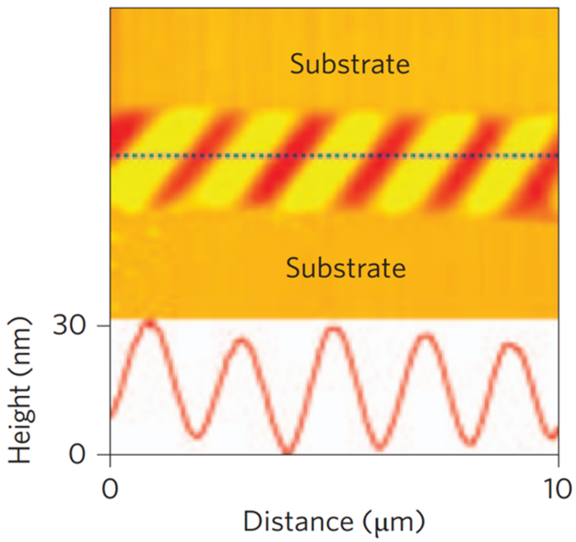
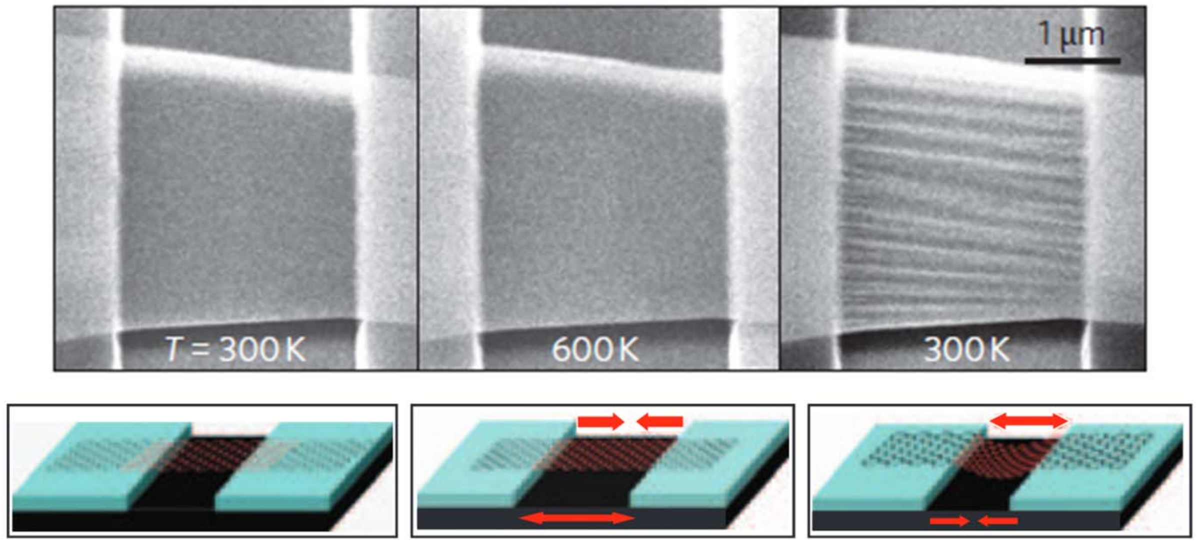
Controlled Ripple Texturing of Suspended Graphene and Ultrathin Graphite Membranes

Group 2
Reuven Birnbaum, Wei Chen, Guannan Chen

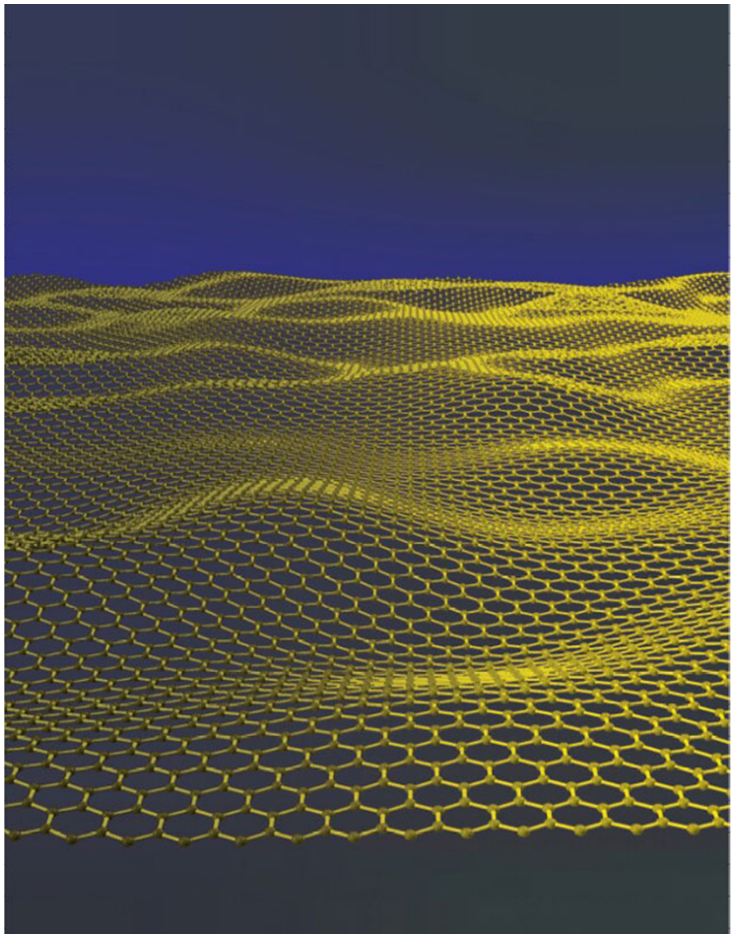




Bao, Wenzhong, et al., *Nature nanotechnology* 4.9 (2009): 562-566.

Outline

- Background
- Summary
    - Amplitude/Wavelength Control
    - Orientation Control
    - Thermal Expansion Coefficient Measurement
    - Conclusion
- Critiques
- Potential Impacts
- Citation Analysis



History of Graphene

- In 2004 Andre Geim and Kostya Novoselov at The University of Manchester extracted single-atom-thick crystallites from bulk graphite. They pulled graphene layers from graphite and transferred them onto thin SiO_2.

- They received the 2010 Nobel Prize in Physics.

Andre Geim

Kostya Novoselov

Why are We Interested in Graphene?

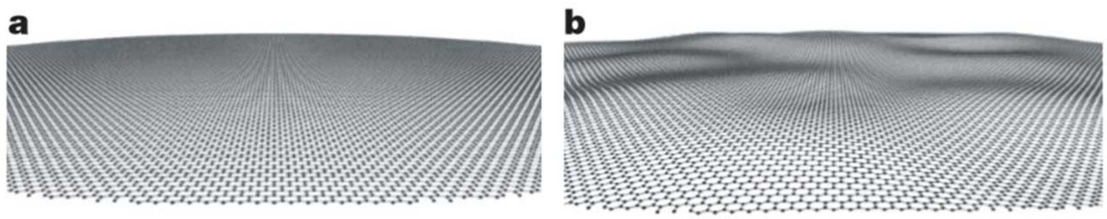
- Graphene is 2D material. (Once people thought it's impossible)
- It is remarkably strong for its very low weight. (100 times stronger than steel)
- It conducts heat and electricity with great efficiency. For example, graphene has a remarkably high electron mobility at room temperature.
- Graphene's charge carriers mimic relativistic particles and are easier and more natural to describe starting with the Dirac equation rather than the Schrödinger equation.

Discovery of Graphene's Ripple

The structure of suspended graphene sheets

J. C. Meyer et al. Nature 446, 60–63 (2007)

This group first observed that suspended graphene sheets are not perfectly flat: they exhibit intrinsic microscopic roughening.



Flat graphene sheet Rippled graphene sheet

Previous Theory about Graphene's Ripple

- Ripples strongly influence electronic properties by inducing effective magnetic fields and changing local potentials.

- The ability to control ripple structure in graphene could allow device design based on local strain and selective bandgap engineering.

F. Guinea, et al., Phys. Rev. B 77, 205421 (2008) Gauge field induced by ripples in graphene.
F. Guinea, et al., Phys. Rev. B 77, 075422 (2008) Midgap states and charge inhomogeneities in corrugated graphene.
V. M. Pereira, et al. http://arXiv.org/abs/0810.4539v1. (2008) All-graphene integrated circuits via strain engineering.

Thermal Expansion Coefficients of Some Materials

The coefficient of thermal expansion describes how the size of an object changes with a change in temperature. There are several important thermal coefficients: volumetric, area, and linear.

Approximate Coefficients of Thermal Expansion at 20°C		
Material	**α (10^{-6}/°C)**	**β (10^{-6}/°C)**
Aluminum	23	69
Concrete	12	36
Diamond	1	3
Glass	9	27
Stainless Steel	17	51
Water*	69	207

the material's linear coefficient of expansion (α)

$$\Delta l = \alpha l_0 \Delta T$$

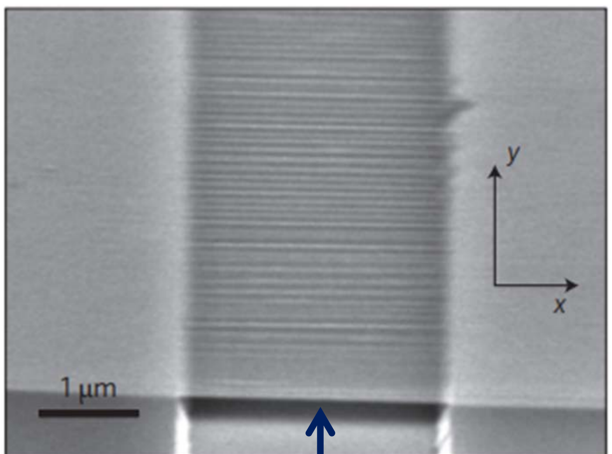
the material's volumetric coefficient of expansion (β)

$$\Delta V = \beta V_0 \Delta T$$

"Thermal Expansion". *Aplusphysics.com*, Web, 1 Dec 2014

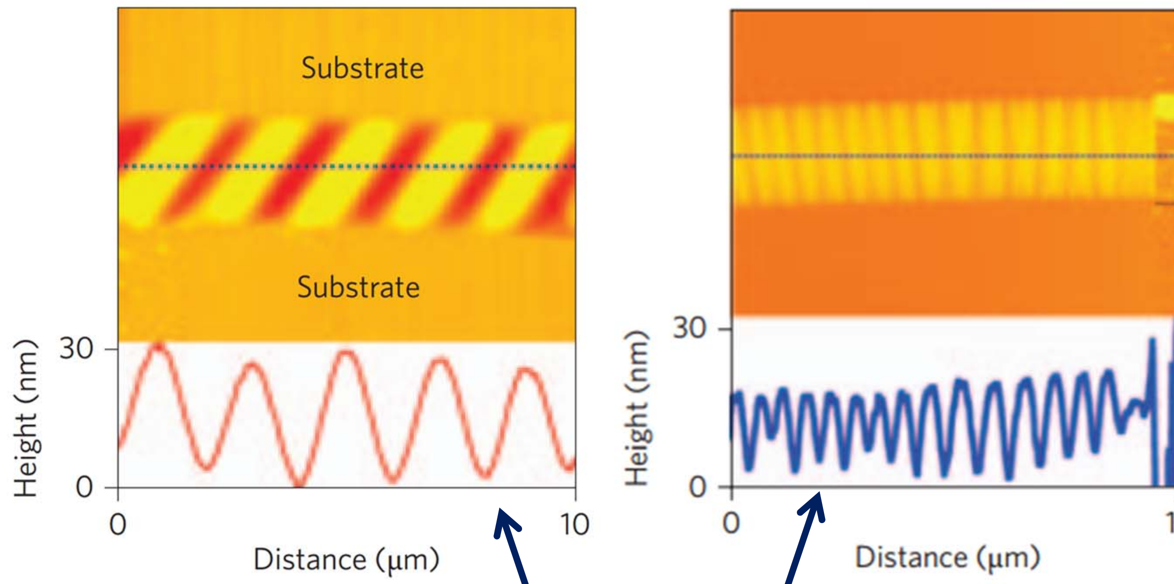
Spontaneous Ripples Form in Graphene

Si/SiO_2 Substrate



Suspended graphene sheet (single layer-16nm thick) taken with a scanning electron microscope

Top: Atomic Force Microscope data of graphene membranes suspended on substrates. Bottom: Line traces taken along dotted lines

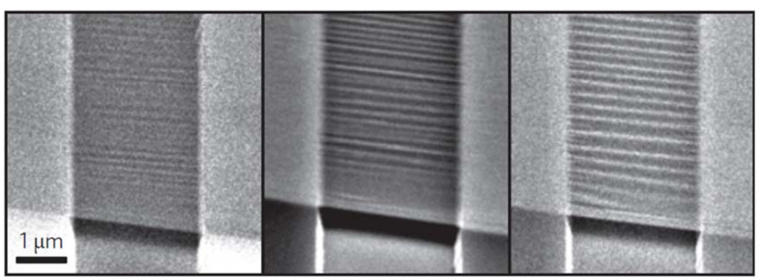


$$\zeta = A sin\left(\frac{2\pi y}{\lambda}\right)$$

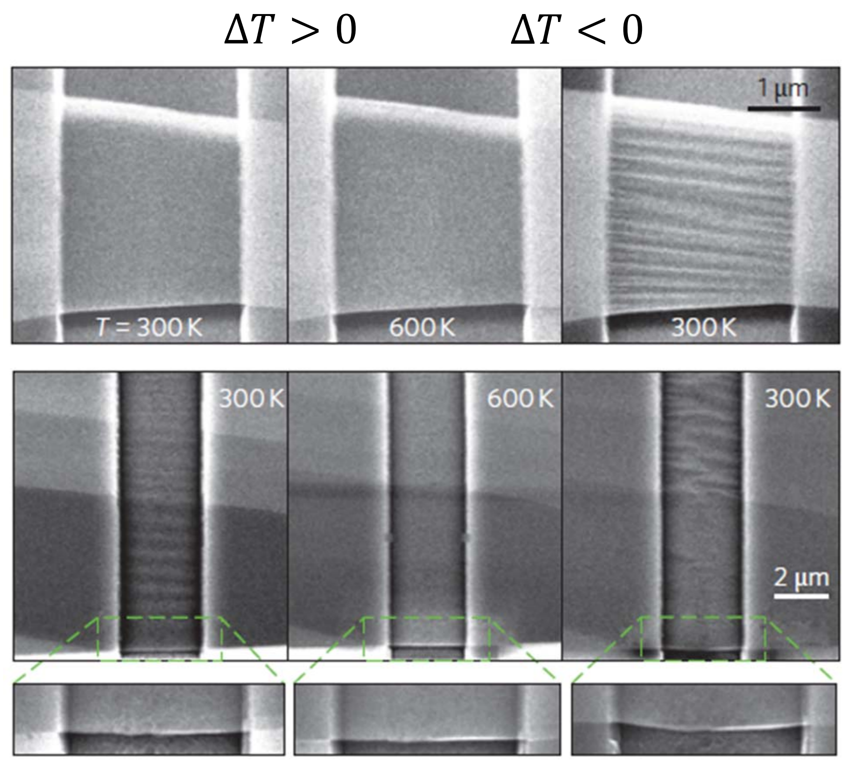
Temperature Changes Induce Ripples

Heating process of graphene sheets removes ripples, while annealing creates them

Data shows dependence on maximum annealing temperature, $\Theta_{\max}$



Before annealing | **After annealing Θ_{max}= 425K** | **After annealing Θ_{max}= 475K**



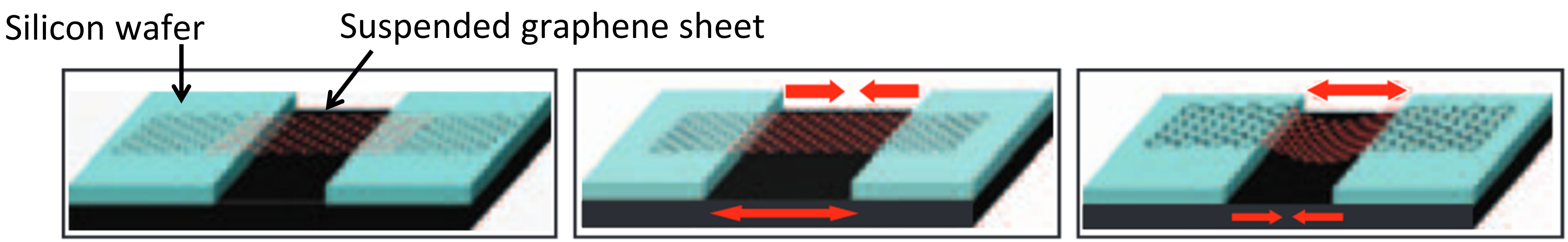
Above: Ripple alterations from temperature change
Left: Ripple dependence on $\Theta_{\max}$

Temperature Changes Induce Ripples (cont.)

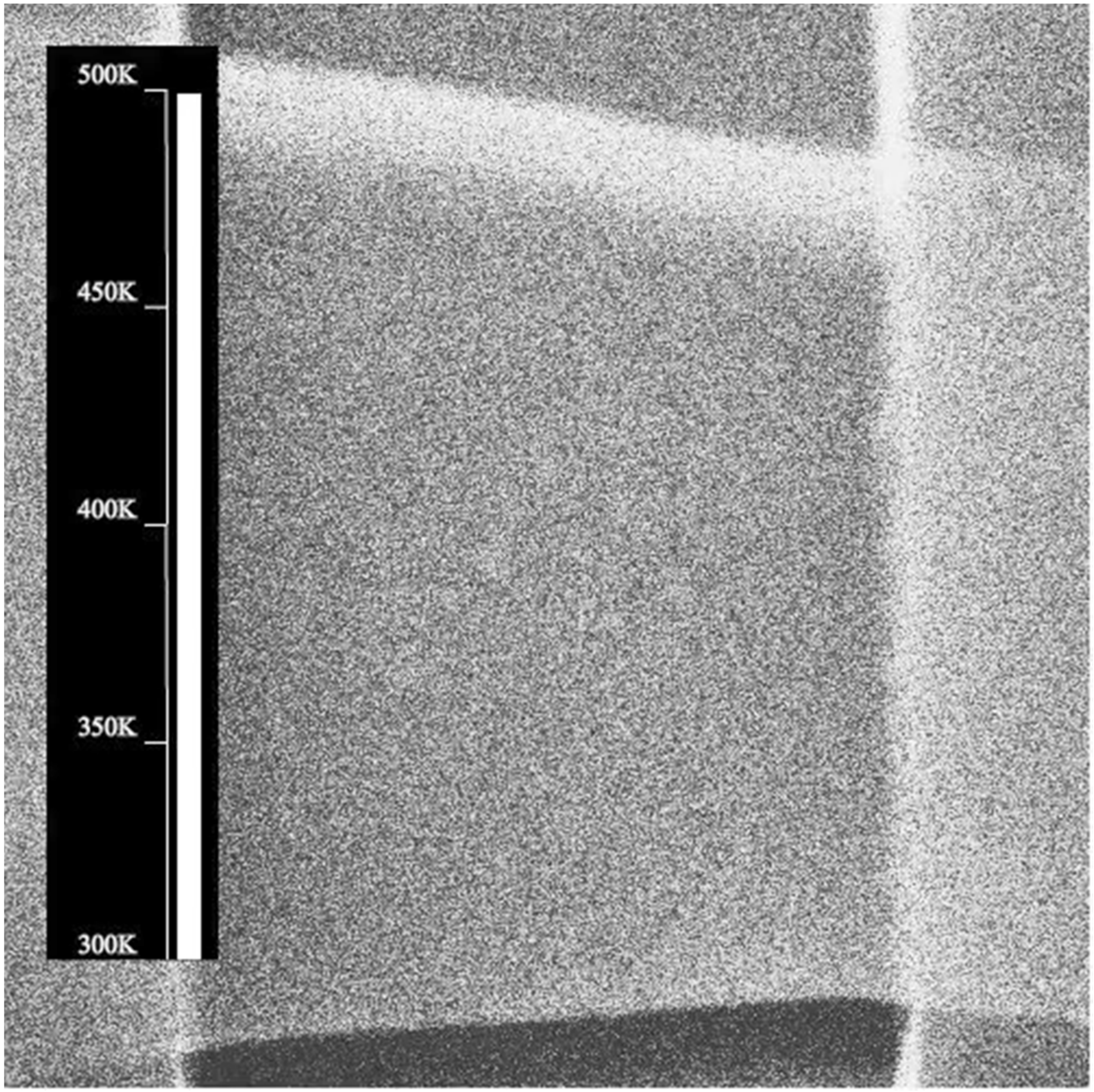
Graphene contracts/expands relative to silicon during heating/cooling $\rightarrow \alpha_{graphene} < \alpha_{silicon}$

When heated the elastic restoring force eventually exceeds the force pinning the membrane to the substrate, causing the membrane to slide over substrate removing preexisting ripples

Annealing process applies compressive strain, and longitudinal buckling and transverse ripples are free to form.



Ripple formation from decreasing temperature



“nnano.2009.191-s2_2.mov.” *Nature.com*, Bao et al. Web. 1 Dec 2014

Ripple Characteristics Controlled with Temperature

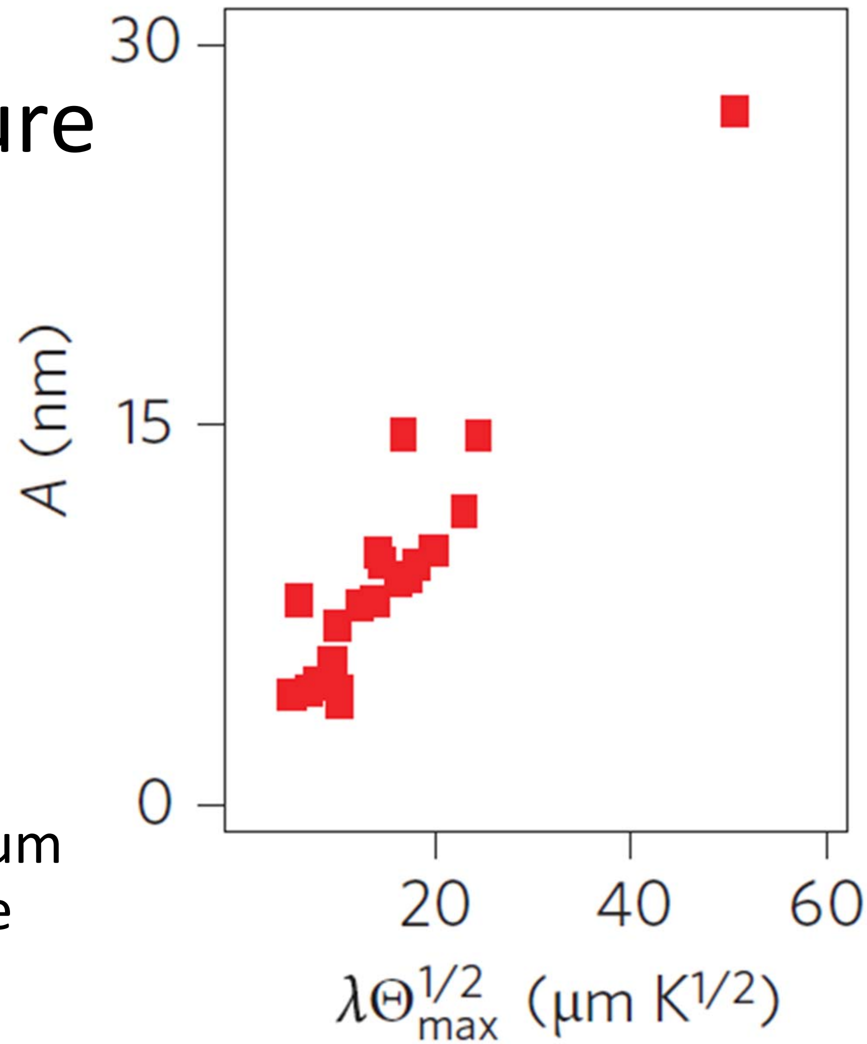
Following thin film elastic theory, compressive strain given by

$$\Delta \approx \sqrt{1 + (\zeta^2/\lambda^2)} - 1$$

producing new amplitudes A' and wavelengths λ'

$$A' \approx \lambda' \sqrt{\Delta}$$

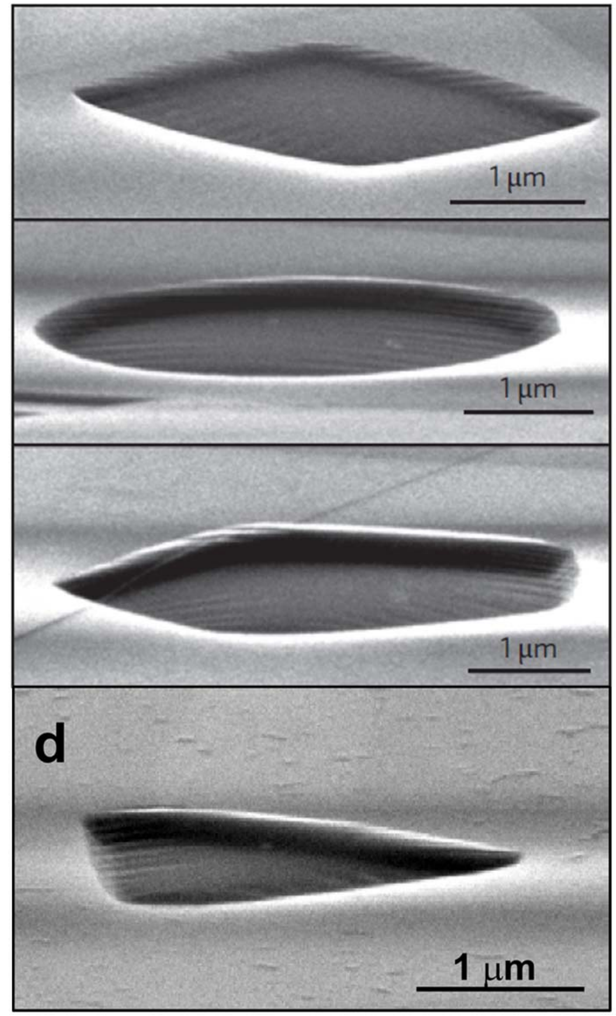
Compressive strain scales with the maximum annealing temperature, giving controllable parameter



Ripple Orientation Control

Ripples are aligned perpendicular to the step like structures in the substrates.

Membranes suspended on different silicon pattern allows two dimensional control of the orientation of the ripples buckling



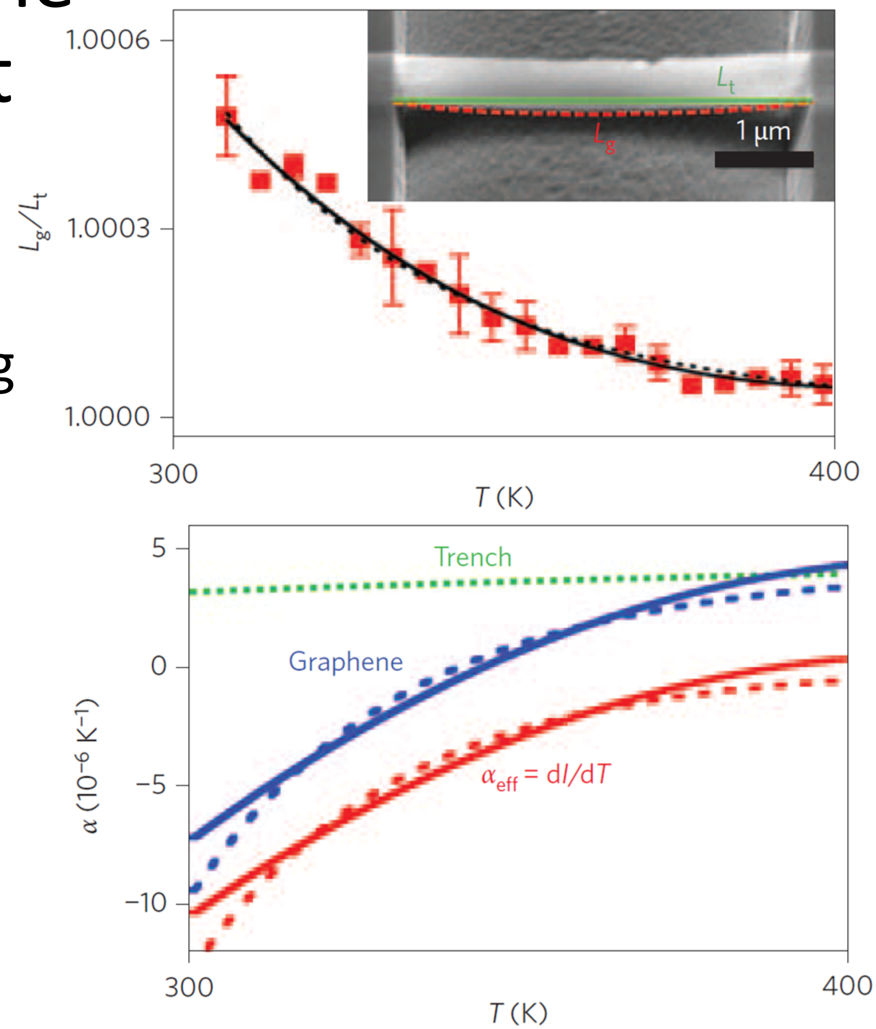
Various ripple formations from substrate patterns

First Measurement of Graphene Thermal Expansion Coefficient (TEC)

The temperature dependent TEC measured for the first time by the sagging process during the 2-hour cool down of a membrane from 450K to 300K.

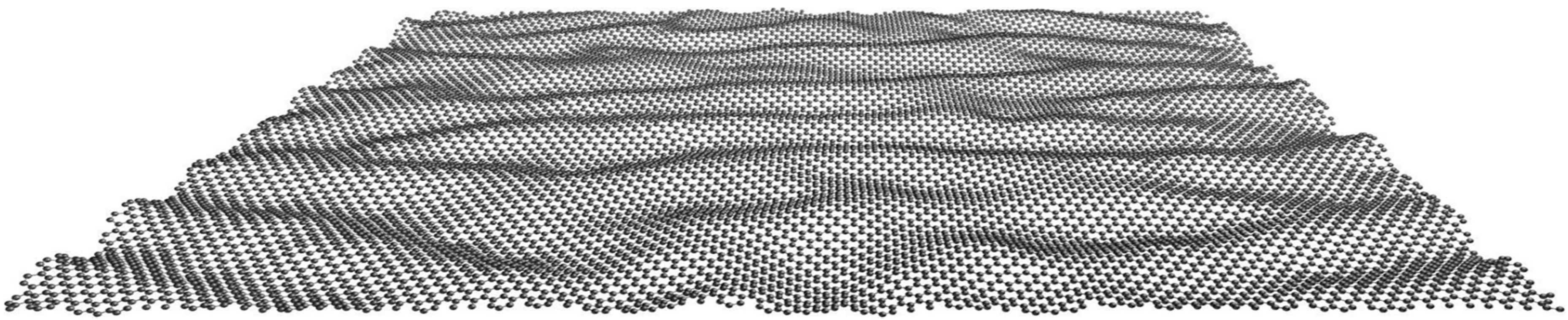
$$\frac{d}{dT}(L_g(T)/L_t(T)) = \alpha_{eff} \approx \alpha - \alpha_t$$

L_g, arc length
L_t, trench length
α, graphene TEC
α_t, trench TEC

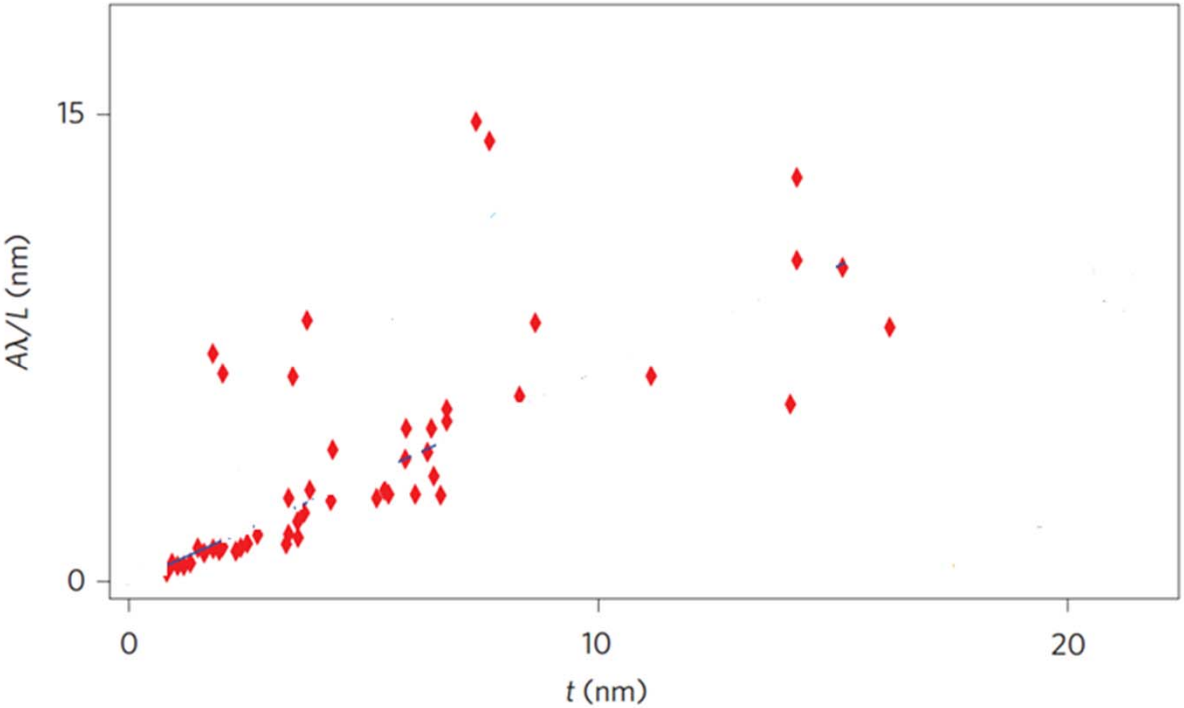


Conclusions

- Adjusting thermal stress → control of ripple amplitude and wavelength
- Modifying substrate pattern → regulates ripple orientation
- First ever temperature dependent graphene TEC measurement



Critiques

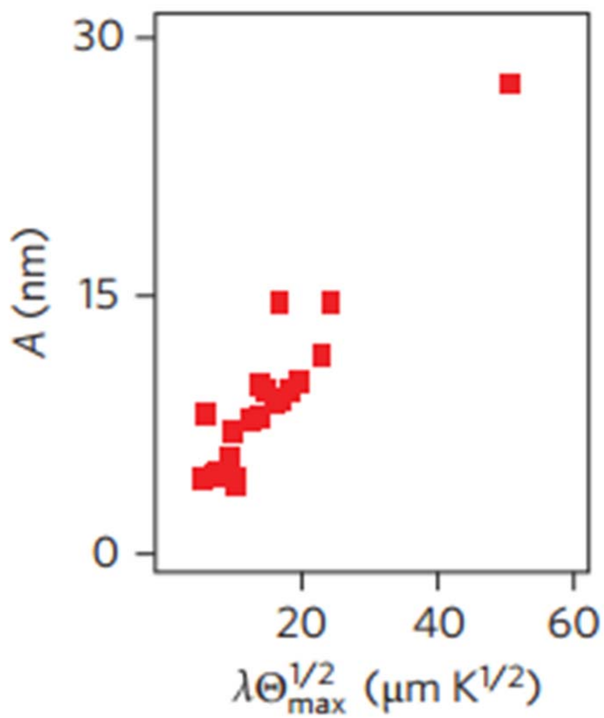


Classical thin-film elasticity theory:

$$\frac{A\lambda}{L} = \begin{cases} \sqrt{\frac{8\nu}{3(1-\nu^2)}}\,t, & biaxial\ shear(b) \\ \sqrt{\frac{8}{3(1+\nu)}}\,t, & inplane\ shear(i) \end{cases}$$

- Poisson Ratio $\nu = 0.165$, does not fit well
- Not convincing that $\frac{A\lambda}{L}$ is proportional to t

Critiques



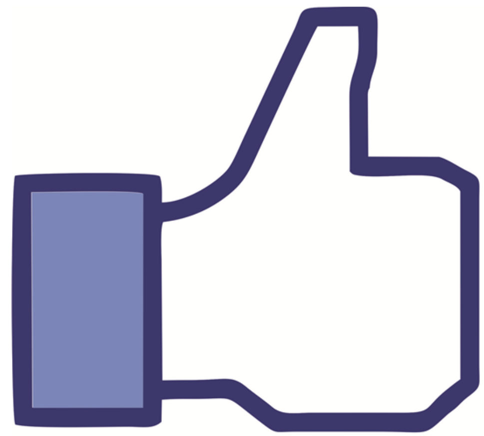
The authors conclude:
"the wavelength and amplitude of the ripples can be controlled by Θ_{max}."

In fact, the ratio of the amplitude to wavelength can be controlled by Θ_{max}

Summary of Critiques

- Qualitatively: Great Job!
  - Readable and accessible to large audience
  - Interesting phenomena
  - Conclusions well supported

- Quantitatively: Not perfect
  - Data poorly fitted to model
  - Inaccurate description of some conclusions



Potential Impacts

- to fundamental research:
  - strain engineering → control properties of graphene (e.g., pseudo magnetic field) → potential interesting phenomena

- to industry:
  - the negative thermal expansion coefficient (TEC) should be taken into account when designing graphene-based electronic devices
  - new methods to fabricate interesting structures (e.g., periodic structures)

Citation Evaluation

- It has been cited over 500 times.

- The availability of high-quality few-layer graphene materials allowed us to study the thermal conductivity.

- It was demonstrated that nano graphene film ripples could be used for strain sensors. It provides a feasible fabrication for graphene flexible electronic devices and strain sensors.

Suchismita Ghosh, et al., Nature Materials 9, 555–558 (2010) Dimensional Crossover Of Thermal Transport In few-layer graphene

Yi Wang, et al., ACS Nano, 2011, 5 (5), pp 3645–3650 Super-Elastic Graphene Ripples for Flexible Strain Sensors

Impact on High Energy Field

Clues for Higgs field !

Some physicists said that vital clues could come from looking at graphene. They argued that ripples in graphene arise from a spontaneous symmetry-breaking process similar to that which separated the weak and electromagnetic forces in the early universe.

P. San-Jose, et al., Phys. Rev. Lett. **106**, 045502 Electron-Induced Rippling in Graphene

Questions?

Thanks for your attention!

Acknowledgments: Prof. Lance Cooper and Prof. Celia Elliott