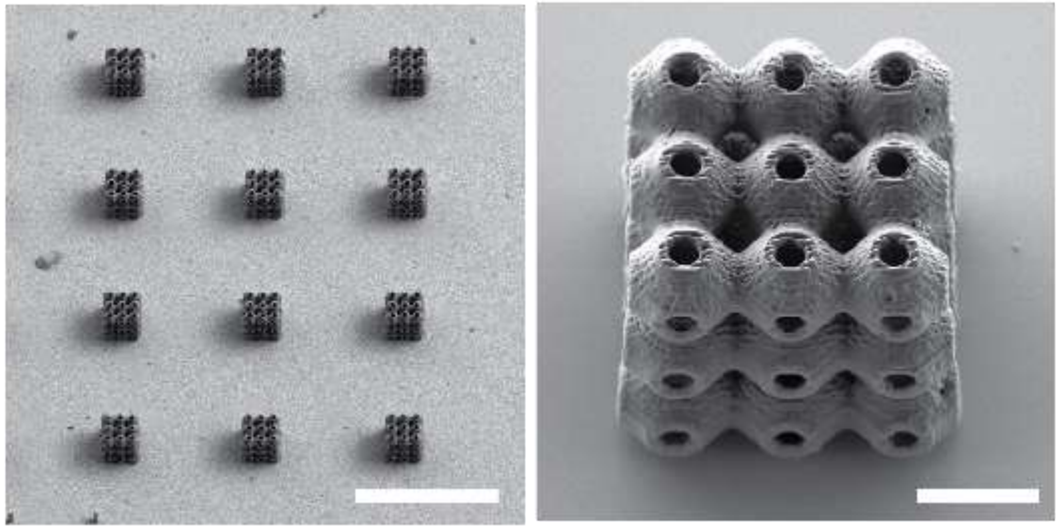
Nano Additive Manufacturing of Challenging Materials

Xun Wendy Gu

Mechanical Engineering and (by courtesy) Materials Science and Engineering

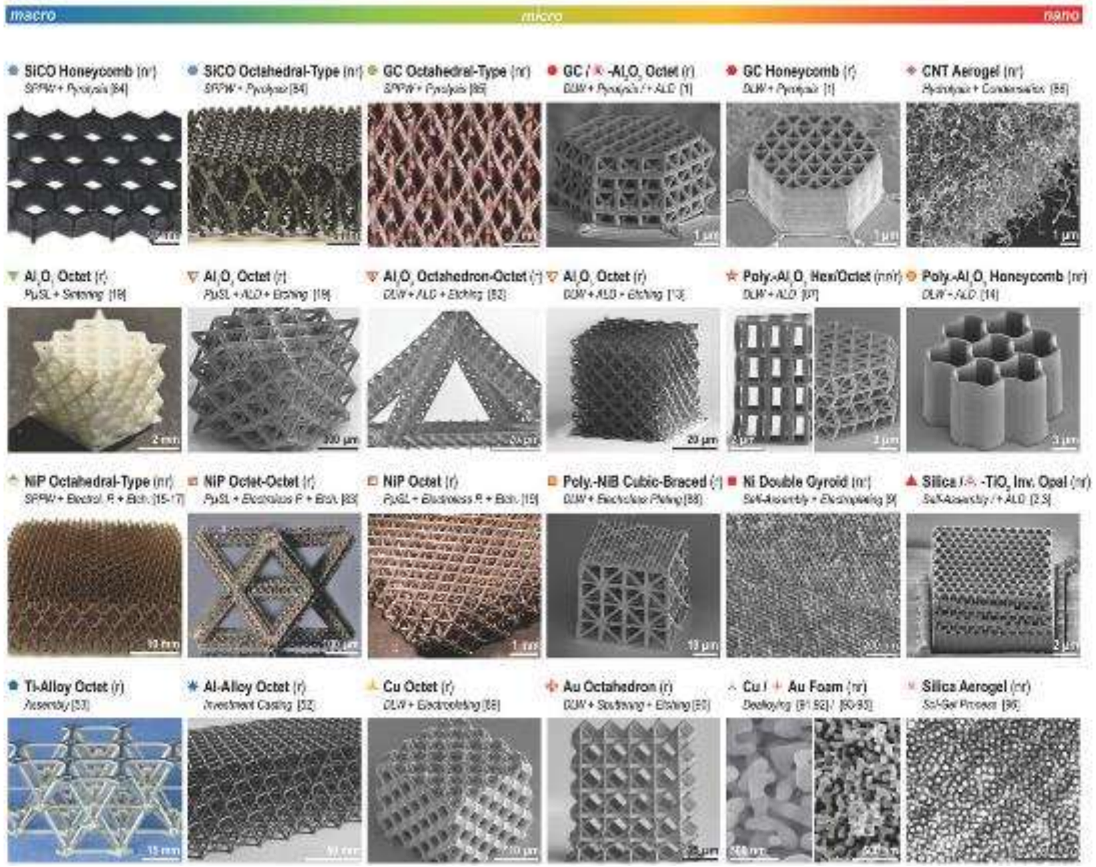
Stanford University



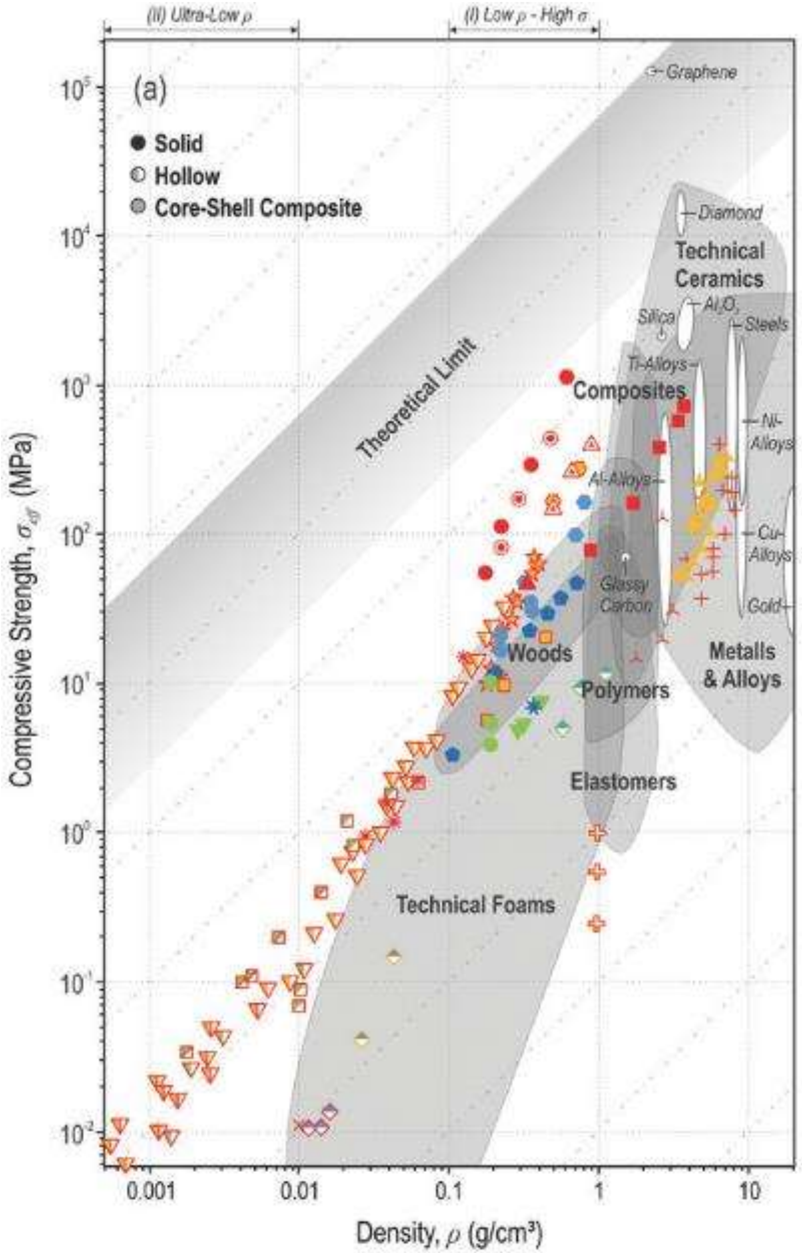
100 um

10 um

Lightweight cellular materials



Bauer et al., *Advanced Materials* (2017)



Two photon lithography

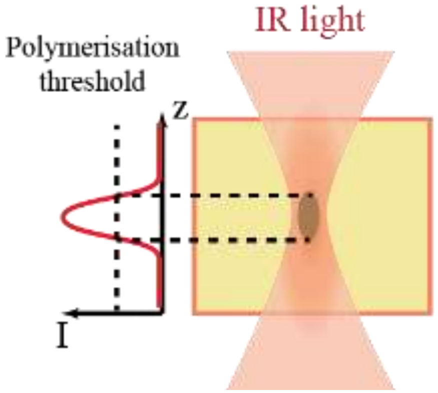


Image from Metalab

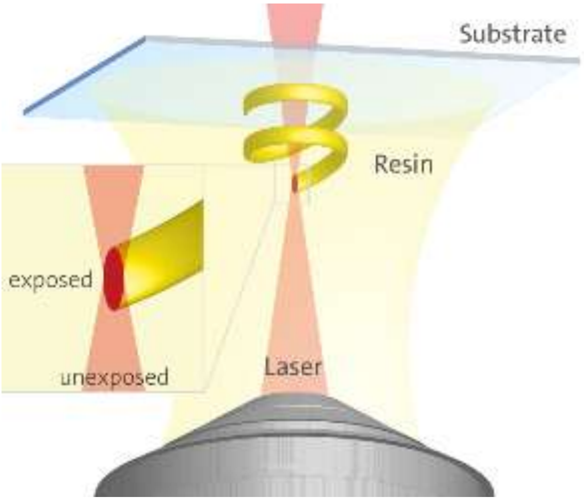
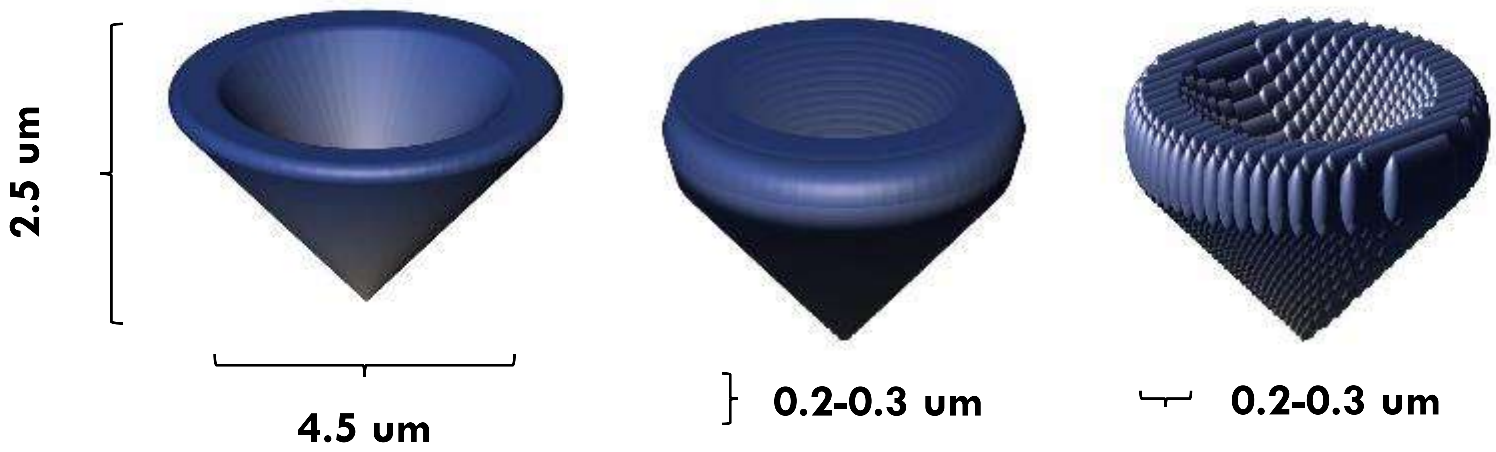
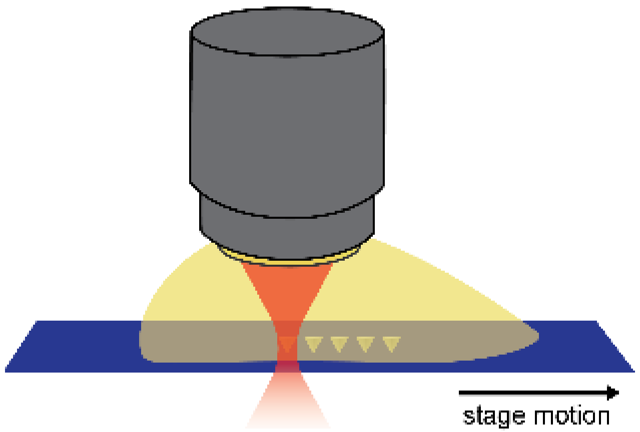


Image from Nanoscribe

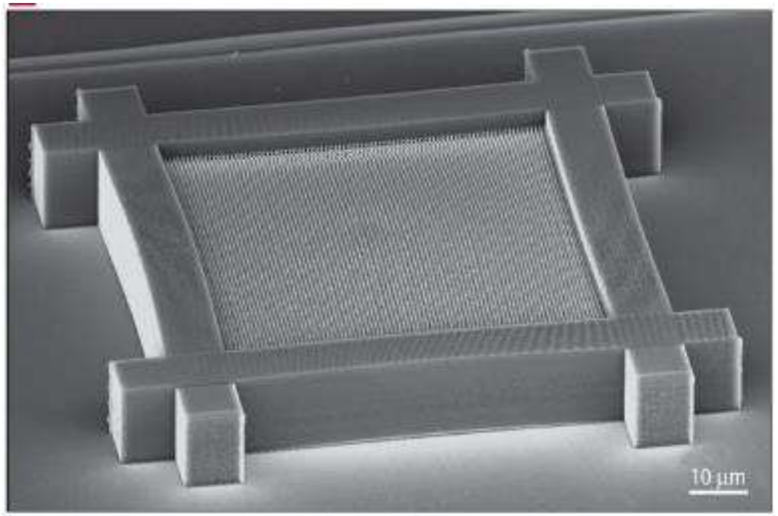
3D Model (CAD) ➔ Z-Slicing ➔ X-Y Slicing (Hatching)

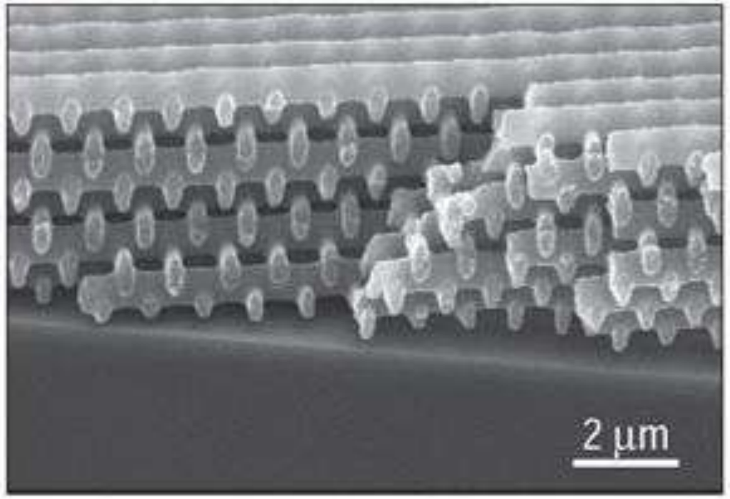


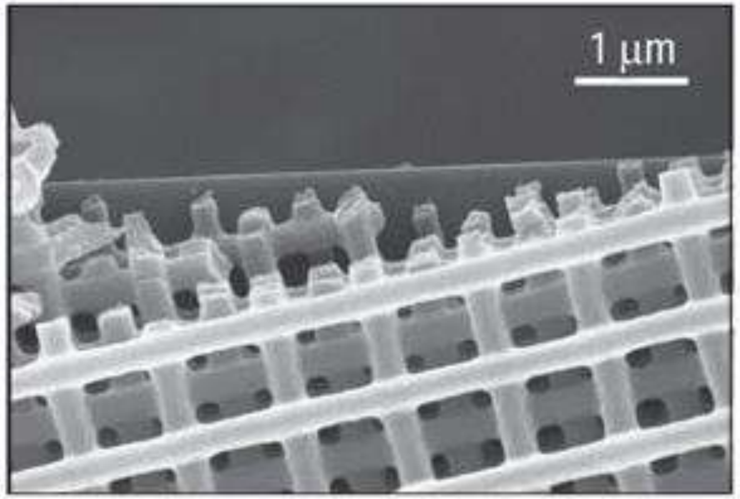
Direct laser writing



Microscale polymer structures







Deubel et al. *Nature Materials* (2004)

Inorganic coating on a polymer scaffold

Polymer with inorganic coating

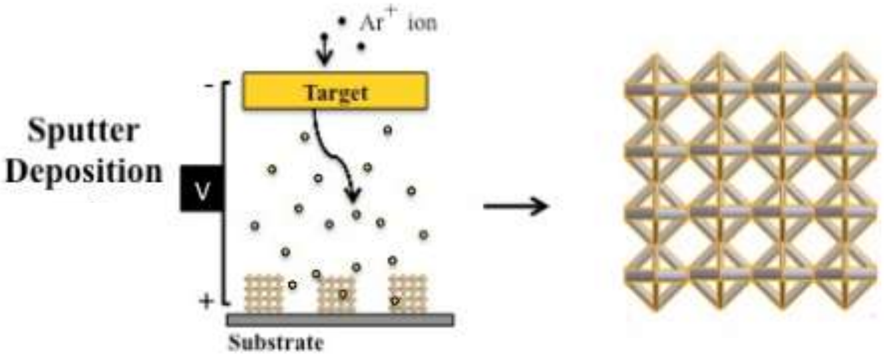
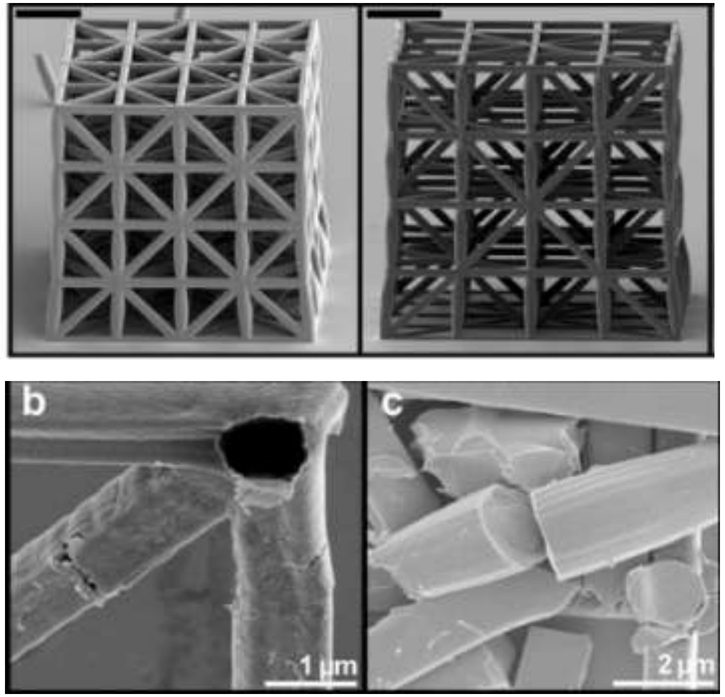


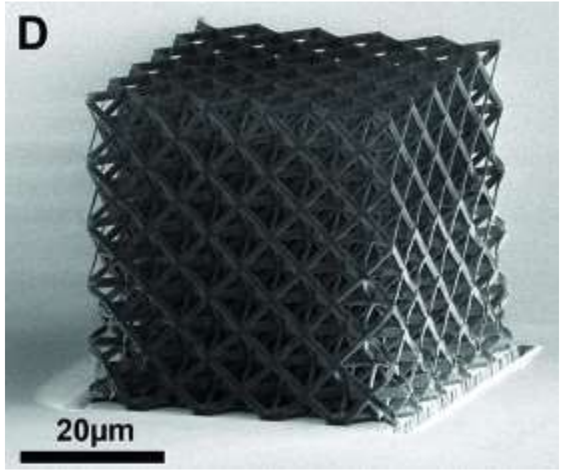
Image from Montemayor *et al.*, *Adv. Eng. Mat.* (2013)

Alumina coated polymer lattices



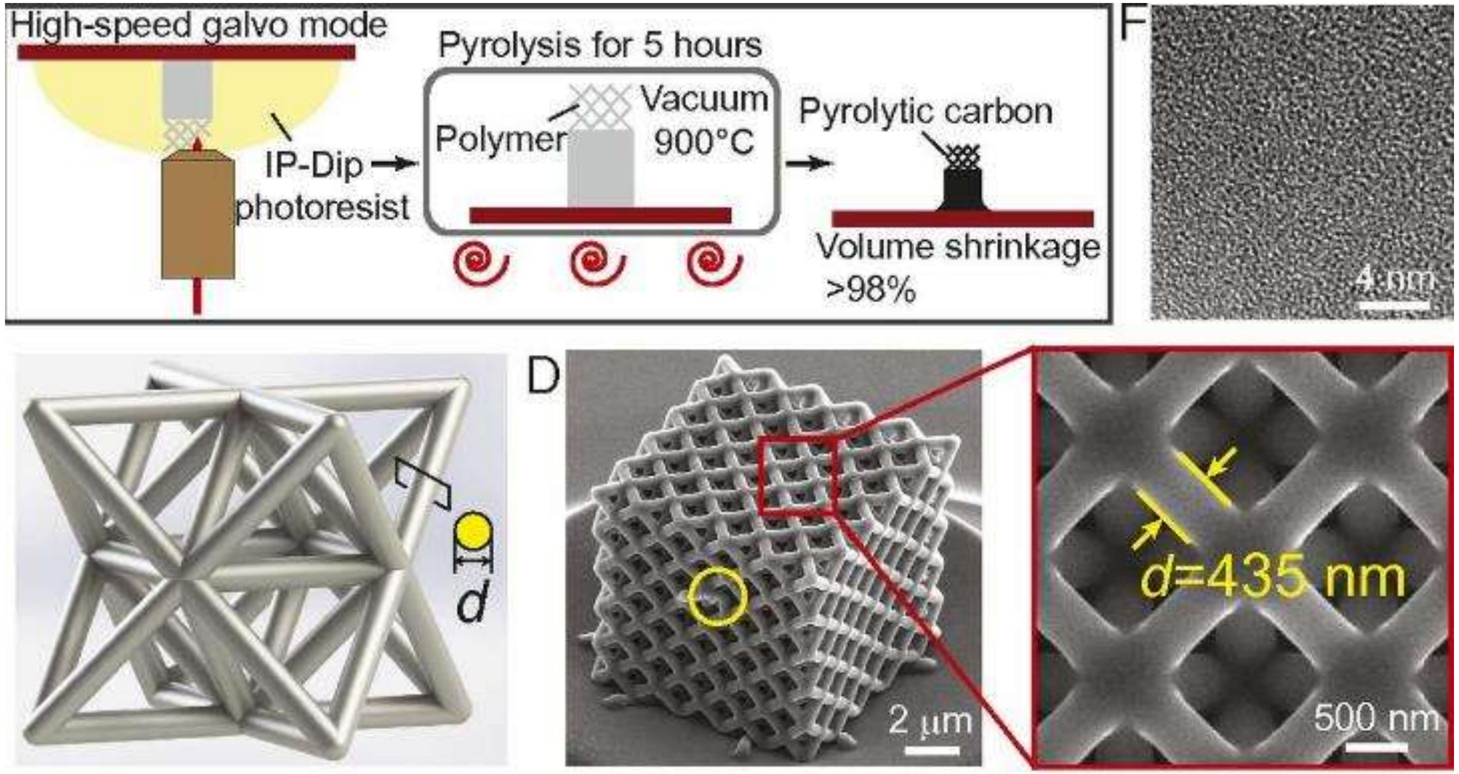
Bauer et al., PNAS (2014)

Hollow alumina

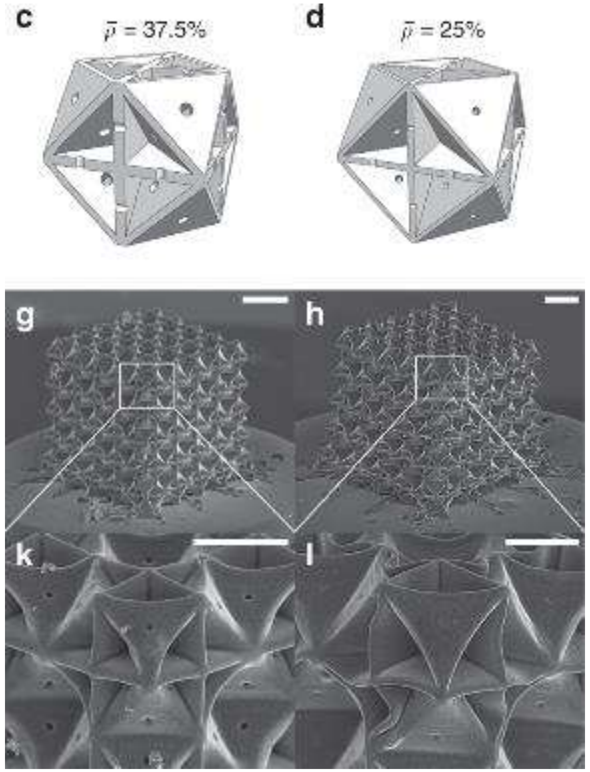


Meza et al., Science (2014)

Transform polymer into glassy carbon

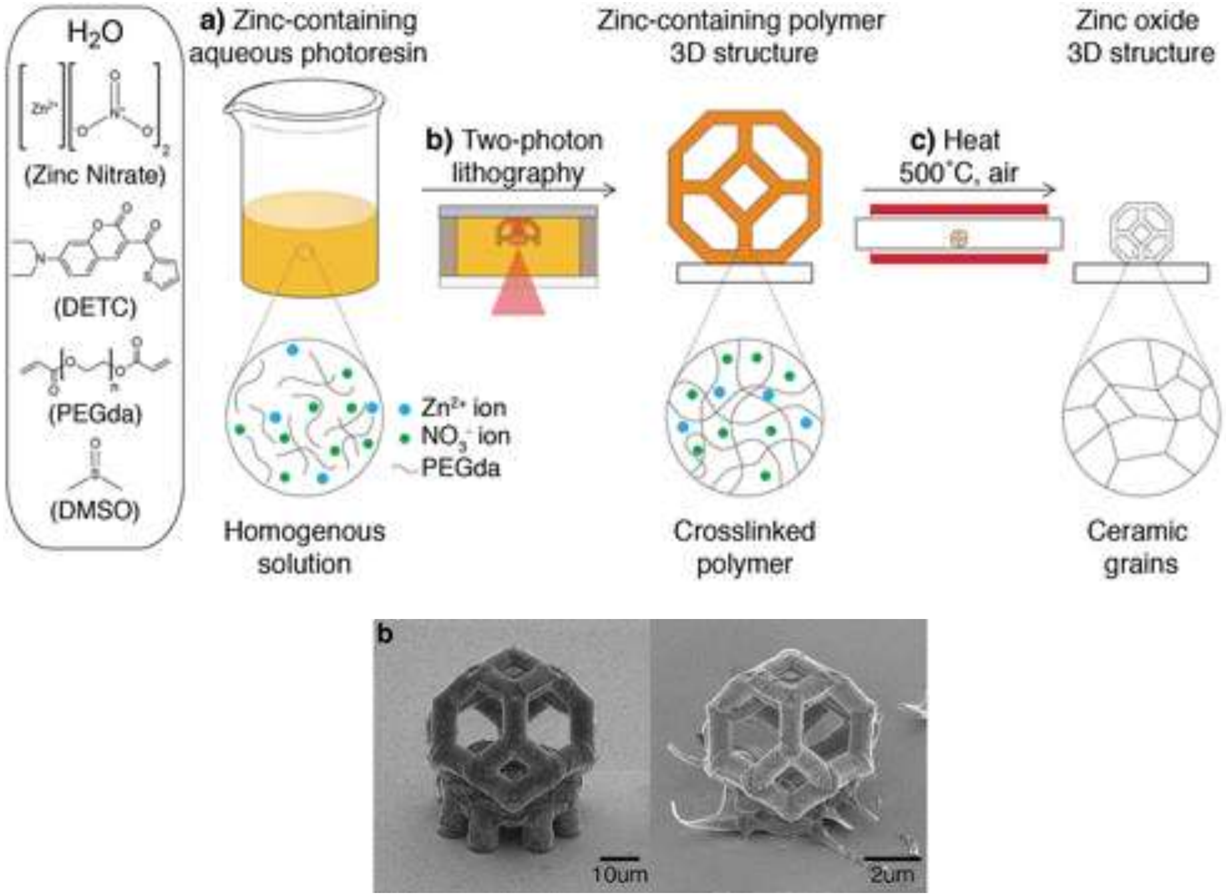


Zhang et al., PNAS (2019)



Crook et al., Nat. Comm. (2020)

Novel resin chemistries for metals and ceramics

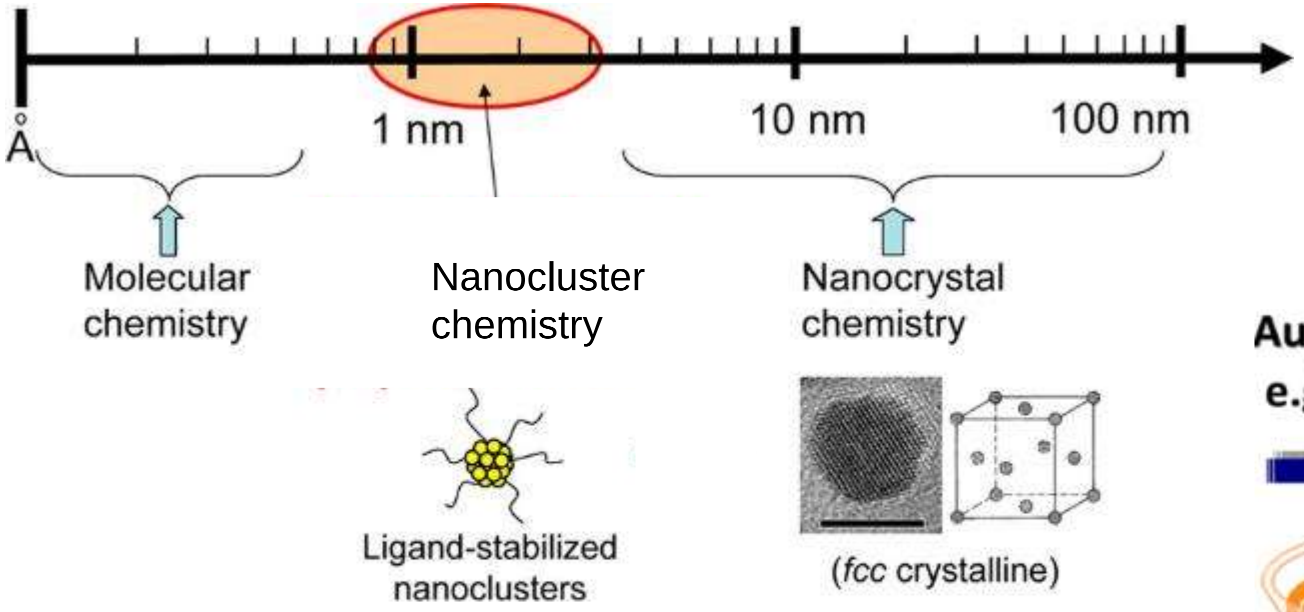


Yee et al., *Advanced Materials* (2019)

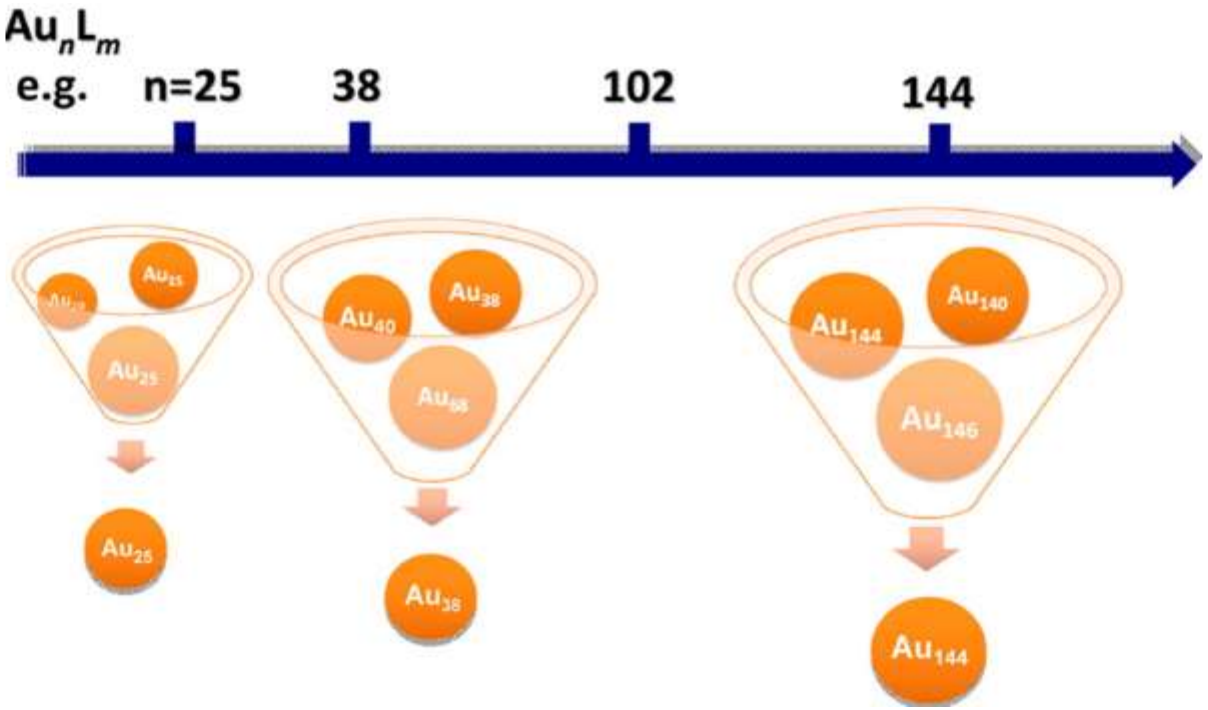
Main ingredients

- Photopolymer
- Photoinitiator
- Metallic precursor

Metallic nanoclusters



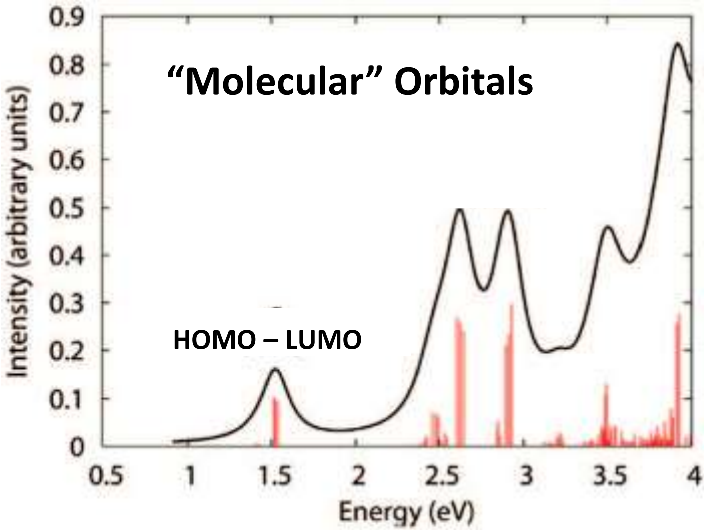
Atomic Precision

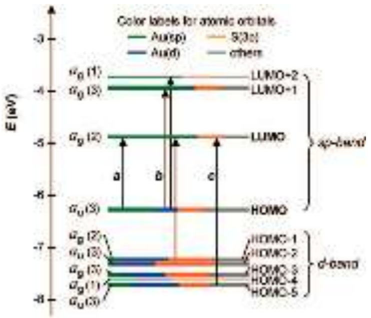


Jin *et al.*, *Chem. Rev.*, **2016**

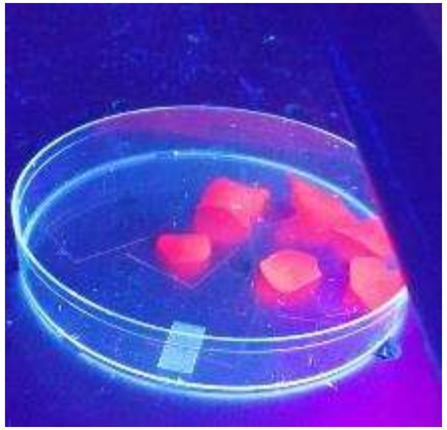
Properties of nanoclusters

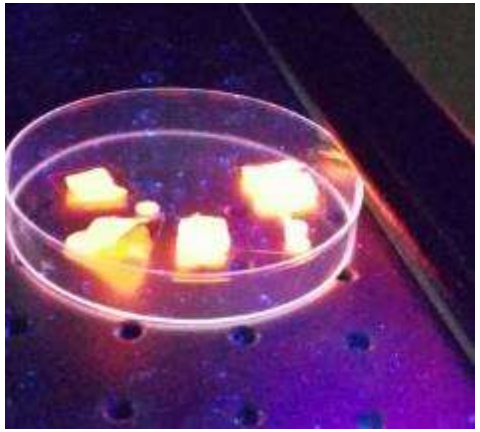
Quantized energy levels





Discrete States

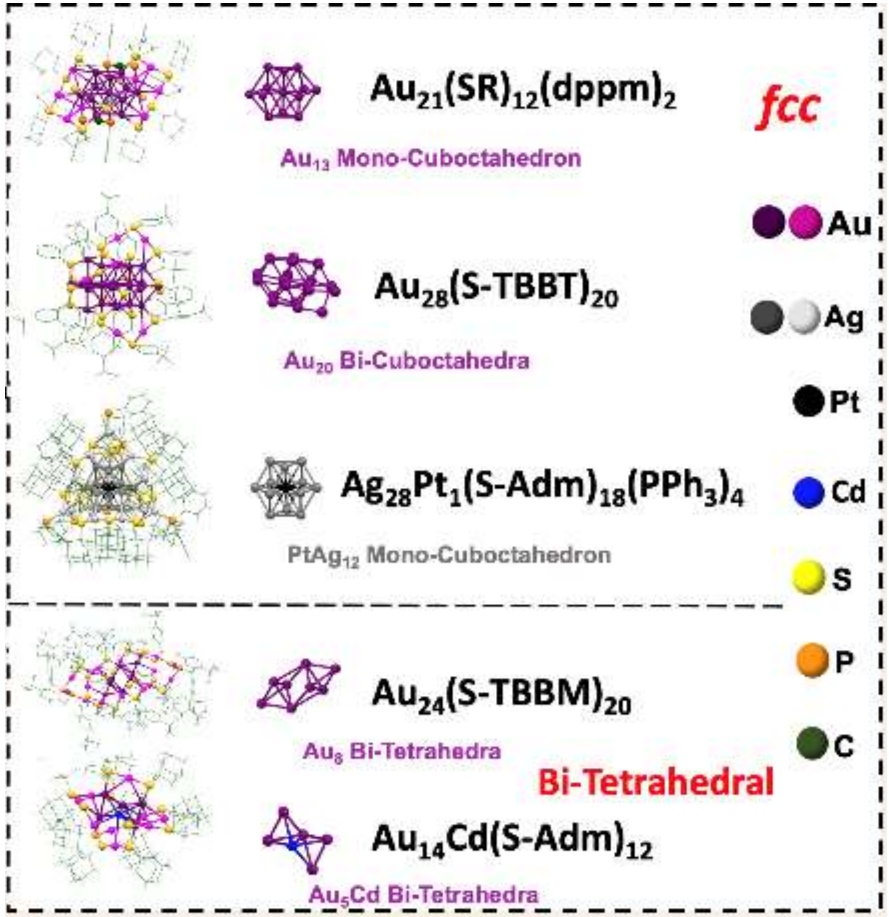


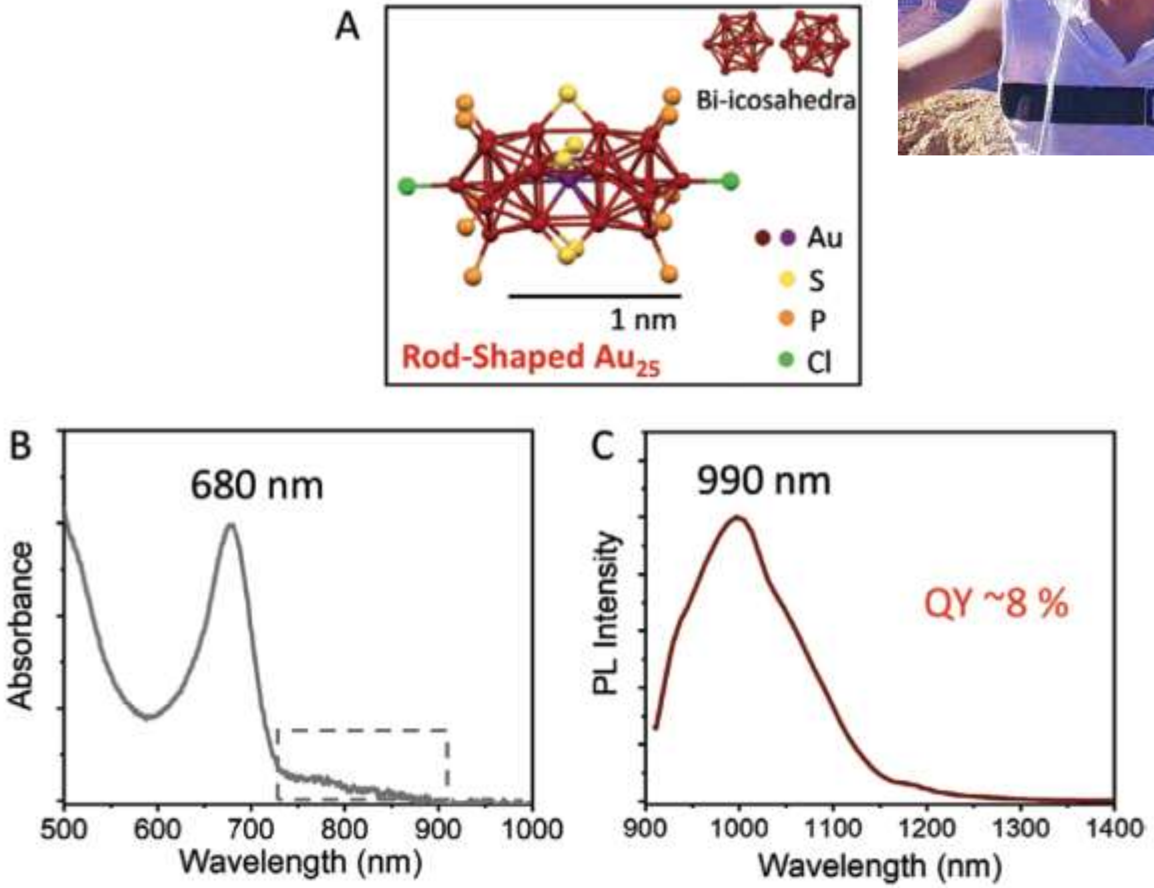


- Luminescent
- Photocatalytic
- Reduction in melting temperature (600-900°C)

Jin *et al.*, *Chem. Rev.*, **2016**

Library of metallic nanoclusters





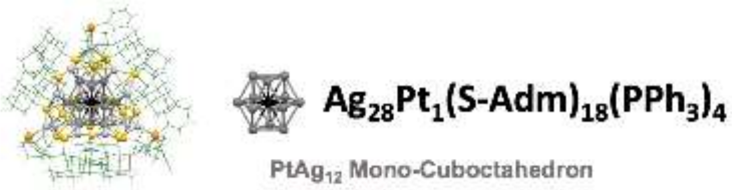
Qi Li, *et al*, *ACS Nano* **2020**

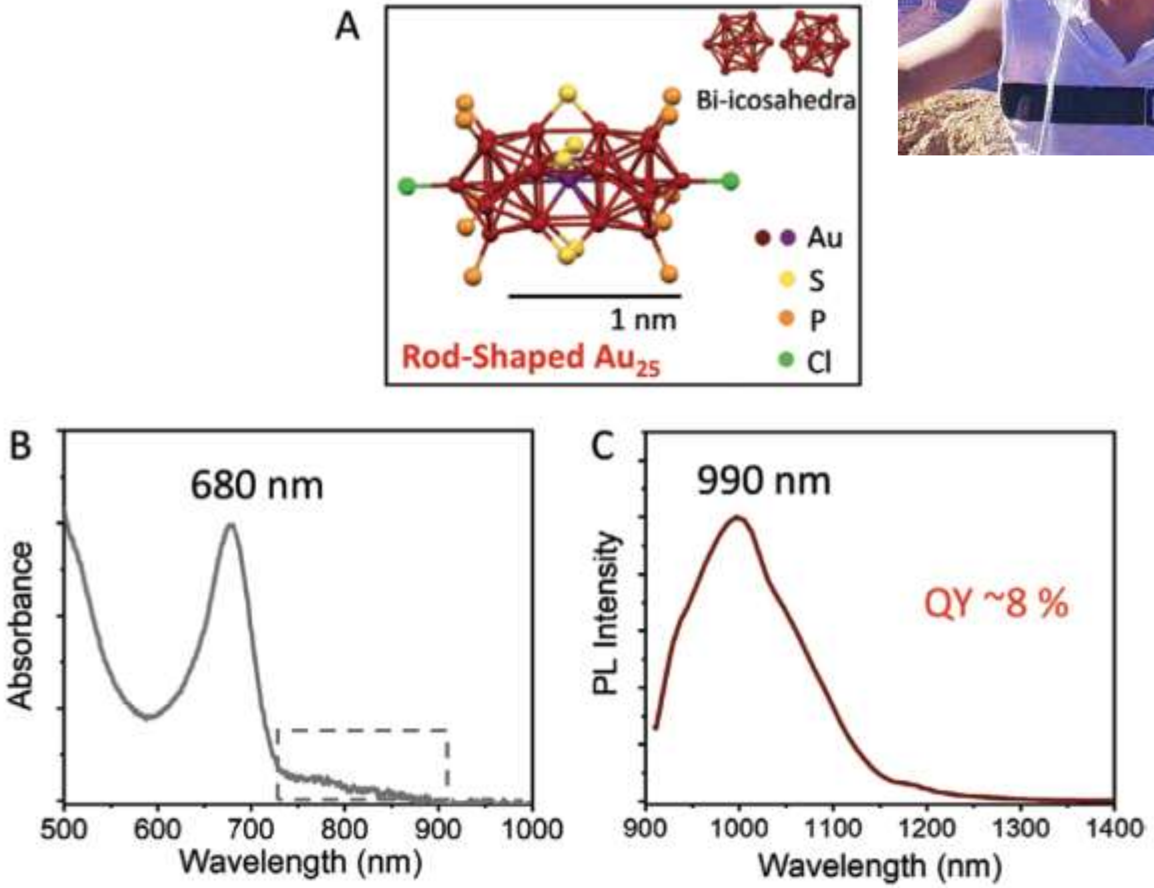
Qi Li, *et al*, *Small* **2021**

Qi Li, *et al*, *ACS Nano* **2021**

Qi Li, *et al*, *Nature Comm* **2020**

Library of metallic nanoclusters





Qi Li, *et al*, *ACS Nano* **2020**

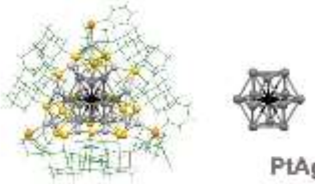
Qi Li, *et al*, *Small* **2021**

Qi Li, *et al*, *ACS Nano* **2021**

Qi Li, *et al*, *Nature Comm* **2020**

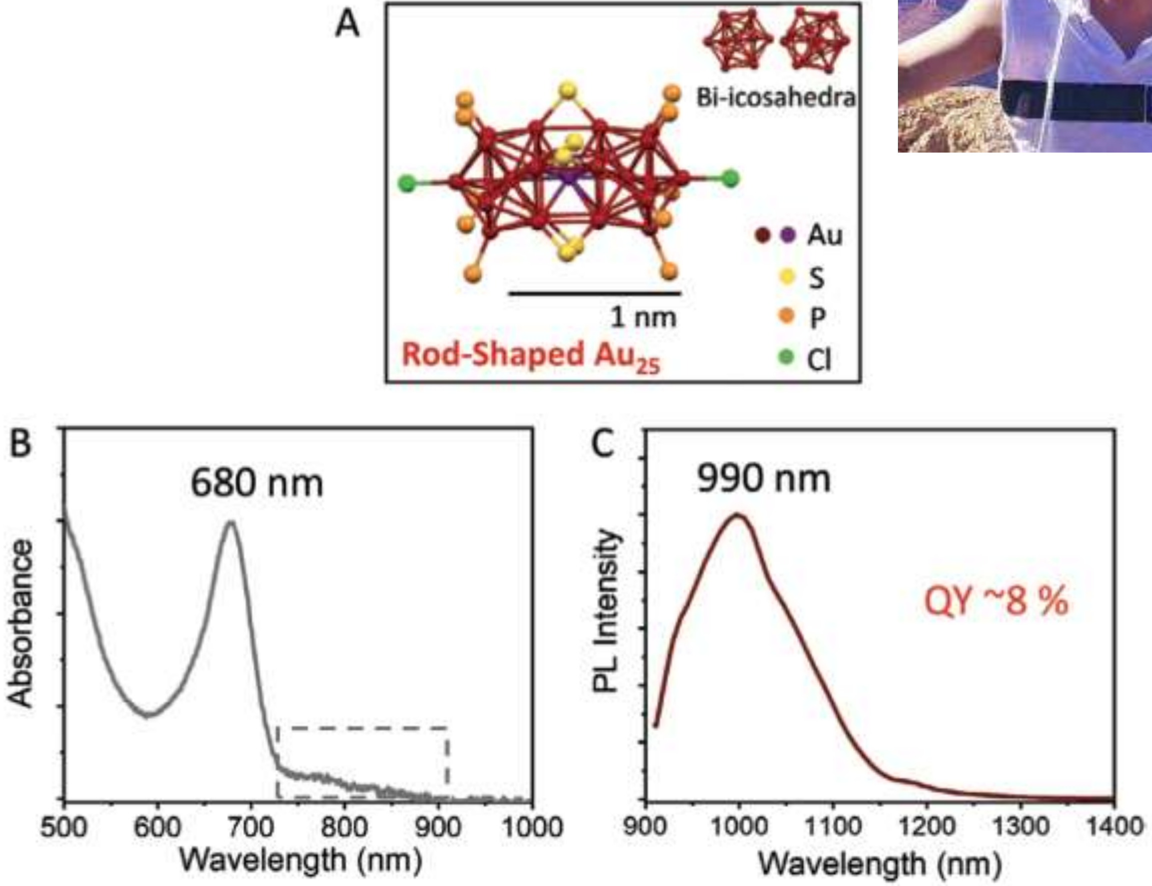
Library of metallic nanoclusters

- High two-photon absorption
- Long exciton lifetime of ~3 μs
- Initiates redox reactions
- Soluble in PETA monomer
- Stable under fabrication conditions



$Ag_{28}Pt_1(S\text{-}Adm)_{18}(PPh_3)_4$

$PtAg_{12}$ Mono-Cuboctahedron



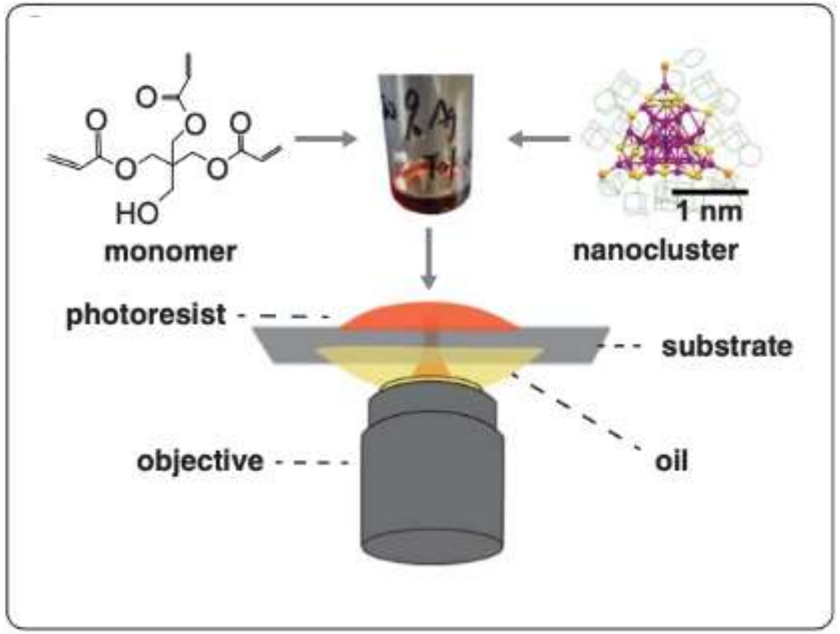
Qi Li, *et al*, *ACS Nano* **2020**

Qi Li, *et al*, *Small* **2021**

Qi Li, *et al*, *ACS Nano* **2021**

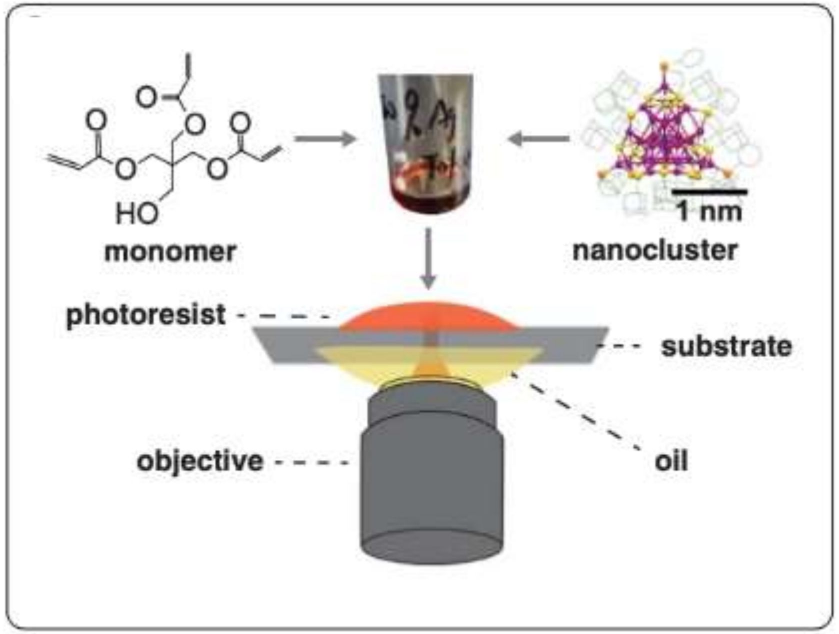
Qi Li, *et al*, *Nature Comm* **2020**

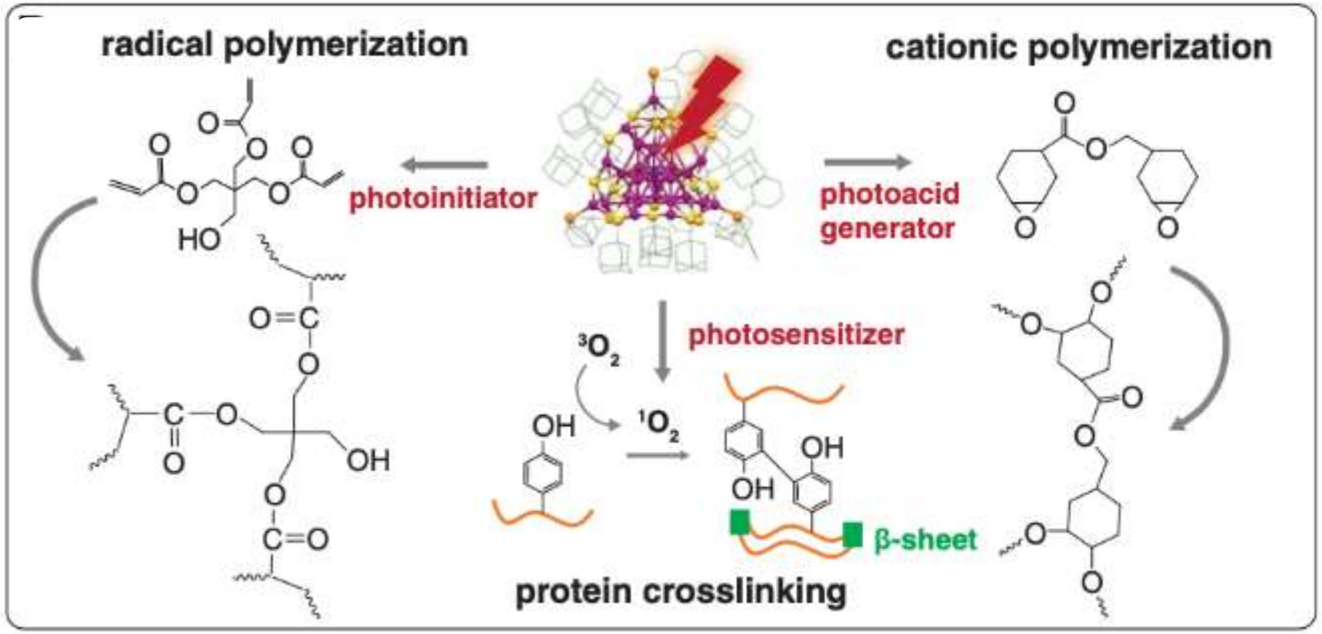
Photochemistry



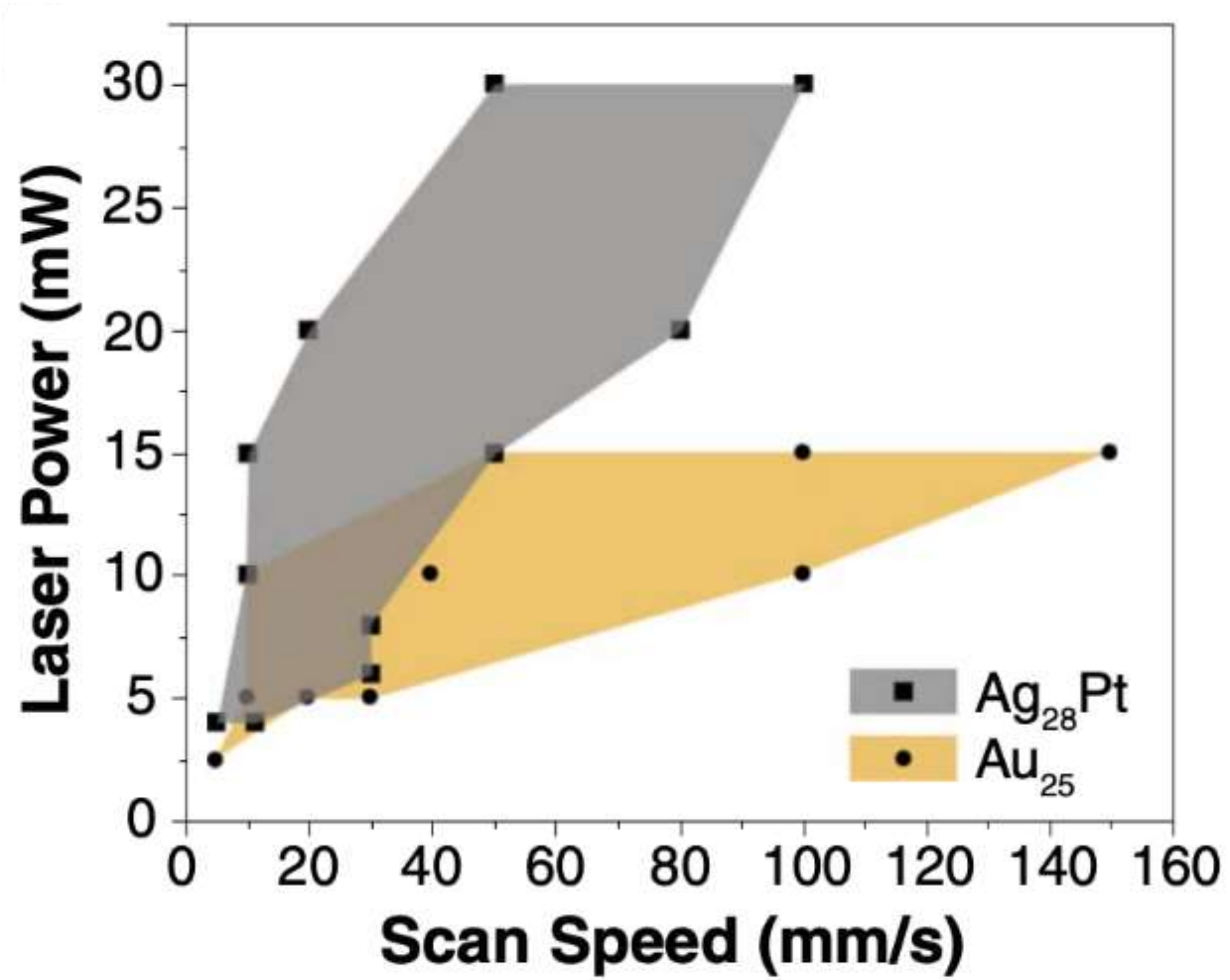
Photochemistry





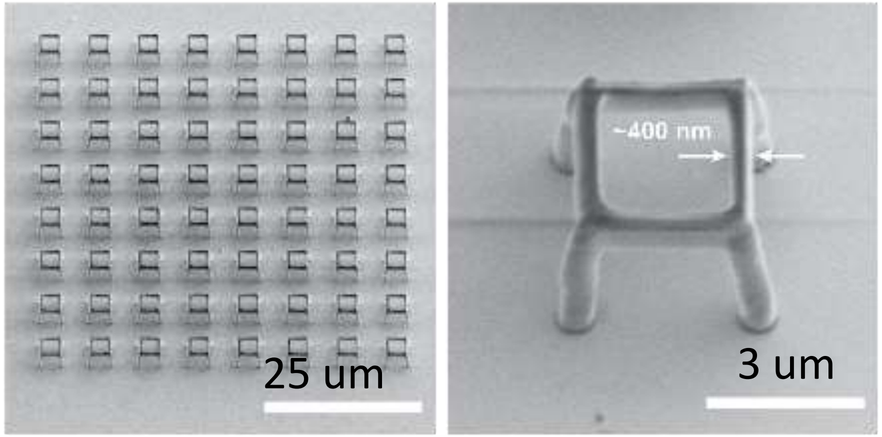


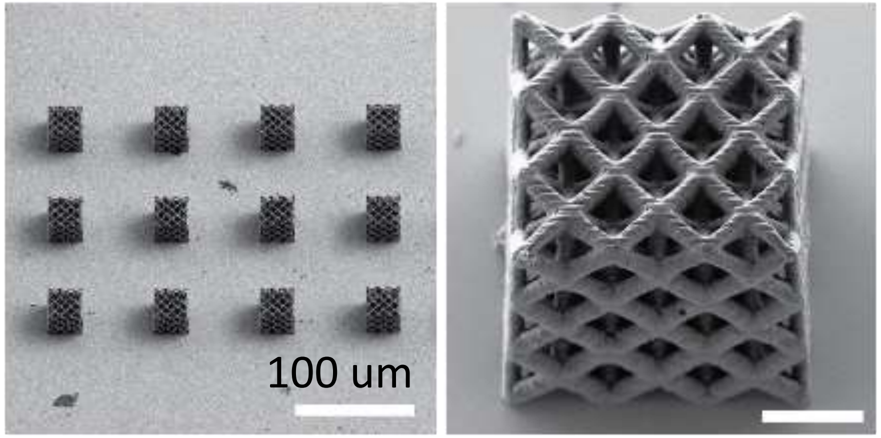
Printability



Nanoscale 3D printing

5 wt% $Ag_{28}Pt$ resin

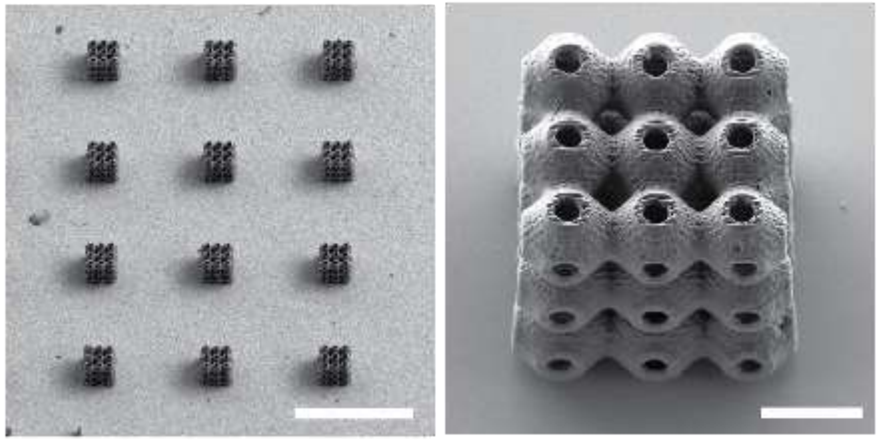




8 wt% Au_{25} resin

10 um

8 wt% $Ag_{28}Pt$ resin

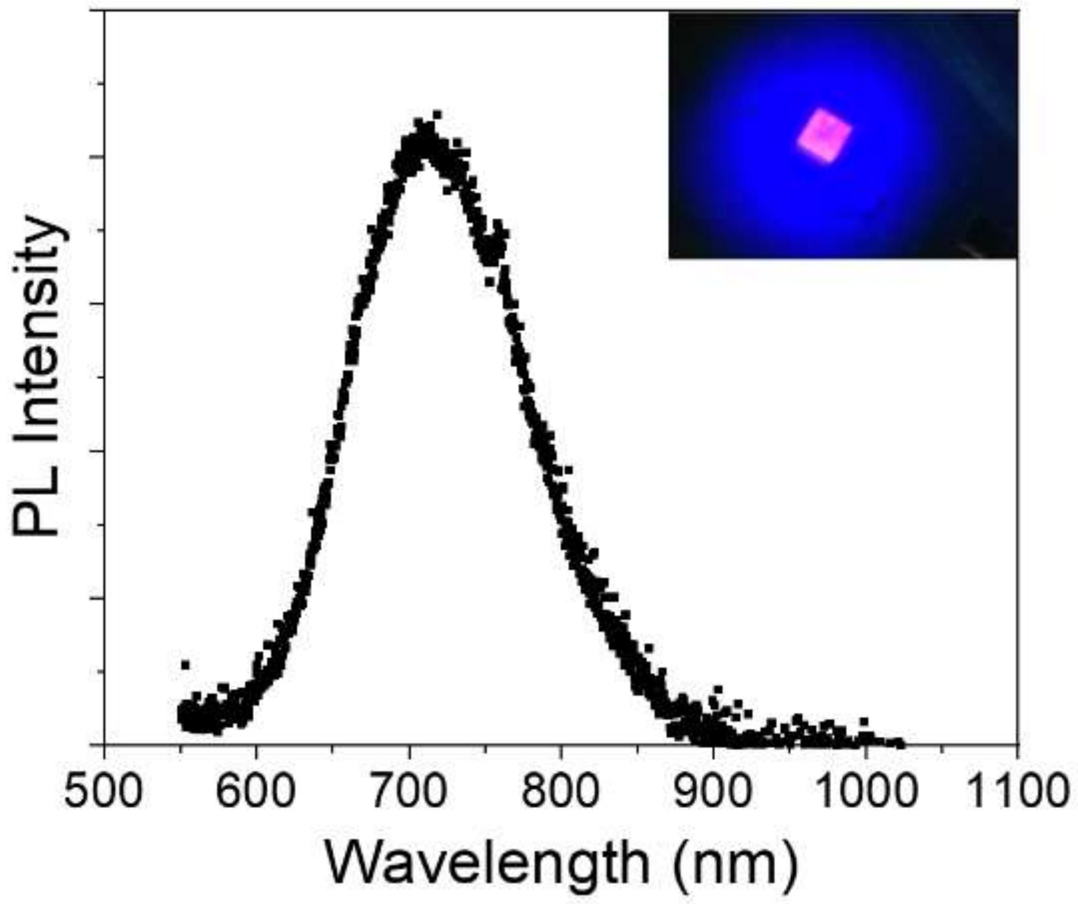


100 um

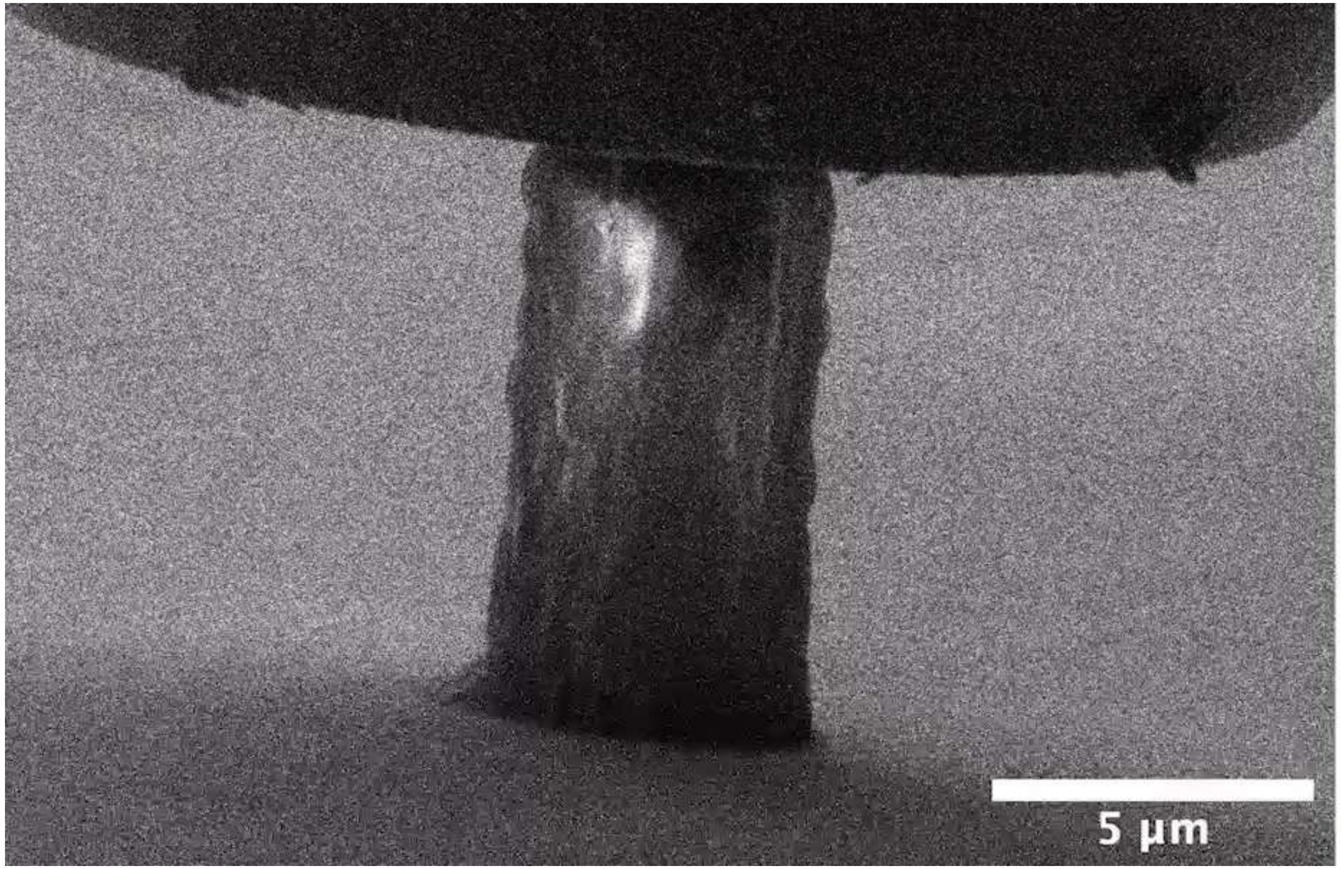
10 um

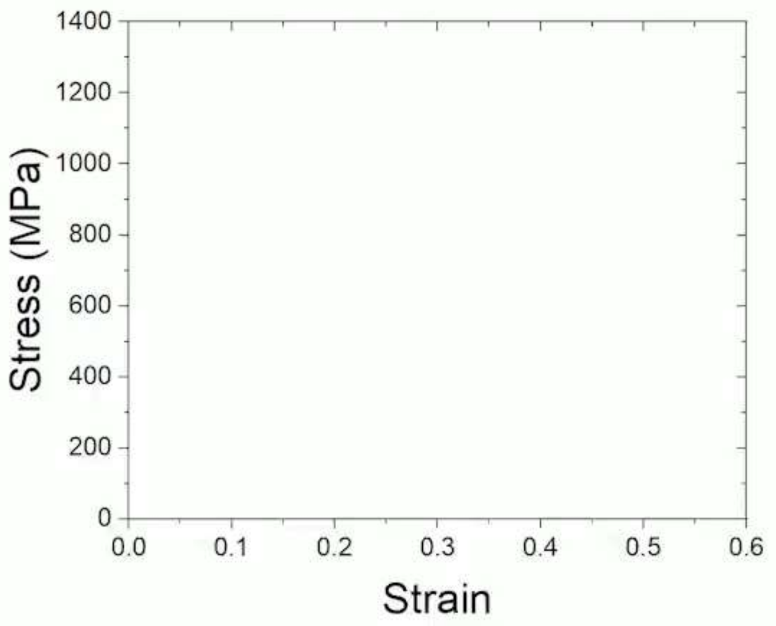
Li*, Kulikowski*, Doan* et al., Science (2022)

Luminescence is preserved

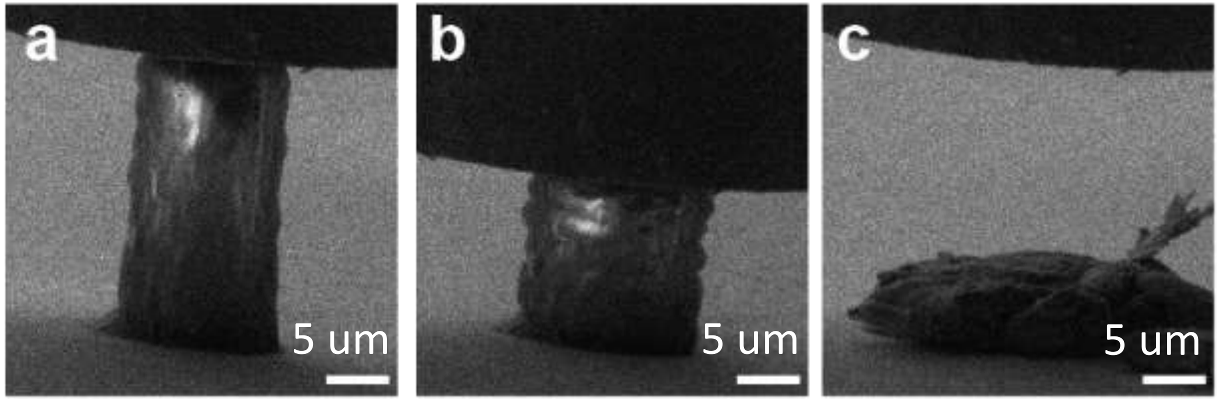


Nanocomposite micropillar in compression

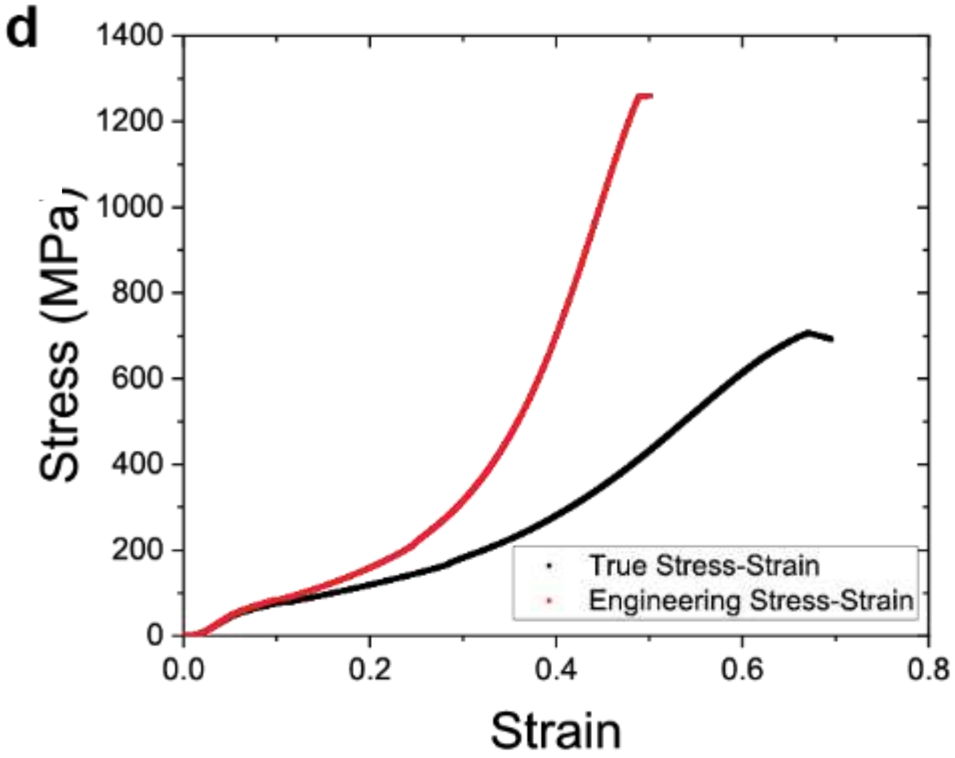




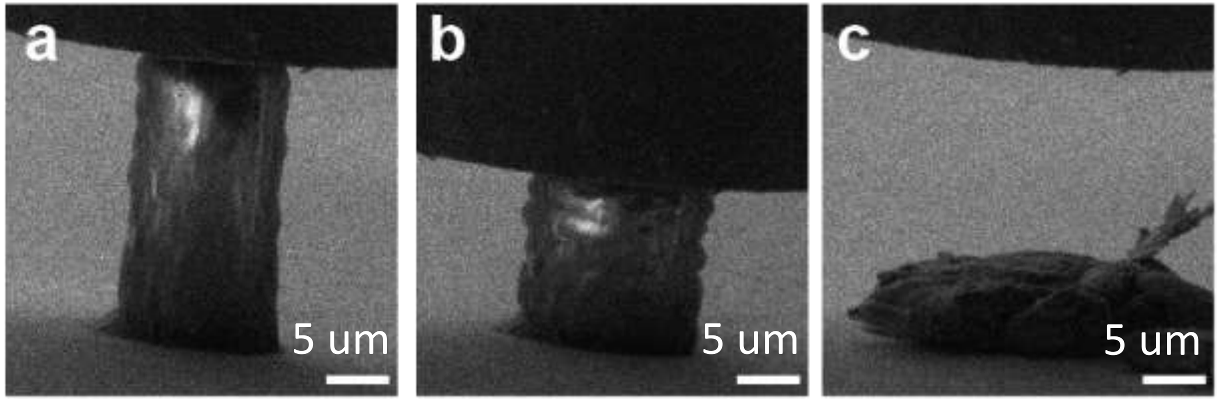
True stress-strain response

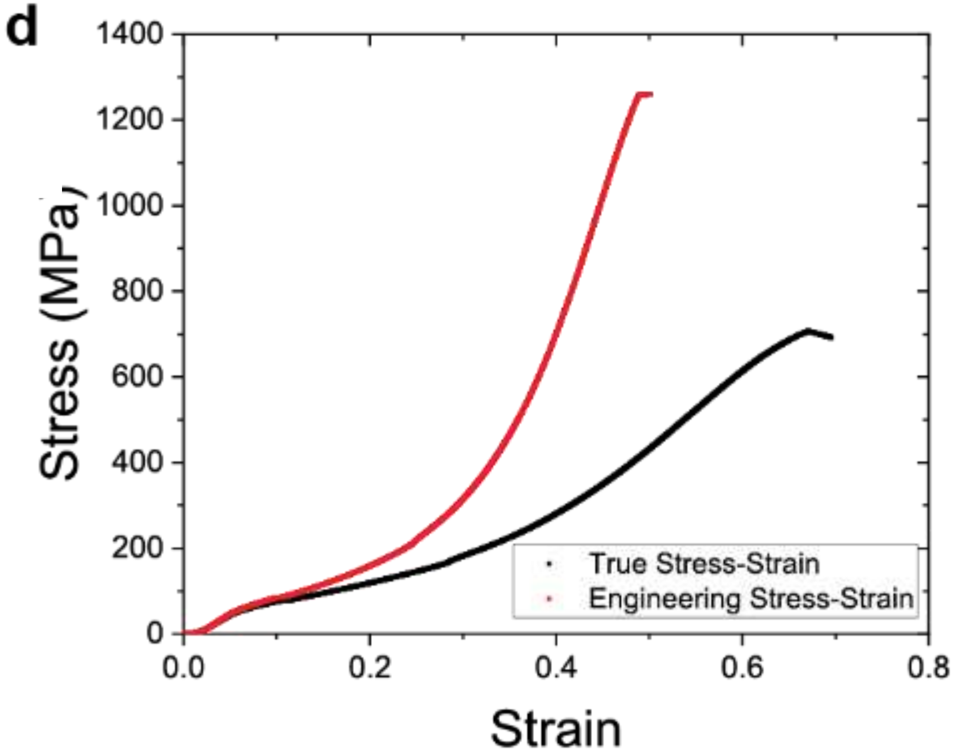


Poisson ratio of 0.4



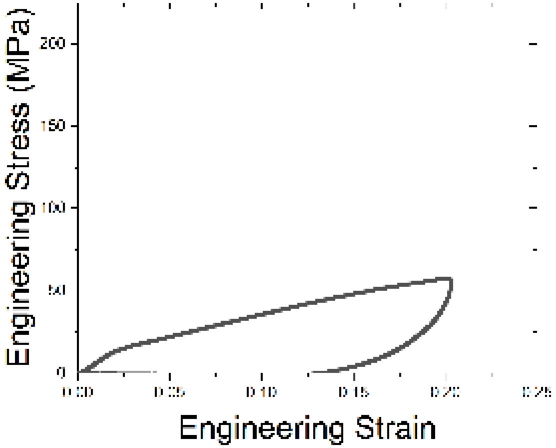
True stress-strain response



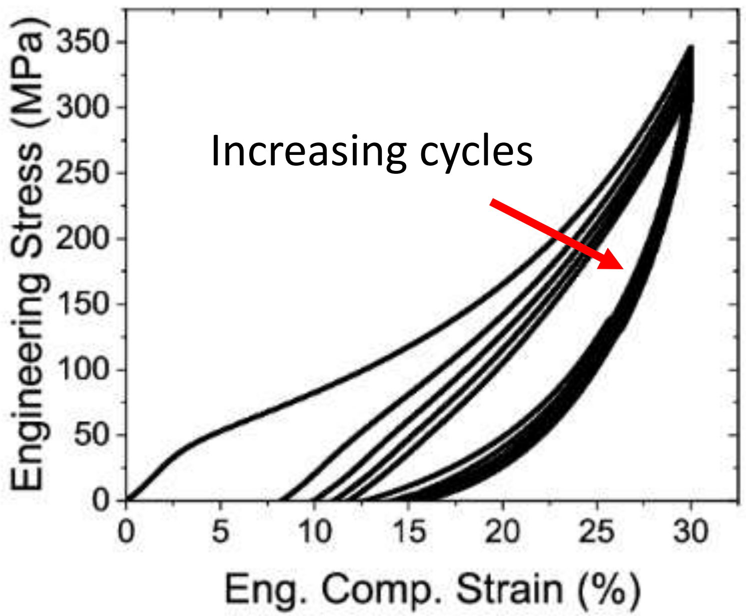


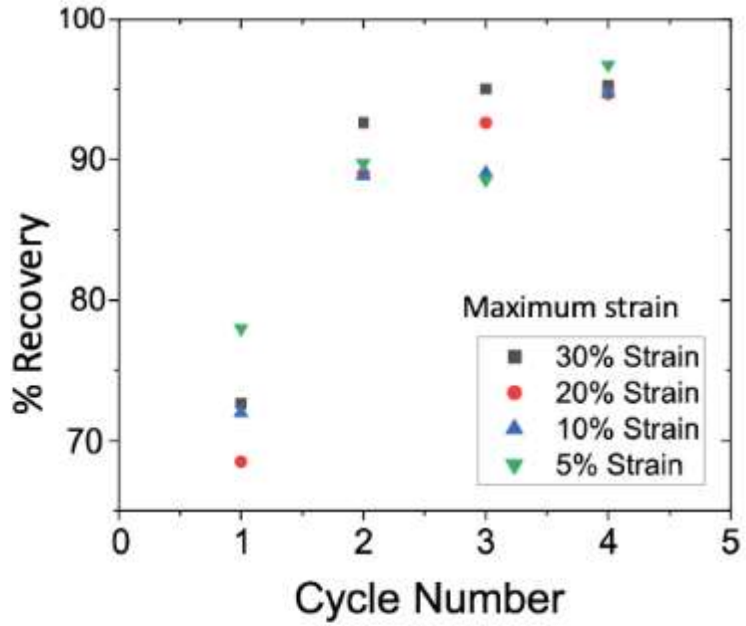
Poisson ratio of 0.4

Polymer resin (Ip-Dip)



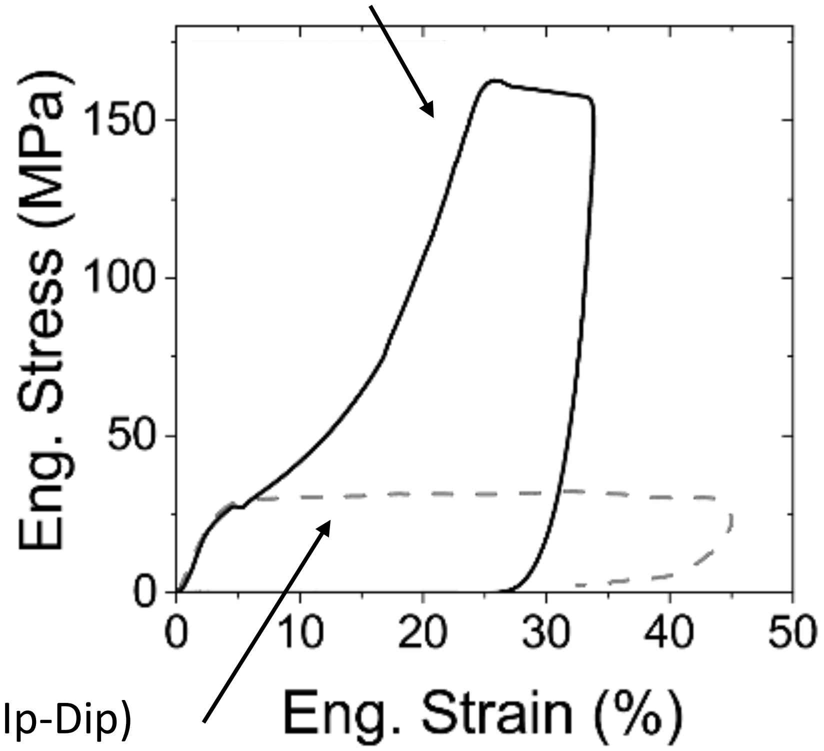
Recoverability



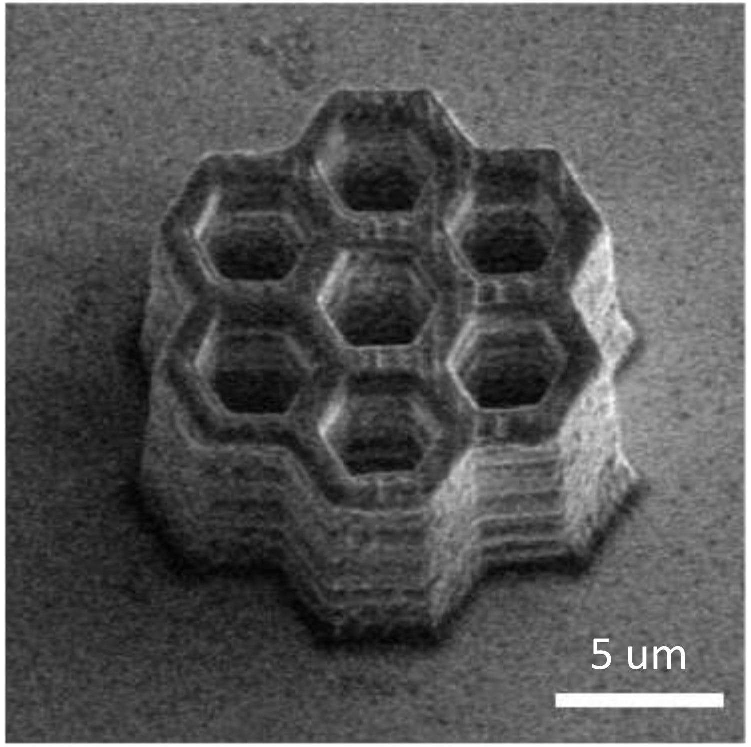


Strain hardening in honeycomb structures

10 wt% $Ag_{28}Pt$ resin



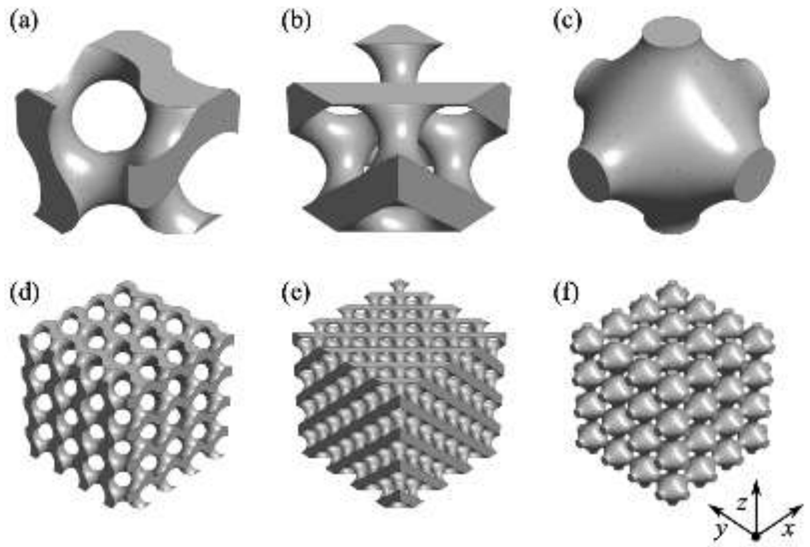
Polymer resin (Ip-Dip)
Mieszala et al., Small (2017)



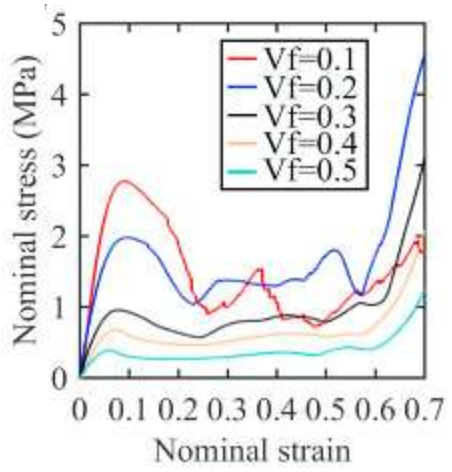
Li*, Kulikowski*, Doan* et al., Science (2022)

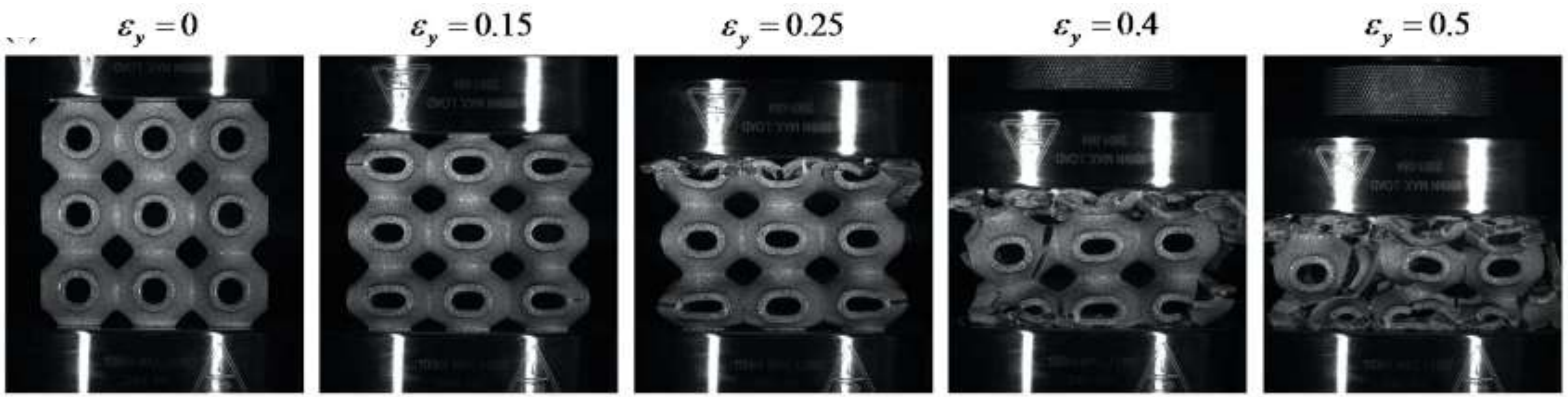
Cellular lattices for energy absorption

Triply periodic minimal surfaces



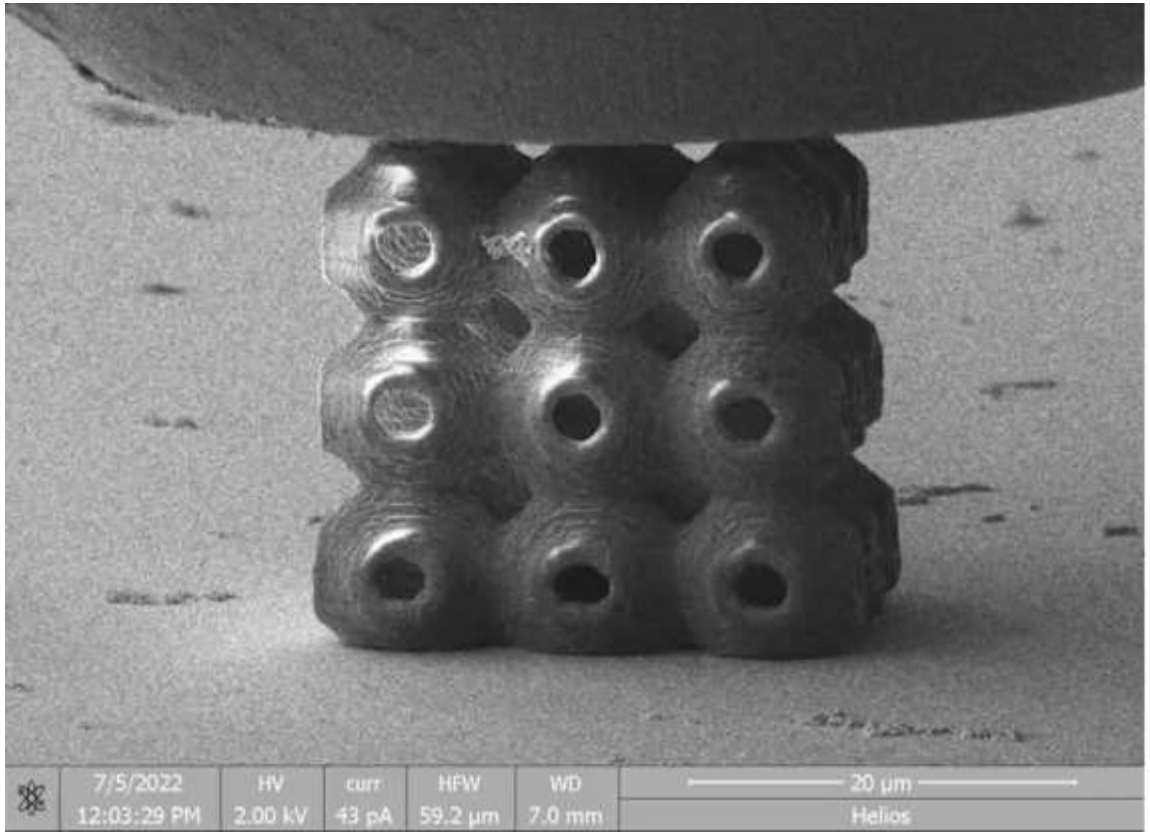
Maskery et al., Polymer (2018)

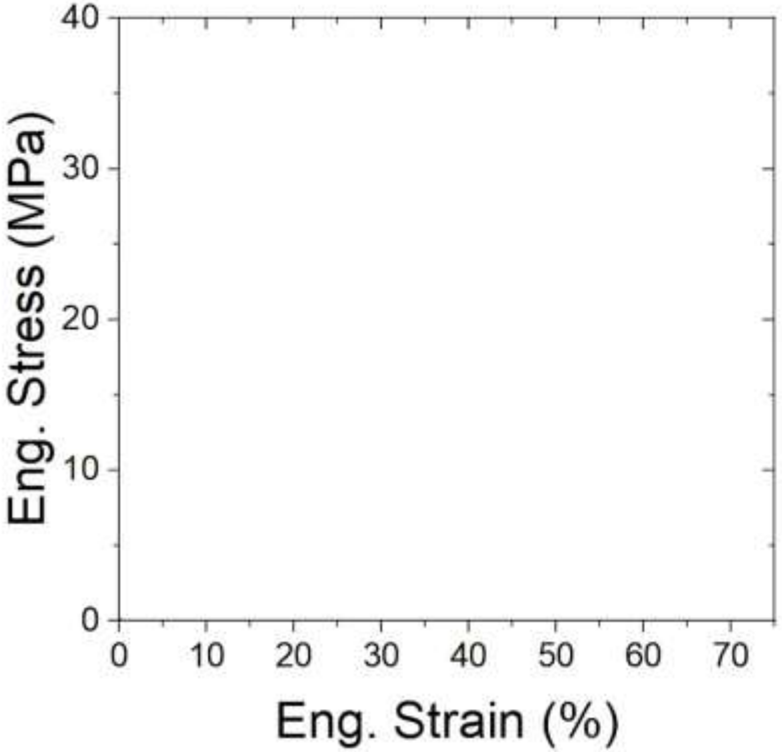




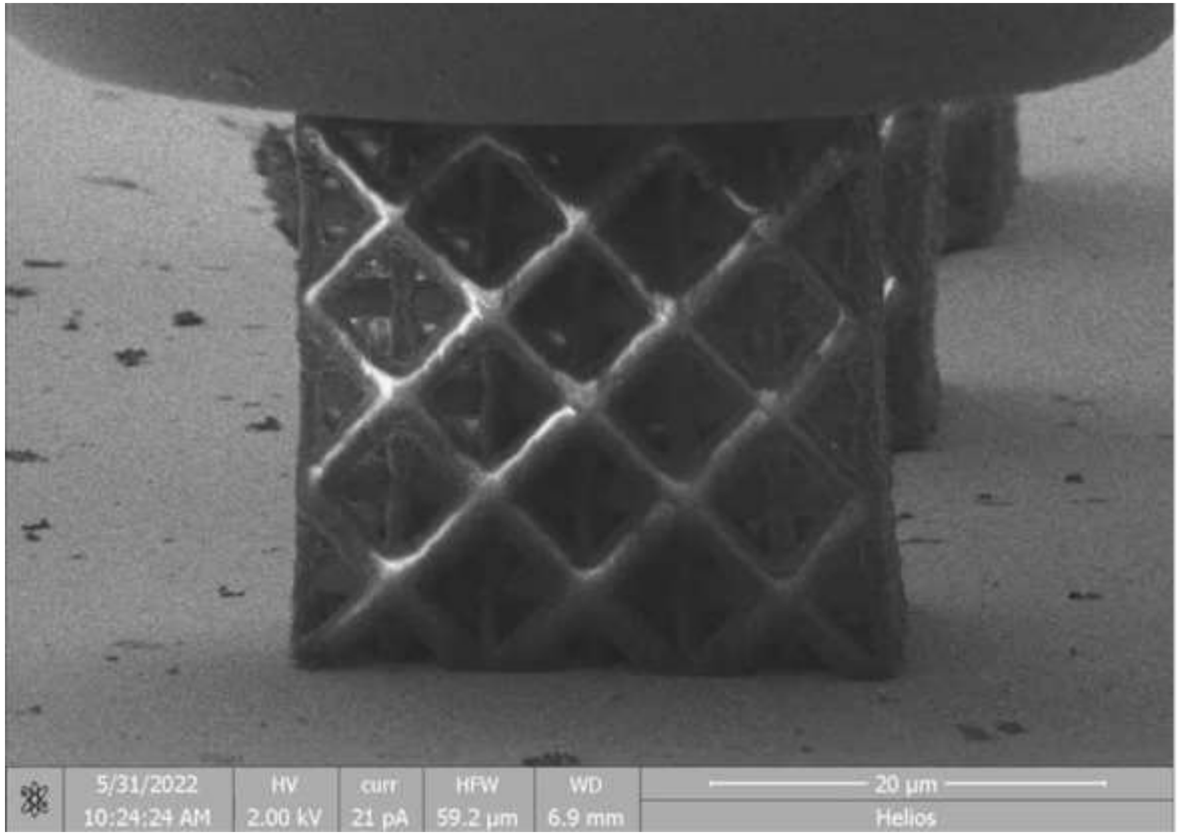
Jiang et al., Additive Manufacturing (2020)

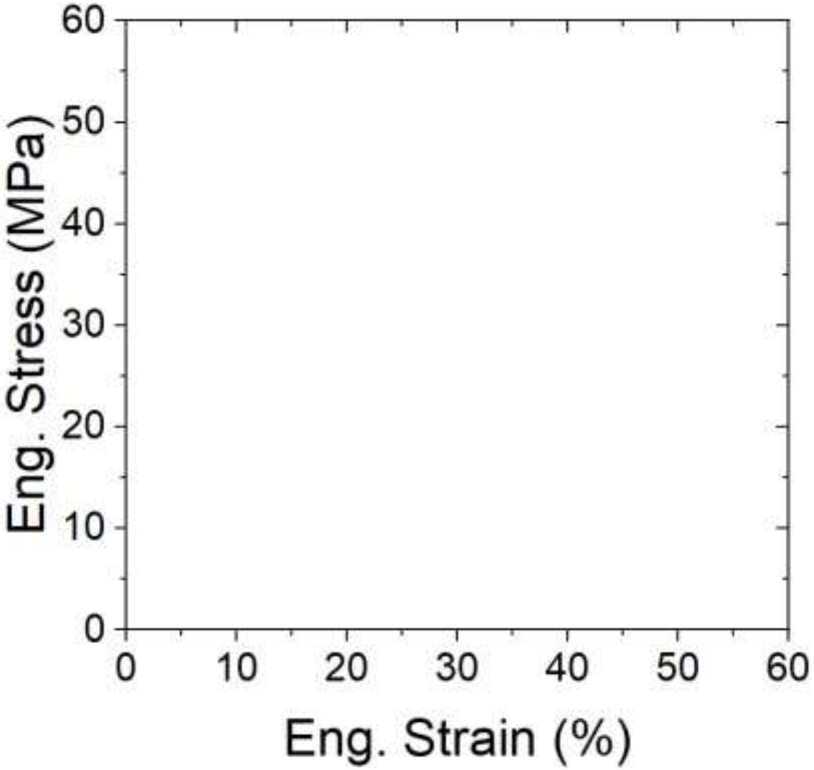
TPMS lattice



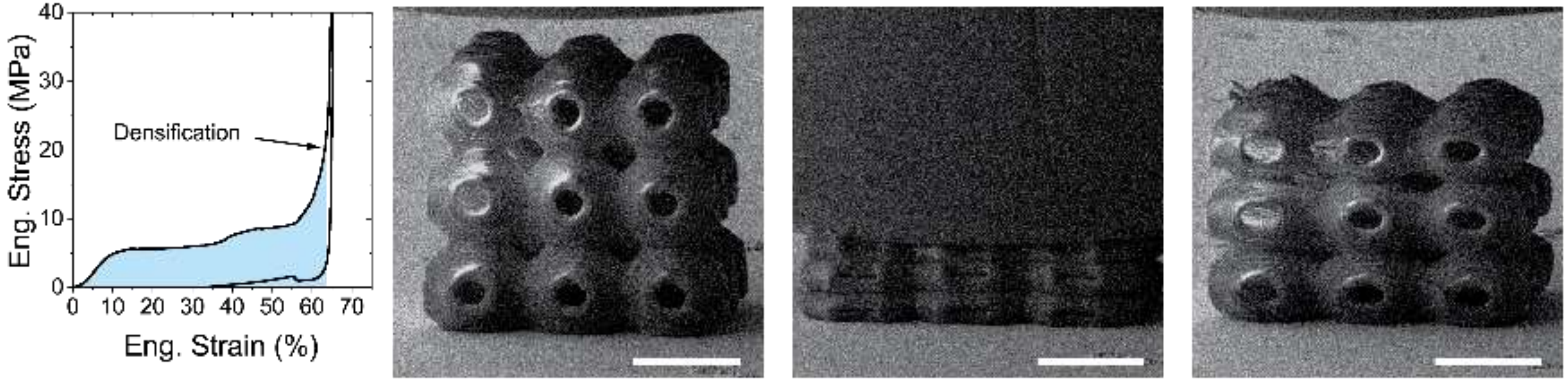


Octet lattice



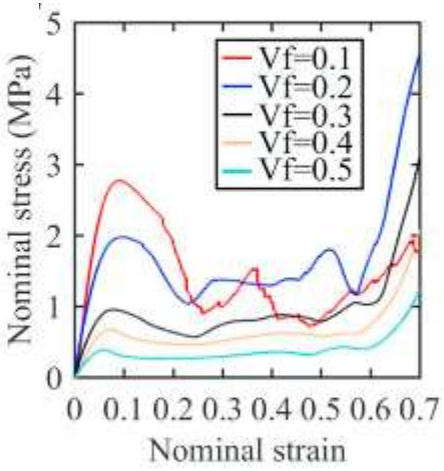


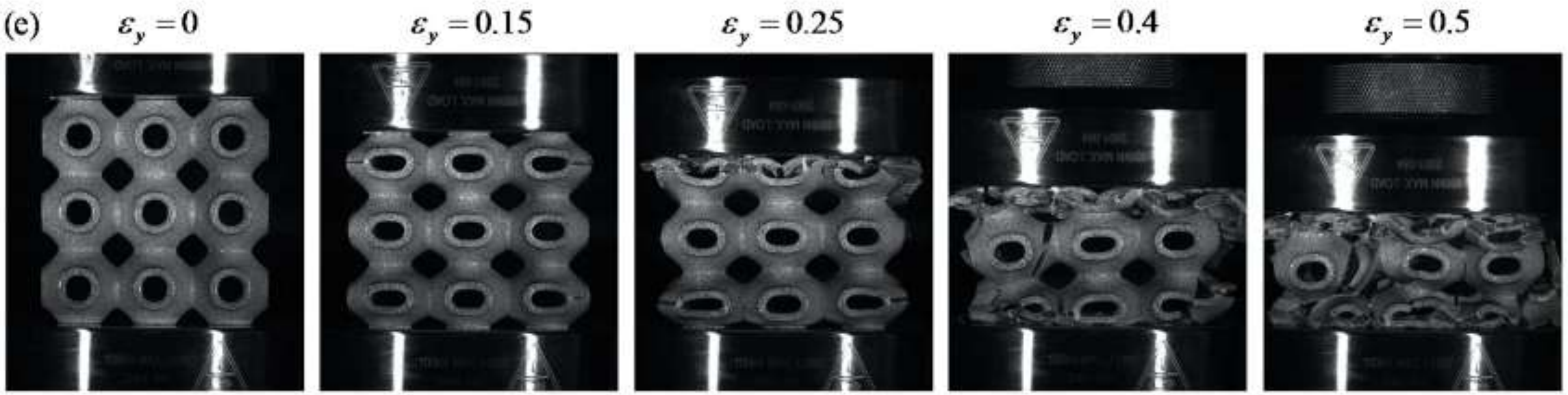
Nanocomposite lattices



10 um

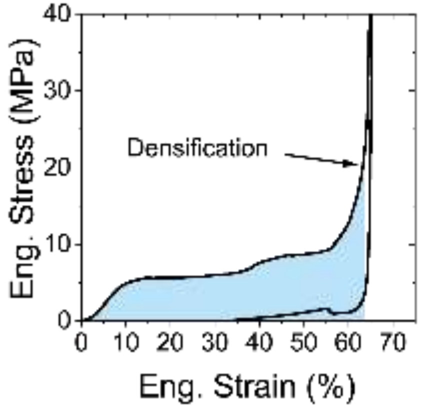
Nanocomposite lattices

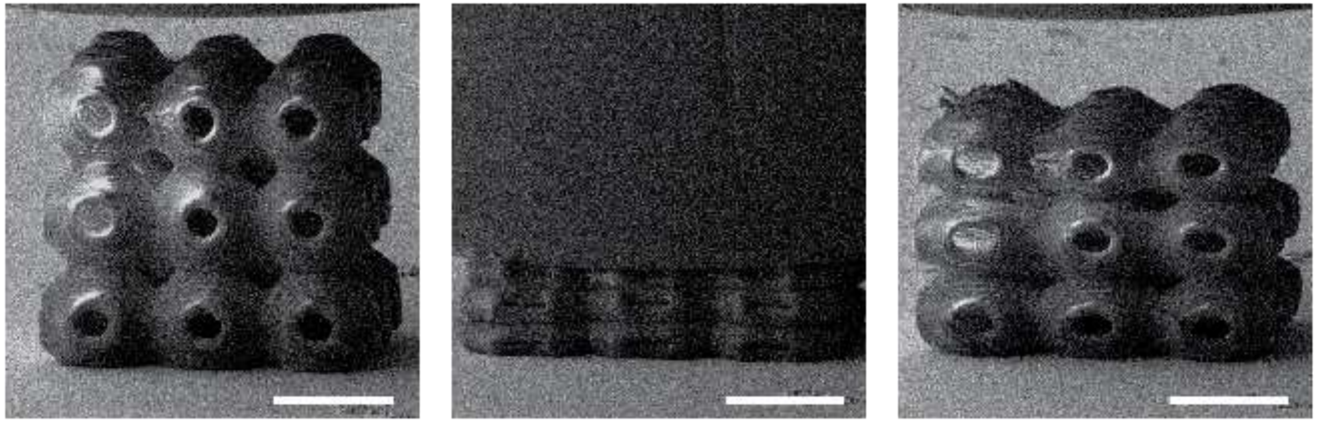




Jiang et al., Additive Manufacturing (2020)

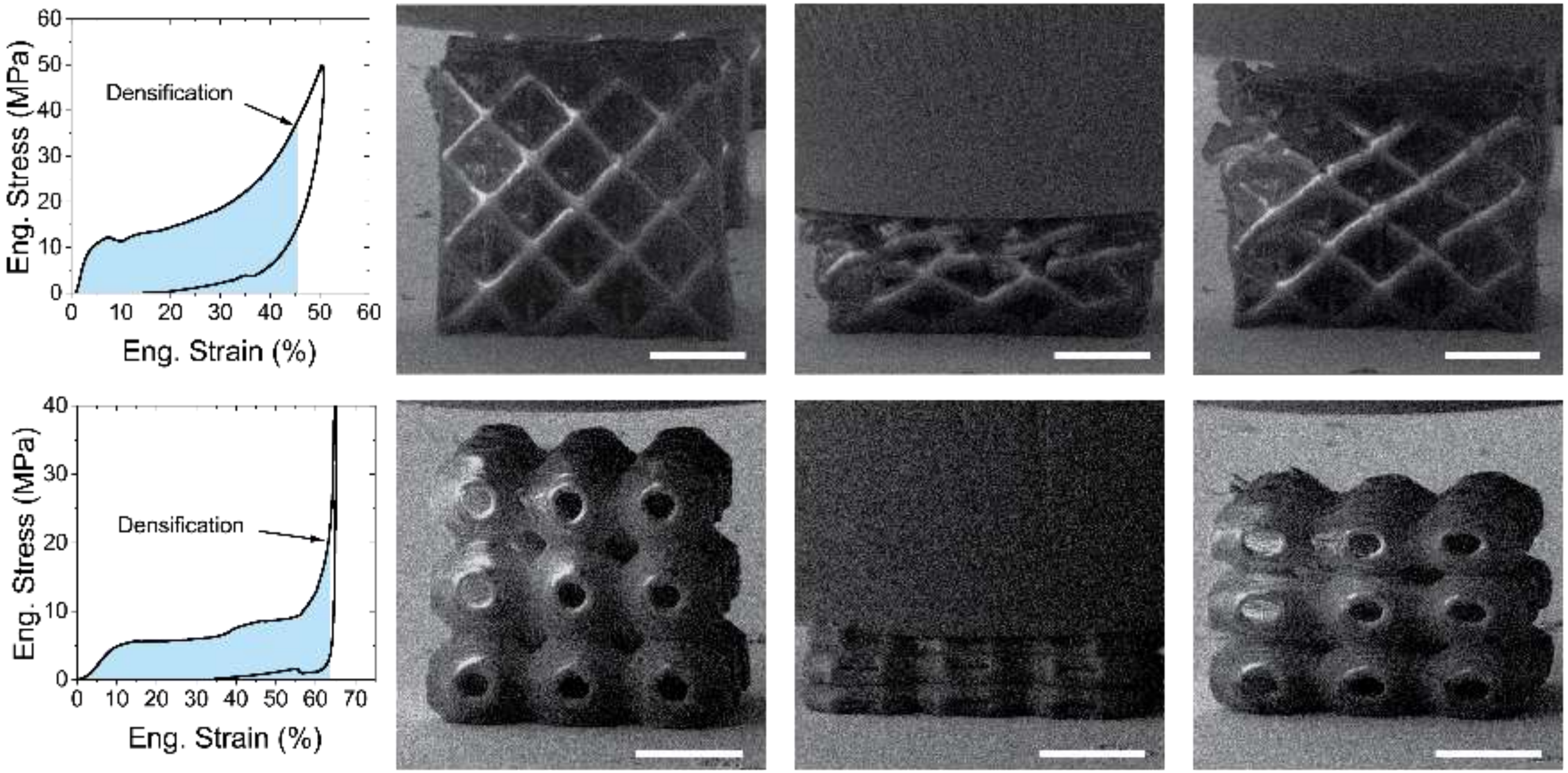
Relative density: 0.2





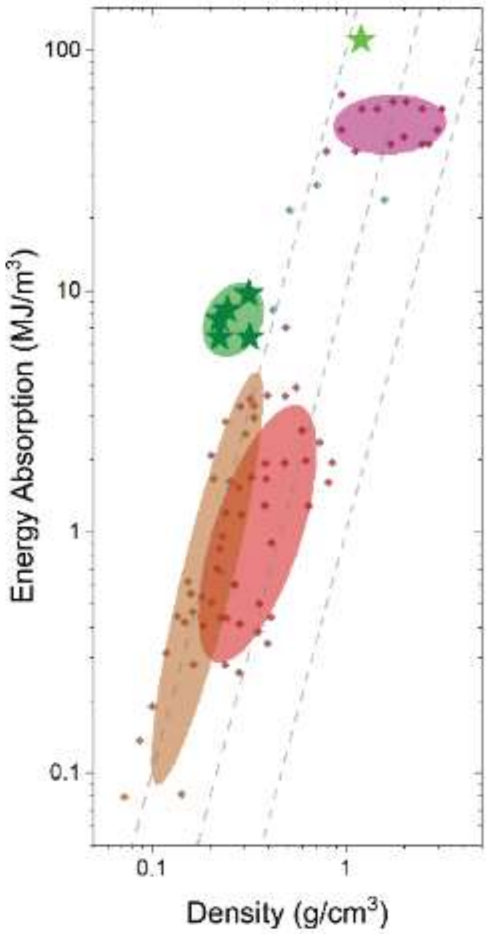
10 um

Nanocomposite lattices



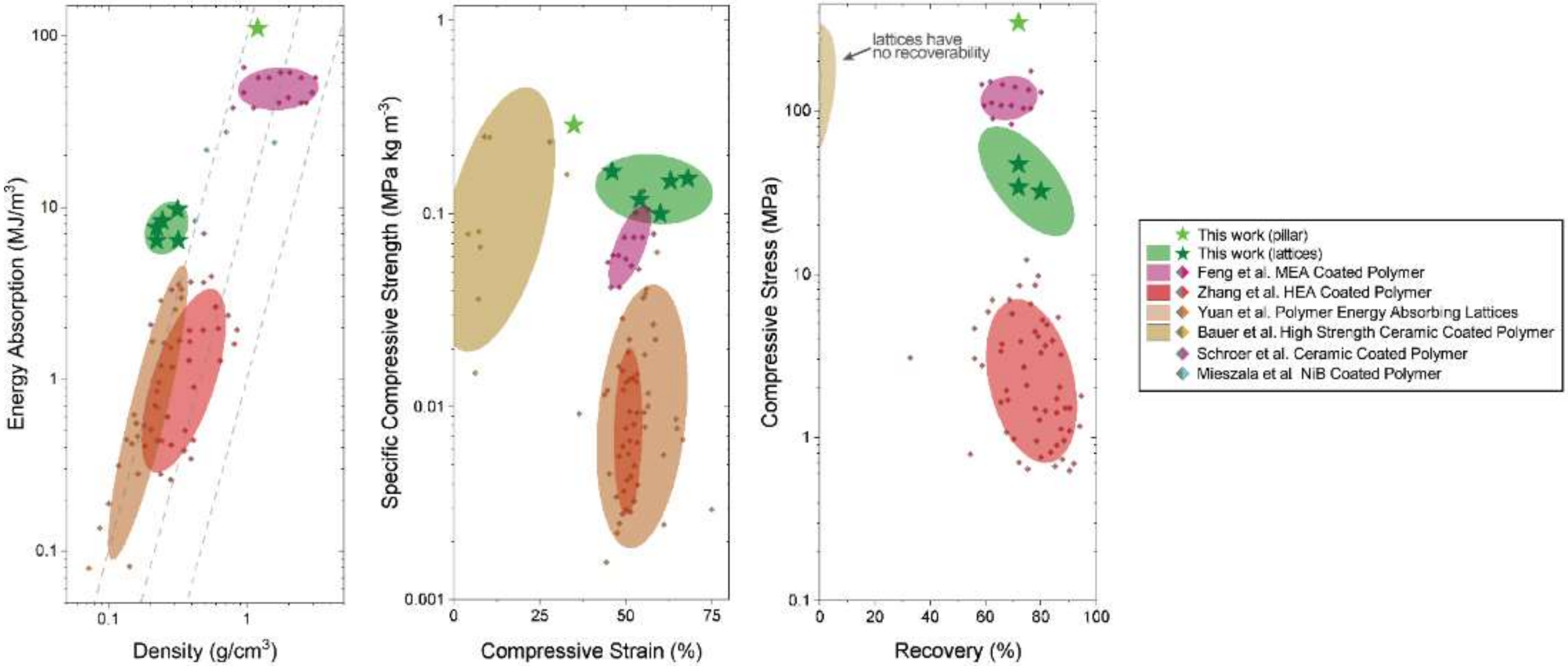
10 um

Comparison to other lattices

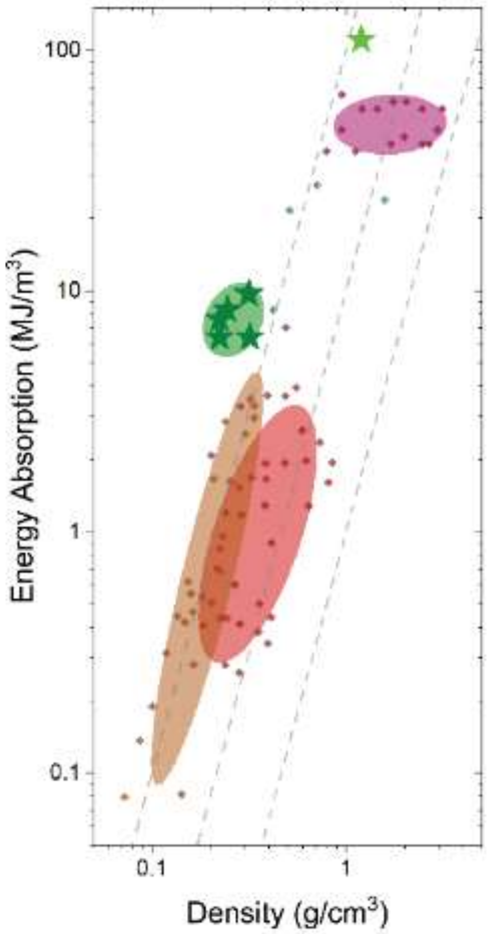


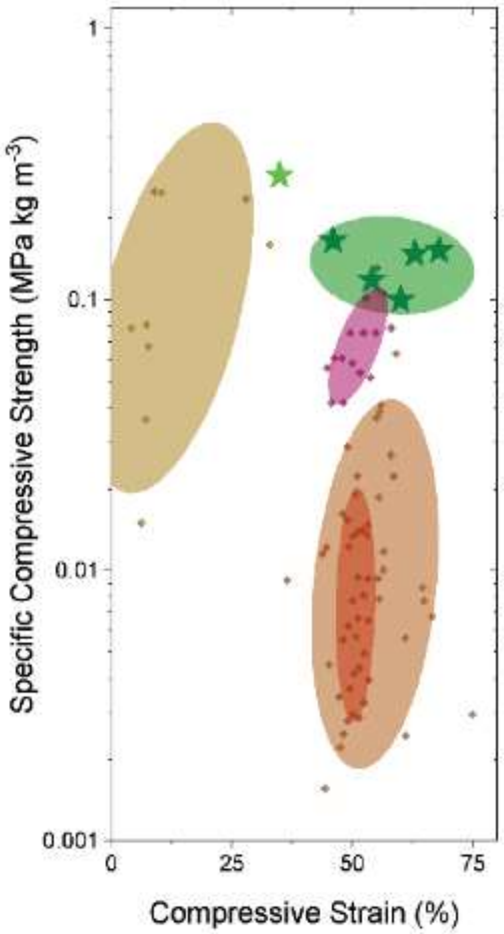
Li*, Kulikowski*, Doan* et al., Science (2022)

Comparison to other lattices



Comparison to other lattices





Rapid manufacturing

Previous fabrication route:
Polymer with inorganic coating

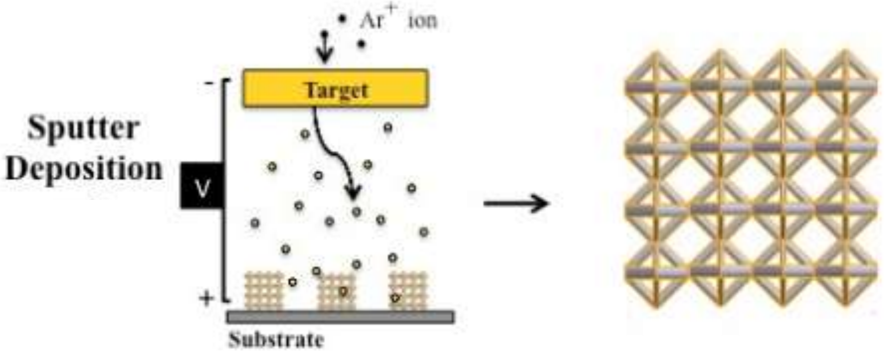
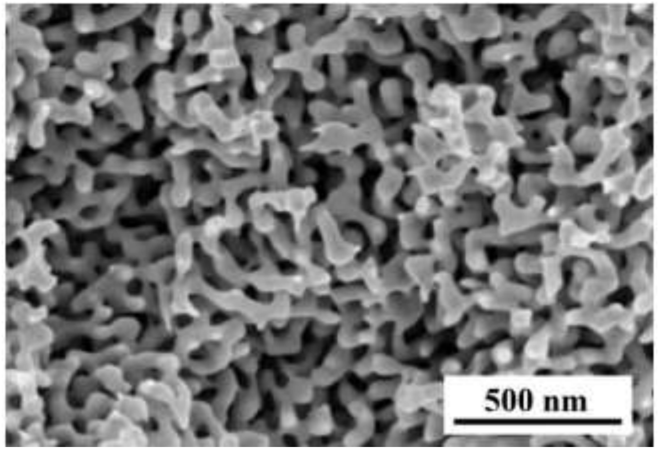
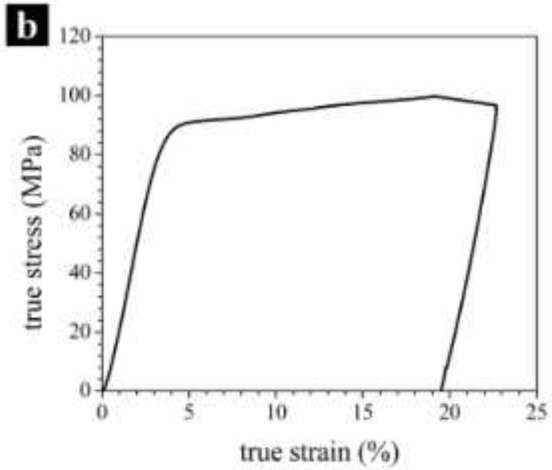


Image from Montemayor *et al.*, *Adv. Eng. Mat.* (2013)

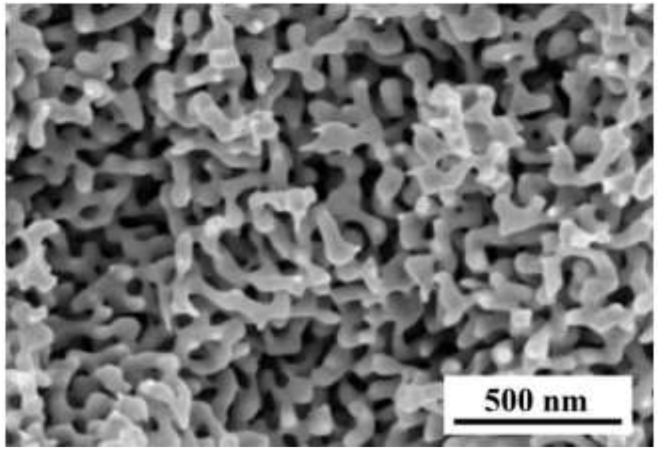
Strong and stiff nanoporous nanostructures

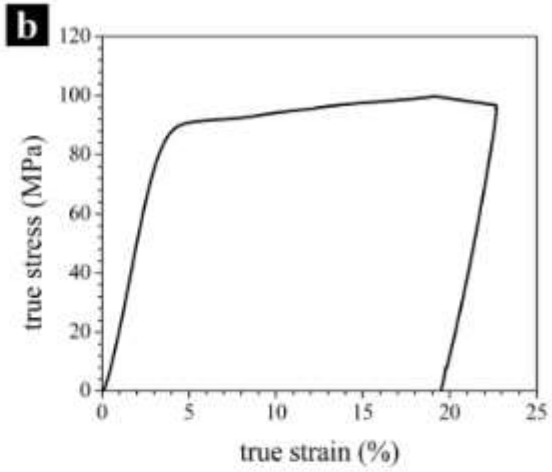




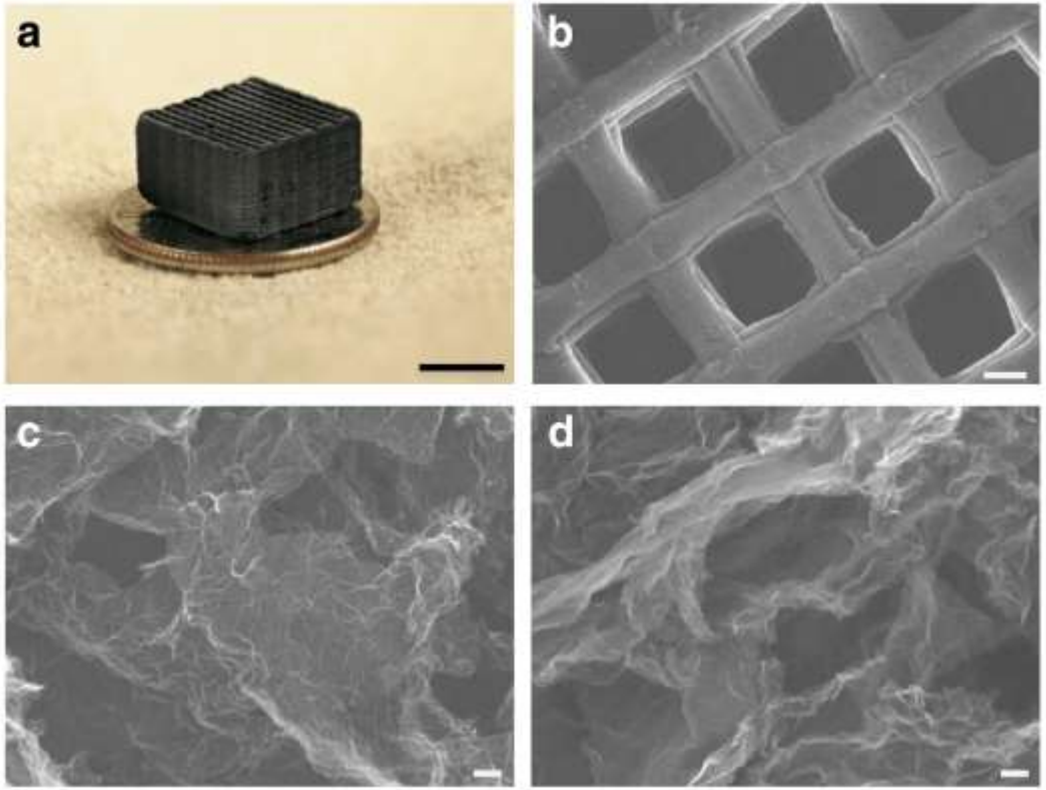
Biener, Hodge et al., Nano Letters (2006)

Strong and stiff nanoporous nanostructures





Biener, Hodge et al., Nano Letters (2006)

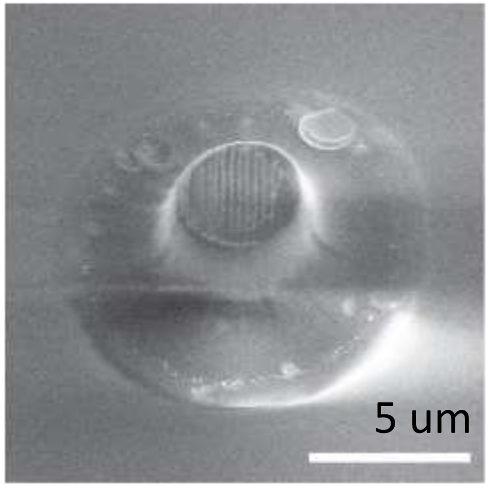


Zhu et al., Nat. Comm. (2015)

Towards additive manufacturing of nano-hierarchical materials

Nanoporous glassy carbon

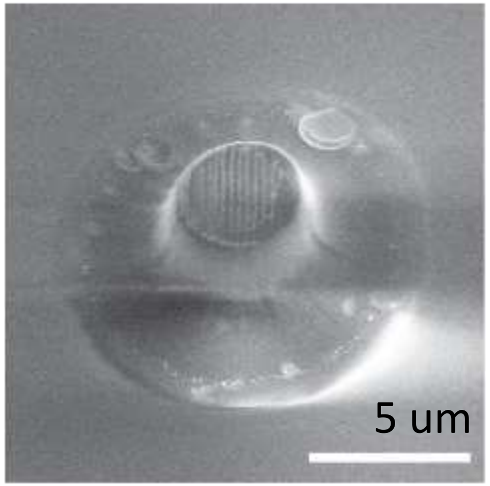
Pyrolysis at 500°C, Ar flow
20 wt% $Ag_{28}Pt$ resin



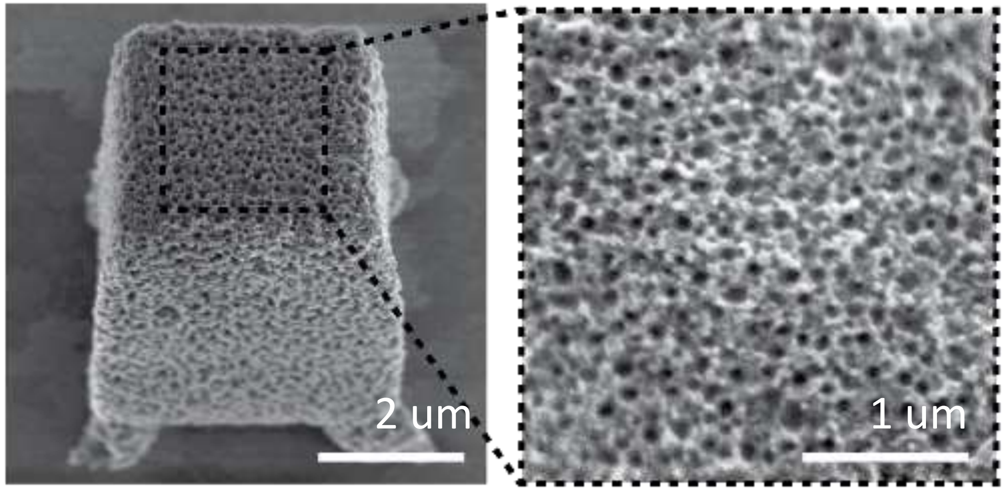
Li*, Kulikowski*, Doan* et al., Science (2022)

Nanoporous glassy carbon

Pyrolysis at 500°C, Ar flow
20 wt% $Ag_{28}Pt$ resin



Pyrolysis at 800°C under argon flow
20 wt% $Ag_{28}Pt$ resin

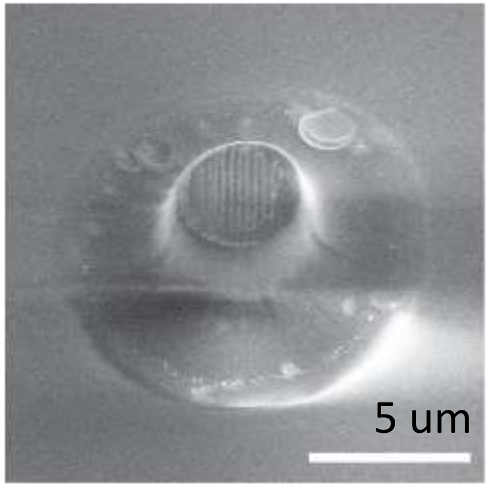


~50% surface porosity

Li*, Kulikowski*, Doan* et al., Science (2022)

Nanoporous glassy carbon

Pyrolysis at 500°C, Ar flow
20 wt% $Ag_{28}Pt$ resin



Pyrolysis at 800°C under argon flow
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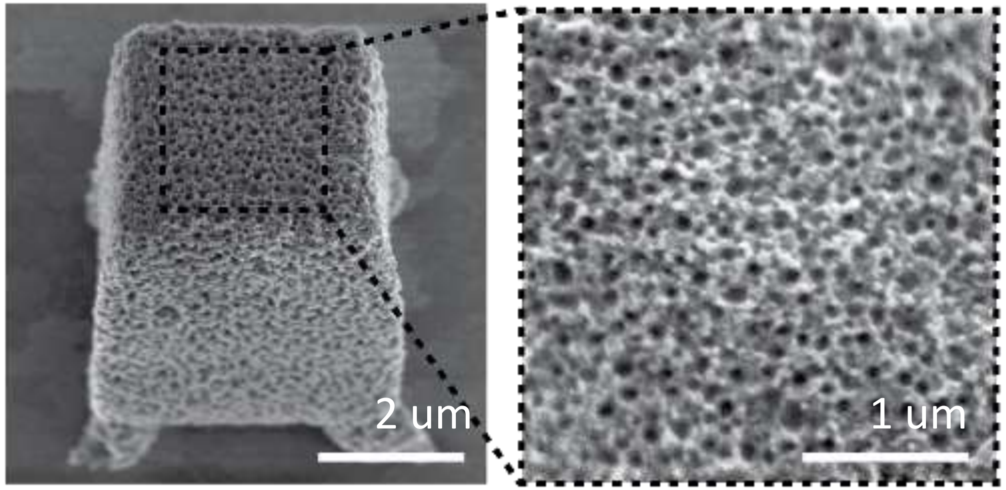
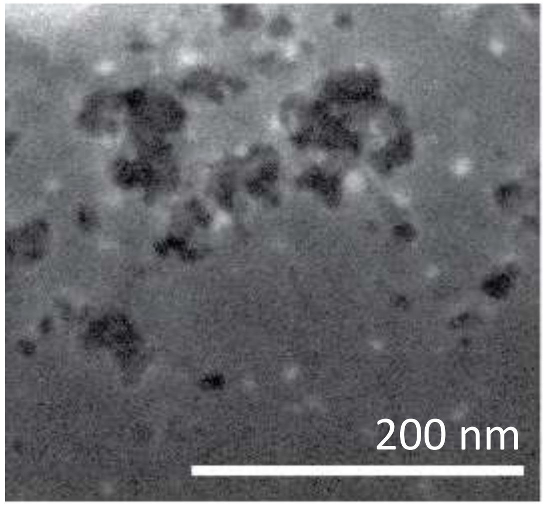
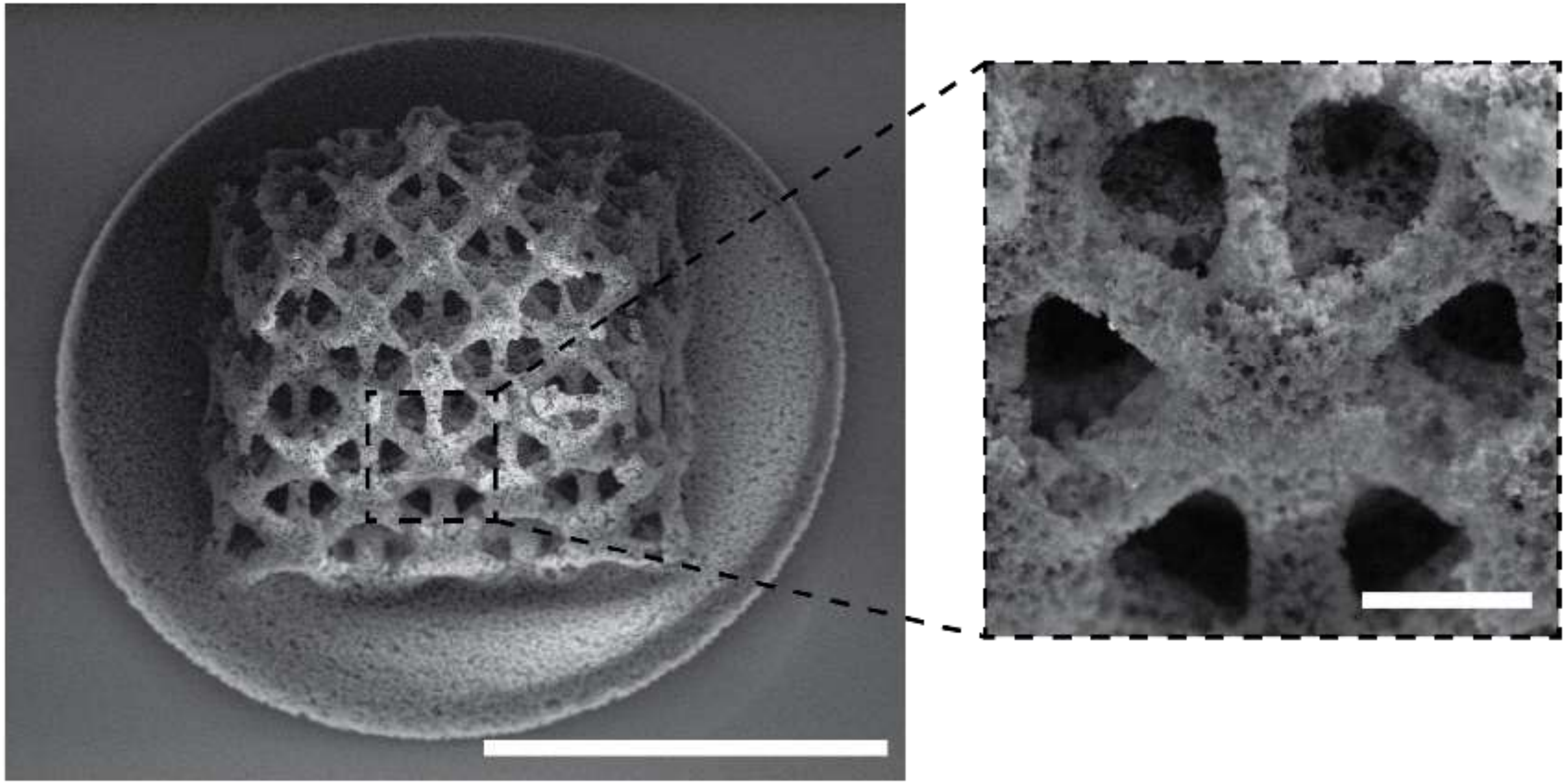


Cross-section



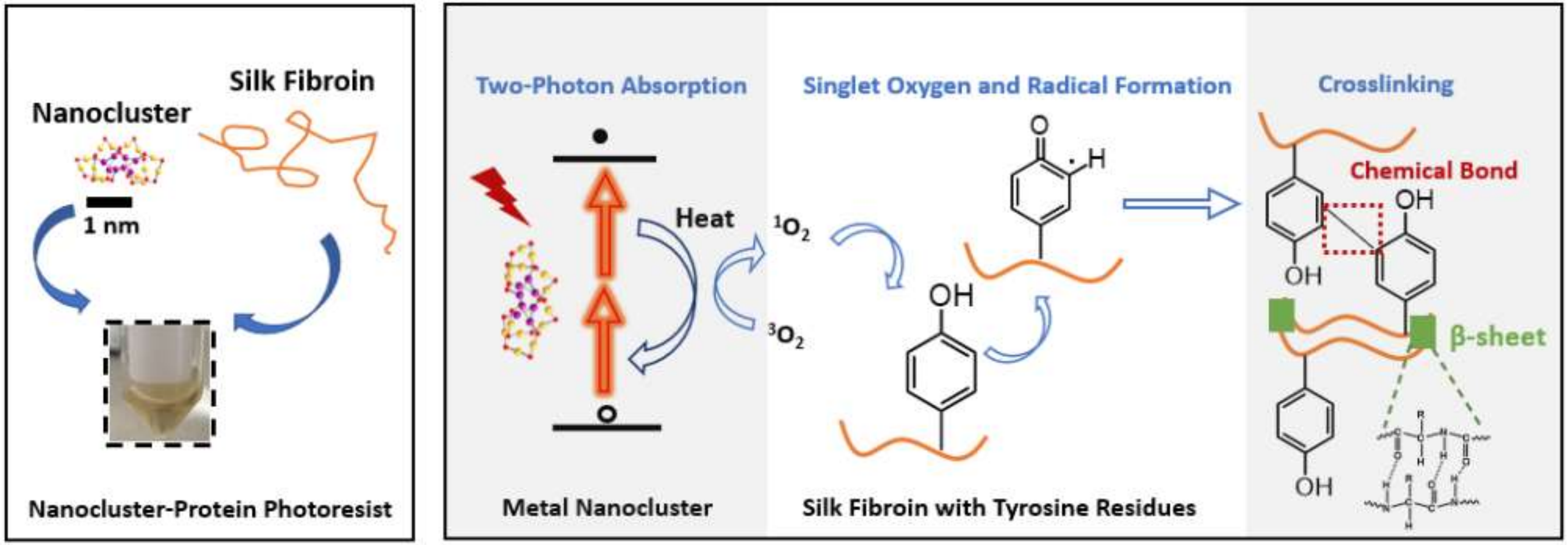
Li*, Kulikowski*, Doan* et al., Science (2022)

Nanoporous octet lattices



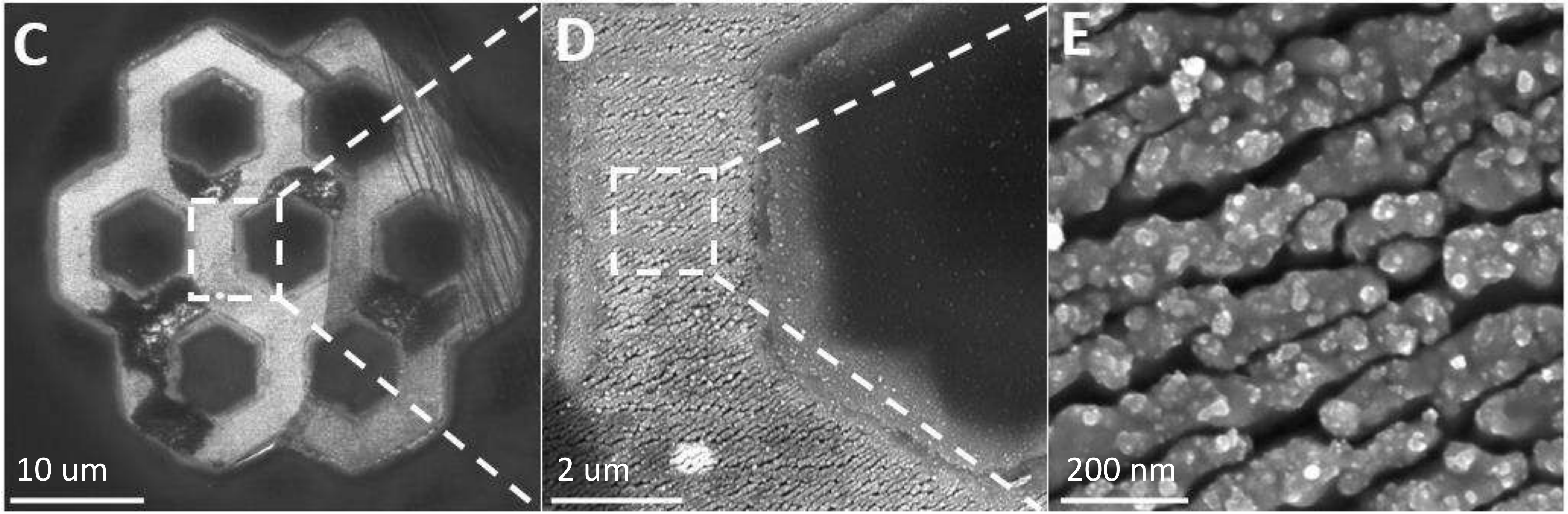
Li*, Kulikowski*, Doan* et al., Science (2022)

Protein photochemistry



Li*, Kulikowski*, Doan* et al., Science (2022)

Anisotropic porosity in printed silk

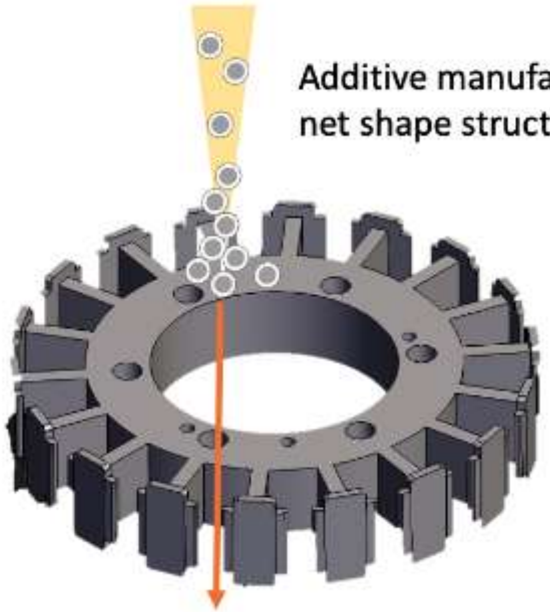


Li*, Kulikowski*, Doan* et al., Science (2022)

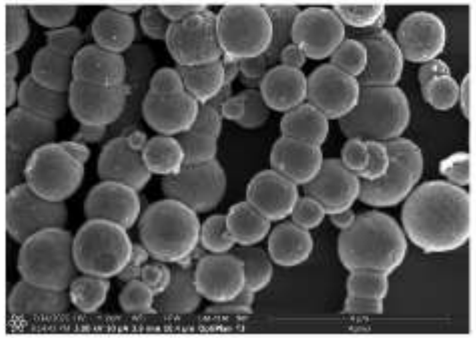
Nanomaterials for 3D printing

- Multifunctional
- Mechanical
- Thermal
- Magnetic

Additive manufacturing of metallic glass-oxide soft magnetic composites



Additive manufacturing of net shape structures



Solution processed metallic glass-oxide core-shell particles

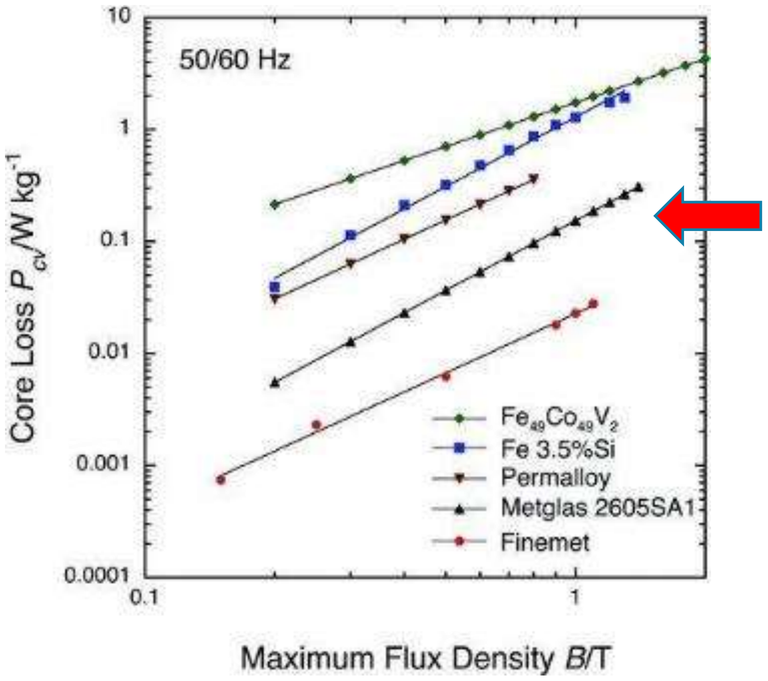
- Optimized material properties
- Simple fabrication process
- Design flexibility

Metric	State of the Art	Proposed
Maximum relative permeability	100,000	150,000
Core loss (W/kg)	200	20
Hardness (VH)	860	950
Cost ($/core)	25	12

Material selection and composite design

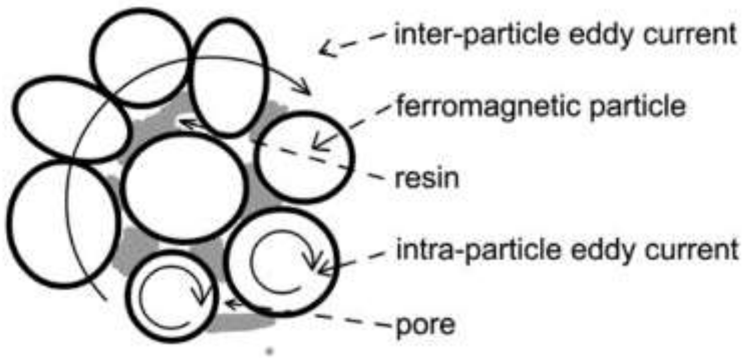
Amorphous metal

- Higher energy efficiency and lower core losses than crystalline magnets
- Good for higher switching frequencies



Gutfleisch, Willard, Bruck, Chen, Sankar, Liu, Adv. Mater. (2010)

Soft magnetic composite

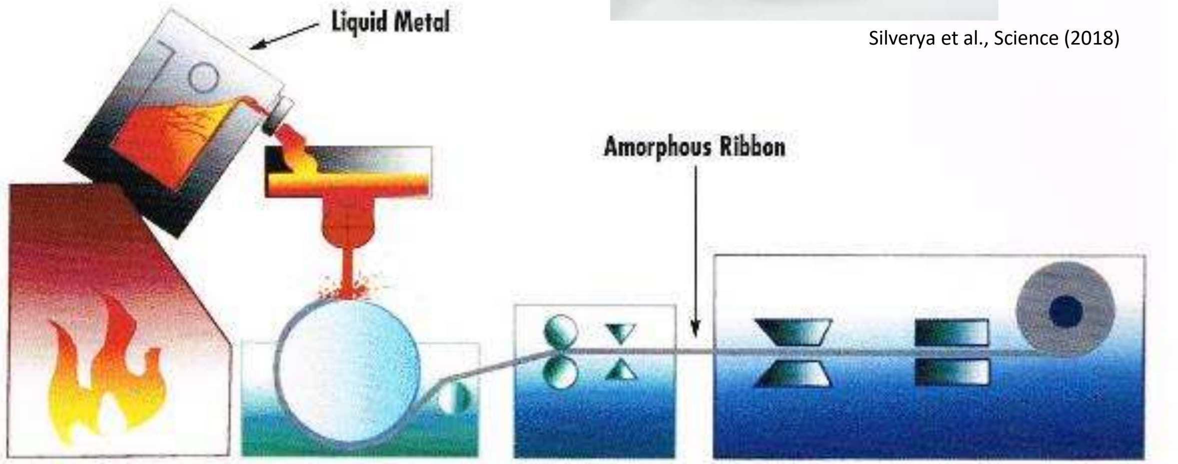


Kollar et al., J. Mag. Mag. Mat. (2013)

Case for additive manufacturing

- Metallic glasses production requires high cooling rates
- Their brittle nature limit their machinability

Silverya et al., Science (2018)



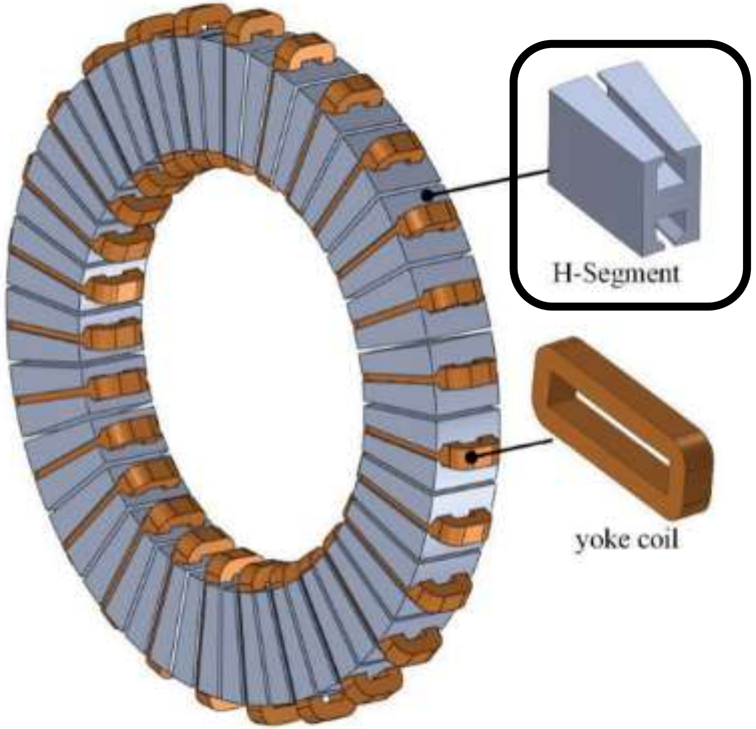
https://metglas.com/company-history/melt-spinning-procress/

Vacuumschmelze.com

Case for additive manufacturing

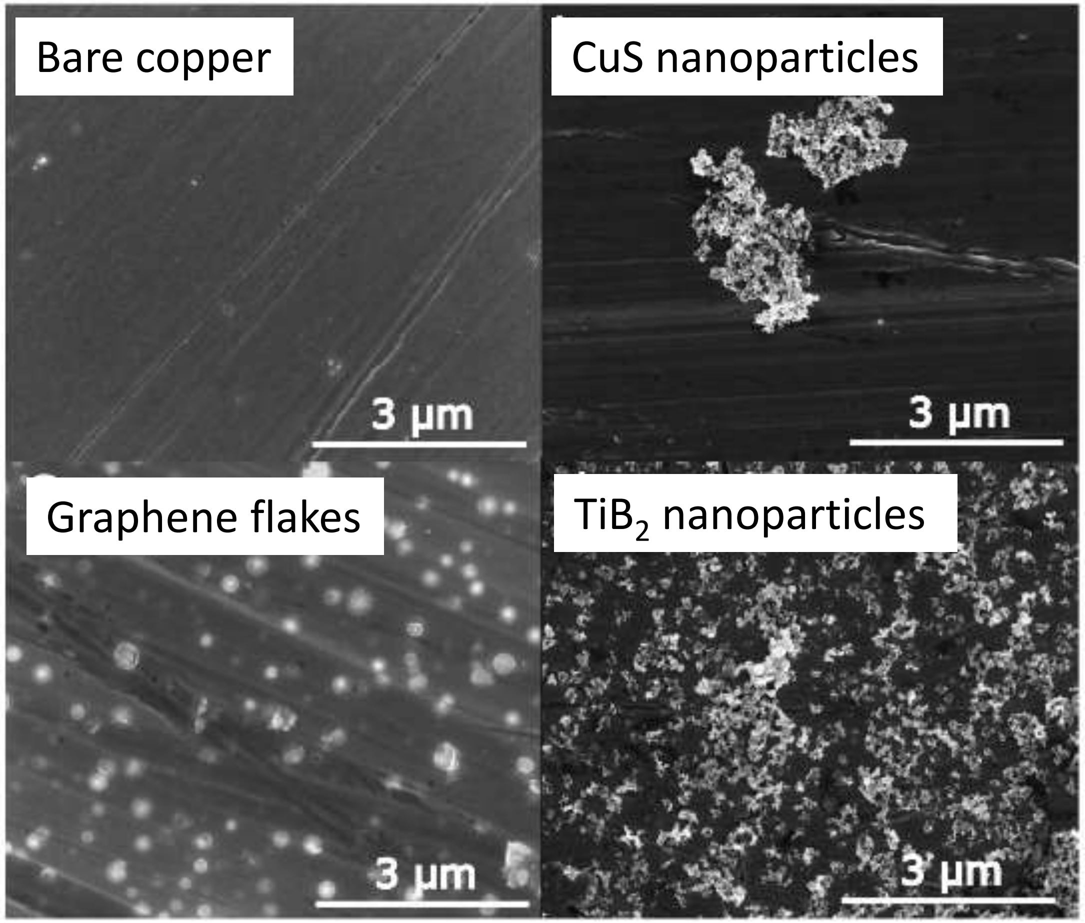
- Complex-shaped metallic glass magnets could enable novel machine design

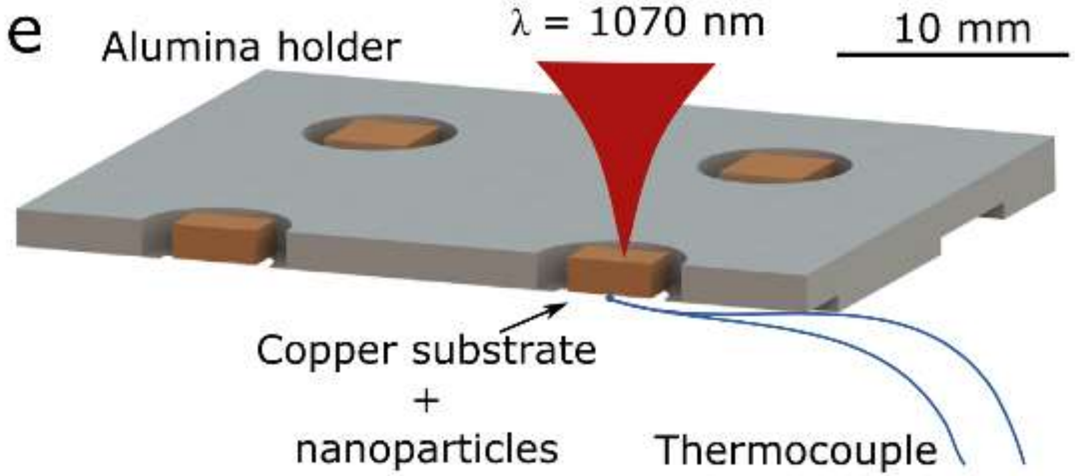
Optimized stator design



Jung, J., & Hofmann, W. (2017). *11th GMM/ETG-Symposium* (pp. 1-6). VDE.

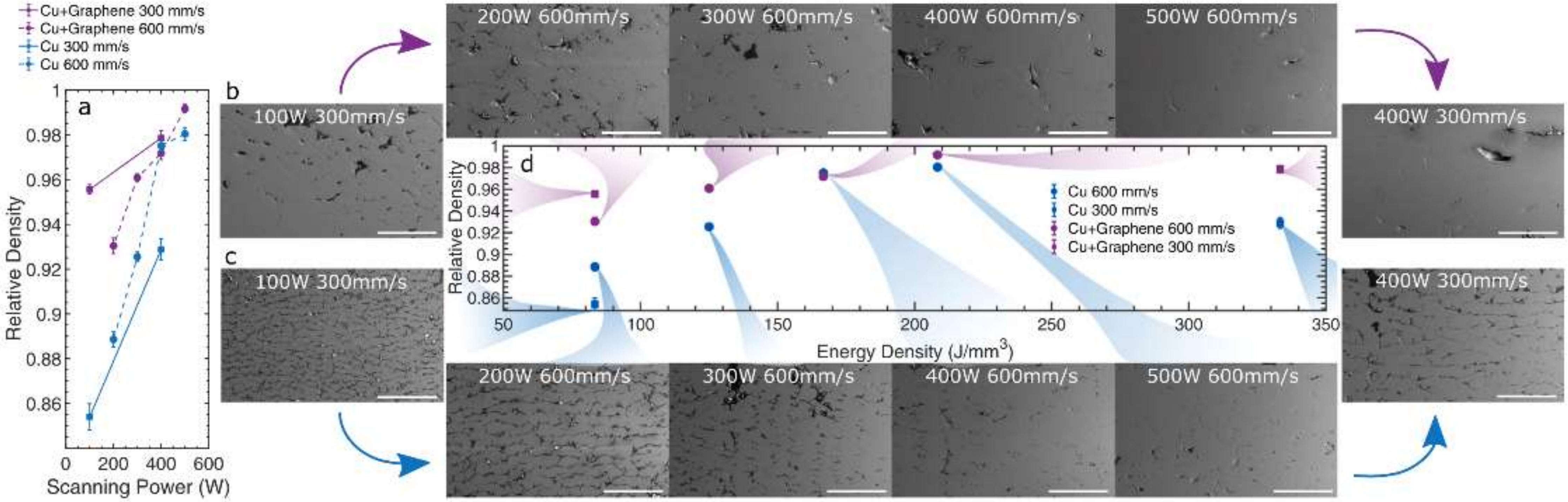
Nanoparticle-enhanced absorptivity of Cu for AM





Tertuliano et al., Additive Manufacturing (2022)

Nanoparticle-enhanced absorptivity of Cu for AM



Tertuliano et al., Additive Manufacturing (2022)

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Juan Rivas, North Surakitbovorn (Stanford)