Mechanically-driven Nano-manufacturing of Atomically-thin Origami and Kirigami Structures

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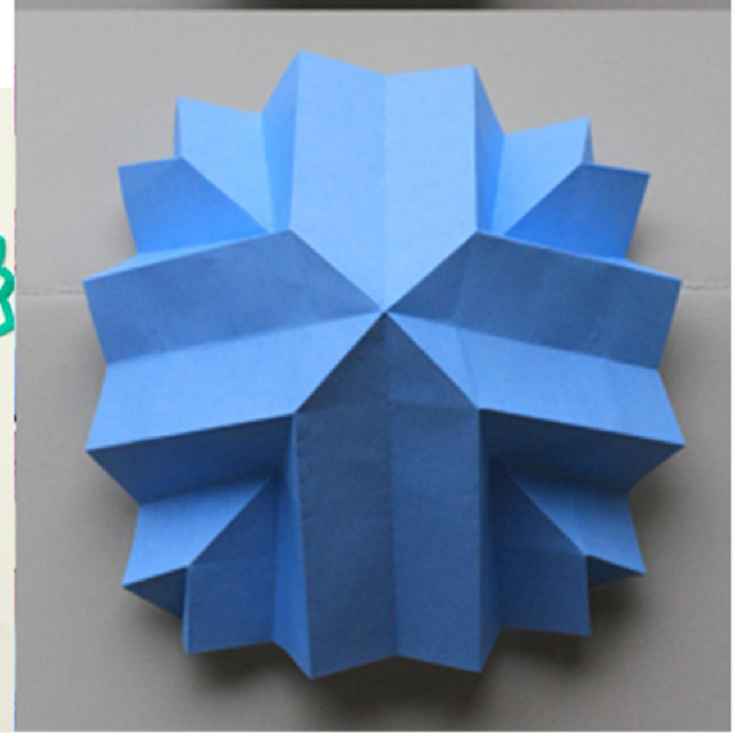
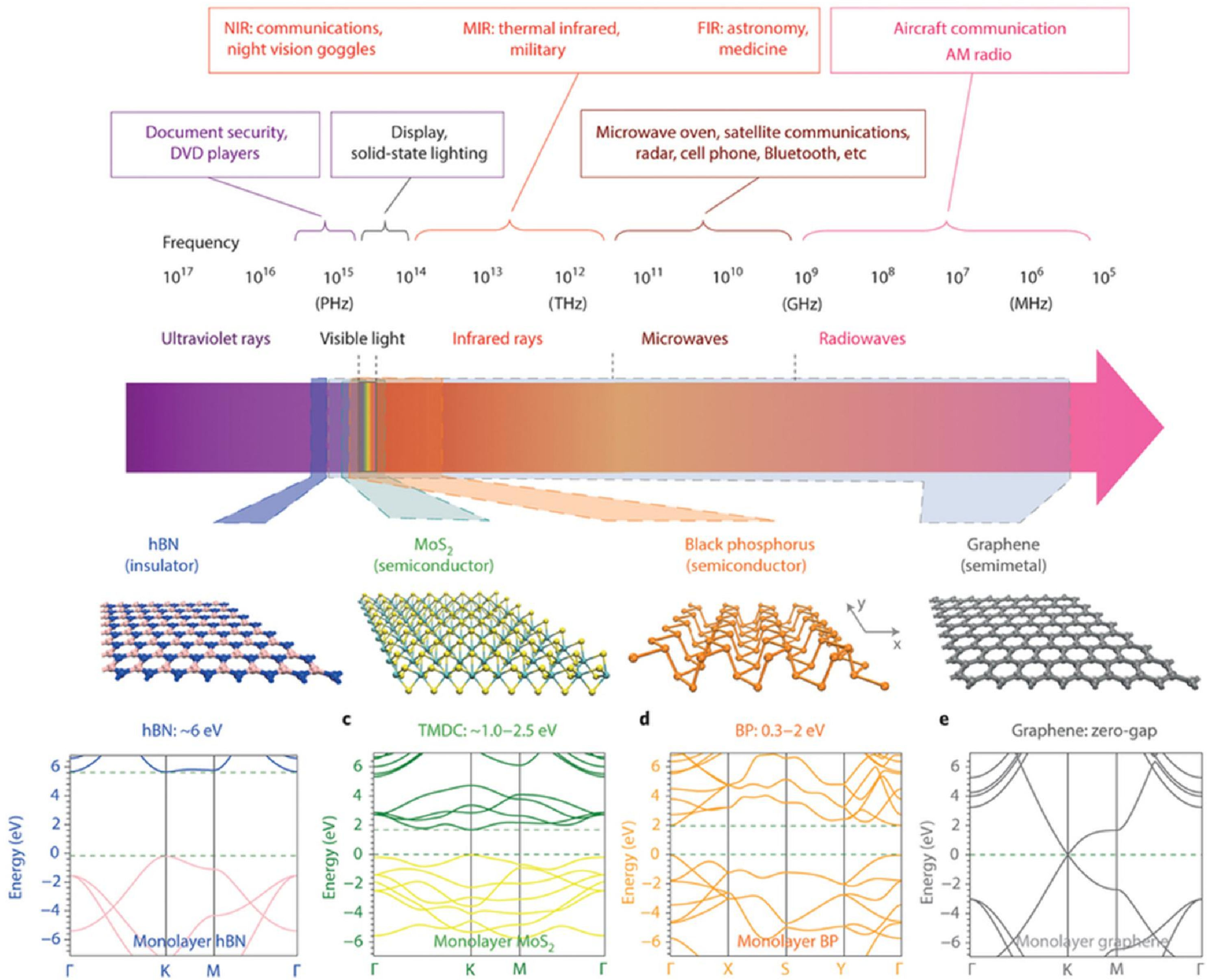
Mechanics of Materials
-Straining
-Deformation
Material Properties
-Thermal
-Chemical
- Electrical/Optical



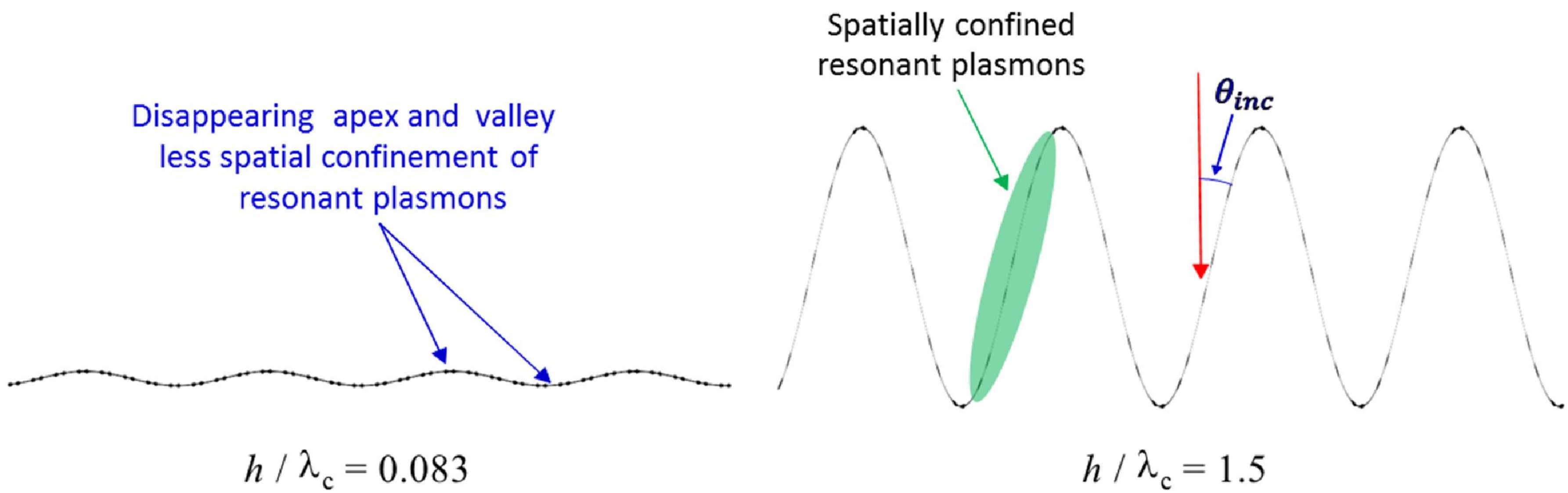



Atomically-thin, 2D Materials



Nature Photonics 8, 899 (2014).

Topography vs. Plasmons

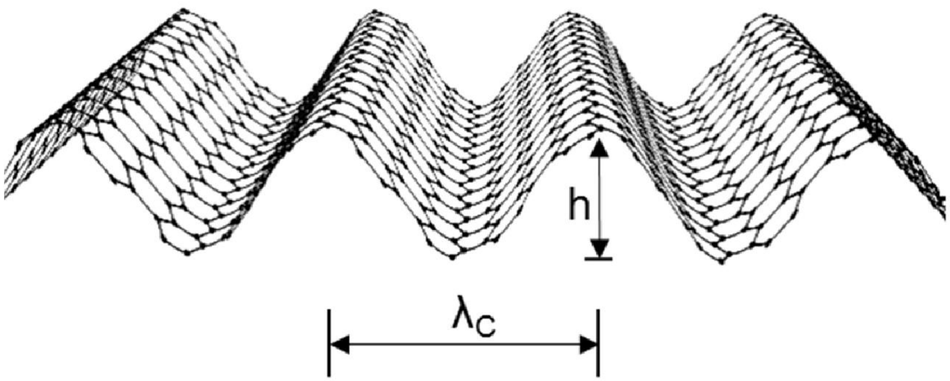


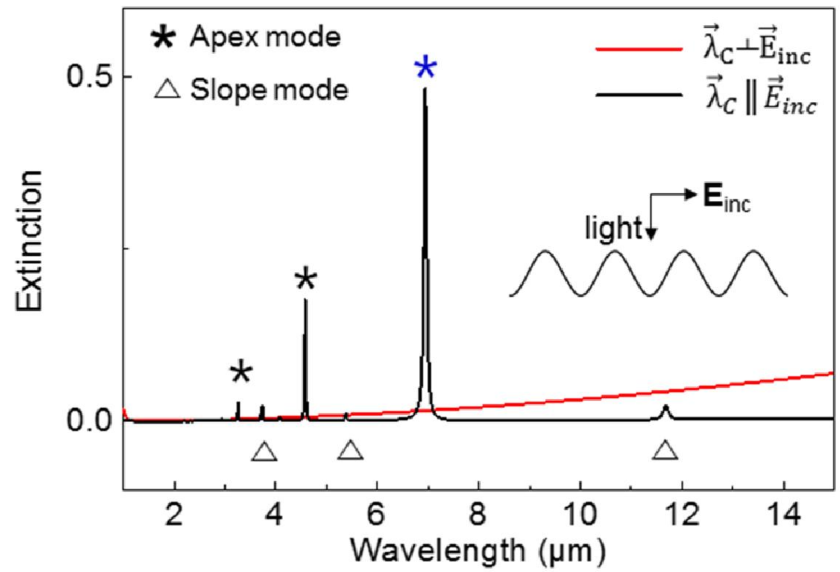
- Crumpling graphene enables the enhanced plasmonic resonance in the near/mid infrared wavelengths (1-10 μm) which is difficult to achieve with the lithographically patterned graphene nanostructures (e.g. graphene ribbons, disks, rings, and stacks).

- Stretching/releasing of crumpled graphene enables new possibilities of reconfigurable graphene plasmonics (meta-materials).

Kang & Nam, ***Light*** 7, 17 (2018).

Topography vs. Plasmons





Random phase approximation method used.
The optical conductivity of graphene is given by

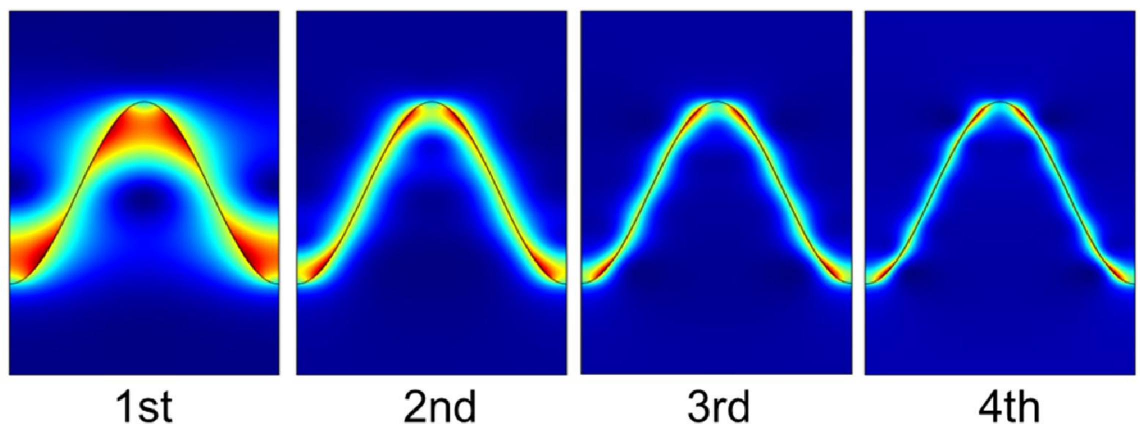
$$\sigma(\omega)=\sigma_{\text{intra}}(\omega)+\sigma_{\text{inter}}(\omega)$$

$$\sigma_{\text{intra}}(\omega)=\frac{2e^2\omega_T}{\pi\hbar}\frac{i}{\omega+i\tau^{-1}}\log\left[2\cosh\left(\frac{\omega_F}{2\omega_T}\right)\right]$$

$$\sigma_{\text{inter}}(\omega)=\frac{e^2}{4\hbar}\left[H\left(\frac{\omega}{2}\right)+i\frac{2\omega}{\pi}\int_0^\infty\frac{H\left(\frac{\omega'}{2}\right)-H\left(\frac{\omega}{2}\right)}{\omega^2-\omega'^2}d\omega'\right]$$

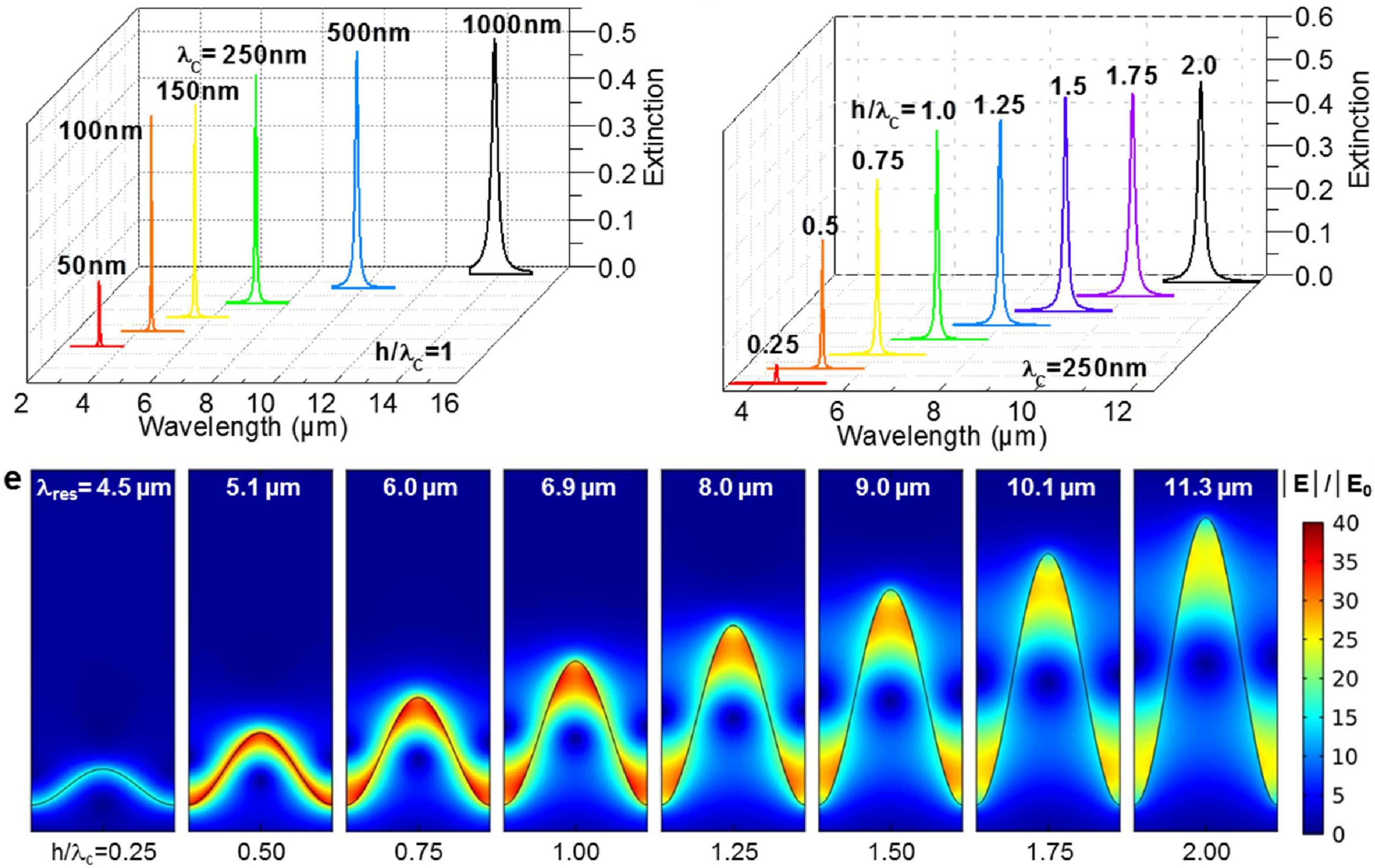
$$H(\omega)=\frac{\sinh(\omega/\omega_T)}{\cosh(\omega_F/\omega_T)+\cosh(\omega/\omega_T)}$$

$$\omega_F=E_F/\hbar,\ \omega_T=k_BT/\hbar,\ \hbar=\frac{h}{2\pi}$$



Kang & Nam, ***Light*** 7, 17 (2018).

Topography vs. Plasmons



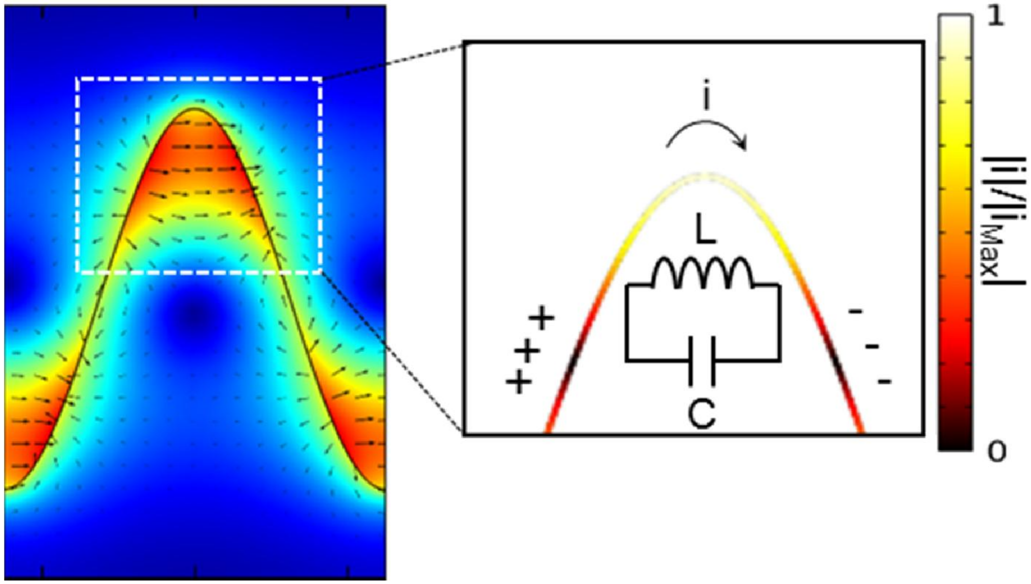
Kang & Nam, ***Light*** 7, 17 (2018).

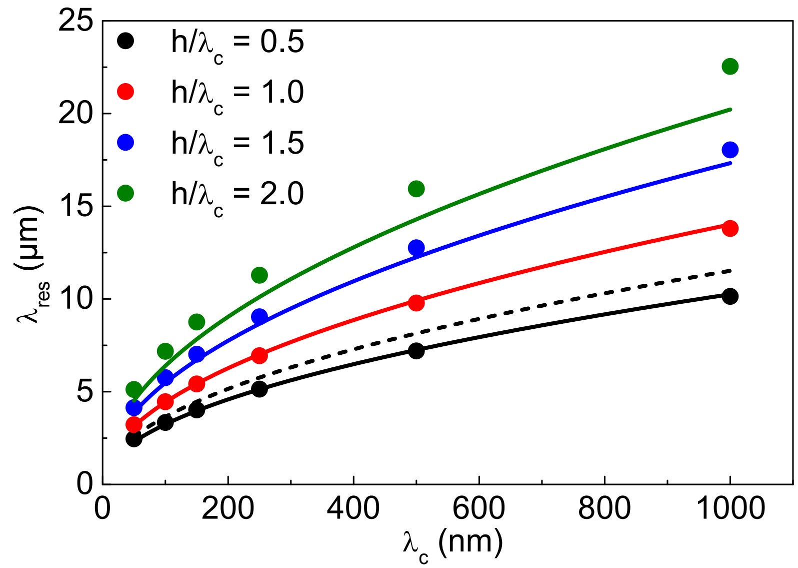
Topography vs. Plasmons

Mechanically Reconfigurable Architectured Graphene Metamaterial for Broadband Tunable Plasmonic Resonances

Kang & Nam, ***Light*** 7, 17 (2018).

Topography vs. Plasmons





Conventional Model

New LC-circuit Model

$$\lambda_{res} = 2\pi c \sqrt{\frac{\hbar^2 \varepsilon_0 (\varepsilon_1 + \varepsilon_2)}{e^2 E_F} \frac{\lambda_c}{2}}$$

$$\lambda_{res} = 2\pi c \sqrt{L_{eff} C_{eff}}$$

$$L_{eff} = \frac{\pi \hbar^2}{e^2 E_F} \lambda_c \qquad C_{eff} = \varepsilon_0 \left(\frac{\varepsilon_1 \varepsilon_2}{\varepsilon_1 + \varepsilon_2} \right) \frac{1}{\alpha} \ln\left[1 + \left(1 + e^{-\alpha} \right) \right]$$

$$\alpha = \pi - 2\tan^{-1}(2h/\lambda_c)$$

Our analytical model accurately describes the surface plasmon resonance of crumpled graphene with small to large h/λ_c (0.2−2).

Kang & Nam, ***Light*** 7, 17 (2018).

Mechanically-driven Nano-manufacturing of Ultrathin Kirigami Structures

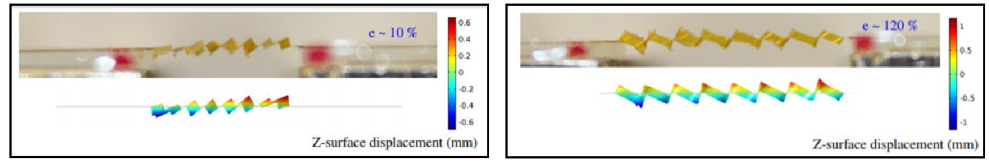
nanoMFG node thrust:
VI Nanoscale Self Assembly

PIs and Students: Aluru & Nam (PIs); De & Yong (students)

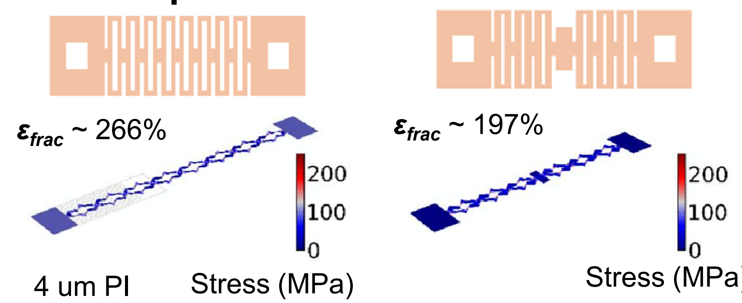
Objectives: Develop a simulation tool capable of nano-mechanics driven manufacturing of ultrathin kirigami structures for meta materials.

(1) Develop continuum mechanics model for several deformation modes
(2) Experimental verification of final structures

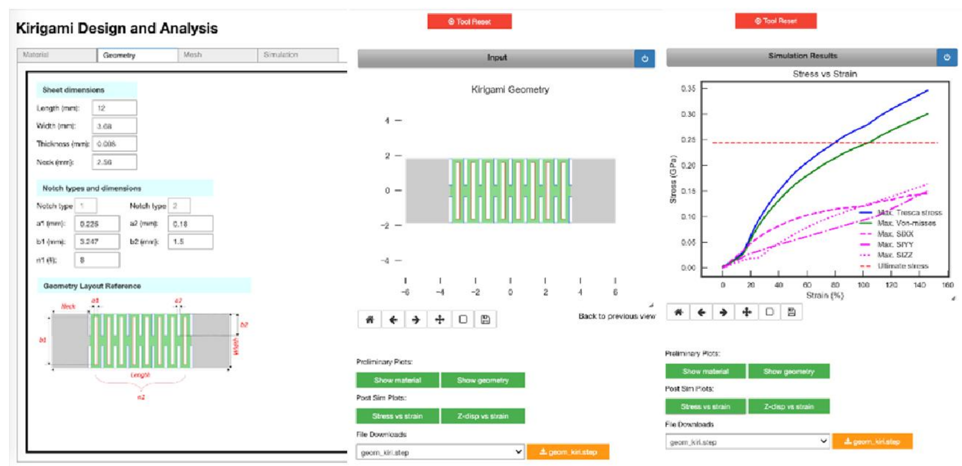
Significance:
Use mechanical self-assembly to create multifunctional structures and morphologies in nanoscale



Experiment vs. Simulation



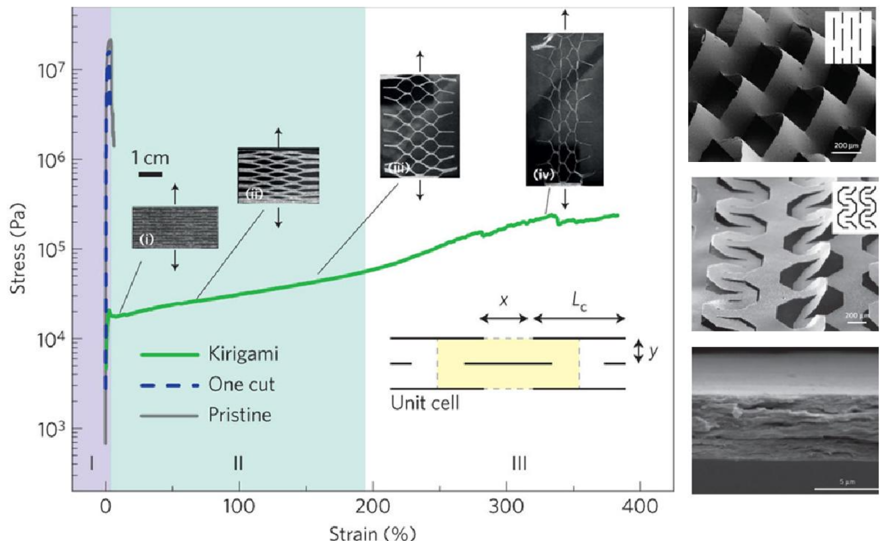
Parametric Optimization



Tool Wireframe

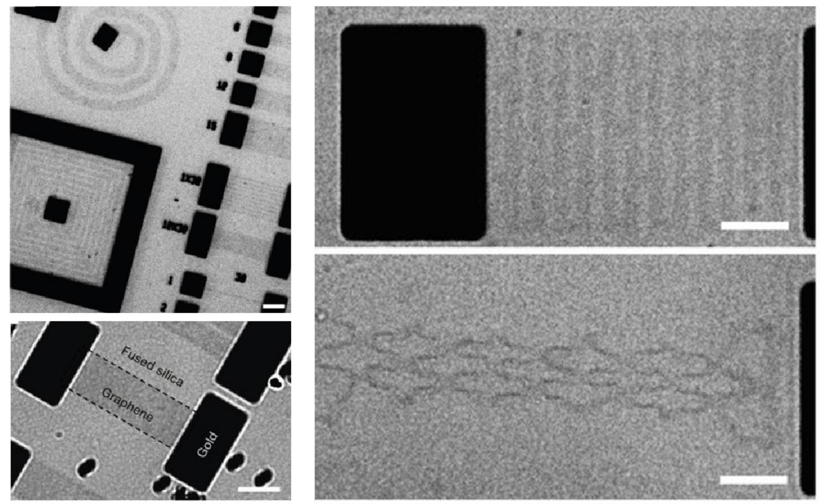
Inspirations for Kirigami Architecture

Kirigami Paper/Nanocomposite



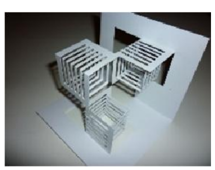
Kotov *et al*., *Nat. Mat*, 14 (2015)

Graphene Kirigami



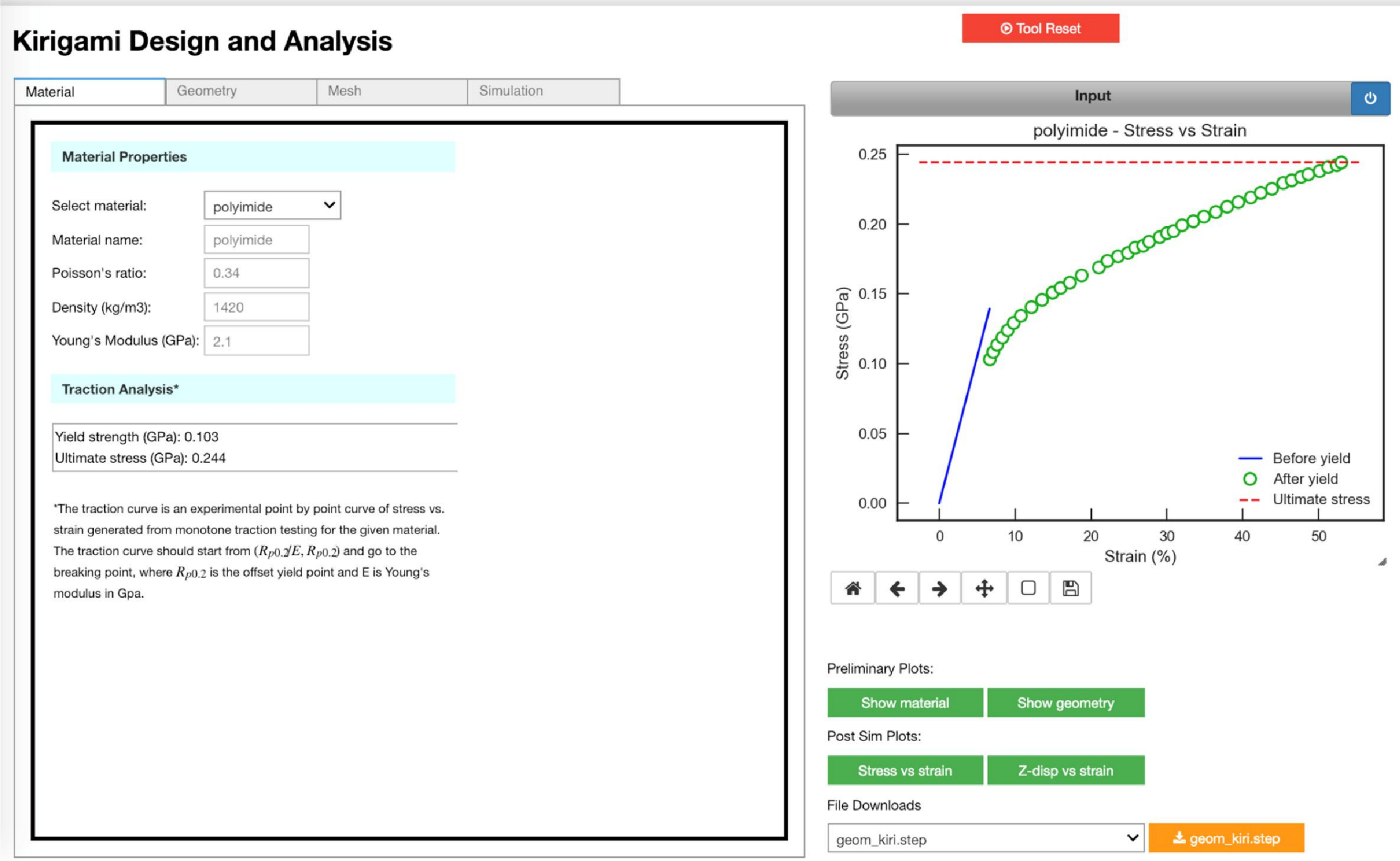
McEuen *et al*., *Nature*., 524 (2015)

- In traditional kirigami, cut or notches are introduced into paper sheets to attain a desirable topology on folding.
- 2D kirigami surface architectures can be transformed into strain-responsive 3D architectures in the vicinity of patterned regions owing to mechanical bi-stability.



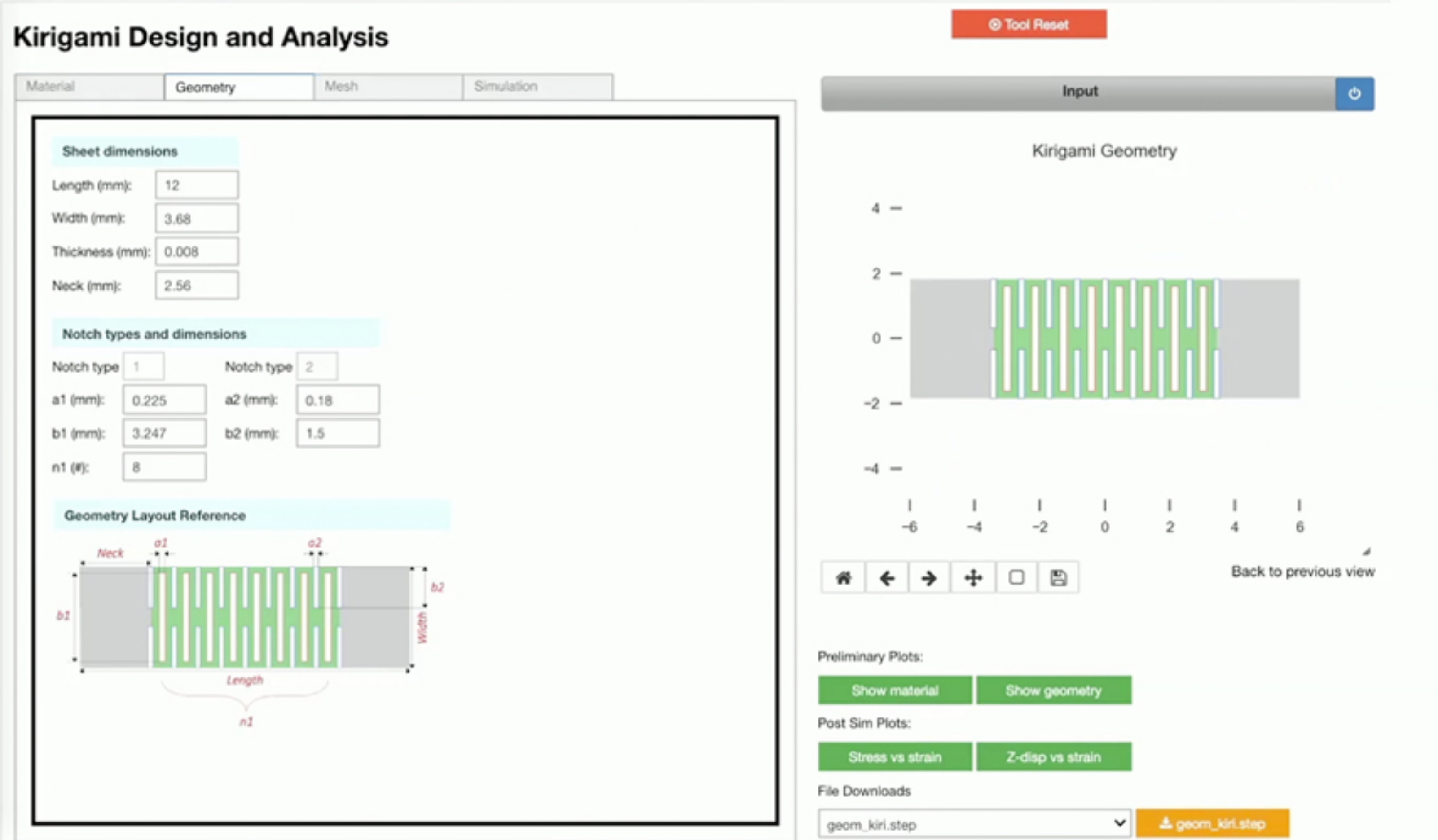


nanoHUB Tool Interface (1)



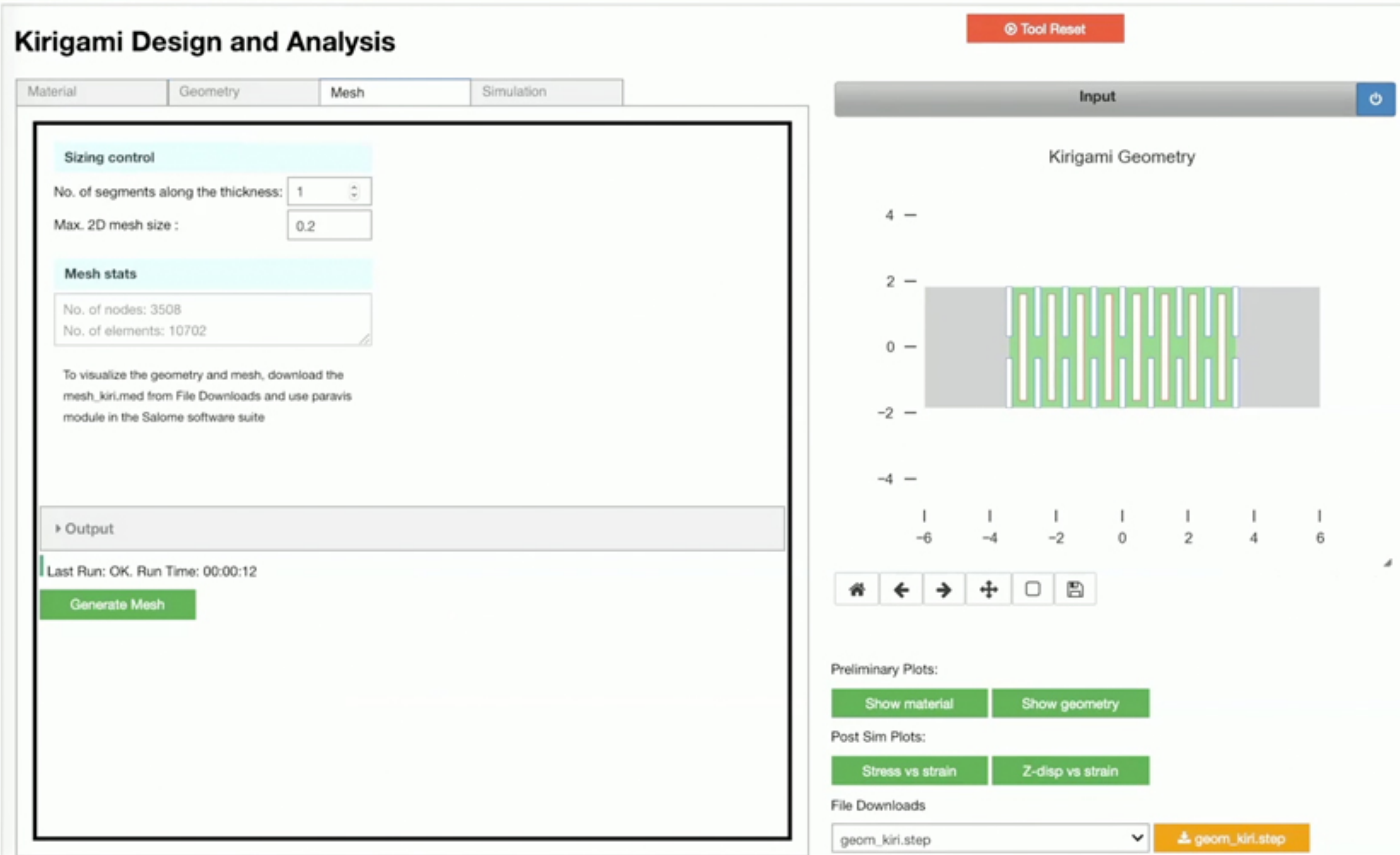
https://nanohub.org/tools/gamian

nanoHUB Tool Interface (2)



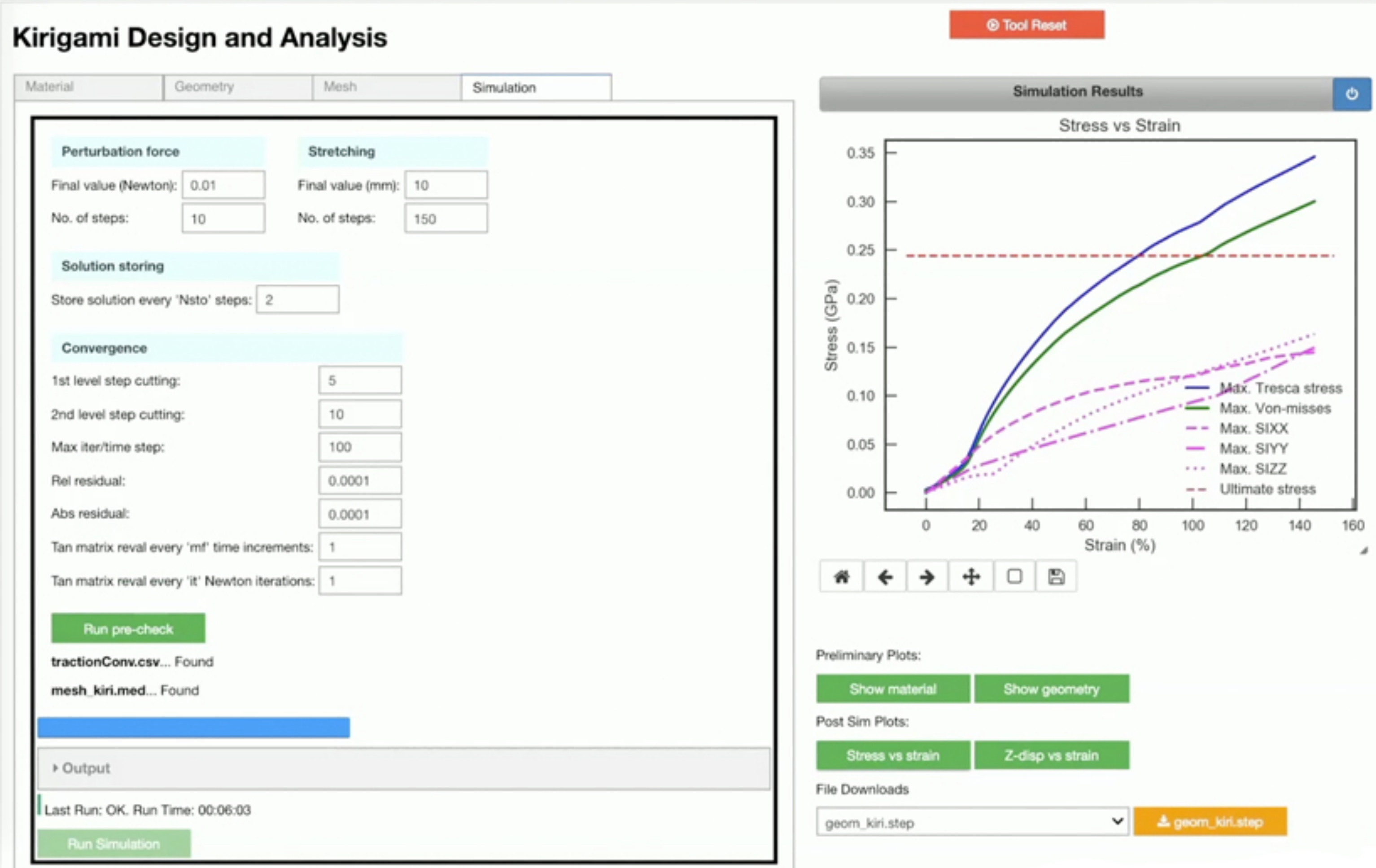
https://nanohub.org/tools/gamian

nanoHUB Tool Interface (3)



https://nanohub.org/tools/gamian

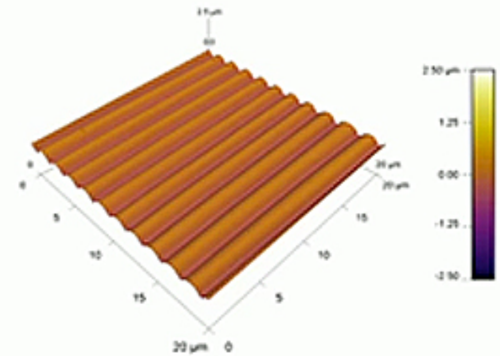
nanoHUB Tool Interface (4)



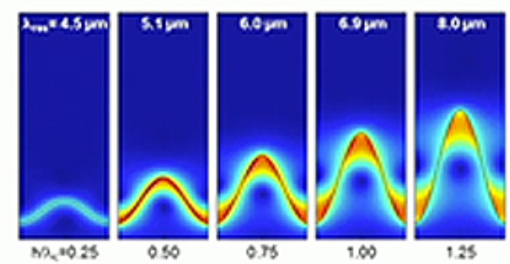
https://nanohub.org/tools/gamian

Conclusions

- **Controlled Deformation for**
  − Reconfigurable plasmonic resonance of corrugated graphene



- **Kirigami Design for**
  − Decoupling mechanical response from electrical properties of the design structure



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