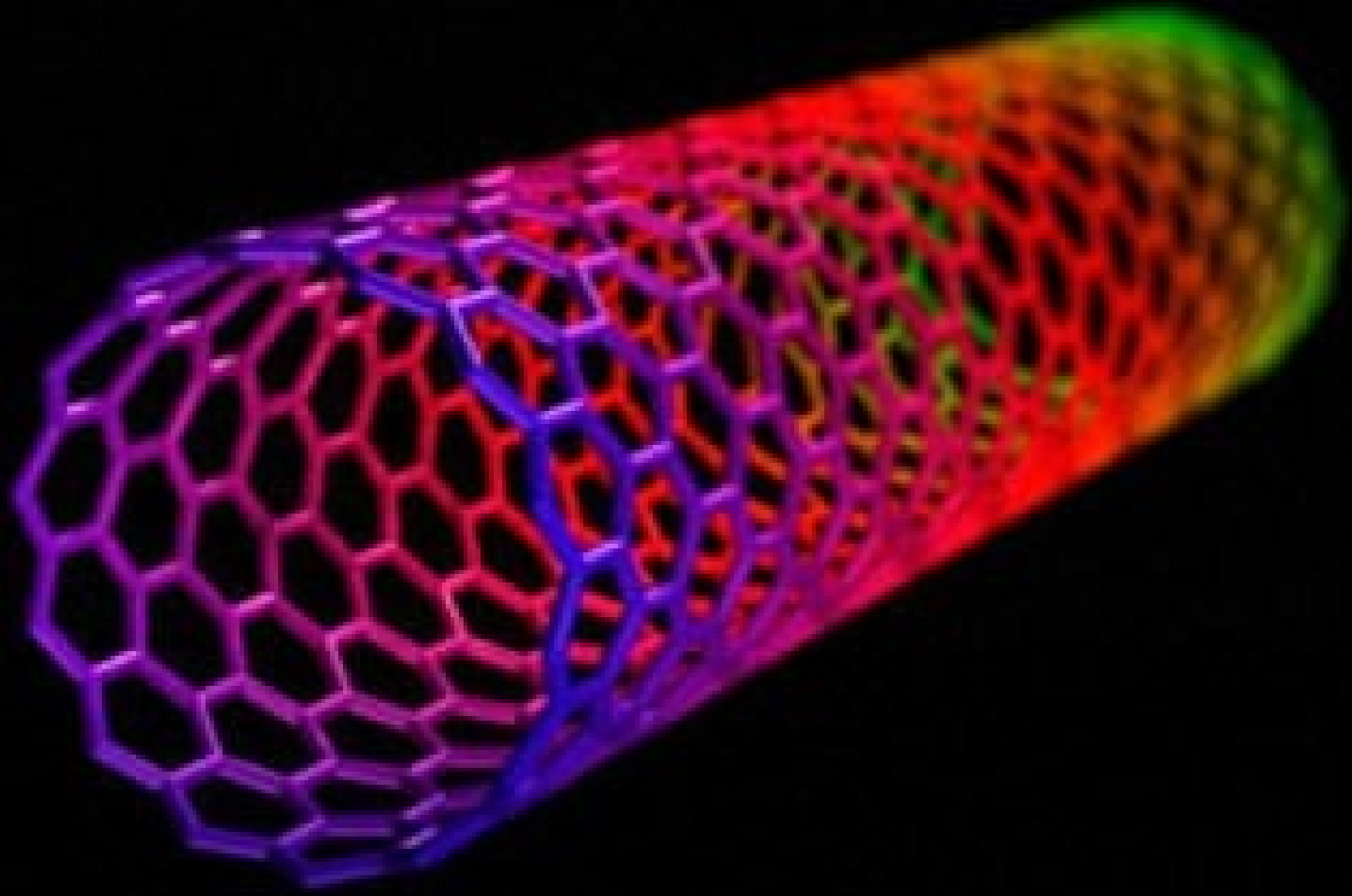


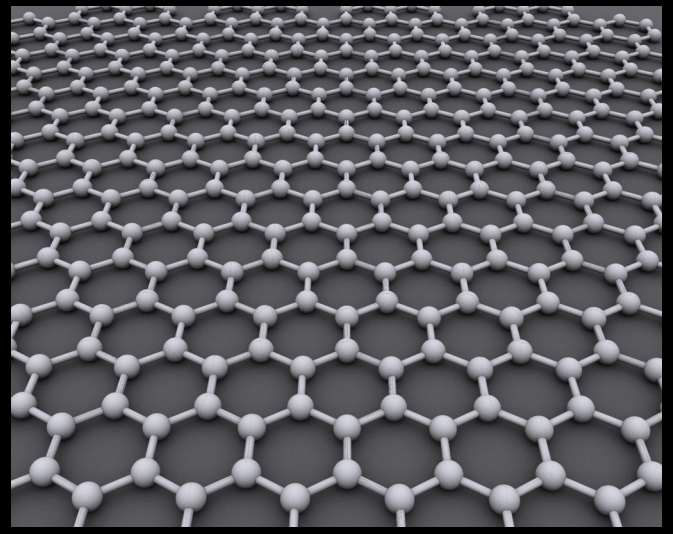
Carbon Nanotubes

Jugraj Singh (s3746143)

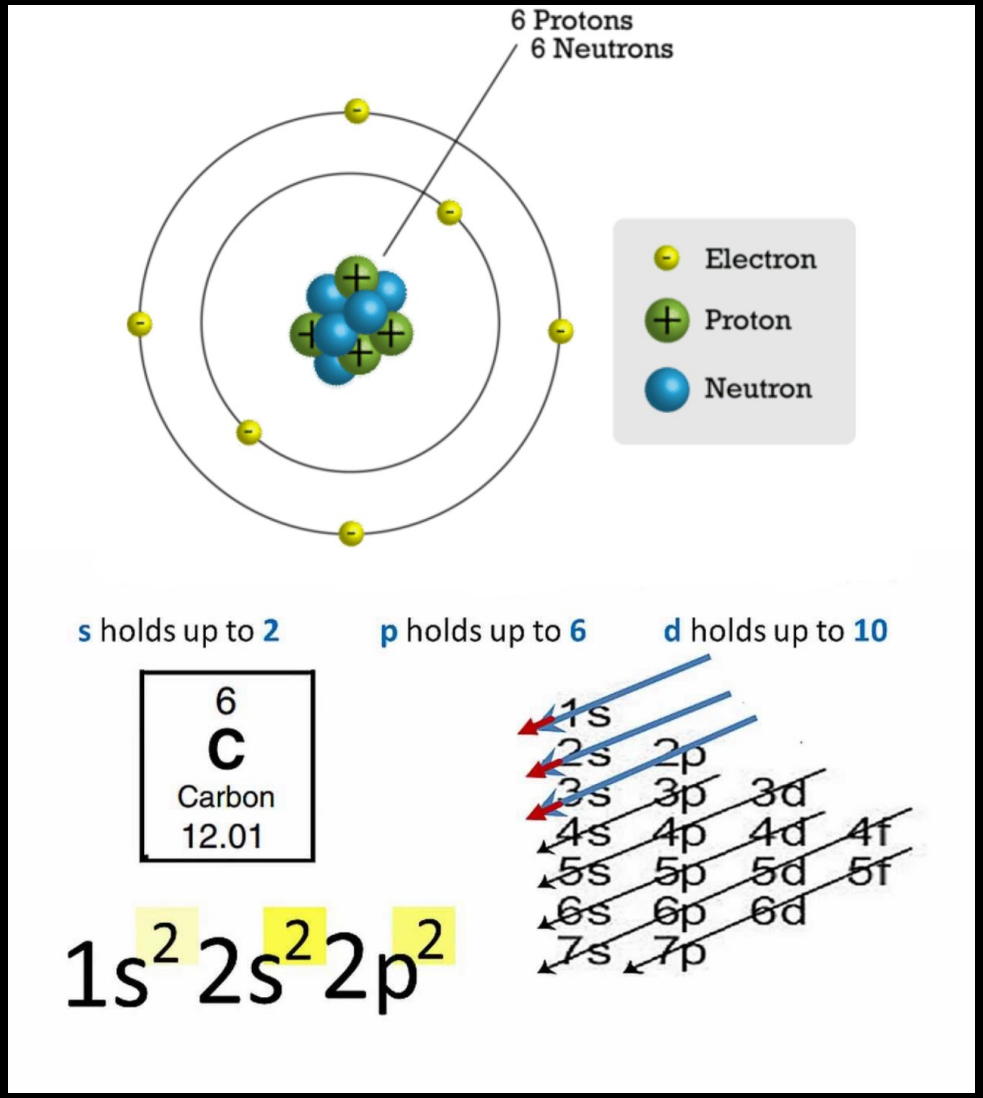
Tristan Voors (s2219220)

Wat is graphene

- Atomic number Z = 6
- Ground-state configuration $1s^2 2s^2 2p^2$
- Sp^2 hybridization



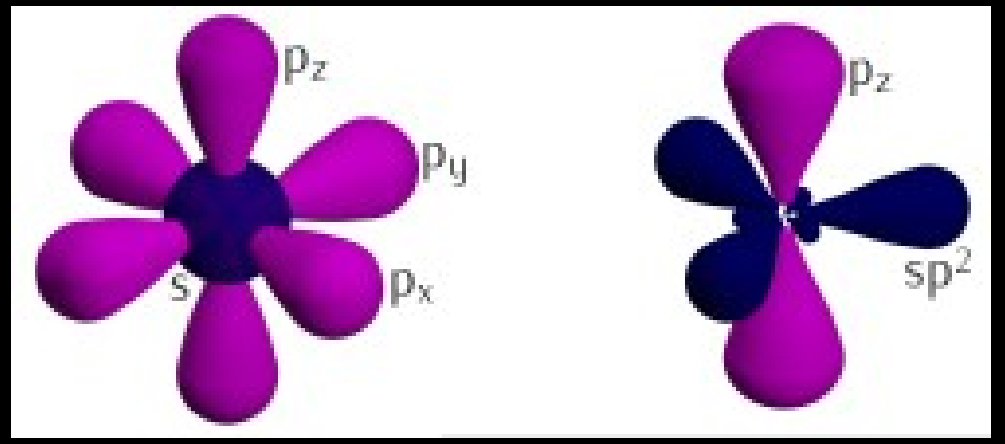
Graphene: A honeycomb structure of carbon atoms [1]



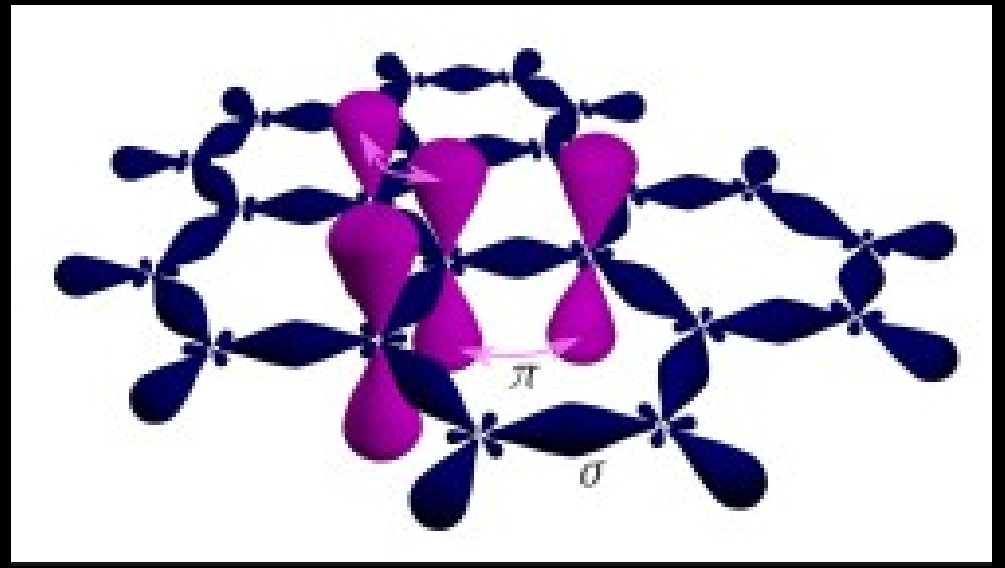
Atomic structure of carbon [2]

Bonding in graphene

- Promoted configuration $1s^2 2s^1 2p^3$
- 3 sp^2 orbitals form 3 σ bonds
- 120° bond angles give a planar structure
- 1 unhybridized p_z orbital remains
- p_z orbitals π bonds with neighbouring p_z orbitals



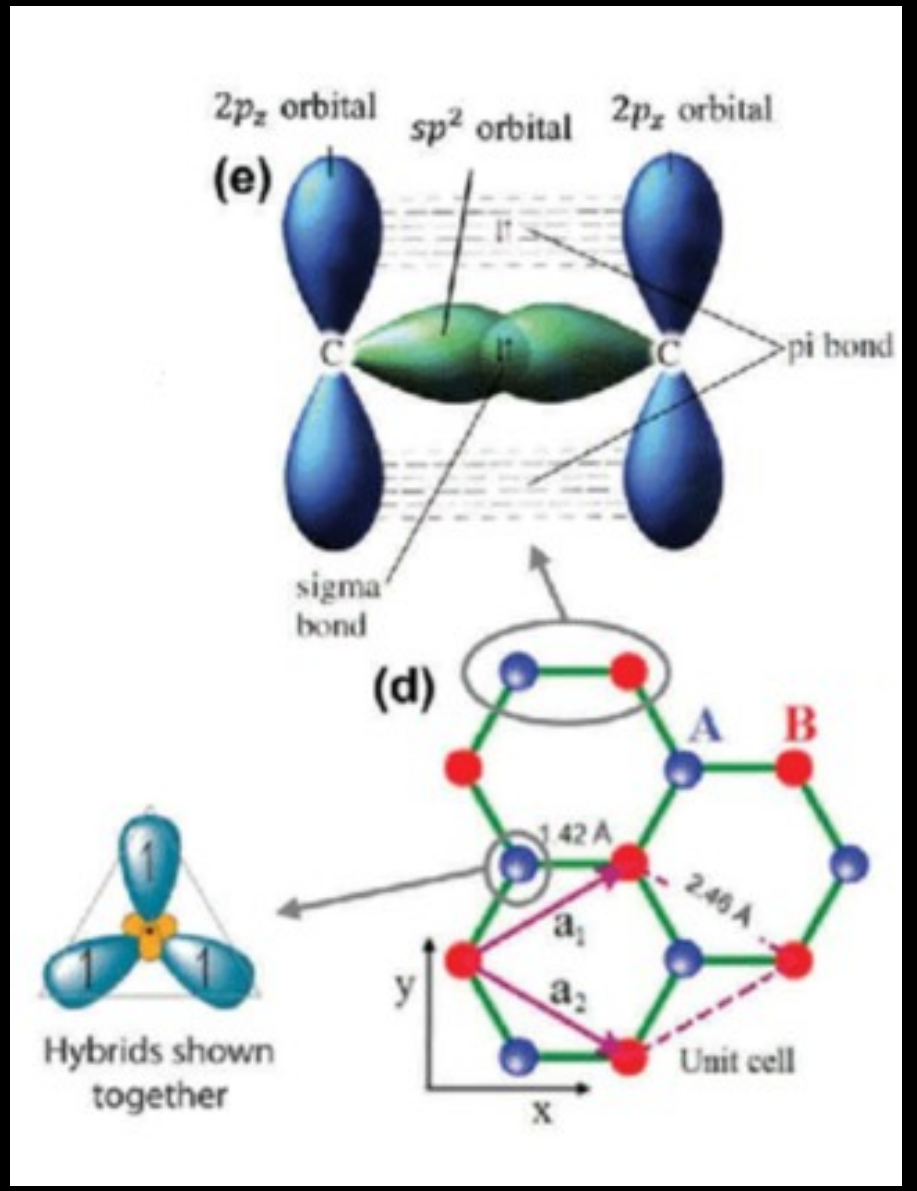
Carbon orbitals form sp^2 orbitals through hybridization [1]



σ and π bonds in graphene [1]

Crystal structure

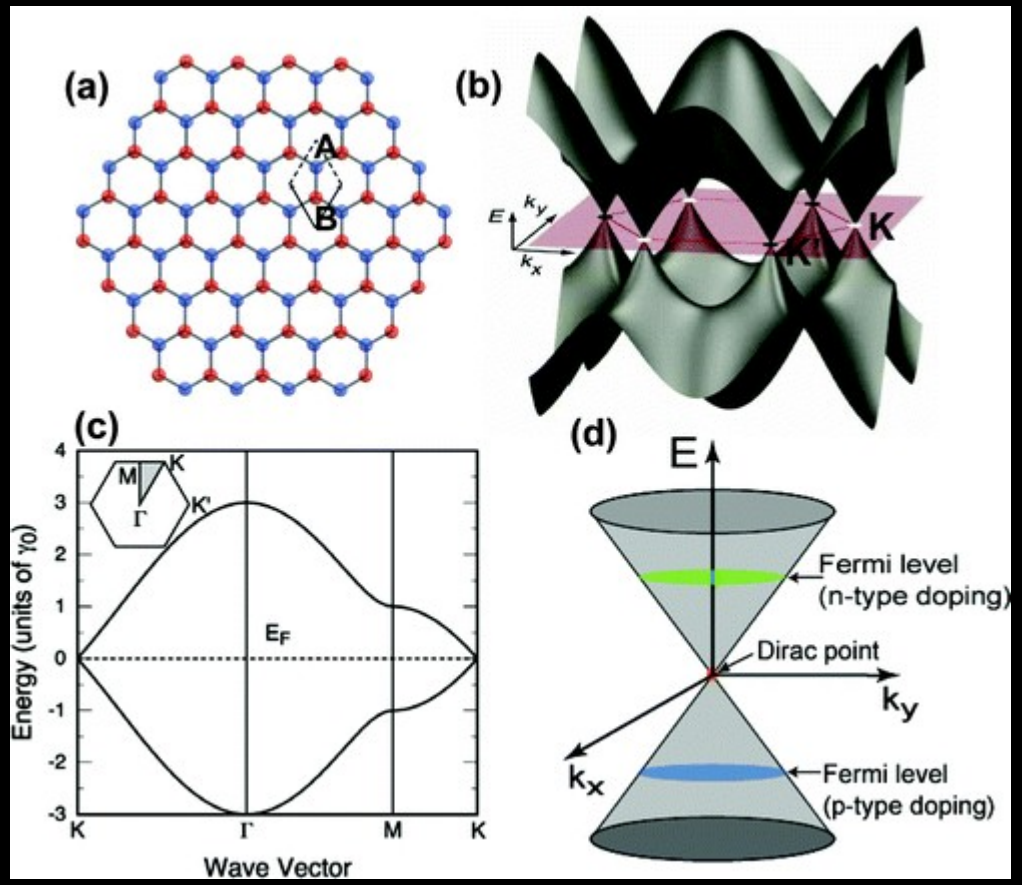
- 2D hexagonal Bravais lattice
- 2-atom basis: A and B
- Primitive vectors a_1 and a_2
- Bond length of 1.42 Å
- Lattice constant of 2.46 Å



Graphene crystal structure [3]

Electrical properties

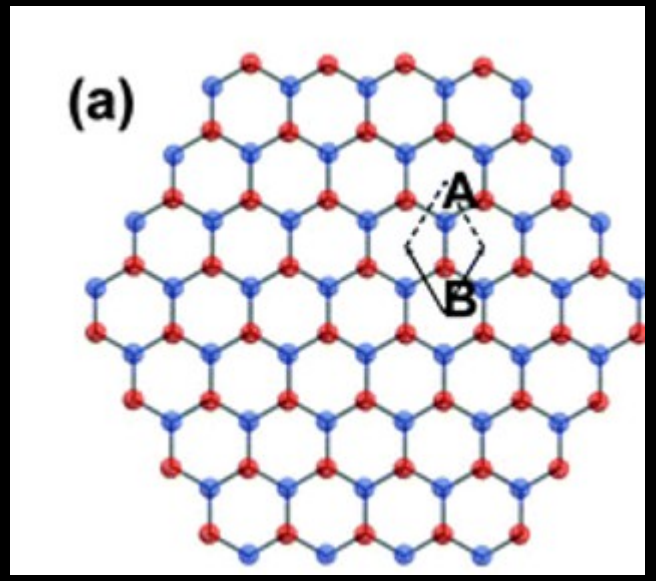
- Delocalized π bond electrons
- Conduction and valence band meet at K and K’
- Dirac point with no band gap
- Graphene behaves as semimetal
- Electron and hole conduction
- Variable carrier concentration
- High mobility
- Conductivity: $\sigma = nq\mu$



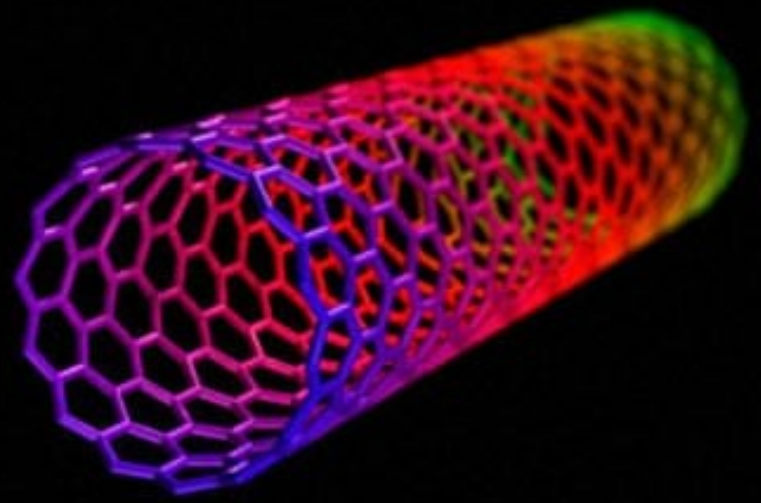
(a) Graphene structure; (b) Graphene valence and conduction band Structure (c) E-k of graphene (d) Energy band structure at K and K′ (Dirac point) [4]

Carbon nano tubes

- $\mathbf{C}_h = n\mathbf{a}_1 + m\mathbf{a}_2$
- Quantized k-values determine if it travels through a Dirac point
- This determines band gap and behaviour as metal or semiconductor



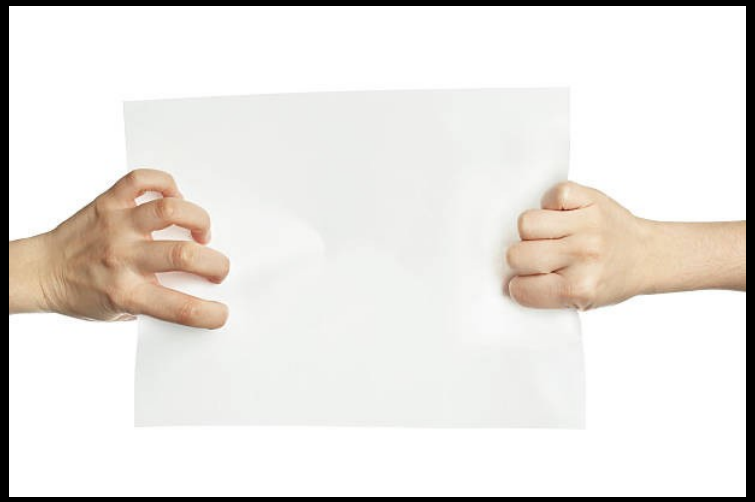
Graphene lattice structure [4]



Carbon nanotube [5]

Mechanical properties

- Extremely strong and stiff
- Elastic Modulus 1 TPa, 5x stronger than steel
- sp2 covalent C-C bonds
- High Tensile strength
- Anisotropic, low elastic modulus radially



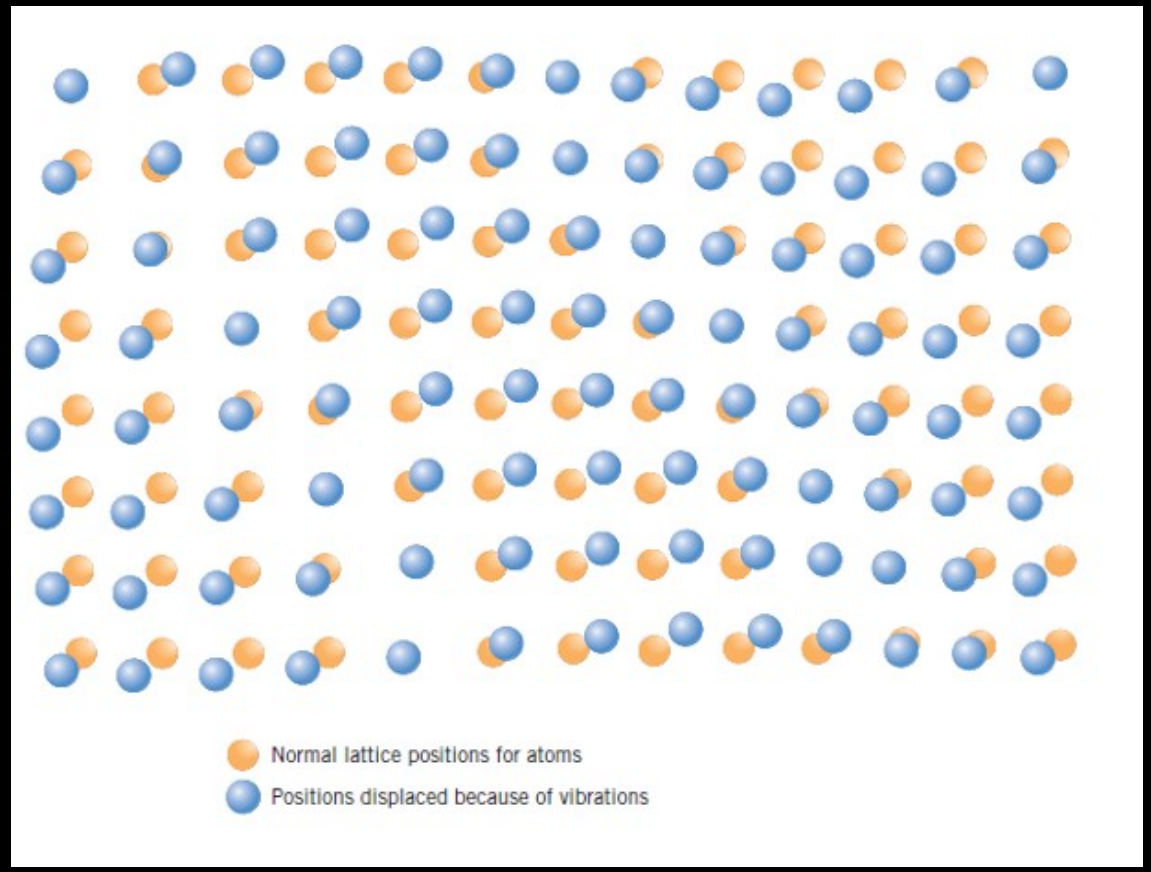


	Modulus of Elasticity		*Shear Modulus*		
Metal Alloy	*GPa*	*10^6 psi*	*GPa*	*10^6 psi*	*Poisson's Ratio*
Aluminum	68	10	25	3.6	0.33
Brass	97	14	37	5.4	0.34
Copper	110	16	46	6.7	0.34
Magnesium	45	6.5	17	2.5	0.29
Nickel	207	30	76	11.0	0.31
Steel	207	30	83	12.0	0.30
Titanium	107	15.5	45	6.5	0.34
Tungsten	407	59	160	23.2	0.28

Elastic Modulus' of different metal alloys [6]

Thermal Properties

- Phonons
  - Covalent C-C bonds, easier transport
  - No electron contribution to thermal conductivity
- Individual CNT (ideal case)
  - High thermal conductivity
  - 3000 to 6000 $Wm^{-1}K^{-1}$
- CNT bundle
  - Lowers thermal conductivity
  - Defects, impurities
  - Structure has high impact



Lattice wave generation in a crystal by means of atomic Vibrations [7]

Surface effects

- Surface atoms are not bonded to maximum # of neighbors
  - Higher energy state, rise in surface energy
  - Adsorption
- Surface to Volume ratio
- Cylindrical S-V ratio $\frac{A}{V} = \frac{2}{h} + \frac{2}{r}, \quad h \gg r \ \rightarrow \frac{2}{r}$
  - As r approaches nanoscale, very high ratio
  - Increased adsorption and greater surface effects
  - Defects of surface scatter phonons and electrons → reduced thermal and electrical transport (especially in single walled CNTs)

Fabrication

- Synthesis
  - Arc Discharge
    - DC arc discharge between two graphite electrodes
    - High energy consumption, not well scalable
  - Laser ablation
    - Pulsing laser vaporizing graphite target
    - High cost, low production rate
  - CVD
    - Industry standard, cost effective, scalable
      - Hydro carbon → Decomposition → C diffusion → C precipitation → CNT

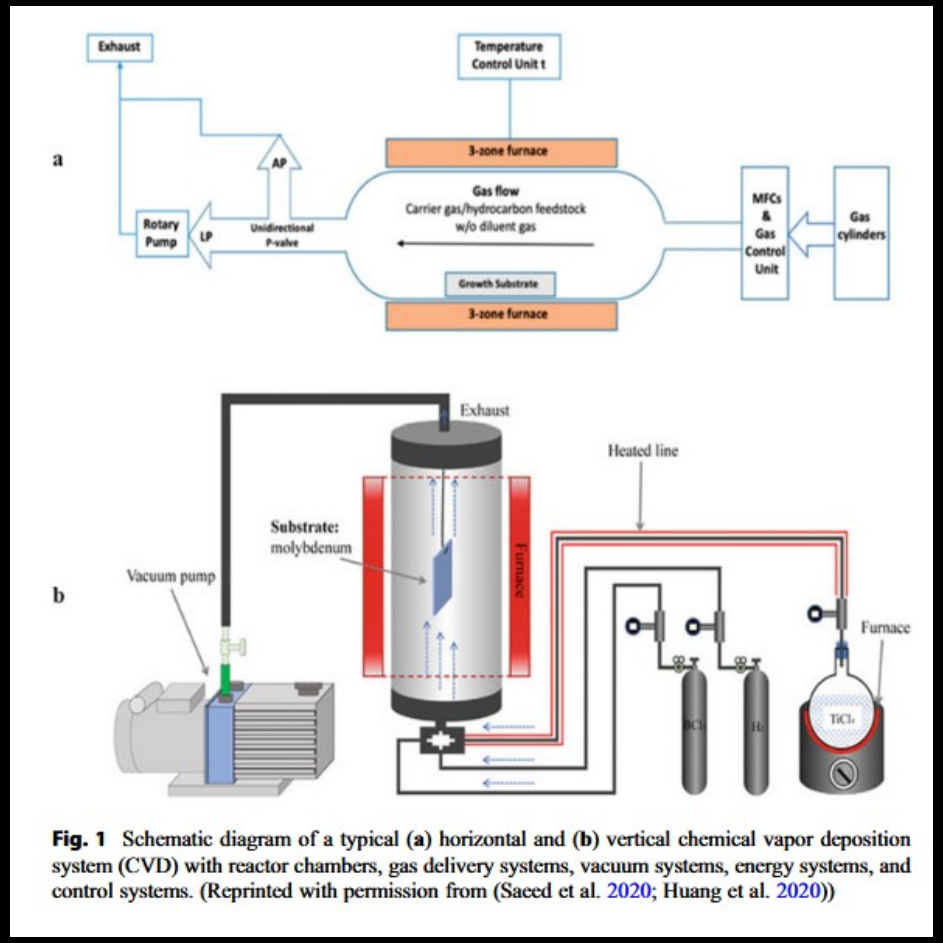
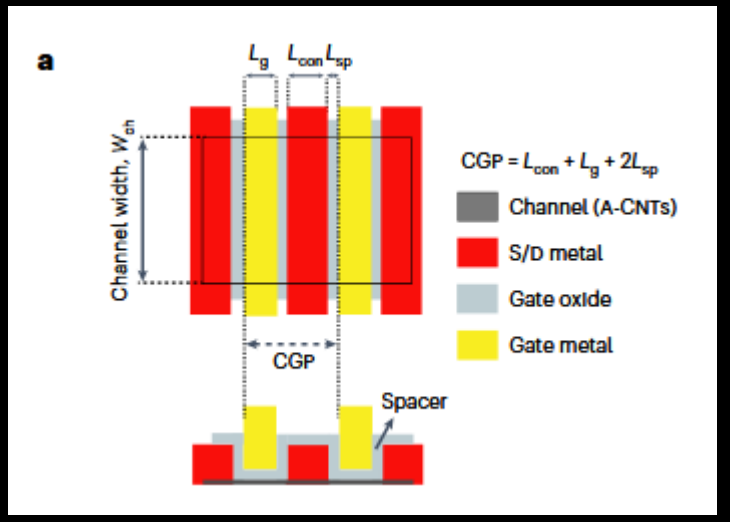


Fig. 1 Schematic diagram of a typical (**a**) horizontal and (**b**) vertical chemical vapor deposition system (CVD) with reactor chambers, gas delivery systems, vacuum systems, energy systems, and control systems. (Reprinted with permission from (Saeed et al. 2020; Huang et al. 2020))

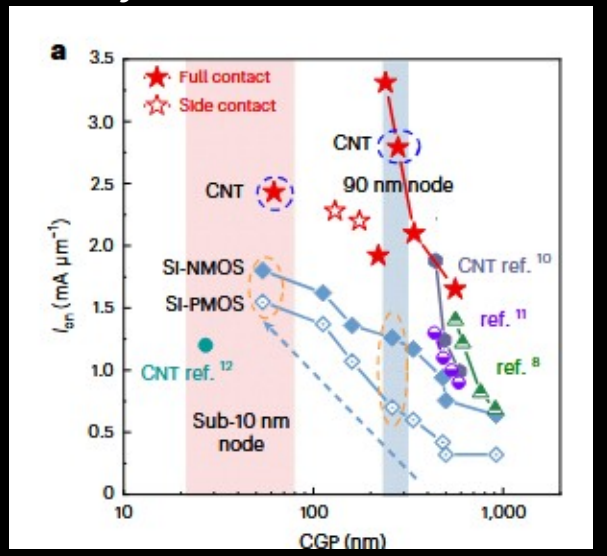
CVD System [8]

Applications

- Recent paper, use in energy efficient transistors (CNT FET)
  - 1D CNT channel, high carrier mobility
  - Scaling potential
  - Demonstrated at corresponding 10nm Si CMOS node, Lin et al. (2023)
  - 55nm Contacted Gate Pitch CNT FET, higher Fermi velocity and carrier mobility
  - HfO_2 high k dielectric and metal gates
  - Lower energy consumption potential
  - No More Moore!
  - But,
    - Challenging manufacturing and integration
    - CNT placement, alignment control is difficult
    - Si CMOS → industry standard for now



Schematic CGP scaled CNT FET [9]



Comparison I_{ON} for various CGP values aligned CNT FETs to silicon technology [9]

References

- [1] Wikipedia contributors. *Graphene*. Wikipedia.
  https://en.wikipedia.org/wiki/Graphene
  Accessed 5 Oct. 2026.

- [2] East Carbon. *Carbon Atom Structure*. East Carbon.
  https://www.eastcarb.com/carbon-atom-structure/
  Accessed 5 Oct. 2026.

- [3] Nadtochiy, A., Gorb, A. M., Gorelov, B. M., Polovina, O., & Korotchenkov, O. *Graphene and Its Derivatives: Concise Review of Some Basic Fundamentals*. Springer.
  https://link.springer.com/chapter/10.1007/978-981-97-2792-6_2
  Accessed 5 Oct. 2026.

- [4] Vasudevan, A., Shvalya, V., Zidanšek, A., & Cvelbar, U. *Tailoring electrical conductivity of two dimensional nanomaterials using plasma for edge electronics: A mini review*.
  https://www.researchgate.net/publication/332381528_Tailoring_electrical_conductivity_of_two_dimensional_nanomaterials_using_plasma_for_edge_electronics_A_mini_review
  Accessed 5 Oct. 2026.

- [5] Becker, A., & Kollmann, L. *Carbon nanotubes: wonder material*. The Guardian.
  https://www.theguardian.com/nanotechnology-world/carbon-nanotubes-wonder-material
  Accessed 5 Oct. 2026.

- [6] Noor Hussein Dhaher, *MATERIALS SCIENCE AND ENGINEERING,*
  https://www.researchgate.net/publication/334465619_MATERIALS_SCIENCE_AND_ENGINEERING
  Accessed 5 Oct. 2026

- [7] William D. Callister, David G. Rethwisch, *Materials Science And Engineering 6th ed.*,
  Accessed on 5 Oct. 2026

- [8] Jiji Abraham, Sabu Thomas, Nandakumar Kalarikkal, *Handbook of Carbon Nanotubes*,
  https://link.springer.com/referencework/10.1007/978-3-030-91346-5
  Accessed on 5 Oct. 2026

- [9] Yanxia Lin, Yu Cao, Sujuan Ding, Panpan Zhang, Lin Xu, Chenchen Liu, Qianlan Hu, Chuanhong Jin, Lian-Mao Peng, Zhiyong Zhang, *Scaling aligned carbon nanotube transistors to a sub-10 nm node*,
  https://doi.org/10.1038/s41928-023-00983-3
  Accessed on 5 Oct. 2026