Tailoring Mechanical Instability of Atomically-thin Materials

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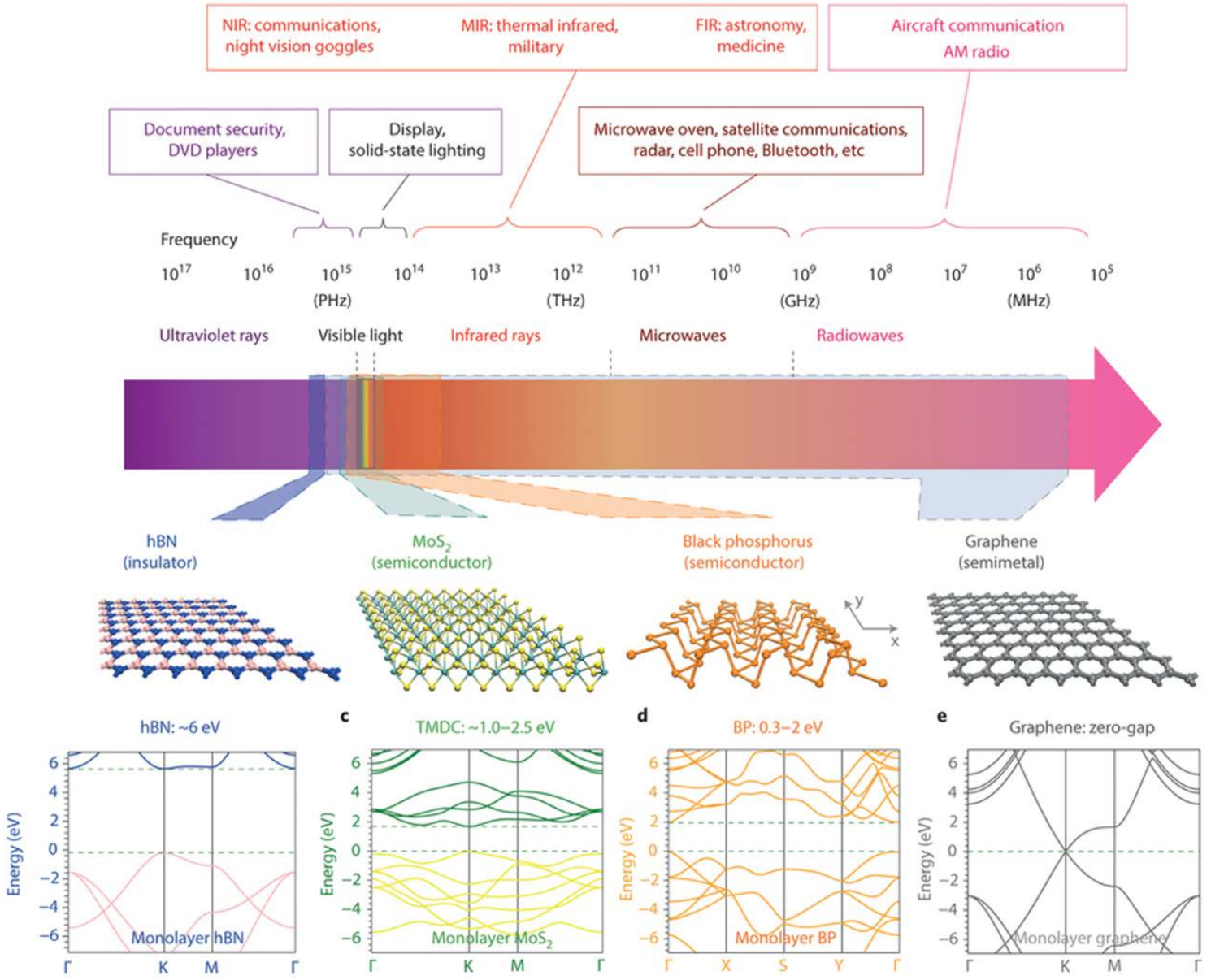
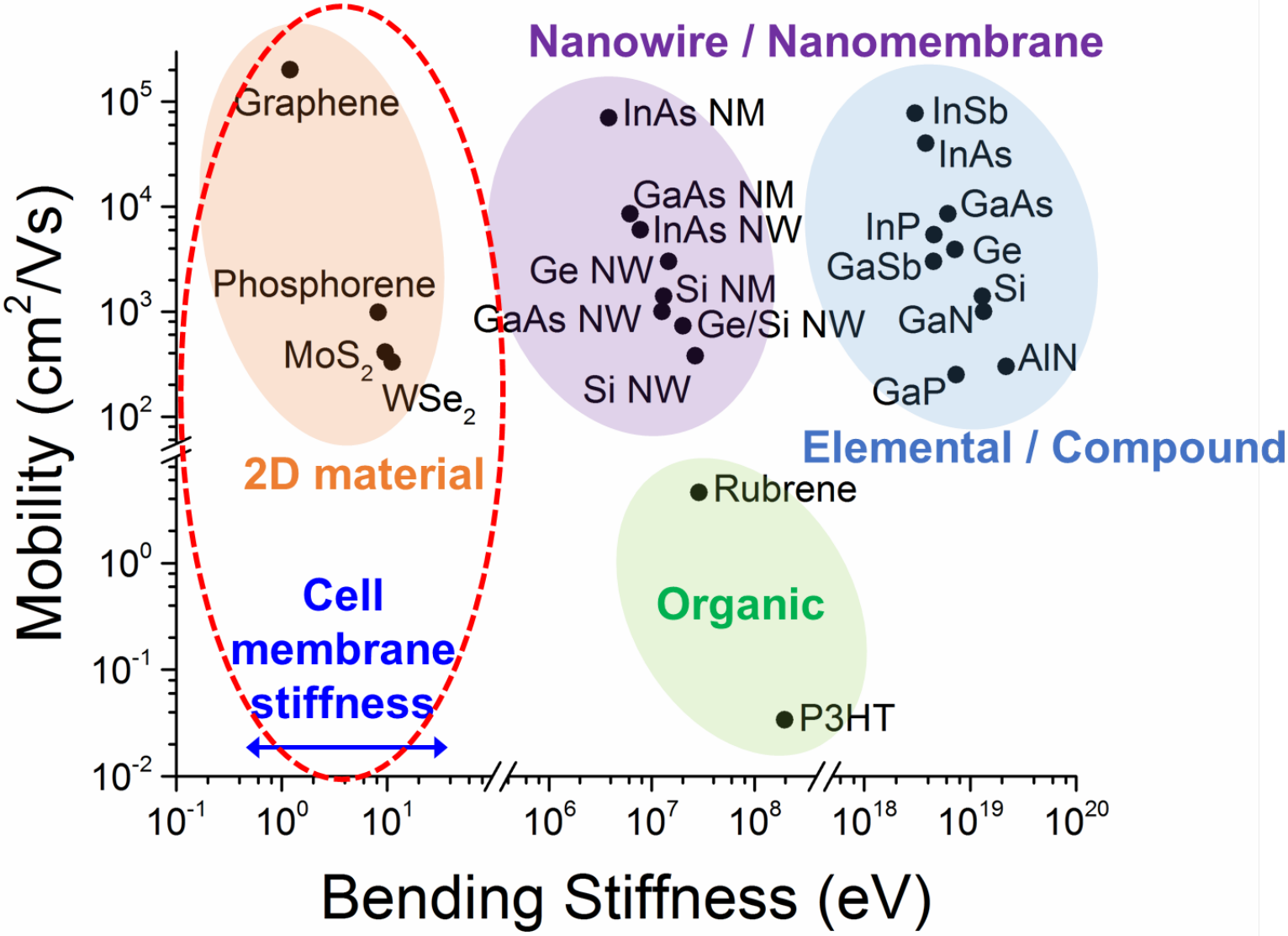
Atomically-thin, 2D Materials

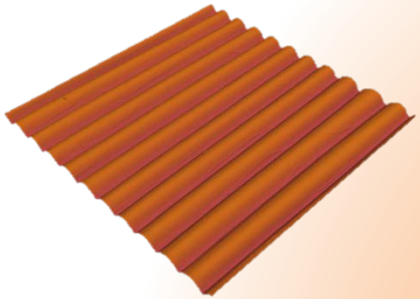


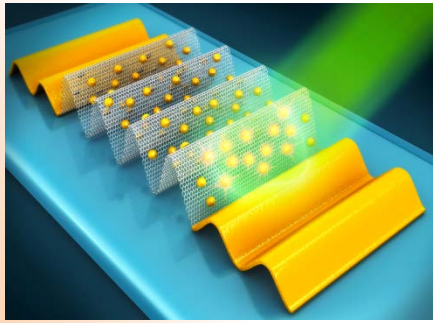
Nature Photonics 8, 899 (2014).

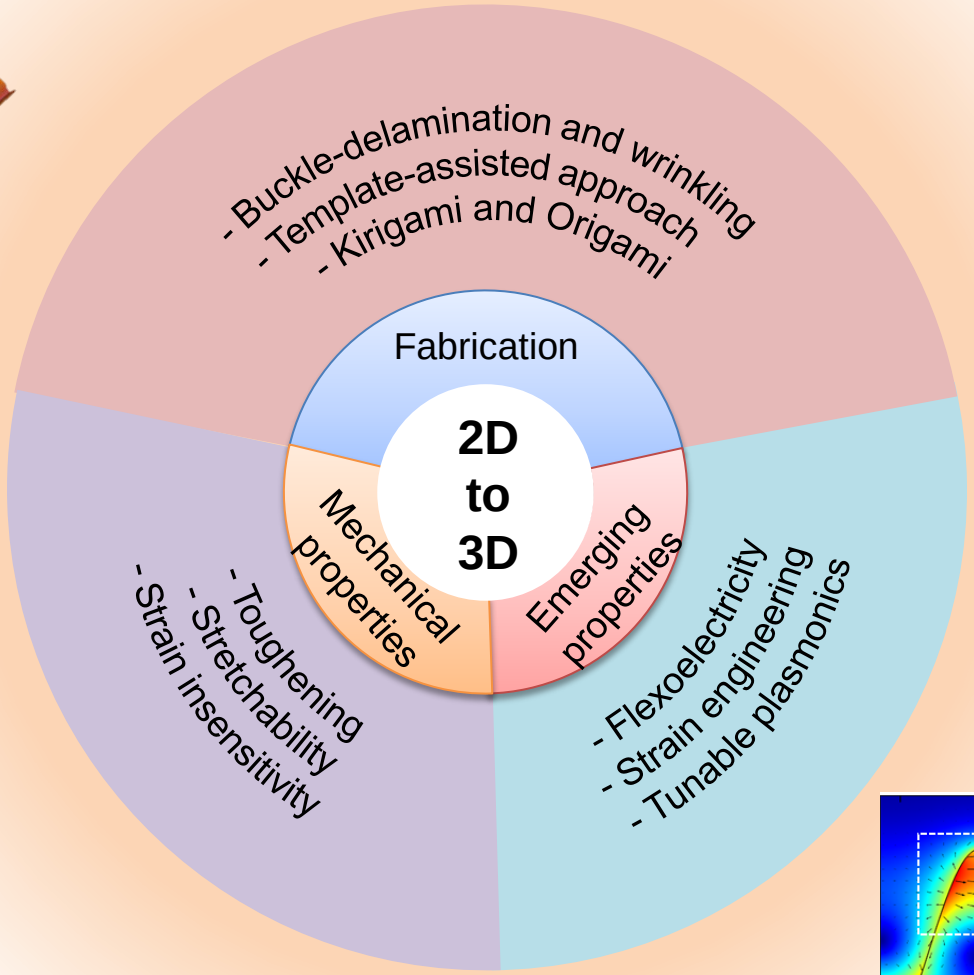
Architecturing 2D Materials

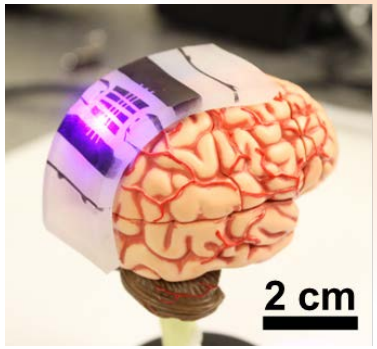


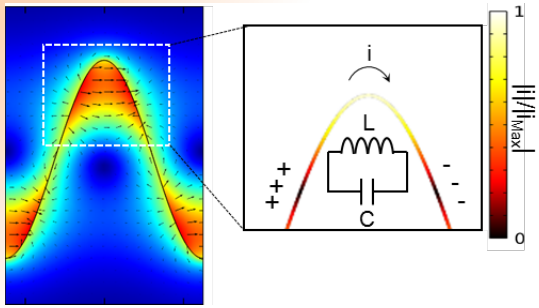
Architecturing 2D Materials





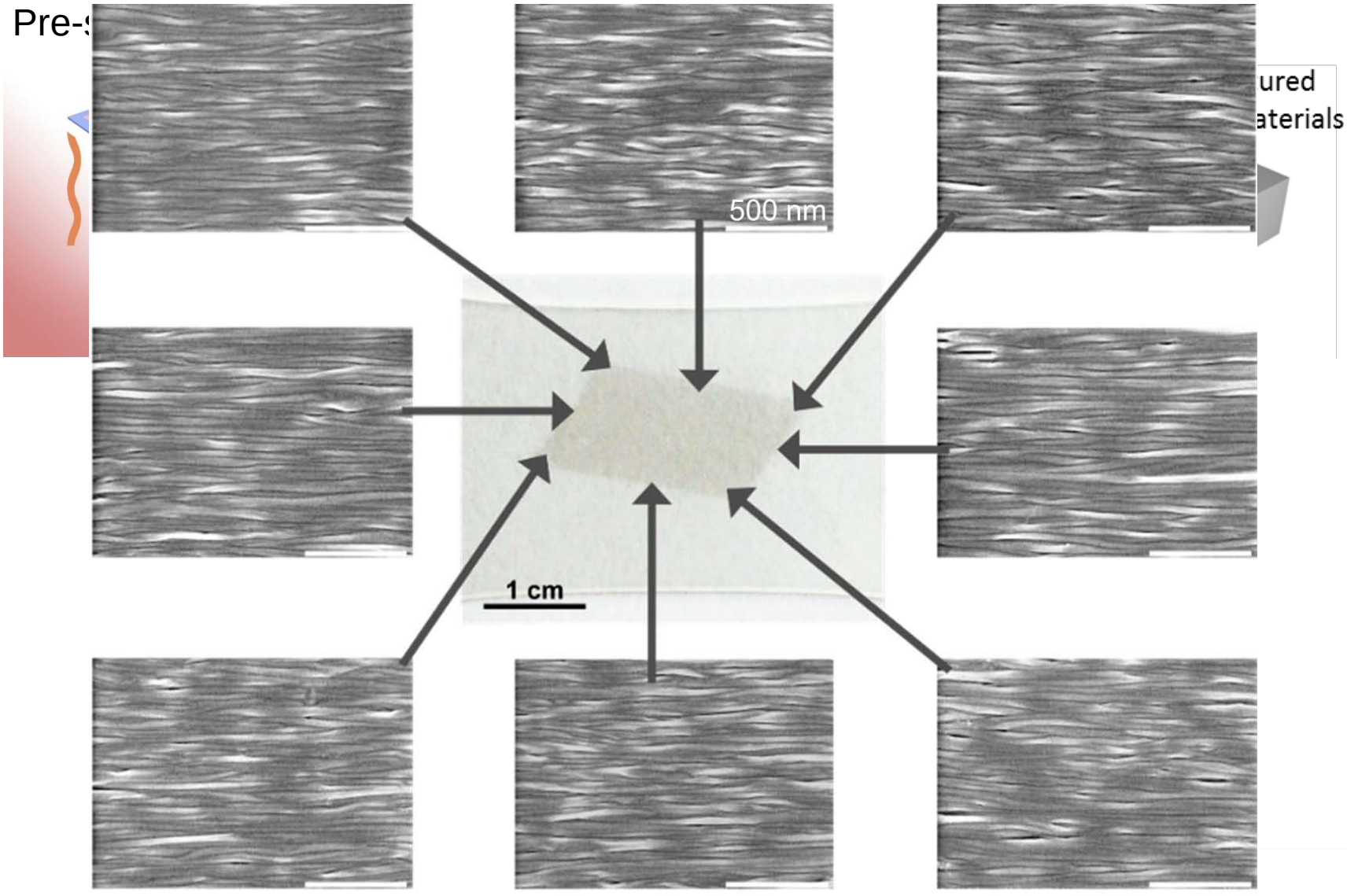






S. Nam *et al*., 2D Materials, 2017, 4, 022002.

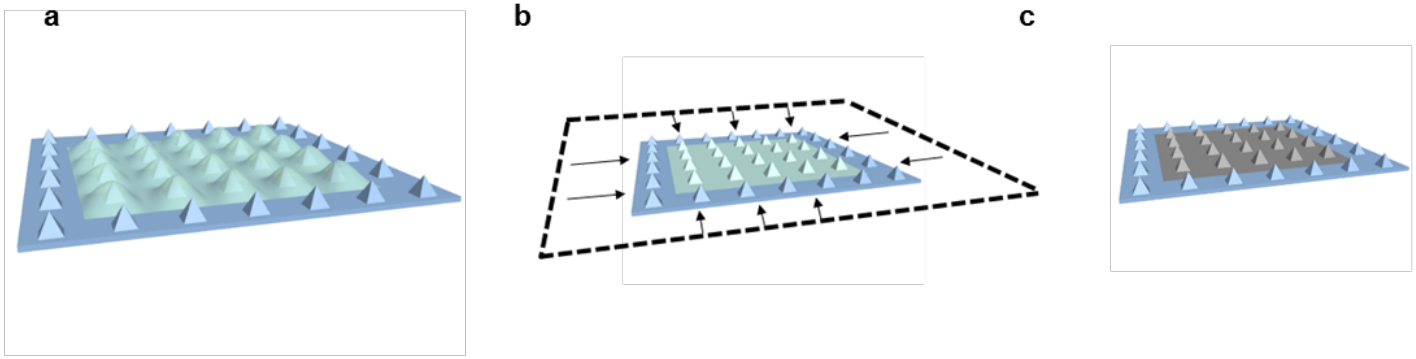
Controlled Out of Plane Deformation



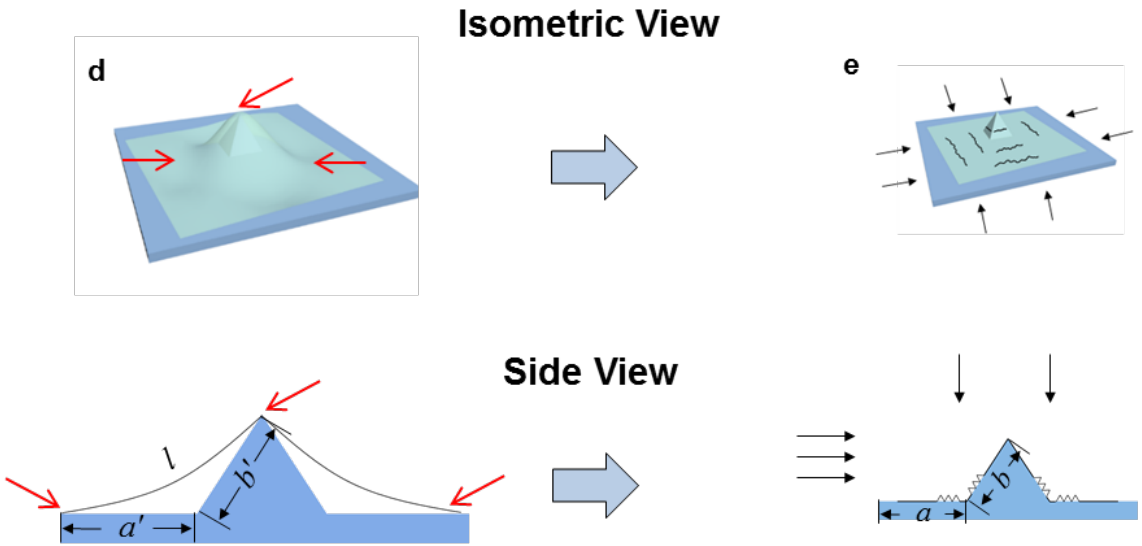
Wang & Kang U.S. Patent 9,908,285 (2018); Wang & Nam, ***Nano Letters*** (2015); Kang & Nam, ***Advanced Materials*** (2016).

3D Structures by Controlled Shrinkage

Overall process of large-area, conformal transfer

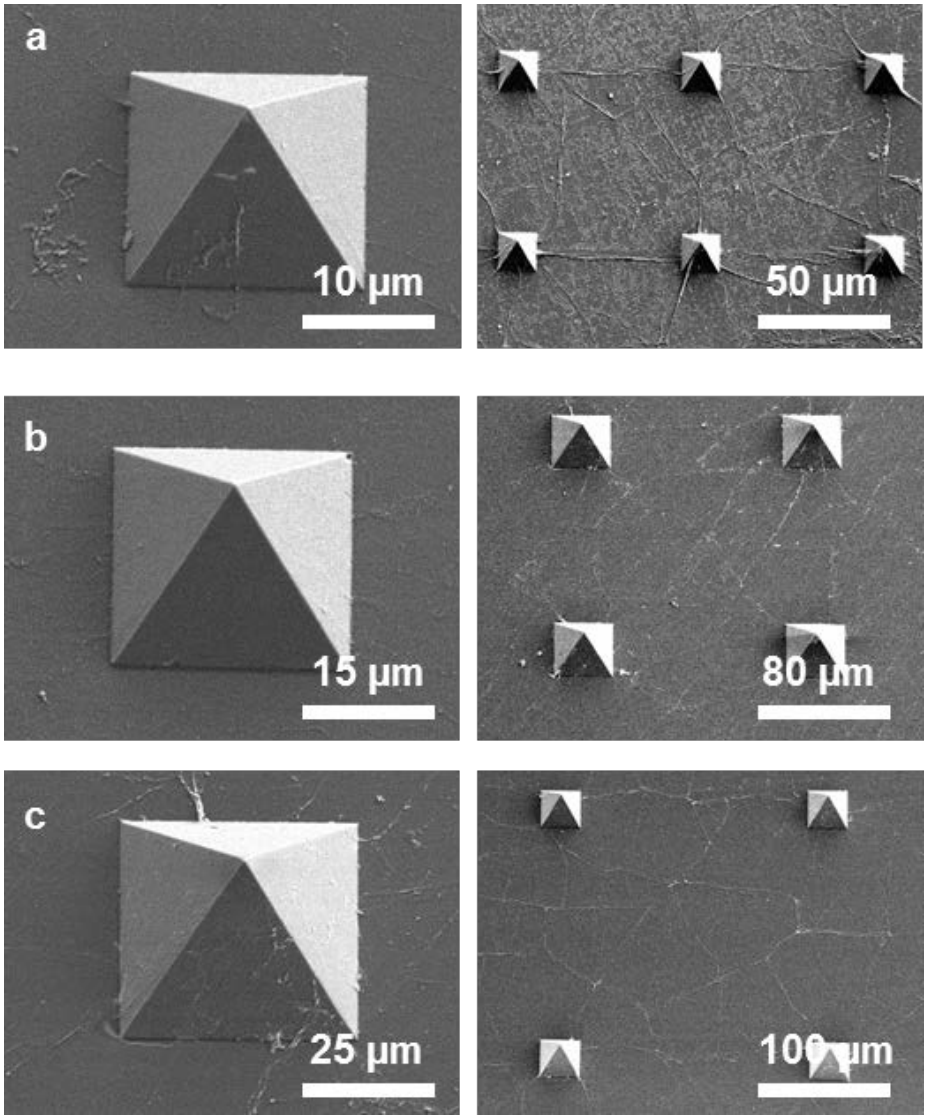


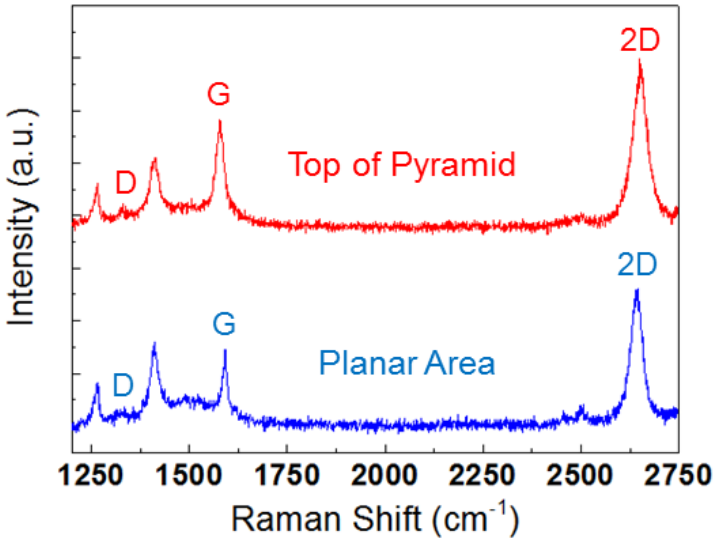
Detailed phenomena during shrinking/conformal adaptation process

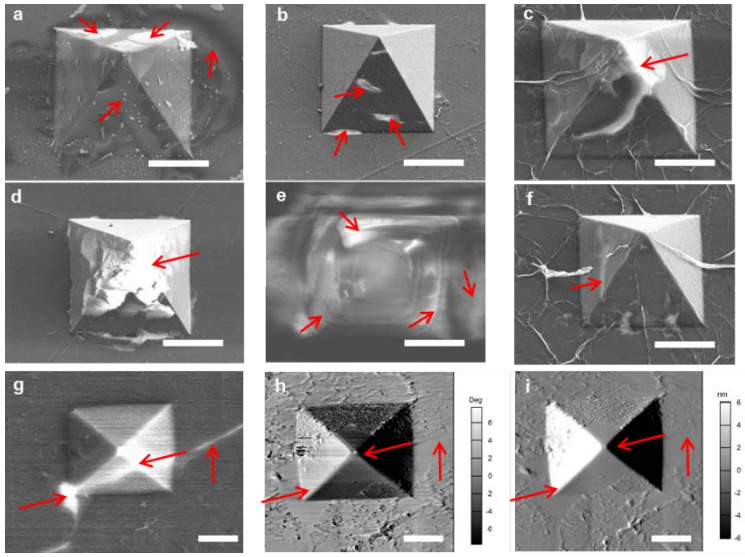


Choi & Nam, ***Nano Letters*** 15, 4525 (2015).

3D Structures by Controlled Shrinkage

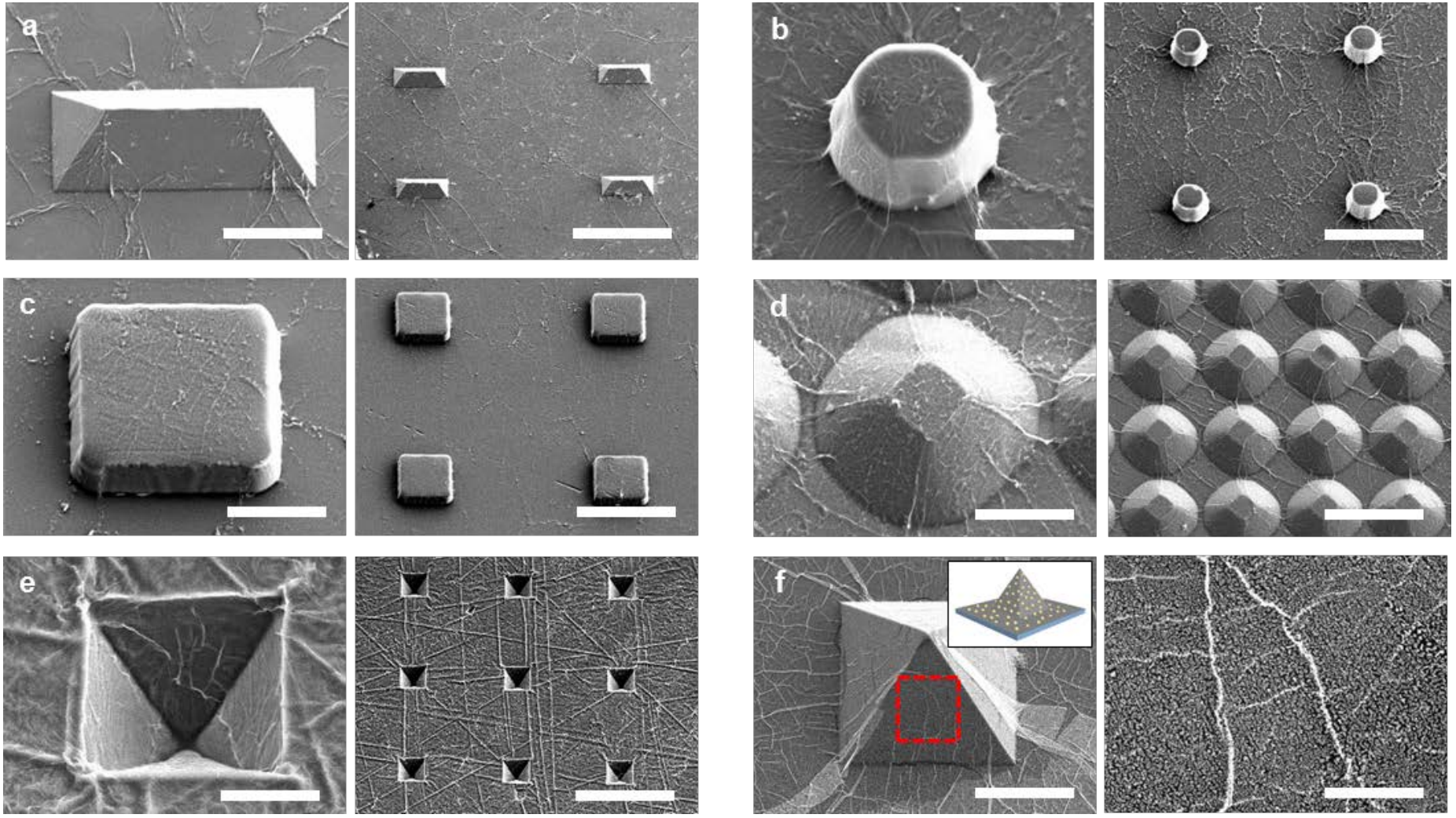






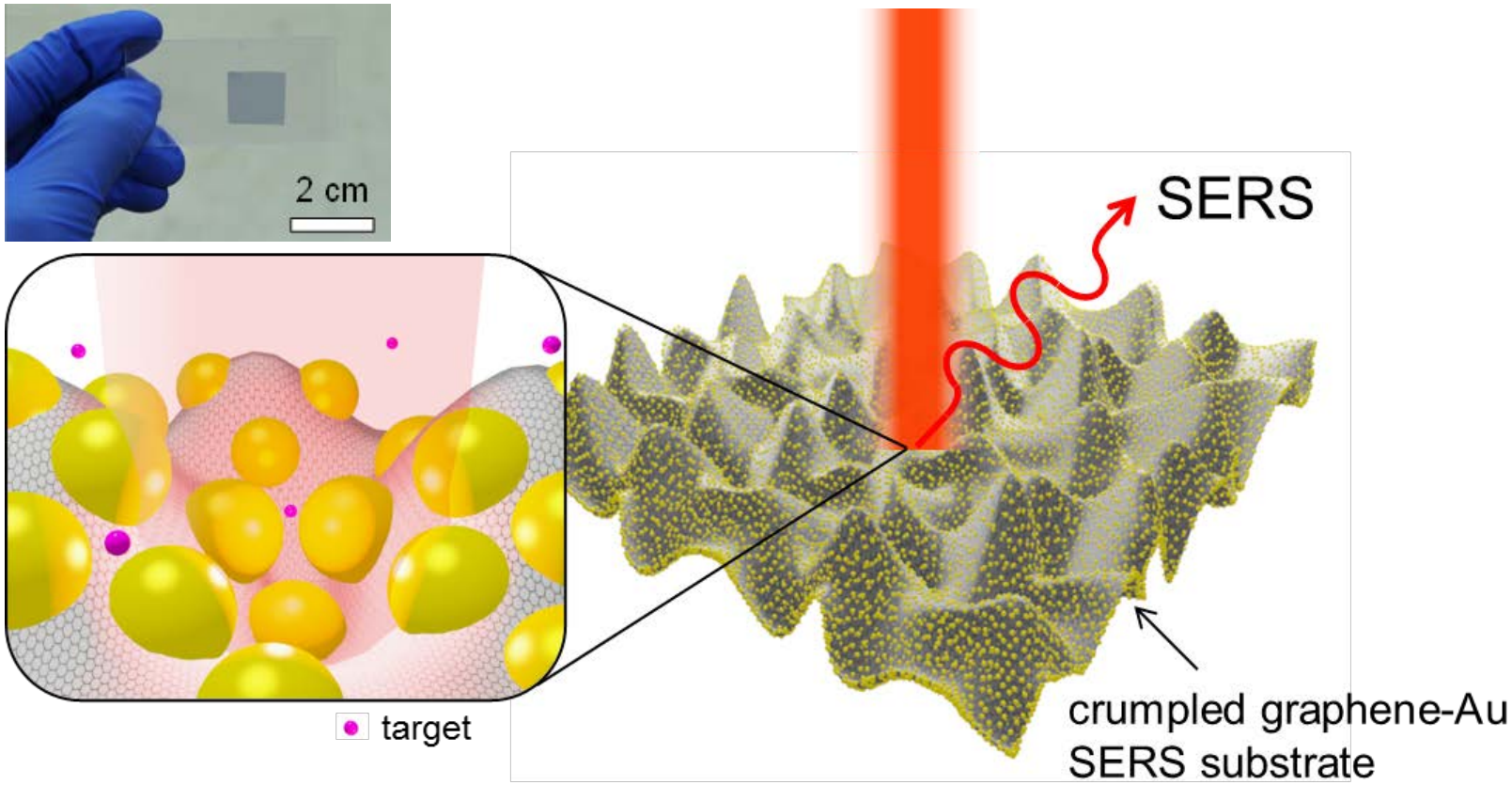
Choi & Nam, ***Nano Letters*** 15, 4525 (2015).

3D Structures by Controlled Shrinkage



Choi & Nam, ***Nano Letters*** 15, 4525 (2015).

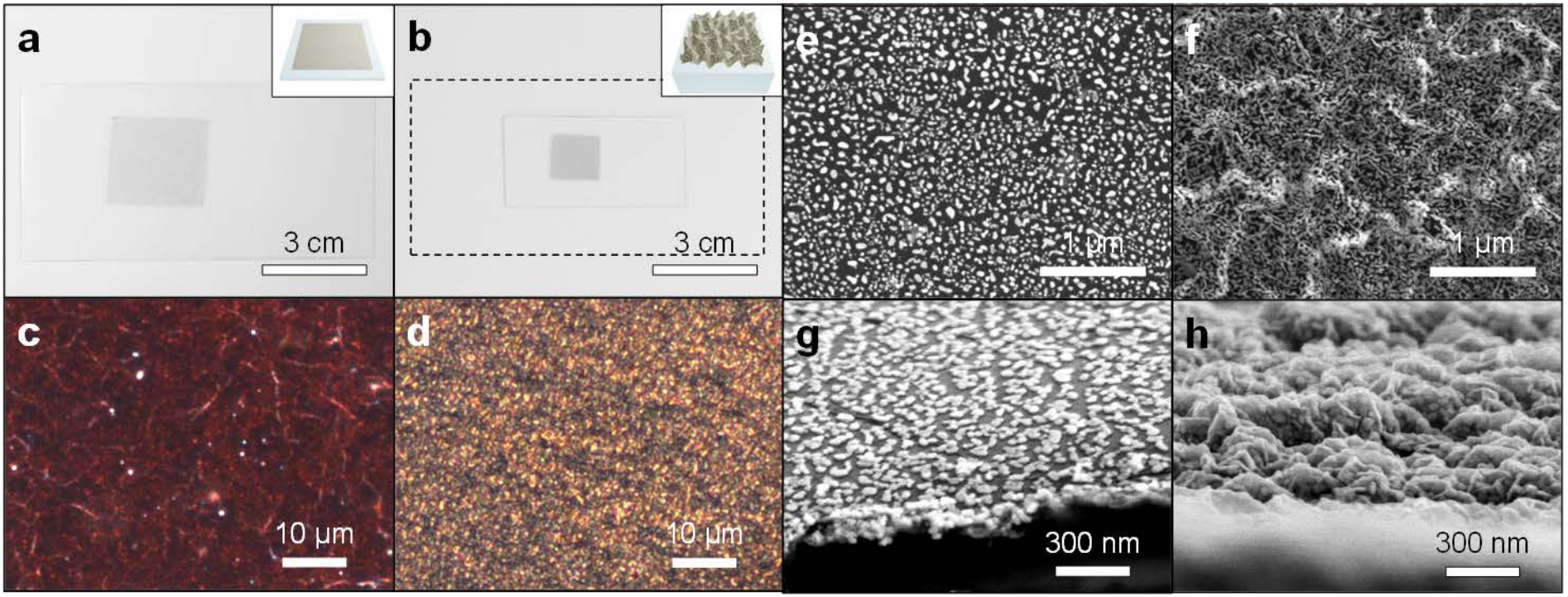
Crumpling of Hybrid 0D-2D Materials



- Au nanoparticles integrated on crumpled 3D graphene could serve as optical signal enhancer as well as light-triggered delivery of biomolecules

Leem & Nam, ***Nano Letters*** 15, 7684 (2015).

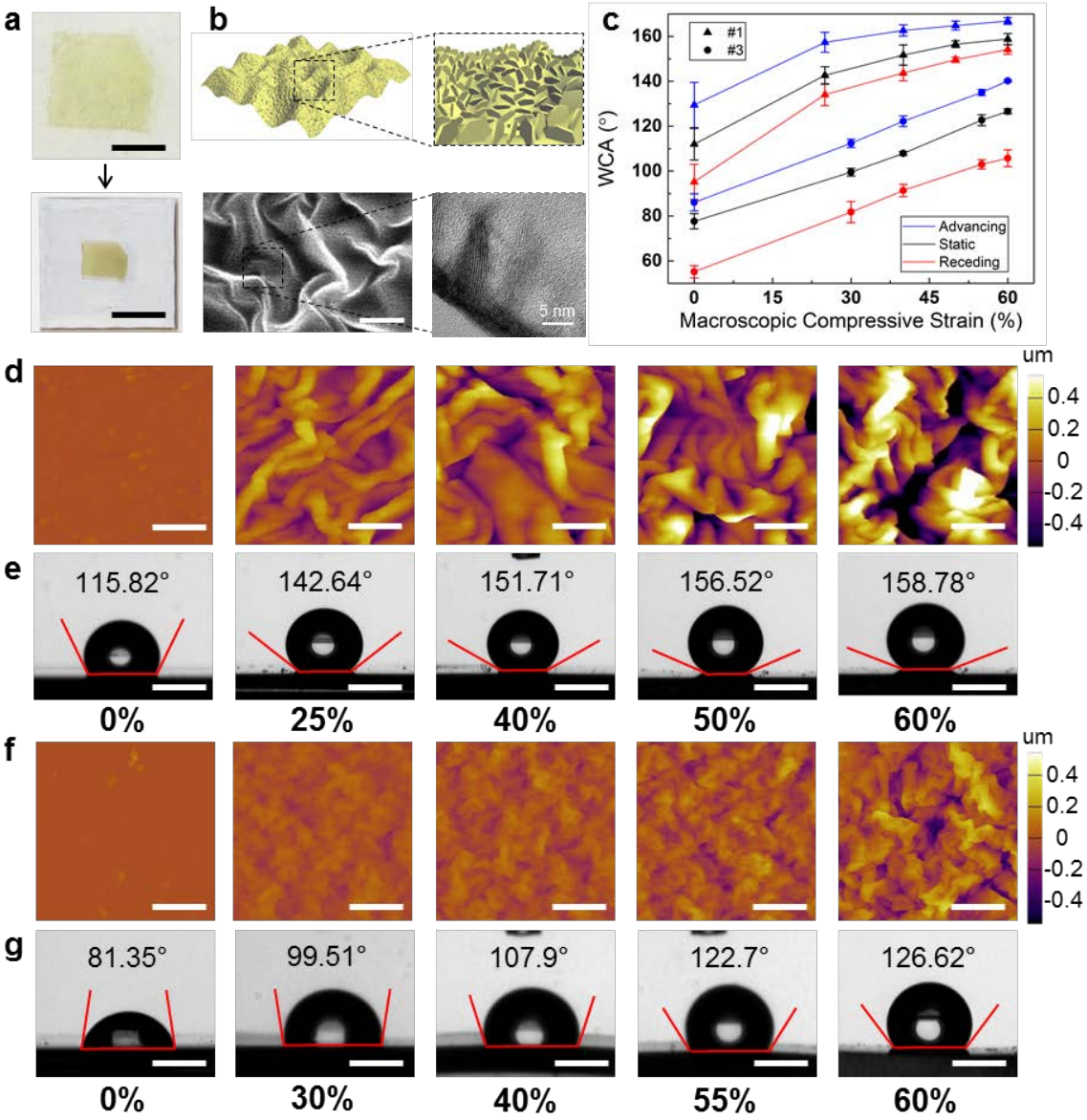
Crumpling of Hybrid 0D-2D Materials



- As shrinkage increases, hybrid graphene-Au 3D structures are formed
- 3D hybrid graphene-Au structures exhibit a microscale crumpled topography and nanoscopic integrated Au antennae
- The structure is fully adaptive to complex microscopic 3D surfaces by the shrinkage process

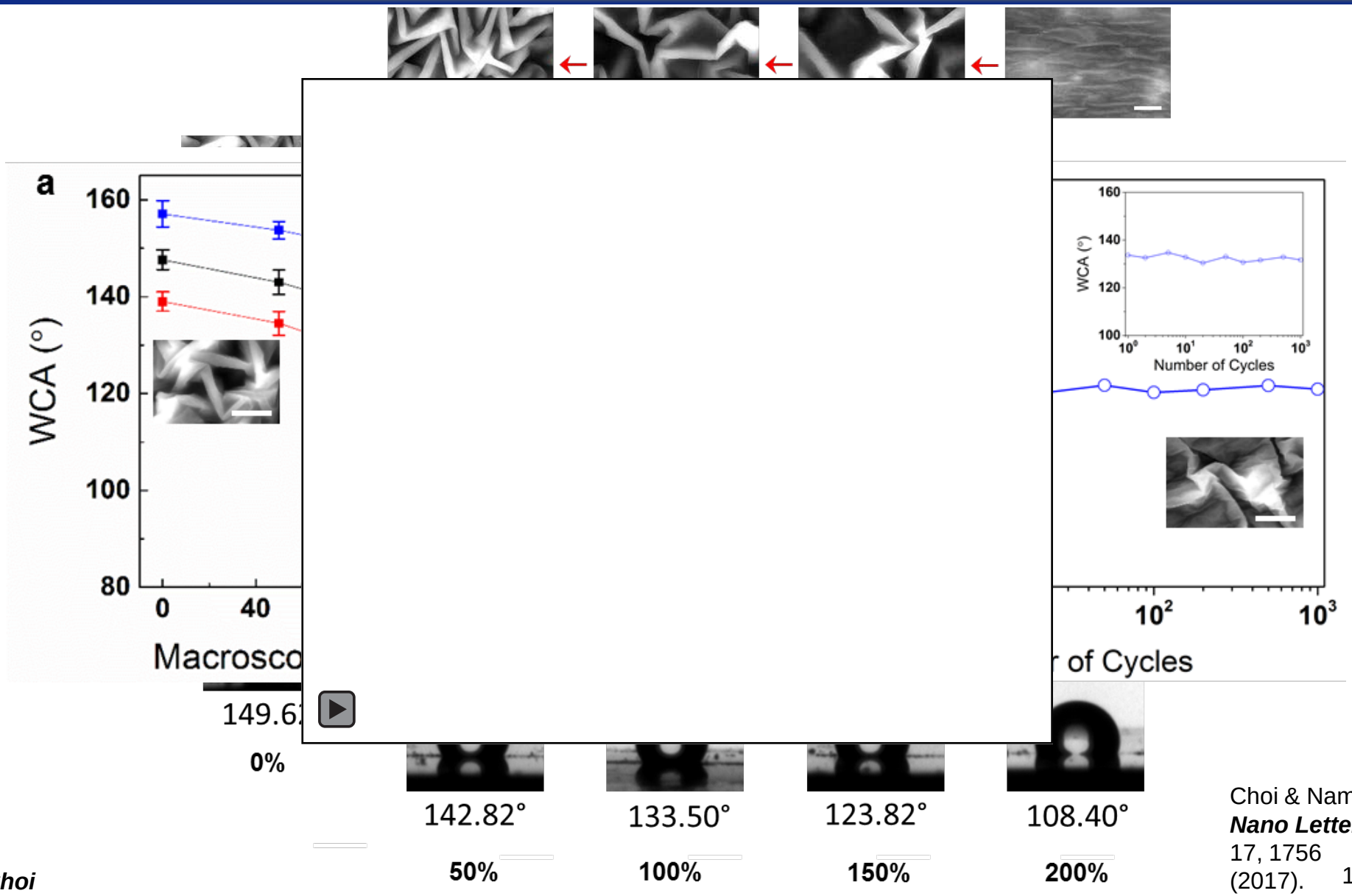
Leem & Nam, ***Nano Letters*** 15, 7684 (2015).

Topography vs. Surface Energy



Choi & Nam, ***Nano Letters*** 17, 1756 (2017).

Topography vs. Surface Energy



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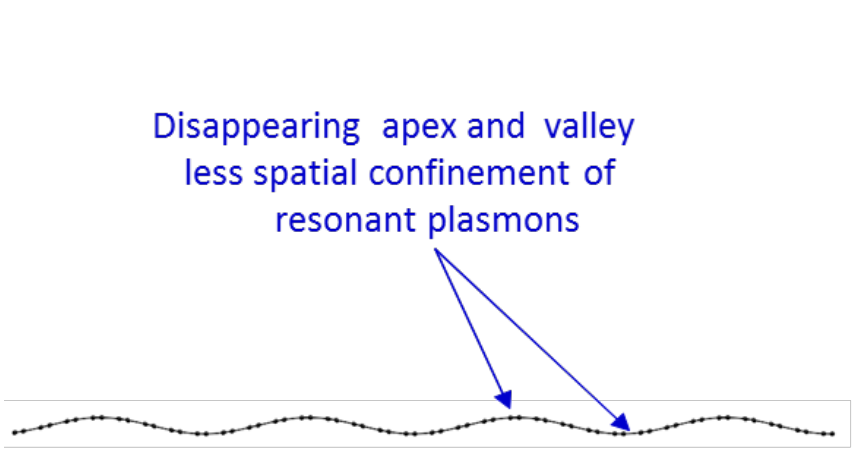
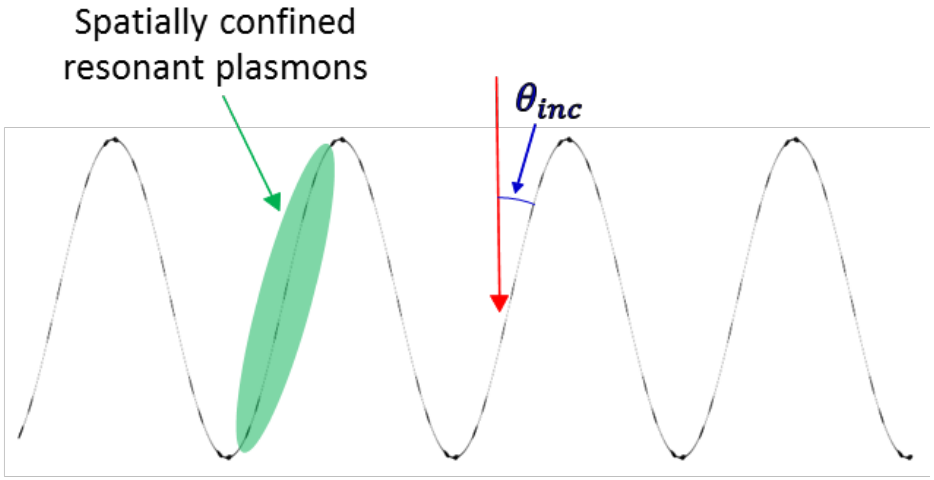
Topography vs. Plasmons



$h / \lambda_c = 0.083$



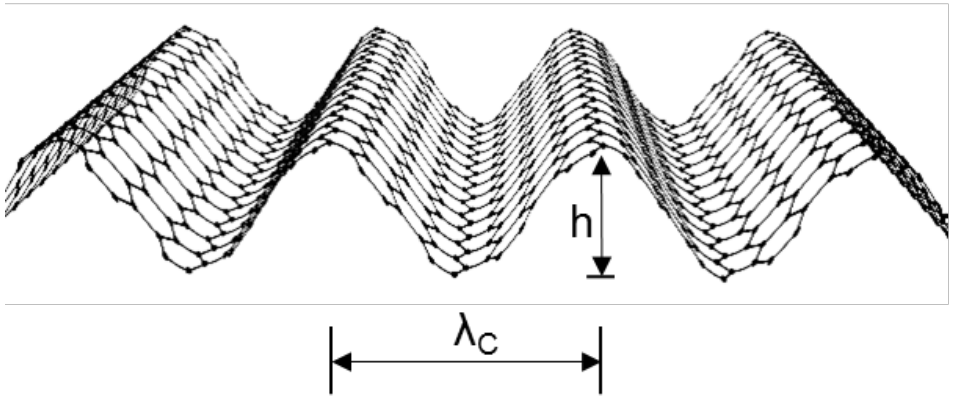
$h / \lambda_c = 1.5$

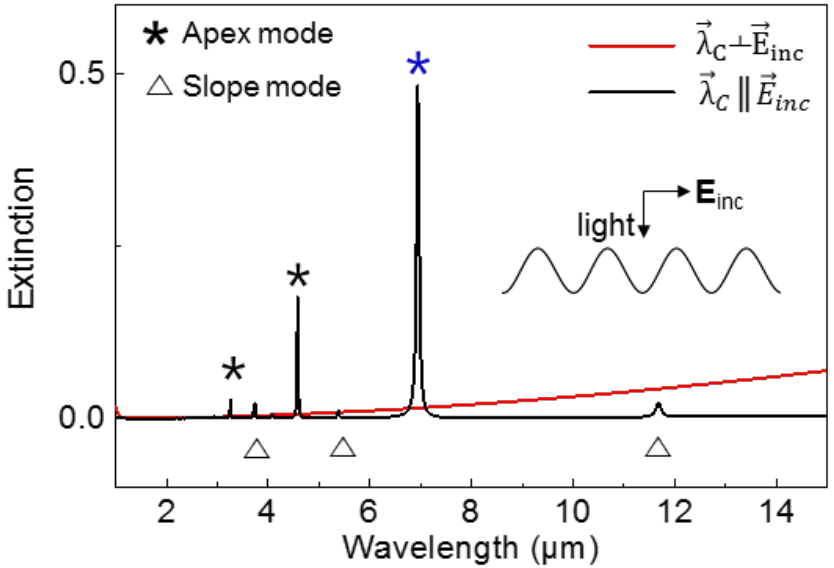
- Crumpling graphene enables the enhanced plasmonic resonance in the near/mid infrared wavelengths (1-10 μm) which is difficult to achieve with the lithographically patterned graphene nanostructures (e.g. graphene ribbons, disks, rings, and stacks).

- 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

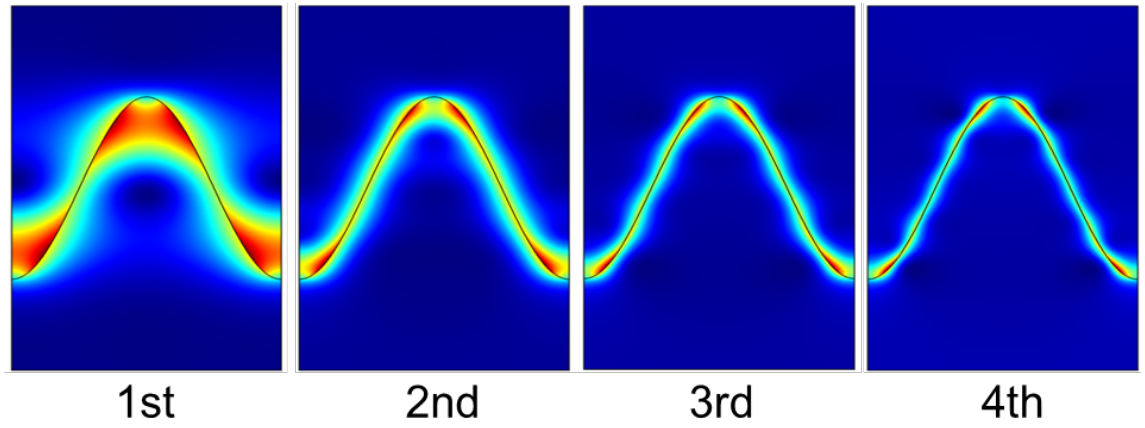
$$\sigma(\omega) = \sigma_{\text{intra}}(\omega) + \sigma_{\text{inter}}(\omega)$$

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

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

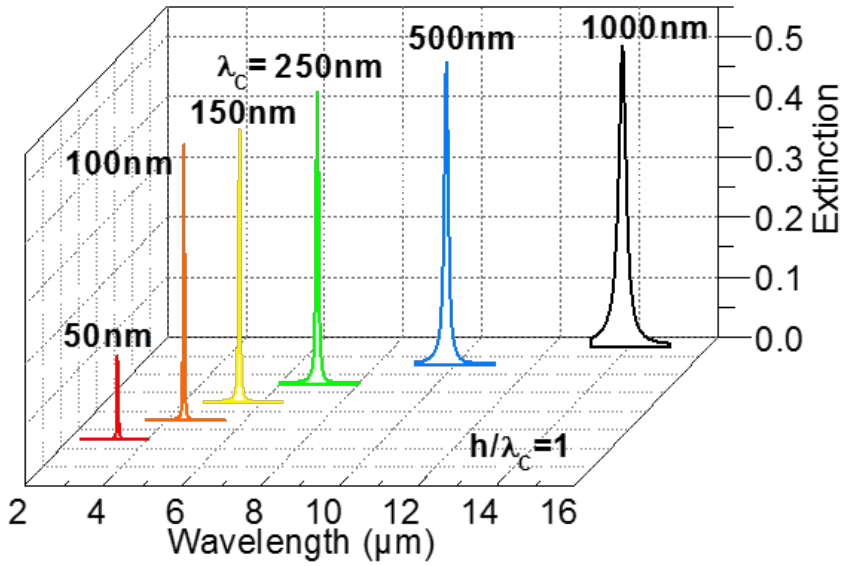
$$H(\omega) = \frac{\sinh(\omega/\omega_T)}{\cosh(\omega_F/\omega_T) + \cosh(\omega/\omega_T)}$$

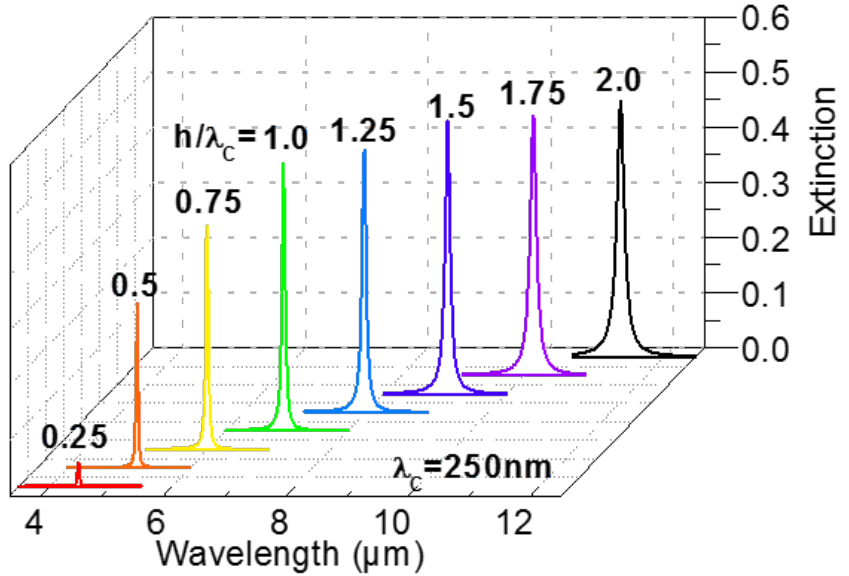
$$\omega_F = E_F/\hbar,\ \omega_T = k_B T/\hbar,\ \hbar = \frac{h}{2\pi}$$

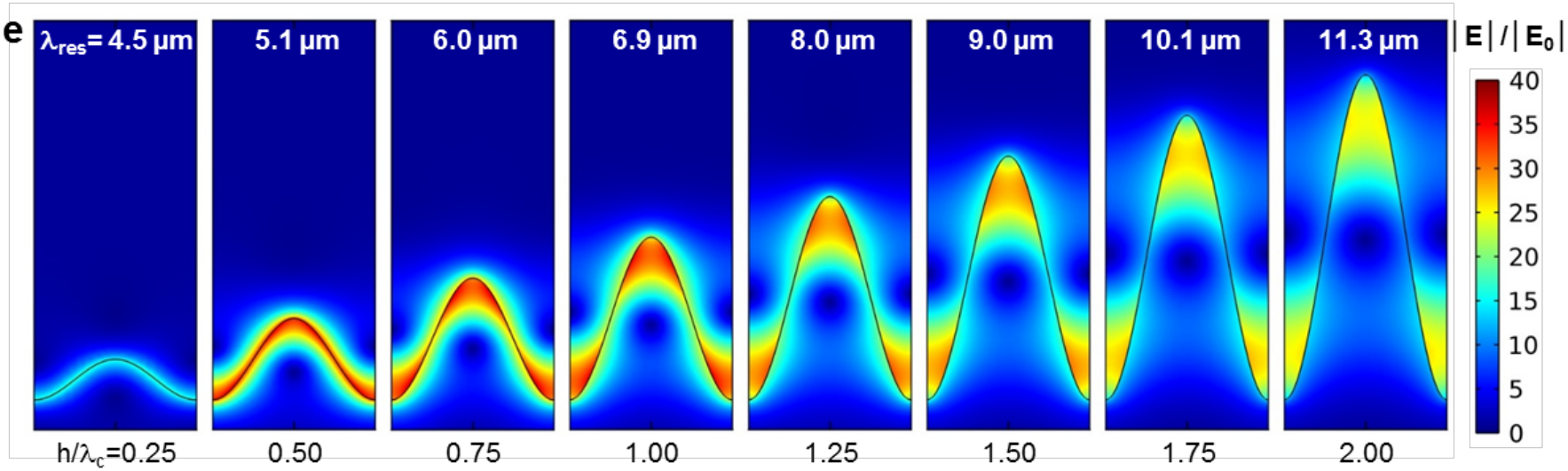


Kang & Nam, ***Light*** 7, 17 (2018).

Topography vs. Plasmons





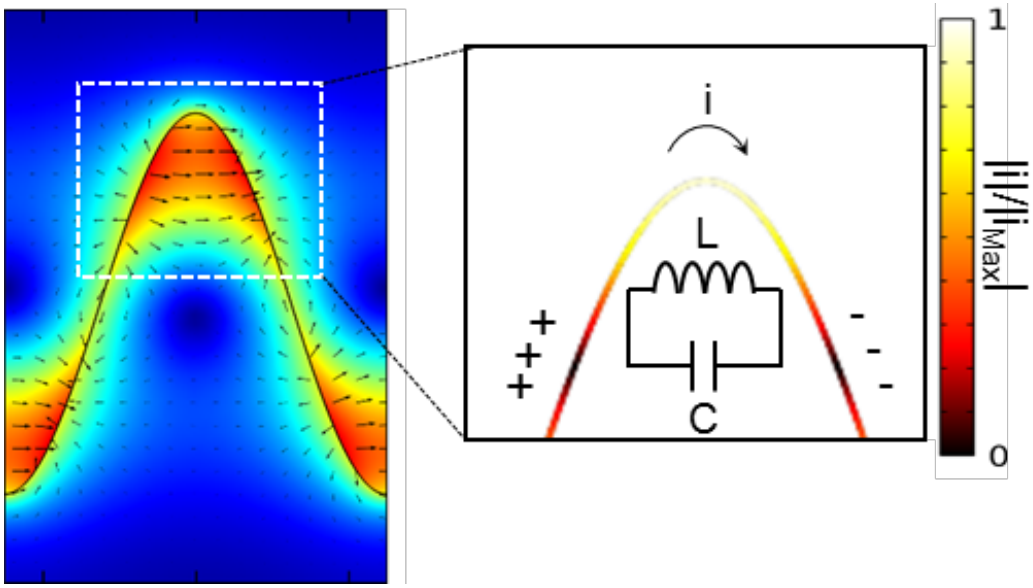


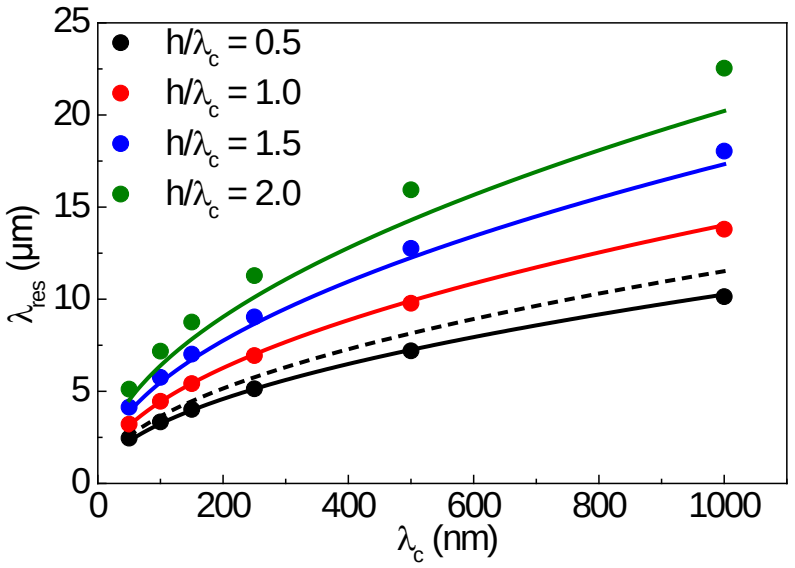
Kang & Nam, ***Light*** 7, 17 (2018).

Topography vs. Plasmons

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

Topography vs. Plasmons





Conventional Model

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

New LC-circuit Model

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

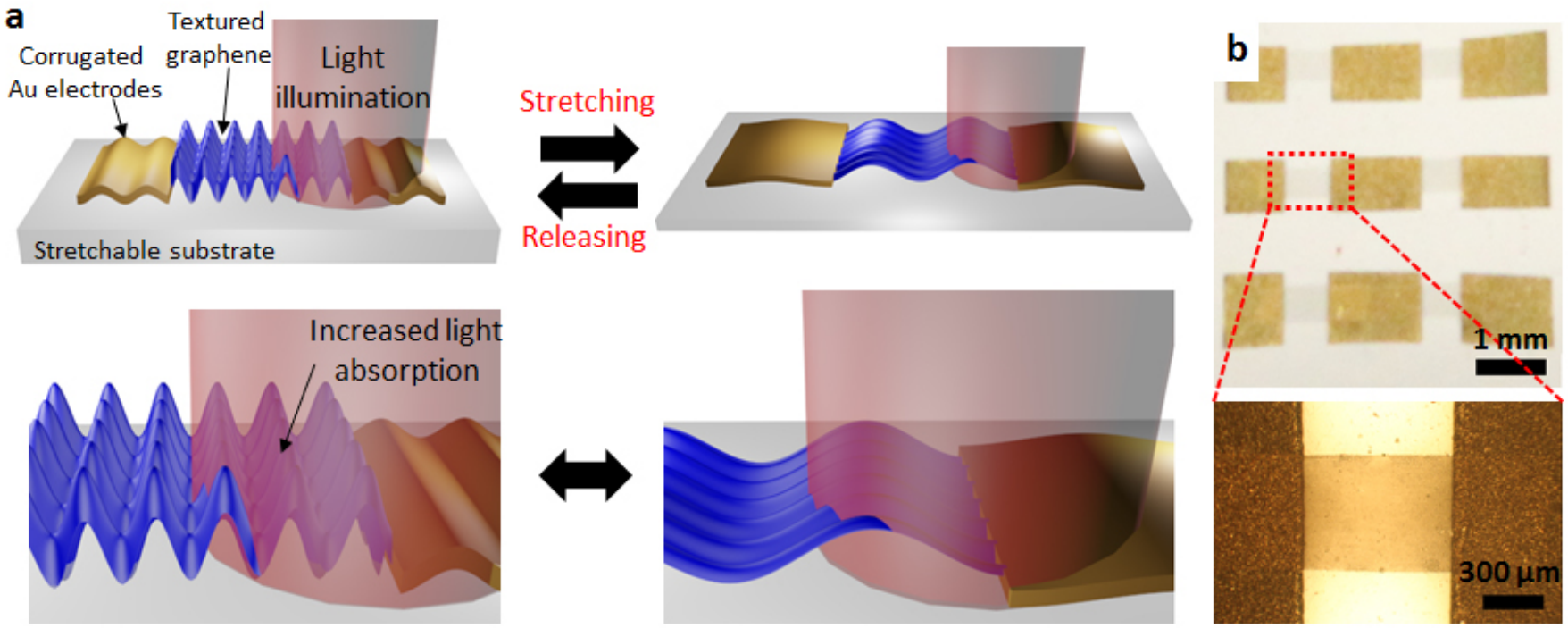
Our analytical model accurately describes the surface plasmon resonance of crumpled graphene with small to large h/λ_c (0.2−2).

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

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

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

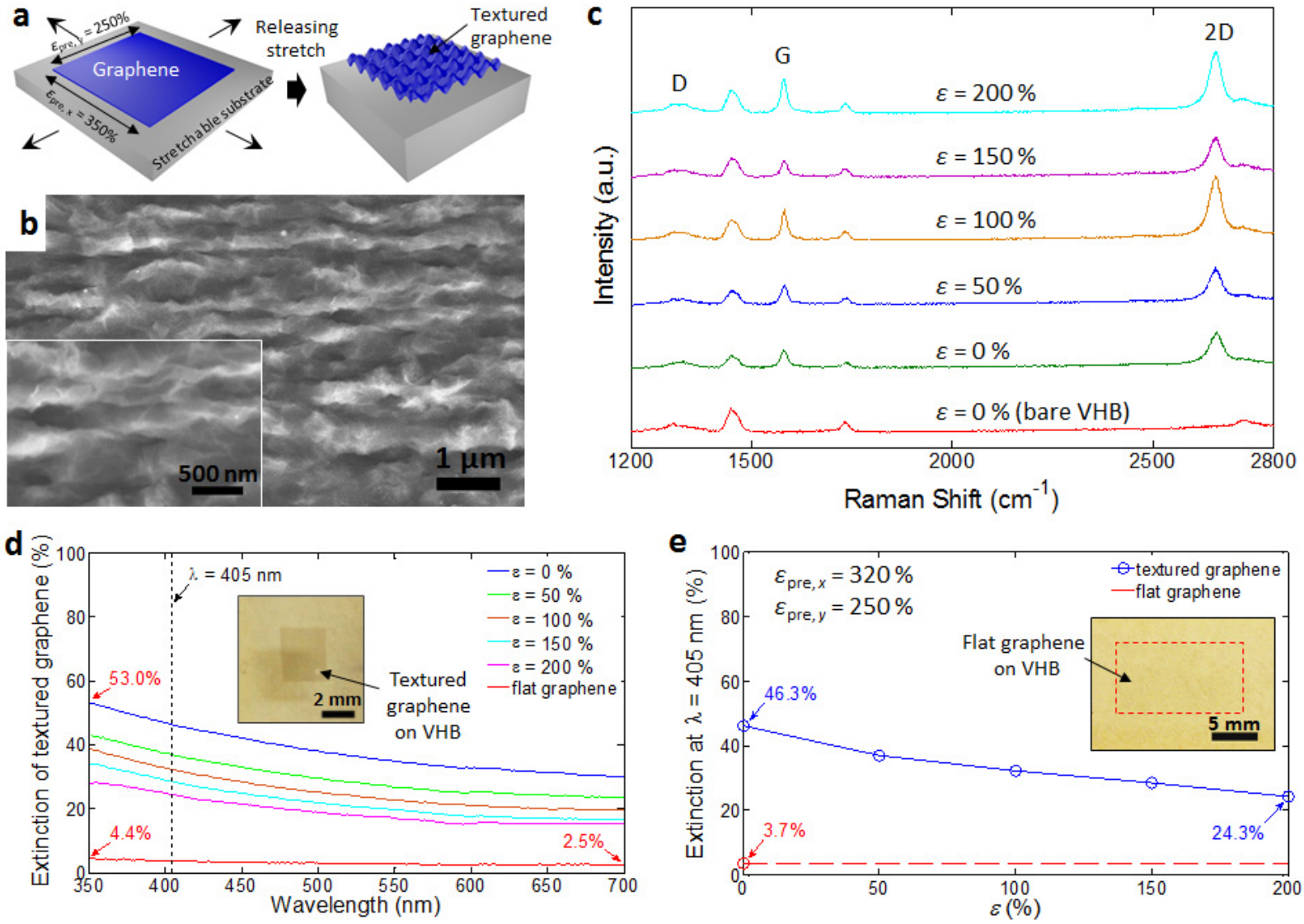
Stretchable Graphene Photodetector with Enhanced & Tunable Photoresponsivity



- Corrugated graphene enables stretchability of graphene photodetector
- The control of corrugation allows modulation of light absorption, which leads to tunable photoresponsivity of graphene photodetector
- 400% increase in photoresponsivity was realized by 200% pre-stretching

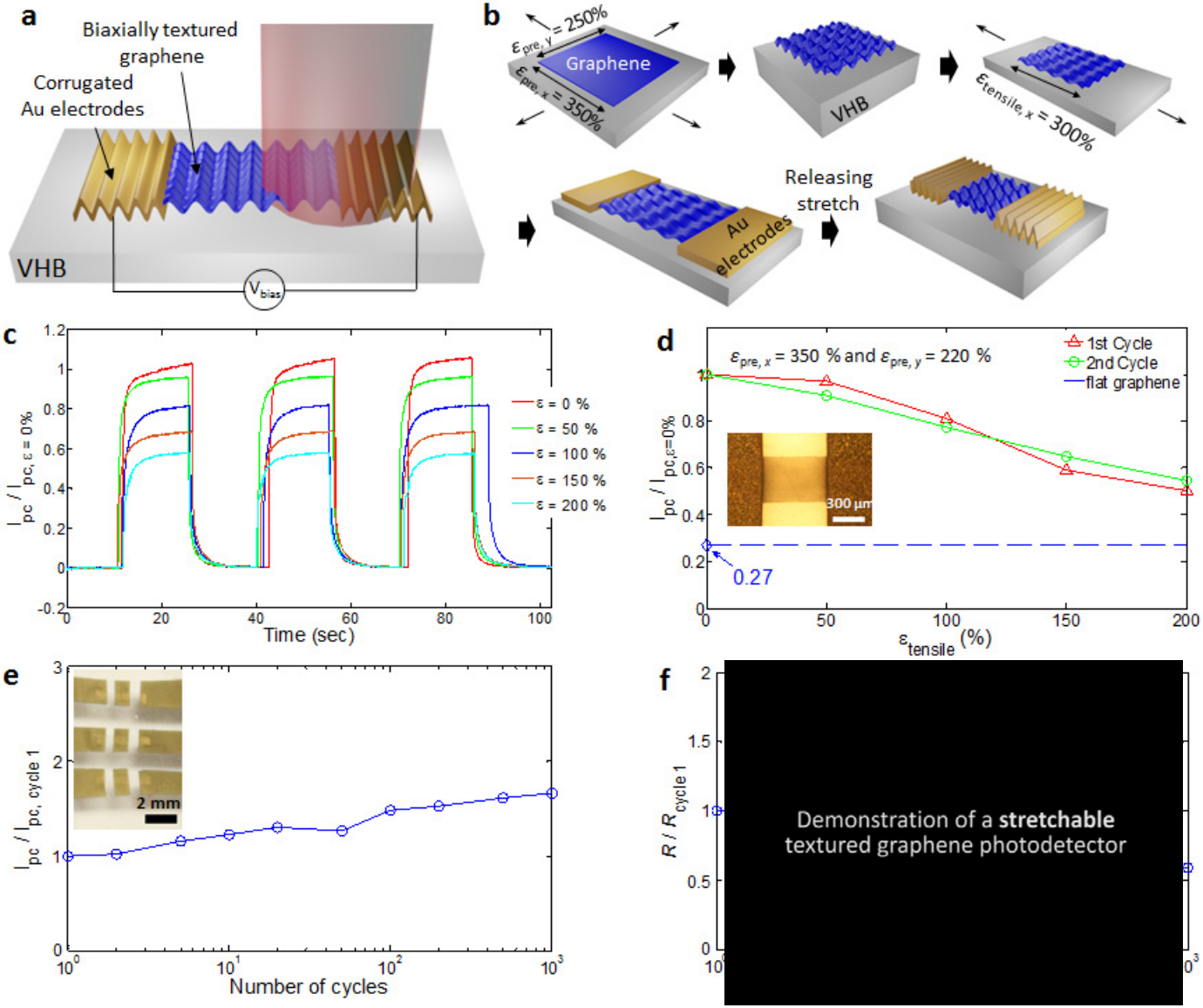
Kang & Nam, ***Advanced Materials*** 28, 4565 (2016) **[Cover]**.

Stretchable Graphene Photodetector with Enhanced & Tunable Photoresponsivity



Kang & Nam, ***Advanced Materials*** 28, 4565 (2016) **[Cover]**.

Stretchable Graphene Photodetector with Enhanced & Tunable Photoresponsivity



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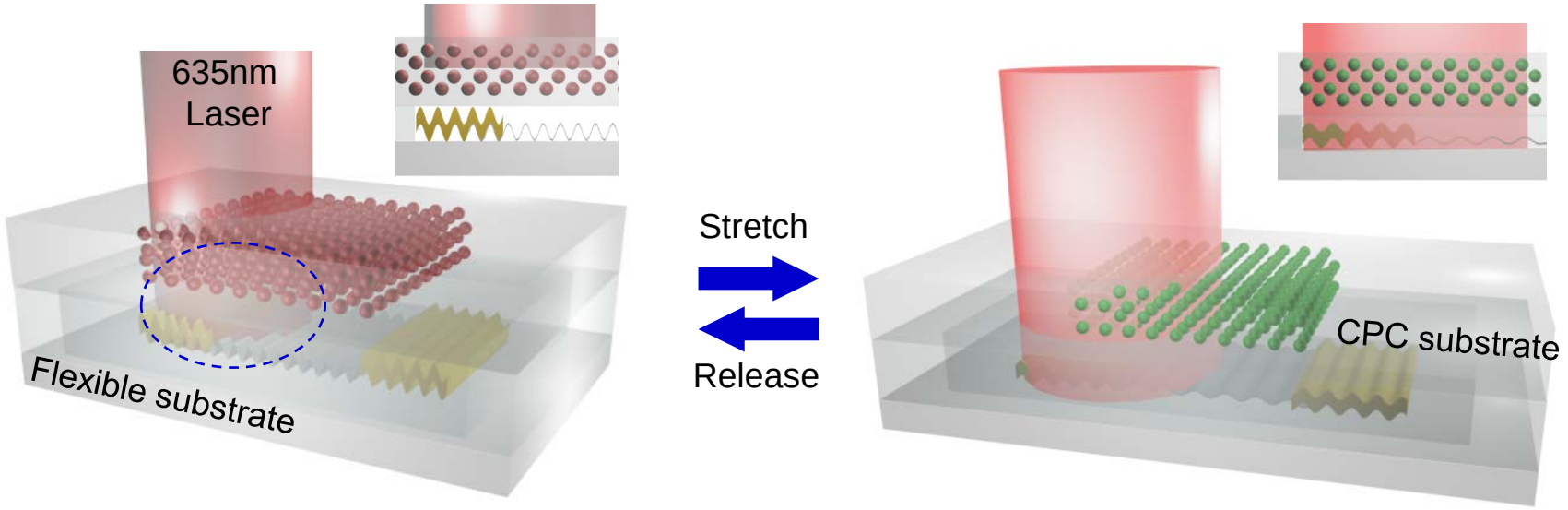
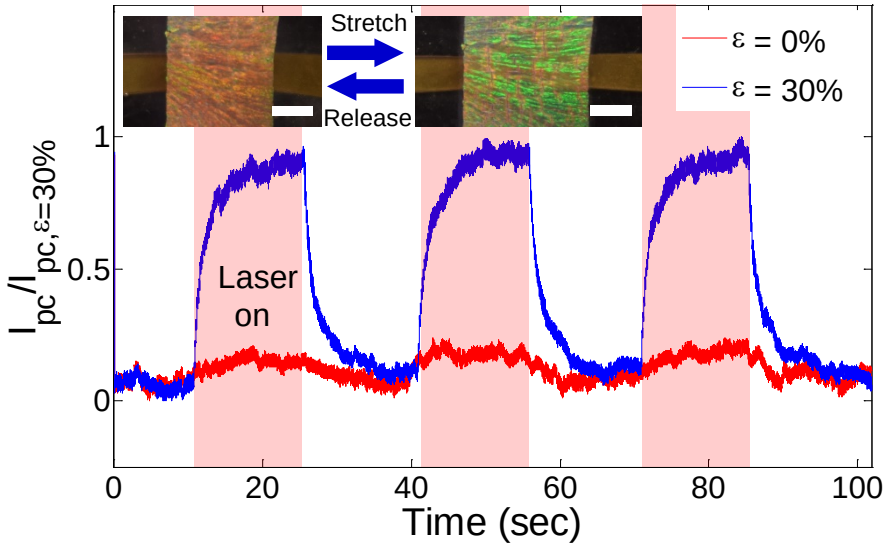
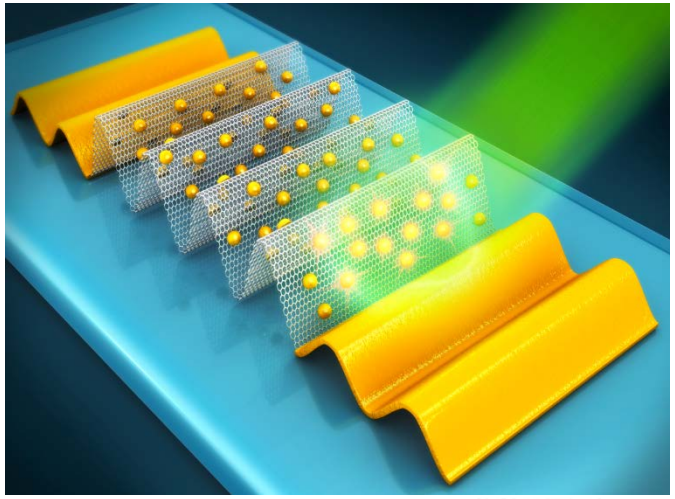
Hybrid Stretchable Graphene Photosensor Integrated with Optomechanical Modulator

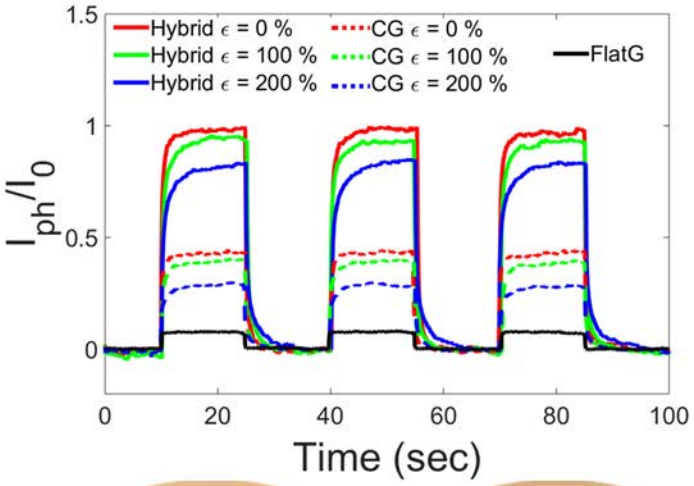


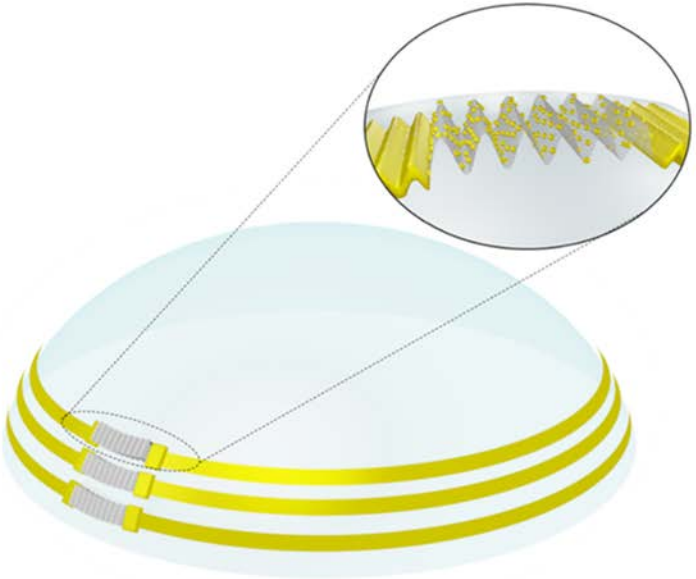


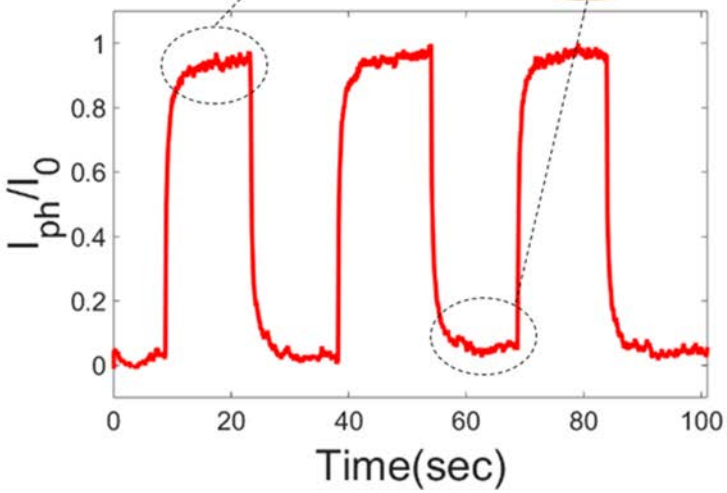
Kang & Nam, ***Advanced Materials*** 28, 4565 (2016) **[Cover]**.

Plasmonically-Enhanced Stretchable Graphene/Au Photodetector with Strain-Tunable Photoresponsivity









Kim

Kim and Nam, ***Nanoscale*** 9, 4058 (2017) **[Cover]**.

Conclusions

- **Mechanical Self-assembly**
  - Out-of-Plane Deformation
  - Integration onto Templates
  - Crumpling Hybrid Materials

- **Emerging Properties**
  - Tunable Surface Properties
  - Reconfigurable Plasmonic Properties
  - Mechanical Stretchability & Strain Tunability