INVESTIGATING THE INTERACTION OF BIOMOLECULAR SYSTMES WITH GRAPHENE-LIKE MATERIALS

M.TECH PROJECT

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AND
MATERIALS SCIENCE

CONTENTS

BACKGROUND AND MOTIVATION

- Given it's high surface area, biocompatibility, adjustable layer numbers and dimension and surface chemistry, Graphene is being used for biomedical research.

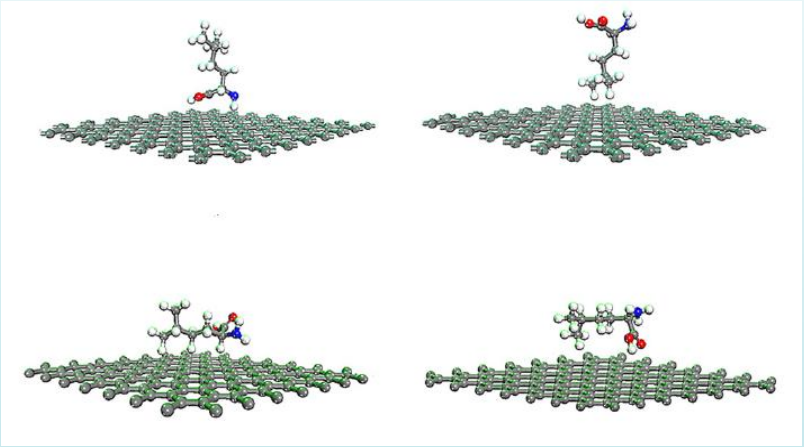


Fig. :L-Leucine interacting with graphene surface in four different. (Qin et. al)

- Valine which is an essential Amino Acid, is important for biological processes of the body and deficiency of it may lead to various ailments.

- Thus, having known the importance of understanding such interactions, we venture into theoretical study of Valine interactions with Graphene and Modified Graphene.

TWO DIMENSIONAL(2-D) MATERIALS

- The 2-D materials field sprouted with the successful synthesis of Graphene by Novoselov, Geim, and co-workers.
- Their unique physical, electronic, optical, and chemical properties as well as the scope of new applications arising from these properties have captivated researchers.

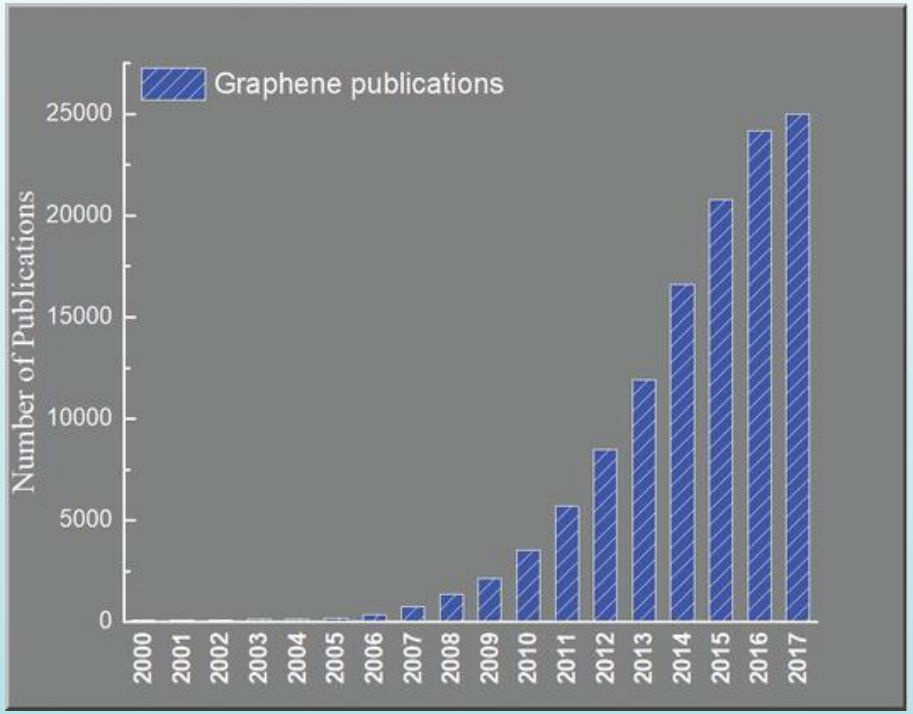


Fig.: Increase in research publications related to Graphene.(source: Google Image)

Fig.: Andre Geim(left) and Novoselov(right).(source: Google Image)

- Their high specific surface area motivates their use in surface-sensitive applications, such as adsorption, catalysis and sensing.

GRAPHENE : THE WONDER MATERIAL

- *Graphene is the name given to sp^2-hybridized carbon atoms arranged in planar sheet and tightly packed in 2D honeycomb lattice.*
- Owing to it's long-range π-conjugation, graphene shows extraordinary thermal, mechanical and electrical properties.

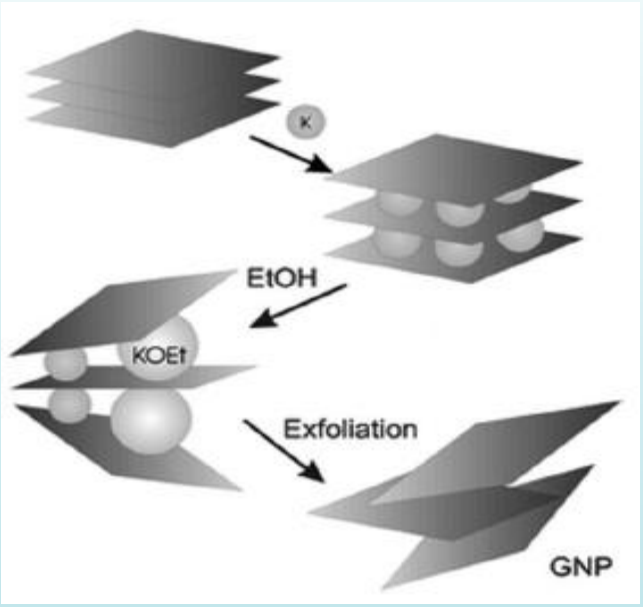


Fig.: Schematic diagram showing the intercalation and exfoliation process to produce thin slabs of graphite.(Wei *et al.*)

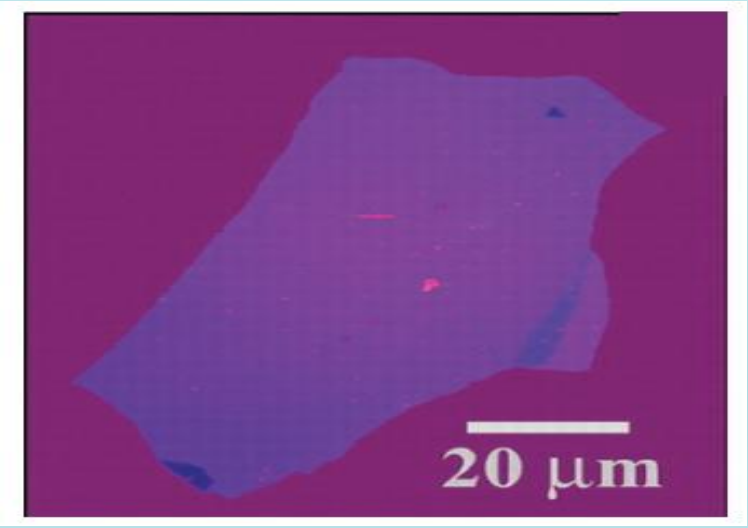


Fig. Single layer graphene was first observed by (Geim et. al.)

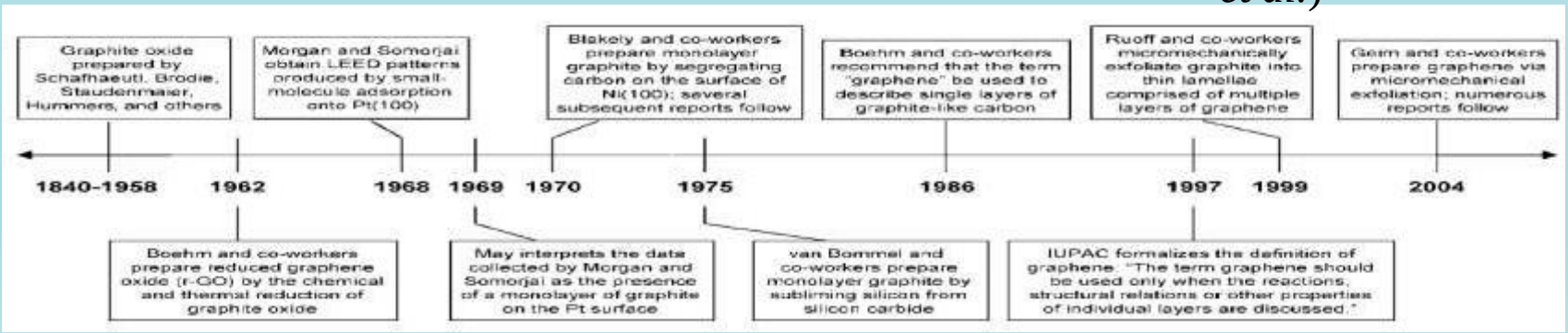


Fig. : Timeline of selected events in the history of the preparation, isolation, and characterization of graphene. (Wei *et al.*)

- C atoms in bi-layer and few-layer Graphene can be stacked in different ways.

- The band-overlap in two conical points (K and K´) in the Brillouin zone of Single-layer graphene(SLG) puts forth an unique electronic structure.

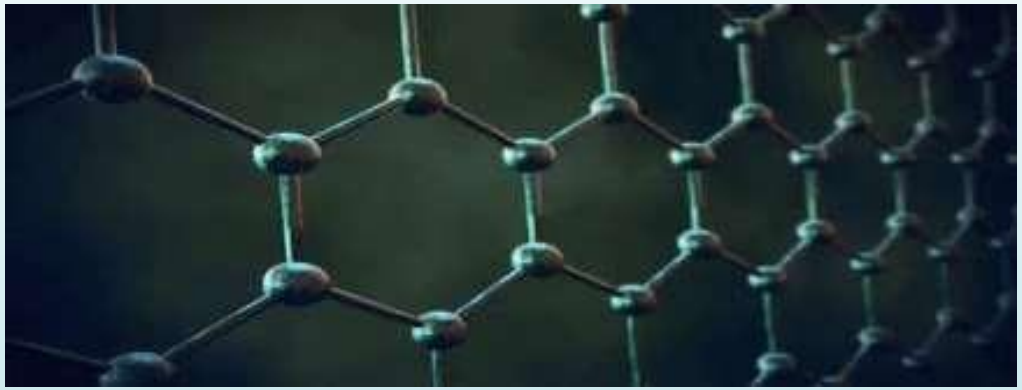


Fig. 2D Hexagonal Structure of Graphene
(Source: Google)

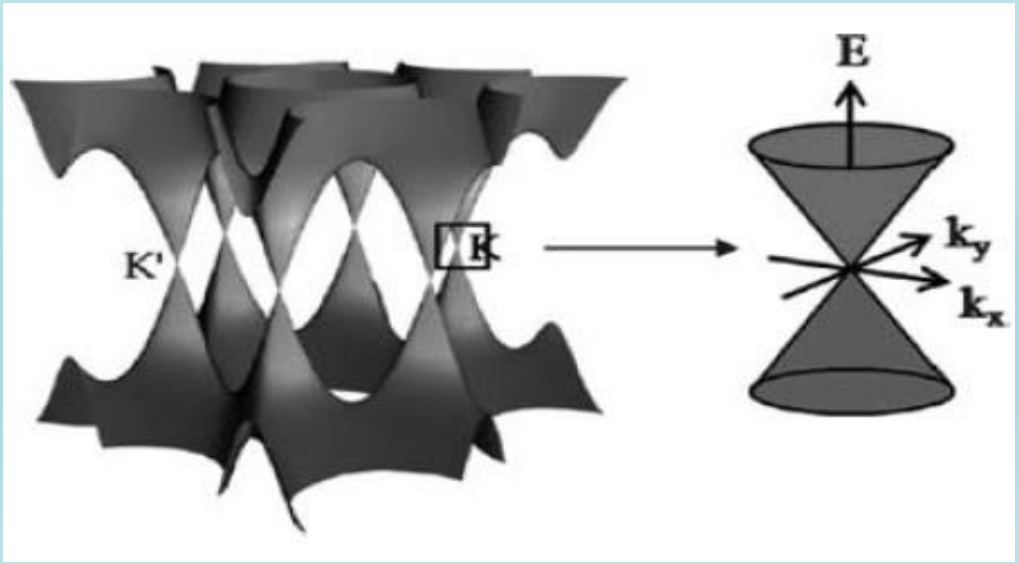


Fig. Band Structure of Graphene (Conrad et. al.)

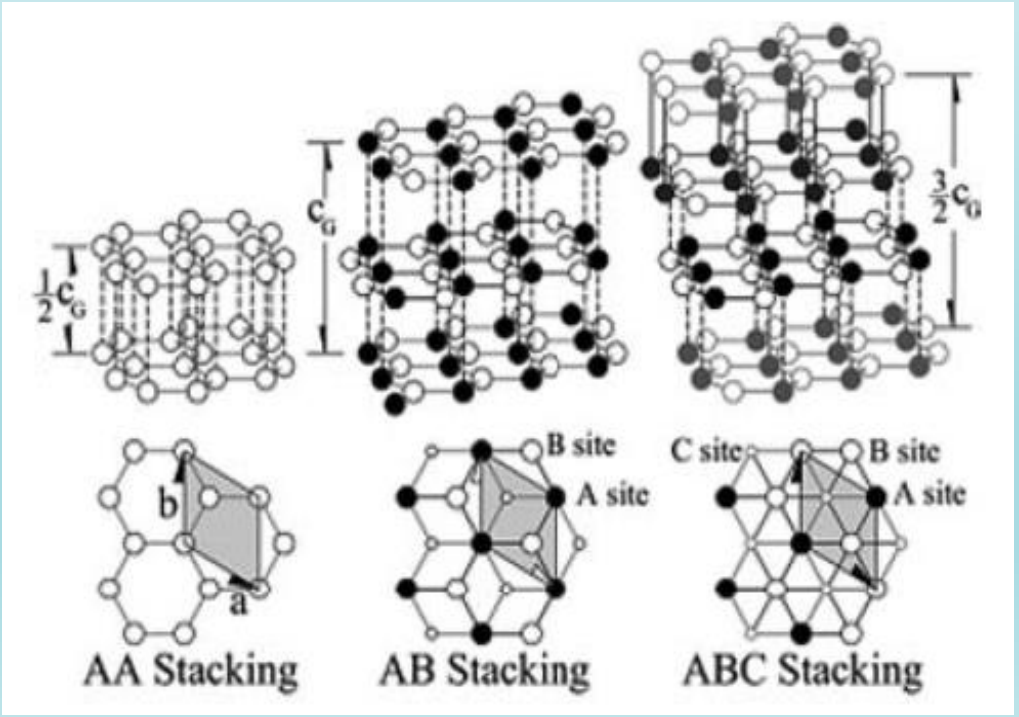


Fig. Different Stacking ways of Graphene (Conrad et. al.)

PROPERTIES RELEVANT TO BIOLOGICAL APPLICATIONS

- **Surface Area**
- **Layer Number**
- **Lateral Dimension**
- **Surface Chemistry**

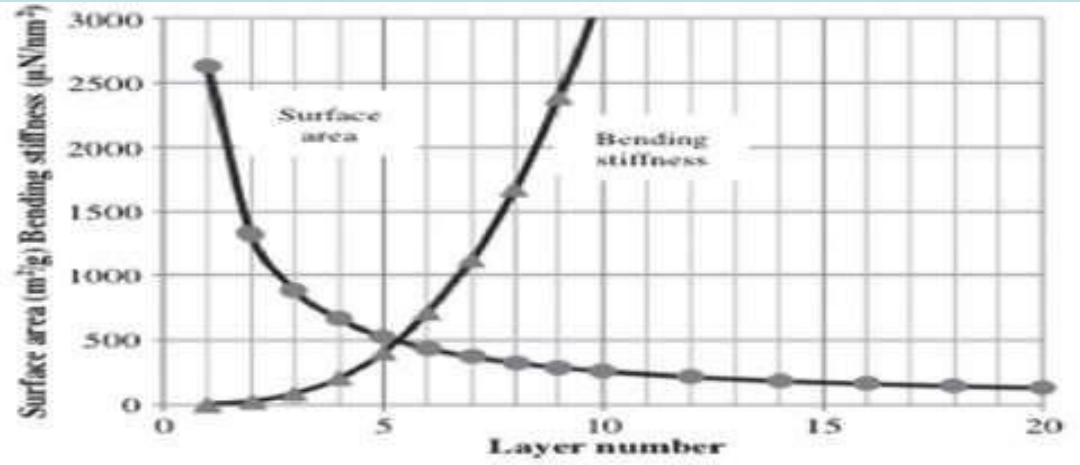


Fig. :Surface area and bending stiffness for ideal GFNs(Kane *et al.*)

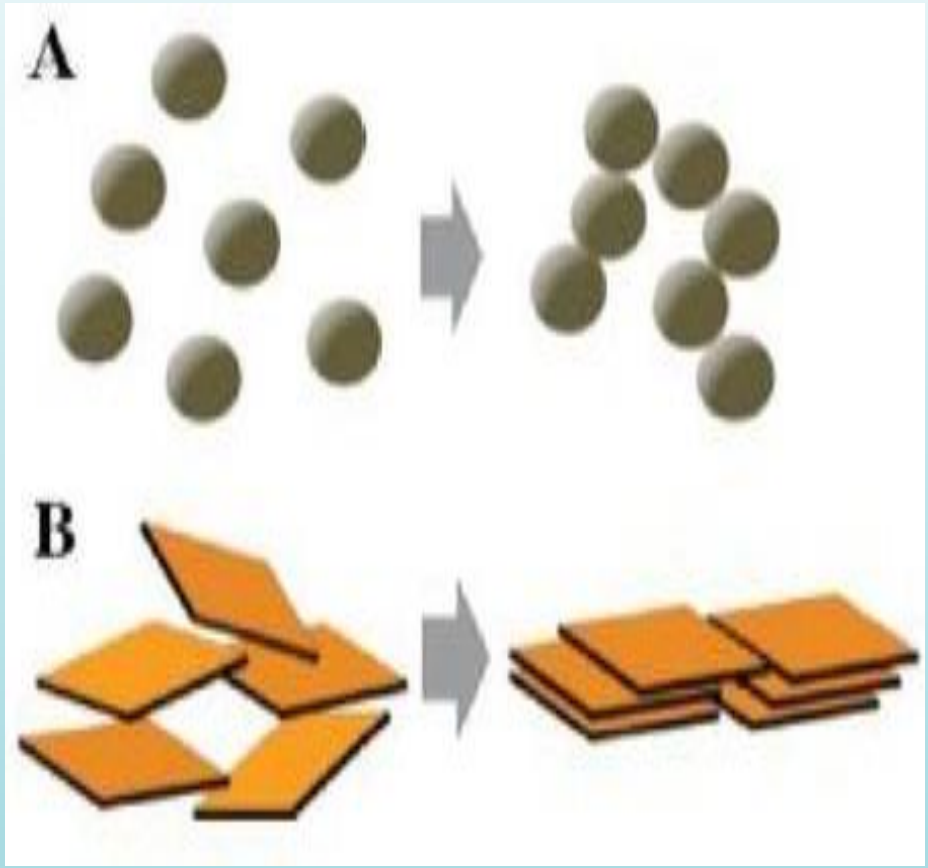


Fig. :Surface area stability during aggregation, filtration, or drying
for spherical (A) and plate-like (B) particles.
(Kane *et al.*)

MODIFIED GRAPHENE AND IT'S APPLICATION

- Absence of semiconducting gap in pristine graphene
  have staggered the use of Graphene.

- Two Approaches to overcome this:
  - ✓ Substitution of C atoms with heteroatoms.
  - ✓ Adsorption of dopants on surface.

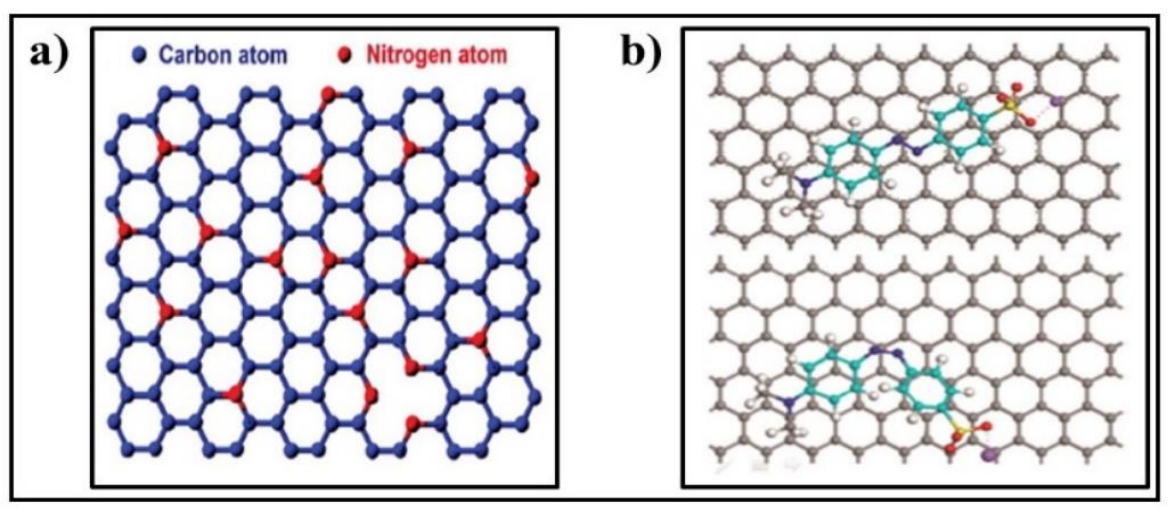


Fig. a)Heteroatom doping in Graphene; b) Doping by adsorption(Liu et. al.)

- In order to further enhance and overcome the challenges in Pristine Graphene, various modified Graphene viz. doped Graphene with N-, B-, Si-,P- etc. have been studied.

- The tailored properties of these modifications have found applications in opto-electronics, electronic devices, photocatalysis and biomedical applications.

AMINO ACID

- Amino Acids are Organic Molecules Containing $-NH_2$ (Amine), -COOH (Carboxyl) and Side Chain(R Group)
- Amino Acids are building blocks of proteins and can reflect common chemical properties of complicated biomolecules

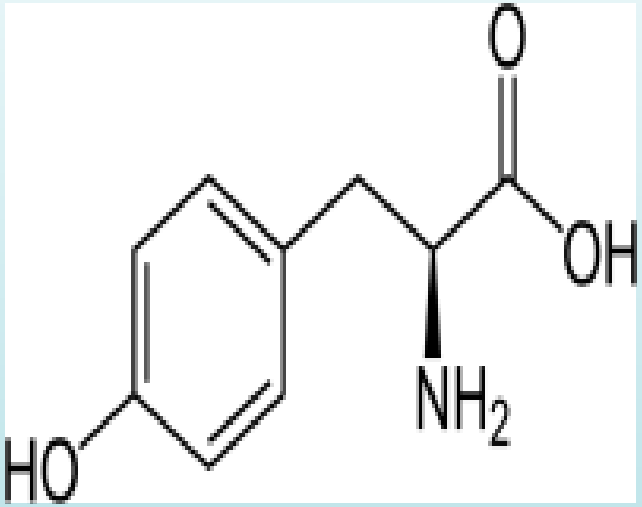


Fig. Tyrosine Structure (Source : google)

- Amino Acids are classified as below:
  - ✓ R Group
  - ✓ R Group and Polarity
  - ✓ Distribution in Protein
  - ✓ Nutritional Requirements
  - ✓ Number of Amine and Carboxyl Group

Essential AA	Nonessential AA	Conditionally essential AA
Arginine	Alanine	Cysteine
Histidine	Asparagine	Glutamine
Isoleucine	Aspartate	Hydroxyproline
Leucine	Glutamate	Proline
Lysine	Glycine	Taurine
Methionine	Serine	
Phenylalanine	Tyrosine	
Threonine		
Tryptophan		
Valine		

Fig. Classification of Amino Acids based on Nutritional Requirements(Source : google)

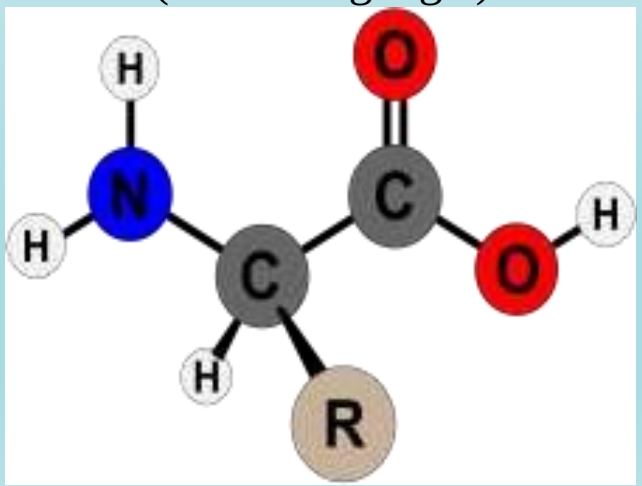


Fig. Amino Acid Structure(Source : google)

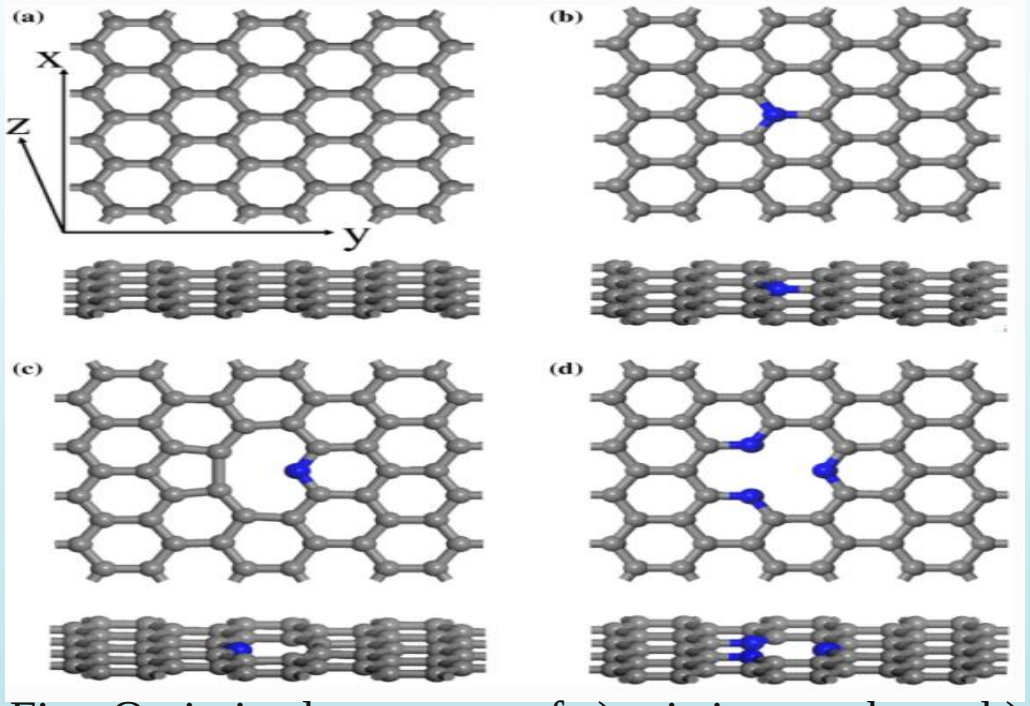


Fig.: Optimized structures of a) pristine graphene, b) graphitic N, c) pyridinic 1N and d) pyridinic 3N.

- N-doped graphene was evaluated to check it's feasibility as a potential sensor for amino acids.
- The strongest interactions were noticed for Pyridinic N

- Graphdyine consists of sp^2 hybridized hexagonal carbon rings connected by 4 sp hybridized.
- The adsorption energies are in the order P>H>GU=G with GD/P having the highest of -1.27eV

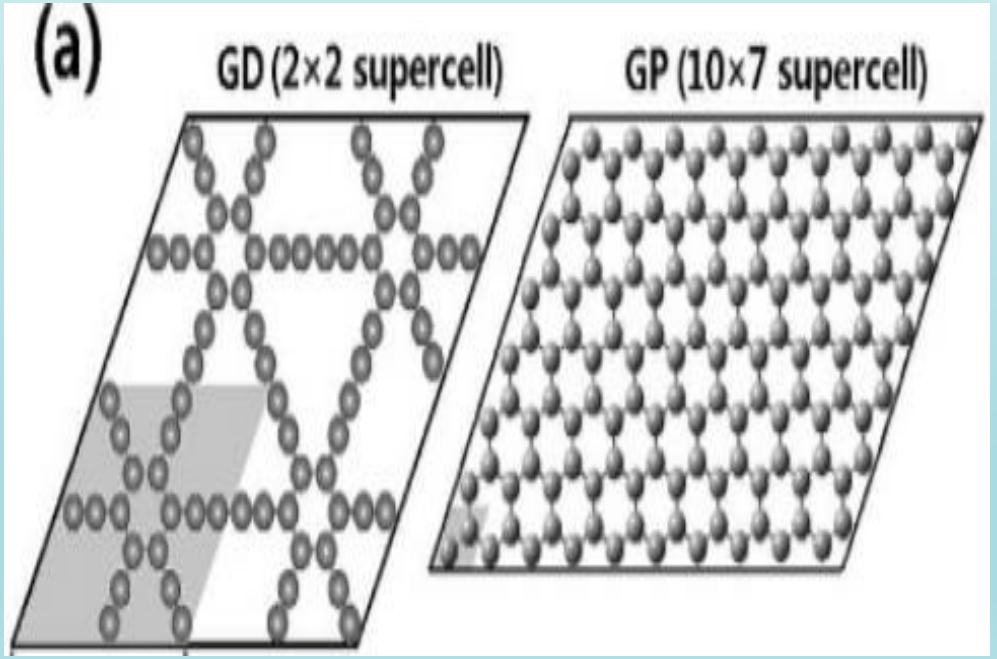


Fig.: Optimized structures of a) Graphdiyne(GD), b) Pristine Graphene(GP).

VALINE ACID

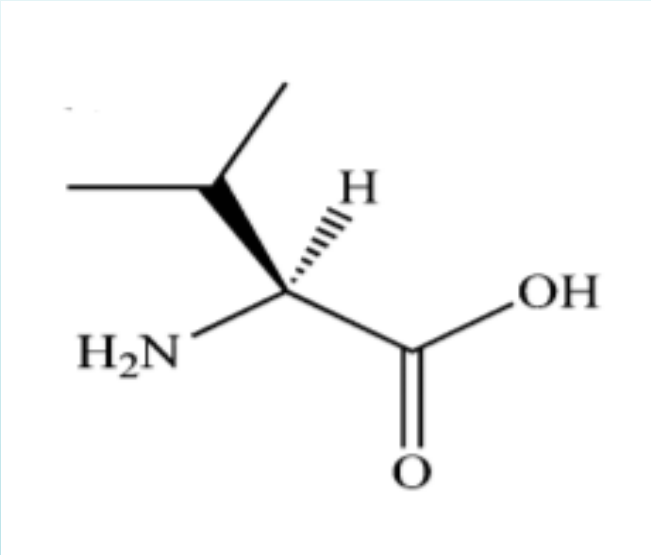


Fig. Chemical Structure of Valine (Singla *et al*.)

- Valine is an aliphatic, extremely hydrophobic essential amino acid.
- It has been linked with number of health disorders.
- High plasma valine concentration is associated with Type 2 Diabetes patients.
- Increased extracellular concentration of valine improves dendritic cell function in cirrhosis patients.

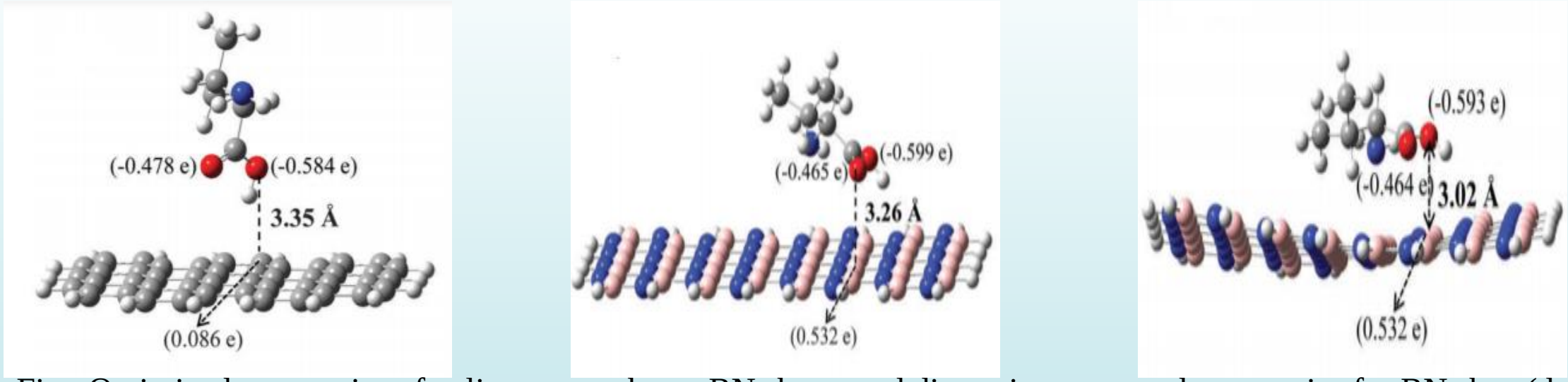


Fig.: Optimized geometries of valine on graphene, BN sheets and dispersion corrected geometries for BN sheet(left to right).(Singla et. al)

- The adsorption study of Valine on Graphene and BN sheets were carried out by Singla et. al.
- The dispersion correction reported negative adsorption energy whereas that without it was positive.
- The adsorption energy values for valine is larger on the BN nanosheet in comparison to the graphene surface as the polar B–N bond enhances van der Waals interactions by incorporating the dipole–dipole interactions.

System	Adsorption energy (kcal mol^{-1})			
	Without dispersion correction		With dispersion correction	
	Gas phase	Solvent phase	Gas phase	Solvent phase
Val/Gra	−3.65	2.93	−89.76	−81.78
Val/BN	0.97	2.09	−161.32	−158.75

Table: Adsorption Energy.(Singla et. al)

OBJECTIVE OF PRESENT WORK

- To obtain a better understanding of the binding mechanism between Modified Graphene nanostructures and biomolecules.

- To assess the differences in the adsorption strength of Valine on different graphene nanostructures, which in turn will allow us to understand the interaction.

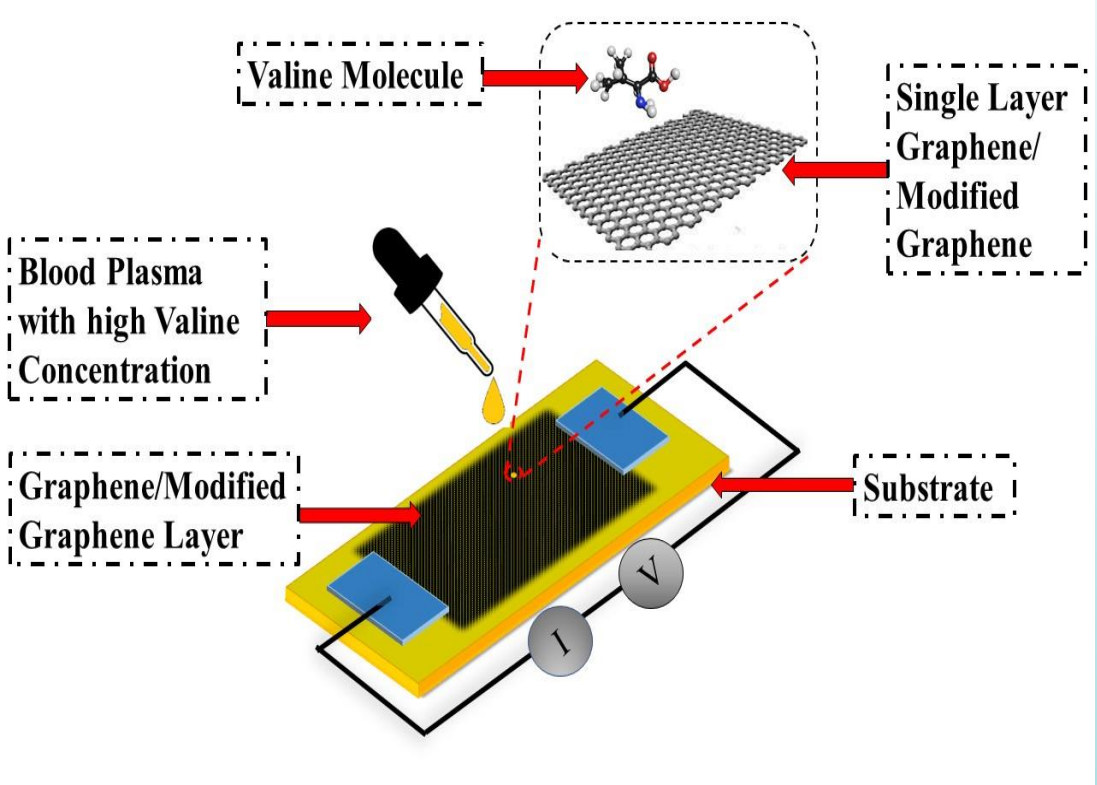


Fig.: Schematic of biosensor application.

- To assess the exquisite differences in the adsorption strength of Valine on different graphene nanostructures, which in turn will allow us to understand the interaction.

CHOICE OF DOPANT

- Here we propose to calculate the structural, electronic and adsorption properties of Si-doped Graphene to show it's potential use as a biological sensor for the essential amino acid : Valine.
- The doping also opens the zero band gap of pristine graphene evident by the separation of the valence and conduction Dirac points.
- Si-doped Graphene is reported to act as a Lewis Acid and therefore show strong interactions with lone pair of the functional groups.
- Interaction of Si-doped Graphene with modified nucleobases showed improved adsorption energies with respect to pristine form.

DENSITY FUNCTIONAL THEORY(DFT)

- DFT is a computational quantum modelling method used to investigate the electronic structure of many-body systems: atoms, molecules and condensed phases.
- The foundation of DFT was laid by the Kohn-Hohenberg Theorem.

Advantages of DFT:

- Provides useful information regarding the structural, electronic, magnetic and optical properties of systems.
- Helps in designing systems with specific properties
- Reduces resources consumption

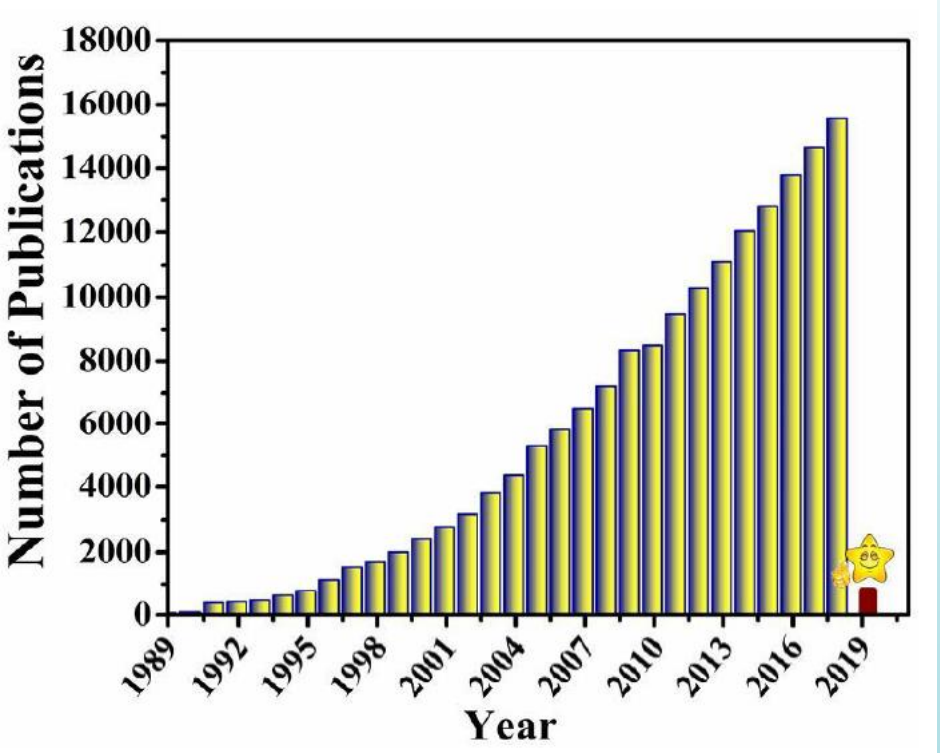


Fig.: Growth of research publications related to DFT calculations.(From web of science data)

COMPUTATIONAL METHODS

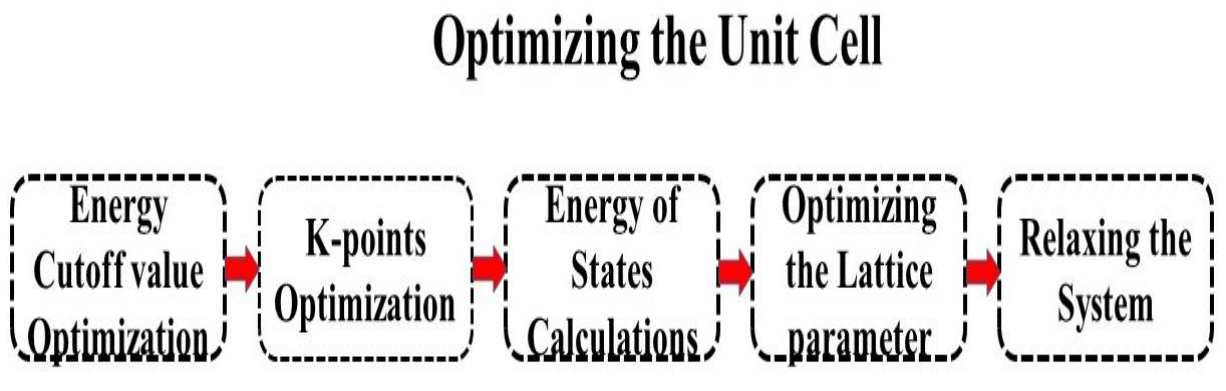


Fig.: Flow diagram for unit cell optimization

- The Energy cutoff value for the unit cell was calculated to be **60 Ry**.
- n for k-points sampling was calculated to be 10 (nk_x and nk_y) and we use a k points grid of **10 X 10 X 1**.
- Lattice Parameter was found out to be **2.457Å**.

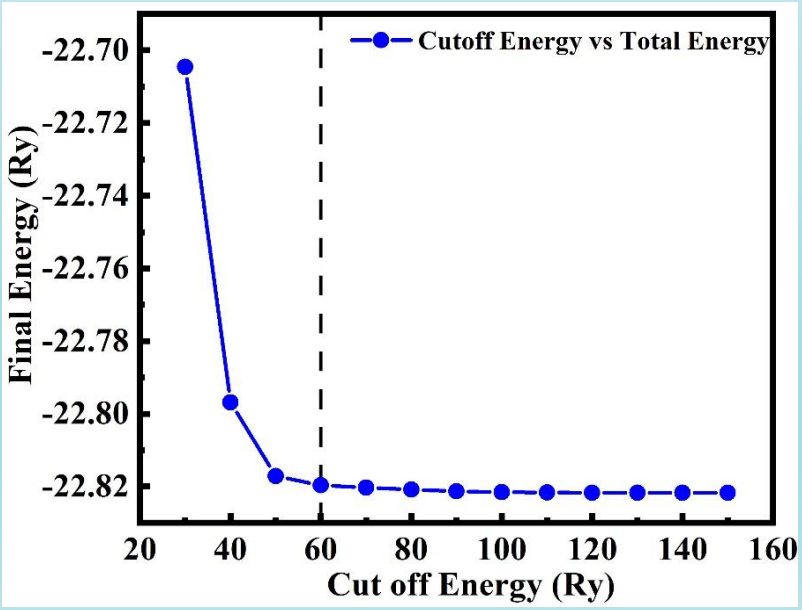


Fig.: Final Energy vs Cut off Energy

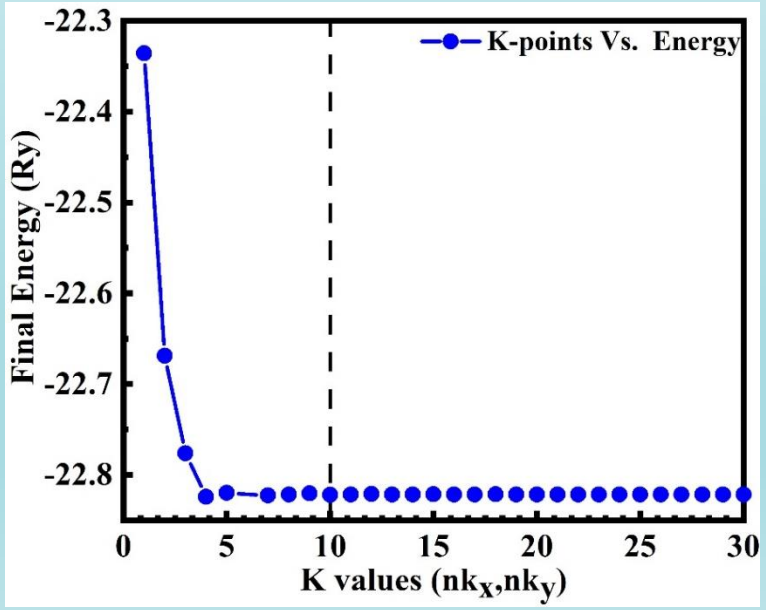


Fig.: Final Energy vs K values

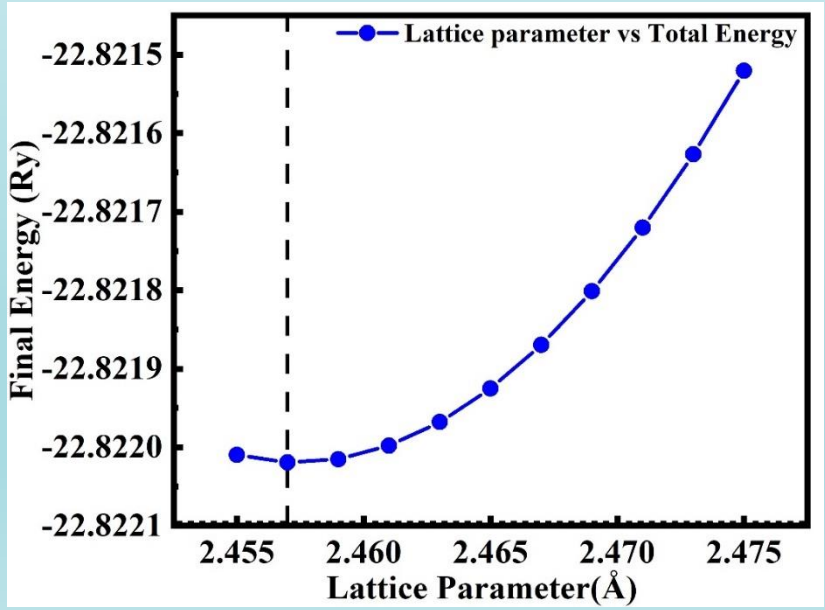


Fig.: Final Energy vs Lattice Parameters

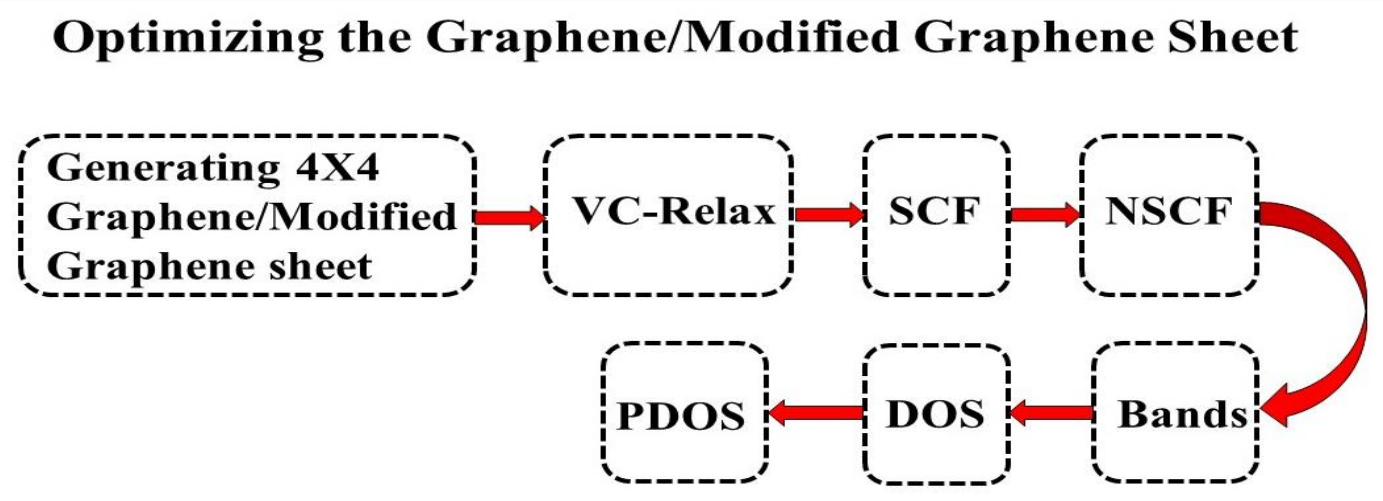


Fig.: Flow diagram for Graphene sheet optimization

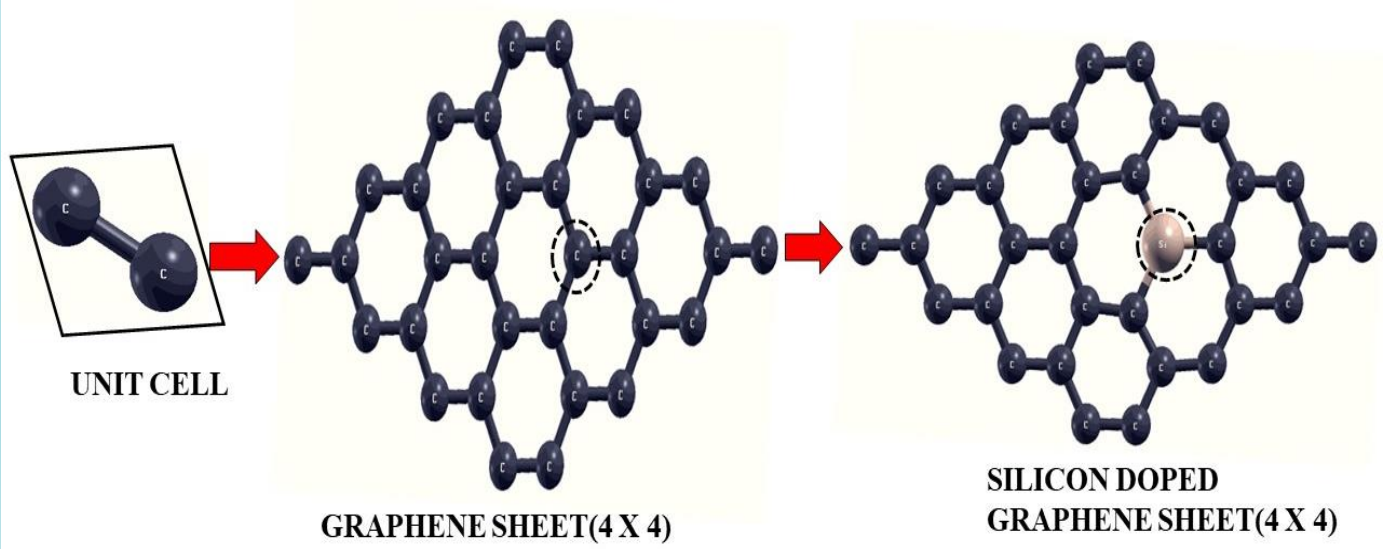
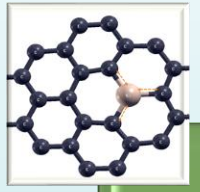


Fig.: Unit Cell, Graphene Sheet and Si-doped Graphene Sheet

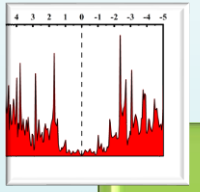
- The optimized unit cell was then used to draw a sheet of **4 X 4** Graphene sheet.
- Cell parameters along with the atomic coordinates of the sheet were relaxed .
- Using the relaxed parameters, **SCF** was performed to obtain the minimum energy i.e., the ground state energy.
- **NSCF** performed to consider denser k-mesh grid.
- After SCF and NSCF, band energy profile was calculated.

RESULTS AND DISCUSSION



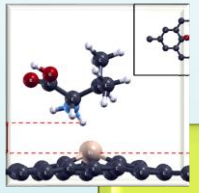
Structural Properties

- Pristine Graphene(G)
- Si-doped Graphene(SG)
- Valine



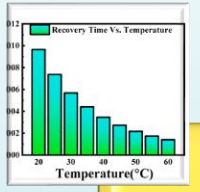
Electronic Properties

- Pristine Graphene(G)
- Si-doped Graphene(SG)



Adsorption

- Adsorption Energy
- Structural Properties
  - G + Valine
  - SG + Valine
- Electronic Properties
  - G + Valine
  - SG + Valine



Recovery Time

- Pristine Graphene + Valine
- Si-doped Graphene + Valine

STRUCTURAL PROPERTIES

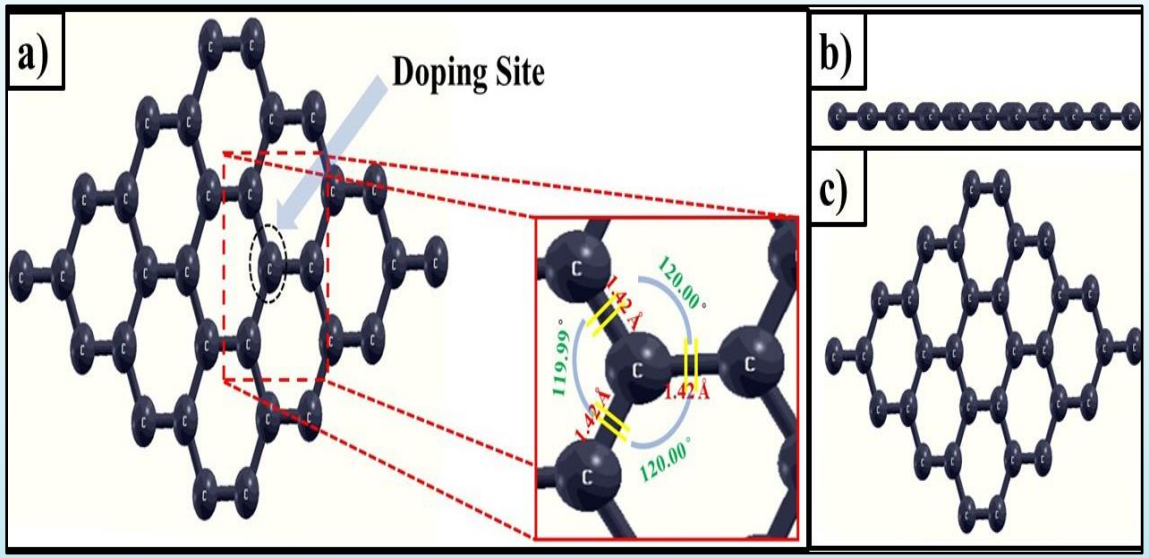
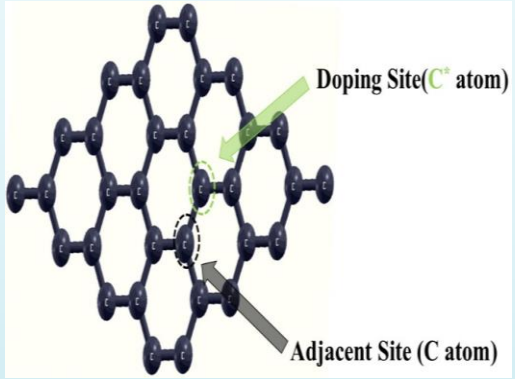


Fig.: Optimized structure of Pristine Graphene

- C-C* bond length for optimized Pristine Graphene sheet was calculated to be **1.42Å.**



- C-C-C bond angles in the hexagonal rings for was calculated to be **~120˚**.

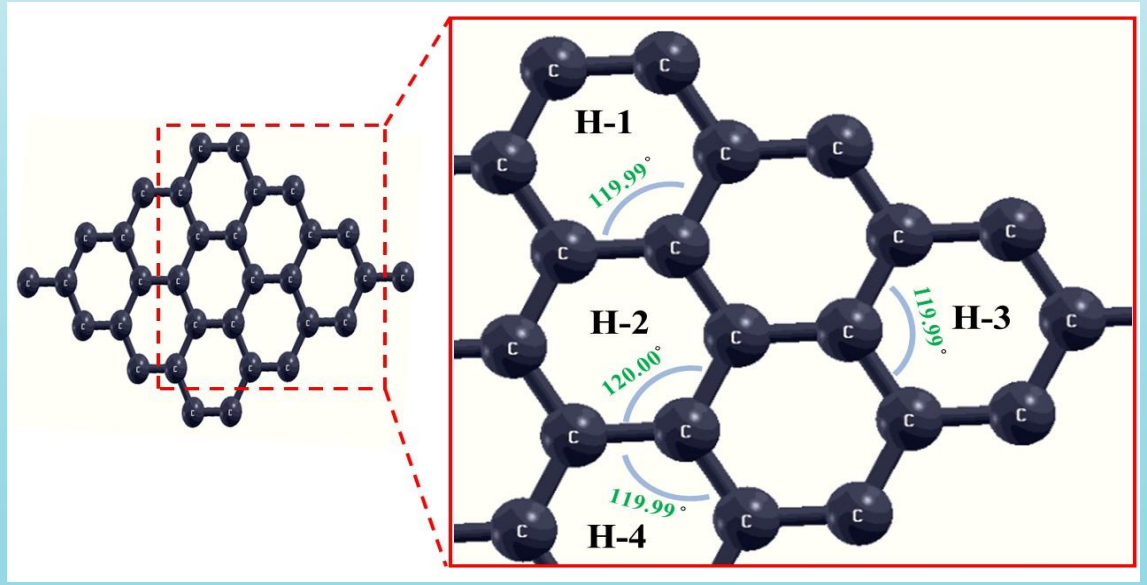


Fig.: Bond angles in the hexagonal rings

System	Bond Length(Å)	Bond Angle(˚)
Pristine Graphene	1.42 (C-C*)	120.00(C-C*-C)
Si-doped Graphene	1.67 (C-Si)	119.99(C-Si-C)
Pristine Graphene + Valine	1.42(C-C*)	120.02(C-C*)
Si-doped Graphene + Valine	1.73(C-Si)	108.07(C-Si-C)

Table: Bond angles and Bond length

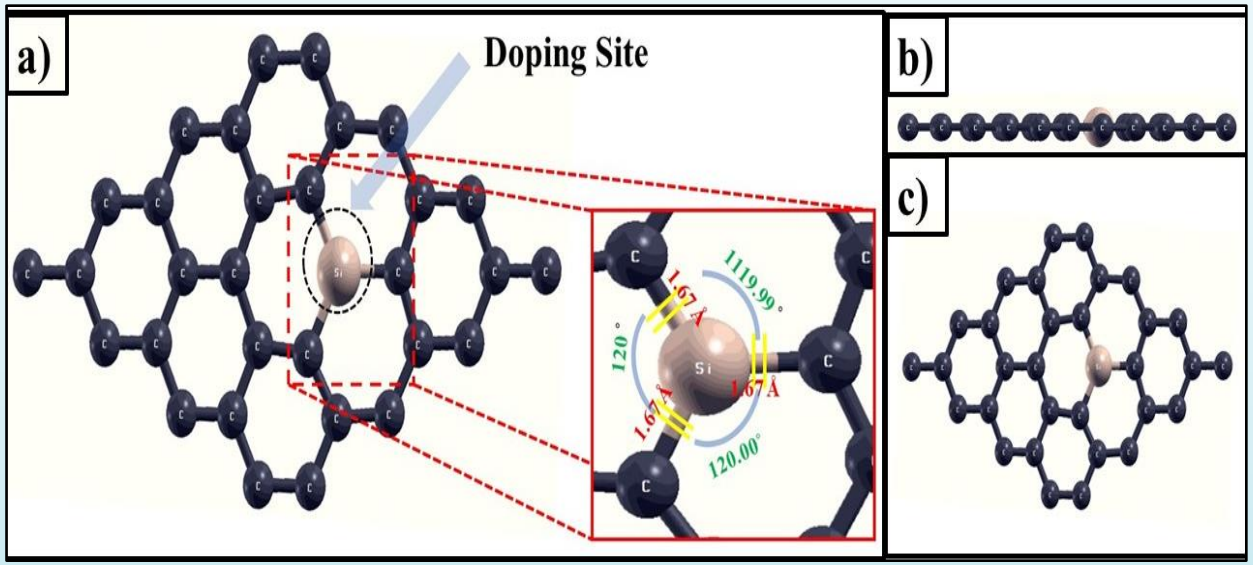


Fig.: Optimized structure of Si-doped Graphene

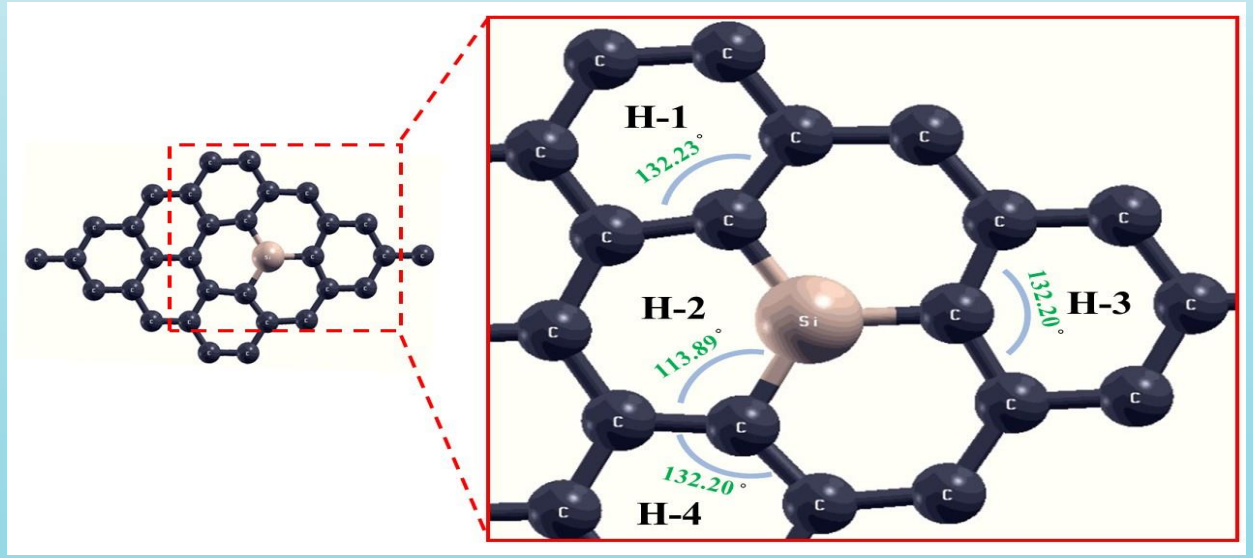


Fig.: Optimized structure of Si-doped Graphene

- C-Si bond length and C-Si-C bond angle for optimized Si-doped Graphene sheet was calculated to be **1.67Å** and **~120˚** respectively .
- Doped sheet remaining planar signifies strong quasi- σ bonds.
- Dopant atom caused distortion in the hexagonal rings adjacent to the doping cite whereas those away continued to be in pristine form.
- The lattice parameter was slightly changed from **9.84Å** in pristine to **10.02Å** in doped system.
- Lowdin's charge analysis showed a transfer of **+2.78e** to the sheet after Si doping.

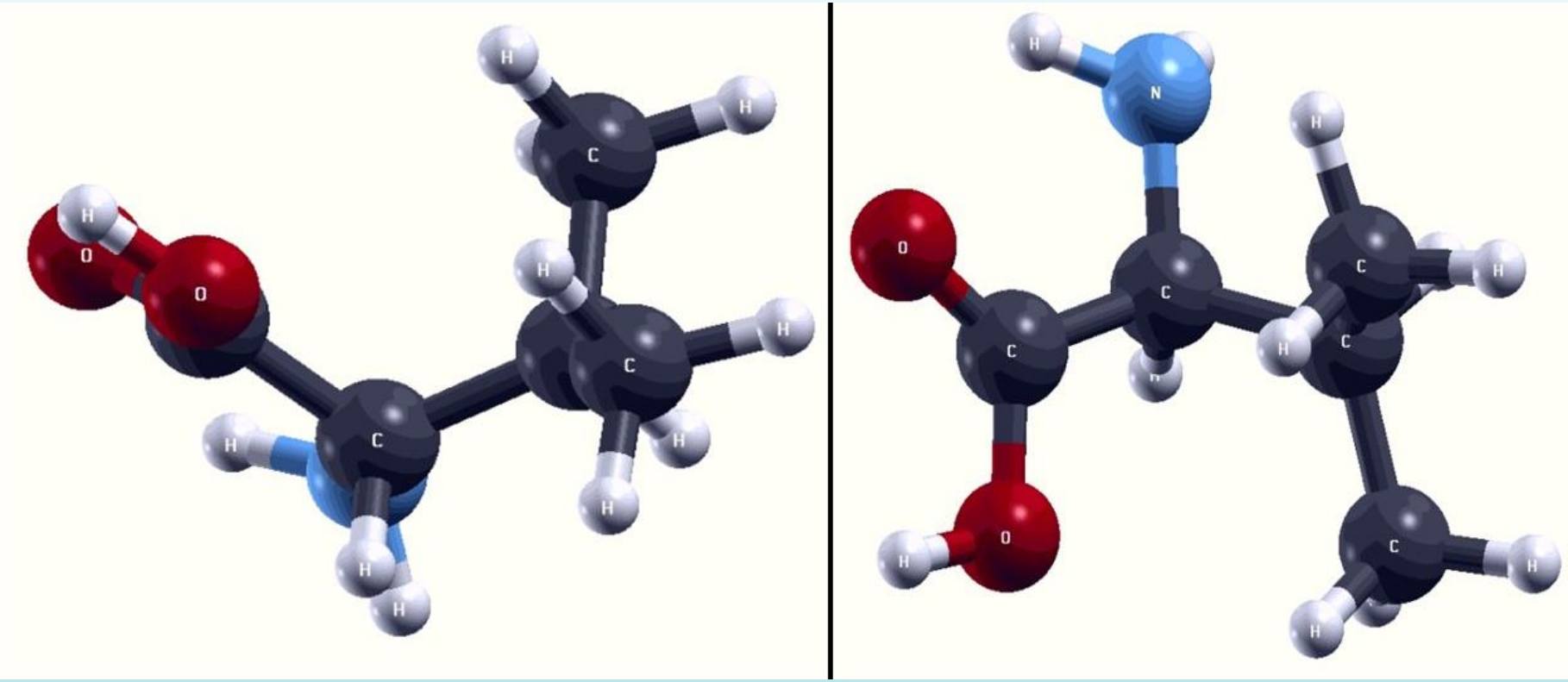


Fig.: Optimized structure of Valine molecule in different orientations.

- For adsorption study, the atomic coordinates of the molecule to be adsorbed i.e., Valine, was relaxed.
- We obtained the starting coordinates from **PubChem** Database.
- The relaxed coordinates where then used to calculate the behaviour of the combined system.

ELECTRONIC PROPERTIES

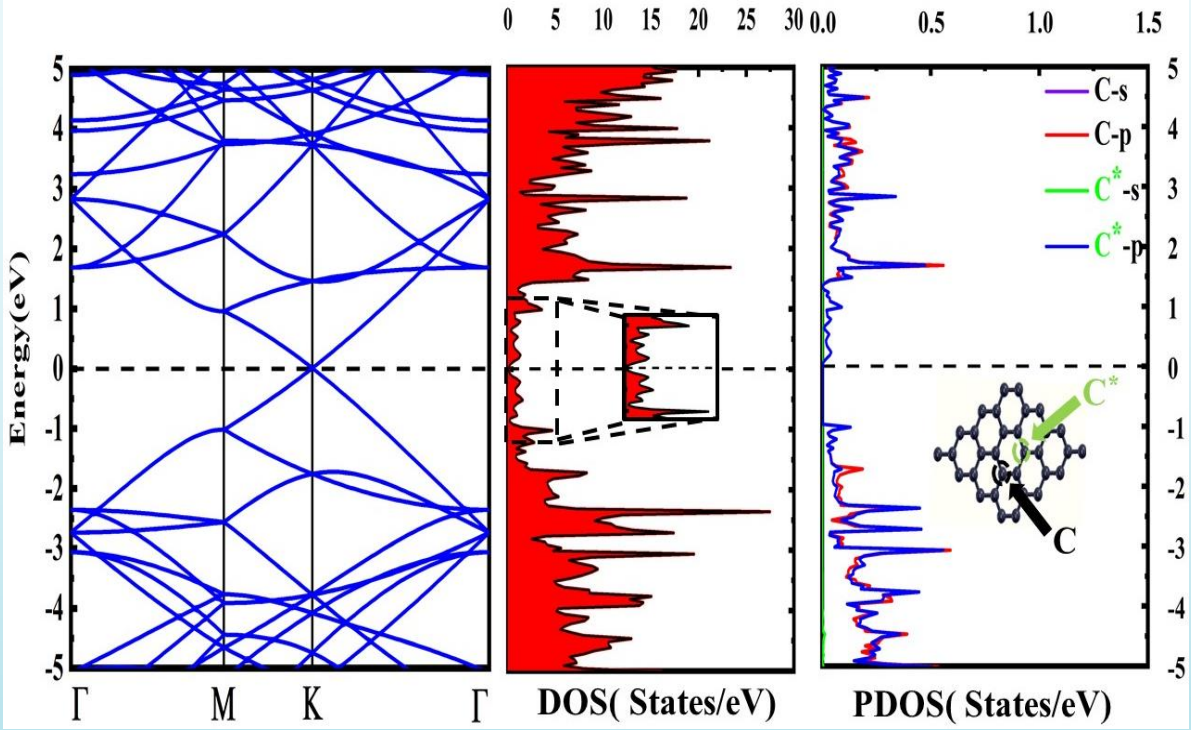


Fig.: Band Energy profile of Pristine Graphene.

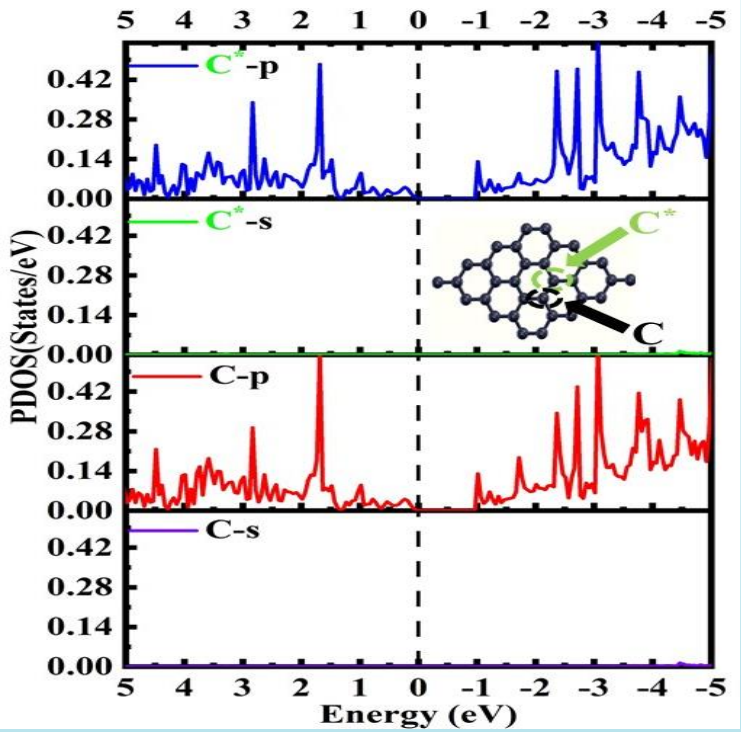
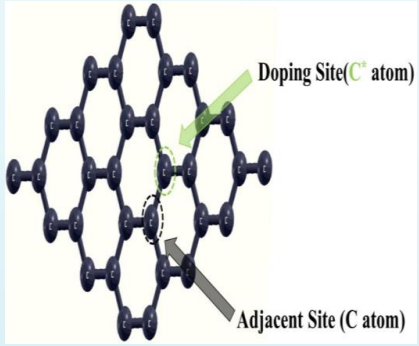


Fig.: PDOS showing orbital contribution.



- The band structure of all the systems are calculated by sampling the k-points in the high symmetry direction of the Brillouin zone along the **Γ-M-K-Γ** k-path.
- Formation of the isotropic Dirac cone is due to the hexagonal symmetry .
- Among the components of the p orbitals of C^* and C atoms, it is the $\mathbf{p_x}$ orbitals of both the atoms that show greater contribution to the total DOS near the Fermi level.

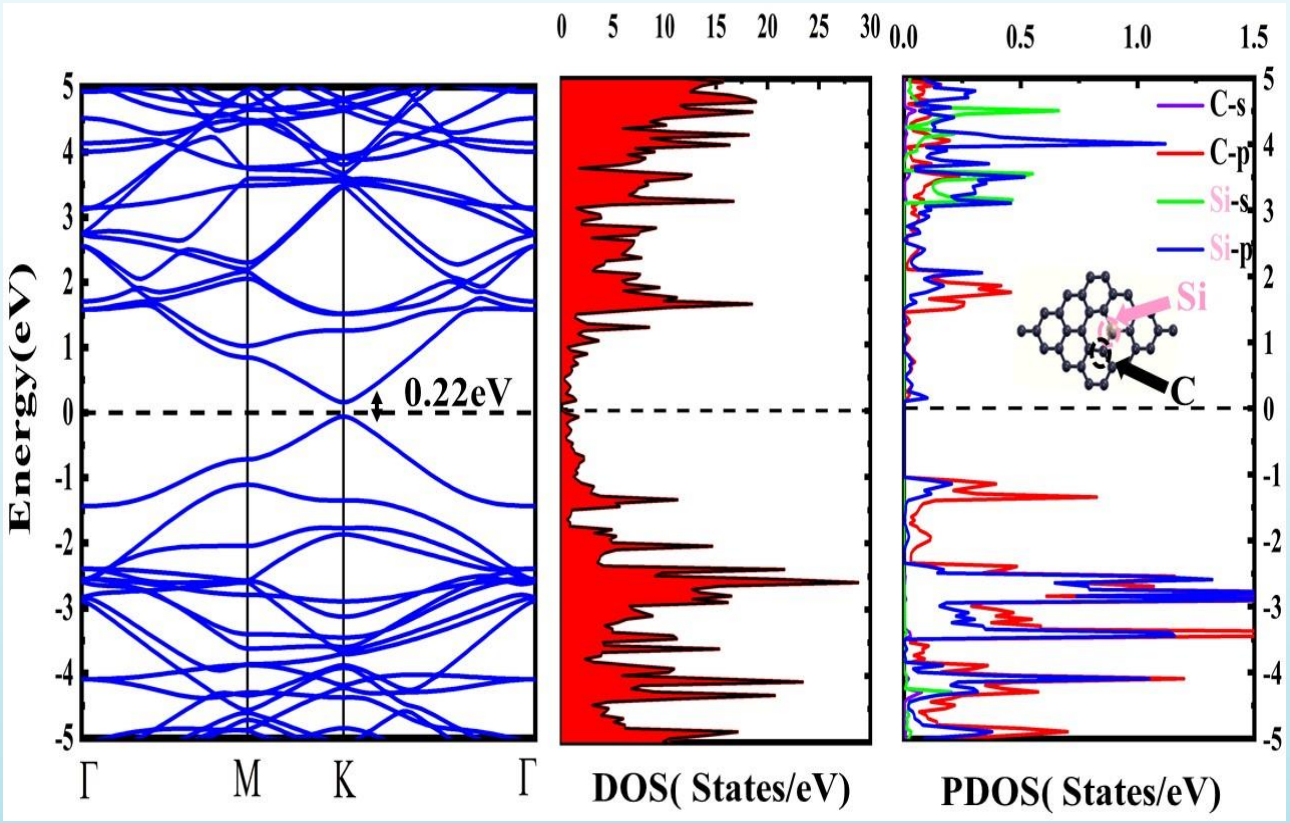


Fig.: Band Energy profile of Si-doped Graphene.

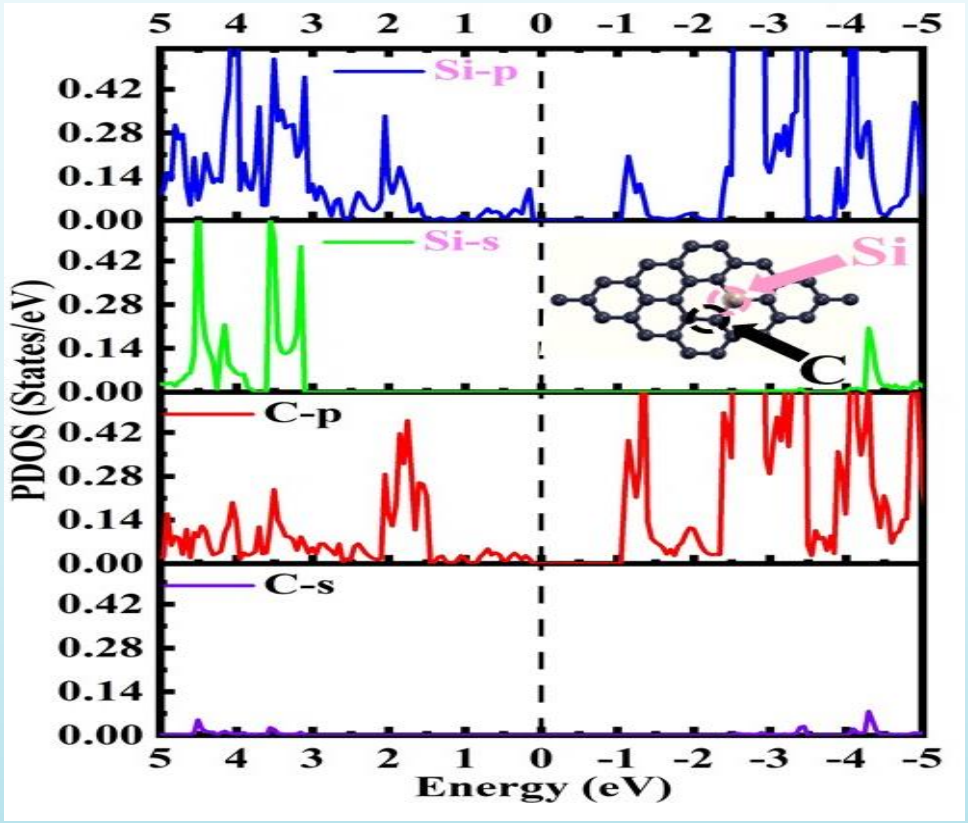


Fig.: PDOS showing orbital contribution.

- When the pristine structure is doped with Silicon, there is a separation of the conduction and valence band Dirac points. The separation was calculated to be **~0.22 eV**.
- While comparing the Fermi energy of these two systems we didn't find much difference and they were almost comparable .
- The **s** and **p** orbitals of **Si** atom along with the **p**-orbital of the adjacent **carbon** atom shows significant contribution to the DOS around E_F.

ADSORPTION

- In order to accurately predict the interaction of nucleobases with nano-surface, the dispersion forces need to be taken into account.

- Here we have implemented Grimme's Dispersion Correction and performed DFT-D2 calculations.

- Ground state energies of the monolayers as well the combined system of the monolayer with the molecule were calculated. E_{ads} was calculated using the equation mentioned below:

$$\mathbf{E_{ad} = E_{Graphene/Modified\ Graphene\text{-}Valine} - (\ E_{Graphene/Modified\ Graphene} + \ E_{Valine})}$$

- The Adsorption energy was found to be **-0.41eV** and **-0.65eV** for Pristine Graphene and Si-doped Graphene respectively.

- Calculations thus show an increase in the adsorption energy by **~60%** for Si-doped over Pristine Graphene.

STRUCTURAL PROPERTIES

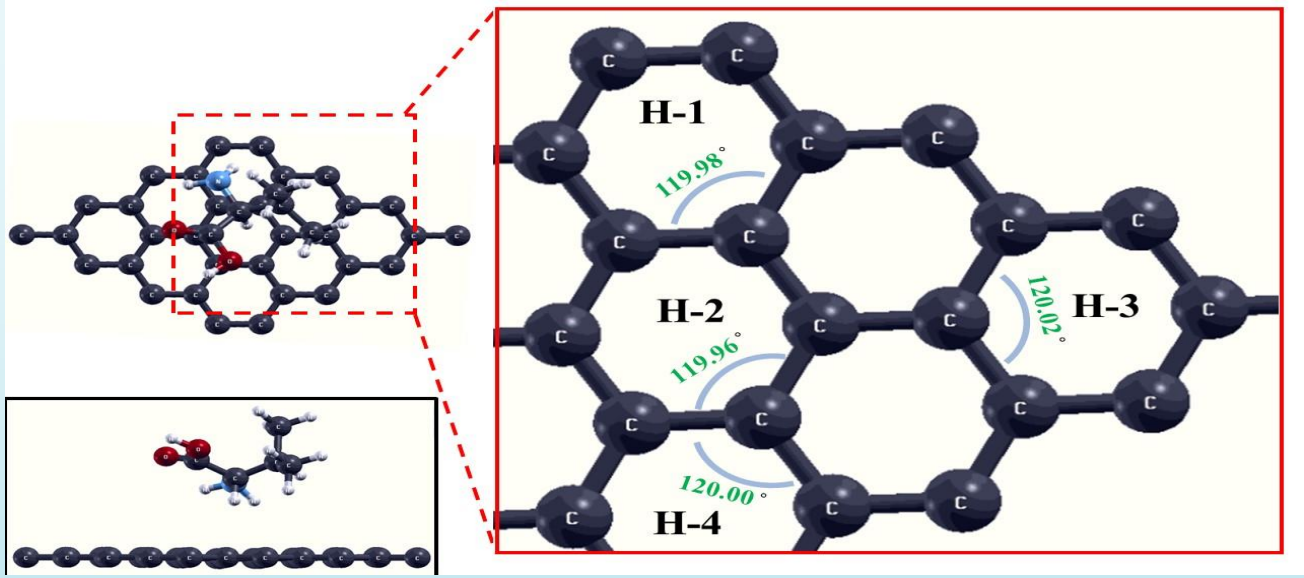


Fig.: Insight of Pristine Graphene structure after adsorption.

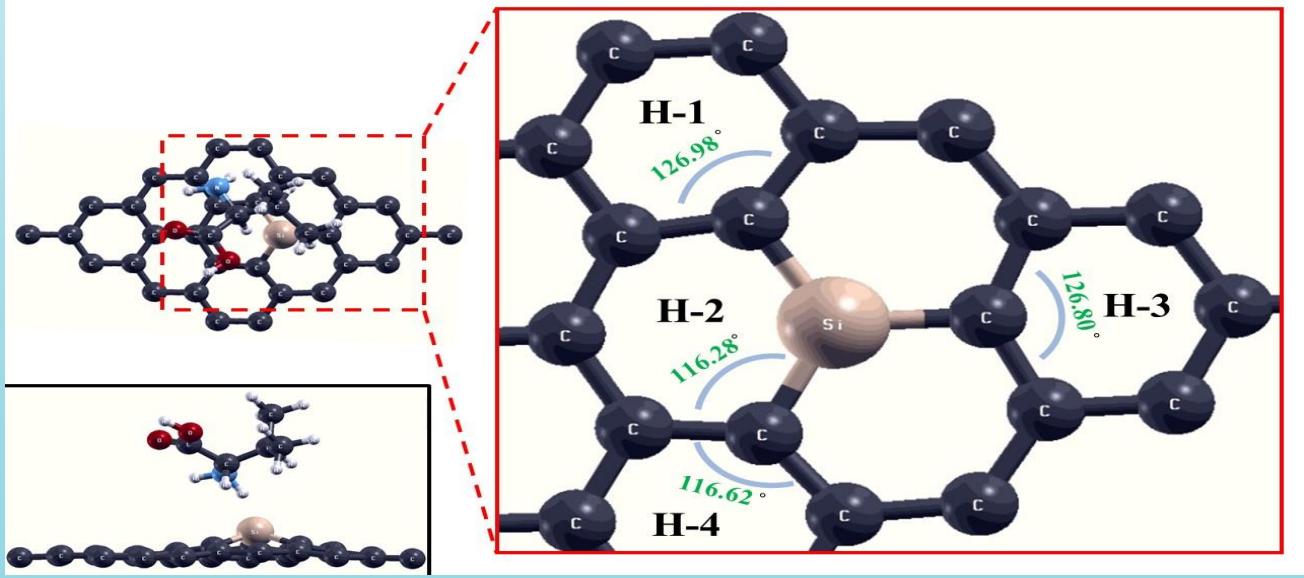


Fig.: Insight of Si-doped structure after adsorption.

- **C-C*** bond length in case of graphene sheet remained almost unchanged whereas the **C-Si** bond length in Si-doped graphene sheet was further stretched to **1.73Å**.
- The **graphene** sheet continued to be **planar** in geometry, the **Si-doped** one showed **stretching** in the Z-axis for the Si atom. . The Si-atom was raised to a height of **1.11 Å**.
- Due to stretching in the Z-direction of the Si atom, the **distortion** of the adjacent hexagonal rings was **reduced** as can be seen in but pristine conditions were not achieved.

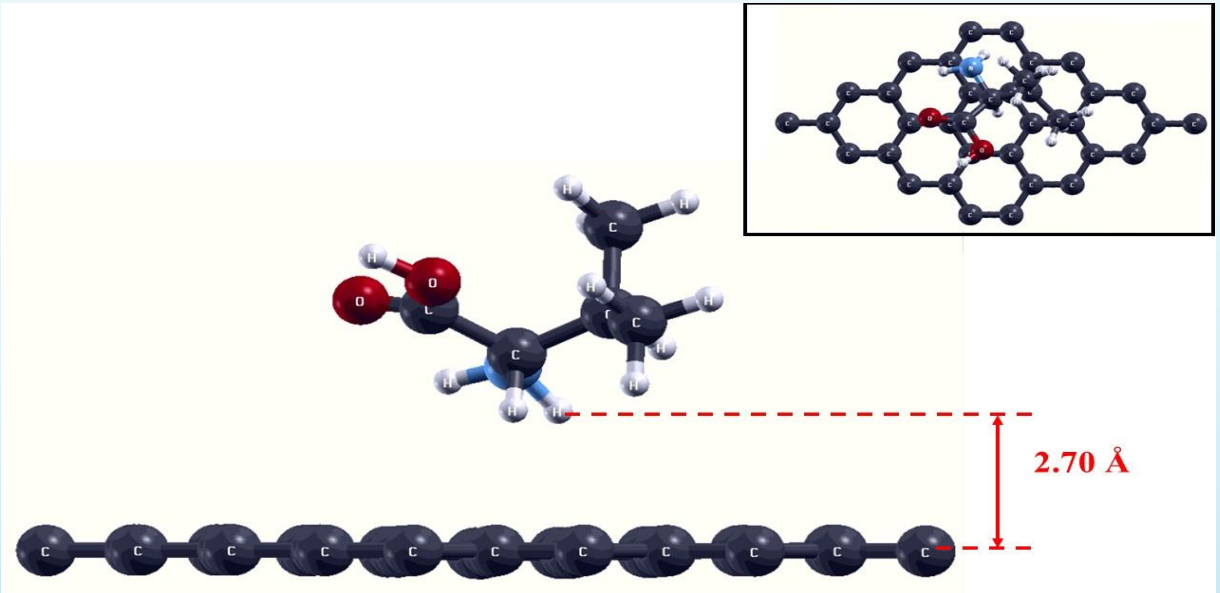


Fig.: Separation distance between pristine surface and Valine.

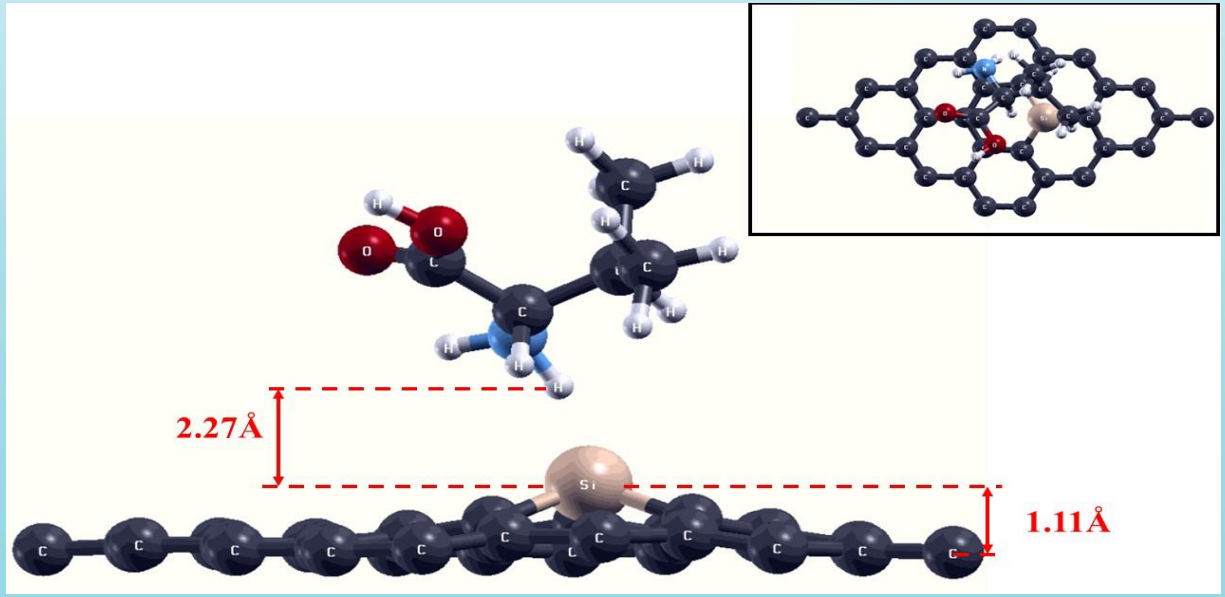


Fig.: Separation distance between doped surface and Valine.

- The height of the molecule above the sheets were calculated to be **2.70 Å** and **2.27Å** for Graphene + Valine and Si-doped Graphene + Valine systems respectively.
- For the combined system we had kept the molecule parallel to the surface at a certain height.
- The possible mode of interaction of two functional group containing valine with the monolayer is via the -NH_2 group.
- Given the range of the distances between the surface and the molecule, it is understood that the type of adsorption is **physisorption**.

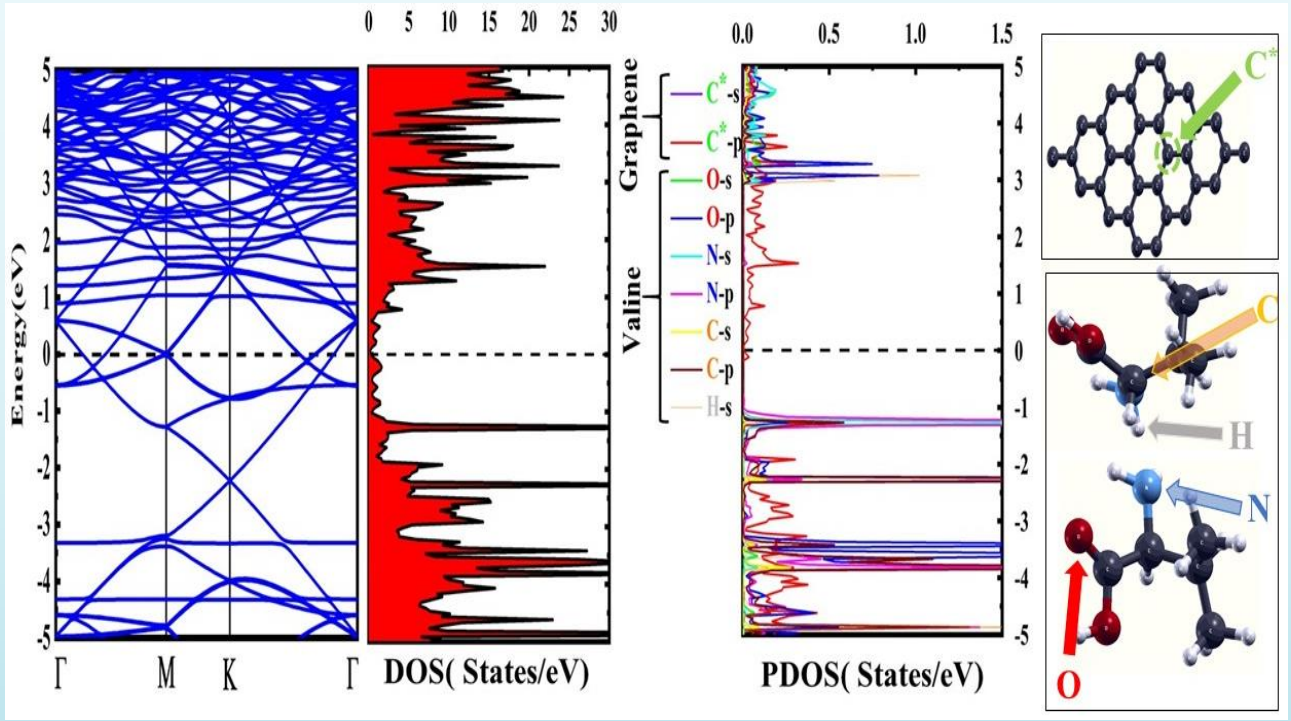


Fig.: Band energy profile of Graphene + Valine.

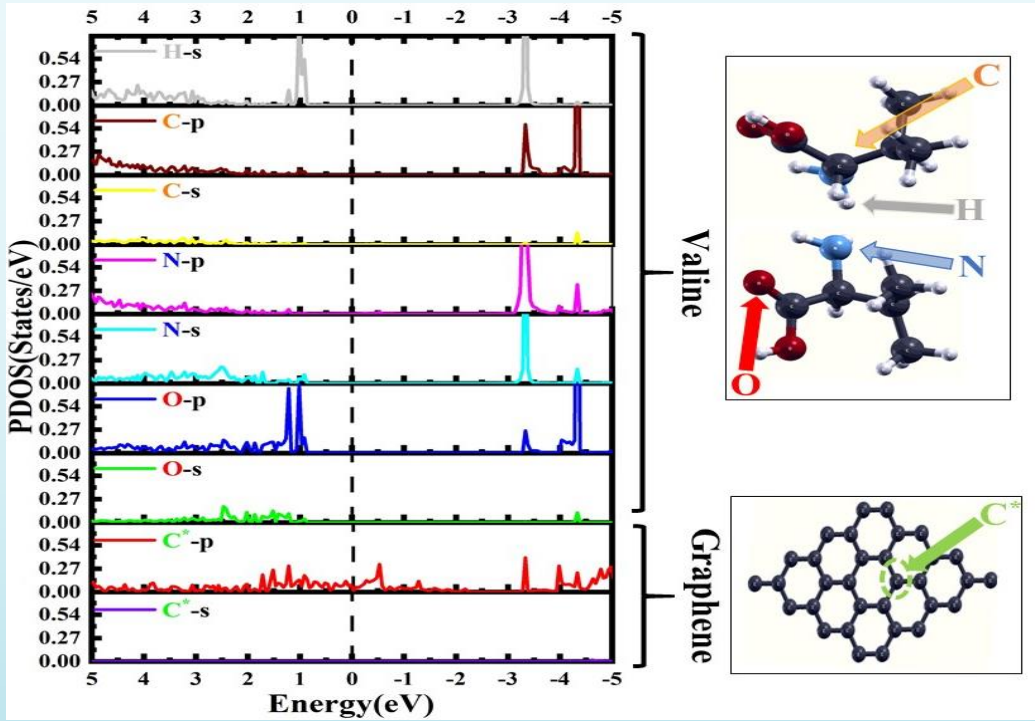


Fig.: PDOS showing orbital contributions.

- In case of Graphene + Valine, we see an increase in energy bands near the Fermi Level. These extra occupied states in the band energy profile are credited to the molecular energy levels of Valine.
- The p orbital contribution of the C^* atom to the DOS remains almost unchanged in case of GV with respect to the pristine one. Apart from the contribution of C^* atom, the PDOS depicts significant contribution from the N,C,H and O atoms present in the molecule.

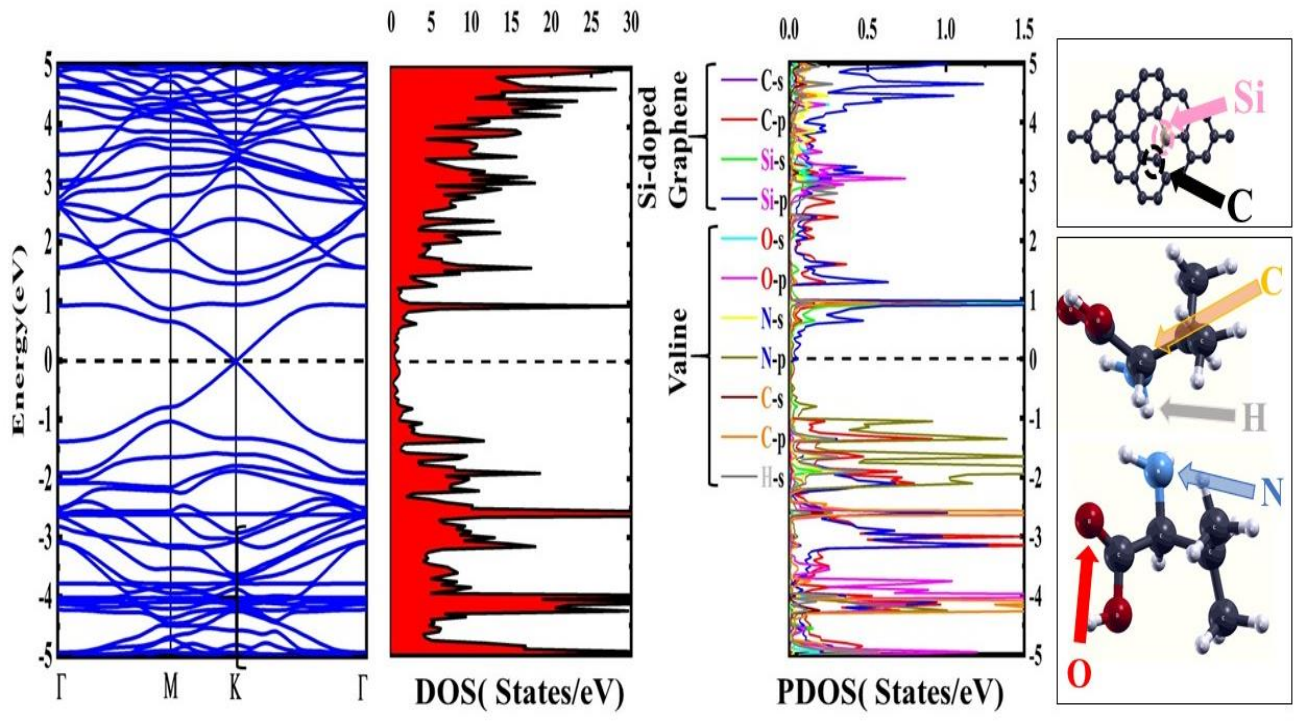


Fig.: Band energy profile of Si-doped Graphene + Valine.

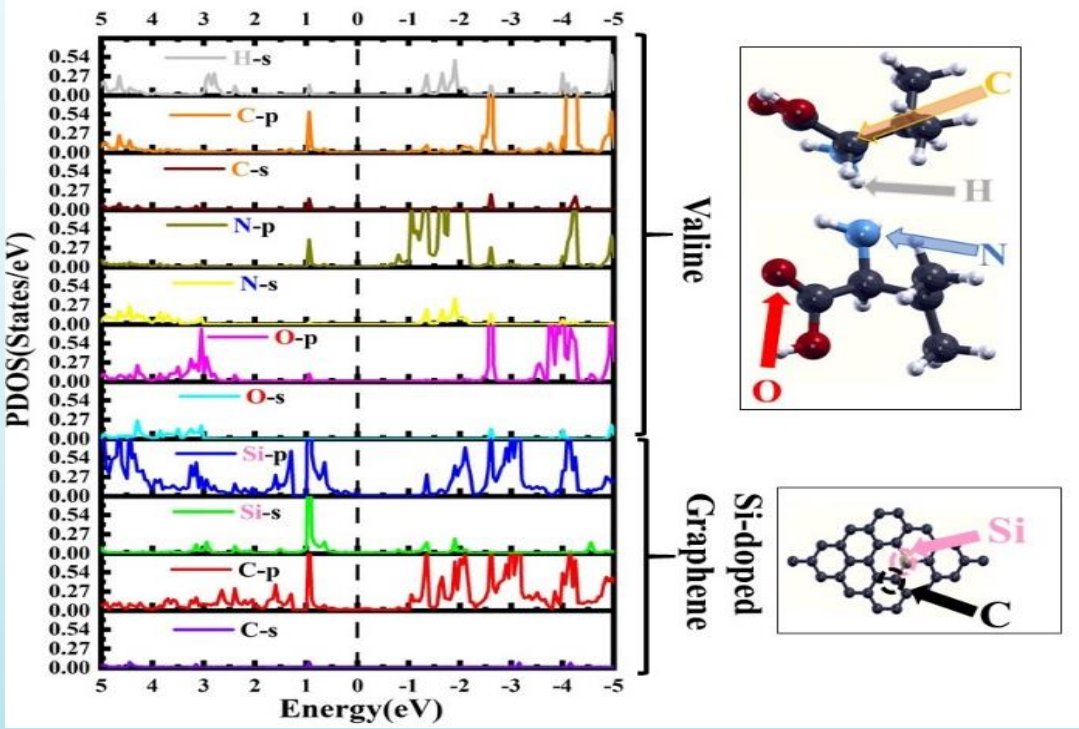


Fig.: PDOS showing orbital contributions.

- Occupied states exist near the Fermi level and is due to the s orbital contribution of the Si of the surface along with the p orbitals of Si, C of the substrate surface and that of N in valine.
- Valine interacts with the doped surface possibly via $–NH_2$ group.
- Lowdin's charge analysis showed a gain of **+0.25e** and **+0.18e** for Graphene and doped Graphene sheet respectively .

RECOVERY TIME

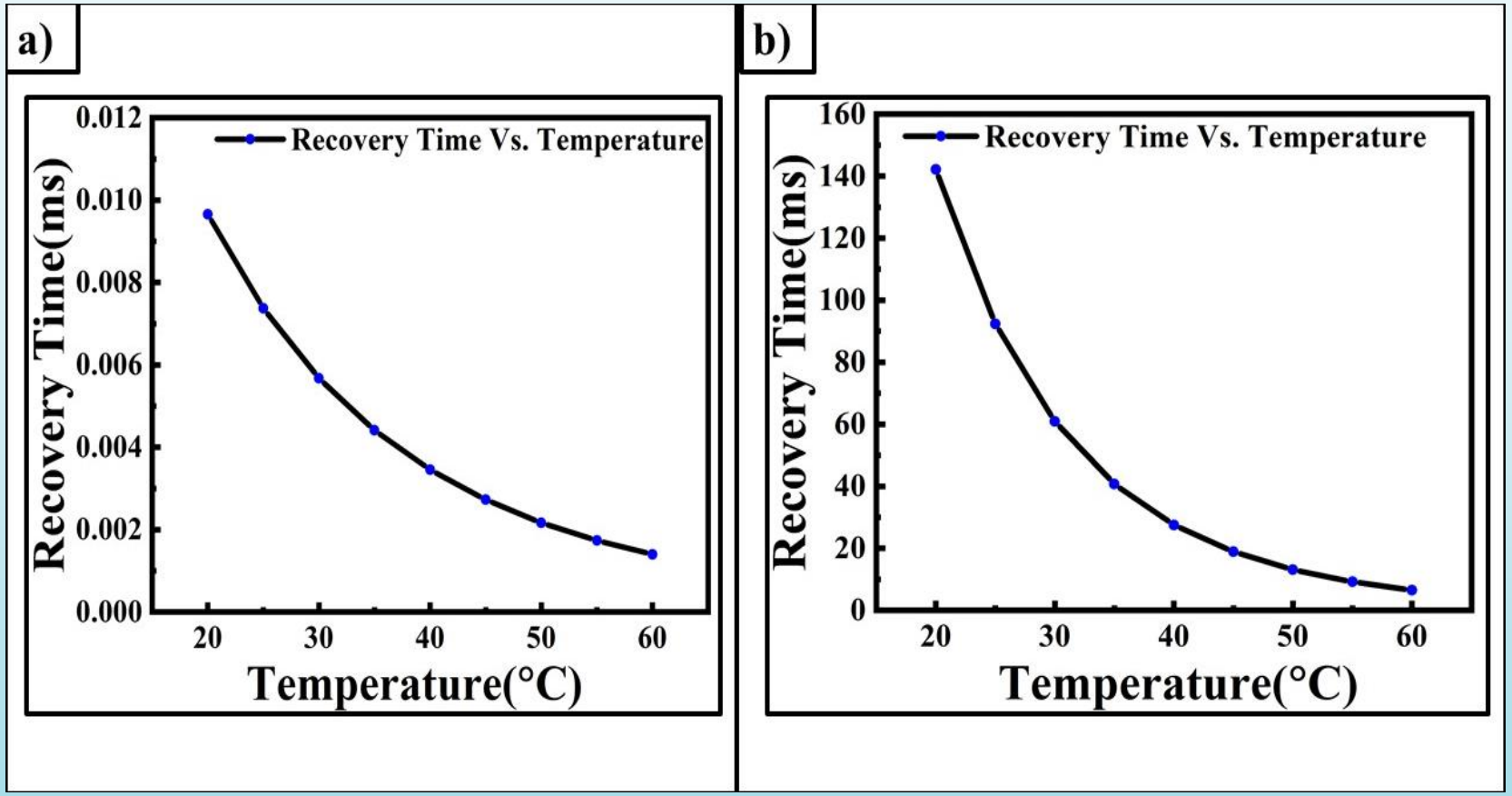


Fig.: Recovery Time Vs Temperature for Valine over a)Graphene and b)Si-doped Graphene.

- The room temperature recovery time was calculated for graphene and Si-doped graphene for Valine was calculated to be **0.0073ms** and **92ms** respectively.

- The recovery time calculation of pristine and Si-doped graphene was done in order to check the feasibility of their use as a carrier of Valine and their reusability.

$$\tau = \upsilon^{-1} e^{\frac{-E_{ads}}{KT}}$$

Where υ is the attempt frequency, T is the temperature and K is the Boltzmann constant

CONCLUSION AND FUTURE SCOPE

- Si atom doping the pristine substrate resulted in a very small band gap of ~ 0.22 eV.
- Adsorption studies of the substrates showed enhanced adsorption energies of valine on Si-doped surface in comparison to that of the pristine form. For doped surface the energy value was calculated to be 0.65eV whereas for pristine it was 0.41eV.
- Recovery time calculations of doped surface showed ultrafast recovery time i.e., 92ms at room temperature and that of pristine surface was almost negligible asserting low adsorption energies.
- The conclusion drawn from this work is that Si-doped Graphene can be used as a biosensor for Valine over Graphene. Also the fact that Si-doped Graphene has already been synthesized experimentally, the reported values in this work can help experimentalist to further investigate this interaction experimentally.

ACKNOWLEDGEMENT

I would like to express a deep sense of gratitude to my guide, Prof. Sumit Saxena and my mentor, Dr. Basant Roondhe for their continuous encouragement and competent guidance.

THANK YOU !!