1.1 Bioconjugated Nanomaterials

The trend to shrink the materials dimensionality are prompted by the unending desire of accessing exclusive properties of material for its utilization in novel areas ranging from device applications to the most needed biomedical applications. The nanostructure materials have emerged as the most appealing material for their utilization in medical diagnostics from the past few years. From the long time nanoparticles such as silica [1] gold [2] and titanium [3] have been the frontier materials to be used as medical diagnostic tool. However, it is critically important to gauge the functional group on the nanoparticle surface for performing the desired activity when it comes to functionalization of nanoparticles. There are few examples, like CNT can be used in drug delivery, sensing and imaging by appropriate functionalization as it makes CNT more biocompatible [4-5]. Bioconjugated systems have immerged as an important candidate for biomedical applications [6-13]. Bioconjugation is a chemical strategy to form an interface between organic/inorganic composite and biomolecule. The combination of organic and inorganic (carbon allotropes and boron nitride allotropes) composites with biomolecules, makes a complex structure with unique properties of both biomolecule as well as nanostructures. Use of inorganic compounds having ionic and covalent interactions provides a versatile material with wide range of electronic properties like high electron mobility, wide bandgap range such as insulator, semiconductor and metals. They also have good thermal stability, mechanical hardness, magnetic and dielectric properties. The organic compounds or biomaterials have emerged as a new class of materials which have tendency to interact with weak van der Waals forces and also have potential of high luminescence efficiency,

mechanical properties, large polarizability and good conducting properties. Due to these diverse properties, these materials have many promising applications in optics, electronics, mechanics, protective coatings, catalysis, sensors, biology, etc.. The ability to tune the electronic properties of bioconjugated materials at nanoscale has opened a regime of new materials with unique electronic properties which are totally different from its constituent organic and inorganic components. Moreover, the nanostructure yields large area for interactions comprising biomolecules which further offers promising pathway to combine biomolecular functionality. This will lead to creation of hybrid nano scaffolds with unique electronic and optical properties. Such scaffolds with definite features are of particular attraction in identification and modulation of biomolecules, protein interaction, protein-nucleic acid interaction, enzyme activity and biometric reactions etc. Since biomolecules are soft molecules and the nanostructures where it forms the interface are hard materials, a controlled precision is required such that the exceptional properties and the nature of the biomolecule can be conserved after the interaction with nanomaterial. Bioconjugation of DNA, peptides and proteins is most challenging because of its peculiar surface chemical heterogeneity.

From the past few years, interest has been developed for the understanding of interaction between nanostructures and biomolecules [13-21], because of unique properties of nanomaterial for their utilization in detection mechanism and medical diagnostic [22], while biomolecule to probe the structure [23-24]. Very recently, new class of materials for bioconjugation have been immerged for biosensing and applications in medical diagnostics such as nanoparticles [25-26], nanowires [27], fullerenes [28] and nanotubes [6,8]. There are two fold advantages of these combined systems of nanostructures and biomolecules; on one

hand there is an effective platform which is developed by DNA decorated carbon nanotube for the higher sensitivity of many gases [29] while on the other hand, probing the DNA with conformational changes in its surrounding concentration of ions provide huge possibility to develop great detection mechanism [22]. Biomolecules can also be used to sort different kind of carbon nanotube as it shows structural specific binding mechanism [21]. From the recent research with the help of surface analysis techniques it was proved that the 2D materials have ability to track single molecule and intermolecular interaction [20]. Explanation for the origin of life by addressing the role of hydrogen bonds between nucleobases of DNA can be achieved by single molecule manipulation with the help of scanning tunneling microscopy technique. The self-assembly of the basic building block in biological macromolecules (nucleobases) on a 2D surface is a general persuasion for the emergence of life under pre-biotic conditions [20]. Low dimensional materials are intensively used in the technological and scientific field because the properties of any bulk material can be controlled and modulated when we reduced its size to quantum dot dimensions ($\approx 20\ nm^3$) [30] which imitates the quantized atomic states. The superiority of 2D material over its bulk counterpart is the potential to form hybrid systems as it is a layered material and can share electronic and mechanical properties. Another advantage of reduced dimensional systems is large surface area for interaction which provides advancement in technology development.

1.2 Low Dimensional Carbon and its Derivatives

Carbon being a basic element for life sustainability has very versatile bonding nature which provides an extensive ability to have many allotropes. In recent past, carbon has been

explored for technology and basic science in its all forms of allotropes such as 3D graphite [31], 1D nanotubes [32], 0D fullerenes [33] and the most popular form i.e. 2D form graphene [34-35]. Graphene a flat monolayer of carbon atoms with tightly packed honeycomb lattice and basis for all carbon allotropes has become an exciting material for research due to its plenty of miraculous properties, such as high carrier mobility [34,36-38], quantum electron transport [36-37], high elastic behaviour [39], tunable bandgap [40] and excellent electrochemical properties [41] which makes it to stand out as a promising material for biosensing, biomedical applications and nano-bioelectronic devices [42-44].

In the carbon family of materials, existence of both types of hybridization can be seen i.e. sp^2 and sp^3 in which sp^2 type carbon have dominance in technology field. The sp^2 hybridization comes in significant geometric range like graphite (three dimensional, 3D), graphene (two dimensional, 2D), carbon nanotubes (one dimensional, 1D) and fullerenes (zero dimensional, 0D). Recently, by combining sp and sp^2 hybridization a new class of carbon allotropes graphyne and graphdiyne has emerged [45-48]. Different geometry possess different electronic properties: bulk form known as graphite have a semi-metallic nature [49] apart from its large resistance in the perpendicular direction of layer plane [50]. In 2D form i.e. graphene which is a zero-gap semimetal having massless carrier [34] possess metallic or semiconducting nature, whereas in 1D carbon nanotubes their characteristics are formed depending on the chirality [51]. The quantum dot type nature can be seen in fullerenes [52]. The sp^3 crystal form of carbon (diamond) possess totally different electronic properties than sp^2, they have wide band gap which gives them semiconducting or insulating nature [53]. The reason behind this

nature in sp^3 hybridization is its tetrahedral geometry which eliminates the possibility of any loosely bound or delocalized electrons.

Apart from all the staggering properties of carbon based nanomaterial, their major hurdle in the path of its bio application is its cytotoxicity [54]. This encourages researcher to explore other two dimensional materials (2D material) having bio compatibility. Recently Boron nitride nanostructures have immerged as a suitable candidate for biological application [55-60].

1.3 Boron Nitride Nanostructure

Boron nitride (BN) is the most explored compound after graphene; it has equal number of alternative boron and nitrogen atoms linked through a covalent bond. The existence of BN is found in many crystal forms: cubic BN (c-BN) which is analogous to diamond, wurtzite BN (w-BN) which is similar to the lonsdaleite, and also in two sp^2-bonded layered configurations, i.e. rhombohedral BN (r-BN) in ABC stacking and hexagonal BN (h-BN) in AB stacking which are similar to rhombohedral graphite and hexagonal graphite respectively. From the recent past nano structures of boron nitride have gathered much attention by the theory and experimental groups. The development of boron nitride nanostructure is closely linked with the carbon nanostructures as BN fullerene and nanotube were developed in 1990s [16, 61-62] which is the year when carbon nanotube (CNT) and fullerene (C60) were made. Similarly white graphene was developed in 2000s [5], nanomesh, nanowire and nanoribbon also followed the path after the development of similar carbon counterparts [63-69].

It is noteworthy that the understanding for the interaction between boron nitride nanostructure and biomolecule are in preliminary state, our focus in the present work is to understand the underline mechanism for this interaction. The full potential of boron nitride is still unexplored for biotechnology. The advantage of boron nitride nanostructure is its chemical and physical properties which makes it a potential carrier for sensors and nanoscale diagnostic tools; vector for delivering of pharmaceuticals or genes ;foundation for field phase and combinational synthesis of biomolecules ; and support for heterogeneous and template biocatalytic reaction.

For this reason, a detailed study is needed to understand the influence of nanostructures on biocompatibility and/or toxicity which will help us to design safe and sustainable materials for biological cargo carrier and advance the nanotechnologies. It has been very challenging task due to limited underline knowledge of physics and chemistry behind the interaction between the limited knowledge about the underlying physics and chemistry behind the interaction between complexity of biomolecules and nanomaterials. In order to fully utilize the novel properties of nano-bioconjugates, a detailed understanding of the nature, physical and chemical mechanisms, structure, and spatial distribution of conjugating molecules and nanomaterials is critically important.

The objective of this work is to address some of the issues mentioned above. In Chapters 3, 4 and 5, we shall discuss some of the features of conjugating biomolecules with the boron nitride nanomaterials and their criticality in deciding the strength of interaction. Specifically, we considered boron nitride nanotube (BNNT), boron nitride nanoribbons

(BNNRs) and newly predicted two dimensional haeckelite boron nitride (2D haeck-BN) as a substrate on which the biomolecules (alkaloids, nucleobases and neurotransmitters) are adsorbed to lead us to different types of interaction depending on their nature and polarities.

1.4 Research Objectives

The present work aims to investigate the site selective/specific interaction (binding) of biomolecules with boron nitride nanostructures such as boron nitride nanotubes (BNNT), boron nitride nanoribbons (BNNR), boron nitride nanosheet (BNNS) etc., by using the quantum chemical calculations based on first principle calculations under the frame work of density functional theory. To provide the knowledge of underlying physics and chemistry behind, biomolecule interactions with the boron nitride nanostructures and the complexity of biomolecules will also be discussed. With increased activities in their synthesis, growth, integration in technology and consumer products, there has also been increased concern about their biological and environmental effects. Therefore, as the production and applications of engineered bioconjugated materials continue to increase, it is deemed critically important and timely to develop an understanding of their health and environmental effects, also to unfold new materials. The specific objectives of the present work are following:

1. To obtain a better understanding of the binding mechanism between boron nitride nanostructures and biomolecules.
2. To assess the exquisite differences in the adsorption strength of several biomolecules on boron nitride nanostructures, which in turn will allow us to understand the interaction of biomolecules with BN nanostructures.

3. To analyze the results of electronic properties in terms of conducting behavior for possible transport applications and also sensing mechanism of biomolecule over nanosurfaces.
4. To investigate theoretically the vibrational properties and understand the structure-dynamics-property relation.
5. To develop the new boron nitride based nanostructures and finds the possibility of their use as biosensor.

1.5 Structure of the Present Thesis

The present thesis is organized in the following manner. Theoretical description of computational methodology used throughout the work is presented in **Chapter 2**. Formalism of density functional theory (DFT) by discussing Kohn-Sham equation to its implementation in Plane Wave pseudopotential code - Quantum Espresso is discussed. An important theoretical description of dispersion corrections to DFT is also discussed.

In **Chapter 3**, a systematic study is described about the interaction mechanism of two alkaloids: caffeine and nicotine molecules with boron nitride nanostructures (BNNT and BNNR) and its possible use for the application of sensing of these molecules using first principle calculations within dispersion corrected density functional theory. A detailed and systematic investigation is performed to obtain the stable geometrical properties, adsorption energy, electronic structure, charge transfer and quantum conductance for two alkaloids. It is shown that the caffeine and nicotine molecules are strongly adsorbed over BNNR than BNNT. The binding strength of these molecules is found to be stronger with the incorporation of

dispersion correction and hence reinforces that the dispersion correction is essential for an accurate description of the adsorption process. No noticeable charge transfer is observed between the molecules and BNNT/BNNR. The caffeine presents stronger physisorption with both nanostructures but more with BNNR as compared to nicotine. The changes in the DOS are due to adsorption of charge donor molecules. More sensitivity of the electronic properties of BNNR in the presence of caffeine and nicotine indicates that the BNNR is a promising nanostructure for the detection of these molecules. The present study emphasizes that the BNNR is an effective substrate to non-covalently binding alkaloid molecules. The reliable conclusions drawn in this study will encourage experimentalists to explore and use these nanostructures as alkaloid carriers, filters and sensors.

In **Chapter 4**, using the *state-of-the-art* first-principle calculations based on density functional theory, we investigated the electronic properties of relatively newly proposed Haeckelite BN (haeck-BN) comprising of square and octagonal rings. The kinetic stability of this haeckelite monolayer has been confirmed by phonon dispersion curves and the phonon density of states. There is not a single phonon mode with imaginary frequency in the entire BZ. The calculated electronic properties of this new BN allotrope haeckelite BN illustrate its direct bang gap semiconducting behavior which is the prime advantage of any material to be utilized for chemical as well as biosensor. To understand the adsorption behavior of the nucleobases on haeck-BN surface, we have included the van der Waals correction term (DFT-D2) in the potentials utilized for the DFT calculations. The comparative analysis of the adsorption mechanism of nucleobases with graphene, BNNT and haeck-BN is discussed in

detail and showed superiority. Our results depict the physisorption of nucleobases on the surface of haeck-BN with the interactions order of G > T > A ≈ C > U respectively. Very less recovery time predicted for G, A, C, T and U reinforces the possibility of haeck-BN for reusable biosensor. The large change in the electronic properties gives the idea of the interaction and its possible use for the detection of these bio molecules. Thus from our results, one may conclude that the haeck-BN may act as an alternative candidate for the sensing application of nucleobases as well as DNA sequencing. We hope that our results will motivate more experimental and theoretical studies on new layered III-V semiconducting materials for biosensing applications.

In **Chapter 5,** we have discussed in detail about the interaction between the neurotransmitters and the boron nitride nanoribbon (ABNNR and ZBNNR). Neurotransmitters are the main chemicals involved to transmit the message through electric signal from one neuron cell to the other. It acts as a chemical messenger in our nervous system which passes the information by relaying it across synapses by means of excitation near neuron or the targeted tissue [41]. Among all neurotransmitters dopamine (DA) and adrenaline (AD) have significant importance. The sensing ability of BNNRs toward these biologically important hormones is studied by calculating electronic properties, adsorption energy and change in work function.

The results of our systematic investigations on electronic and vibrational properties of various hybrid bioconjugated systems have been summarized in **Chapter 6**. Variation of properties of conjugated materials compared to their pristine form has been concluded

discussing possible applications in science and technology followed by a brief discussion on possible future work.

References

1. J. C. Delvenne, S. N. Yaliraki and M. Barahona, *Proc. Natl. Acad. Sci. U.S.A* **107**, 12755 (2010**)**.
2. A. Delmotte, E. W. Tate, S.N. Yaliraki and M. Barahona, *Phys Biol* **8**, 055010 (2011).
3. N. Krishnamoorthy, M. H. Yacoub and S. N. Yaliraki, *Biomaterials* **32**, 7275 (2011).
4. R. Grima, S. N. Yaliraki and M. Barahona, *Journal of Physical Chemistry B* **114,** 5380 (2010).
5. N. G. Chopra, R. J. Luyken, K. Cherrey, V. H. Crespi, M. L. Cohen, S. G. Louie and A. Zettl, *Science* **269**, 966 (1995).
6. R. J. Chen, S. Bangsaruntip, K. A. Drouvalakis, N. W. S. Kam, M. Shim, M. Y. Li, W Kim, P. J. Utz and H. Dai, *J. Proc. Natl. Acad. Sci. U.S.A.* **100,** 4984 (2003).
7. R. J. Chen, Y. G. Zhang, D. W. Wang and H. J. J. Dai, *J. Am. Chem. Soc.* **123**, 3838 (2001).
8. Y. Kang, Y. C. Liu, Q. Wang, J. W. Shen, T. Wu and W. J. Guan, *Biomaterials* **30,** 2807 (2009).
9. D. Pantarotto, C. D. Partidos, R. Graff, J. Hoebeke, J. P. Briand, M. Prato and A Bianco, *J. Am. Chem. Soc.* **125**, 6160 (2003).
10. S. S. Wong, E. Joselevich, A. T. Woolley, C. L. Cheung and C. M. Lieber, *Nature* **394**, 52 (1998).
11. Z. G. Chen, J. Zou, G. Liu, F. Li, Y. Wang, L. Z. Wang, X. L. Yuan, T. Sekiguchi, H. M. Cheng and G.Q. Lu, *ACS Nano* **2**, 2183 (2008).
12. G. Ciofani, *Expert Opin. Drug Deliv* **7**, 889 (2010).
13. S. Gowtham, R. H. Scheicher, R. Ahuja, R. Pandey and S. P. Karna, *Phys. Rev. B* **76**, 033401 (2007).

14. A. Das, A. K. Sood, P. K. Maiti, M. Das, R. Varadarajan and C. N. R. Rao, *Chemical Physics Letters* ***453***, 266 (2008).
15. A. N. Enyashin, S. Gemming and G. Seifert, *Nanotechnology* **18**, 245702 (2007).
16. S. Gowtham, R. H. Scheicher, R. Pandey, S. P. Karna and R. Ahuja, *Nanotechnology* **19** 125701 (2008).
17. E. S. Jeng, A. E. Moll, A. C. Roy, J. B. Gastala and M. S. Strano, *Nano Letters* **6**, 371 (2006).
18. R. R. Johnson, A. T. C. Johnson and M. L. Klein, *Nano Letters* ***8***, 69 (2008).
19. S. Meng, P. Maragakis, C. Papaloukas and E. Kaxiras, *Nano Letters* **7,** 45 (2007).
20. F. Ortmann, W. G. Schmidt and F. Bechstedt, *Phys. Rev. Lett.* **95**, 186101 (2005).
21. X. M. Tu, S. Manohar, A. Jagota and M. Zheng, *Nature* ***460***, 250 (2009).
22. D. A. Heller, E. S. Jeng, T. K. Yeung, B. M. Martinez, A. E. Moll, J. B. Gastala and M. S. Strano, *Science* **311**, 508 (2006).
23. A. Rajendran, C. J. Magesh and P. T. Perumal, *Bba-Gen Subjects* **1780**, 282 (2008).
24. V. G. Vaidyanathan and B. U. Nair, *J Inorg Biochem* **95**, 334 (2003).
25. R. Hong, N. O. Fischer, A. Verma, C. M. Goodman, T. Emrick and V. M. Rotello, *J. Am. Chem. Soc* **126**, 739 (2004).
26. C. C. You, S. S. Agasti, M. De, M. J. Knapp and V. M. Rotello, *J. Am. Chem. Soc* **128**, 14612 (2006).
27. Y. Cui, Q. Q. Wei, H. K. Park and C. M. Lieber, *Science* **293**, 1289 (2001).
28. H. Benyamini, A. Shulman-Peleg, H. J. Wolfson, B. Belgorodsky, L. Fadeev and M. Gozin, *Bioconjugate Chemistry* **17**, 378 (2006).
29. C. Staii and A. T. Johnson, *Nano Letters* **5**, 1774 (2005).
30. N-M. Park, T-S. Kim and S-J. Park, *App. Phy. Lett.* **78,** 2575 (2001).
31. N. B. Brandt, S. M. Chudinov, and Y. G. Ponomarev, in Modern Problems in Condensed Matter Sciences, edited by V. M. Agranovich and A. A. Maradudin North Holland, Amsterdam, Vol. 20.1, 1988.
32. S. G. Rao, L. Huang, W. Setyawan and S. H. Hong, *Nature* **425**, 36 (2003).

33. M. Sawamura, K. Kawai, Y. Matsuo, K. Kanie, T. Kato and E. Nakamura, *Nature* **419**, 702, (2002).
34. K. S. Novoselov, A. K. Geim, S. V. Morozov, D. Jiang, Y. Zhang, S. V. Dubonos, I. V. Gregorieva and A. A. Firsov, *Science* **306**, 666 (2004).
35. C. Berger, Z. M. Song, T. B. Li, X. B. Li, A. Y. Ogbazghi, R. Feng, Z. T. Dai, A. N. Marchenkov, E. H. Conrad and P. N. First, *J. Phys. Chem. B* **108**, 19912 (2004).
36. K. S. Novoselov, A. K Geim, S. V. Morozov, D. Jiang, M. I. Katsnelson, I. V. Grigorieva, S. V. Dubonos and A. A. Firsov, *Nature* **438,** 197 (2005).
37. Y. Zhang, Y. W. Tan, H. L. Stormer and P. Kim, *Nature* **438**, 201 (2005).
38. C. Berger, Z. Song, X. Li, X. Wu, N. Brown, C. Naud, D. Mayou, T. Li, J. Hass, A. N. Marchenkov, et al. *Science* **312**, 1191 (2006).
39. C. Lee, X. Wei, J. W. Kysar and J. Hone, *Science* **321**, 385 (2008).
40. M. Y. Han, B. Oezyilmaz, Y. Zhang and P. Kim, *Phys. Rev. Lett.* **98**, 206805 (2007).
41. M. Pumera, A. Ambrosi, A. Bonanni, E. L. K. Chng and H. L. Poh, *Trends Anal. Chem.* **29**, 954 (2010).
42. A. H. C. Neto, Guinea, F. N. M. R Peres, K. S. Novoselov and A. K. Geim, *Rev. Mod. Phys*. **81**, 109 (2009).
43. J. S. Bunch, A. M. Van der Zande, S. S. Verbridge, I. W. Frank, D. M. Tanenbaum, J. M. Parpia, H. G. Craighead and P. L. McEuen, *Science* **315**, 490 (2007).
44. R. M. Westervelt, *Science* **320**, 324 (2008).
45. D. Malko, C. Neiss, F. Viñes and A. Görling, *Phys. Rev. Lett.* **108**, 086804 (2012).
46. R. H. Baughman, H. Eckhardt and M. Kertesz, *J Chem. Phys*. **87**, 668 (1987).
47. Y. Li, L. Xu, H. Liu and Y. Li, *Chem. Soc. Rev*. **43**, 2572 (2014).
48. N. Narita, S. Nagai, S. Suzuki and K. Nakao, *Phys. Rev. B* **58**, 11009 (1998).
49. Partoens, B. and F.M. Peeters, *Phys. Rev. B* **74,** 075404 (2006).
50. P.R. Wallace, *Phys. Rev.* **71,** 622 (1947).
51. J. W. G. Wildoer, L. C. Venema, A. G. Rinzler, R. E. Smalley and C. Dekker, *Nature*. **391**, 59 (1998).

52. M. S. Golden, M. Knupfer, J. Fink, J. F. Armbruster, T. R. Cummins, H. A. Romberg, M. Roth, M. Sing, M. Schmidt, *J. Phys. Condens. Matter*. **7,** 8219 (1995).
53. F. Herman, *Phys. Rev*. **88,** 1210 (1952).
54. G. Jia, H. Wang, L. Yan, X. Wang, R. Pei, T. Yan, Y. Zhao and X. Guo, *Environ. Sci. Technol*. **39**, 1378 (2005).
55. B. Roondhe, S. D. Dabhi and P. K. Jha, *Appl. Surf. Sci*. **441**, 588 (2018).
56. S. D. Dabhi, B. Roondhe and P. K. Jha, *Phys. Chem. Chem. Phys*. **20**, 8943 (2018).
57. G. Ciofani, V. Raffa, A. Menciassi and A. Cuschieri, *Nano Today* **4**, 8 (2009).
58. G. Ciofani, V. Raffa, A. Menciassi and A. Cuschieri, *Biotechnol. Bioeng*. **101**, 850 (2008).
59. B. Roondhe and P. K. Jha, *J. Mater. Chem. B* **6**, 6796 (2018).
60. G. Ciofani, S. Danti, D. D'Alessandro, L. Ricotti, S. Moscato, G. Bertoni, A. Falqui, S. Berrettini, M. Petrini, V. Mattoli and A. Menciassi, *ACS Nano* **4**, 6267 (2010).
61. O. Stephan, Y. Bando, A. Loiseau, F. Willaime, N. Shramchenko, T. Tamiya and T. Sato, *Appl. Phys. A: Mater. Sci. Process.* **67**, 107 (1998).
62. D. Golberg, Y. Bando, O. Stephan and K. Kurashima, *Appl. Phys. Lett.*, **73**, 2441 (1998).
63. K. S. Novoselov, D. Jiang, F. Schedin, T. J. Booth, V. V. Khotkevich, S. V. Morozov and A.K. Geim, *P. Natl. Acad. Sci. U.S.A.* **102**, 10451 (2005).
64. M. Corso, W. Auwarter, M. Muntwiler, A. Tamai, T. Greber, J. Osterwalder, *Science* **303,** 217 (2004).
65. K. F. Huo, Z. Hu, F. Chen, J. J. Fu, Y. Chen, B. H. Liu, J. Ding, Z. L. Dong and T. White, *Appl. Phys. Lett.* **80,** 3611 (2002).
66. Y. J. Chen, H. Z. Zhang and Y. Chen, *Nanotechnology* **17,** 786 (2006).
67. S. K. Gupta, H. R. Soni and P. K. Jha, *AIP Advances* **3**, 032117 (2013).
68. P. K. Jha and H. R. Soni, *J. Appl. Phys.* **115**, 023509 (2014).
69. H. R. Soni and P. K. Jha, *Solid State Commun*. **189**, 58 (2014).