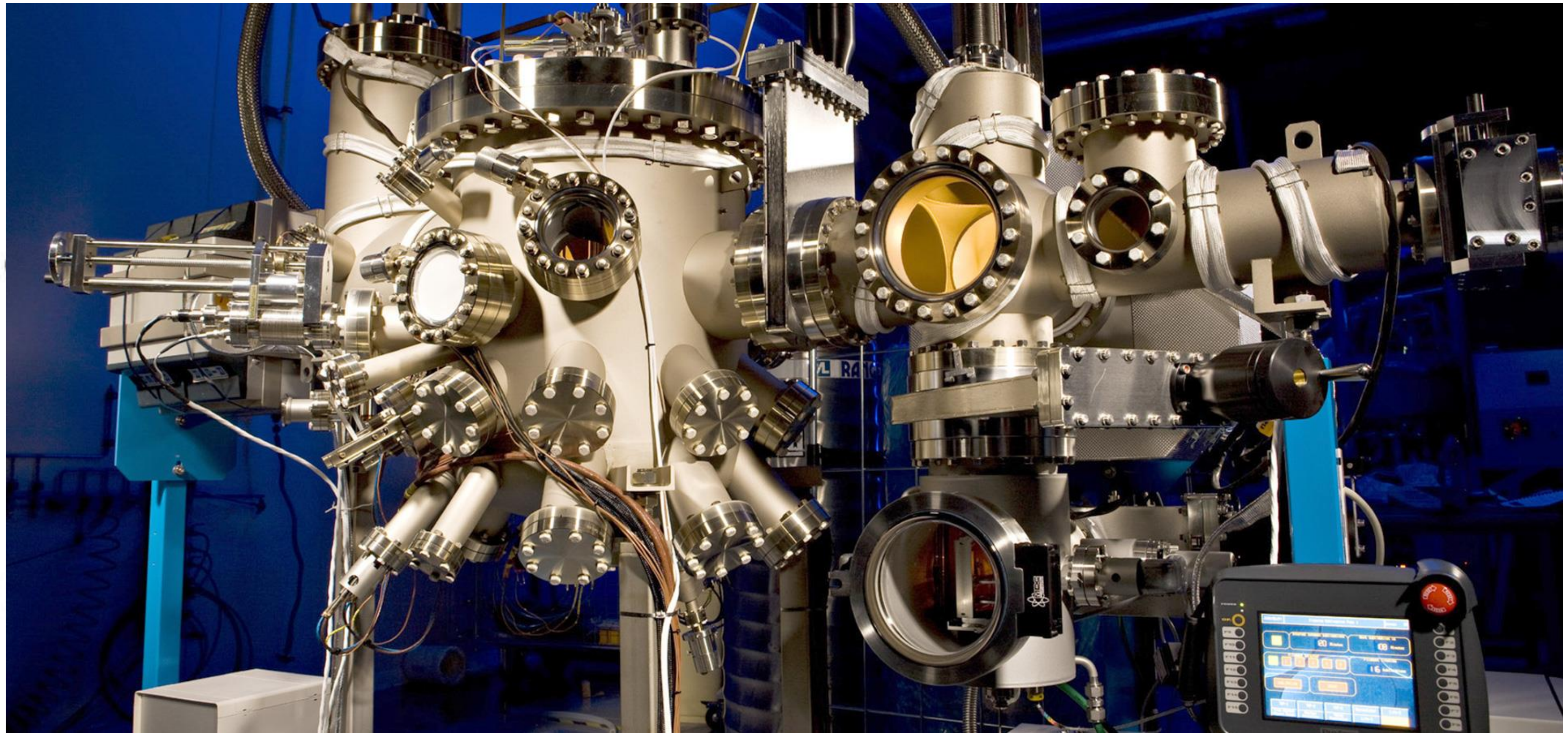
d) Positioning of perovskite microcrystal lasers

a) Solution epitaxial lasers rivaling vapor phase deposited ones

Molecular Beam Epitaxy (MBE)

https://www.riber.com/



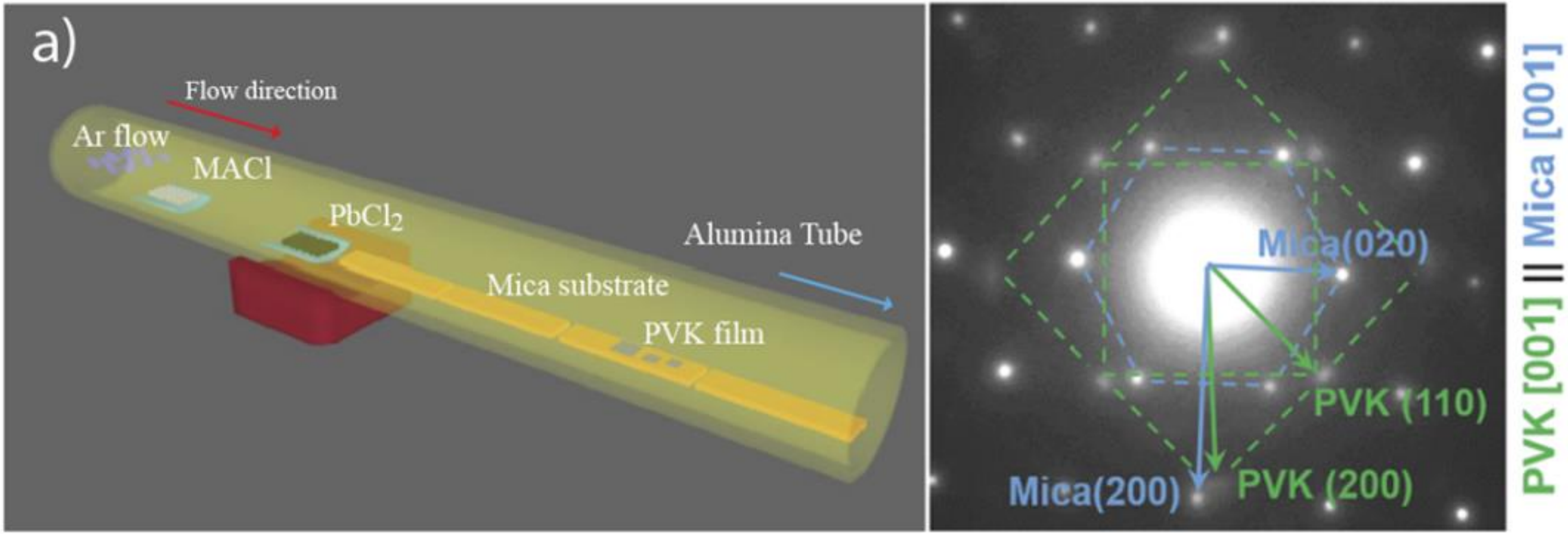


Wang *et al.*, ACS Appl. Mater. Interfaces **11**, 32076 (2019)

a) Solution epitaxial lasers rivaling vapor phase deposited ones

Chemical Vapor Deposition (CVD)

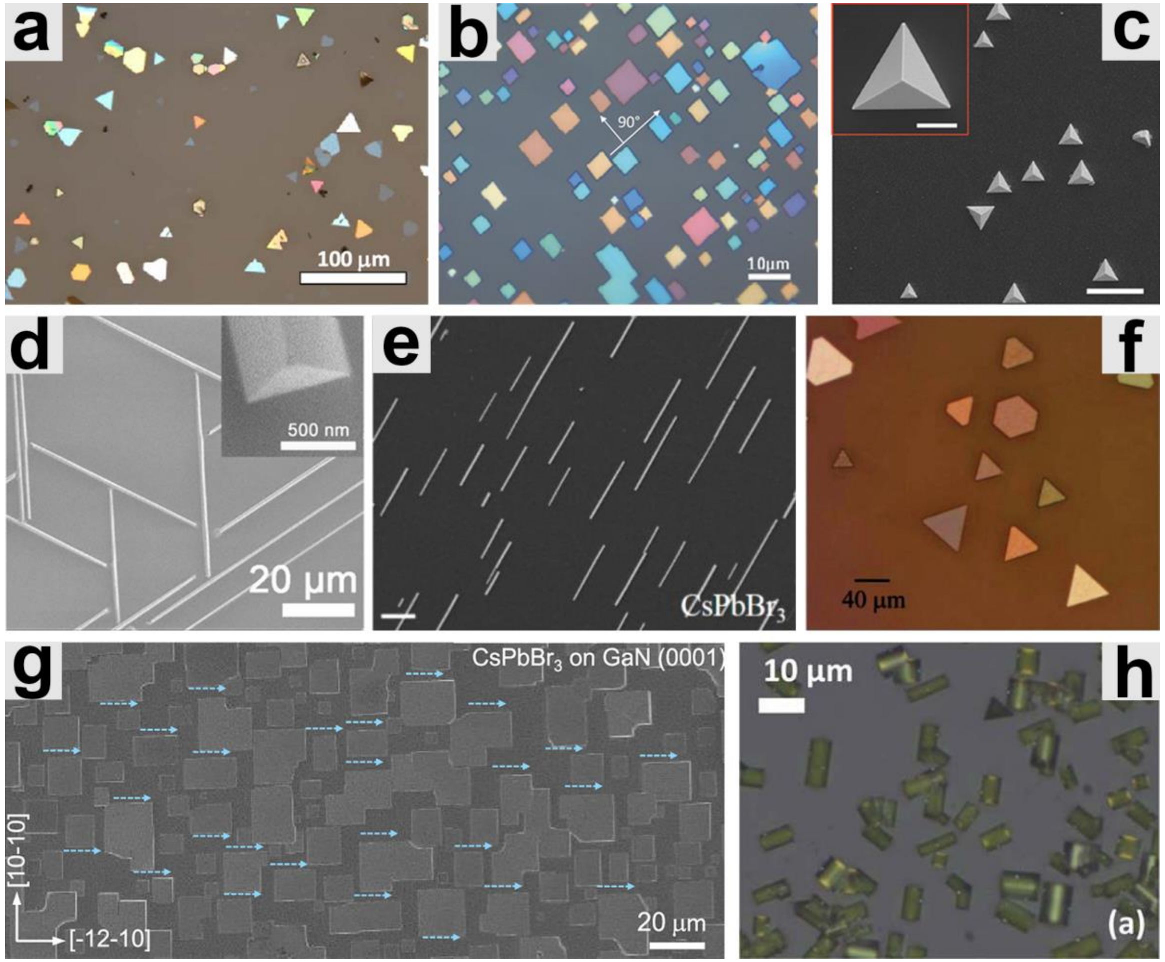
$MAPbCl_3$



Wang *et al.*, Cryst. Growth Des. **15**, 4741 (2015)

a) Solution epitaxial lasers rivaling vapor phase deposited ones

Vapor-Phase Epitaxial Lasers



Material and cavity geometry	Lasing threshold (µJ/cm²)	Q-factor	Growth method	Substrate	Operation Temp.	Pump Laser	Year	
$MAPbI_3$ triangular nanoplatelet	37	650	CVD	mica	RT	400 nm, 150 fs, 1 kHz	2014	(a)
$MAPbI_{3-x}Br_x$ triangular nanoplatelet	128	900						
$CsPbBr_3$ square nanoplatelets	2.2	~3530	CVD	mica	RT	400 nm, 50 fs, 1 kHz	2016	(b)
$MAPbBr_3$ cube-corner pyramid	92–2200	~960	CVD	mica	80-200 K	400 nm, 80 fs, 1 kHz	2018	(c)
$MAPbBr_3$ cube-corner pyramid	26, 75	—		mica/Ag	80, 300 K			
Composition graded $CsPbBr_xI_{3-x}$ triangular nanowire	16 (521 nm)	~1737	CVD	mica	RT	400 nm, 150 fs, 1 kHz	2018	(d)
	28 (556 nm)	~1390						
$CsPbBr_3$ triangular nanowire	4	2675	Thermal evaporation	sapphire	RT	470 nm, 100 fs, 1 kHz	2018	(e)
$CsPbI_3$ triangular nanowire	21	2256						
$CsPbCl_3$ triangular nanowire	11	1931				400 nm, 100 fs, 1 kHz		
$MAPbI_3$ triangular nanoplatelet	18.7	2600	CVD	mica	RT	343 nm, 290 fs, 6 kHz	2019	(f)
$CsPbBr_3$ rectangular microplatelet	700	~781	CVD	GaN	RT	400 nm, 80 fs, 1 kHz	2019	(g)
$CsPbBr_3$ rectangular microrod	136	5360	CVD	mica	RT	355 nm, 350 ps, 1 kHz	2021	(h)

a) Zhang et al. *Nano Letters* 14, 5995 (**2014**) b) Zhang et al. *AFM* 26, 6238 (**2016**) c) Mi et al. *Small* 14, 1703136 (**2018**) d) Huang et al. *AM* 30, 1800596 (**2018**)
e) Wang et al. *ACS Nano* 12, 6170 (**2018**) f) Li et al. *AFM* 29, 1805553 (**2019**) g) Zhao et al. *ACS Nano* 13, 10085 (**2019**) h) Wu et al. *Opt. Express* 29, 37797 (**2021**)

a) Solution epitaxial lasers rivaling vapor phase deposited ones

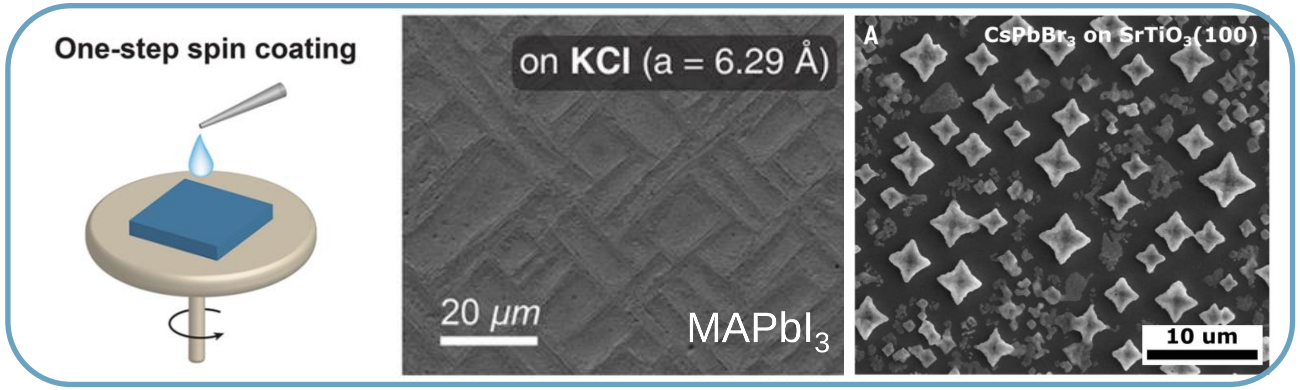
Solution–Phase Epitaxial Growth

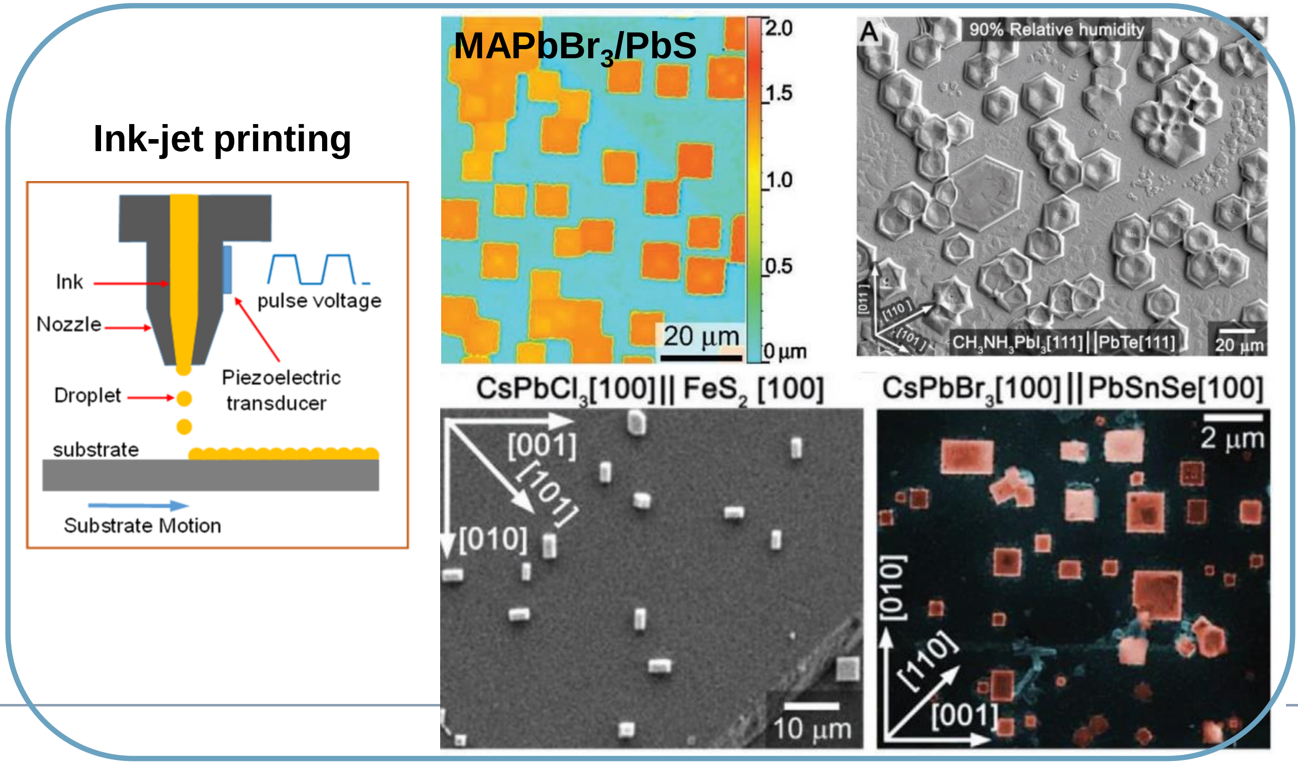
	Solution Phase	Vapor Phase
Facile processing	✓	✗
Low temperature	✓	✗
No vacuum	✓	✗
Low-cost fabrication	✓	✗
Low-energy usage	✓	✗

Ji et al., Nano Lett. 18, 994 (**2018**)

Kelso et al., Science 364, 166 (**2019**)

Sytnyk et al., Adv. Funct. Mater. 30, 2004612 (**2020)**



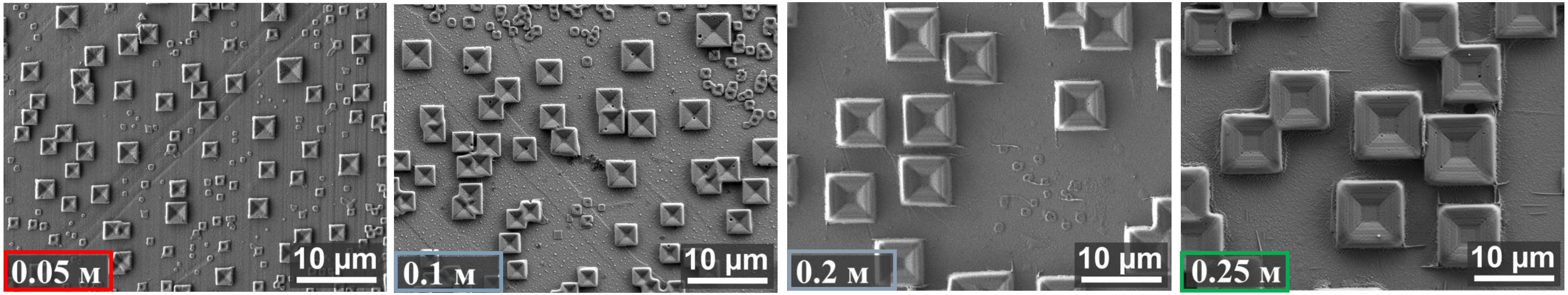


a) Solution epitaxial lasers rivaling vapor phase deposited ones

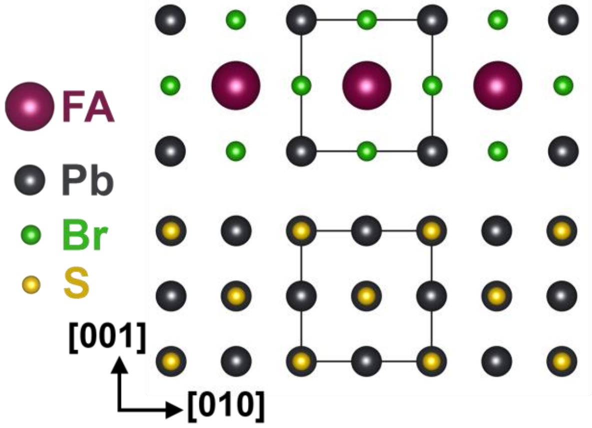
Epitaxial lasers by drop casting

Precursor Concentration

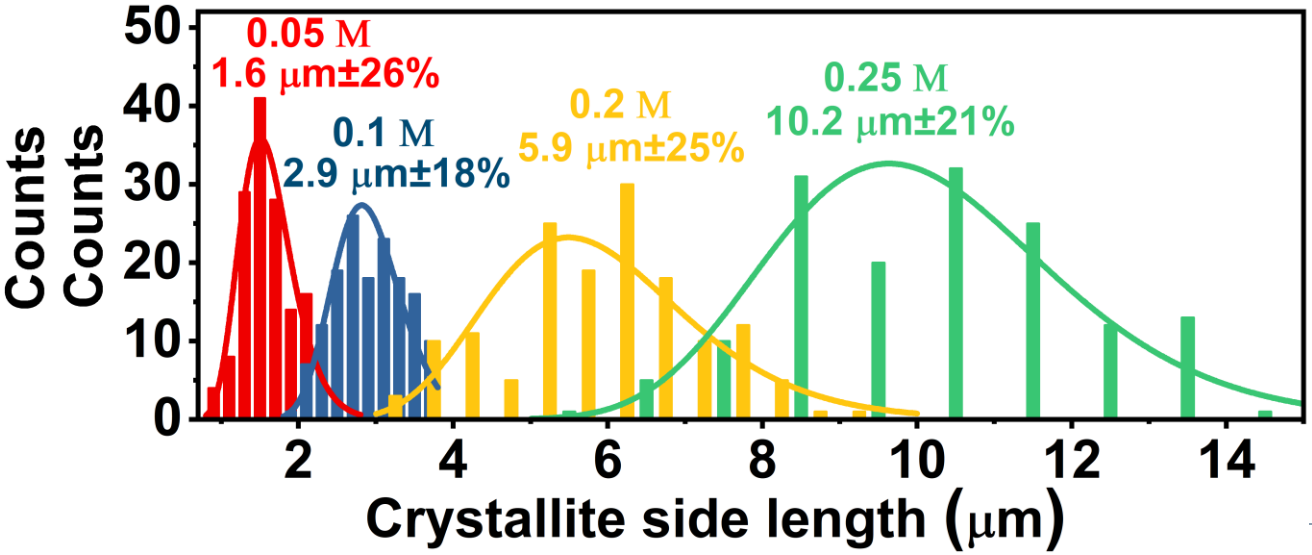
0.05 M **0.1 M** **0.2 M** **0.25 M**



Solvent:
DMF+DMSO (3:1)
T_S=80°C
Humidity = 80-90%
Bromium/Methanol treatment



Lattice mismatch ≈ 0.57 %

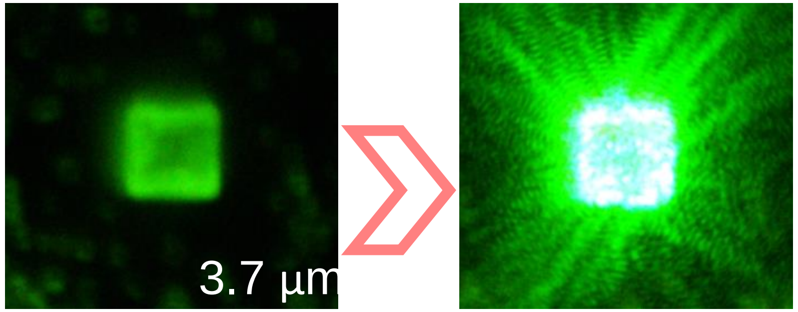


Hany Afify et al., Adv. Optical Mater. 10, 2200237 (**2022**)

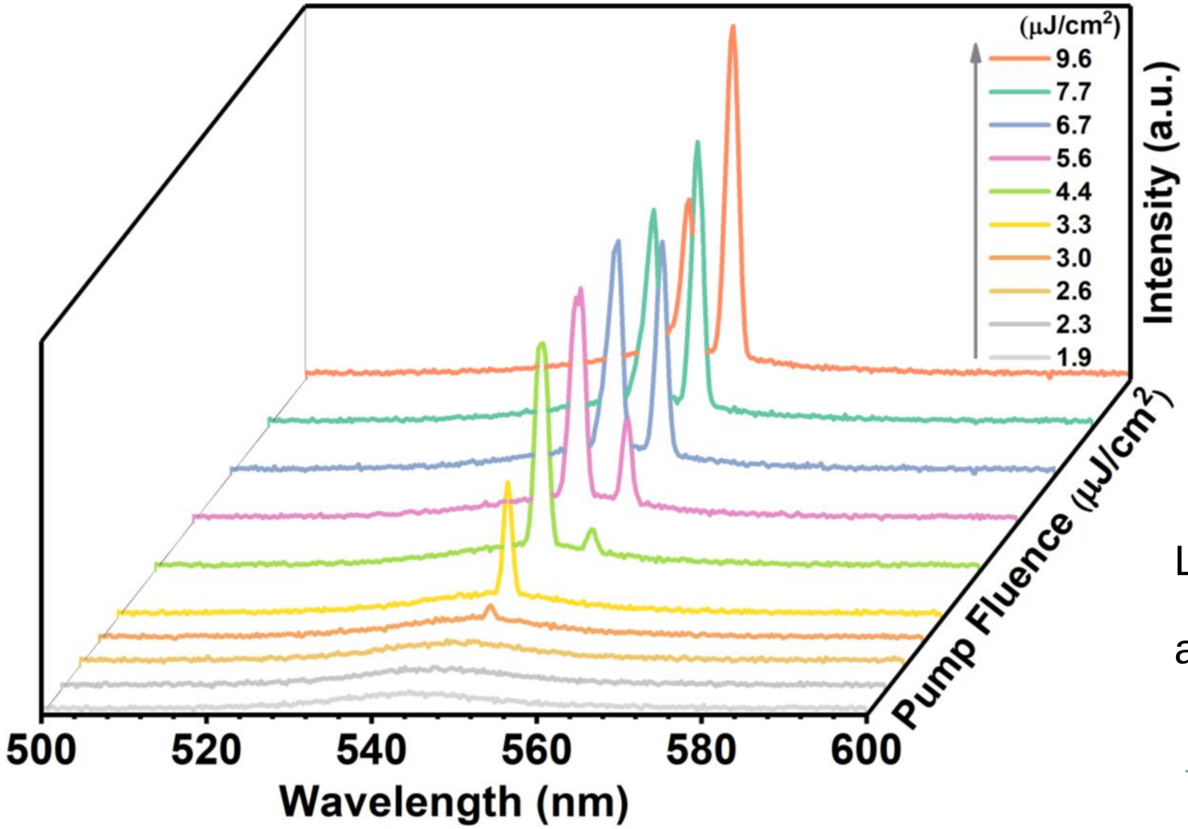
a) Solution epitaxial lasers rivaling vapor phase deposited ones

Epitaxial lasers by drop casting

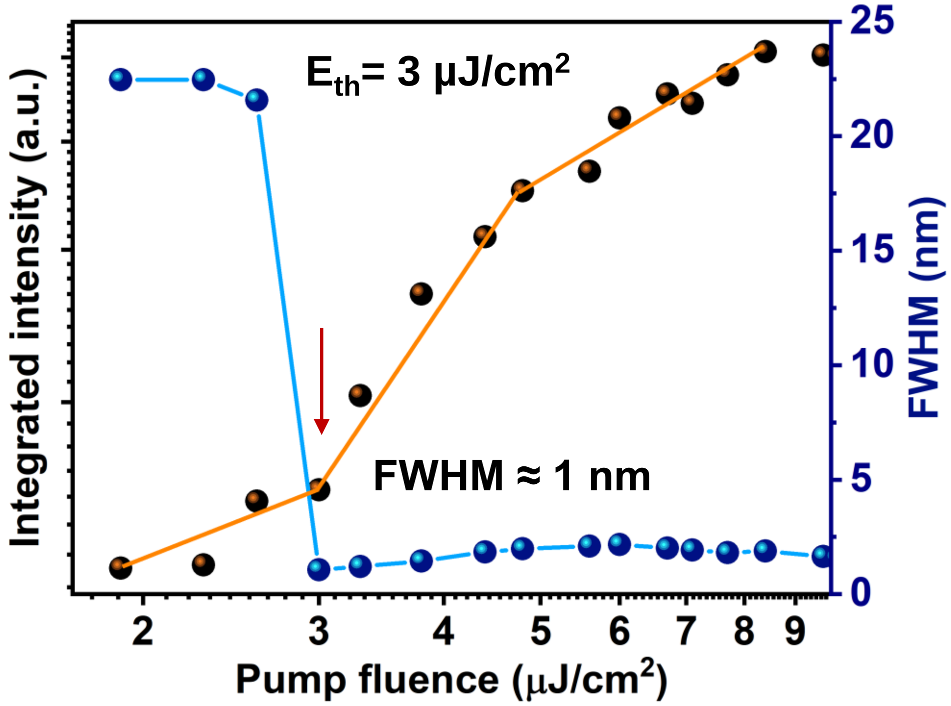
At low pump fluences



Above lasing threshold



520 nm fs laser (>350 fs, 500 kHz)



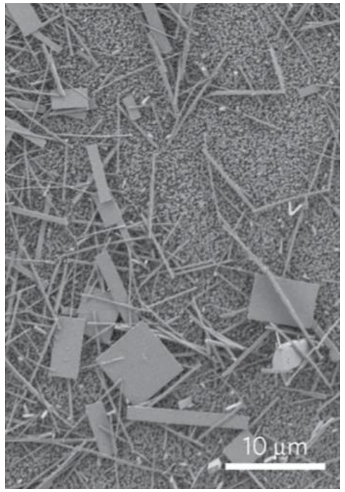
Lowest threshold for $FAPbBr_3$ in literature

and among lowest 20% of reported values for Pb-perovskites.

a) Solution epitaxial lasers rivaling vapor phase deposited ones

Antisolvent vapor assisted crystallization

AVC on glass



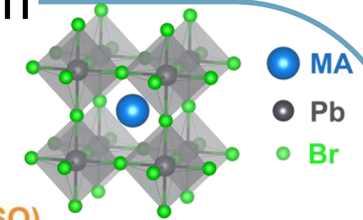
Zhu et al., Nature Materials 14, 636 (**2015**)

AVC on mica

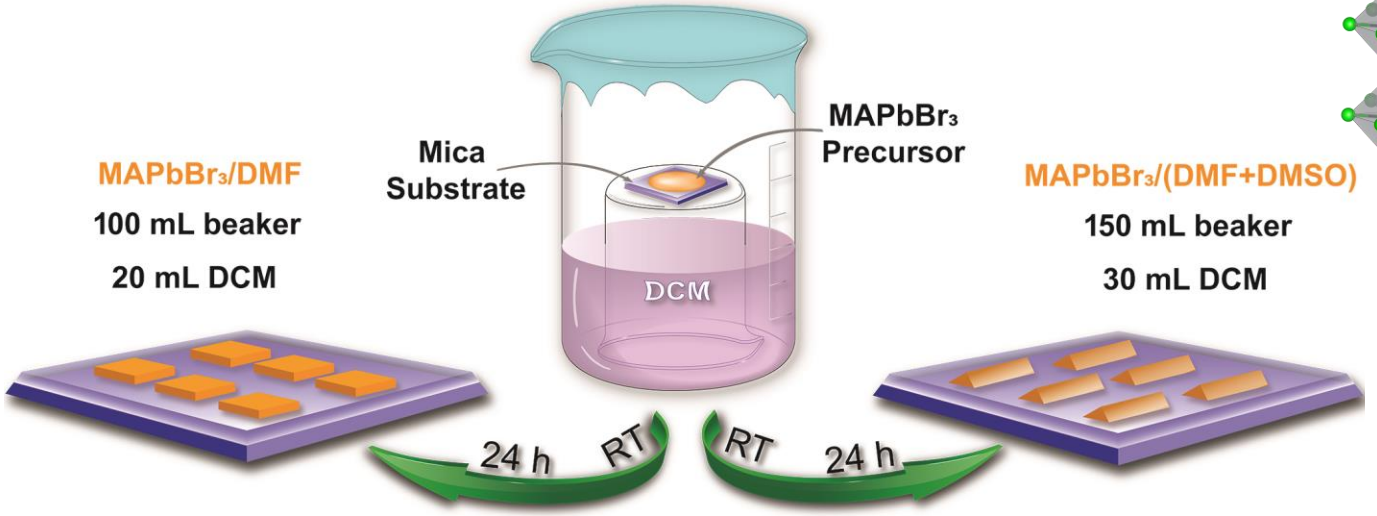
Hany Afify et al., Adv. Funct. Mater. 32, 2206790 (**2022**)

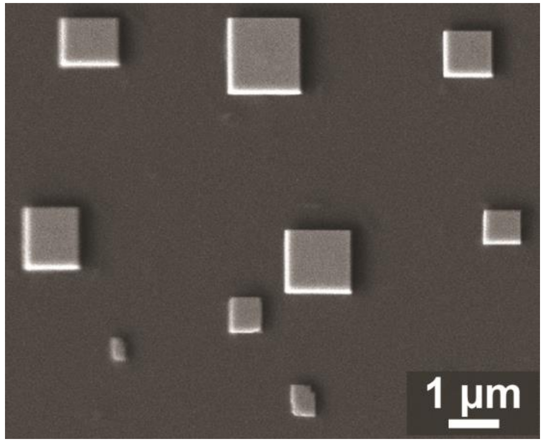
Micro-cuboid

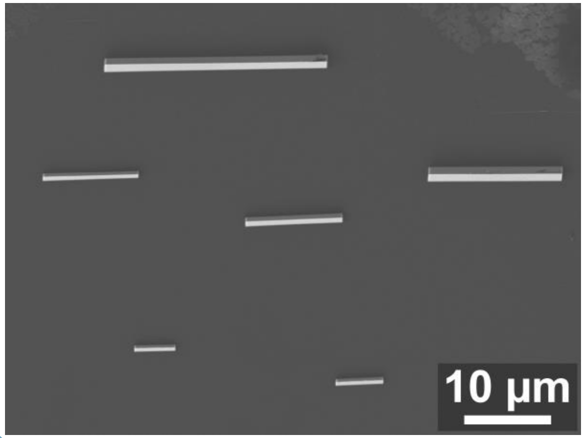
Micro-prism

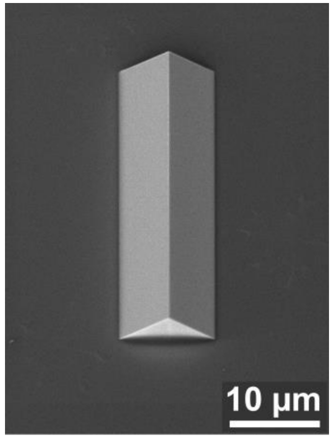


$MAPbBr_3$:
$CH3NH_3PbBr_3$

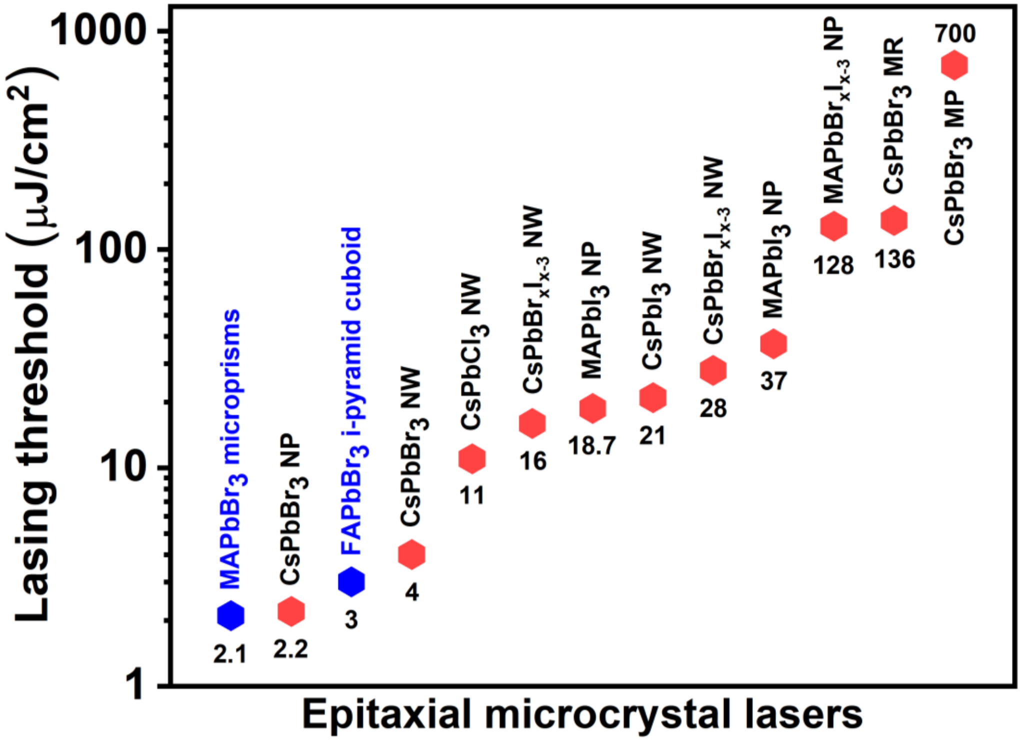








a) Solution epitaxial lasers rivaling vapor phase deposited ones



Solution epitaxy outperforms vacuum epitaxy

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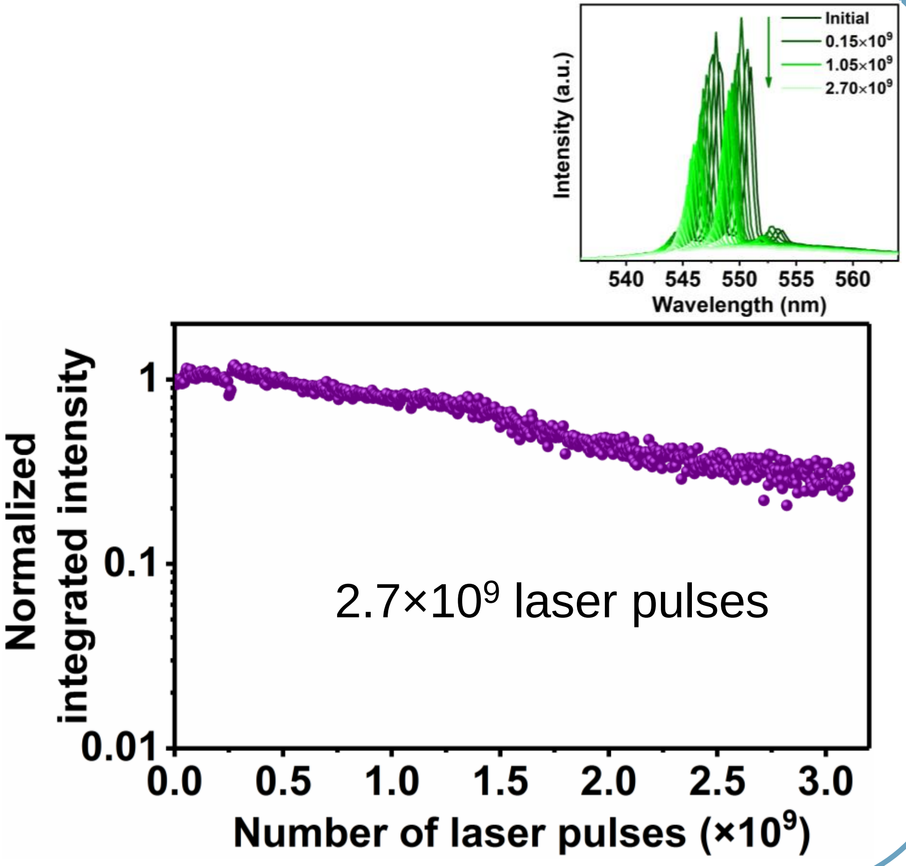
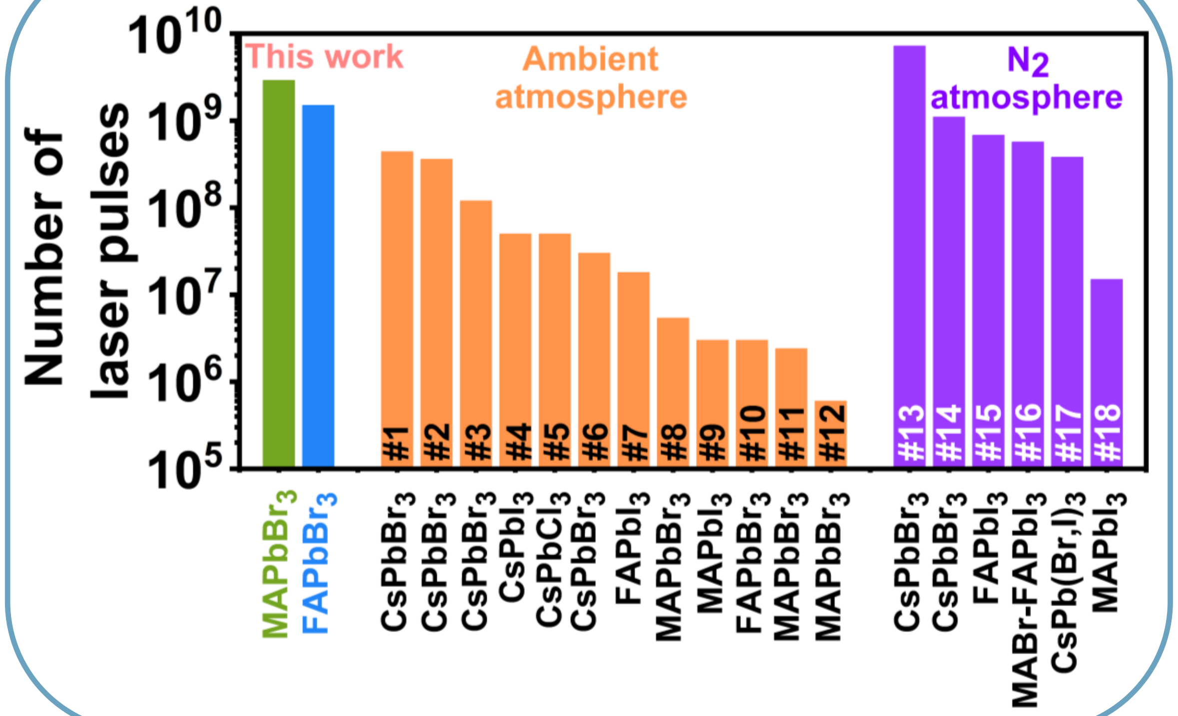
a) Solution epitaxial lasers rivaling vapor phase deposited ones

Operation Stability



Record high photostability



Contens

a) Solution epitaxial lasers rivaling vapor phase deposited ones.

2024

b) Squeezing the threshold of microcrysal microcavity laser

c) Surface passivation of epitaxial microstructures

d) Positioning of perovskite microcrystal lasers

b) Squeezing the threshold of microcrysal microcavity laser

What to squeeze - threshold power (and not threshold energy) -> change from fs to ns excitation

$FAPbBr_3$

How to squeeze - optimize microresonator dimensions

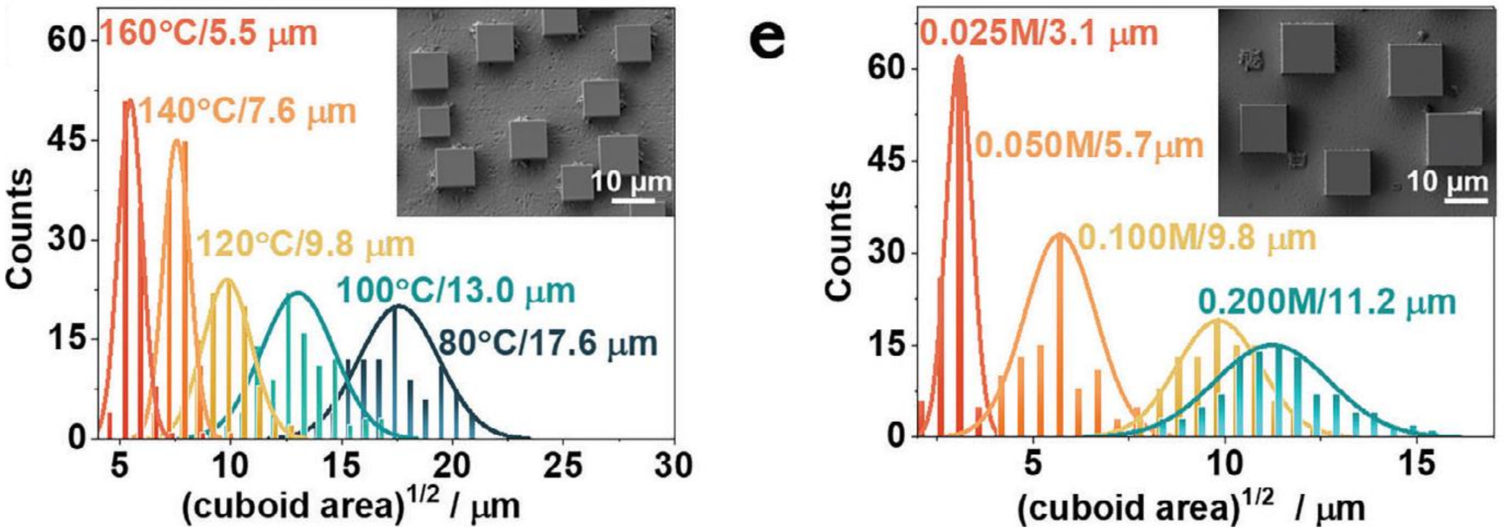
- optimize perovskite material

- optimize excitation conditions (repetition rate)

Size control

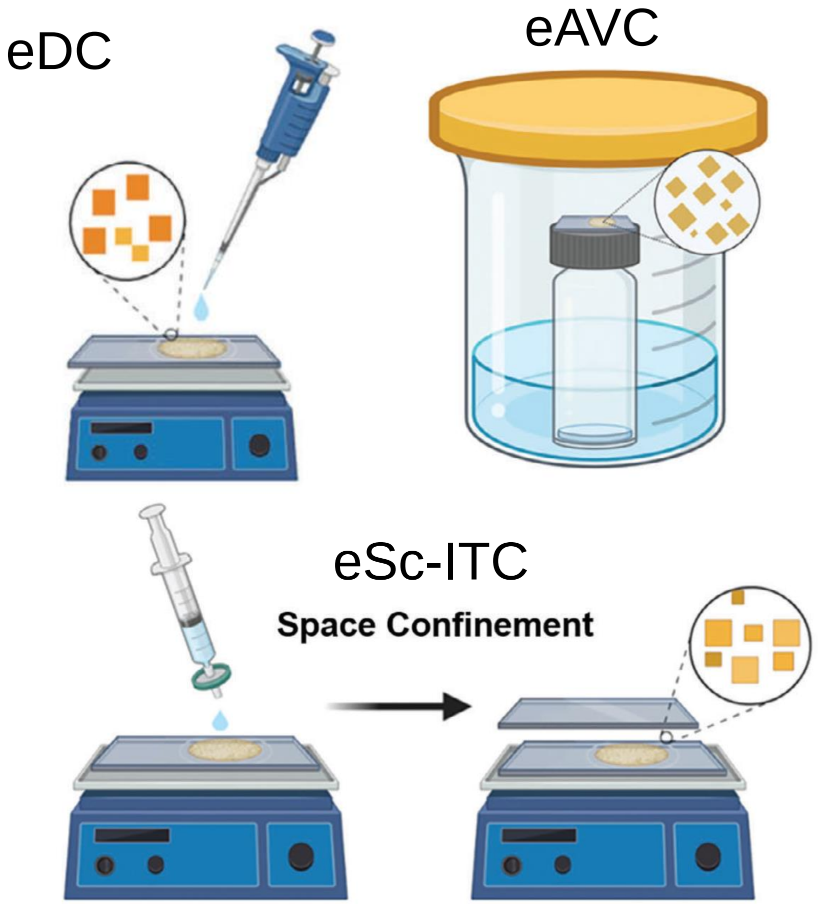
Drop casting from DMF/GBL

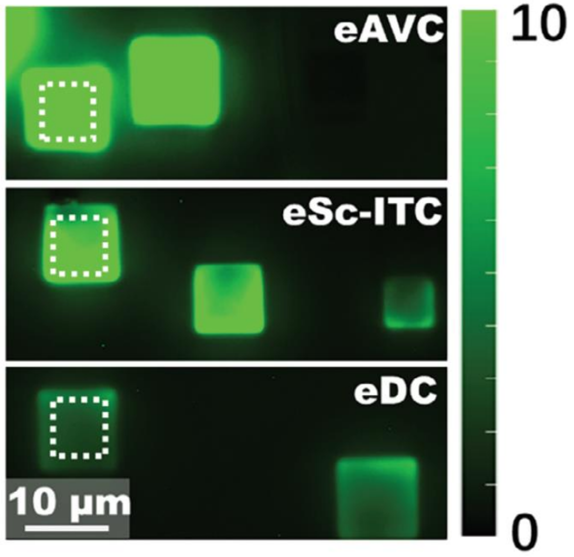
1.5 µl drop 3 min drying

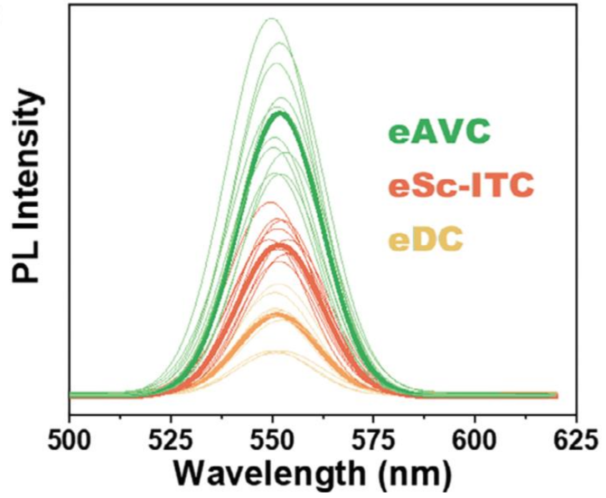


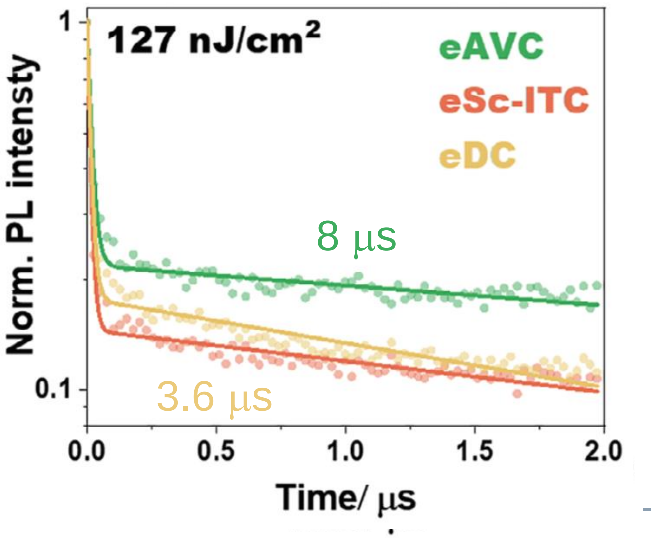
b) Squeezing the threshold of microcrysal microcavity laser

Quality optimization: epitaxial growth by



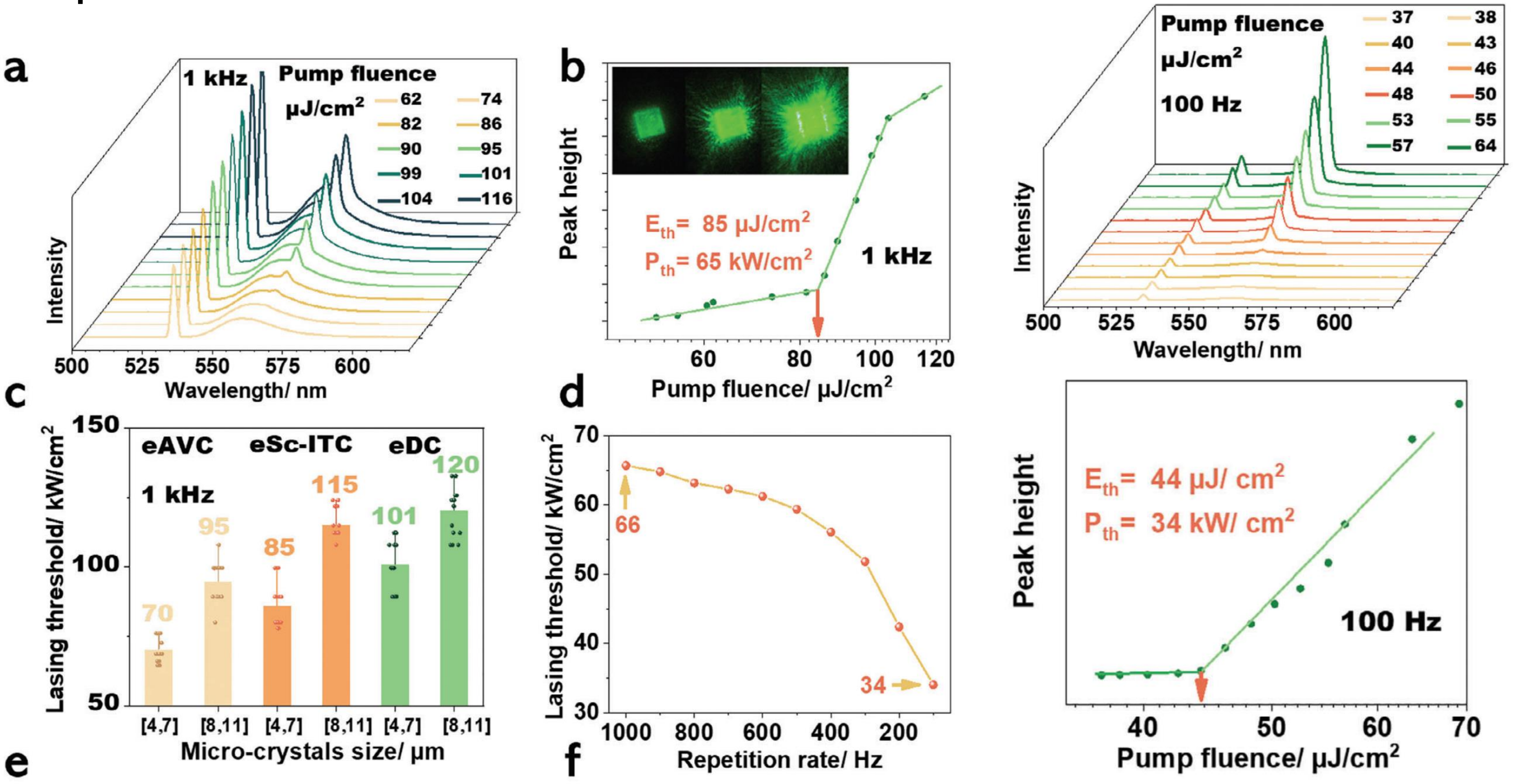






b) Squeezing the threshold of microcrysal microcavity laser

Optimize the excitation conditions



This is the new threshold power for epitaxial perovskite lasers, independent of material.

Summary

Solution epitaxial perovskite micro-crystal lasers exhibit similar performance as vacuum deposition ones, but are much easier and cheaper in preparation.

Optimizing microcrystal lasers includes size control, material improvement and selection of laser parameters.

Surface passivation is important for any epitaxial microstructures.

They can be positioned by seeds.

Principle investigators

Principle investigators

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V. Rehm

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DFG Deutsche Forschungsgemeinschaft