Mechanical properties of freely suspended semiconducting graphene-like layers based on MoS_2

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Graphene-based applications:

Electrical

K. Novoselov et al. *Nature* **2005**, *438*, 197.
K. Novoselov et al. *Science* **2007**, *315*, 1379.

Dirac fermions
High mobility

Mechanical

C. Lee, et al., *Science* **2008**, *321*, 385.

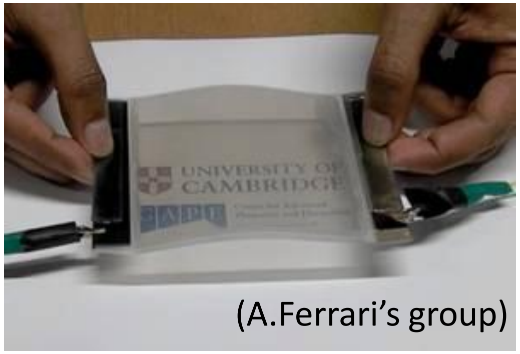
C. Lee, et al., *Science* **2010**, *328*, 76.

Young's modulus of 1 TPa
Tough

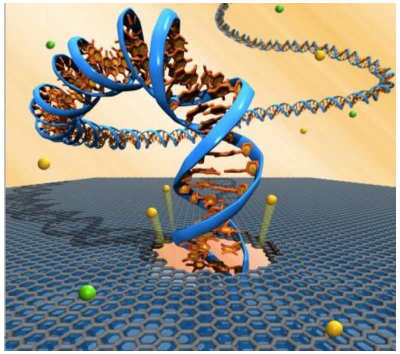
Optical

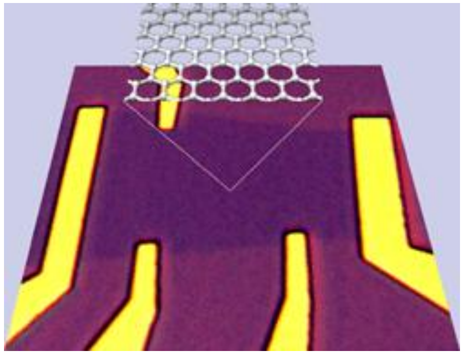
K. S. Kim, et al., *Nature* **2009**, *457*, 706
G. Eda, G. Fanchini, M. Chhowalla, *Nature Nanotech.* **2008**, *3*, 270.

Very loy absorbtion BUT conducting



(A.Ferrari's group)





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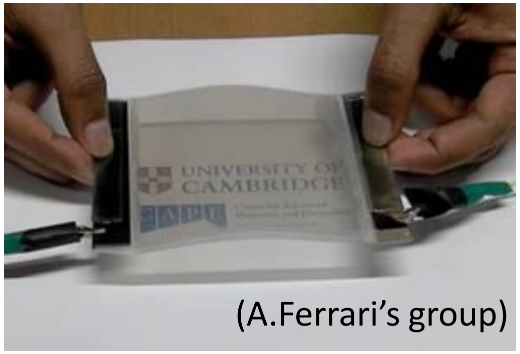
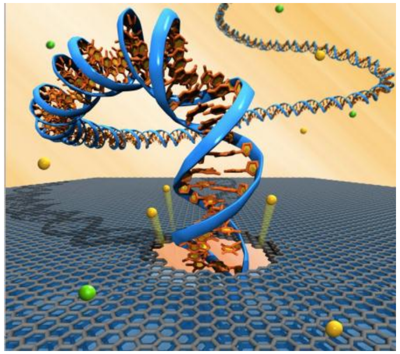
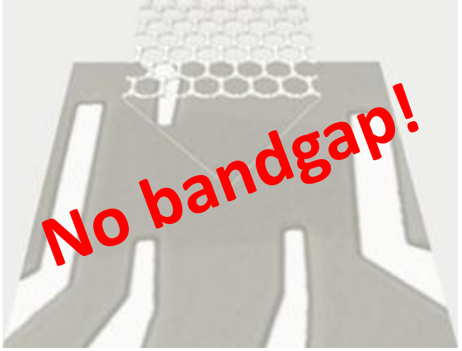




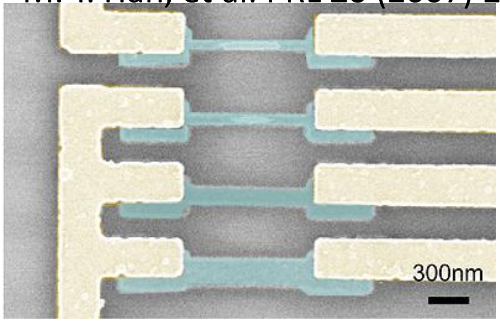


State of the art in thin MoS_2

Graphene nanoribbons:

Lateral confinement → Bandgap
Difficult integration (E-Beam & 1D Geometry)

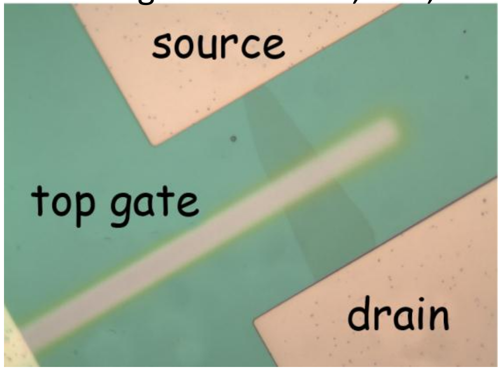
M. Y. Han, et al. PRL **20** (2007) 206805



Electric field in graphene bilayer:

Tunable
Only from 0 to 250 mV

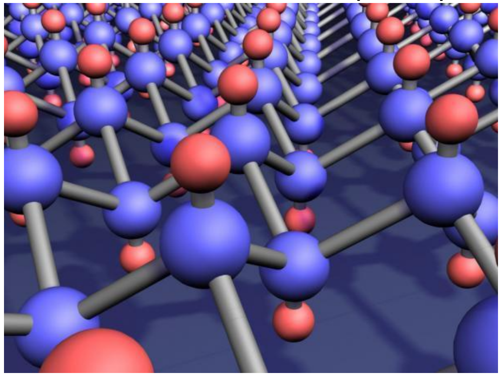
Y. Zhang et al. Nature, 459, 820 (2009)



Hydrogenated graphene:

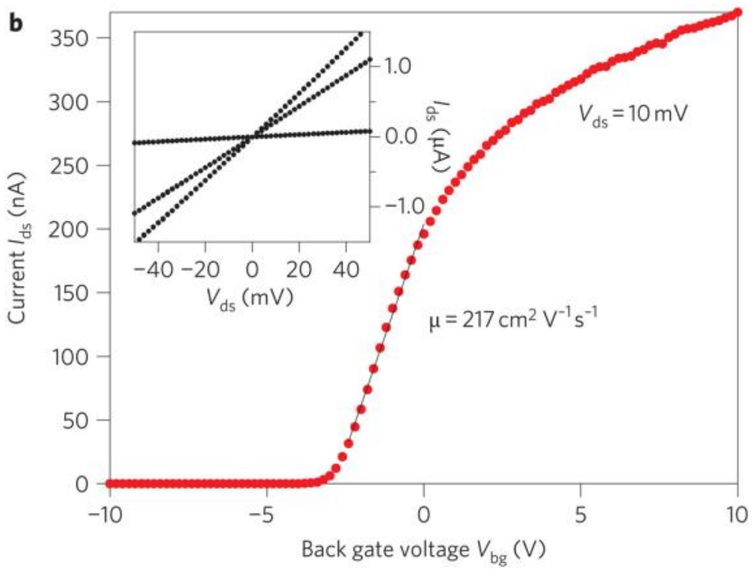
Change hybridization → Bandgap
Reversible
Low mobility

Elias et al. Science 30 (2009)



Motivation

Why to spend effort in creating a bandgap in graphene when you could just start with a semiconducting material and go from there?



Nature Nanotech. 2011, 6, 147.

1.8 eV direct bandgap

200 cm^2/Vs – 800 cm^2/Vs (larger than semiconducting graphene)

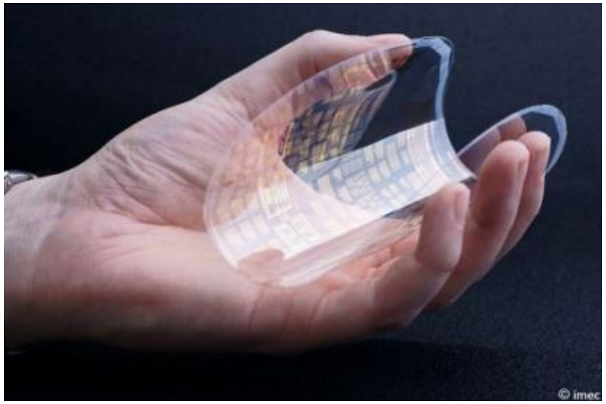
High on/off ratios!

Andres Castellanos-Gomez
http://sites.google.com/site/andrescastellanosgomez/

Motivation

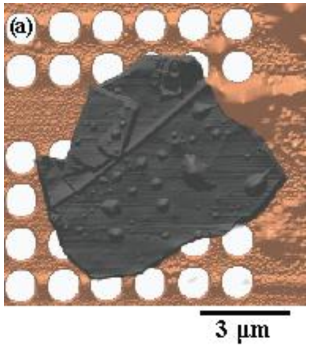
Proposed as a candidate for flexible semiconducting devices

(but the mechanical properties of ultrathin MoS_2 are unexplored so far)

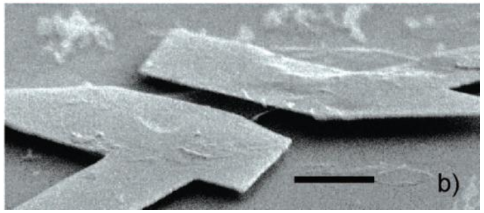


Fundamental physics: Mechanical properties of 2D crystals

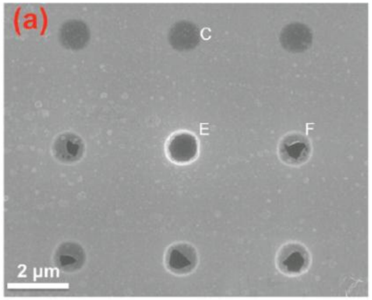
(up to now: graphene, graphene oxide and boron nitride)



Menno (APL 2007)



C. Gomez-Navarro (Nano lett. 2008)

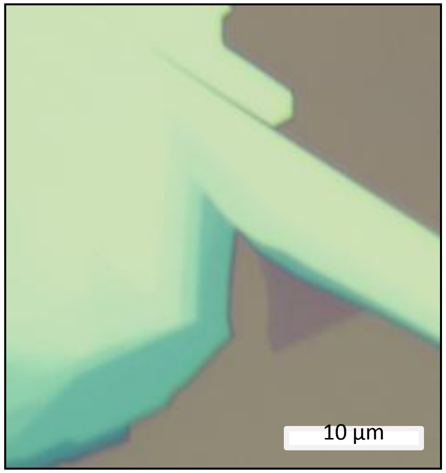


Li Song (Nano lett. 2010)

Fabrication and characterization of MoS_2 flakes

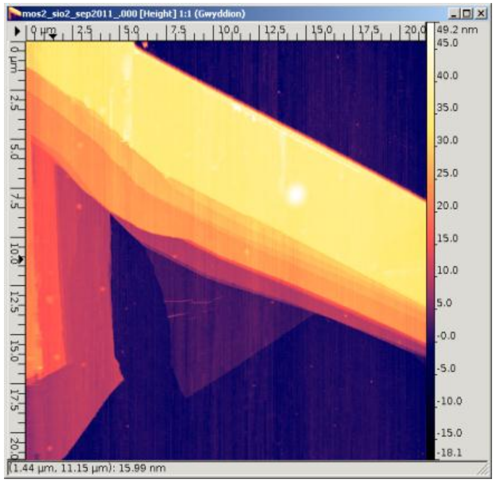
PDMS is used instead of scotch tape to avoid traces of glue.

Optical microscopy

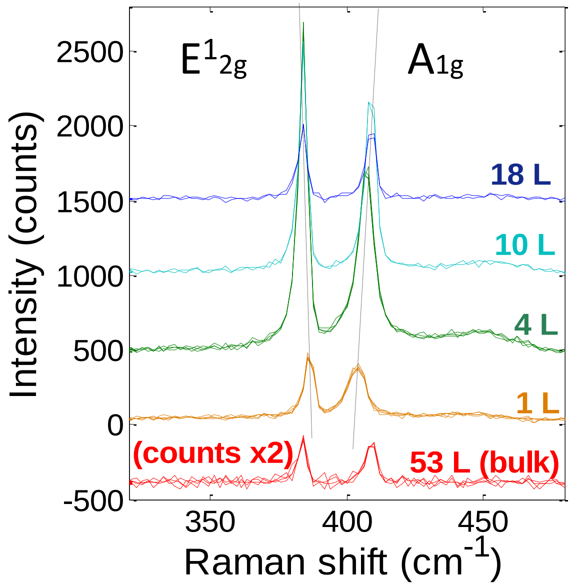


A. Castellanos-Gomez
App. Phys. Lett. (2010)

AFM



µ-Raman

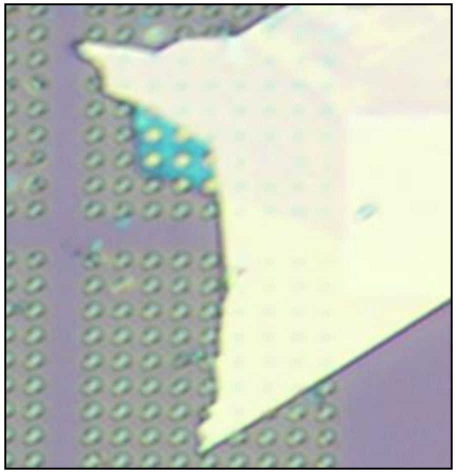


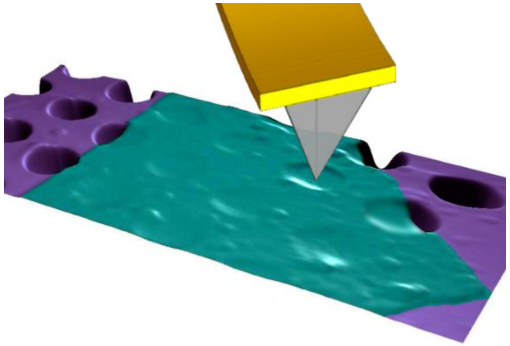
Lee et al.
ACS Nano 2010

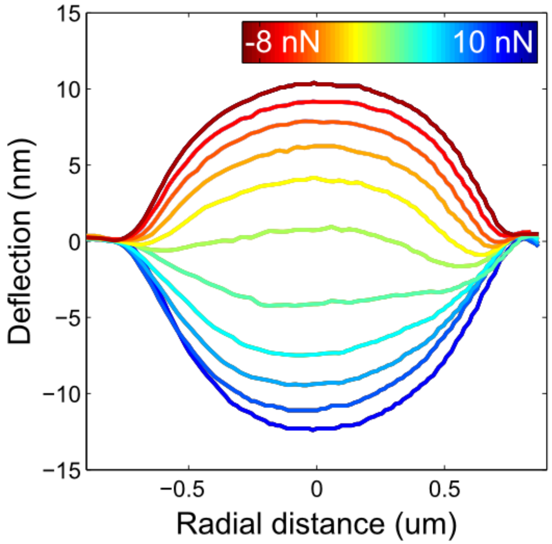
Deposition onto pre-patterned substrate

Clean (e-beam patterning is performed before deposition)

Elastic deformations
(Contact mode AFM)







Freely suspended MoS_2 flakes

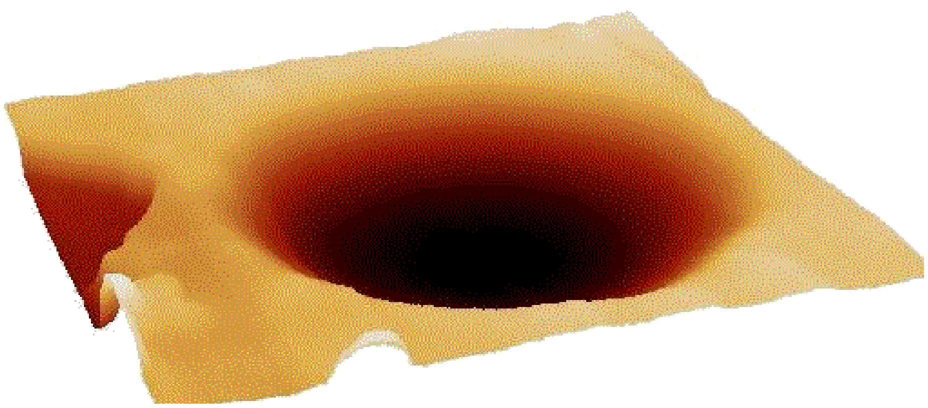
TU Delft — Delft University of Technology

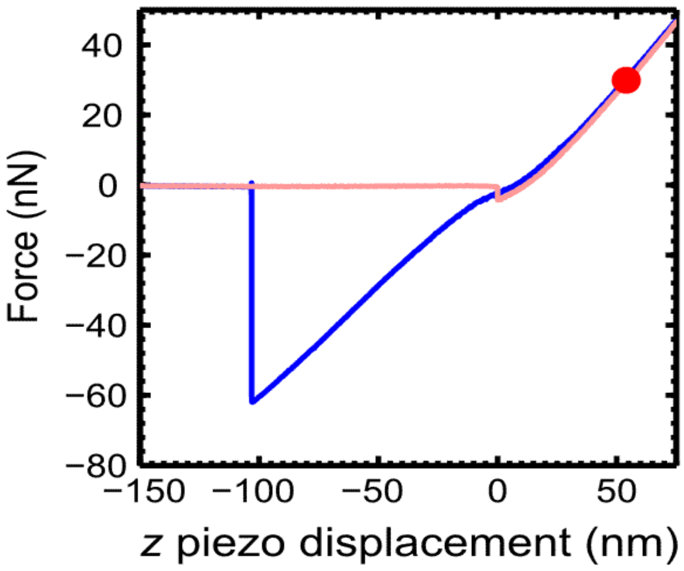
Deposition onto pre-patterned substrate

Clean (e-beam patterning is performed before deposition)

Elastic deformations
(Contact mode AFM)

Reversible deflections up to 30 nm





Andres Castellanos-Gomez
http://sites.google.com/site/andrescastellanosgomez/

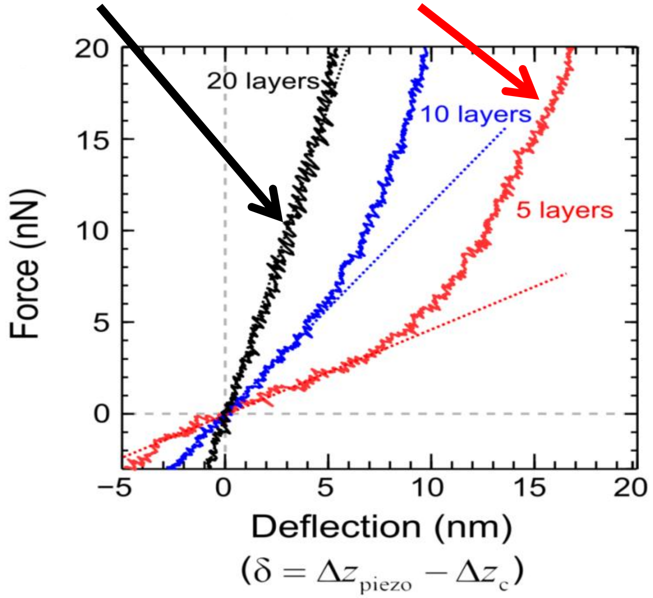
Bending test experiment

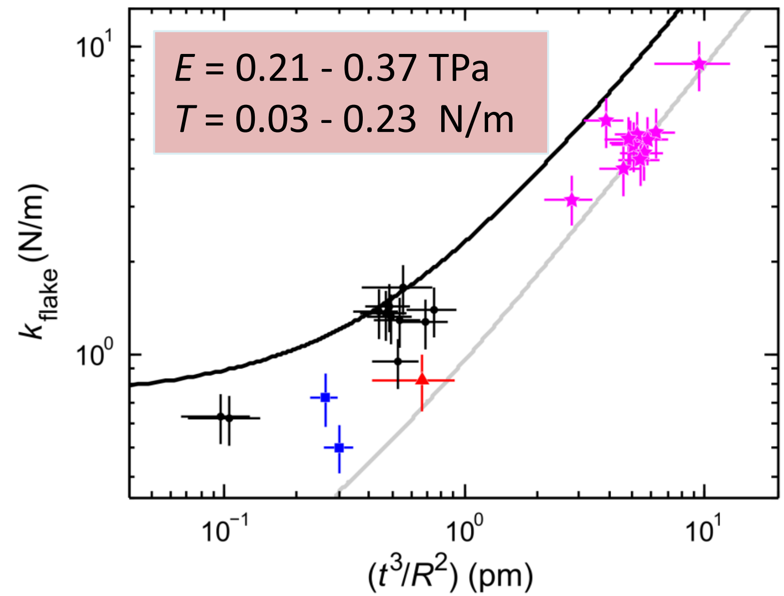
TU Delft — Delft University of Technology

Estimation of the Young's modulus and the pre-tension:

Bending of an elastic disc

Displacement induced tension (membrane-like)





$$k_{flake} = \frac{4\pi E}{3\left(1-\upsilon^2\right)} \cdot \left(\frac{t^3}{R^2}\right) + \pi T$$

k_{flake} is proportional to t^3

Slope related to E
Interception related to T

Estimation of the Young's modulus and the pre-tension:

Non-linear FZs can be accounted for with a simple mechanical model.

3 components

In agreement with previous estimation.

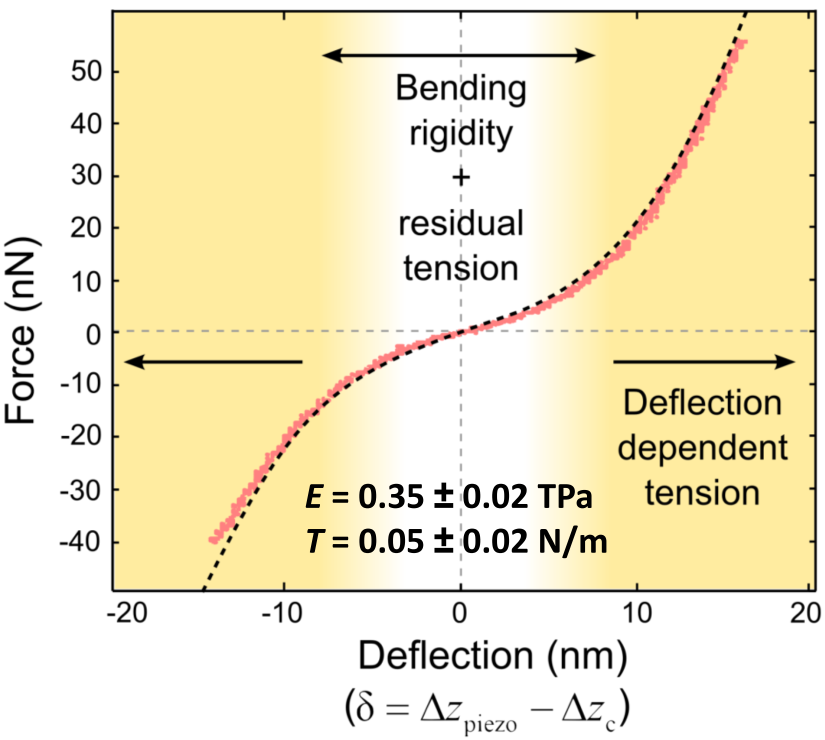
Flake-to-flake variations.

Stretching membrane under pre-tension

$$F = \left[\frac{4\pi E}{3(1-\nu^2)} \cdot \left(\frac{d^3}{R^2} \right) + \pi T \right] \delta + \frac{q^3 E d}{R^2} \delta^3$$

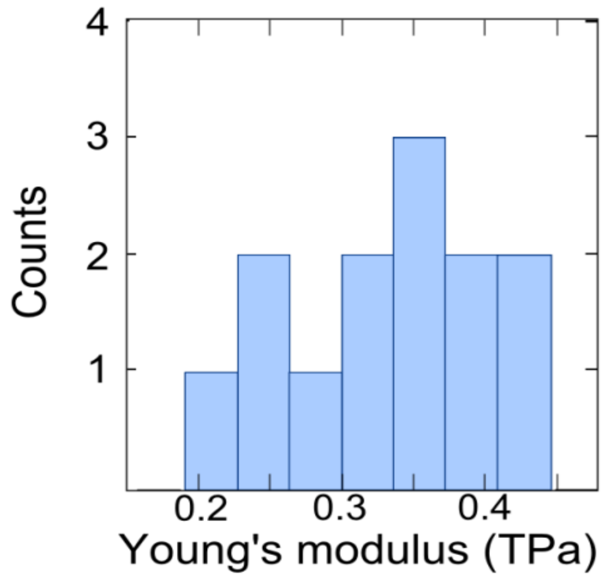
Bending rigidity term

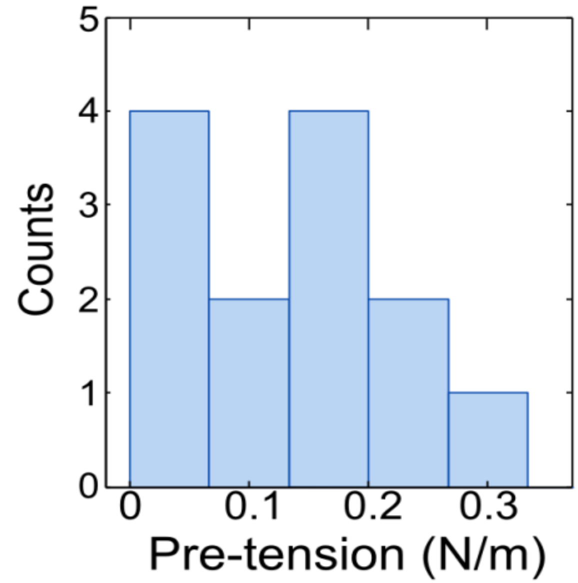
Stiffening of a membrane during the strecthing



Bending test experiment

Flake-to-flake variation of E and T:





Crystal-to-crystal variation

- Clamping
- Stacking faults
- Etc…

13 membranes 5-10 layers (R=550 nm)

E = 0.33 ± 0.07 TPa
T = 0.13 ± 0.10 N/m

Summary

Mechanical properties of MoS_2

Reversible deformation UP TO ~ 30 nm

High E:

E_{MoS_2} ~ 0.3 TPa

Comparable to Graphene (~ 0.5 TPa) or Graphene Oxide (~ 0.25 TPa)

Much larger than other 2D crystals: h-BN (~0.03 TPa) [Li et al. 2009]

Low variations of E value: (low defect density)

E_{MoS_2} (0.21 – 0.42) TPa

Graphene: 0.02 – 3 TPa [Poot et al. 2008]

Graphene oxide: 0.08 – 0.7 TPa [Gómez-Navarro et al. 2008]

⇒ Elastic, Stiff, High quality

MoS_2 nanolayers fulfill the expectations to be used in flexible semiconducting applications.

NEMS based on MoS_2 membranes?

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