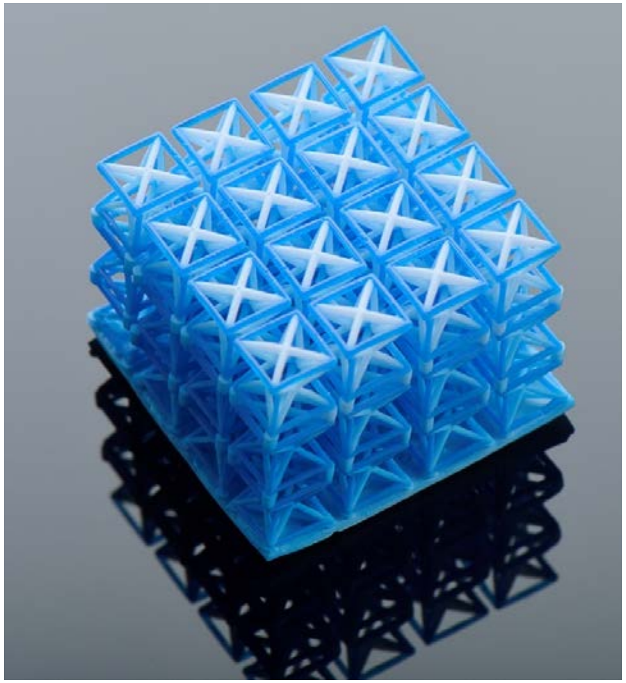
Achieving More with Less: Architecting Metamaterials with Additive Manufacturing



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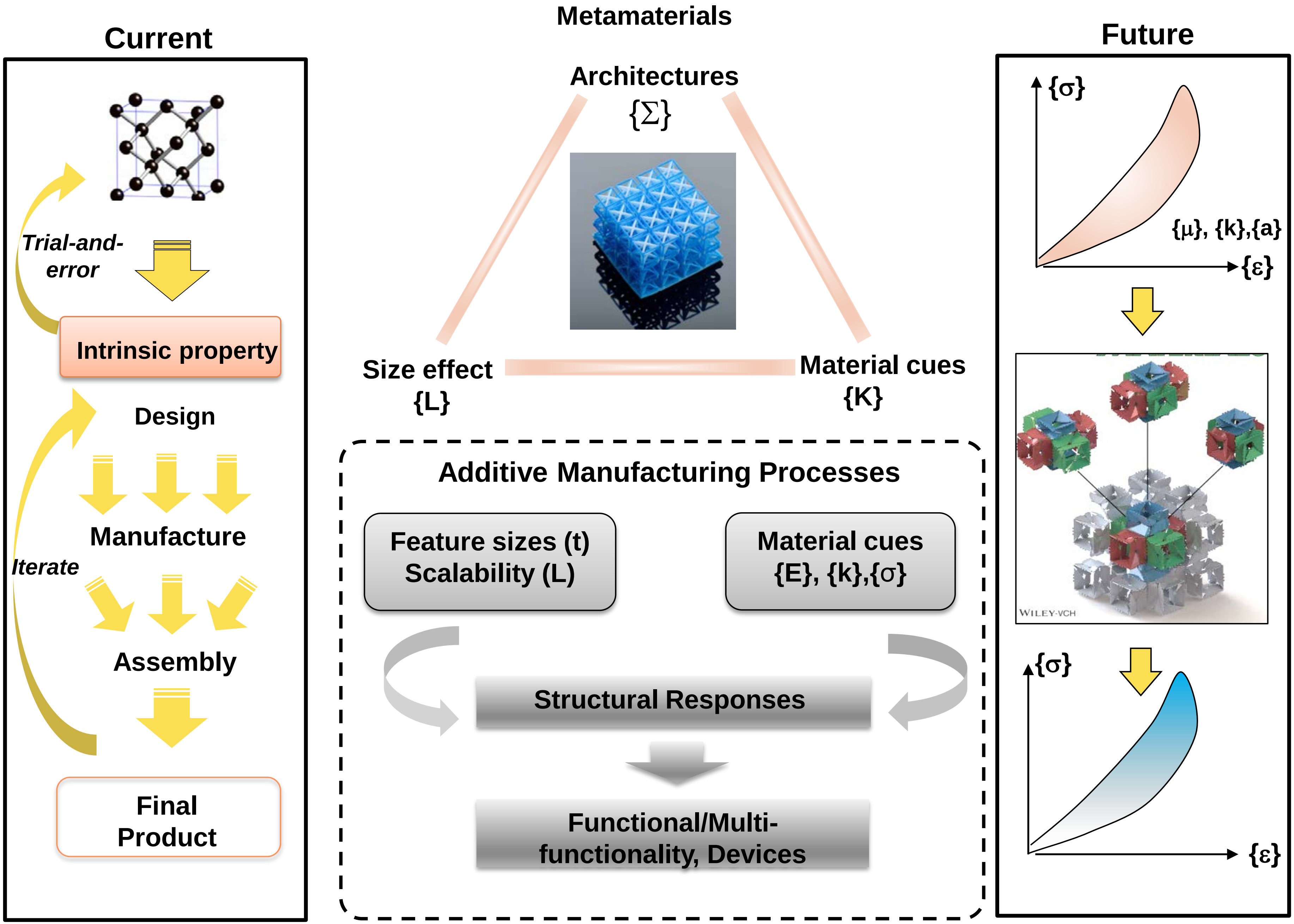
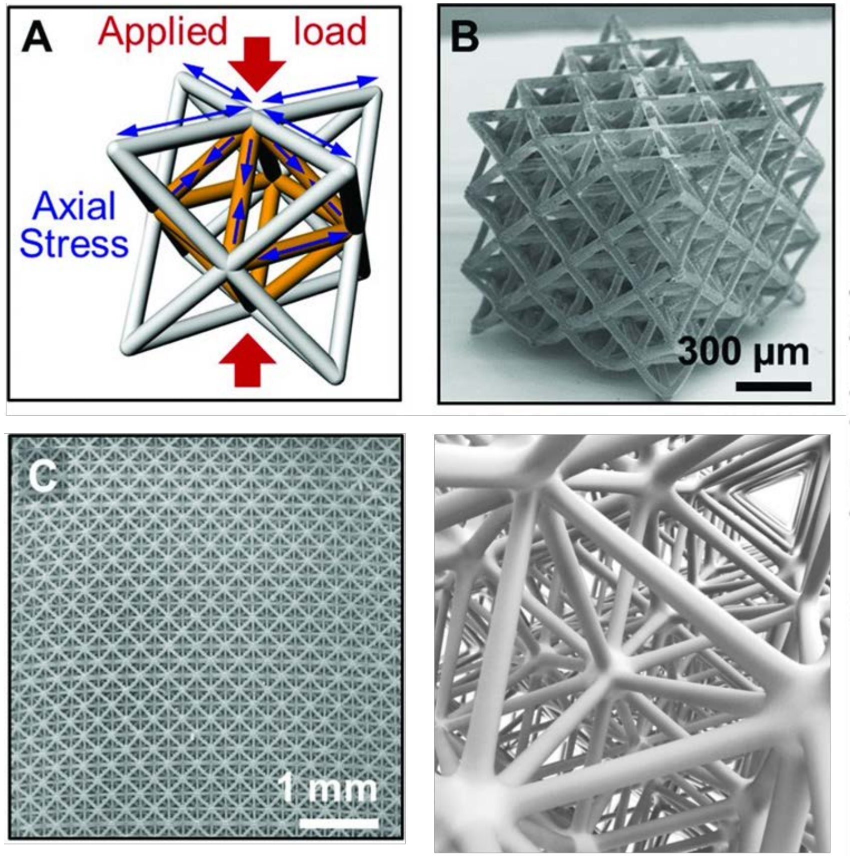
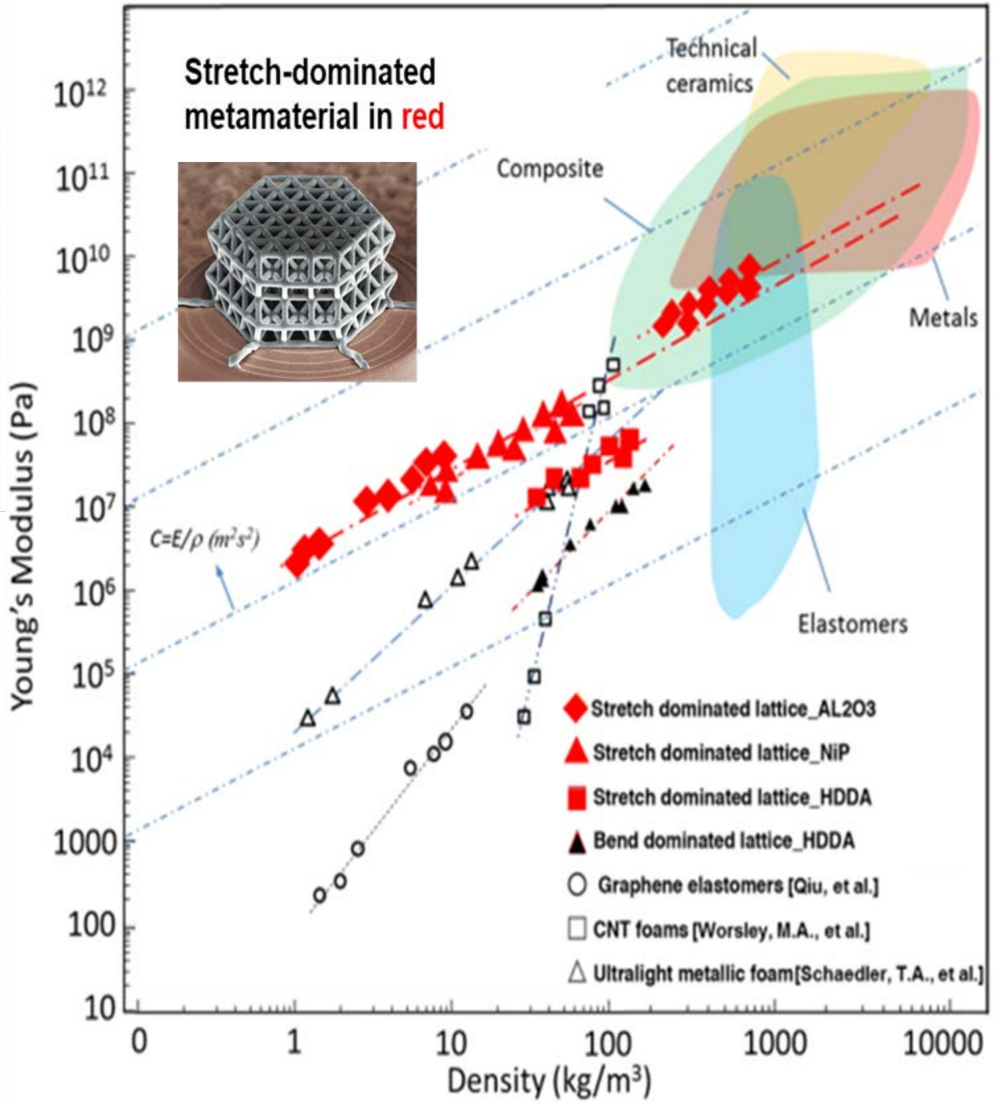
Architected Metamaterials



Ultralight, Ultrastiff Metamaterials

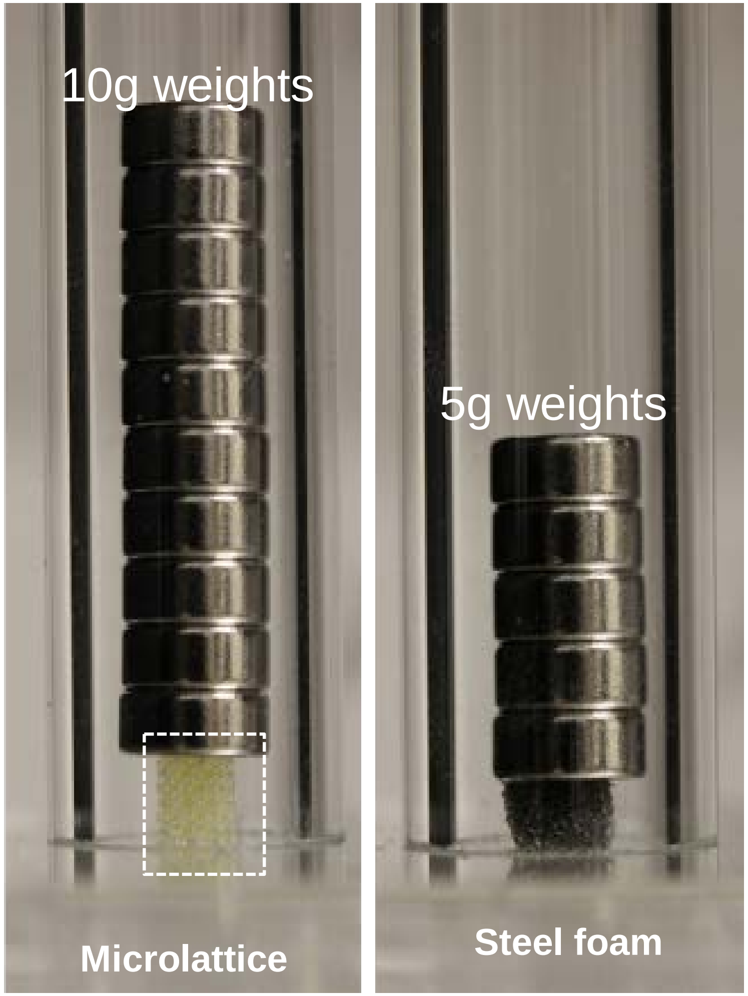


Z =12

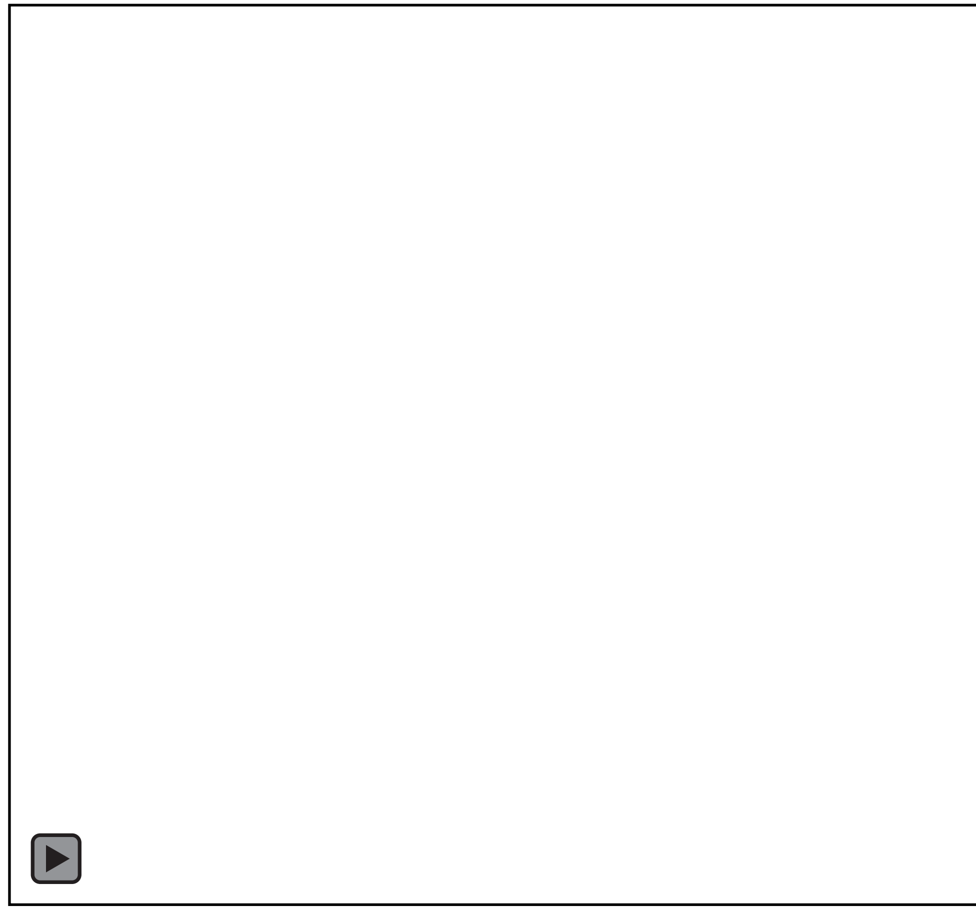


Zheng, *et al*., *Science* June 20, 2014.

Ultralight Weight, Ultrastiff, Metamaterials: Carry 10,000 of their Weight without Visible Deformation



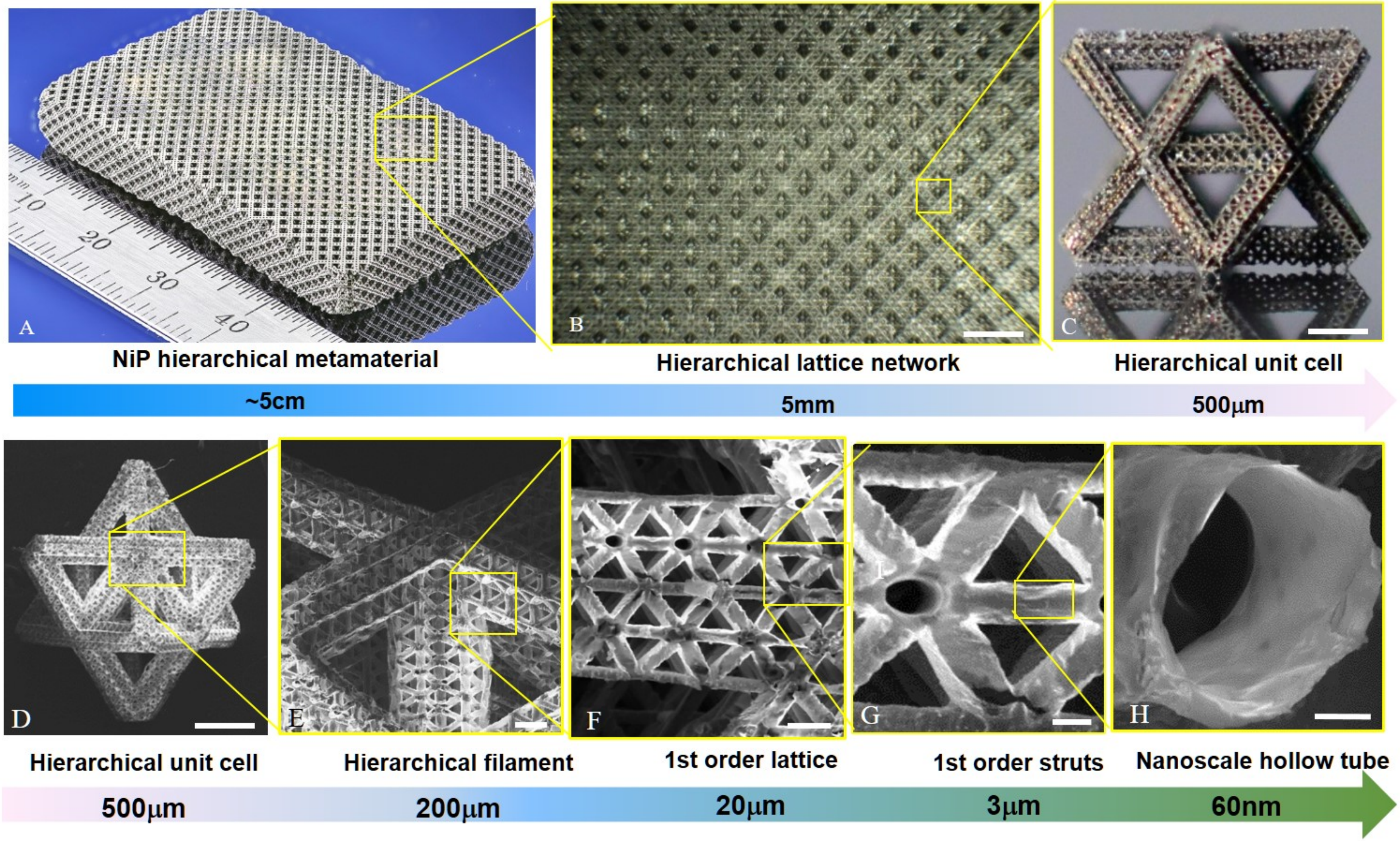
1-10 kg/m^3 500 kg/m^3



Complete elastic recovery over 90% strain

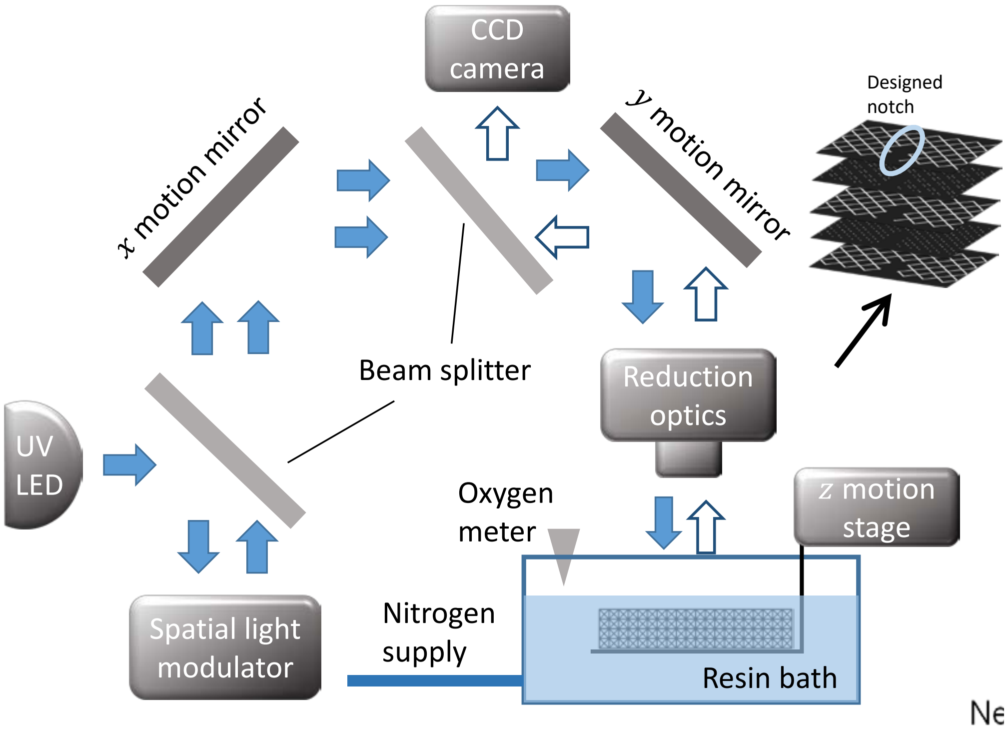
Zheng, *et al.*, *Science* June 20, 2014.

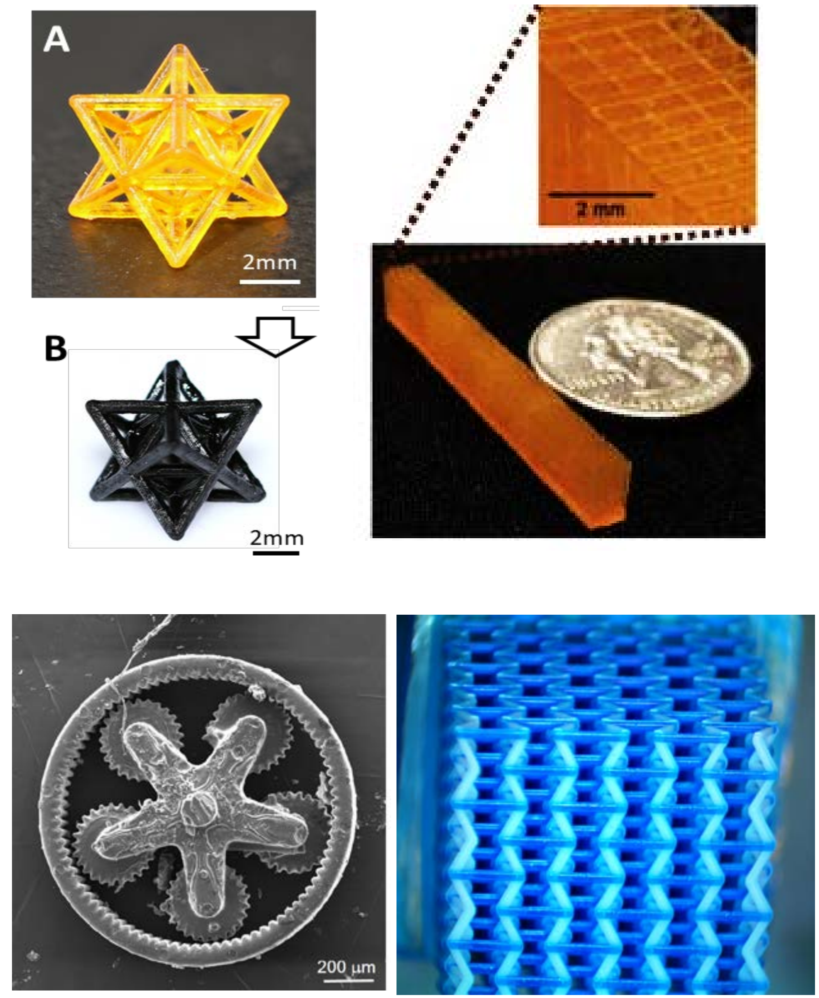
Multi-scale metallic metamaterials --- across over 7 orders of magnitude in lengthscale



Zheng et al., Nature Materials, 15, 1100, 2016

Custom Projection Micro-stereolithography





- Controlled oxygen inhibitions and feedbac
- Focusing optics; Sub-micron resolutions
- Scanning optics

AM via preceramic monomers (SiOC)

Cui, Journal of Material Research, 2018

Combining and inserting hybrid micro-architectures over multiple hierarchies

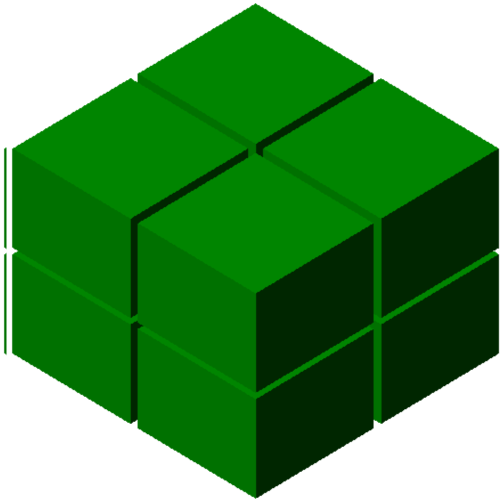
$$\frac{\sigma_n}{\sigma_{n-1}} = k_n\left(\frac{\rho_n}{\rho_{n-1}}\right)^{m_n}$$

Mathematical recursion from high rank to its next lower rank hierarchy

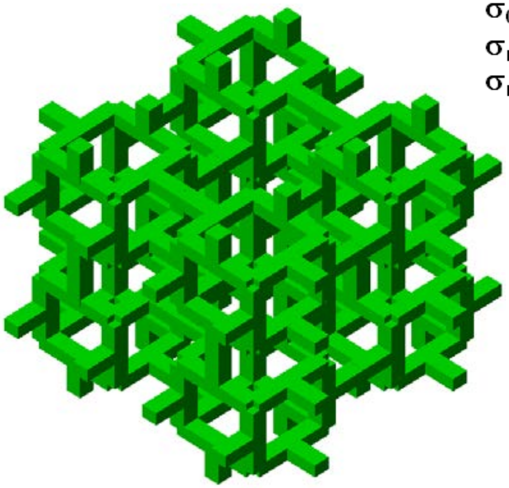
$$\frac{\sigma_1}{\sigma_0} = k\left(\frac{\rho_1}{\rho_0}\right)^{m_1}$$

Classical model relating material strength to its building block

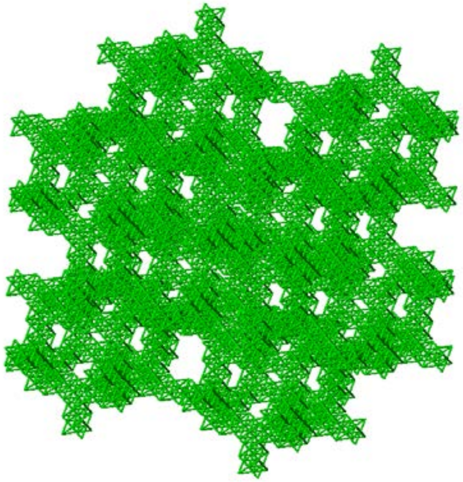
σ_0 base material strength
σ_n rank n material strength
σ_{n-1} strength of building block of rank n material



Material with hierarchy 0
ρ_1/ρ_0=1



Material with hierarchy 1
ρ_1/ρ_0=0.1



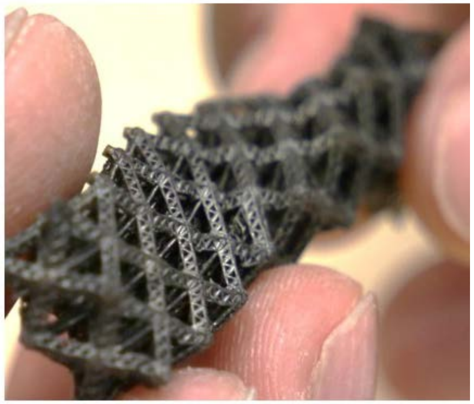
Material with hierarchy 2
ρ_2/ρ_0=0.01

Super compressibility in multi-scale metallic metamaterials

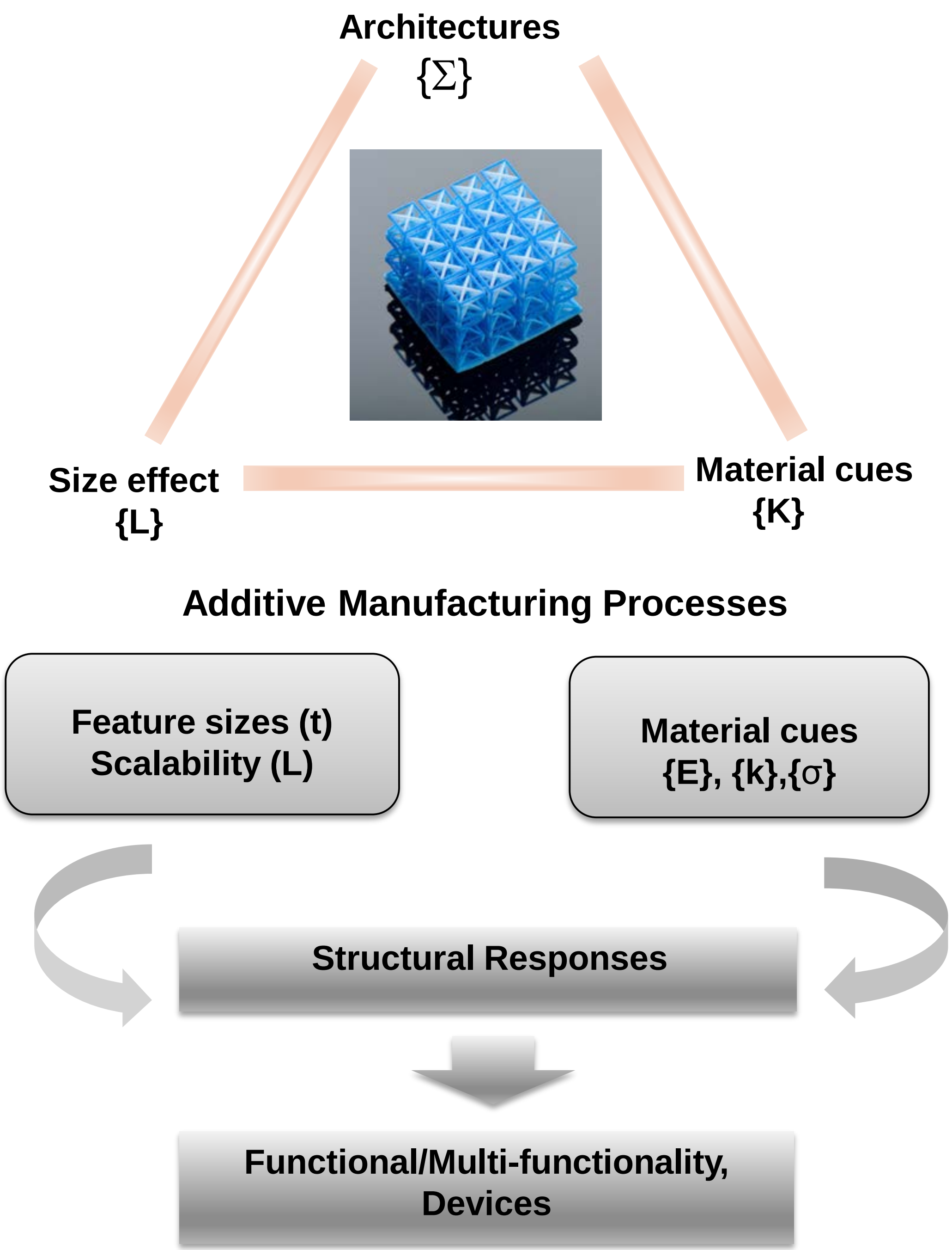
Ultralight Metallic material compression movie

Complete elastic recovery over 90% strain

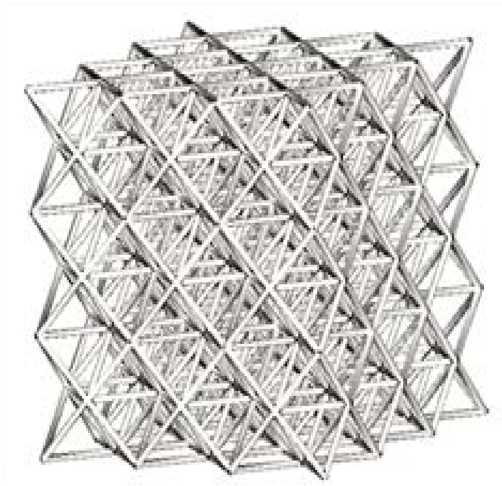
Wall thickness 60nm



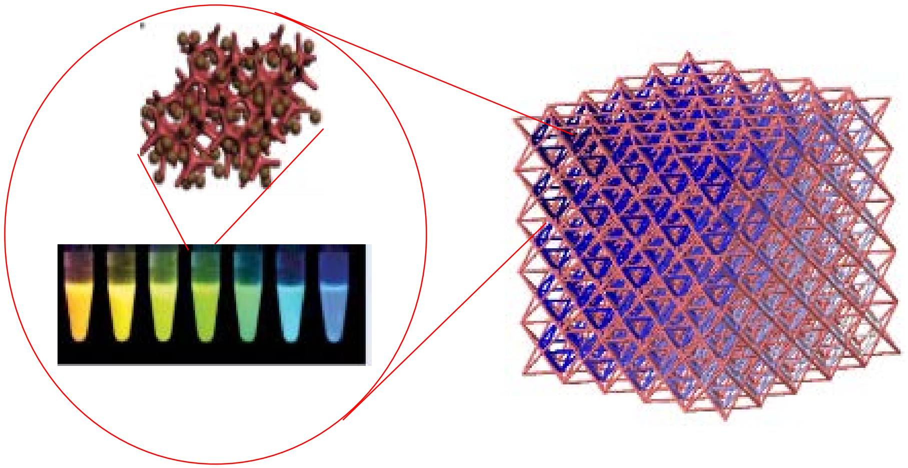
Zheng et al., Nature Materials, 2016

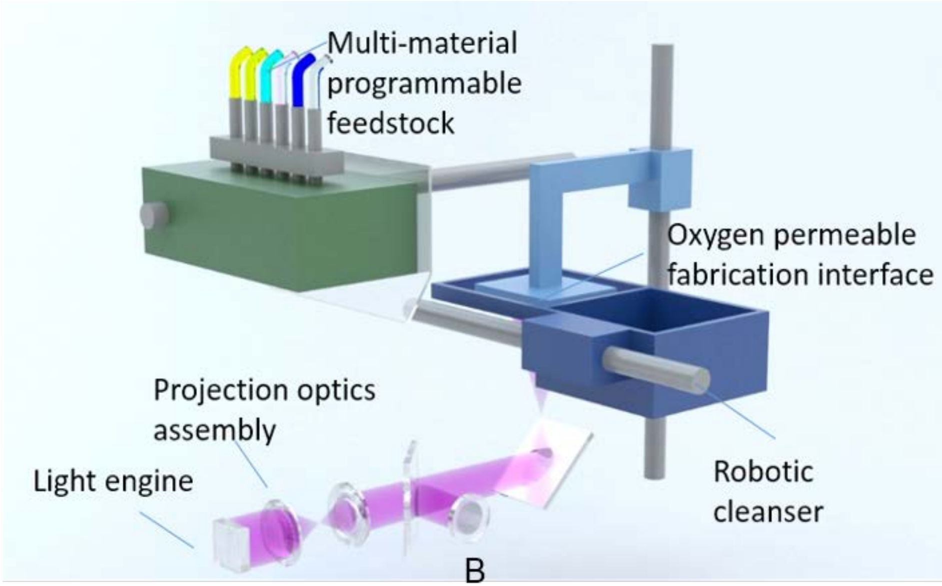

Architectures
{Σ}
Size effect
{L}
Material cues
{K}
Additive Manufacturing Processes
Feature sizes (t)
Scalability (L)
Material cues
{E}, {k},{σ}
Structural Responses
Functional/Multi-functionality,
Devices

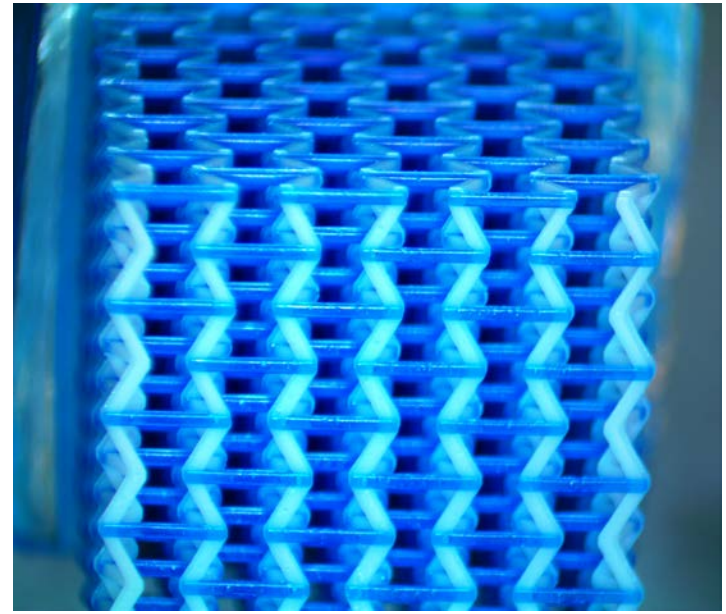
Architecting Encoded Properties



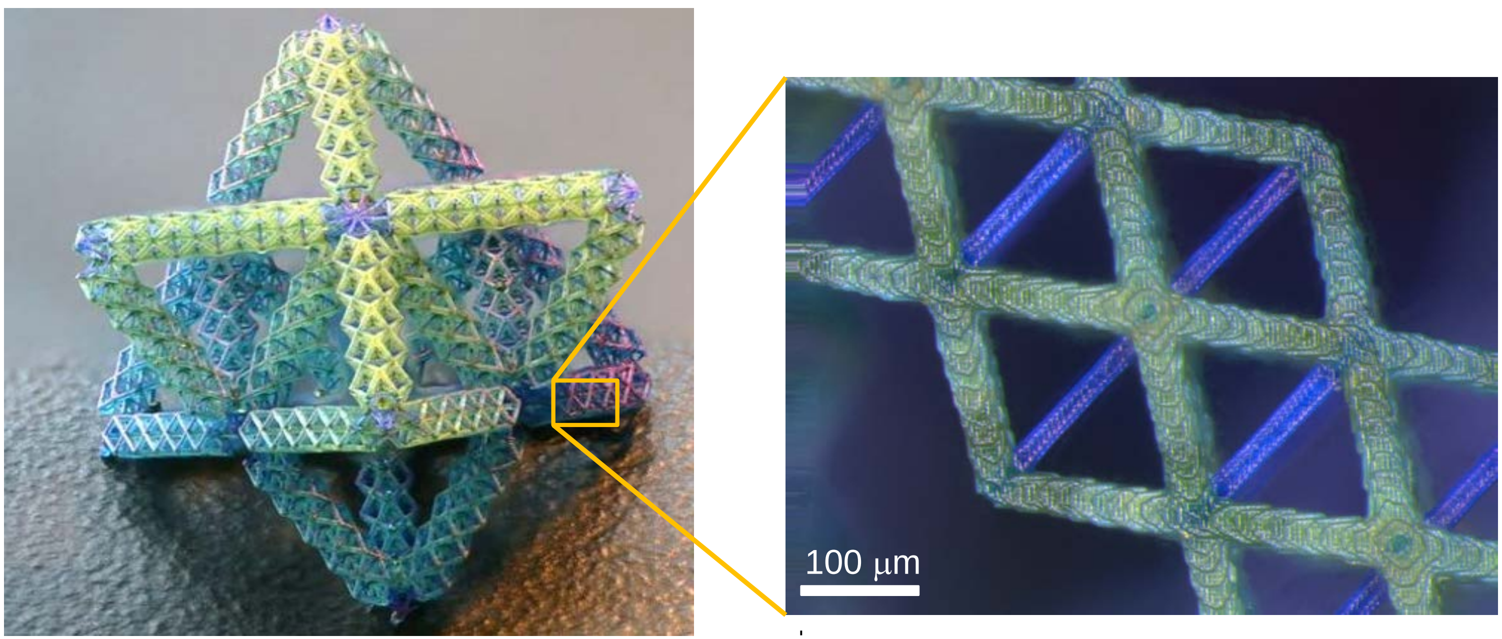
Functional Materials and Properties



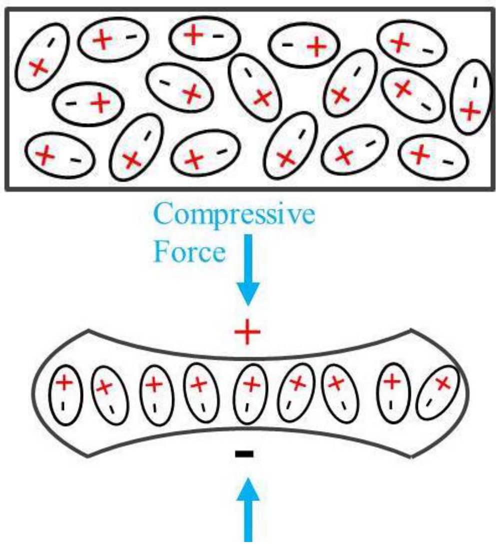


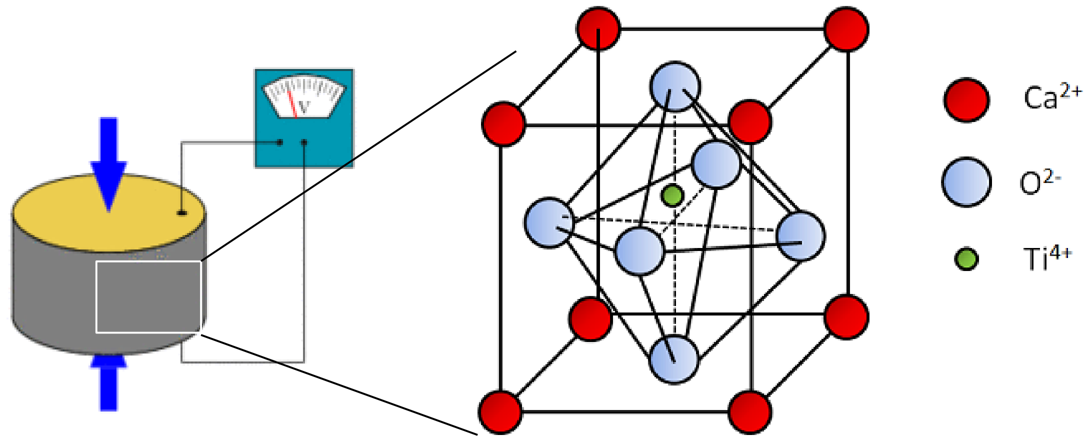


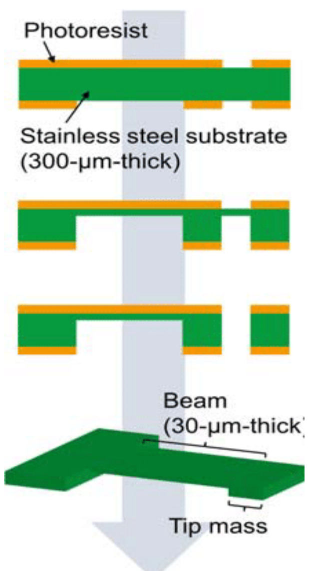
Chen et al., Sci. Rep. 2017

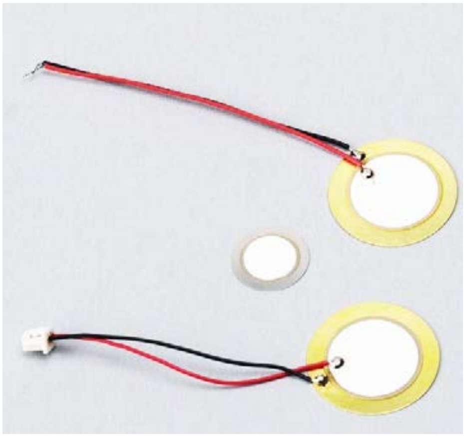


Ferroelectric materials



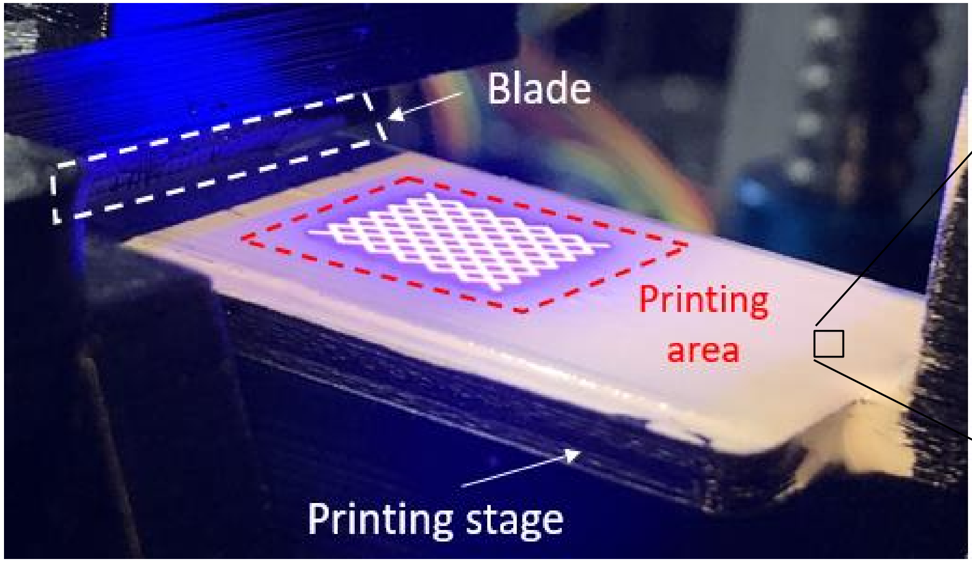


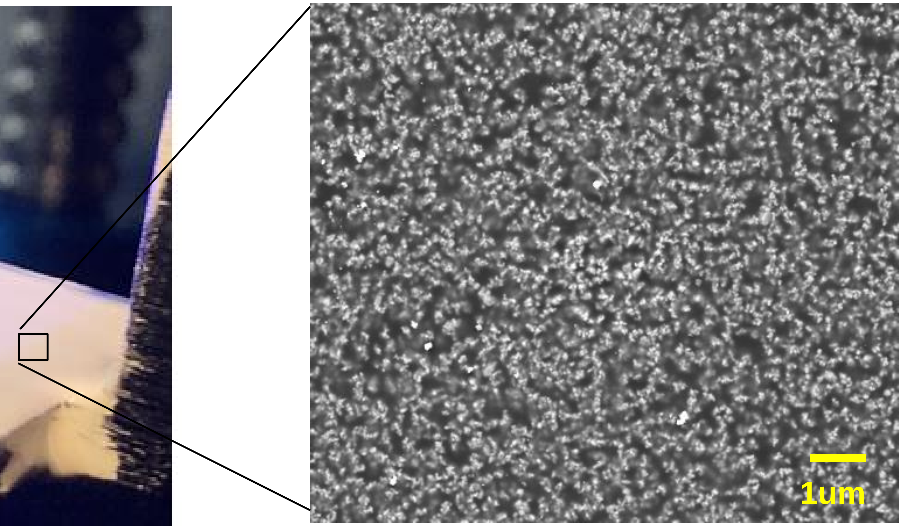


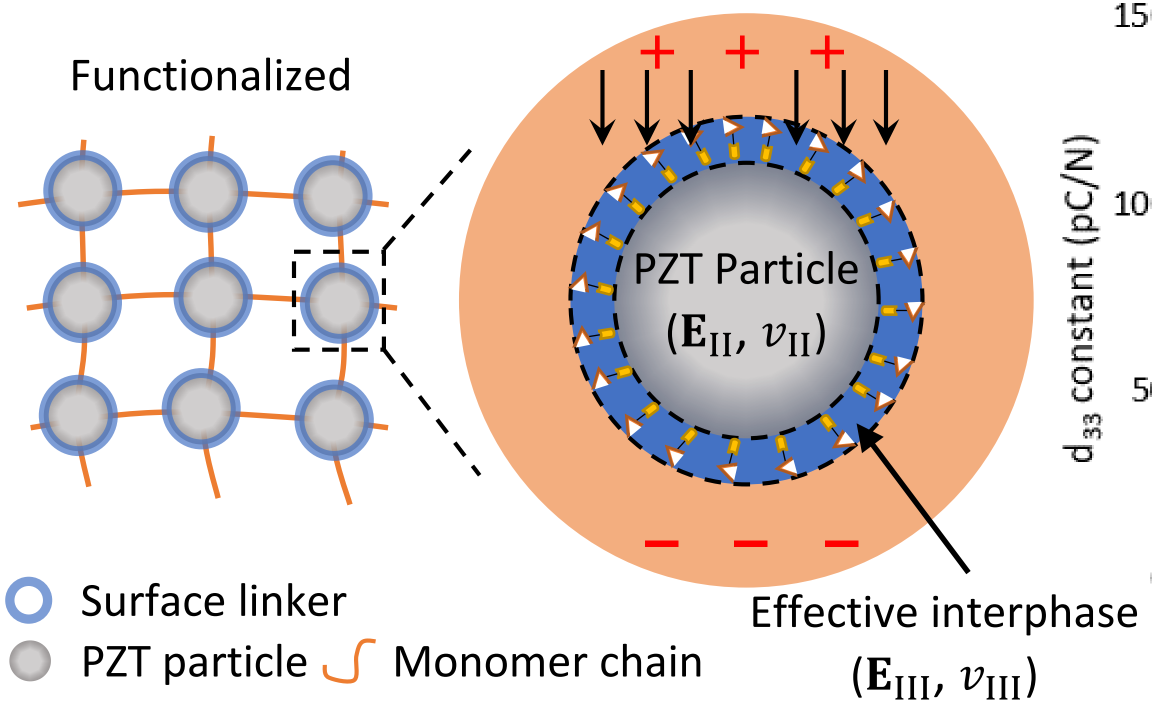


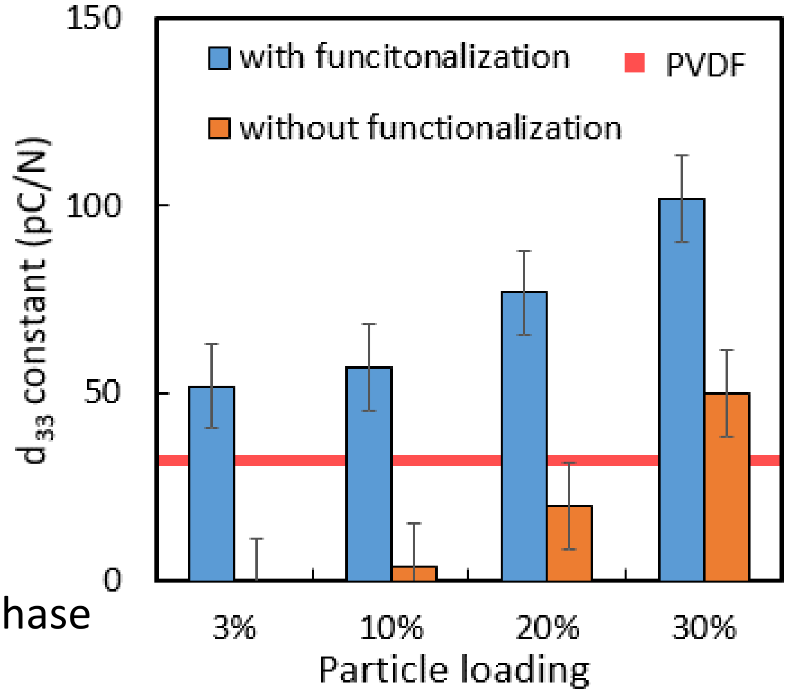
- Polarization Dictated by bulk materials
- Brittleness
- Manufacturability

AM of perovskite piezoelectric materials

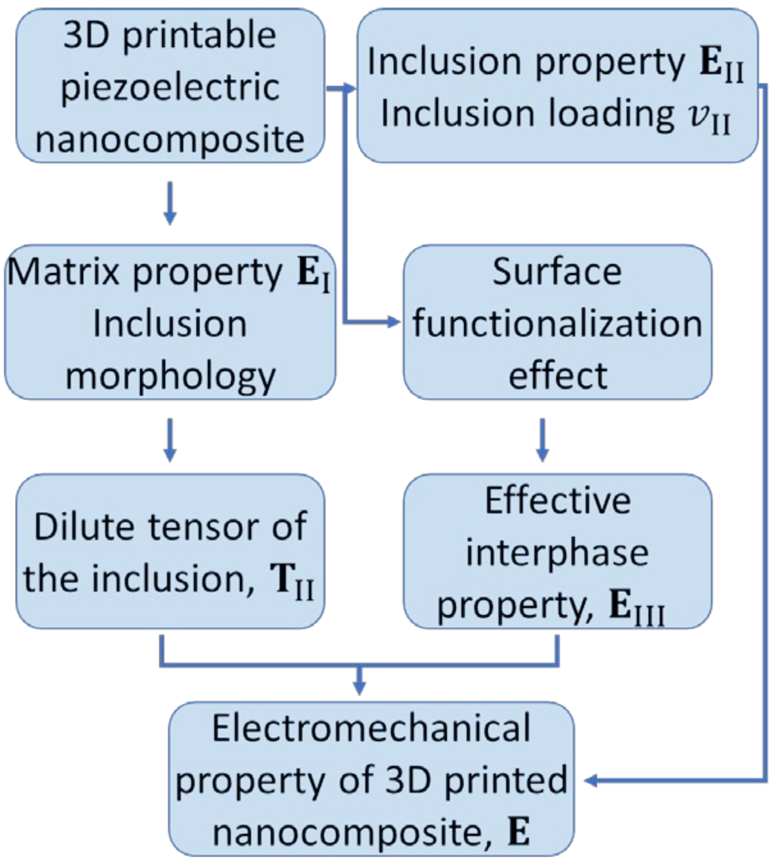


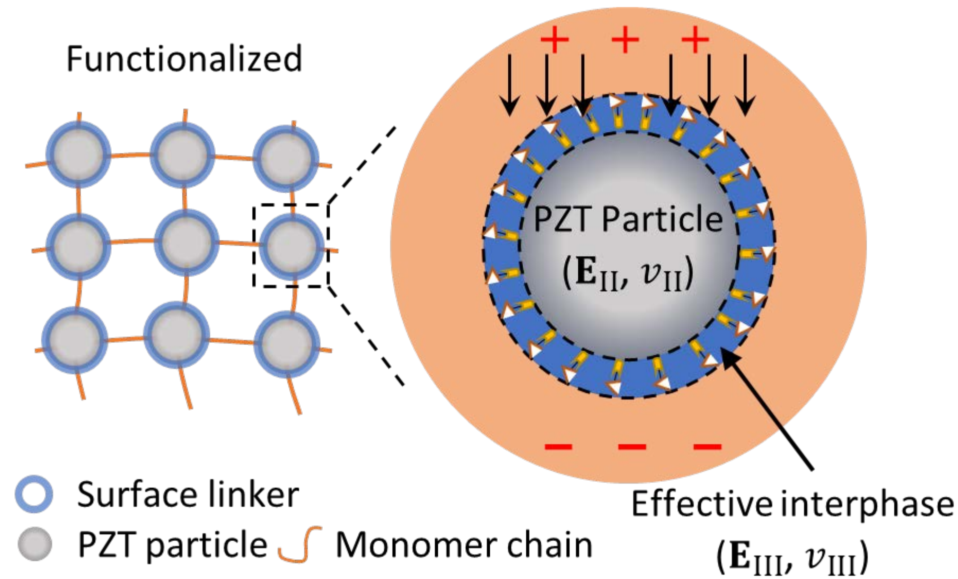




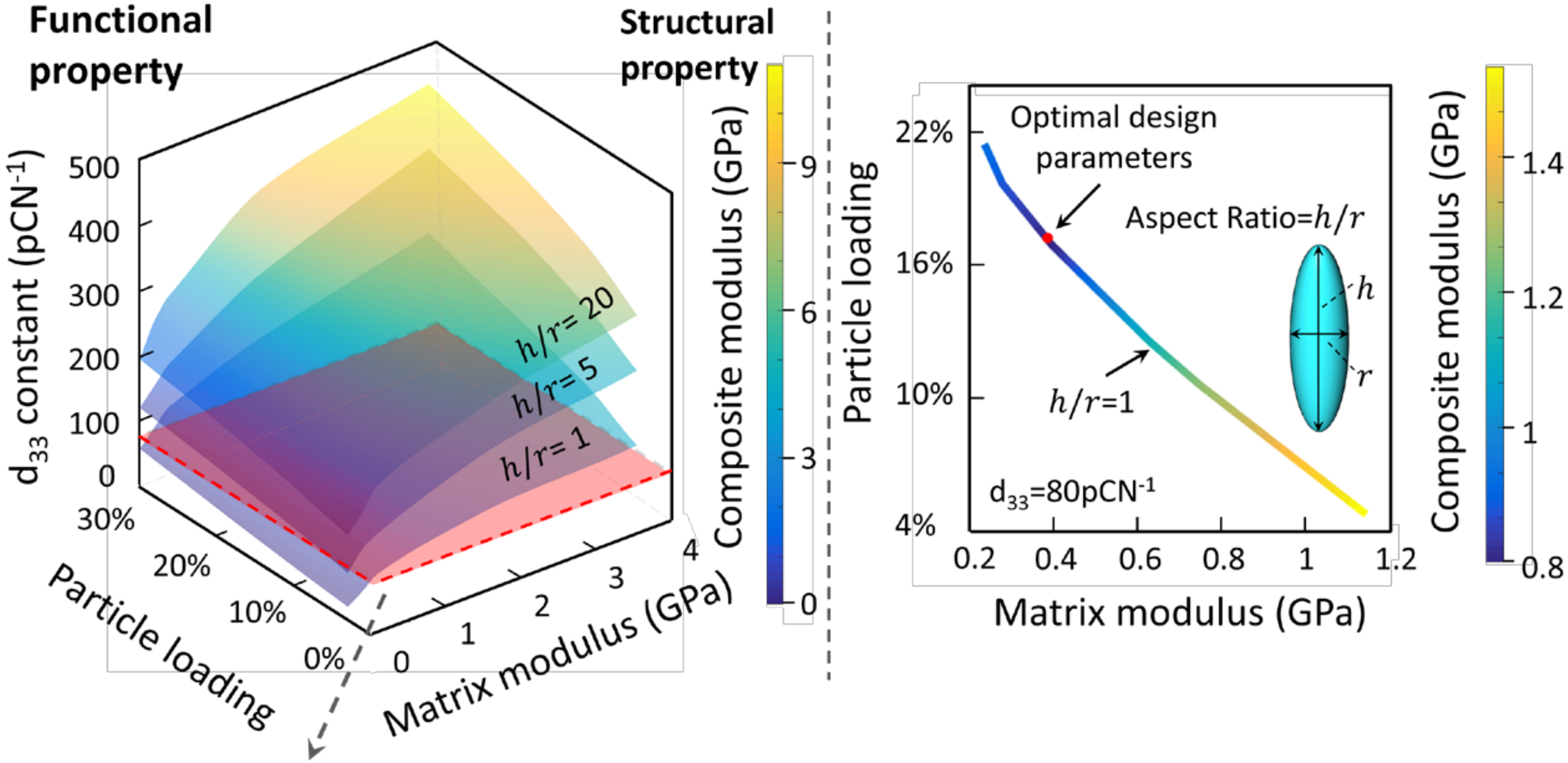


Effect of Surface Functionalization ---- Effective Interphase model





$$\mathbf{E} = \mathbf{E}_{\mathrm{I}} + \left(v_{\mathrm{I}}\mathbf{I} + (v_{\mathrm{II}} + v_{\mathrm{III}})\mathbf{T}_{\mathrm{III}}\right)^{-1} \left((v_{\mathrm{II}} + v_{\mathrm{III}})(\mathbf{E}_{\mathrm{III}} - \mathbf{E}_{\mathrm{I}})\mathbf{T}_{\mathrm{III}} + v_{\mathrm{II}}(\mathbf{E}_{\mathrm{II}} - \mathbf{E}_{\mathrm{III}})\mathbf{T}_{\mathrm{II}}\right)$$



Target functional property of the piezoelectric nanocomposites.

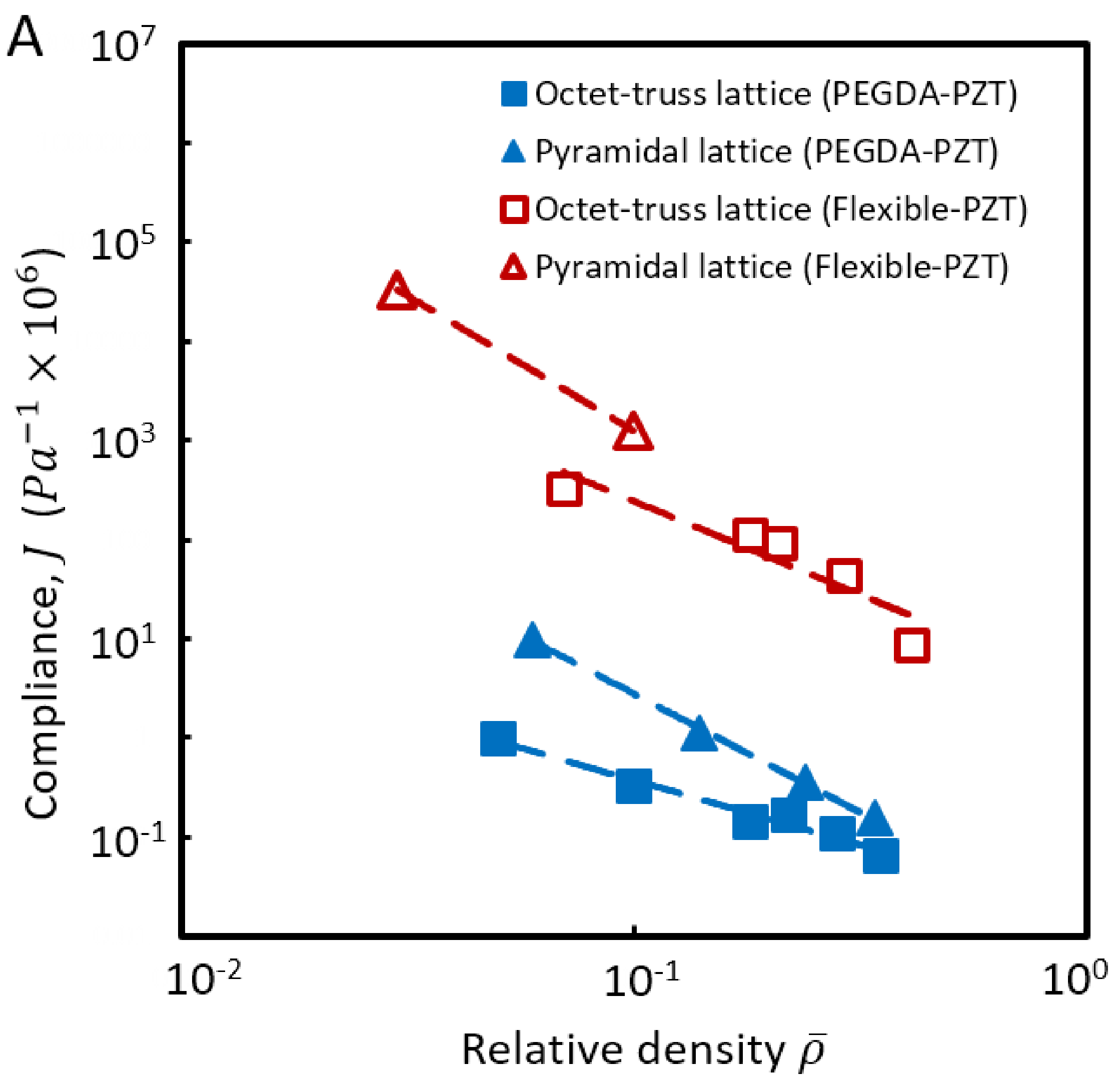
Slice the 3D property surfaces

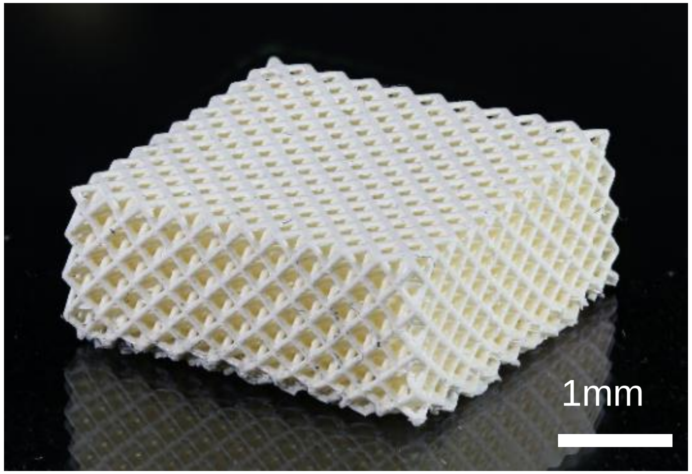
Design parameters of the nanocomposite that yields optimal structural flexibility.

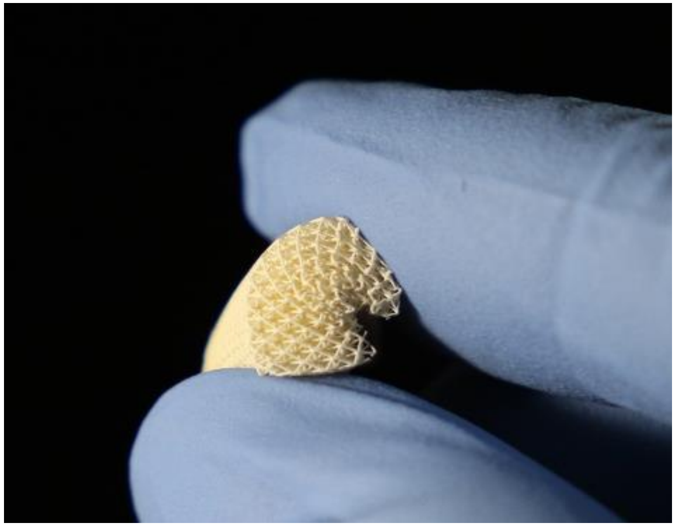
r_{II})

Yao et al., Advanced Functional Materials, 2019

Tunable elasticity ---- Flexible Energy Harvester







Cui et al., Nature Materials, 2019,

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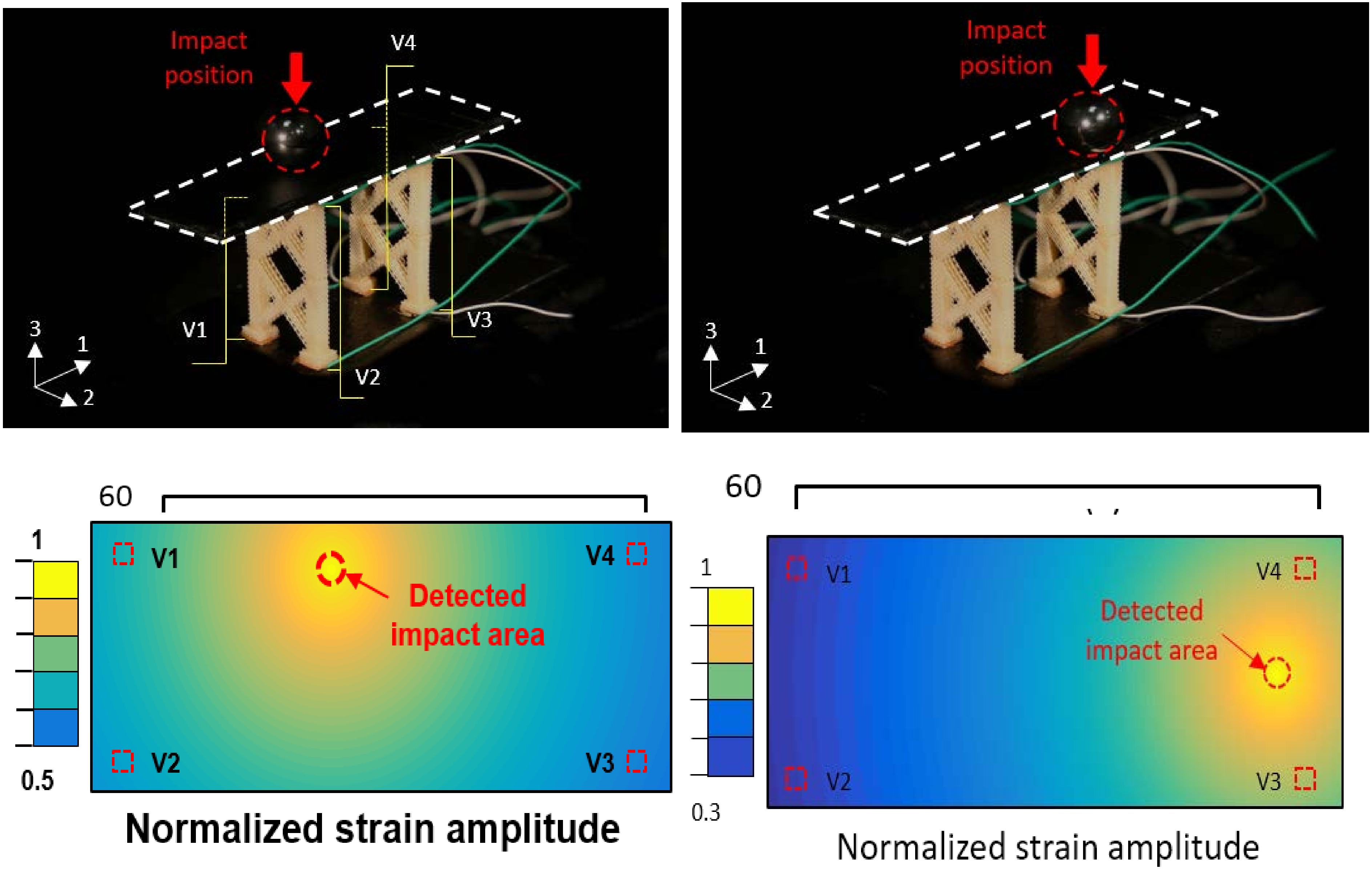
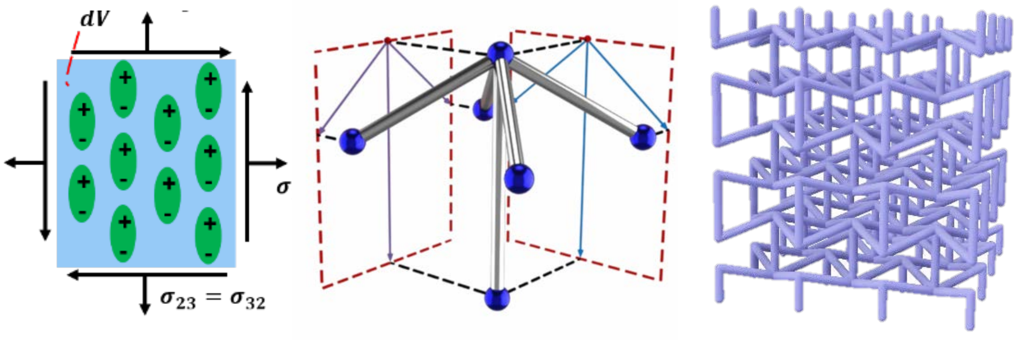
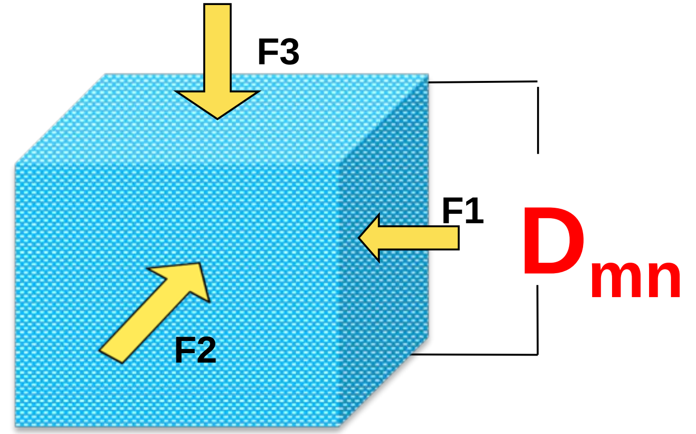
Impact Self-sensing: Drop weight tests



Cui et al., Nature Materials, 2019,

Design arbitrary piezoelectric tensor





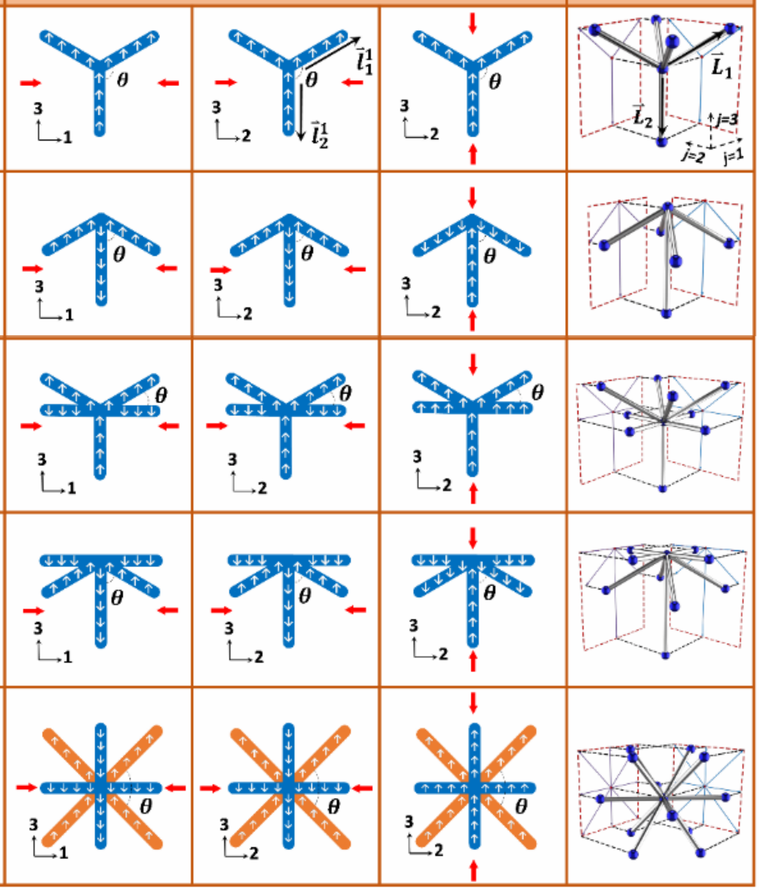
Effective Piezoelectric Coefficient

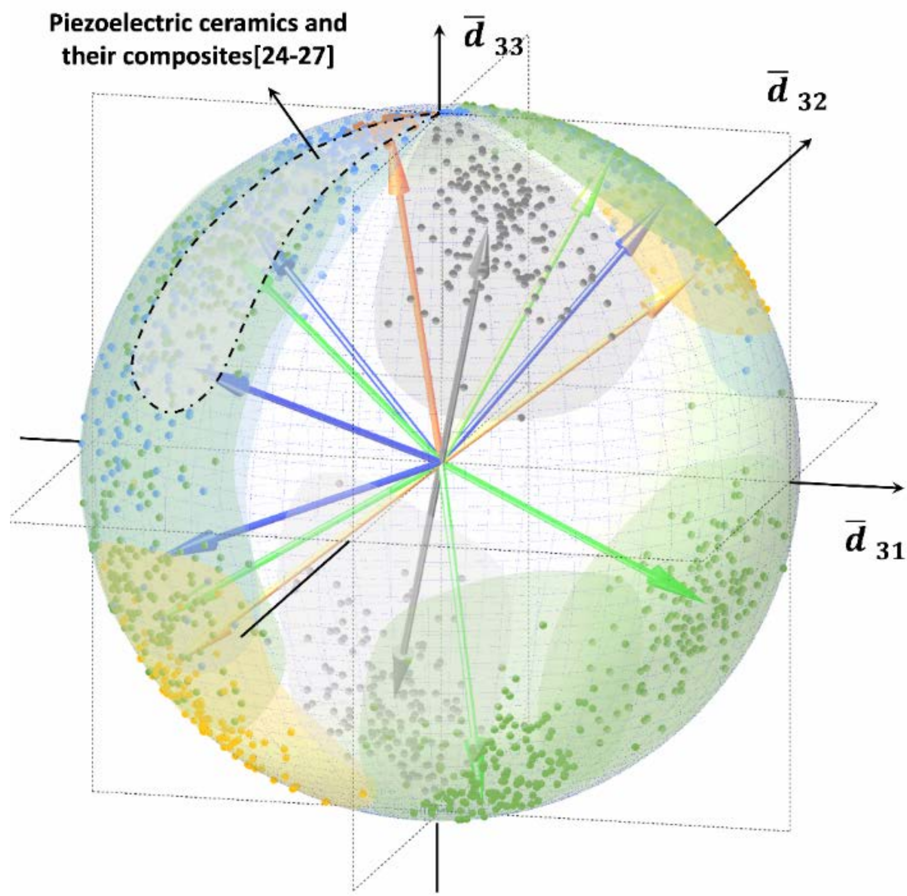
$$[d_{eff}] = \begin{bmatrix} 0 & 0 & 0 & 0 & d_{15}^{eff} & 0 \\ 0 & 0 & 0 & d_{24}^{eff} & 0 & 0 \\ d_{31}^{eff} & d_{32}^{eff} & d_{33}^{eff} & 0 & 0 & 0 \end{bmatrix}$$

Designing arbitrary ferroelectric tensors– achieving tailorable anisotropy

Method: Assembly of 3D piezoelectric unit cells

Projection (Identical)	Electric displacement map			3D Node unit
3-strut, N=5 (+ + +)				
3-strut, N=5 (- - +) & (- - -)				
5-strut, N=9 (+ + +)				
5-strut, N=9 (- - +) & (- - -)				
8-strut, N=12 (- - +) & (≈0 ≈0 +)				

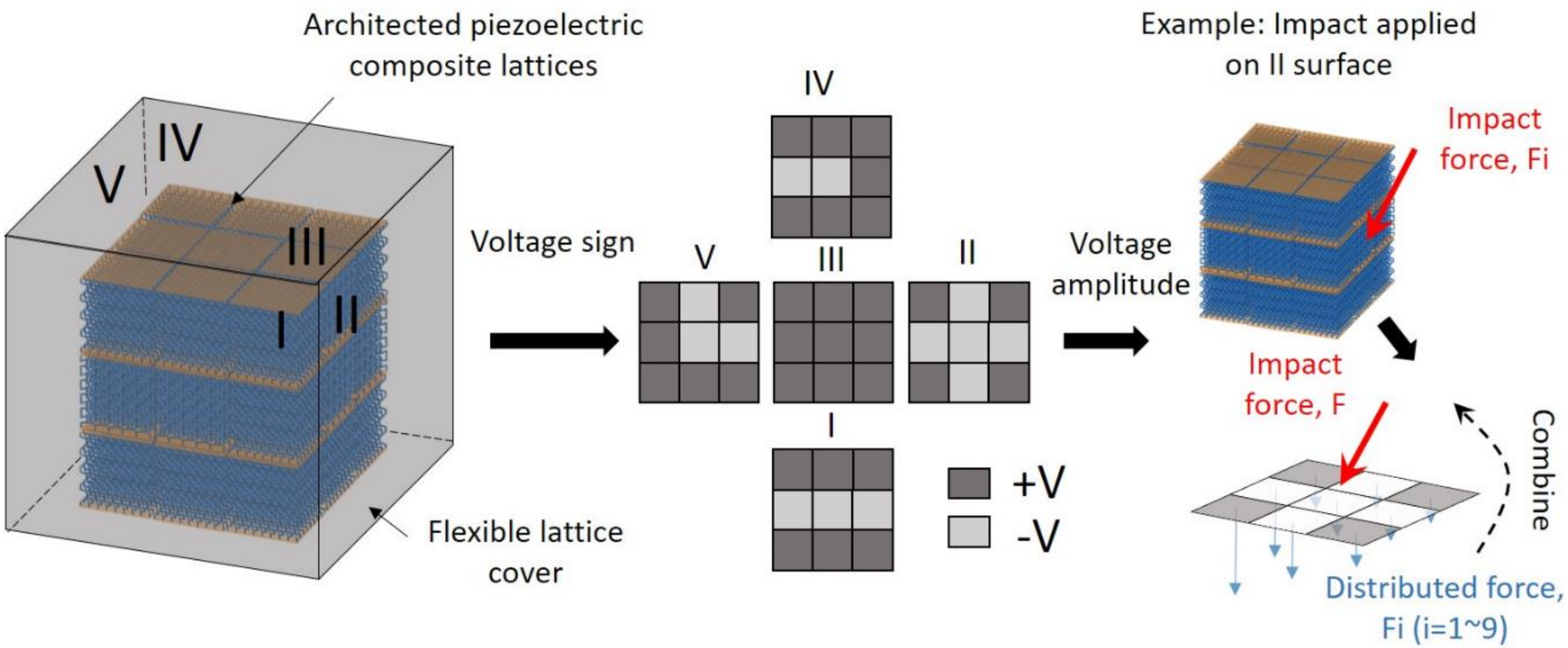




- *Computational design of arbitrary piezoelectric tensor;*
- *Design of targeted anisotropy space through 3D electric displacement*

https://www.nature.com/articles/s41563-018-0268-1

Vector sensing from programmed anisotropy



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Vector Sensor from a single block

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