The growth and friction properties of 2D materials

Superlubricity & Intercalation

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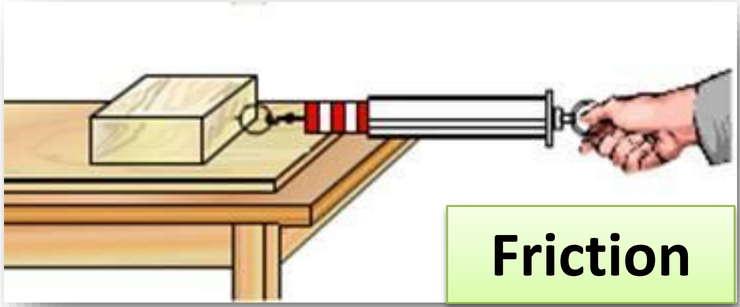
Content

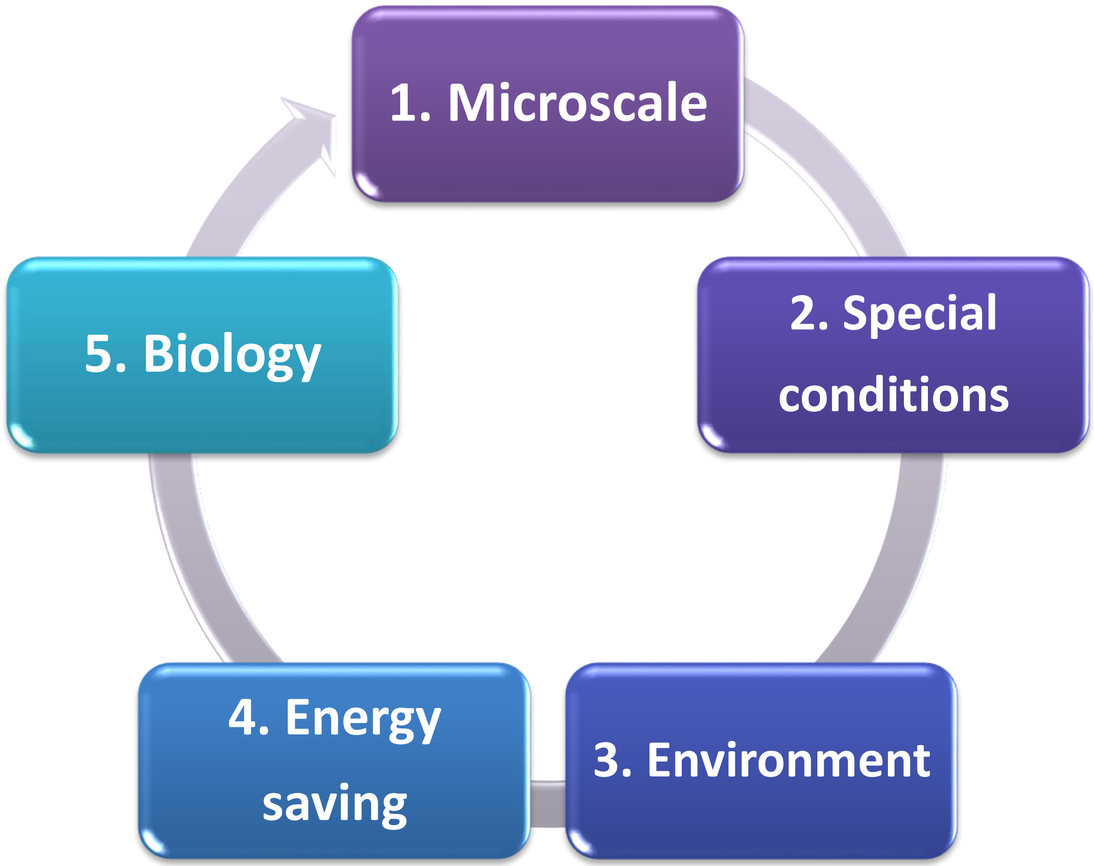
1. Tribology
2. Nanofriction
3. Superlubricity
4. Intercalation

1. Tribology Research content



And other surface engineering technology

1. Tribology Research area



2. Nanofriction Development

1982
- 3D atomic pictures were scanned by STM.

1987
- Friction at nanoscale was measured by the modified AFM (called FFM recently).

1991
- Surface topography at nanoscale was Obtained by AFM.

Why to study on nanofriction?

- To serve for the Micro/nano devices.
- To establish the bridge between macroscale and nanoscale.

2. Nanofriction My research topic

Topic: The growth and friction properties of 2D materials

Key words: Superlubricity & Intercalation

Instruments： FFM & AFM

2D materials: Graphene, MoS_2 and h-BN.

Conductive

Insulative

Semi-conductive

3. Superlubricity Definition & Category

Similar words: Superfluid, Superconductor……

Structrural	Thermo	Dynamic	Static
• **Surface contact:** lateral stiff and incommensurate	• **Critical velocity:** increase with T	• **Excitation switch:** Modulated bias voltages	• **Critical normal load:** stick-slip motion changes into sliding mode.

Intercalation

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[1] A. Socoliuc, et al., *Science*, 313 (2006).

4. Intercalation A "sandwich" system

The research of intercalation

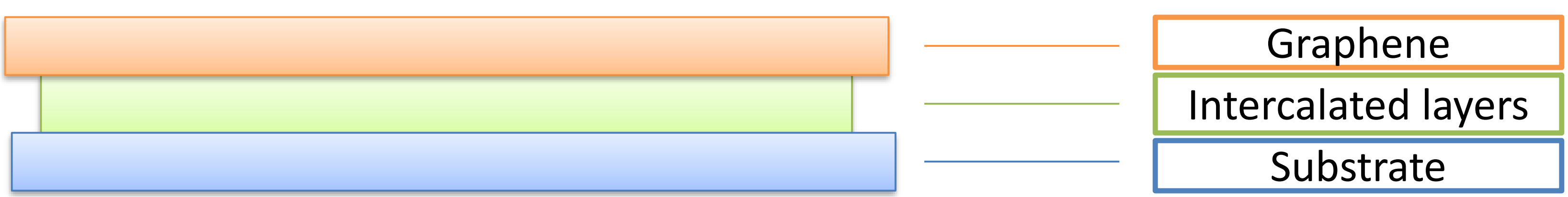
- Devoted to investigation of the electronic structure and physical properties

The theory of intercalation

- Metal atom-aided defect formation and self-healing of C–C bonds at high temperature

The function of intercalation

- The strong interaction has been blocked and the graphene is more nearly free-standing



4. Intercalation Substrate

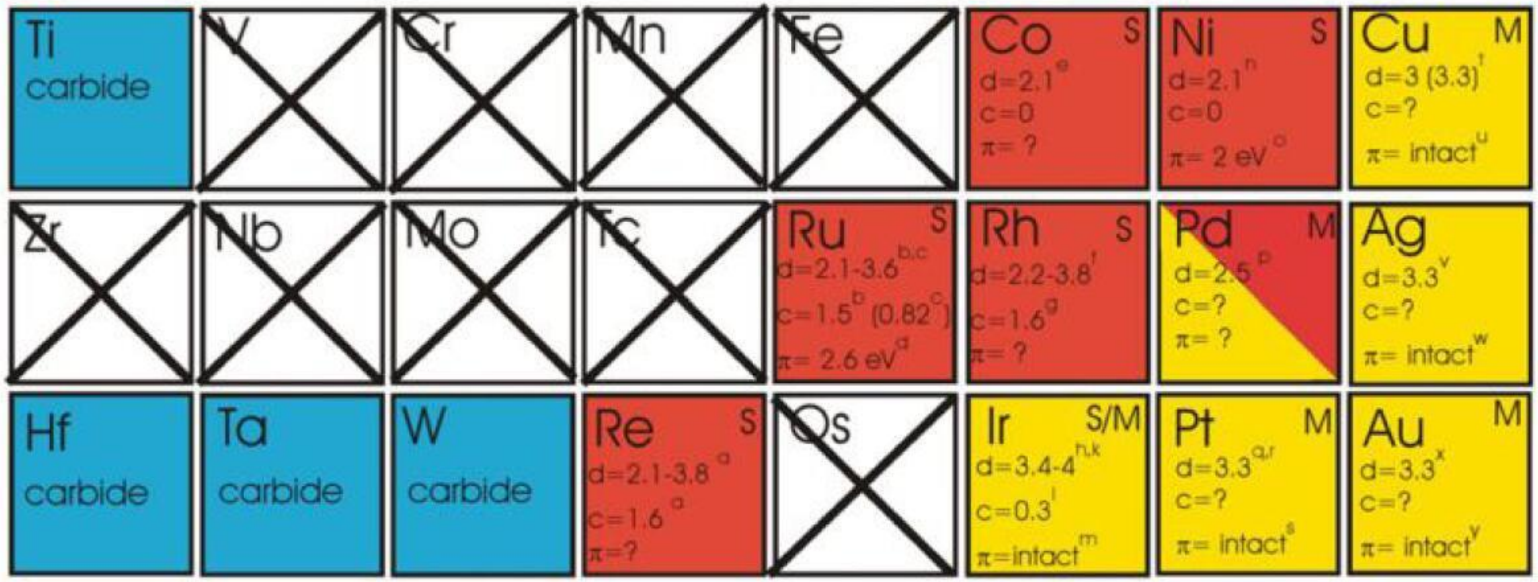


Fig. 1 For the elements labeled in blue, graphene may grow on the bulk-carbides of these elements. Elements in red are characterized as metals that interact strongly with graphene and elements in yellow are those that interact weakly. 'S' or 'M' in the upper right corner of each element-box indicates if graphene forms single or multiple rotational domains.

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[2] M. Batzill, *Surf Sci Report*, 67 (2012).

4. Intercalation Substrate

Table 1 Thermal expansion coefficient of Graphene/Metal

Metal	Gr	Ir	Re	Rh	Pt	Ru	Pd	Co	Ni	Au	Cu	Ag
α ($\times 10^{-6}$ K^{-1})	< 1	6.5	6.6	8.4	9.0	9.4	11.5	12.4	13.0	14.2	18.5	19.5

Table 2 Melting point of metal

Metal	Ag	Cu	Au	Ni	Co	Pd	Pt	Rh	Ru	Ir	Re
$T_{melting}$ (°C)	962	1065	1065	1455	1497	1554	1772	1963	2254	2447	3186

Table 3 Carbon solubilities (atom%) in different transition metals at 1000 °C

Metal	Au	Ag	Cu	Rh	Ir	Ru	Pt	Ni	Co	Re	Pd
C solubility (atom%)	0.01	0.01	0.04	0.89	1.35	1.56	1.76	2.03	3.41	4.39	5.98

Table 4 Graphene–Metal separation

Metal	Ru (111)	Re (0001)	Co (0001)	Ni (111)	Rh (111)	Pd (0001)	Au (111)	Pt (111)	Cu (111)	Ag (111)	Ir (111)
G–M separation (nm)	0.21	0.21	0.21	0.21	0.22	0.25	0.33	0.33	0.33	0.33	0.34

4. Intercalation Substrate — Ir

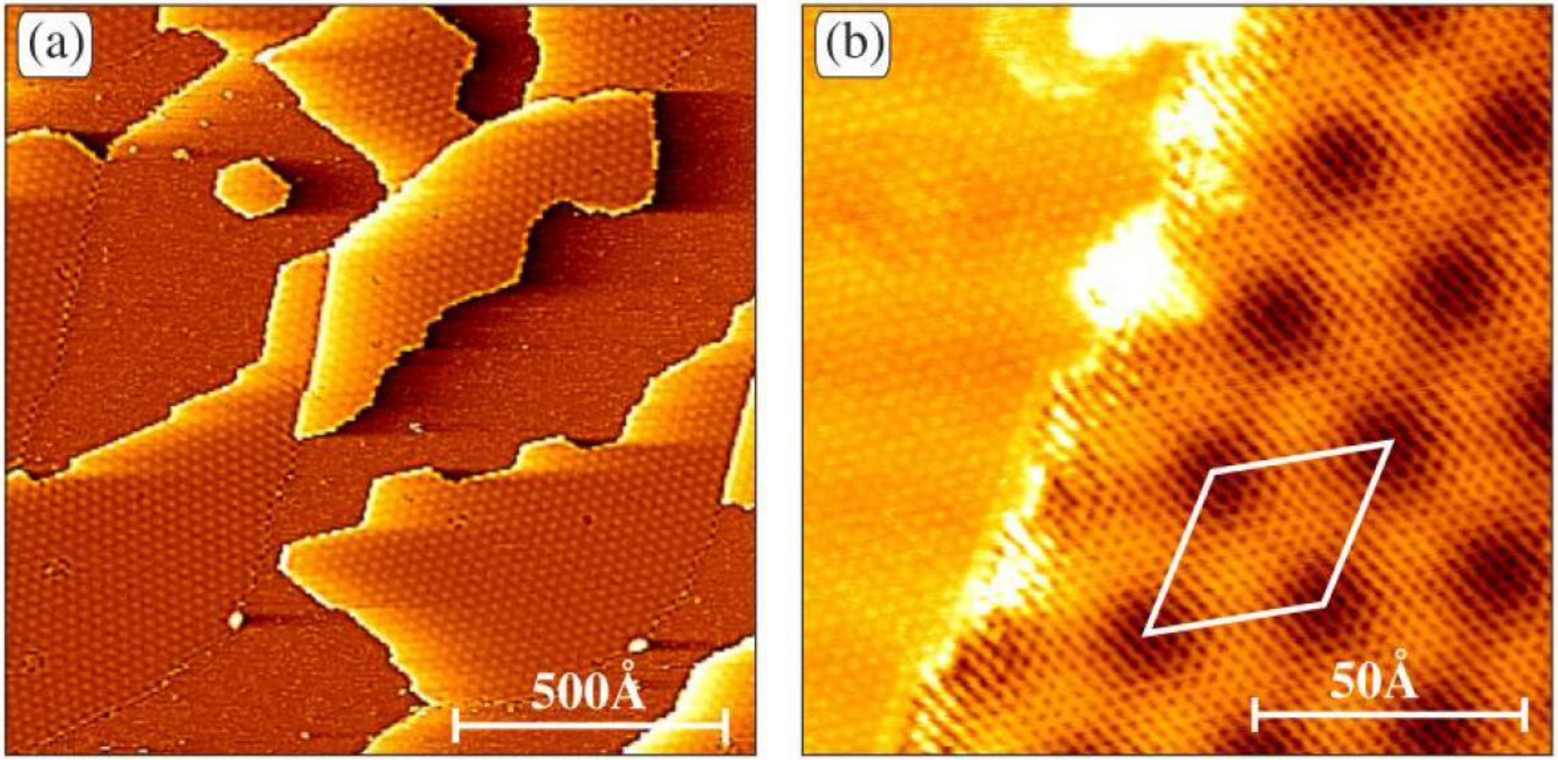

Fig. 8 (a) Graphene on Ir(111). The moiré with its 25.3Å periodicity is clearly visible (1300Å×1300 Å, UT =1.5V and IT =0.5 nA). (b) Attached to an iridium step edge (left) lies a graphene flake (100Å×100 Å, UT =–0.17V and IT =21 nA).

[3] J. Coraux , et al., New J Phys, 11 (2009).

4. Intercalation Intercalated layers

Table 2 The ionization potentials of elements (eV)

H																	He
Li	Be											B	C	N	O	F	Ne
5.40	9.67											8.31	11.3	14.5	13.6	17.4	
Na	Mg											Al	Si	P	S	Cl	Ar
5.15	7.66											5.99	8.16	10.5	10.4	13.0	
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
4.50	6.12	6.57	6.83	6.76	6.78	7.45	7.91	7.89	7.65	7.74	9.41	6.01	7.91	9.83	9.77	11.8	
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
4.18	5.70	6.23	6.64	6.77	7.10	7.29	7.37	7.47	8.35	7.59	9.01	5.79	7.35	8.66	9.02	10.5	
Cs	Ba	Ce	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
3.90	5.22	5.55	6.83	7.90	7.99	7.89	8.72	9.13	9.03	9.24	10.4	6.12	7.43	7.30	8.43	9.24	

Low ionization potential

High ionization potential

Basic principle of Intercalation:

Atoms with low IP (Cs, K, Ba,...) form a **monolayer film** of the intercalate under the graphene layer, whereas atoms with high IP (Pt, Au, Si,...) form a **thick multilayer film**.

[4] A. Ya, et al., Phys Uspekhi, 36 (1993).

4. Intercalation

Intercalated layers

Annealing Temperature for Ir(111) intercalated system

Intercalation	Annealing T	Remarks
Grphene / Ba / Ir(111)	600 °C, 30%; 1300 °C, 50%	
Grphene / Pt / Ir(111)	700 °C, 100%	
Grphene / Si / Ir(111)	700°C, ~100%	Two part (thick)
Grphene / C / Ir(111)	<427 °C, × >727 °C, up-down layers	
Grphene / Ag / Ir(111)	<627 °C, thick film >627 °C, desorbe	×
Grphene / Al / Ir(111)	~27 °C, ×; ~900 °C, √	
Grphene / Ir / Ir(111)	800~1000 °C	
Grphene / Cu / Ir(111)	900 °C	
Grphene / C_{60} / Ir(111)	Monolayer, ×; Thick layers, √	Different structures

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[5] S. Mikhailov, Published by InTech, 2011.

4. Intercalation

Intercalated layers — C_{60}

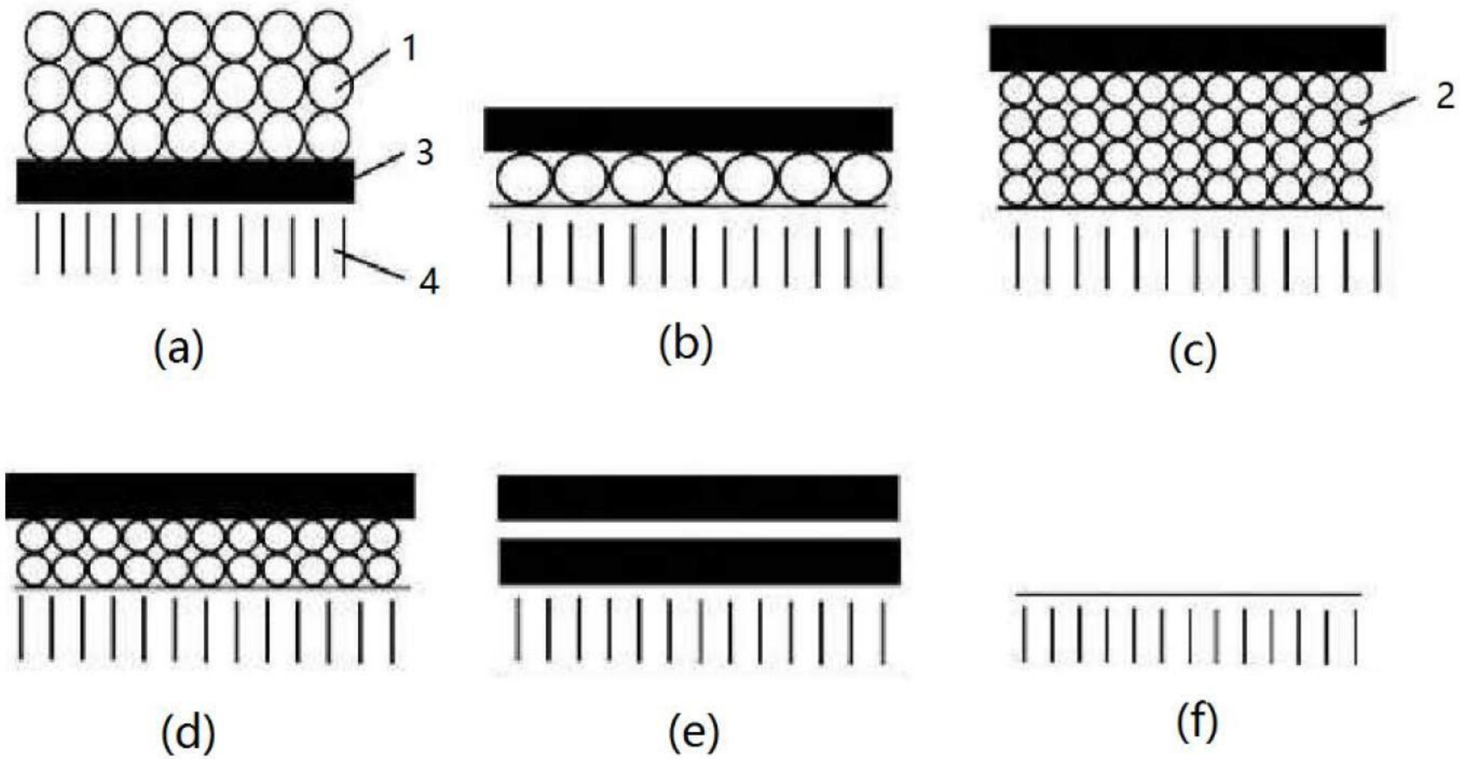

Fig. 5 Schematic for intercalation of the graphene layer on Ir(111) by molecular C_{60}: 1) deposited multilayer film of molecular C_{60}; 2) single carbon atom; 3) graphene layer; 4) iridium substrate. Temperature: (a) 27°C; (b) 527°C, (c) 927°C; (d) 1327°C; (e) 1627°C; (f) 1927°C.

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[5] S. Mikhailov, Published by InTech, 2011.

Thank you !

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