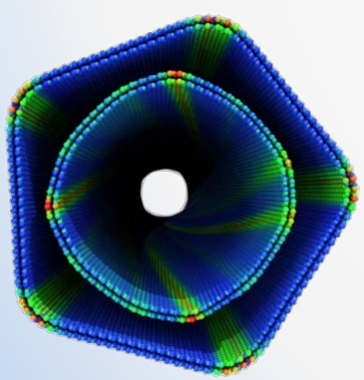
THE RAYMOND AND BEVERLY SACKLER CENTER
FOR COMPUTATIONAL MOLECULAR AND MATERIALS SCIENCE

TEL AVIV UNIVERSITY אוניברסיטת תל אביב

Modeling Inter-layer Interactions in Layered Materials



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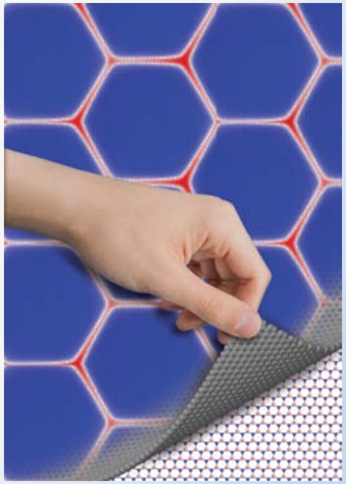
Tel-Aviv University



Trend in Nanotribology 2017, ICTP-COST, Trieste, Italy
28/06/2017

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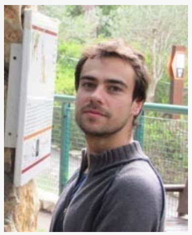

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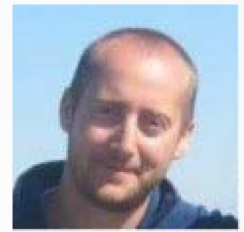

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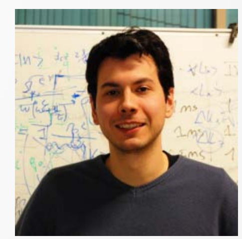

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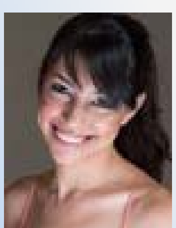

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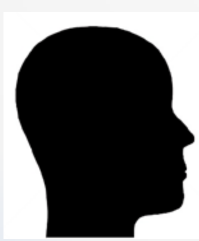

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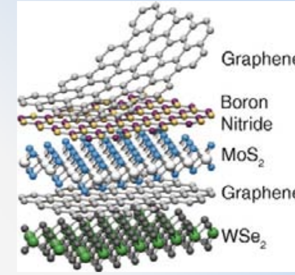
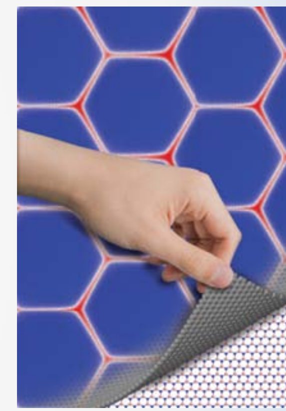
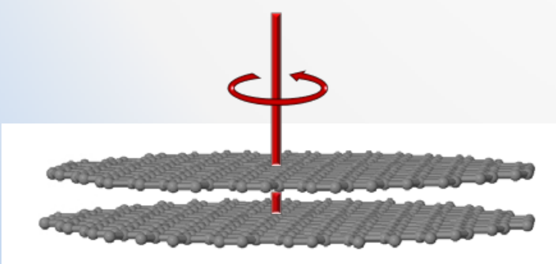
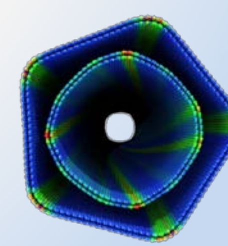
Outline



- Why layered materials?
- Levels of modeling.
- Classical intra- and inter-layer force fields.
- Applications of classical force-fields:
  - ✓ Structure of Graphene/*h*-BN hetero-structures.
  - ✓ ~~Robust superlubricity in layered hetero-junctions.~~
  - ✓ Faceting in multi-walled nanotubes.
  - ✓ Inter-wall friction in CNTs and BNNTs.
- ~~Electron transport across twisted graphene interfaces.~~
- Summary and outlook.

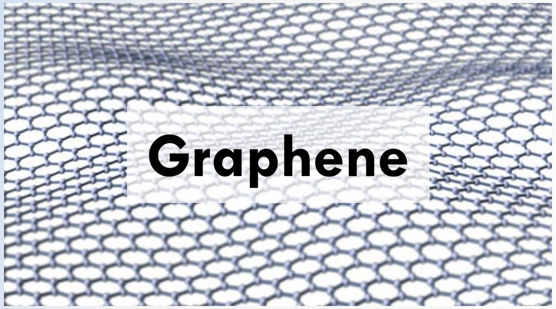


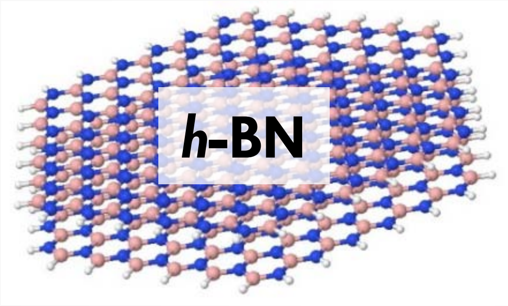


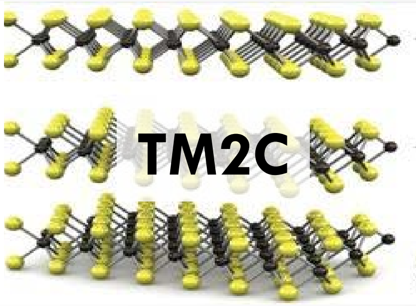


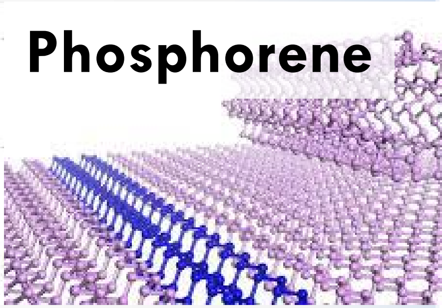
Layered Materials at the Nanoscale

- A large family of materials

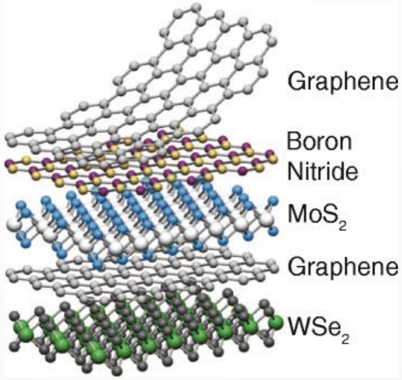




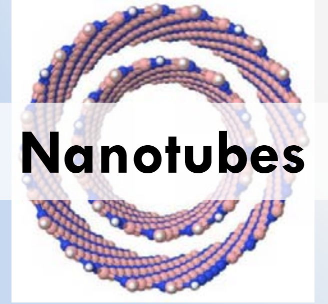


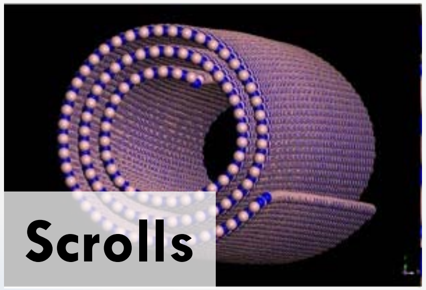


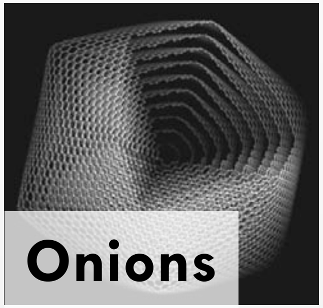
- Diverse structures



Sheets



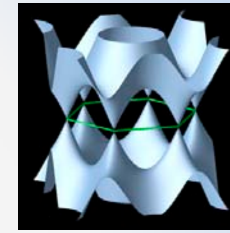


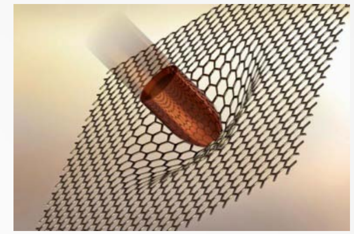


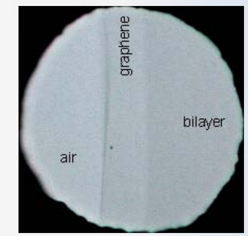
Layered Materials at the Nanoscale

<u>Unique properties</u>

- Controllable electronic properties.
- Enhanced mechanical rigidity.
- Structural anisotropy.
- Optical activity.
- Efficient heat transport.
- …

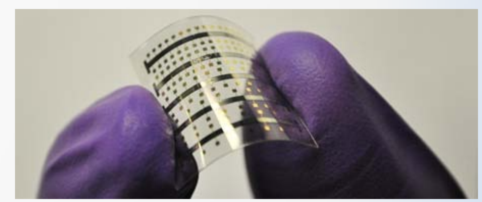


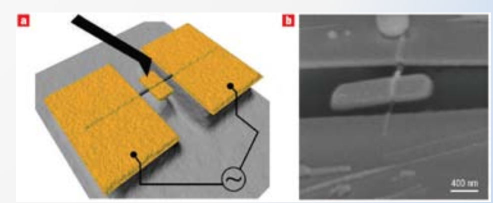


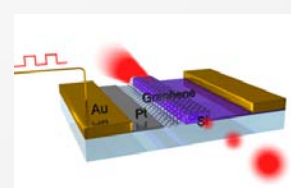


<u>Possible applications</u>

- Electronics and spintronics devices.
- Nano-electromechanical systems.
- Optics and communication.
- Tribology and solid lubrication.
- …

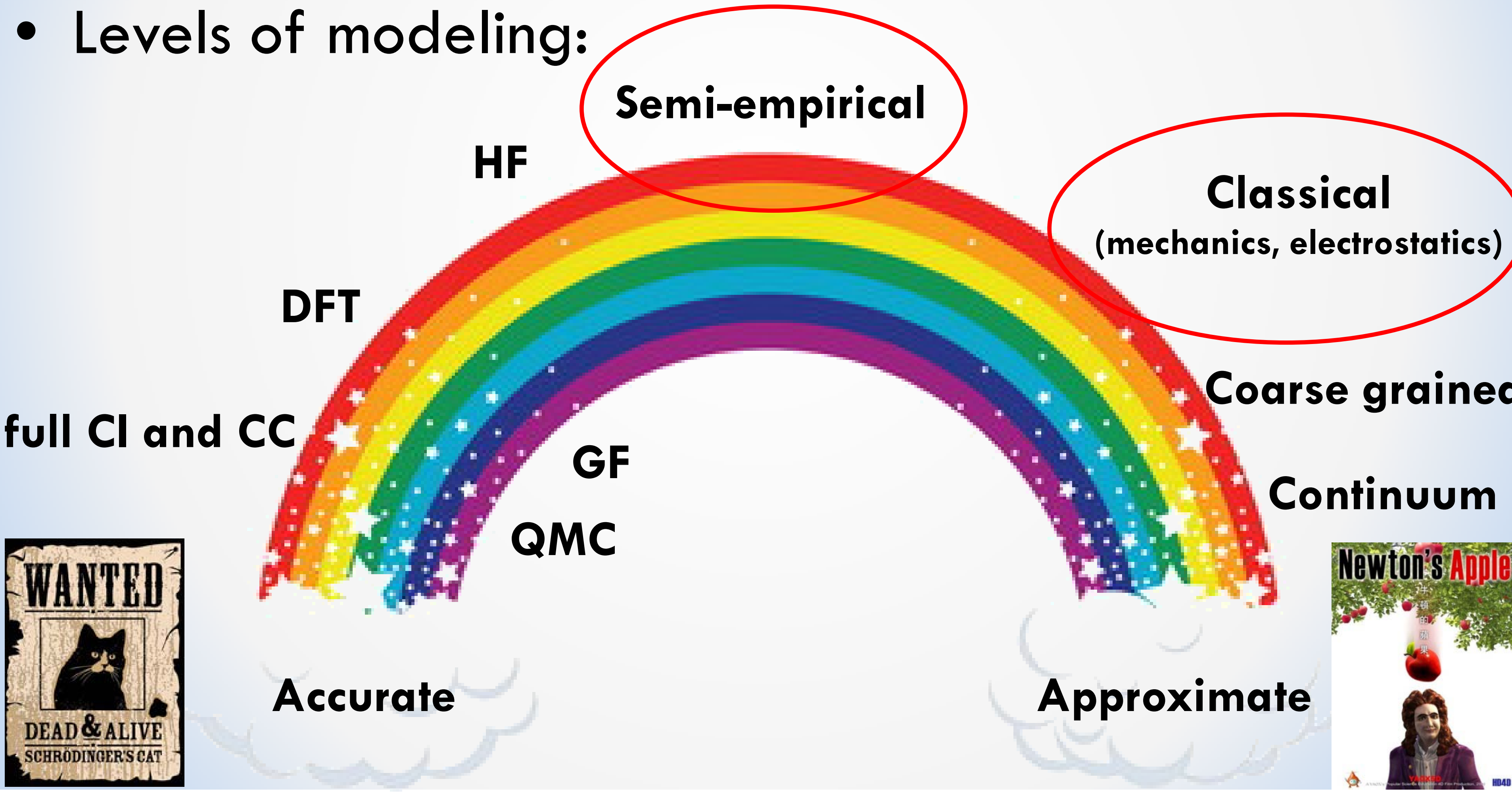




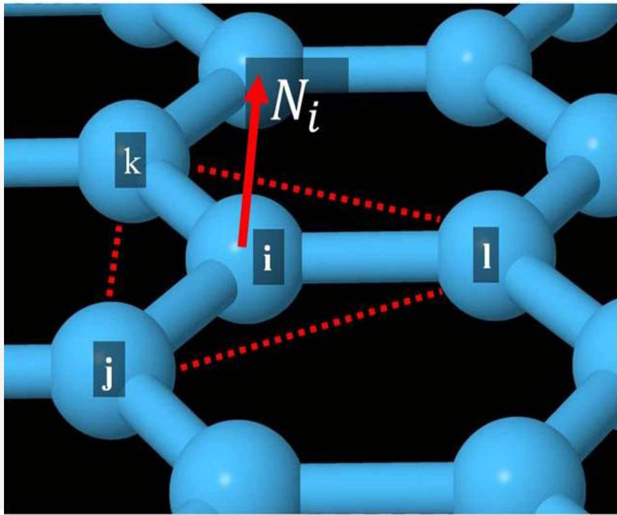


Modeling Nanoscale Layered Materials

- At the nanoscale modeling and simulations are accurate and efficient.
- Levels of modeling:

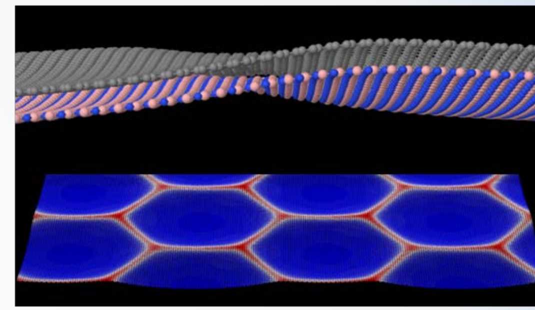


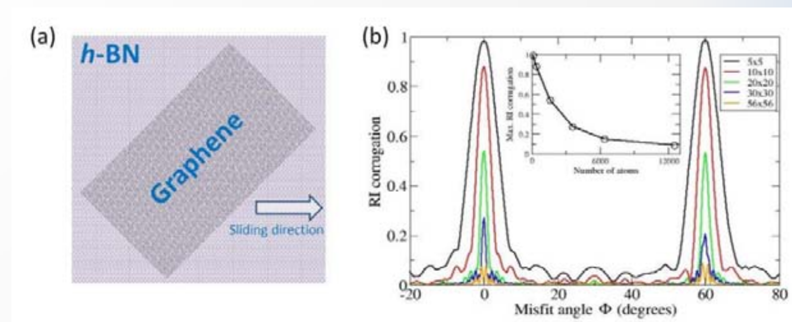
Classical Force-Fields Construction



Classical Force-Fields

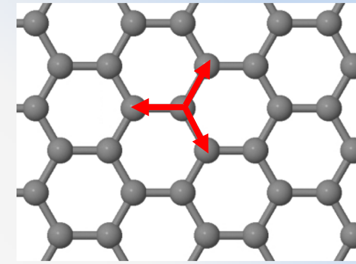
- Classical force-fields can be used to model many properties of layered materials:
  - ✓ Structural
  - ✓ Mechanical
  - ✓ Tribological
  - ✓ Heat transport
  - ✓ Chemical





- Layered materials are anisotropic by nature.
- Calls for a separate treatment of intra- and inter-layer interactions.

Intra-Layer Potentials



- Intra-layer interactions are often modeled via:
  - ✓ Bonded two-body interactions (distances). $V_{ij} = k_{ij}\left(r_{ij} - r_0\right)^2$
  - ✓ Bonded three-body interactions (angles). $V_{ijk} = k_{ijk}\left[\cos\left(\theta_{ijk}\right) - \cos\left(\theta_0\right)\right]^2$
  - ✓ Bonded four-body interactions (dihedrals and Impropers).

$$V_{ijkl} = k_{ijkl}\left[1 + \cos\left(n_{ijkl}\phi_{ijkl} - \phi_0\right)\right]$$

$$V_{ijkl} = k_{ijkl}\left(\phi_{ijkl} - \phi_0\right)^2$$

  - ✓ Van der Waals.

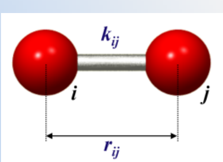
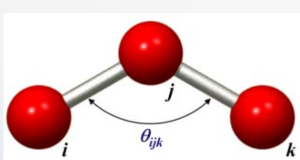
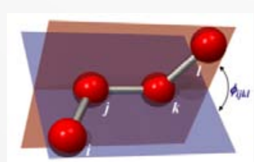
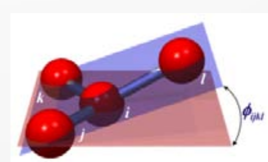
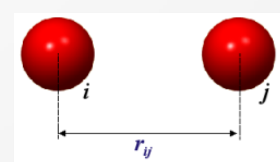
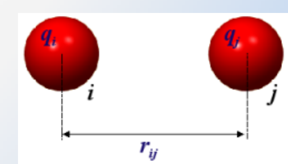
$$V_{vdw} = 4\varepsilon\left[\left(\frac{\sigma_{ij}}{r_{ij}}\right)^{12} - \left(\frac{\sigma_{ij}}{r_{ij}}\right)^{6}\right]$$

  - ✓ Electrostatics.

$$V_{Coul} = \frac{kq_iq_j}{r_{ij}}$$

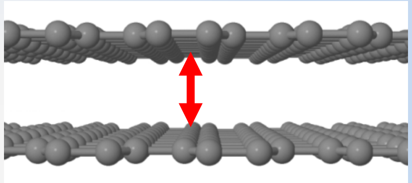
- Examples:

Tersoff, Brenner, AIREBO, REAXFF, AMBER, CHARMM, MM4, …

http://cbio.bmt.tue.nl/pumma/index.php/Theory/Potentials

Inter-Layer Potentials



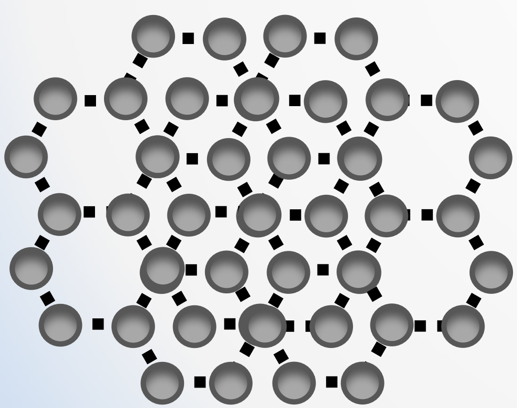
- Inter-layer interactions often include:
  - ✓ Isotropic long-range dispersive attractions.
  - ✓ (An)isotropic short-range Pauli repulsions.
  - ✓ Electrostatics.
- Examples:

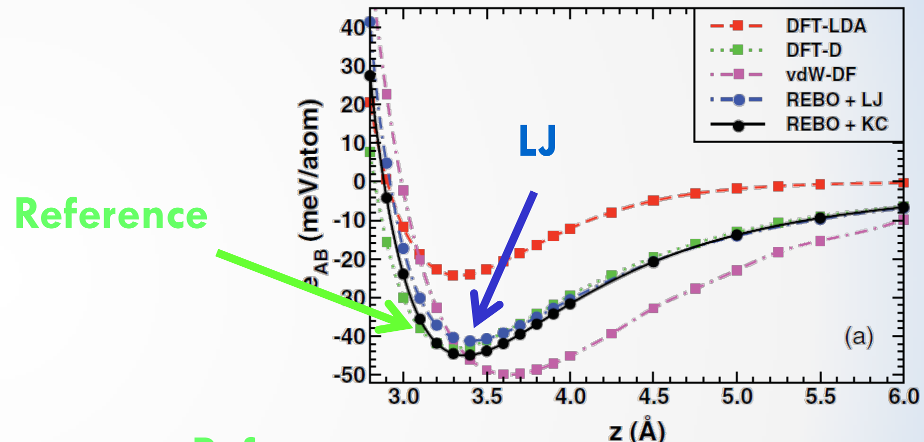
  Lennard-Jones/Morse, Kolmogorov-Crespi, *h*-BN ILP, *h*-BN/graphene ILP

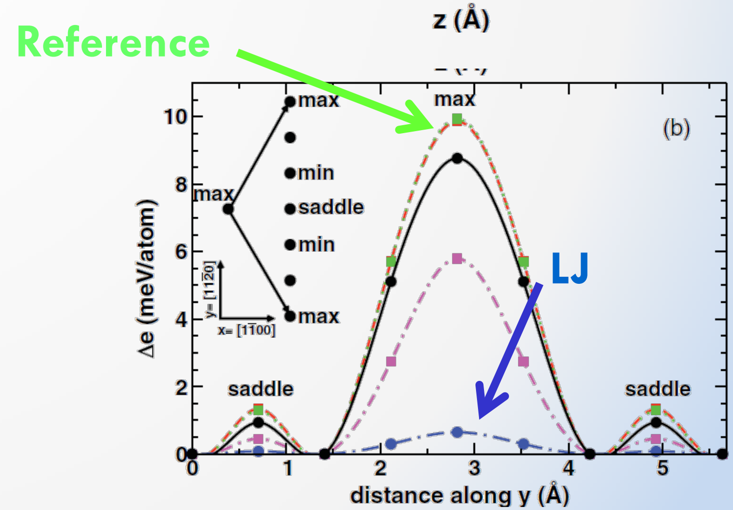
- A **range-separation cutoff** or a **clear layer separation** is required to apply the two terms simultaneously.

Isotropic Interlayer Potential for Graphene

- Isotropic potentials often provide a good description of the interlayer binding energy curve.
- However it predicts too shallow sliding energy curves.



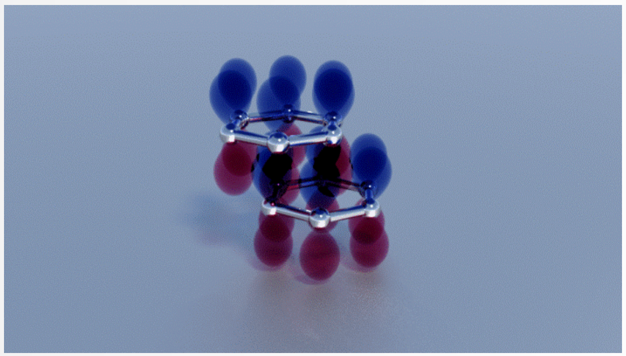




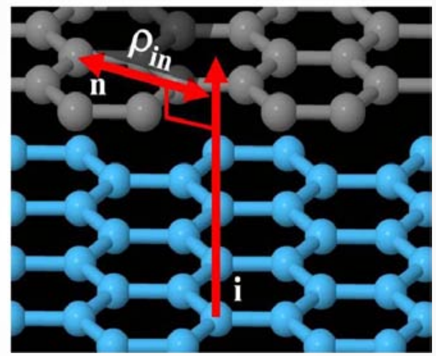
M. Reguzzoni A. Fasolino E. Molinari and M. C. Righi, Potential energy surface for graphene on graphene. *Phys. Rev. B* 2012, **86**, 245434.

Anisotropic Interlayer Potential for Graphene
Kolmogorov & Crespi (KC)

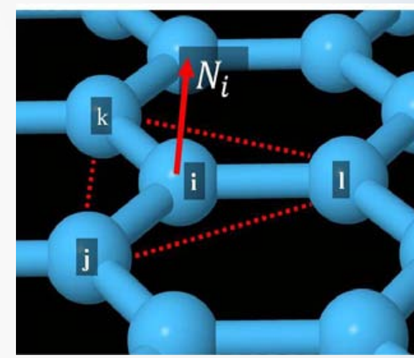
- **Pauli repulsions** depend on the **lateral distance** between two atoms on adjacent layers as they cross each-other during the sliding process.



Lateral distance



Normal



$$V(\mathbf{r}_{ij},\mathbf{n}_i,\mathbf{n}_j) = e^{-\lambda(r_{ij}-z_0)}[C + f(\rho_{ij}) + f(\rho_{ji})] - A\left(\frac{r_{ij}}{z_0}\right)^{-6}$$

Repulsive Morse-like term

Anisotropic Gaussian term

Attractive LJ-like term.

$$\rho_{ij}^2 = r_{ij}^2 - (\mathbf{n}_i\mathbf{r}_{ij})^2,$$

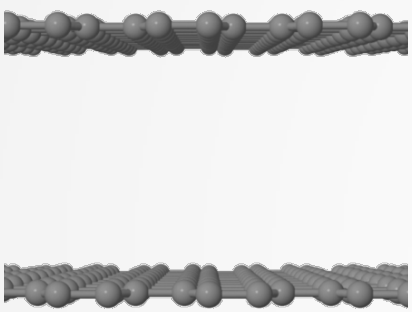
$$\rho_{ji}^2 = r_{ij}^2 - (\mathbf{n}_j\mathbf{r}_{ij})^2,$$

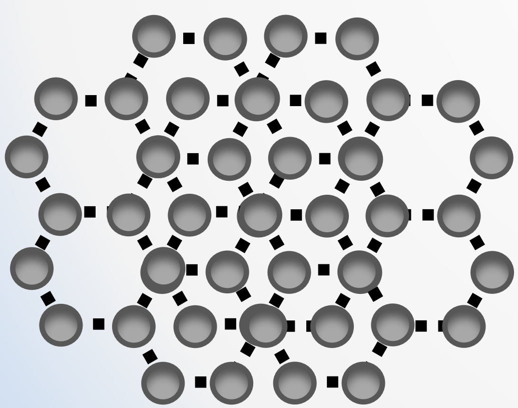
$$f(\rho) = e^{-(\rho/\delta)^2}\sum C_{2n}(\rho/\delta)^{2n}.$$

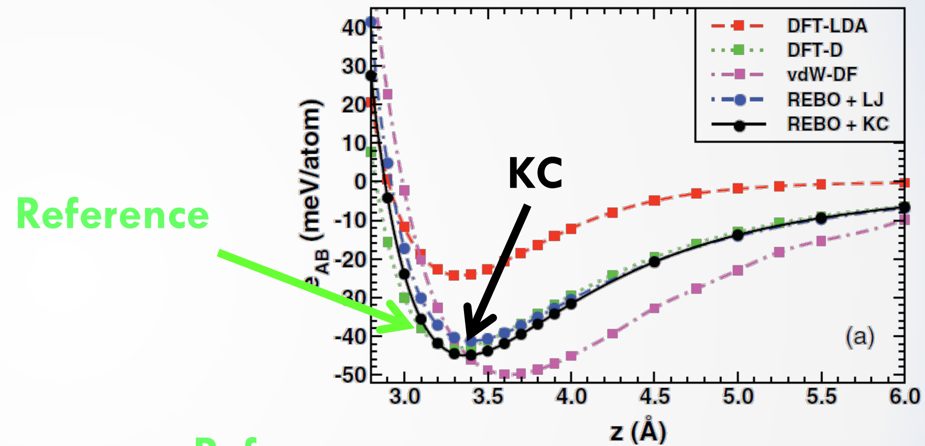
Kolmogorov, A. N.; Crespi, V. H., Registry-Dependent Interlayer Potential for Graphitic Systems. *Phys. Rev. B* 2005, **71**, 235415.

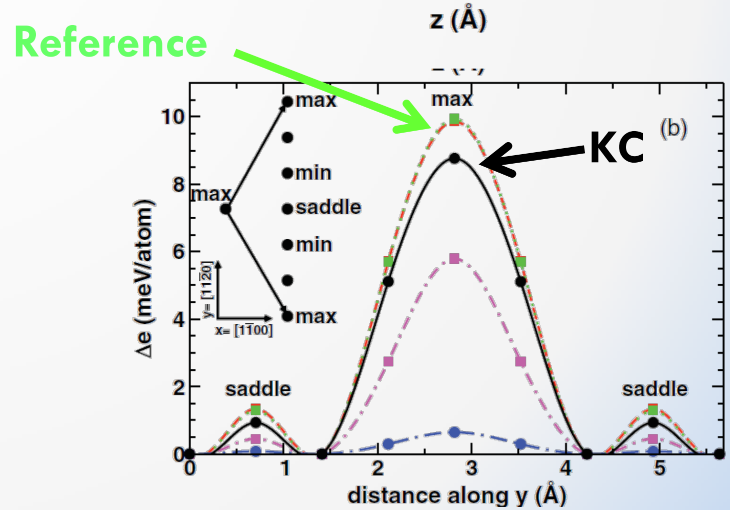
Anisotropic Interlayer Potential for Graphene Kolmogorov & Crespi (KC)

- KC can describe both motions simultaneously for **graphene**.



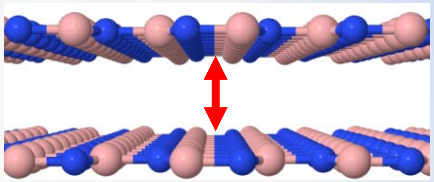






M. Reguzzoni A. Fasolino E. Molinari and M. C. Righi, Potential energy surface for graphene on graphene. *Phys. Rev. B* 2012, **86**, 245434.

Anisotropic Interlayer Potential for *h*-BN
h-BN ILP



- *h*-BN ILP follows the spirit of the KC potential.
- vdW + repulsion:

$$E_{vdW} = e^{\alpha_{ij}\left(1-\frac{r_{ij}}{R_{ij}}\right)}\left[\varepsilon_{ij} + C\left(e^{-\left(\frac{\rho_{ij}}{\gamma_{ij}}\right)^2} + e^{-\left(\frac{\rho_{ji}}{\gamma_{ij}}\right)^2}\right)\right] - \frac{1}{1+e^{-d\left(\frac{r_{ij}}{S_r r_{eff}}-1\right)}}\frac{C_6}{r_{ij}^6}$$

Repulsive Morse-like term

Anisotropic Gaussian term

Short-range Fermi-Dirac damping term

Attractive LJ-like term.

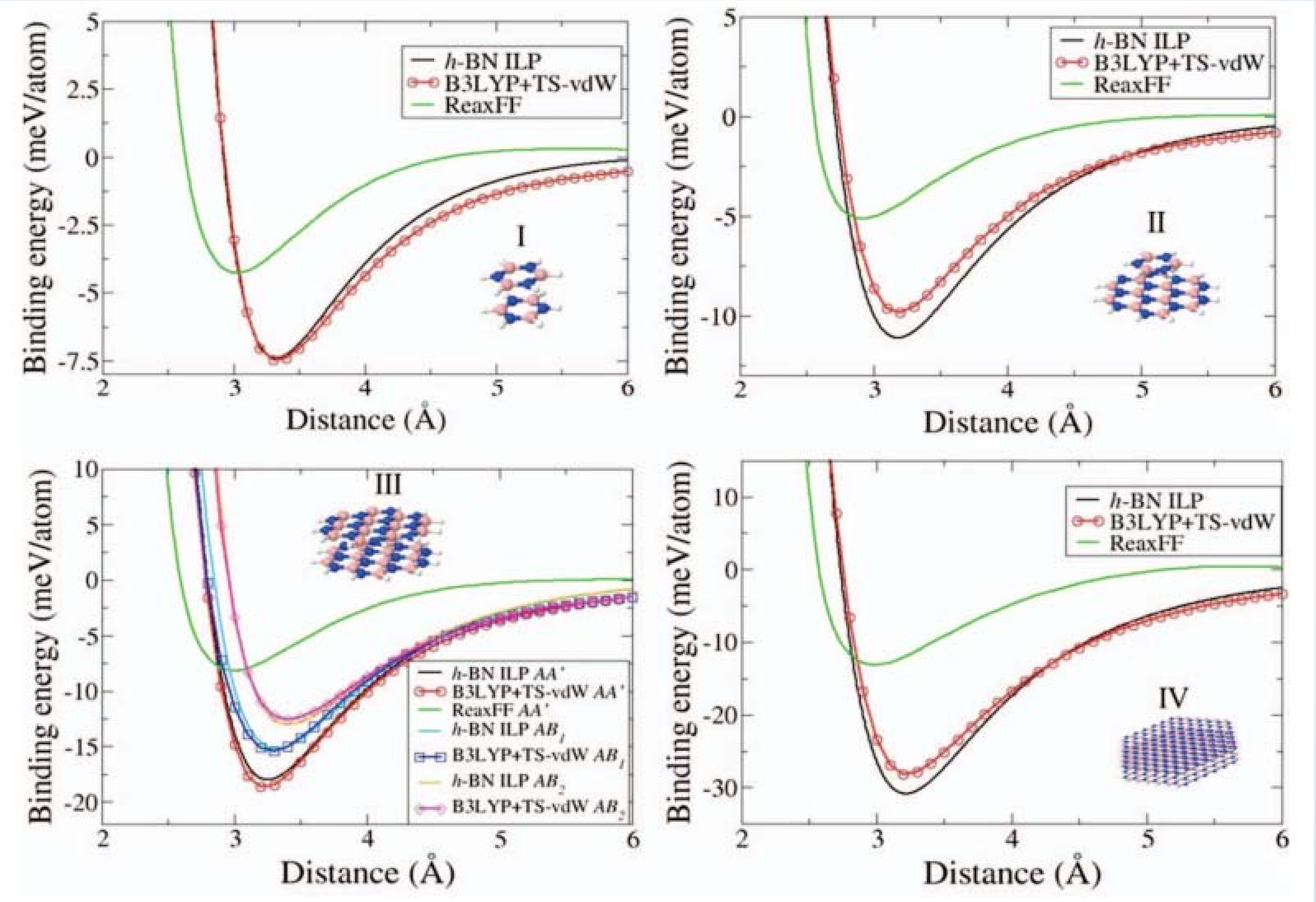
- Coulomb interactions between partially charged atomic centers:

$$E_{Coul} = k\frac{q_i q_j}{\sqrt[3]{r_{ij}^3 + \left(\frac{1}{\lambda_{ij}}\right)^3}}$$

- vdW parameters taken from TS-vdW calculations.
- All parameters fine tuned against TS-vdW DFT.

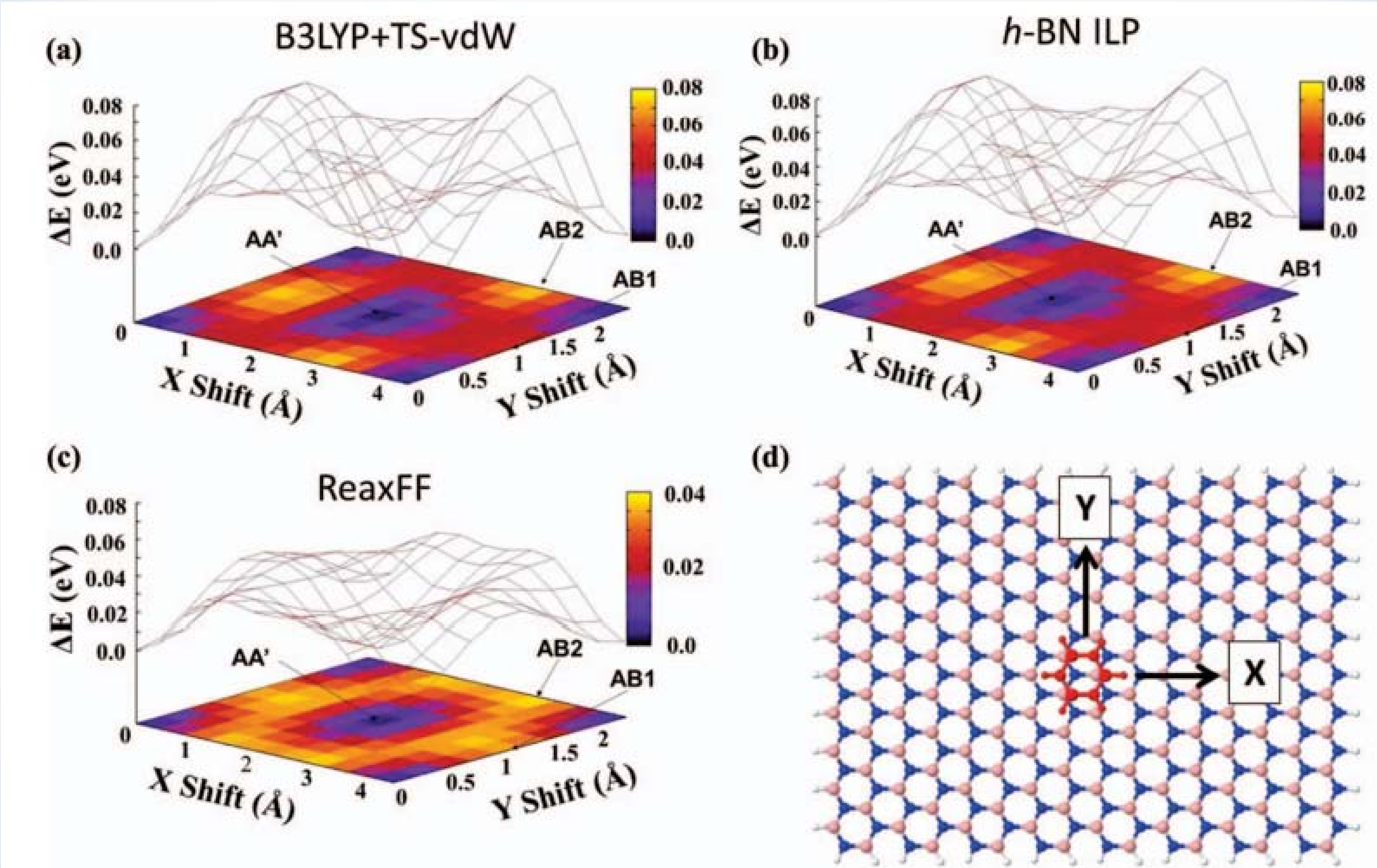
Leven, I.; Azuri, I.; Kronik, L.; Hod, O., Inter-Layer Potential for Hexagonal Boron Nitride. *J. Chem. Phys.* 2014, 140, 104106

h-BN ILP performance - Binding



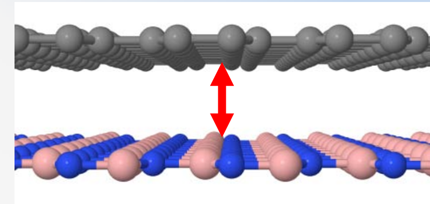
Leven, I.; Azuri, I.; Kronik, L.; Hod, O., Inter-Layer Potential for Hexagonal Boron Nitride. *J. Chem. Phys.* 2014, 140, 104106

h-BN ILP performance - Sliding

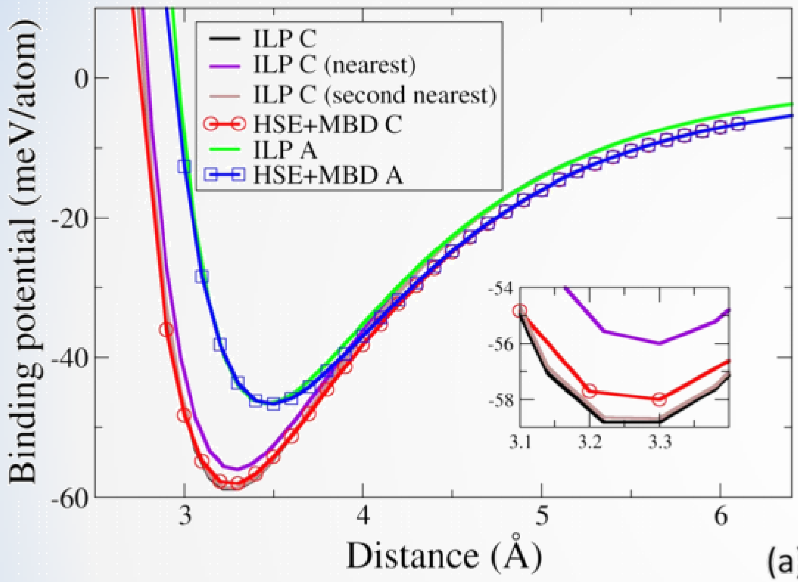


Leven, I.; Azuri, I.; Kronik, L.; Hod, O., Inter-Layer Potential for Hexagonal Boron Nitride. *J. Chem. Phys.* 2014, 140, 104106

Graphene/*h*-BN ILP

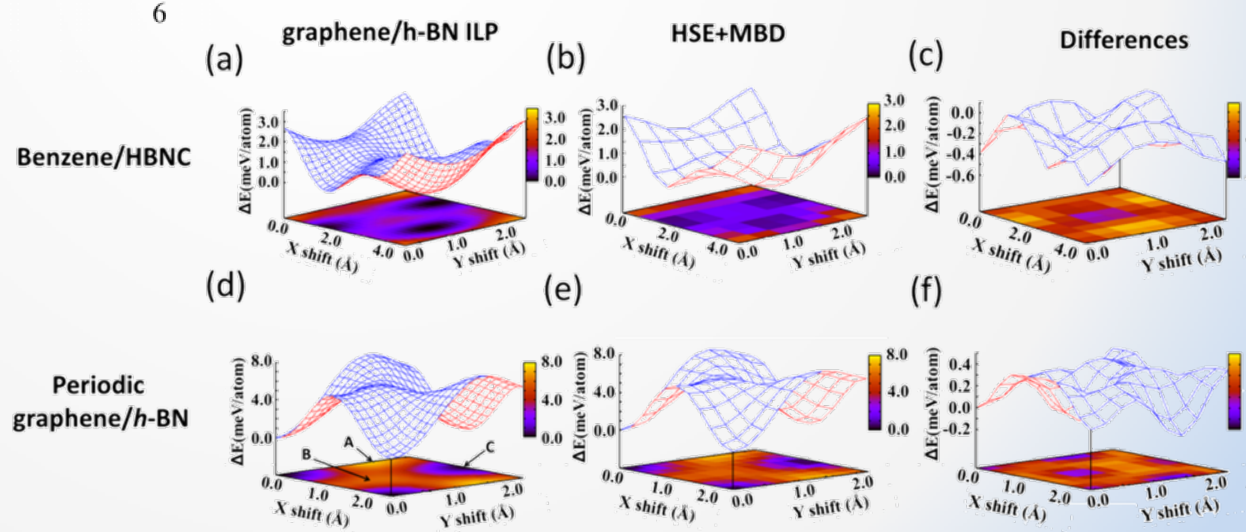


- Same functional form as the *h*-BN ILP without Coulomb interactions.



Binding energy of bulk graphene/*h*-BN alternating stacks.

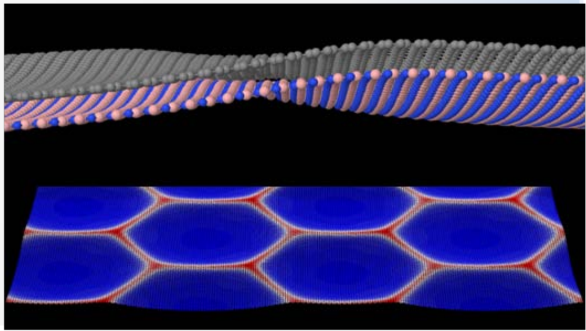
Sliding energy landscapes



I. Leven, T. Maaravi, I. Azuri, L. Kronik, and **O. Hod**, *J. Chem. Theory Comput.* **12**, 2896-2905 (2016).

Classical Force-Fields Applications

Graphene/*h*-BN Heterojunctions



Graphene/*h*-BN Hetero-Structures

LETTERS
nature materials
PUBLISHED ONLINE: 14 JULY 2013 | DOI: 10.1038/NMAT3695

Epitaxial growth of single-domain graphene on hexagonal boron nitride

Wei Yang[1], Guorui Chen[2], Zhiwen Shi[1], Cheng-Cheng Liu[1,3], Lianchang Zhang[1,4], Guibai Xie[1], Meng Cheng[1], Duoming Wang[1], Rong Yang[1], Dongxia Shi[1], Kenji Watanabe[5], Takashi Taniguchi[5], Yugui Yao[3], Yuanbo Zhang[2] and Guangyu Zhang[1]*

Field-Effect Tunneling Transistor Based on Vertical Graphene Heterostructures

L. Britnell,[1] R. V. Gorbachev,[2] R. Jalil,[2] B. D. Belle,[2] F. Schedin,[2] A. Mishchenko,[1] T. Georgiou,[1] M. I. Katsnelson,[3] L. Eaves,[4] S. V. Morozov,[5] N. M. R. Peres,[6,7] J. Leist,[8] A. K. Geim,[1,2]* K. S. Novoselov,[1]* L. A. Ponomarenko[1]*

LETTERS
nature nanotechnology
PUBLISHED ONLINE: 22 AUGUST 2010 | DOI: 10.1038/NNANO.2010.172

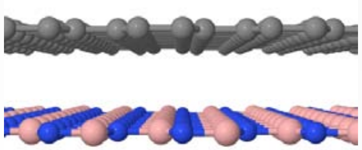
Boron nitride substrates for high-quality graphene electronics

C. R. Dean[1,2]*, A. F. Young[3], I. Meric[1], C. Lee[4,5], L. Wang[2], S. Sorgenfrei[1], K. Watanabe[6], T. Taniguchi[6], P. Kim[3], K. L. Shepard[1] and J. Hone[2]*

LETTER
doi:10.1038/nature11408

Graphene and boron nitride lateral heterostructures for atomically thin circuitry

Mark P. Levendorf[1]*, Cheol-Joo Kim[1]*, Lola Brown[1], Pinshane Y. Huang[2], Robin W. Havener[2], David A. Muller[2,3] & Jiwoong Park[1,3]



LETTERS
nature nanotechnology
PUBLISHED ONLINE: 22 JUNE 2015 | DOI: 10.1038/NNANO.2015.131

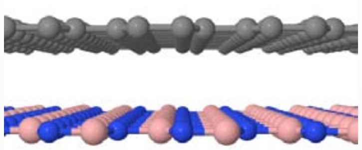
Graphene on hexagonal boron nitride as a tunable hyperbolic metamaterial

S. Dai[1], Q. Ma[2], M. K. Liu[1,3], T. Andersen[2], Z. Fei[1], M. D. Goldflam[1], M. Wagner[1], K. Watanabe[4], T. Taniguchi[4], M. Thiemens[5], F. Keilmann[6], G. C. A. M. Janssen[7], S-E. Zhu[7], P. Jarillo-Herrero[2], M. M. Fogler[1] and D. N. Basov[1]*

LETTERS
nature materials
PUBLISHED ONLINE: 13 FEBRUARY 2011 | DOI: 10.1038/NMAT2968

Scanning tunnelling microscopy and spectroscopy of ultra-flat graphene on hexagonal boron nitride

Jiamin Xue[1], Javier Sanchez-Yamagishi[2], Danny Bulmash[2], Philippe Jacquod[1,3], Aparna Deshpande[1]†, K. Watanabe[4], T. Taniguchi[4], Pablo Jarillo-Herrero[2] and Brian J. LeRoy[1]*



LETTER
doi:10.1038/nature12187

Cloning of Dirac fermions in graphene superlattices

L. A. Ponomarenko[1], R. V. Gorbachev[2], G. L. Yu[1], D. C. Elias[1], R. Jalil[2], A. A. Patel[3], A. Mishchenko[1], A. S. Mayorov[1], C. R. Woods[1], J. R. Wallbank[3], M. Mucha-Kruczynski[3], B. A. Piot[4], M. Potemski[4], I. V. Grigorieva[1], K. S. Novoselov[1], F. Guinea[5], V. I. Fal'ko[3] & A. K. Geim[1,2]

nature physics
ARTICLES
PUBLISHED ONLINE: 28 APRIL 2014 | DOI: 10.1038/NPHYS2954

Commensurate–incommensurate transition in graphene on hexagonal boron nitride

C. R. Woods[1], L. Britnell[1], A. Eckmann[2], R. S. Ma[3], J. C. Lu[3], H. M. Guo[3], X. Lin[3], G. L. Yu[1], Y. Cao[4], R. V. Gorbachev[4], A. V. Kretinin[1], J. Park[1,5], L. A. Ponomarenko[1], M. I. Katsnelson[6], Yu. N. Gornostyrev[7], K. Watanabe[8], T. Taniguchi[8], C. Casiraghi[2], H-J. Gao[3], A. K. Geim[4] and K. S. Novoselov[1]*

Massive Dirac Fermions and Hofstadter Butterfly in a van der Waals Heterostructure

B. Hunt,[1]* J. D. Sanchez-Yamagishi,[1]* A. F. Young,[1]* M. Yankowitz,[2] B. J. LeRoy,[2] K. Watanabe,[3] T. Taniguchi,[3] P. Moon,[4]† M. Koshino,[4] P. Jarillo-Herrero,[1]‡ R. C. Ashoori[1]‡

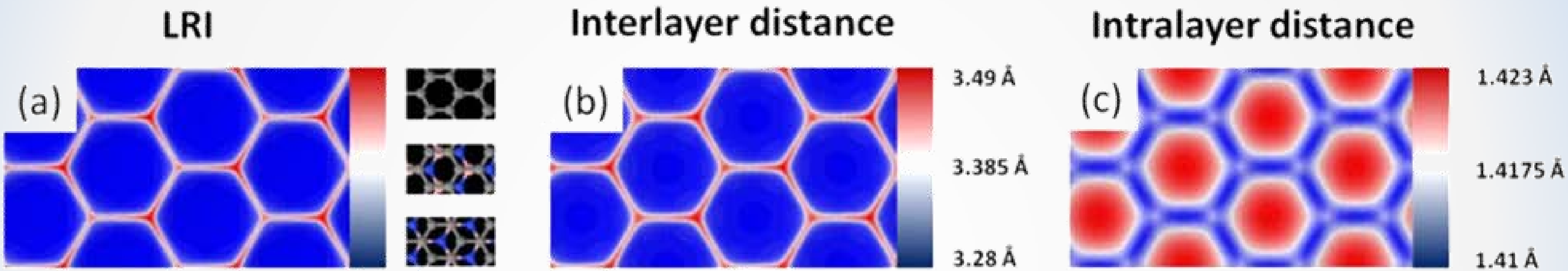
LETTER
doi:10.1038/nature12186

Hofstadter's butterfly and the fractal quantum Hall effect in moiré superlattices

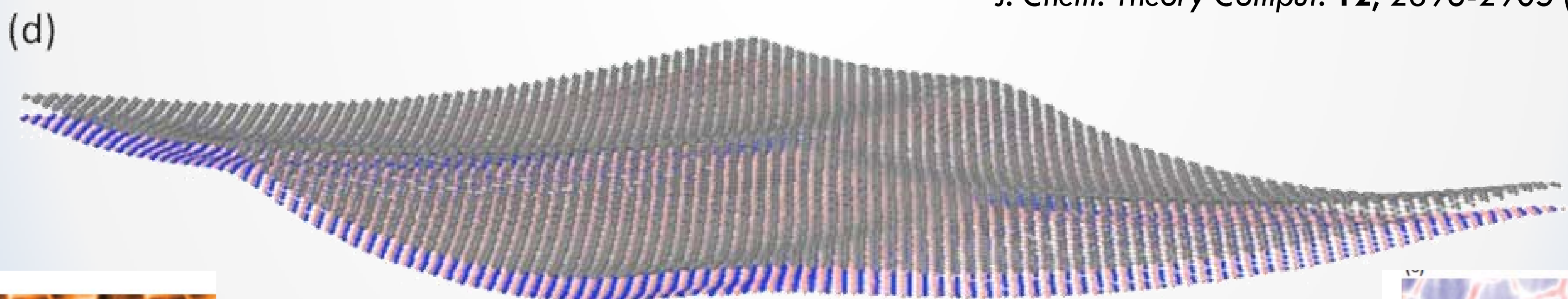
C. R. Dean[1], L. Wang[2], P. Maher[3], C. Forsythe[3], F. Ghahari[3], Y. Gao[2], J. Katoch[4], M. Ishigami[4], P. Moon[5], M. Koshino[5], T. Taniguchi[6], K. Watanabe[6], K. L. Shepard[7], J. Hone[2] & P. Kim[3]

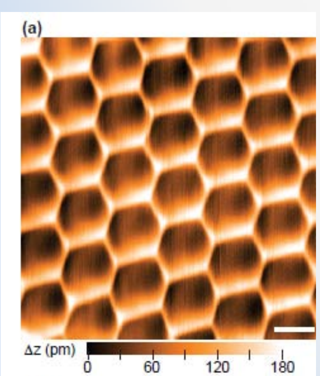
Graphene/*h*-BN Hetero-Structures

- Graphene and *h*-BN have an intralayer lattice mismatch of 1.83%.
- Moiré patterns result in domain walls.

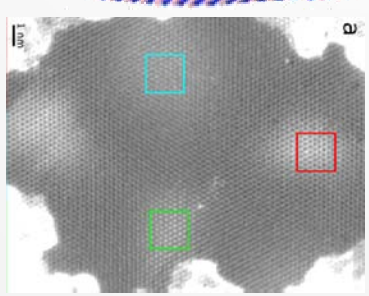


J. Chem. Theory Comput. **12**, 2896-2905 (2016).



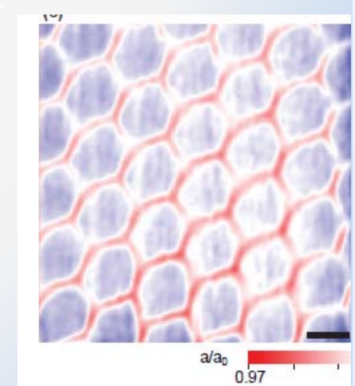


Surface corrugation



Nano Lett. **17**, 1409–1416 (2017)

Intra-layer bond lengths

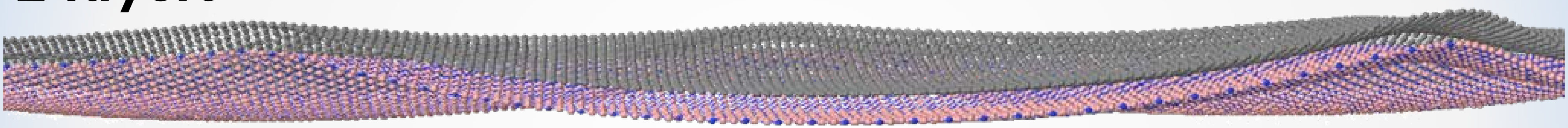


Graphene/*h*-BN Hetero-Structures

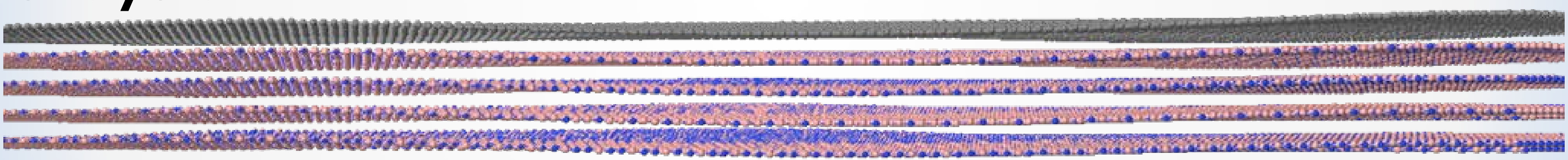
- The number of layers and interlayer misfit angle dictate the relaxed structure.

0° Misfit angle

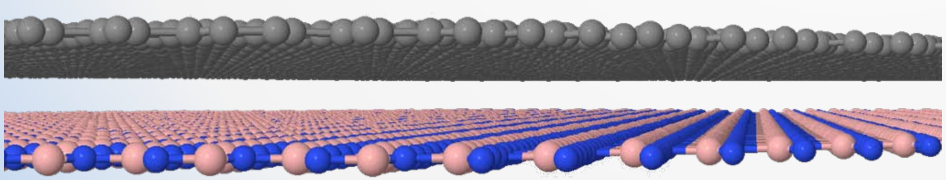
2 layers



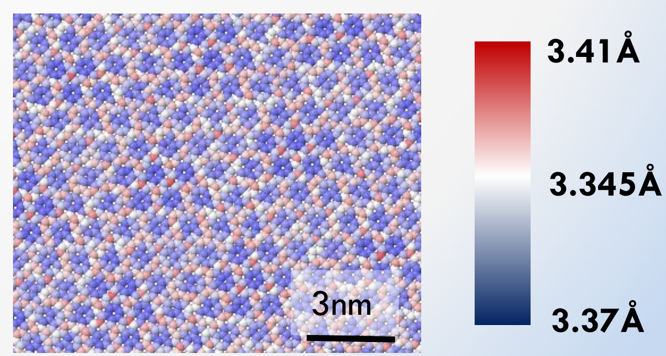
5 layers



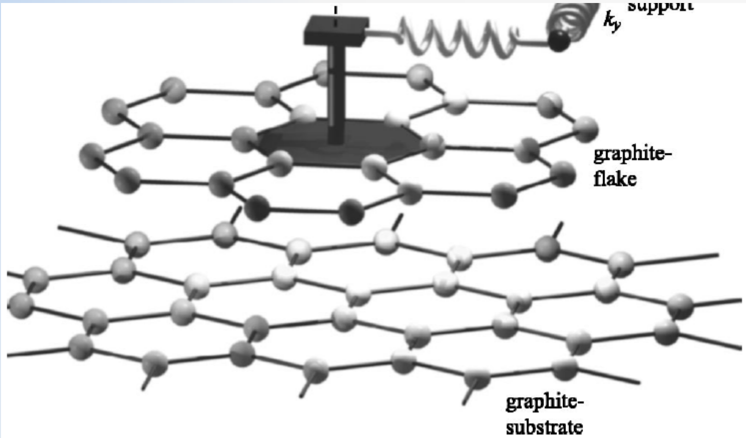
20° Misfit angle, bilayer



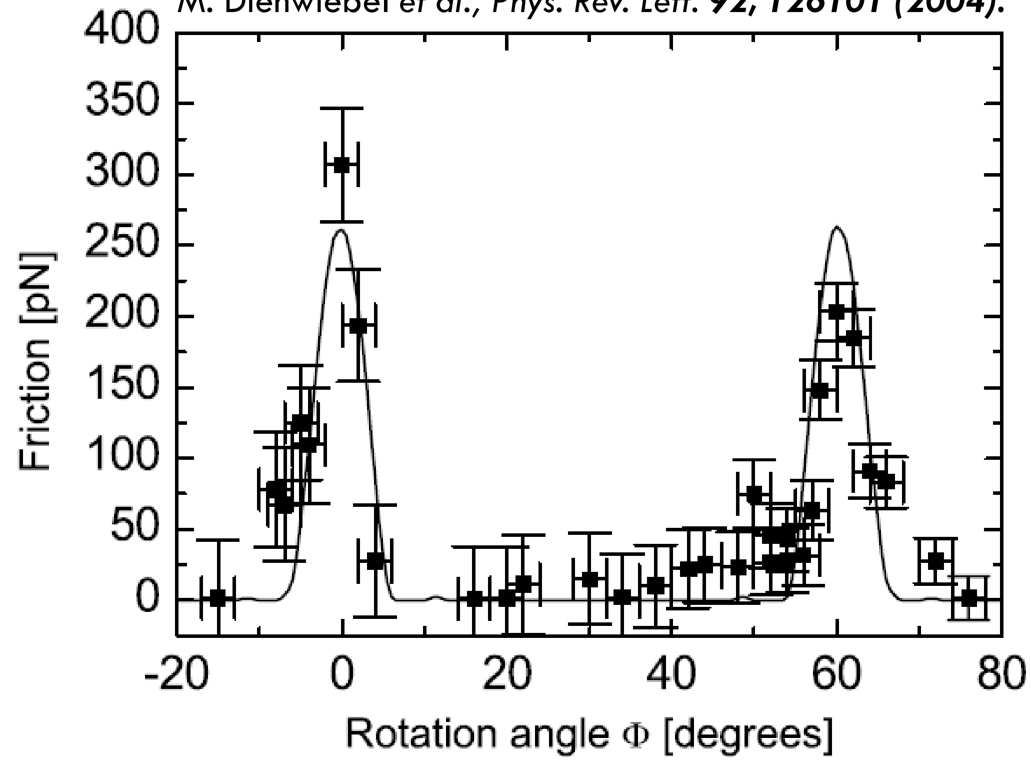
corrugation ~0.03Å

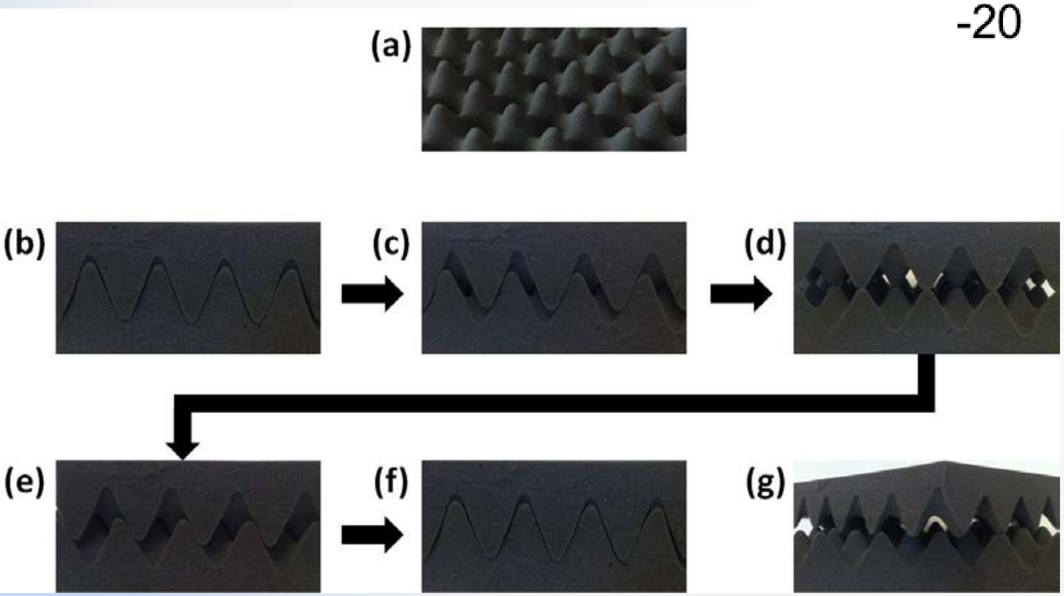


Robust Superlubricity in Heterojunctions



M. Dienwiebel *et al.*, *Phys. Rev. Lett.* ***92, 126101 (2004).***





Can nanoscale graphitic interfaces exhibit sustainable superlubric behavior?

Robust Superlubricity in Heterojunctions

PRL **100,** 046102 (2008) PHYSICAL REVIEW LETTERS week ending 1 FEBRUARY 2008

Torque and Twist against Superlubricity

Alexander E. Filippov,[1] Martin Dienwiebel,[2,3] Joost W. M. Frenken,[2] Joseph Klafter,[4] and Michael Urbakh[4]

Nanoscale graphene flakes dynamically rotate and lock in the commensurate high friction state.

THE JOURNAL OF PHYSICAL CHEMISTRY Letters

Letter

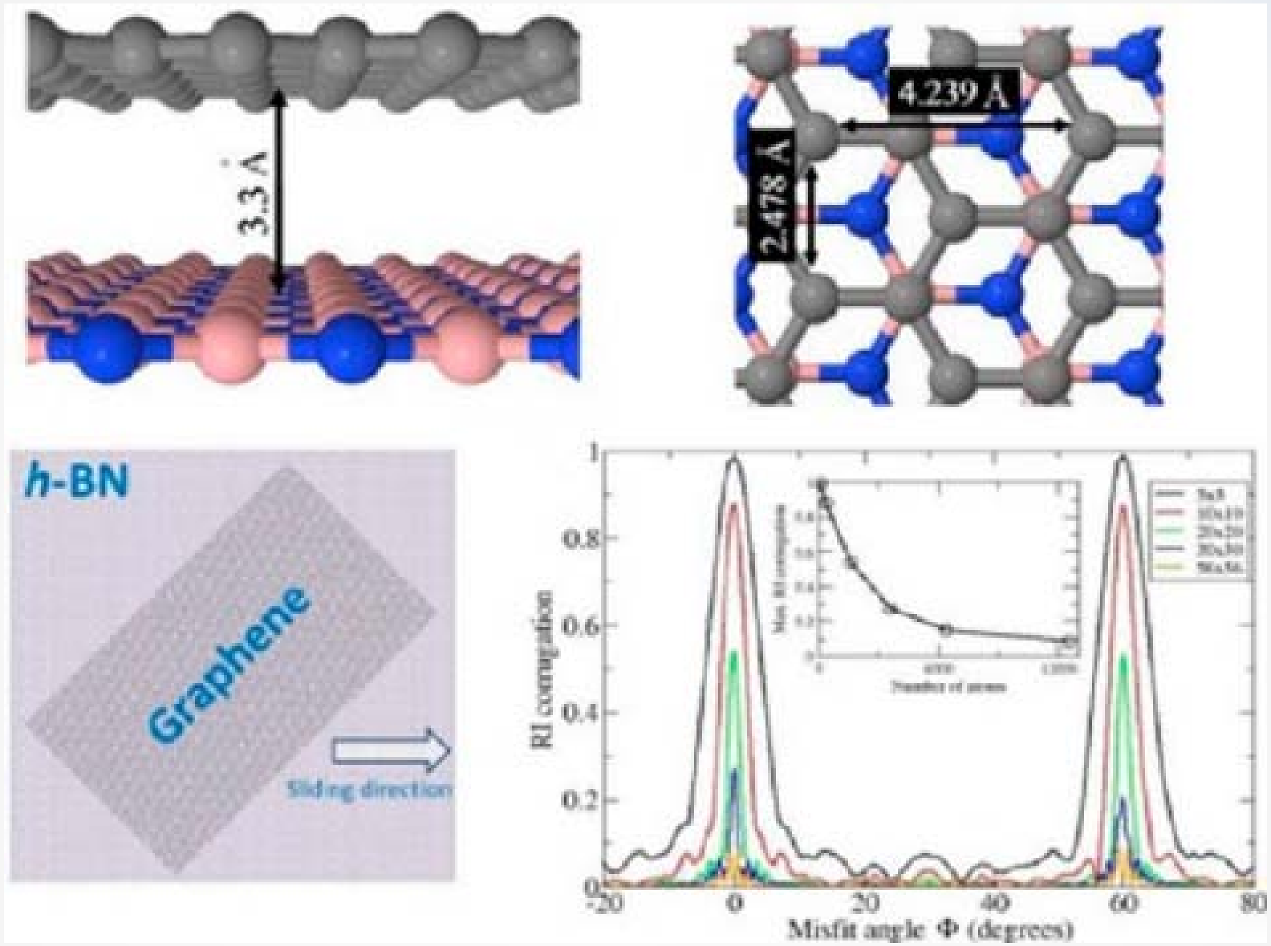
pubs.acs.org/JPCL

Robust Superlubricity in Graphene/*h*-BN Heterojunctions

Itai Leven, Dana Krepel, Ortal Shemesh, and Oded Hod*

Due to the intrinsic 1.8% lattice vector mismatch of the hexagonal lattices of graphene and *h*-BN their heterogeneous junction is expected to present superlubric behavior regardless of their relative orientation.

Robust Superlubricity in Heterojunctions



- Geometric modeling of rigid surfaces using the Registry Index method demonstrated that for large enough flakes robust superlubricity can be achieved by considerably reducing the PES (and hence friction) anisotropy.
- Neglecting dynamic effects!

Robust Superlubricity in Heterojunctions

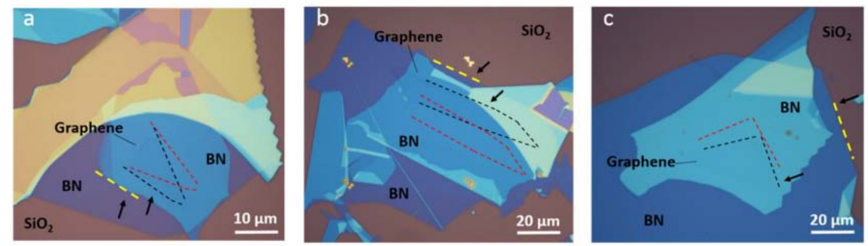
Self orientation of graphene sandwiched between *h*-BN surfaces.

Evidence for a fractional fractal quantum Hall effect in graphene superlattices

Lei Wang[1,2], Yuanda Gao[1], Bo Wen[3], Zheng Han[3], Takashi Taniguchi[4], Kenji Watanabe[4], Mikito Koshino[5], James Hone[1], ...

+ See all authors and affiliations

Science 04 Dec 2015:
Vol. 350, Issue 6265, pp. 1231-1234
DOI: 10.1126/science.aad2102



Self orientation of graphene on *h*-BN.

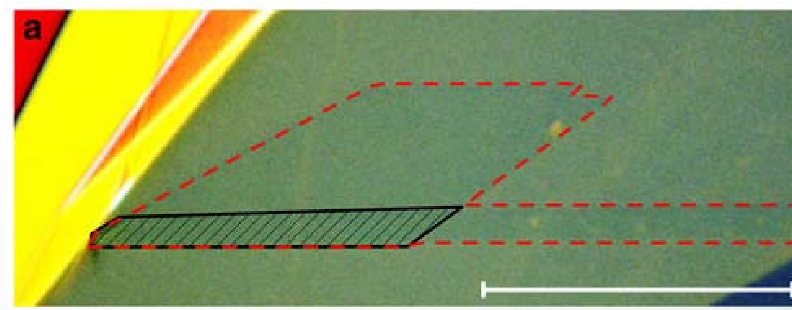
nature COMMUNICATIONS

Article | OPEN

Macroscopic self-reorientation of interacting two-dimensional crystals

C. R. Woods, F. Withers, M. J. Zhu, Y. Cao, G. Yu, A. Kozikov, M. Ben Shalom, S. V. Morozov, M. M. van Wijk, A. Fasolino, M. I. Katsnelson, K. Watanabe, T. Taniguchi, A. K. Geim, A. Mishchenko & K. S. Novoselov

Figure 1: Optical and atomic force microscopy of a self-rotating flake.



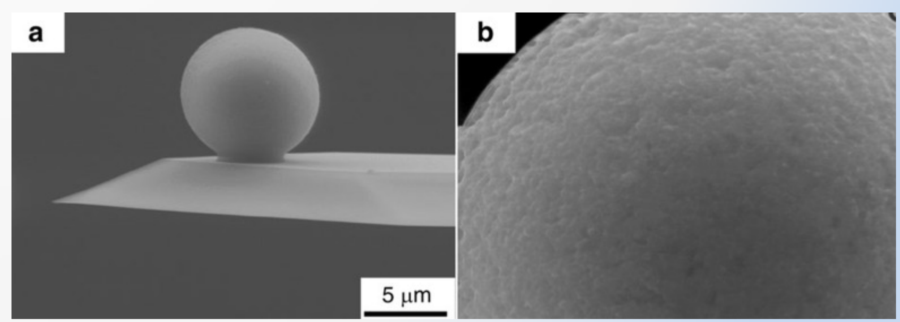
Multi-contact superlubricity in graphene/graphene and graphene/*h*-BN junctions.

nature COMMUNICATIONS

Nat Commun. 2017; 8: 14029. PMCID: PMC5316838
Published online 2017 Feb 14. doi: 10.1038/ncomms14029

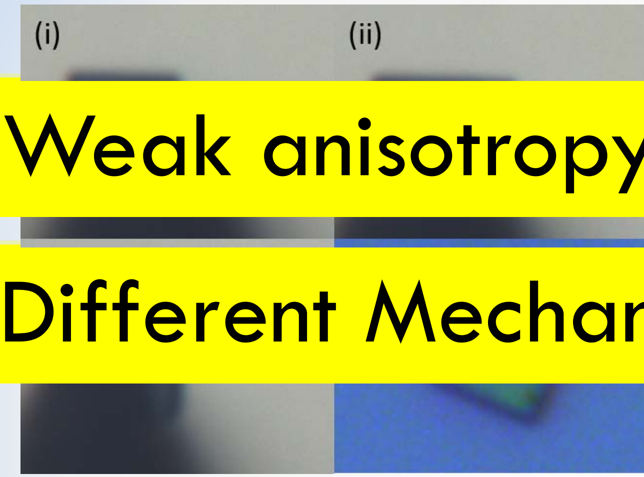
Robust microscale superlubricity under high contact pressure enabled by graphene-coated microsphere

Shu-Wei Liu,[1] Hua-Ping Wang,[2] Qiang Xu,[3] Tian-Bao Ma,[a,1] Gui Yu,[b,2] Chenhui Zhang,[1] Dechao Geng,[2] Zhiwei Yu,[1] Shengguang Zhang,[3] Wenzhong Wang,[3] Yuan-Zhong Hu,[1] Hui Wang,[1] and Jianbin Luo[c,1]



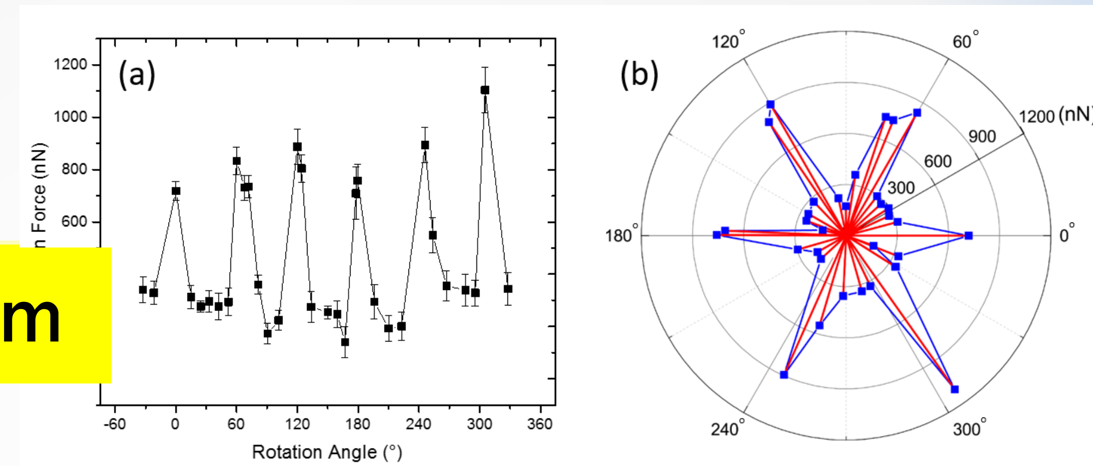
Robust Superlubricity in Heterojunctions

Robust superlubricity in microscale graphene/*h*-BN heterostructures

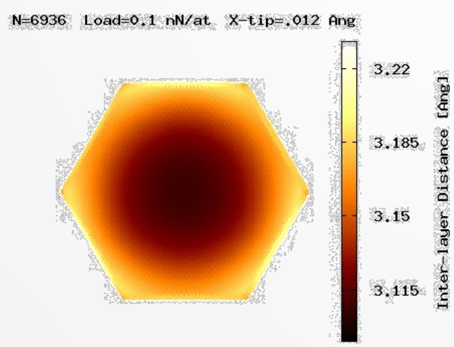


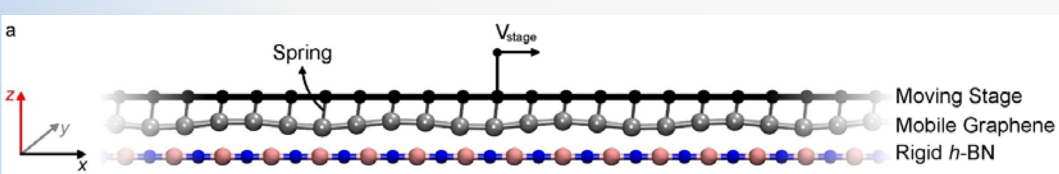
Weak anisotropy

Different Mechanism



Some cool fully atomistic molecular dynamics simulations



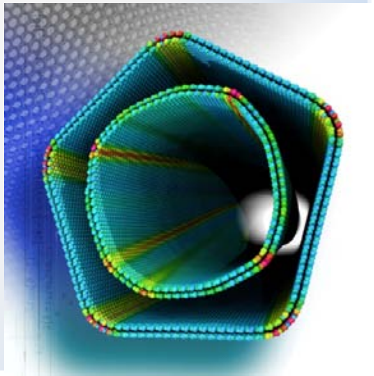


Davide Mandelli

Tomorrow @ 14:20

Classical Force-Fields Applications

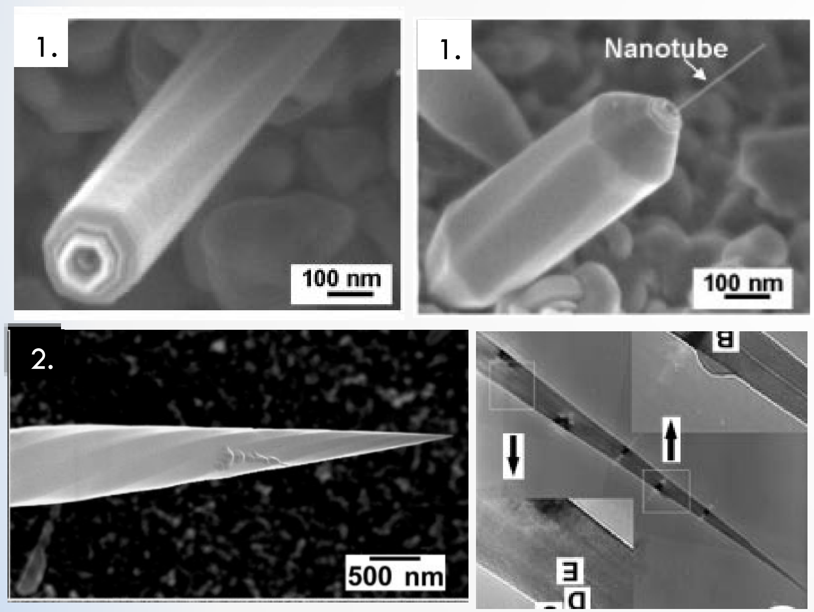
Nanotube Faceting



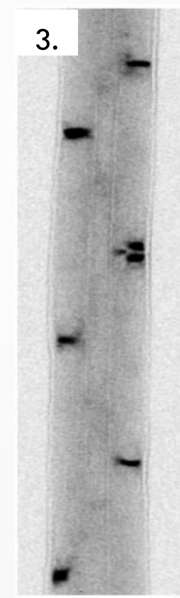
Faceting in Multi-Walled Nanotubes

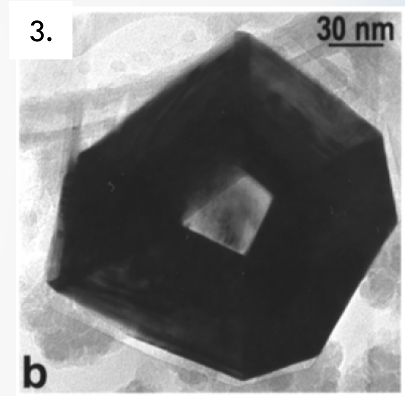
- Nanotubes are often considered to have cylindrical cross sections.
- MWNTs can exhibit circumferential faceting.
- Faceting is more abundant in MWBNNTs than in MWCNTs.

Carbon



BN

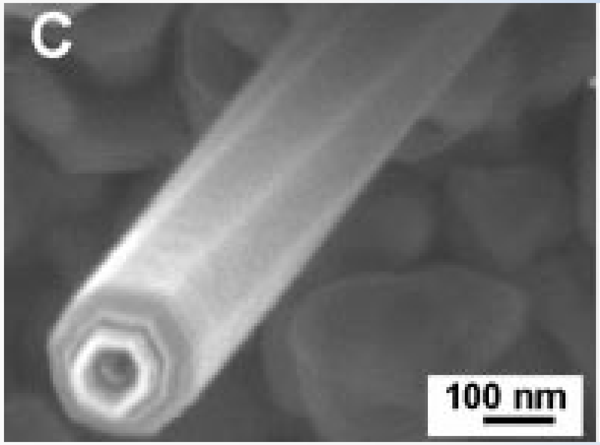




1. G. Zhang, X. Jiang, E. Wang, *Science* **300**, 472 (2003).
2. Y. Gogotsi, J. A. Libera, N. Kalashnikov, M. Yoshimura, *Science* **290**, 317 (2000).
3. A. Celik-Aktas, J. Zuo, J. F. Stubbins, C. Tangc and Y. Bando, Acta Cryst. (2005). A61, 533.

Faceting in Multi-Walled Nanotubes

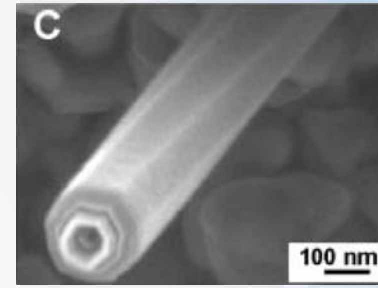
- Open questions:



  - ✓ Why do facets form?
  - ✓ What dictates the number of facets?
  - ✓ What determines the facet helicity?
  - ✓ Why are facets more abundant in MWBNNTs than in MWCNTs?
  - ✓ How does faceting influence the mechanical and tribological properties of MWNTs?

Nanotube Faceting and Local Registry

Science, 290, 317 (2000)



- The anisotropic interlayer potential of Kolmogorov and Crespi (*Phys. Rev. B* **71**, 235415 (2005)) for graphitic systems and our *h*-BN-ILP (*J. Chem. Phys.* **140**, 104106 (2014)) are used to perform geometry optimizations of double walled nanotubes.

I. Leven, R. Guerra, A. Vanossi, E. Tosatti, and **O. Hod**, "Multi-Walled Nanotube Faceting Unravelled", *Nat. Nanotechnol.* **11**, 1082-1086 (2016).

✓ ZZ@ZZ and AC@AC DWNTs form facets.

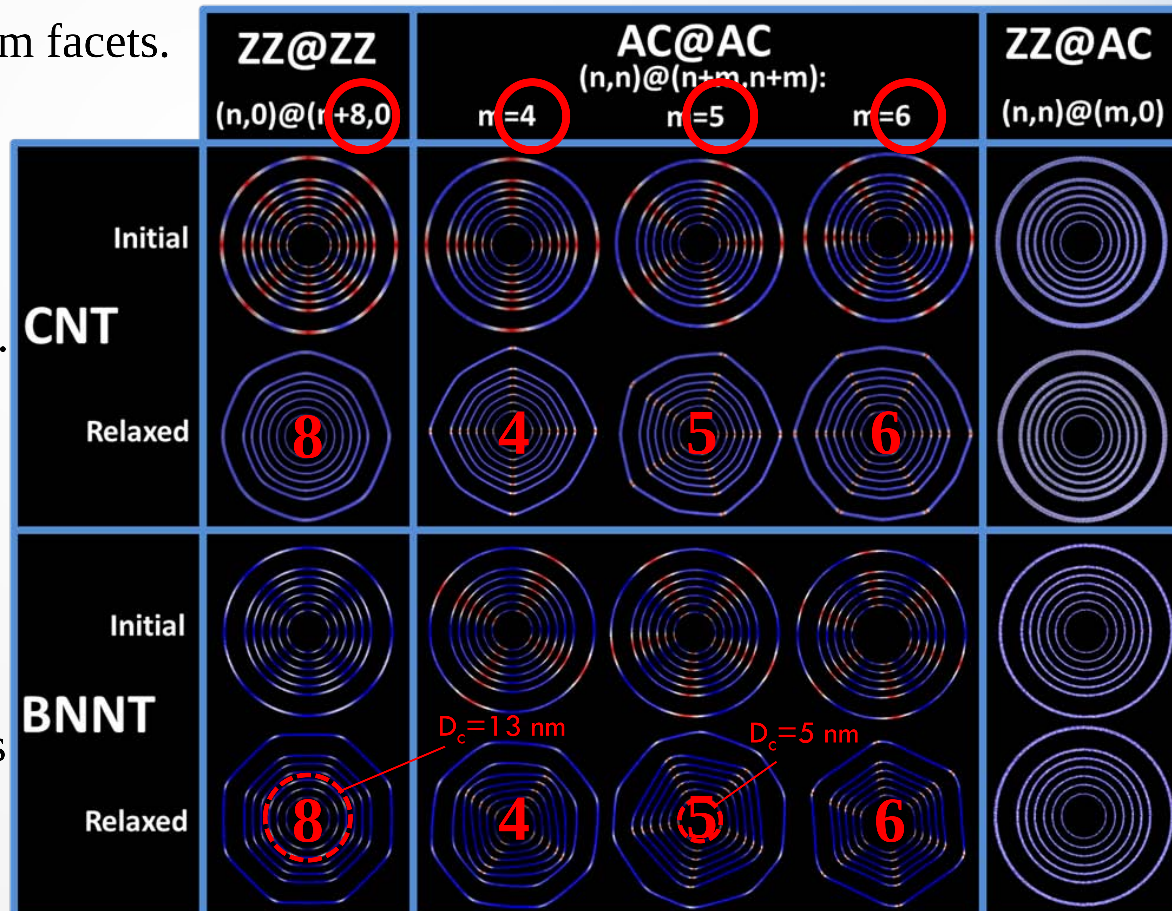
✓ ZZ@AC do not facet.

✓ The critical diameter for faceting is 5-13 nm in agreement with experiment (*Nano Lett.* **12**, 6347-6352 (2012)).

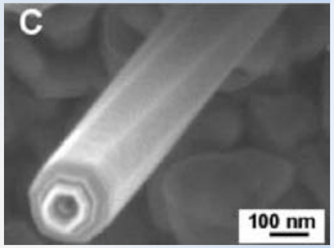
✓ Number of facets equals the difference in the number of circumferential unit cells.

✓ Local registry patterns reveal that the difference in circumferential unit cells distributes evenly around the nanotube.

✓ Bad registry regions form vertices.

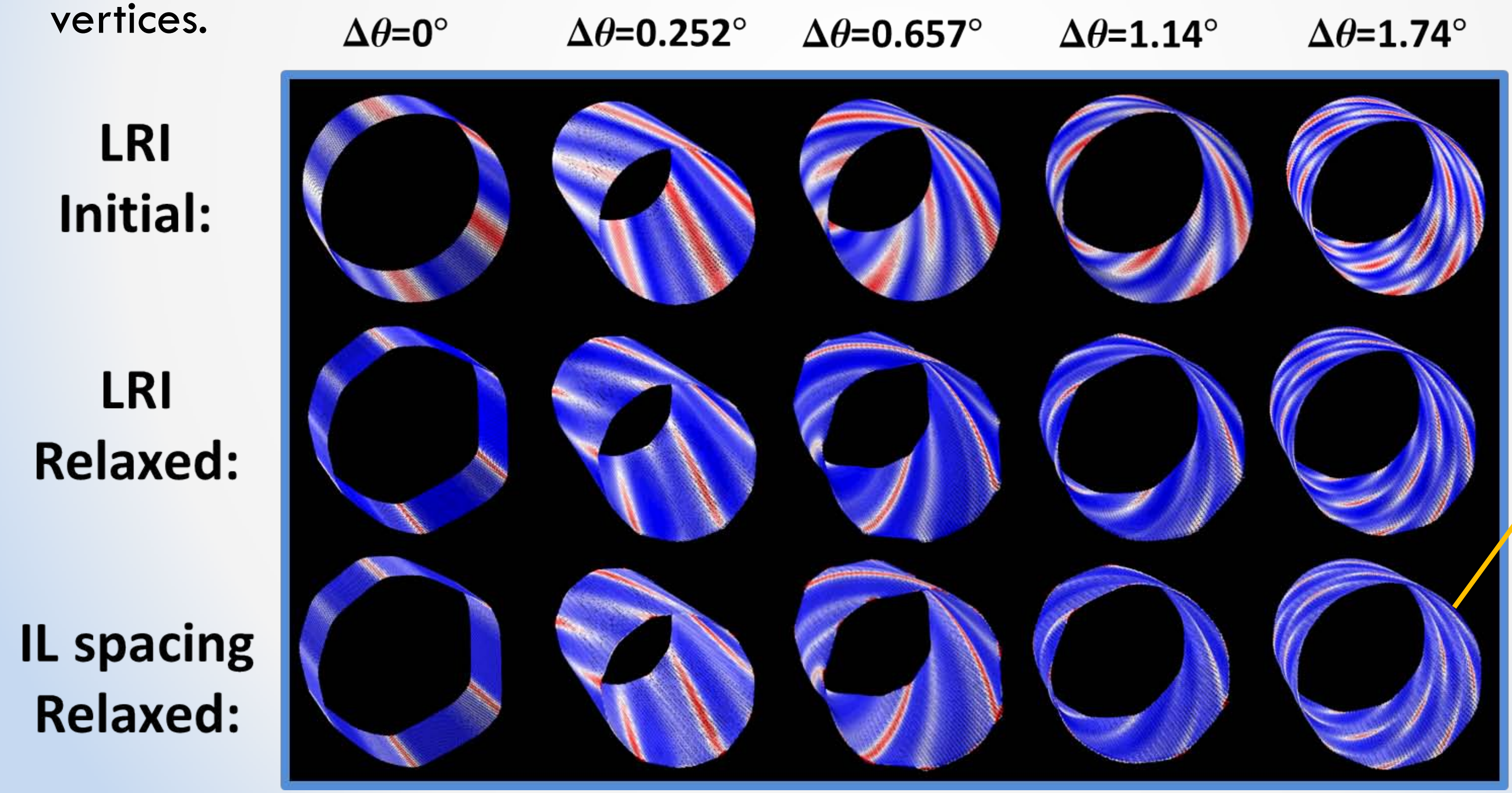


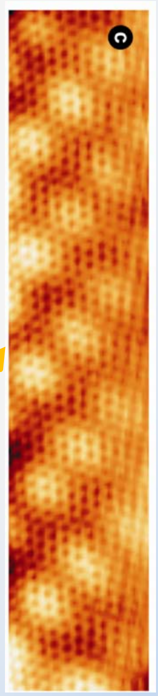
Chiral DWNT Nanotube Faceting



Science, 290, 317 (2000)

- Local registry patterns determine faceting in chiral DWNTs, as well.
- Mono-chiral DWNTs form non-uniform axial patterns.
- Bi-chiral DWNTs form spiraling facets. Their helical angle grows with the chiral angle difference and their length reduces.
- The interlayer spacing is close to equilibrium at the facets and increases at the vertices.



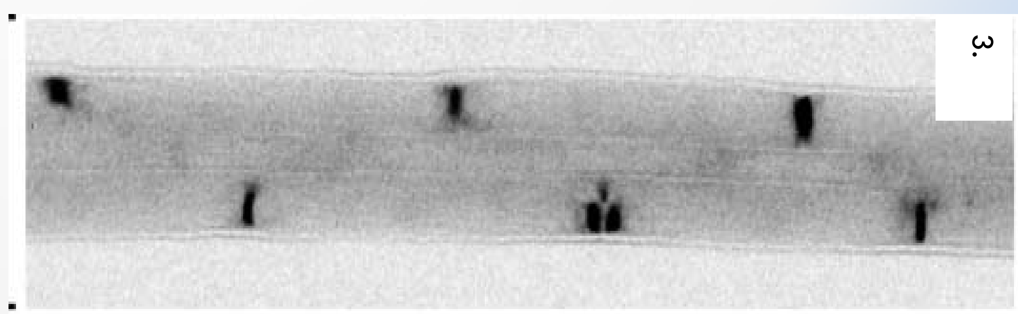


Carbon **61**, 379 (2013)

I. Leven, R. Guerra, A. Vanossi, E. Tosatti, and **O. Hod**, "Multi-Walled Nanotube Faceting Unravelled", *Nat. Nanotechnol.* **11**, 1082-1086 (2016).

Why is faceting more abundant in BNNTs than in CNTs?

- Faceting requires chiral angle matching between adjacent layer.
- MWBNNTs present high uniformity in the chirality of the different layers whereas MWCNTs have a much wider distribution of wall chiralities.
- This is a result of the larger interlayer adhesion in *h*-BN and the weak, yet important (when summed over large surfaces), electrostatic interactions between the partially charged atomic centers in BNNT that is absent in CNTs.



Classical Force-Fields Applications

Nanotube Friction

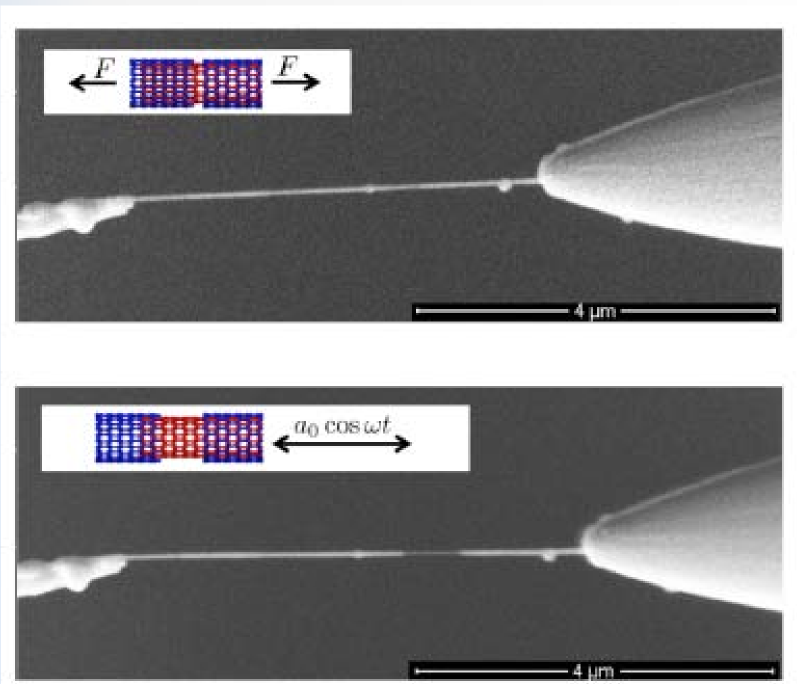
Enhance Friction in MWBNNTs

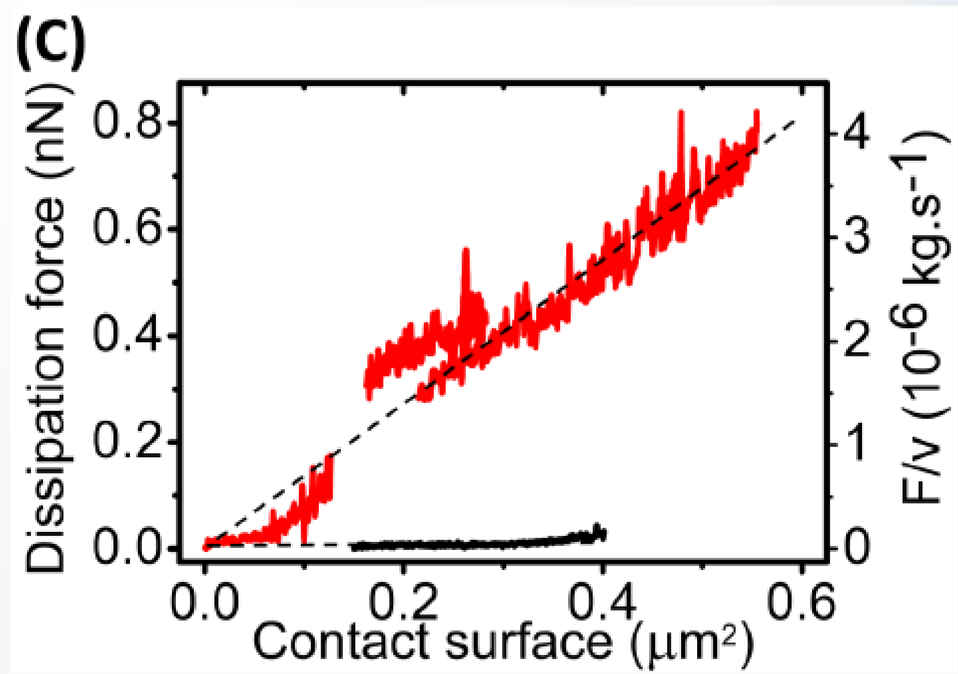
LETTERS
PUBLISHED ONLINE: 1 JUNE 2014 | DOI: 10.1038/NMAT3985
nature materials

Ultrahigh interlayer friction in multiwalled boron nitride nanotubes

A. Niguès[1], A. Siria[1*], P. Vincent[1], P. Poncharal[1] and L. Bocquet[1,2]

688 NATURE MATERIALS | VOL 13 | JULY 2014 | www.nature.com/naturematerials

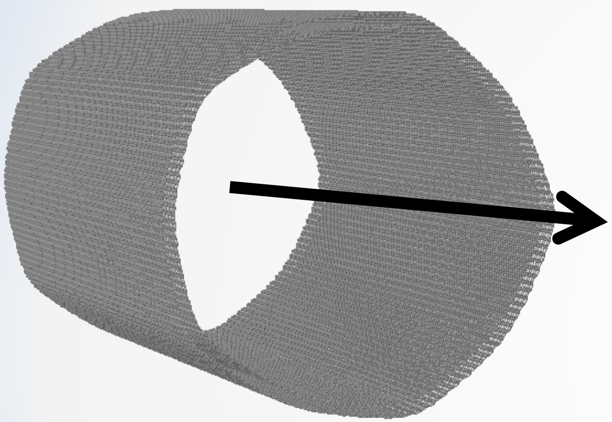


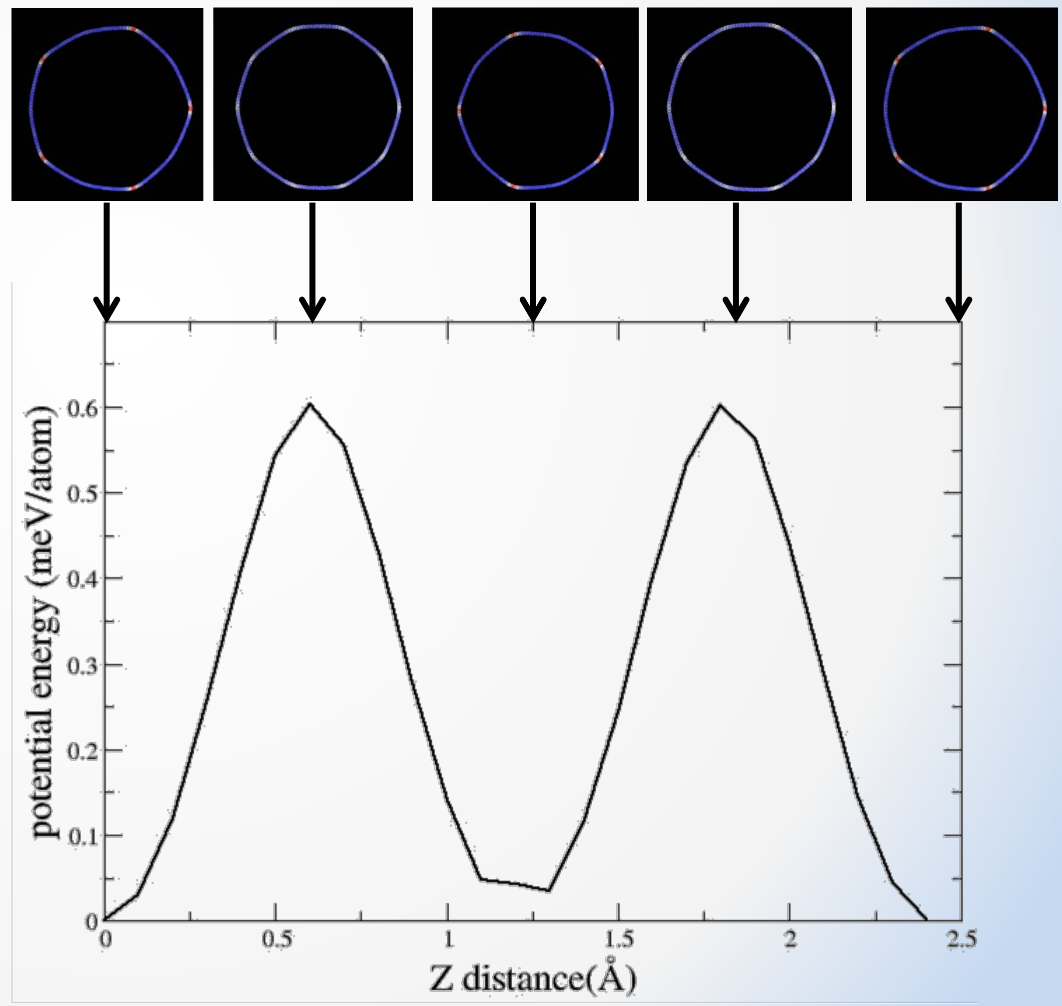


Facet Superstructure Reconfiguration

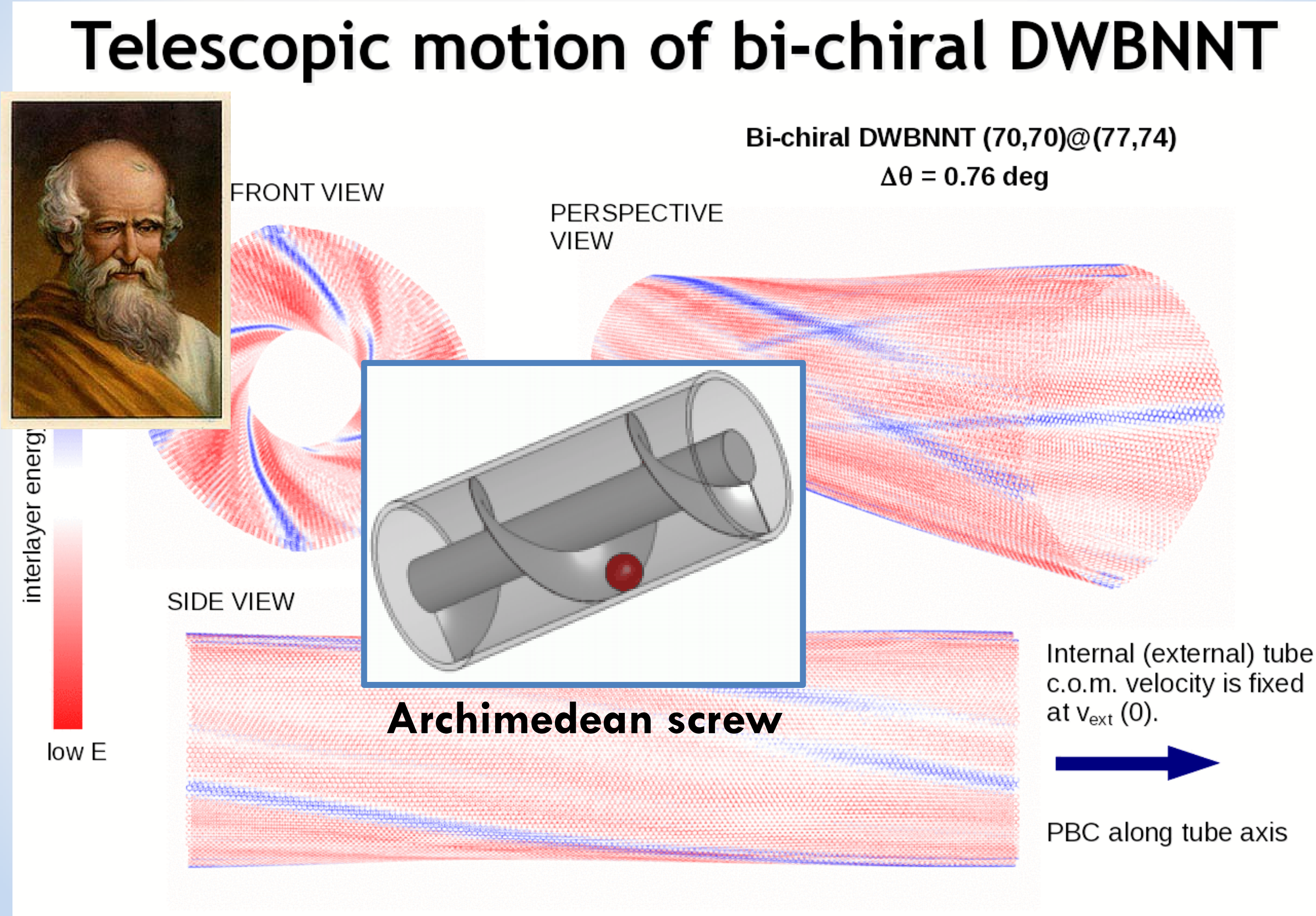
- Inter-wall pullout can cause facet superstructure reconfiguration

AC (75,75)@(80,80) DWCNT

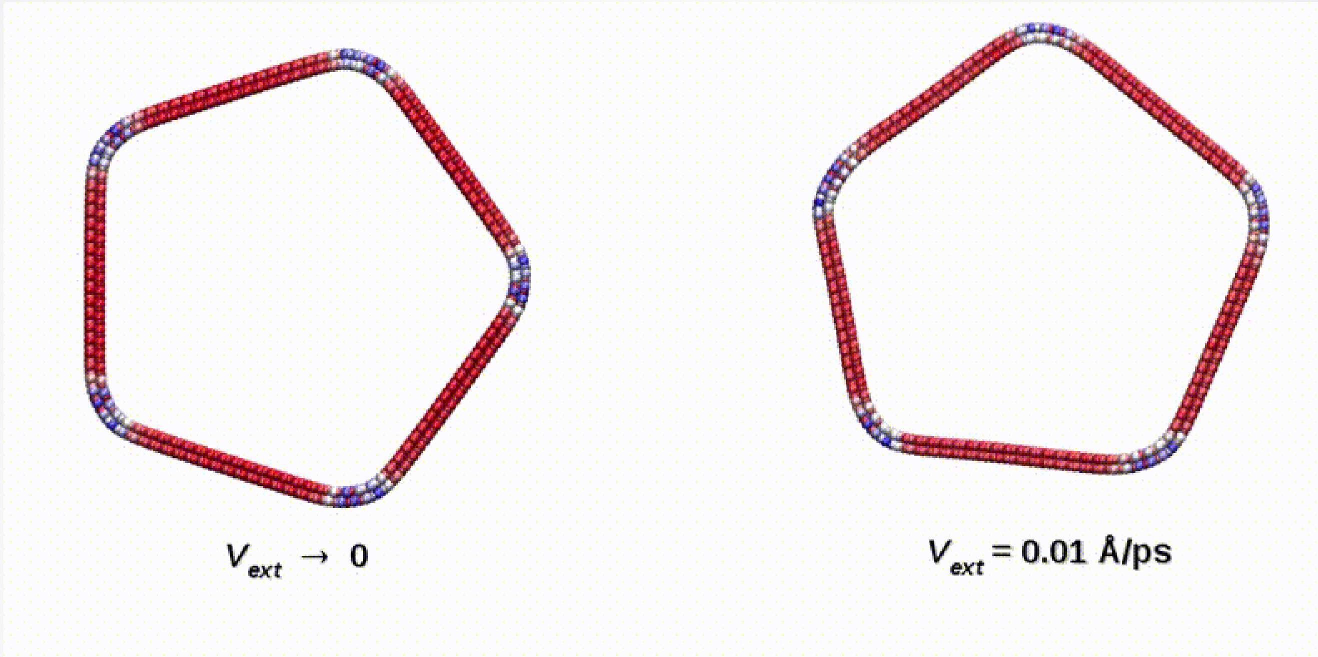




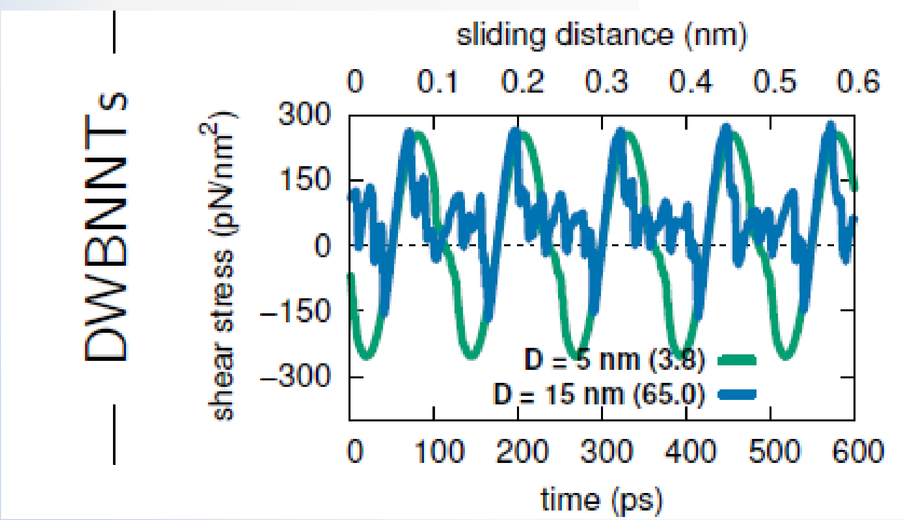
Facet Superstructure Reconfiguration

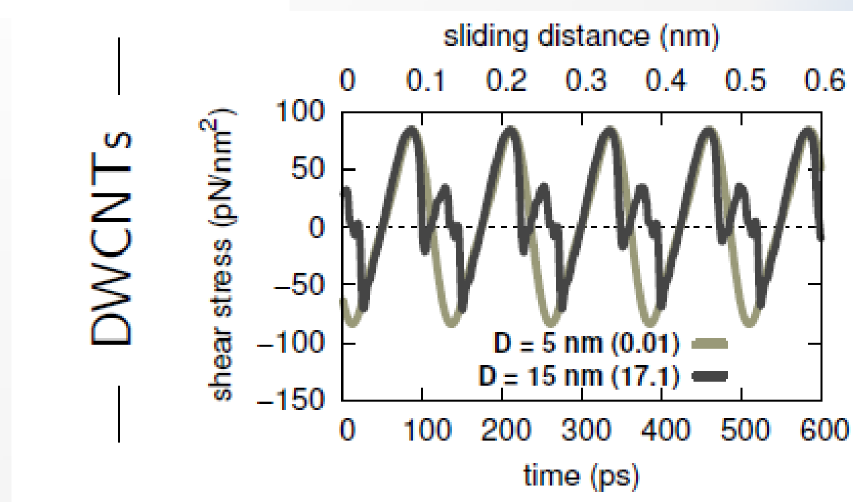


Faceting Induced Friction



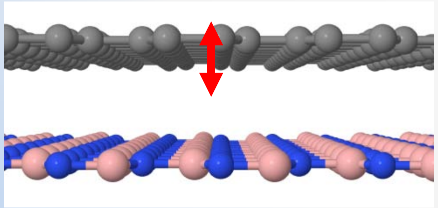
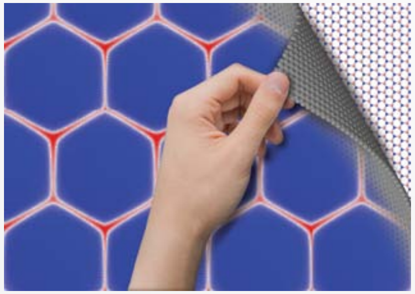
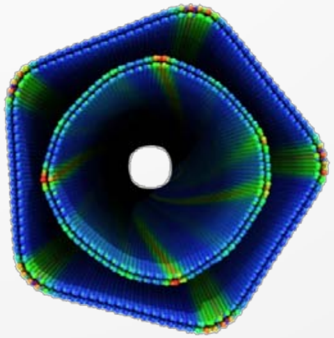
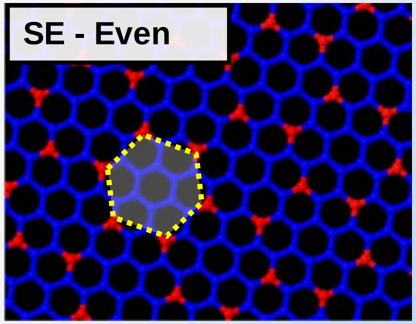
Armchair





Conclusions

- ✓ Dedicated inter-layer force-fields have been developed for *h*-BN and graphene/*h*-BN.
- ✓ Inter-layer registry patterns dictate the super-structure of domain-wall formation in graphene/*h*-BN and faceting in multi-walled nanotubes.
- ✓ These are manifested in their tribological characteristics.
- ✓ Cross-layer transport is also highly dependent on the inter-layer registry.
- ✓ The force-field is transferable to other 2D materials.

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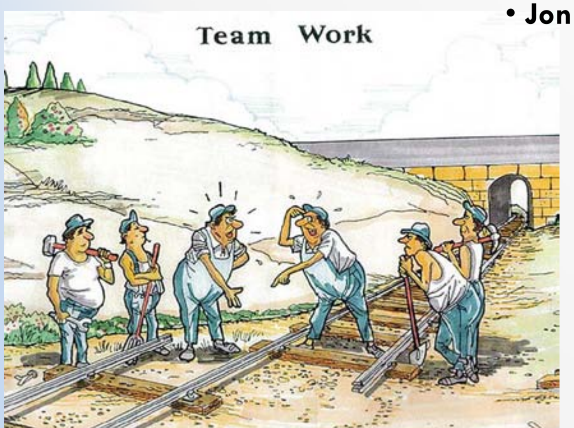

And you

For your attention!