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Exploring the sensing potential of Fe-decorated h-BN toward harmful gases: a DFT study

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Gas sensing technology has a broad impact on society, ranging from environmental and industrial safety to healthcare and everyday applications, contributing to a safer, healthier, and more sustainable world. We studied pure and Fe-decorated hexagonal boron nitride (h-BN) gas sensor for monitoring of carbon-based gases using density functional theory (DFT). The calculations utilized the Generalized Gradient Approximation with the Perdew–Burke–Ernzerhof (GGA-PBE) exchange–correlation functional. The novelty of our study lies in the investigation of the adsorption of harmful gases such as carbonyl sulfide, carbinol, carbimide, and carbonyl fluoride on both pure and Fe-decorated h-BN. The deviation in structural, electronic, and adsorption properties of h-BN due to Fe decoration has been studied along with the sensing ability to design said material towards carbon monoxide (CO), carbon dioxide (CO₂), carbonyl sulfide (COS), carbinol, (CH₄O), carbimide (CH₂N₂), and carbonyl fluoride (CF₂O) gases. Gases such as CO, COS, CH₂N₂, and CF₂O exhibited chemisorption, while CO₂, and CH₄O exhibited physisorption behavior. The introduction of Fe altered the semiconductor properties of h-BN and rendered it metallic. Enhanced electronic properties were observed due to a robust hybridization occurring between the d-orbitals of Fe-decorated BN and the gas molecules. The extended recovery periods observed for gases, aside from CO₂, indicate their adhesive interactions with Fe-decorated h-BN. The reduction in desorption duration as temperature rises allows Fe-decorated h-BN to function as a reversible gas sensor. This research opens up a novel pathway for the synthesis and advancement of cost-effective, environmentally friendly double-atom catalysts with high sensitivity for capturing and detecting molecules such as CO, COS, CH₂N₂, CO₂, CH₄O, and CF₂O.

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1. Introduction

Gas sensing has garnered significant interest in the modern world's management of climate pollution due to its widespread application in industrial control, medical treatment, indoor air quality management, and various other domains. Scientists have started looking into alternative sensing materials in response to the increased demand for gas sensors that are particularly sensitive, specific, stable, reversible, and versatile.^{1–5} In recent times, there has been a significant increase in the concentrations of harmful gases such as CO,

CO₂, NO, NH₃, and SO₂ in the atmosphere.^{6,7} In the context of gas-sensing applications, a wide range of structures with diverse sizes, including bulk materials, have undergone considerable advancements.⁸ The remarkable electrical conductivity, minimal electrical interference, and substantial surface-to-volume ratio of two-dimensional (2D) materials have harvested considerable attention.⁹ The groundbreaking discovery of graphene has sparked a substantial increase in researcher interest in 2D materials. However, due to its low sensitivity and zero band gap, graphene is not ideal for sensing applications.¹⁰ Graphene, the initial elemental 2D structure to be synthesized, has been utilized for detecting hazardous gases such as CO, NO, NO₂, NH₃, and more.¹¹ Lately, methods like atom substitution, adsorption, and the fabrication of heterostructures have been utilized to enhance the magnetic and electrical characteristics of 2D materials. These advancements find applications across various domains, including gas sensing, rechargeable batteries, and spintronics.^{12–17}

Researchers have identified hexagonal boron nitride (h-BN), which shares similarities with graphene, as a valuable material for gas-sensing applications. In comparison to graphene, h-BN offers superior structural, chemical, and enhanced optical

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properties, in addition to possessing a wide band gap and impressive thermal stability.^{18–20} It emerges as a viable material for gas detection due to its exceptional thermal stability and impressive thermal conductivity, particularly in challenging environmental conditions. Both through computational simulations and empirical observations, various gas molecules have been found to adsorb onto the surface of h-BN, including but not limited to NO₂, NO, NH₃, CO, CH₄, and H₂.^{21,22} In our prior research, a monolayer of h-BN was computationally designed and employed as a substrate to enhance the mechanical, electronic, and thermal properties of borophene for use in lithium-ion batteries as well as for gas sensing applications.^{23,24}

Zhu *et al.* created a lateral heterojunction model through the synthesis of h-BN-graphene, observing variations in the bandgap of graphene with changes in the proportion of h-BN. Furthermore, they established adsorption structures for HCN, CO, NH₃, and Cl₂, conducting energy band calculations separately for the h-BN and Graphene segments within the h-BN-graphene lateral heterojunctions. In another study, the adsorption behavior of various gas molecules, including H₂S, SO₂, NH₃, and NO₂, was investigated on a diboron dinitride monolayer with point defects.^{25,26}

Various approaches were undertaken to investigate the potential applications of h-BN, including the introduction of Fe doping on BN to examine its role in enhancing CO oxidation activity,²⁷ a computational design was employed to create a bilayer of h-BN for the assessment of its gas-sensing capabilities towards gases like CO₂, NO₂, and SO₂.²⁸ Additionally, dopants such as silver, silicon, manganese, and cobalt have been introduced into h-BN to augment its capability to adsorb a wide range of harmful gases.^{29–31} To date, there have been no documented instances of utilizing Fe decoration on h-BN for the detecting of harmful gases.

In this research, we explore the adsorption of harmful gases, which include CO, CO₂, COS, CH₄O, CH₂N₂, and CF₂O, on Fe-decorated h-BN with the aim of assessing their potential for gas sensing applications. We systematically studied the structural parameters, adsorption properties, charge transfer, electronic properties, and sensing performance of the said material. The findings from these result analyses indicate that Fe-decorated h-BN displays favorable attributes for applications in detecting noxious gases.

2. Computational details

All computations were performed utilizing the Linear Combination of Atomic Orbitals (LCAO) approach within the BAND module of the Amsterdam Density Functional (ADF) software.³² In ADF-BAND, we employed Slater-type orbital basis functions, renowned for their precision in modeling electron interactions near the nucleus. In our calculations, we employed the TZP basis set, conducting all-electron calculations without any core orbital restrictions.^{33,34} The structural geometry was optimized without imposing any constraints. The calculations utilized the Generalized Gradient Approximation with the Perdew–Burke–Ernzerhof (GGA-PBE) exchange-correlation functional.³⁵

The Kohn–Sham equations were solved for both the hexagonal lattice unit cell and the supercell of h-BN. The structural optimization utilized the quasi-Newton optimization method, specifically designed for handling delocalized modes when updating coordinates. Input files and parameters were configured through the graphical user interface (GUI) of the BAND code. BAND allows for the selection of periodicity/dimensions (1D for chains, 2D for slabs, and 3D for bulk) to implement periodic boundary conditions. Starting with the hexagonal unit cell of h-BN, simulations were conducted in both bulk and slab periodicities to investigate the material's 2D properties. Various electronic properties were examined using different parameters. Single point (SP) calculations were employed to compute nuclear gradients and derivatives of the Hessian for the optimized geometry, enabling the assessment of electronic properties.^{32,34,36,37} We employed the D3-Grimme correction (DFT-D3) to account for van der Waals (vdW) effects, thereby enhancing the accuracy of the representation of long-range interactions between gas molecules and Fe-decorated h-BN.³⁸ The convergence criteria were set as energy (10^{−5} eV), gradient (0.02 eV Å^{−1}), and step-convergence (10^{−3} Å) for all structure relaxation.

The following equation was employed to calculate the binding energy

$$E_b = E_{(\text{Fe-decorated BN})} - E_{\text{BN}} - E_{\text{Fe}} \quad (1)$$

where E_b is the binding energy, $E_{(\text{Fe-decorated BN})}$ is the energy of the Fe decorated h-BN, E_{BN} is the total energy of the pristine h-BN, and E_{Fe} is the total energy of the Fe metal.^{39,40}

The following equation was utilized to calculate adsorption energy

$$E_{\text{ads}} = E_{(\text{material+gas})} - (E_{\text{material}} + E_{\text{gas}}) \quad (2)$$

Here $E_{(\text{material+gas})}$ is the sum of the total energy of the gas on the Material, E_{material} is the energy of the Fe-decorated h-BN, and E_{gas} is the total energy of a gas molecule.^{17,39} Using the Hirshfeld charge analysis method, we computed the charge transfer between the gas molecules and Fe-decorated h-BN.

3. Results and discussion

3.1. Geometry exploration

In this context, we are discussing the optimal configuration of both the pure and Fe-decorated h-BN, as illustrated in Fig. 1a and b. We opted a 4 × 4 × 1 cell configuration to construct h-BN, each B and N contained 12 atoms. The lattice parameters of pure h-BN are $a = 10.25$ Å and $b = 8.85$ Å. The band distance between B–N is 1.48 Å. The angle between B–N–B or N–B–N are found to be same as 120°. The average B–N bond lengths appear to remain consistent even after the adsorption of a Fe atom. These findings align well with the information found in the existing literature.^{29,30}

There are four possible adsorption sites on h-BN: the hollow (H), top on the nitrogen site (N), top on the boron site (B) and between the boron and nitrogen atom as (Br). These adsorption sites for Fe atom are labelled in Fig. 1a. The hollow site



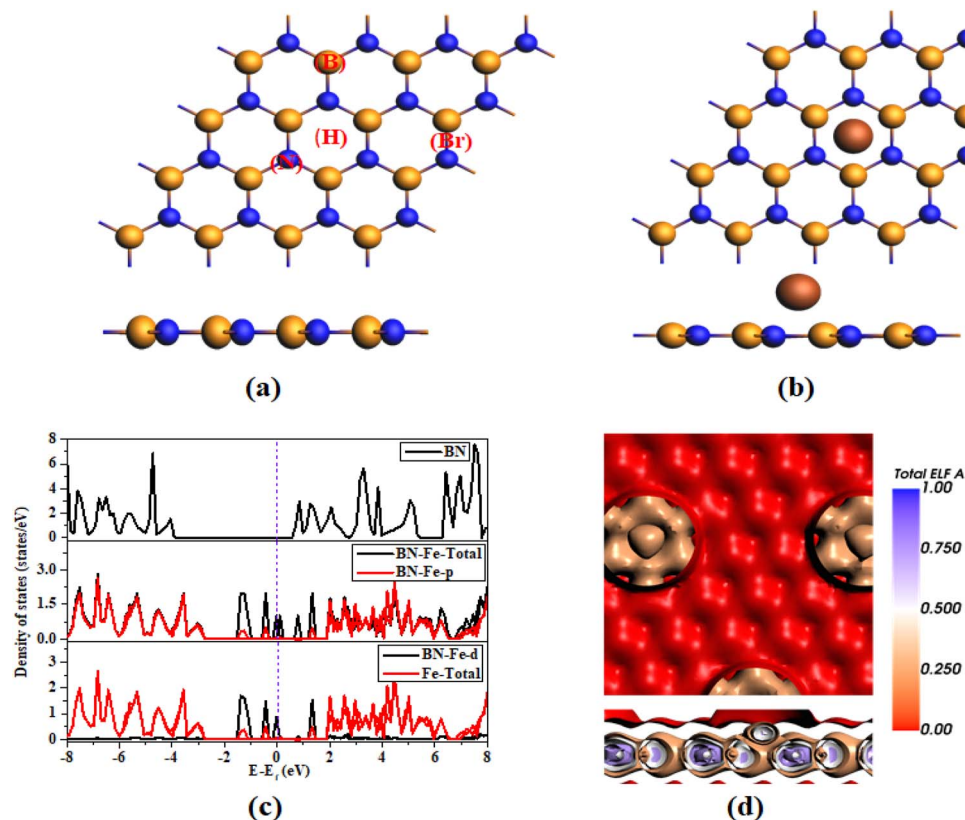


Fig. 1 Optimized geometry of (a) pure (b) Fe-decorated (c) DOS of pure and Fe-decorated h-BN (d) ELF map of Fe decorated h-BN.

appeared as preferable site due to its highest negative adsorption energy. The Fe decorated on the H site of the -BN has binding energy of -4.07 eV. The negative binding energy value indicates that the adsorption of Fe on h-BN is thermodynamically stable.

The Fig. 1c presents the DOS for both pure h-BN and Fe-decorated h-BN. The Fig. 1c shows the semiconducting behavior of h-BN with band gap of (4.5 eV) and after the adsorption of Fe on h-BN its behavior changes from semiconductor to metallic. The total DOS for the Fe-decorated h-BN monolayer exhibits a noticeable leftward shift when compared to the TDOS of the pure h-BN, indicating a transition to lower energy levels. Simultaneously, there is an overlap between the valence and conduction bands. This overlap contributes to the metallic bonding and allows electrons to move easily between energy states, resulting in a substantially higher electron distribution compared to the pristine h-BN monolayer. This suggests an enhancement in the substrate's conductivity following the introduction of Fe doping. These alterations demonstrate a shift in the system's behavior, there is a large number of available states at Fermi level for electrons to occupy. This contributes to the high conductivity of metallic materials. The contribution of the p-orbital to the DOS collectively forms both the valence band (VB) and conduction band (CB) in the system, as illustrated in Fig. 1c. The system's metallic behavior can be attributed to the presence of the d orbital within the system in combination with the total DOS of the Fe element. Additionally, the states of Fe significantly contribute to the

formation of the VB and CB, as illustrated in Fig. 1c. These findings suggest a substantial alteration in the electronic structure of h-BN due to the incorporation of Fe. The resulting increased stability of the structure contributes to improving its gas-sensing performance. These results are consistent with the literature.^{27,31}

3.2. The adsorption of gases on pure and Fe-decorated h-BN

In this section, we will explore the effectiveness of Fe-decorated h-BN in adsorbing gases such as CO, CO₂, COS, CH₄O, CH₂N₂ and CF₂O. To achieve highly stable adsorption arrangements, gas molecules are initially placed in different orientations in proximity to Fe-decorated h-BN. Fig. 2 illustrates optimized configurations after the adsorption of gases on Fe-decorated h-BN, displaying views from both the x-axis and z-axis perspectives. From the Fig. 2, it is evident that CO, COS, CH₂N₂, and CF₂O exhibit chemisorption behavior, whereas the others display physisorption. The carbon atoms of gases (CO, COS, and CH₂N₂), whereas the oxygen atom of the gas CF₂O, are attached to the Fe atom, confirming chemisorption behavior.

Table 1 presents the values for adsorption energy. The presence of negative values in the adsorption energy indicates that all the adsorption systems release energy, making them exothermic and facilitating spontaneous reactions. In case of pure h-BN the CF₂O exhibits highest adsorption energy while CO shows lowest. Regarding Fe-decorated h-BN, CF₂O gas displayed the highest adsorption energy at -7.2 eV, while CO₂



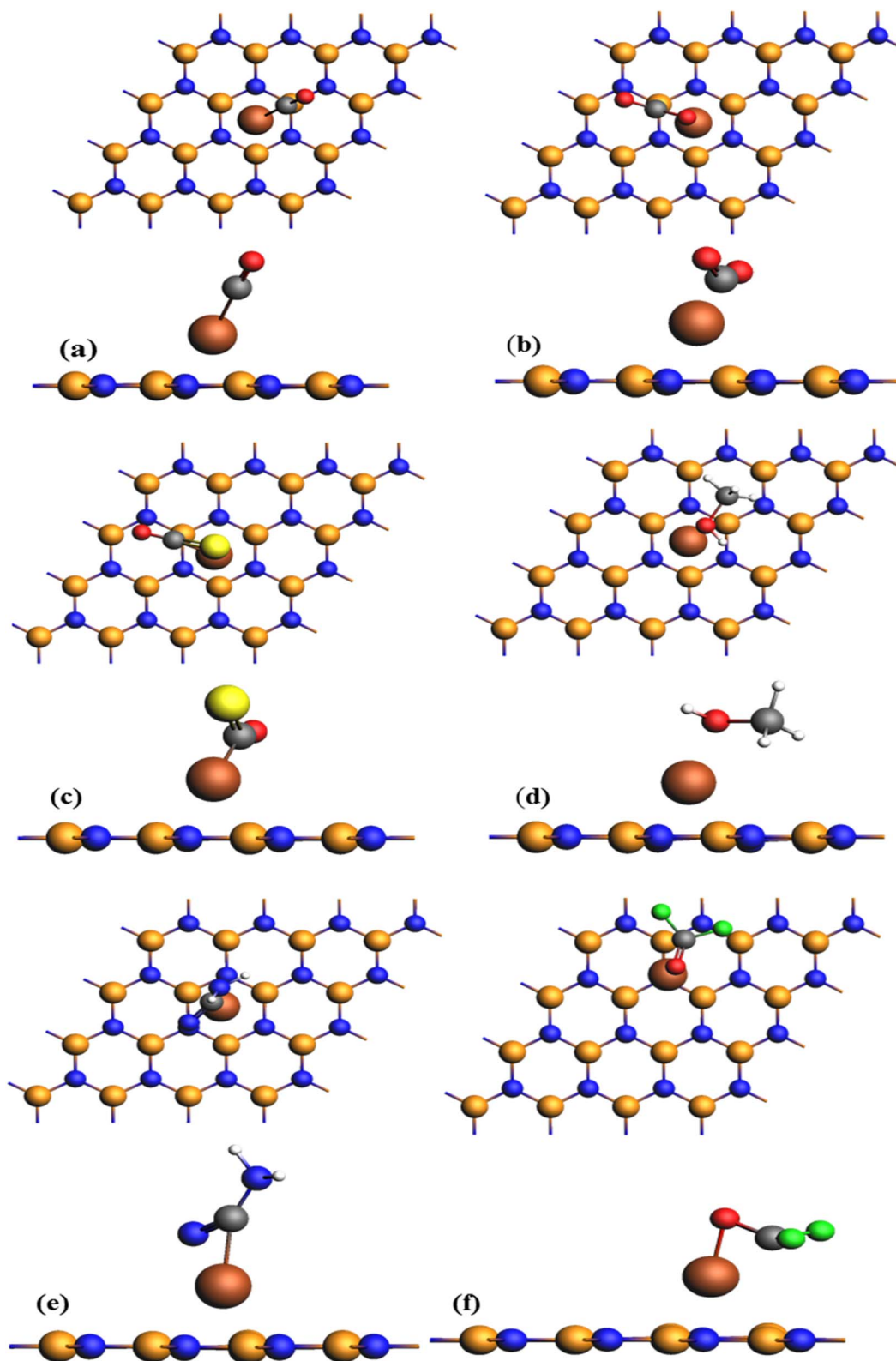


Fig. 2 Optimized structures of different gases such as (a) CO (b) CO₂ (c) COS (d) CH₄O (e) CH₂N₂ (f) CF₂O adsorbed on Fe-decorated h-BN.

exhibited the lowest at -1.42 eV. This also confirms the weak or physisorption behavior of CO₂. The better adsorption energy (most negative) suggests that the adsorption of a gas on the

material is more intensive and energetically favorable.^{42–46} Therefore, Fe decoration enhanced the adsorption energy values than pure h-BN.



Table 1 Adsorption energy values of adsorbed gases on pure and Fe-decorated h-BN

Literature/gases (eV)	CO	CO ₂	COS	CH ₄ O	CH ₂ N ₂	CF ₂ O
Boron nitride (this work)	-1.28	-1.42	-1.78	-2.36	-3.47	-6.41
Fe-decorate h-BN (this work)	-5.79	-1.42	-2.89	-3.168	-4.47	-7.2
Fe-decorated antimonene ¹⁷	-2.35	—	-2.31	—	—	—
Fe-doped Al ⁴¹	-2.11	—	—	—	—	—

In our earlier investigation, antimonene was adorned with iron (Fe), and its gas sensing capabilities were explored. Various noxious gases, including CO, COS, NO, NO₂, NH₃, and SO₂, were adsorbed onto the Fe-decorated antimonene. The corresponding adsorption energy values were determined as -2.35 eV, -2.31 eV, -3.69 eV, -2.19 eV, -0.24 eV, and -1.54 eV. The elevated values of adsorption energy position this material as highly promising for applications in gas sensing.¹⁷

L.-Y. Guo *et al.* adsorb the silver (Ag) atom on pure h-BN to study the harmful gases such as NO, NO₂, and SO₂F₂. They found the adsorption energy values as -0.817 eV, 1.893 eV, and -1.361 eV respectively. The adsorption of an Ag atom on BN exhibits a pronounced adsorption effect on gases, which can assist in discerning gas type, concentration, and production rate.³⁰ M. T. Ahmed *et al.* doped cobalt (Co) and manganese (Mn) on h-BN to study it for hazardous gases PH₃, NH₃, CH₄, O₃, H₂S, and SO₂. The doping of Co changed the behavior of h-BN to conductor while Mn changed it to semiconductor. The adsorption energy found negative for all the studied gases that confirms the exothermic behavior.²⁹

Pandey *et al.* investigated the adsorption characteristics of three environmentally significant gases H₂, CO, and NO on both the pristine aluminene surface and the aluminene surface substituted with transition metal (TM) atoms. Interestingly, enhanced adsorption is observed for all gases on the TM-substituted aluminene compared to the pristine case. The recovery time results suggest that the adsorption of H₂ and CO gases on pristine aluminene, as well as H₂ gas on TM-functionalized aluminene surfaces, holds promise for use as a reusable gas sensor and for gas storage with subsequent facile release.⁴¹

In our prior study, we utilized computational methods to design interfaces involving borophene and boron nitride for the purpose of sensing industry-related gases, including CO, NO, CO₂, NH₃ and NO₂. The adsorption energy values for these gases are -2.7 eV, -1.8 eV, -3.7 eV, -3.4 eV and 4.0 eV.²⁴

Nemati-Kande *et al.* studied the adsorption of different halomethanes such as CH₃F, CH₃Cl and CH₃Br on pristine, Al- and Ga-doped BN.⁴⁷ Esrafil *et al.* doped carbon on h-BN and studied its sensing properties for NO and NO₂ toxic gases. The inference drawn suggests that the adsorption of CO, CO₂, H₂O, or NH₃ on C-doped h-BN sheets is significantly less pronounced in comparison to NO and NO₂. The adsorption energy values decorated with C on B sites are -1.37 eV, -2.17 eV while on N site -1.77 eV and -2.49 eV.⁴⁸ This suggests that the adsorption of a Fe atom onto h-BN enhances the adsorption energies for all the gas systems studied.

3.3. Geometric analysis before and after gases adsorption

The significance of h-BN is indeed underscored by numerous studies focusing on its synthesis and characterization. For instance, Nicolosi *et al.* provided experimental validation of the hexagonal structure of boron nitride nanosheets, employing techniques like transmission electron microscopy (TEM), X-ray diffraction (XRD), and scanning electron microscopy (SEM). Wang *et al.*, in a separate investigation, presented experimental findings on the synthesis and characterization of graphene/h-BN heterostructures, which further affirmed the hexagonal lattice arrangement of boron nitride layers. Additionally, Kim *et al.* detailed experimental methodologies for the controlled synthesis of hexagonal boron nitride monolayers, complemented by geometric characterization utilizing atomic force microscopy (AFM) and high-resolution transmission electron microscopy (HRTEM). These studies collectively contribute to the extensive body of research supporting the understanding of h-BN and its properties.^{49–52}

Fig. 2 illustrates the optimized arrangements of CO, CO₂, COS, CH₄O, CH₂N₂, and CF₂O molecules when adsorbed on Fe-decorated h-BN. The bond lengths of CO before optimization is (Fe–C) is 1.73 Å and (Fe–O) is 1.90 Å. After optimization, the bond length (Fe–C) increases to 1.77 Å and (Fe–O) is 2.94 Å. It displayed high chemisorption and interaction behavior. The COS gas molecule had the same behavior, with increase in bond length of (Fe–C) from 1.73 Å to 1.77 Å, and (Fe–O) bond length also increases from is 1.90 Å to 2.94 Å. A large change occurs in between the bond lengths of Fe and O. Due to low interaction with the Fe-decorated h-BN, CH₄O and CO₂ gas molecules showed physisorption behavior. The bond length before adsorption for CO₂ gas molecules is (Fe–O) is 2.54 Å and (Fe–C) is 2.22 Å, after adsorption it increases to (Fe–O) is 3.02 Å and (Fe–C) is 1.93 Å. For gas CH₄O bond length (Fe–C) is 1.95 Å before adsorption, after adsorption bond length (Fe–C) become 2.96 Å. The bond length before adsorption (Fe–C) is 1.44 Å and 1.57 Å for CH₂N₂ and CF₂O gas molecules, respectively, while it increases to (Fe–C) 1.87 Å and 1.93 Å.

The interactions between the mentioned gases indicate that Fe-decorated h-BN demonstrates chemisorption behavior with CO, COS, CH₂N₂, and CF₂O, while CH₄O and CO₂ exhibit physical adsorption.

3.4. Electronic properties analysis

The Density of States (DOS) distribution is of paramount importance for analyzing orbital interactions in each of the depicted adsorption systems in Fig. 3. It facilitates a more



profound understanding of the electronic analysis of gas and its adsorption on Fe-decorated h-BN.

Fig. 3 illustrates the d- and total DOS profiles of Fe, capturing the characteristics of the conduction and valence bands within the Fe-decorated h-BN. The adsorption of CO and carbinol gases did not alter the behavior of the Fe-decorated h-BN, while the other gases induced a shift in behavior towards a semiconductor-like characteristic. Hybridization was identified among the DOS of the gas, Fe, and d states within the system at the Fermi level, serving as confirmation of the metallic behavior associated with the adsorption of CO and carbinol.

Prominent resonance peaks within the valence band, observed among the DOS of the gas, Fe, and d-states of the system, provide confirmation of the chemisorption behavior exhibited by CO, COS, CH_2N_2 , and CF_2O gases. These peaks were detected within the energy ranges of (0 eV to -1 eV), (-0.4 eV to -2 eV), (-0.1 eV to -2.5 eV), and (-0.4 eV to -1.3 eV) for the gases CO, COS, CH_2N_2 , and CF_2O , respectively. Furthermore, the DOS behavior of the Fe-decorated h-BN is inhibited by CO_2 gas, with no evidence of hybridization. This validates the physisorption nature of the gas interaction with the material.

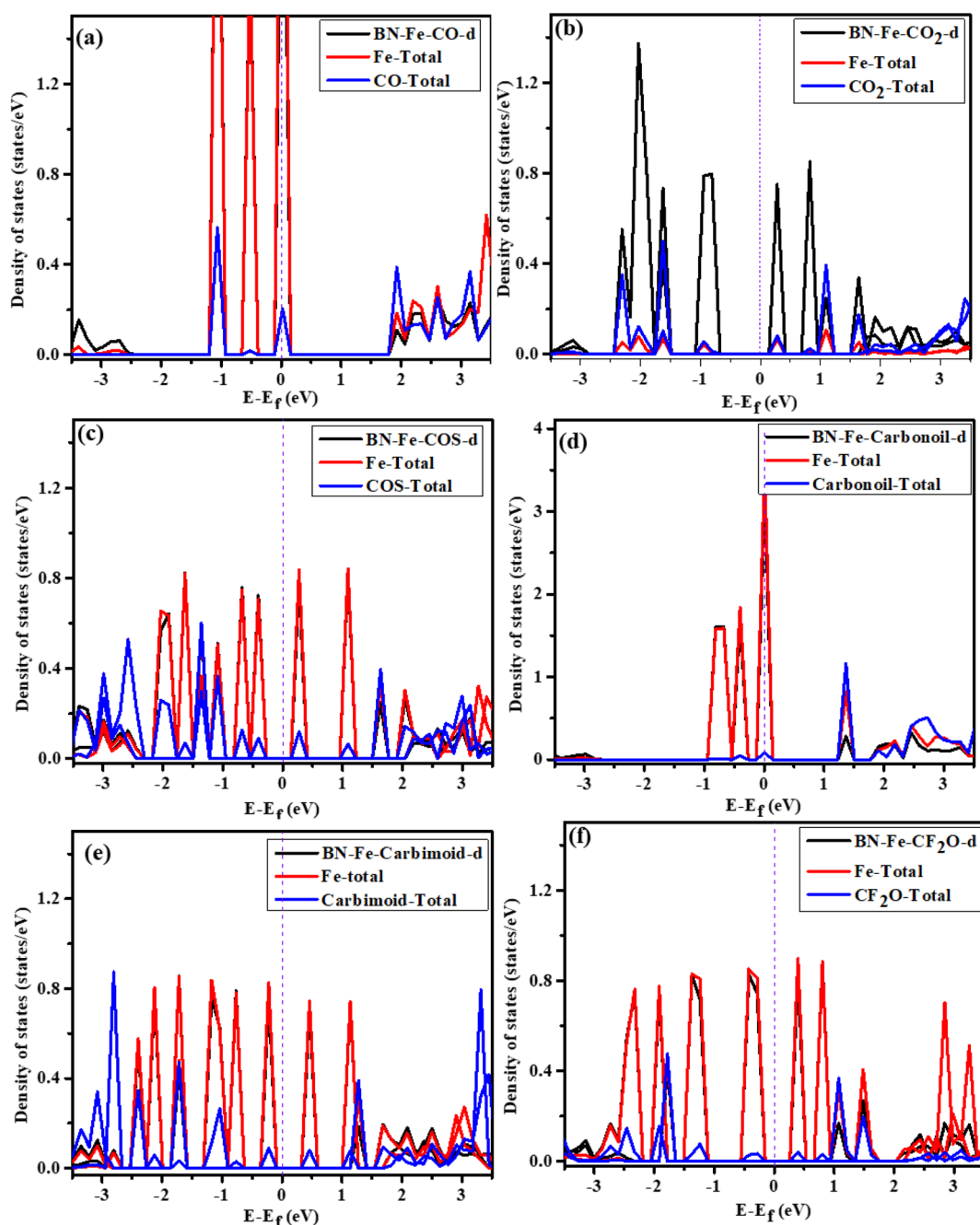


Fig. 3 Density of States of the adsorption of (a) CO (b) CO_2 (c) COS (d) CH_4O (e) CH_2N_2 (f) CF_2O gases on Fe-decorated h-BN.



In conclusion, the gases CO, COS, CH₂N₂, and CF₂O exhibit enhanced electrical properties due to their hybridization with Fe-decorated h-BN, and this correlation aligns well with the adsorption energy. In addition, the analysis of gas adsorption for all these gases reveals noble metallic behavior, which is conducive to gas detection.

3.5. Charge investigation

We investigate interaction of gas molecules with the h-BN coated with Fe using Hirshfeld charge analysis. The introduction of Fe onto pure h-BN induces alterations in its electronic properties. While the initial band gap of pure h-BN is 4.5 eV, indicative of its semiconducting nature, this characteristic transforms into a metallic behavior upon Fe adsorption. The observed reduction in the band gap serves as compelling evidence for the substantial interaction between Fe metal and the h-BN surface. This interaction is primarily attributed to the electron-withdrawing effect exerted by the electron-rich nitrogen atoms of h-BN, causing a transfer of electronic density from Fe metal to h-BN. This charge transfer mechanism is responsible for the semiconductor-to-metal transition in the Fe/h-BN system, presenting it as a promising sensor for detecting the adsorption of specific hazardous molecules.⁵³

Table 2 presents the charge values for systems with adsorbed gas on Fe-decorated h-BN. Evaluating the adsorption and detection of gases on the substrate can be assessed through charge analysis. The charge analysis shows that, on average, 0.209e charges are moved from the B atoms to the nearby N atoms because the N atom has a higher electronegativity, demonstrating that the pure BN's B–N bonds are somewhat ionic. Upon gas adsorption, boron and nitrogen atoms exhibit a partial negative and positive charge, respectively.

As electropositive elements, Fe displays the most substantial partial positive charges within the structure of Fe-decorated h-BN. Due to the attraction of electrons toward the electronegative elements in the adsorbed gas molecules; the partial positive charge of Fe became enhanced. Due to their electronegativity, the elements (N, O, S, and F) have partially negative charges, indicating that they are electron acceptors. The partially positive charges on the elements (B, Fe, and H) indicate that B, Fe, and H are electron donors.

In CH₄O, the C atom has a partially negative charge, whereas in CO, COS, CO₂, CH₂N₂, and CF₂O, it shows a partially positive

charge. As a result, the C atom acts as an electron acceptor in the CH₄O molecule but an electron donor in the CO, COS, CO₂, CH₂N₂, and CF₂O molecules as shown in the Table 2. In CO and CO₂ gases, the carbon (C) atom transfers a charge of $-0.146e$ and $-0.185e$ to the oxygen (O) atom, respectively. Similarly, the O and S atoms in COS gas molecules develop charges of $-0.176e$ and $-0.071e$, correspondingly, due to charge transfer from C atoms.

3.6. Possibility of gas sensor

Usually, the adsorption of gases onto a host material results in changes in its electronic properties. The DOS results for Fe-decorated h-BN with adsorbed gases indicate alterations in the band gap due to gas adsorption. This alteration in the bandgap due to gas adsorption is a contributing factor to the changes in electrical conductivity. Let's examine the potential use of Fe-decorated h-BN as a gas sensor. Crucial factors such as sensitivity, stability, selectivity, and recovery, along with adsorption attributes like charge transfer and adsorption energy, are pivotal in modifying the DOS and enhancing electrical conductivity. These characteristics are essential for a material to function effectively as a reliable gas sensor.⁵⁴ When a gas molecule chemically bonds to the 2D sheets, resulting in a substantial E_{ads} value (indicative of chemisorption), it is usually accompanied by a significant exchange of charge and a reduction in the separation distance between the molecule and the sheet. Under such circumstances, the sheet has the potential to serve as a proficient gas sensor for the detection and sensing of gas molecules.⁴¹ Therefore, the significant E_{ads} values suggest that gas molecules predominantly undergo chemisorption on both pure and Fe-decorated h-BN, except for a few instances like COS and CH₄O, which exhibit a preference for physisorption.

The evaluation of a gas sensor's sensitivity involves comparing the electrical conductivity (σ) of the systems before and after the adsorption of gas. The bandgap and temperature can be used to determine a material's electrical conductivity (σ) using the formula.^{55–57}

$$\sigma = A \exp\left(\frac{-E_g}{2K_B T}\right) \quad (3)$$

Here, A is certain constant, T represents the temperature at 300 K; K_B stands for Boltzmann's constant, and E_g denotes the band

Table 2 Hirshfeld Charge distribution of pristine and gas-adsorbed Fe-decorated h-BN

Elements	BN (e)	Fe-BN (e)	Fe-BN + CO (e)	Fe-BN + CO ₂ (e)	Fe-BN + COS (e)	Fe-BN + CH ₄ O (e)	Fe-BN + CH ₂ N ₂ (e)	Fe-BN + CF ₂ O (e)
B	0.209	0.205	0.212	0.213	0.216	0.203	0.212	0.214
N	-0.209	-0.205	-0.207	-0.206	-0.206	-0.210	-0.207	-0.203
Fe	—	0.175	0.063	0.150	0.089	0.019	0.063	0.177
C	—	—	0.013	0.127	0.041	-0.019	0.005	0.159
O	—	—	-0.146	-0.185	-0.176	-0.111	—	-0.201
S	—	—	—	—	-0.071	—	—	—
H	—	—	—	—	—	0.059	0.130	—
N	—	—	—	—	—	—	-0.159	—
F	—	—	—	—	—	—	—	-0.092



Table 3 Electrical conductivity (σ) for the remarked gases at different temperatures

Gases	σ ($\Omega^{-1} \text{ m}^{-1}$) at $T = 300 \text{ K}$	σ ($\Omega^{-1} \text{ m}^{-1}$) at $T = 600 \text{ K}$	σ ($\Omega^{-1} \text{ m}^{-1}$) at $T = 900 \text{ K}$
CO ₂	4.97×10^{-9}	7.01×10^{-5}	1.7×10^{-3}
COS	1.2×10^{-5}	3.4×10^{-3}	2.2×10^{-2}
CH ₂ N ₂	2.96×10^{-6}	1.71×10^{-3}	1.43×10^{-2}
CF ₂ O	2.15×10^{-7}	4.62×10^{-4}	5.97×10^{-3}

gap of the configurations. Table 3 shows the electrical conductivity at different temperature.

Our calculations show that the bandgap of Fe-decorated h-BN, adsorption of CO and CH₄O are 0 eV. Therefore, their conductivity becomes maximum. A slight shift in the bandgap causes an immediate change in electrical conductivity. After gas adsorption, the gas molecules CO, COS, CO₂, CH₄O, CH₂N₂ and CF₂O have different band gaps: such as (0 eV, 0.58 eV, 0.99 eV, 0 eV, 0.66 eV and 0.79 eV) respectively.

The conductivity of COS is greater as compare to other gases mentioned in the table because it has small band gap. With rising temperature, conductivity also experiences an increase. Table 3 reveals a direct relationship where conductivity increases as the temperature rises.

The formula for sensitivity (S)^{58,59} is

$$\text{Sensitivity, } S = \left| \frac{\sigma_{\text{gas}} - \sigma_{\text{pure}}}{\sigma_{\text{pure}}} \right| \times 100\% \quad (4)$$

Here, σ_{gas} and σ_{pure} indicate to the electrical conductivity of the gas-adsorbed and pure systems, respectively. CO, and CH₄O, have 100% sensitivity whereas CO₂, COS, CH₂N₂ and CF₂O each have different. The bar chart in Fig. 4a illustrates that CF₂O exhibits the highest sensitivity, followed by COS, surpassing all other gases. Thus, all gas molecules show preferred detection on Fe-decorated h-BN surfaces. Selectivity is determined by dividing the most sensitive gas by all the other gases, as illustrated in the corresponding plot in Fig. 4b. CF₂O has sensitivity ratios of 1.05 to COS, 1.63 to CO₂, 1.24 to CO, 6.20 to CH₄O, and 11.27 to CH₂N₂ respectively. The results indicate that the sensor exclusively identifies CF₂O when it is present.

Apart from sensitivity, stability is another critical attribute of an effective gas sensor. If gas adsorption doesn't cause structural distortion, it is expected that the sheet will retain its stability. Therefore, it is reasonable to infer that the analyzed substrates remain stable when exposed to the gas adsorption under consideration.

We conducted a comparative analysis to measure the selectivity of these gases by calculating the ratios of the gas that exhibited the highest sensitivity to the others. In terms of a gas molecule's selectivity when interacting with a sheet, preference is given to the gas molecule with a higher observed E_{ads} over the one with a lower E_{ads} . Our adsorption energy results unequivocally show that CF₂O gas molecules exhibit the highest degree of adsorption on the analyzed surfaces, followed by CO, and then the other gases as outlined in Table 1.

Selectivity is evaluated by dividing the most sensitive gas by all the other gases, and you can see the corresponding chart in Fig. 4b. CF₂O exhibits sensitivity ratios of 1.63 to CO₂, 1.05 to COS, and 11.27 to CH₂N₂, respectively. The corresponding bar chart is displayed in Fig. 4b. These outcomes indicate that the sensor specifically identifies CF₂O in its presence. The selectivity among all gases becomes evident when compared to each other, primarily due to the substantial charge transfer between the gas and the surface, as well as a notable change in the electronic DOS following CO gas adsorption in contrast to the other two gas molecules.

3.6.1 Recovery time analysis. Evaluating sensors relies heavily on reusability, which typically represents the minimal duration necessary for a sensor to release adsorbed gases from its surface. To thoroughly assess the potential of Fe-decorated h-

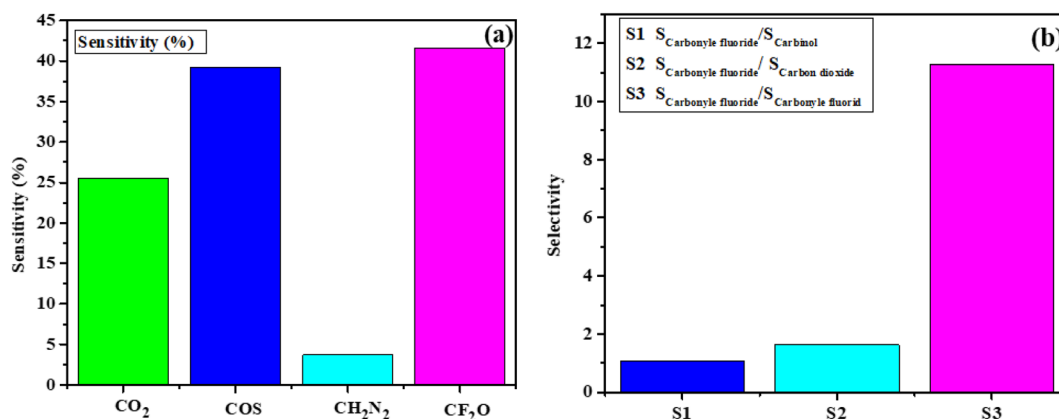


Fig. 4 (a) Sensitivity of the gas sensor based on Fe-decorated h-BN towards gas molecules, including carbon dioxide, carbonyl sulfide, carbimide, and carbonyl fluoride. (b) The selectivity of Fe-decorated h-BN sensor for carbonyl fluoride detection.



BN as a gas sensor, this section is dedicated to investigating the minimum desorption time required for six gases to detach from the surface of the sensing material, which is Fe-decorated h-BN. The recovery time measures the duration it takes for the gas to dissipate from the surface of the material, serving as a crucial metric for evaluating the detectability capability of sensing materials. The Van't Hoff–Arrhenius expression can be employed for the calculation of the recovery time in alignment with the principles of state theory.⁶⁰

$$\tau = \nu_0^{-1} \exp\left(\frac{-E_{\text{ads}}}{K_{\text{B}}T}\right) \quad (5)$$

where K_{B} is the Boltzmann's constant ($8.62 \times 10^{-5} \text{ eV K}^{-1}$), T is the temperature, and frequency $\nu_0 = 10^{12} \text{ s}^{-1}$.^{16,61} In order to achieve reversible gas capture, the adsorption energies should fall within the range of -0.60 to -1.0 eV , respectively.⁶² A greater E_{ads} would increase the challenge of gas desorption, but an increase in temperature would considerably expedite the process. The usability of the sensor relies on the recovery time values, which range from milliseconds to a few seconds. Nevertheless, an excessively brief recovery time implies inadequate adsorption capability, making it impractical for effective gas detection in the first place.⁵⁹ A more negative adsorption energy corresponds to an extended duration. Conversely, smaller values indicate reversible gas sensors. In this study, the recovery time is evaluated under conditions of visible light exposure and at different temperature. Table 1 displays the recovery times for all the examined gases computed at various temperatures.

Ahmed *et al.* employed first principles to explore the gas sensing application of cobalt- and manganese-doped boron nitride nanosheets. The calculated recovery time for the pristine material falls within the range of 10^{-12} s to 10^{-8} s , while the doping of Co and Mn increases it to 10^{38} s and 10^{41} s , respectively, attributed to higher adsorption energies.²⁹

Xu *et al.* investigated the adsorption behaviors of H_2S , SO_2 , NH_3 , and NO_2 gas molecules on strategically defective diboron dinitride (n-BN) monolayers under various conditions, including the presence and absence of an external electric field and moisture. Recovery times for H_2S , NH_3 , SO_2 , and NO_2 on the n-BN monolayer were calculated at temperatures of 300 K, 473 K, 573 K, and 673 K. At 300 K, it is observed that H_2S , SO_2 , and NO_2 exhibit prolonged recovery times, measuring $2.4 \times 10^{14} \text{ s}$, $5.9 \times 10^{43} \text{ s}$, and $1.6 \times 10^{54} \text{ s}$, respectively, indicating challenges in desorption from the surface. Conversely, NH_3 demonstrates a shorter recovery time of 2.7 s at room

temperature, showcasing its potential for efficient reuse in gas sensing and capturing applications.²⁵

The greater recovery times for all gases at $T = 300 \text{ K}$ demonstrate their strong interaction with the Fe-decorated h-BN. In other words, the desorption of CO , CO_2 , COS , CF_2O , and CH_4O gases from the surface is essentially impossible. For practical use, it is too difficult because the high gas recovery time of the Fe-decorated h-BN. The values of desorption time decrease, as the temperature rises as in Table 4. As a result, at high temperatures, the Fe-decorated h-BN behaves as a reversible gas sensor.

Therefore, the Fe-decorated h-BN sensor is ideal for gas sensing.

3.7. Electron localization function (ELF) analysis

The Electron Localization Function (ELF) serves as a valuable tool in quantum chemistry for scrutinizing electron distribution within a system, furnishing insights into the probability of locating an electron at a specific spatial point. ELF pertains to the kinetic energy density, serving as a metric for assessing both the concentration and dispersion of electrons.^{63,64} The ELF ranges from 0.5 to 1.0, encompassing both bonding and nonbonding electron regions. Within this range, localized electron positions, such as those within a nucleus shell, covalent bonds, or a lone pair, are commonly observed. ELF values ranging from 0.0 to 0.5 signify weak van der Waals interactions, while electron delocalization occurs between electron shells.⁶⁵

The colors discernible in the ELF map mirror these distinct electron density patterns. Within our investigation, these colors denote potential variations in electron density and bonding attributes. Fig. 1d displays the ELF of Fe-decorated h-BN. The red hue observed on the h-BN sheet and brown around the Fe atoms, hints at interactions between the metal atoms and the adjacent atoms in the h-BN sheet. These interactions encompass charge transfer between the Fe and h-BN.

ELF analysis also reveals regions of higher electron density. Fig. 5 illustrates the ELF images of gases adsorbed on Fe-decorated h-BN, displaying some variations in electron density for COS , CH_4O , and CH_2N_2 adsorbed on Fe-decorated h-BN. In contrast, CO , CO_2 , and CF_2O adsorbed on Fe-decorated h-BN exhibit a consistent brown coloration around the gas, akin to Fe-decorated h-BN. However, there are observable pattern changes resulting from gas adsorption on Fe-decorated h-BN.

Table 4 Recovery time for the mentioned gases at different temperatures

Gases	τ (s) at $T = 300 \text{ K}$	τ (s) at $T = 600 \text{ K}$	τ (s) at $T = 900 \text{ K}$	τ (s) at $T = 1200 \text{ K}$
CO	2.50×10^{85}	4.98×10^{36}	2.92×10^{20}	2.23×10^{12}
COS	3.40×10^{36}	1.85×10^{12}	1.50×10^4	1.36
CO_2	7.03×10^{11}	8.39×10^{-1}	8.89×10^{-5}	1.60×10^{-7}
CH_4O	1.51×10^{41}	3.99×10^{14}	5.42×10^5	1.99×10^1
CH_2N_2	1.61×10^{63}	3.40×10^{25}	1.05×10^{13}	5.85×10^6
CF_2O	5.41×10^{108}	2.87×10^{48}	2.02×10^{28}	1.69×10^{18}



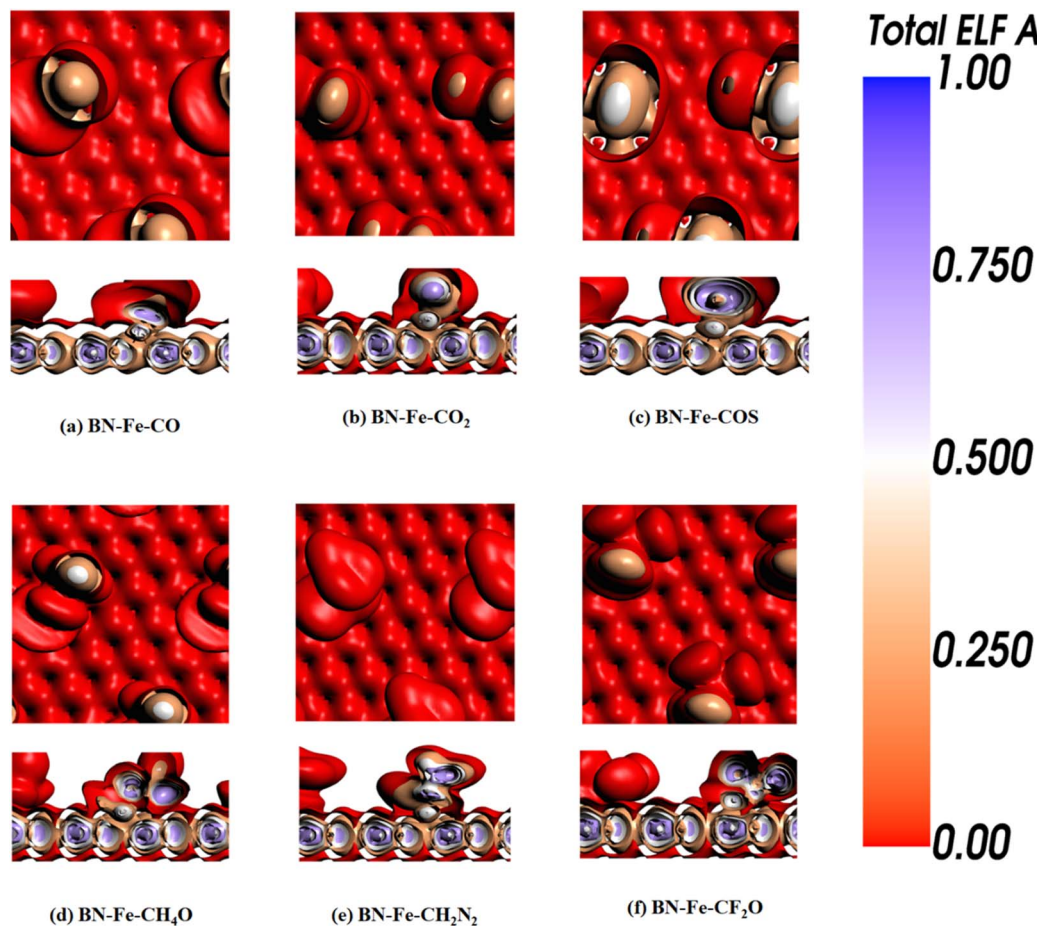


Fig. 5 ELF map of B_4C_3 monolayer adsorbed with 3d-TM. (a) BN-Fe-CO, (b) BN-Fe-CO₂, (c) BN-Fe-COS, (d) BN-Fe-CH₄O, (e) BN-Fe-CH₂N₂, (f) BN-Fe-CF₂O. The ELF values for the red, white, and blue colored sections are 0.00, 0.50, and 1.0, respectively.

4. Conclusions

We employed van der Waals dispersion-corrected Density Functional Theory (DFT) to investigate the adsorption of harmful gases, specifically CO, CO₂, COS, CH₄O, CH₂N₂, and CF₂O, on both pristine and Fe-decorated h-BN. The behavior of h-BN shifted from its semiconductor nature to a metallic state upon the adsorption of the Fe atom. The adsorption energy values experienced an increase upon the decoration of Fe on h-BN. Therefore, Fe-decorated h-BN is preferable than pure. CO₂ and CH₄O gases demonstrate physisorption, whereas CO, COS, CH₂N₂, and CF₂O gases exhibit chemisorption behavior. Among the gases, CF₂O had the highest adsorption energy, while CO₂ exhibited the lowest. The DOS results indicate that the adsorption of CO and CH₄O gases does not alter the conductive behavior of Fe-decorated h-BN. Performing accurate DFT calculations for systems involving gas molecules and surfaces can be computationally expensive, especially for large or complex systems. This may limit the size of the system that can be effectively studied. Involving of Basis Set Superposition Error (BSSE) corrections may improve the results. The sensitivity values for CO and CH₄O are both determined to be 100%, while the sensitivity for other substances varies. CF₂O has sensitivity

ratios of 1.05 to COS, 1.63 to CO₂, 1.24 to CO, 6.20 to CH₄O, and 11.27 to CH₂N₂ respectively. Results show that the sensor only detects CF₂O when it is present. The extended recovery times for all gases at $T = 300$ K demonstrate their strong interaction with the Fe-decorated h-BN. ELF analysis are well agreed with the hirshfeld charge analysis. Moreover, the brown coloration indicates a concentrated electron density in regions where CO, CO₂, and CF₂O are adsorbed onto the h-BN sheet, suggesting the potential presence of covalent or polar covalent bonds involving carbon, oxygen, and fluorine atoms in CO, CO₂, and CF₂O with the h-BN sheet. Furthermore, at elevated temperatures, it might serve as a reversible gas sensor. These discoveries provide valuable theoretical insights for advancing the experimental design of innovative gas detection sensors incorporating Fe-decorated h-BN.

Conflicts of interest

The authors declare no conflict of interest.

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