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A direct four-electron process on Fe–N₃ doped graphene for the oxygen reduction reaction: a theoretical perspective†

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As one of the potential candidates for electrocatalysis, non-precious transition metal and nitrogen co-doped graphene has attracted extensive attention in recent years. A deep understanding of the oxygen reduction reaction (ORR) mechanism including the specific active sites and reaction pathways will contribute to the further enhancement of the catalytic activity. In this study, the reaction mechanism for ORR on Fe–N₃ doped graphene (Fe–N₃-Gra) is investigated theoretically. Our results show that Fe–N₃-Gra is thermodynamically stable. The ORR elementary reactions take place within a small region around the Fe–N₃ moiety and its adjacent six C atoms. HOOH does not exist on the catalyst surface, indicating a direct four-electron process for Fe–N₃-Gra. The kinetically most favorable pathway is O₂ hydrogenation, in which the formation of the second H₂O is the rate-determining step with an energy barrier of 0.87 eV. This value is close to 0.80 eV for pure Pt, suggesting that Fe–N₃-Gra could be a potential electrocatalyst. Free energy changes at different electrode potentials are also discussed.

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1. Introduction

Fuel cells (FCs) have attracted worldwide attention because of their high energy conversion efficiency, high power density, and low emission.¹ The electrochemical performance of a fuel cell largely relies on the oxygen reduction reaction (ORR) at the cathode which determines the efficiencies of the energy conversion and storage. The ORR is, however, sluggish and thus a highly efficient cathode catalyst is required.^{2,3} Up to now, the most effective cathode catalysts for the ORR have been the Pt-based catalysts.^{4–6} Nonetheless, their large-scale commercial applications are limited by high cost, poor CO

tolerance, and low durability and stability.⁷ Therefore, alternative materials that are earth-abundant, cost-effective and have high catalytic activities comparable to or higher than those of Pt-based catalysts are in demand. In this aspect, the pioneering work was done by Jasinski in 1964, which reported that the cobalt phthalocyanine could be used as catalyst for oxygen reduction.⁸ Based on this idea, in recent years, the transition metal-coordinated (*e.g.*, Fe, Co and Mn) nitrogen-doped carbon matrix (M–N_x-C) electrocatalysts for the ORR have been studied extensively as promising alternatives to Pt-based catalysts in experiments.^{9–18} The non-precious metal catalysts derived from polyaniline, iron, and cobalt show high catalytic activity with remarkable performance and stability as well as excellent four-electron selectivity (hydrogen peroxide yield <1.0%).⁹ The current density of the cathode made with the microporous Fe–N_x-C catalyst could be equal to that of a Pt-based cathode at a cell voltage of larger than 0.9 V.¹⁰ The Co–N_x co-doped graphene has comparable ORR performance to the commercial Pt–C electrocatalysts.¹³ The Mn-doped glycine-derived carbon catalyst has a high catalytic activity for the ORR and low half-wave potential than that of commercial Pt–C.¹⁷ Furthermore, theoretical studies have been also available for M–N_x-C electrocatalysts for the ORR^{19–23} and these studies revealed that they possess high catalytic activity for the ORR.

Among the M–N_x-C catalytic systems, Fe–N_x-C electrocatalysts are studied most both experimentally^{9–12,18,24–27} and theoretically.^{19,20,28–32} In-depth structure-to-property relation

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† Electronic supplementary information (ESI) available: Fig. S1 is possible configurations for each adsorbed species (side-on O₂, end-on O₂, O + O, O, OH, OOH, O + OH, OH + OH, H₂O and H) involved in the ORR on the Fe–N₃ embedded in graphene (Fe–N₃-Gra). Fig. S2 is O hydrogenation into OH (d₁). Fig. S3 is the HOOH decomposed process with time. See DOI: 10.1039/c7ra03157b



presents an evidence that Fe–N_x centers are the active sites playing a key role in oxygen reduction reaction.¹¹ Indeed, Fe–N₄ moiety as the catalytic active site was observed by diverse experimental studies.^{24,33,34} The atomic structure of highly active Fe–N₄-Gra has been analyzed by X-ray absorption spectroscopy²⁴ and high-resolution transmission electron microscopy.³⁵ The current density of ORR to the number of in-plane Fe–N₄ centers was identified using Mössbauer spectra.³³ Theoretical studies also confirmed that Fe–N₄ doped graphene has high catalytic activity for ORR comparable to that of Pt catalyst with Fe–N₄ moiety as active sites.^{19,20,31} The most favorable reaction pathway for Fe–N₄ doped graphene is a four-electron OOH dissociation process.²⁰ Besides Fe–N₄, Fe–N₃ doped carbon matrix has been also studied for ORR in the pyrolyzed catalyst.^{11,12} The experimental study suggests that the Fe–N₃ doped graphene also exhibits high ORR activity, high stability, and low H₂O₂ production.³⁶ Theoretical studies revealed that the Fe–N₃ doped graphene is thermodynamically stable with the negative formation energy.^{30,37} Clustered Fe–N₃ structures can cleave the O–O bond very easily.²⁹ However, up to date, the catalytic activity and the detailed mechanism for ORR remain unclear for Fe–N₃-C catalysts. In particular, for Fe–N₄ doped graphene, direct four-electron process is observed for ORR both experimentally¹² and theoretically.²⁰ For Fe–N₃ doped graphene, however, it is not clear whether it catalyzes the four-electron direct reduction of O₂ molecule to water or also catalyzes the second step HOOH reduction to water through a two-electron process.¹² Therefore, it is highly necessary to unravel the physical insights of Fe–N₃ doped graphene from the atomic and electronic point of view. To achieve this goal, the catalytic active sites and the reaction pathways for Fe–N₃ doped graphene have been studied by using the density functional theory (DFT) in this work.

2. Computational details

2.1 Methods

All spin-polarized DFT^{38,39} calculations were performed using the Vienna ab initio simulation package (VASP).^{40,41} The interactions between valence electrons and frozen cores were described by the projector augmented wave (PAW) method.⁴² The electronic exchange–correlation energy was treated by the generalized gradient approximation of the Perdew–Burke–Ernzerhof (PBE) functional.⁴³ The kinetic energy cutoff was set to be 400 eV for the plane-wave expansion. A 5 × 5 × 1 Monkhorst–Pack grid was used to provide sufficient accuracy in the integration of the Brillouin zone.⁴⁴ The transition state (TS) searches were performed by employing the climbing image nudged elastic band (CI-NEB) method,⁴⁵ and was confirmed by only one imaginary frequency on the potential energy surface. For geometry optimizations and TS searches, the convergence tolerances of the electronic and ionic iterations were set to 10^{−5} eV and 0.05 eV Å^{−1}, respectively. The van-der-Waals (vdW) interactions were considered by using the semiempirical scheme proposed by DFT-D2 method of Grimme^{46,47} in all of the calculations.

Free energy calculation of each elementary reaction on the Fe–N₃-Gra surface was performed based on computational hydrogen electrode (CHE) model suggested by Nørskov *et al.*⁴⁸ The computational detail of the free energy change (ΔG) is as follows:

$$\Delta G = \Delta E + \Delta ZPE - T\Delta S + \Delta G_{\text{pH}} + \Delta G_{\text{U}} \quad (1)$$

where ΔE is the reaction energy obtained from DFT calculations, ΔZPE is the zero point energy correction, T is the temperature (298.15 K), and ΔS is the entropy change. ΔG_{pH} is the correction of H⁺ free energy by the concentration, $\Delta G_{\text{pH}} = k_{\text{B}}T \times \ln 10 \times \text{pH}$, where k_{B} is the Boltzmann constant and $T = 300$ K. $\text{pH} = 0$ is assumed for acidic medium. $\Delta G_{\text{U}} = -neU$, where n is the number of transferred electrons and U is the electrode potential. In acidic environment, the U values range from 0 to 1.23 V.⁴⁸

2.2 Models

A 5 × 5 hexagonal supercell of graphene (containing 50 atoms) with Fe–N₃ coordinated structure (Fig. 1a) was built based on the experimental studies.^{11,12} The lattice parameters were $a = b = 12.3$ Å, and the graphene sheets were separated by a 15 Å vacuum layer along the c direction to avoid interactions between periodic images. All atoms were allowed to relax during the geometry optimization. To check the stability of Fe–N₃-Gra, the formation energy was calculated as:

$$\Delta E_{\text{f}} = E_{\text{Fe-N}_3\text{-Gra}} + 4\mu_{\text{C}} - (E_{\text{Gra}} + 3\mu_{\text{N}} + \mu_{\text{Fe}}) \quad (2)$$

where $E_{\text{Fe-N}_3\text{-Gra}}$ and E_{Gra} are the total energies of Fe–N₃ doped graphene (Fe–N₃-Gra) and the pristine graphene, respectively. μ_{C} is the chemical potential of the carbon atom defined as the total energy per carbon atom in a pristine graphene.³² μ_{N} is the chemical potential of nitrogen taken as one-half of the total

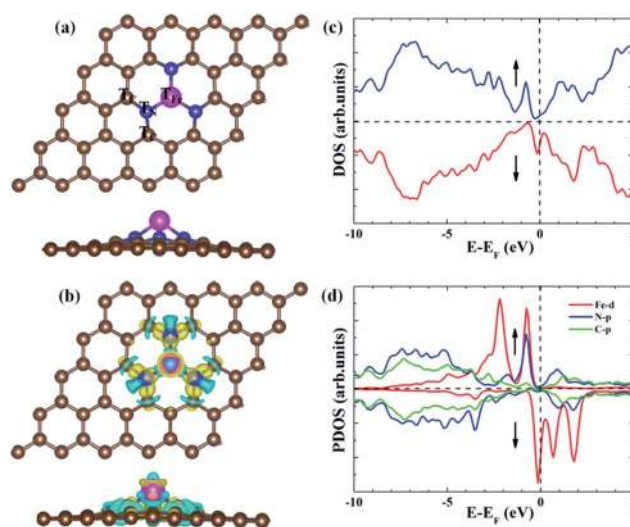


Fig. 1 (a) Possible adsorption sites on the Fe–N₃-Gra involved in the ORR. (b) The differential charge density distribution for Fe–N₃-Gra. Isosurface value = 0.01. The cyan and yellow colors represent charge accumulation and depletion, respectively. (c) The total density of states (DOS) for Fe–N₃-Gra. (d) Partial DOS for Fe–N₃-Gra.



energy of the N₂ molecule in the gas phase.^{30,37} μ_{Fe} is computed for an isolated Fe atom.^{22,37,49}

The adsorption energy (ΔE_{ads}) was calculated as:

$$\Delta E_{\text{ads}} = E_{\text{adsorbate/Fe-N}_3\text{-Gra}} - (E_{\text{adsorbate}} + E_{\text{Fe-N}_3\text{-Gra}}) \quad (3)$$

where $E_{\text{adsorbate/Fe-N}_3\text{-Gra}}$, $E_{\text{adsorbate}}$ and $E_{\text{Fe-N}_3\text{-Gra}}$ are the total energies of the Fe-N₃-Gra with adsorbate, the isolated adsorbate, and clean Fe-N₃-Gra, respectively.

3. Results and discussion

3.1 Structure and electronic properties of Fe-N₃-Gra

Compared with the formation energy of -0.95 eV from Kattel *et al.*³⁷ and -1.0 eV from Kabir *et al.*,³⁰ our calculated formation energy for Fe-N₃-Gra is -1.66 eV, slightly larger than the previous results due to the different model system and the consideration of the Van der Waals interactions in this work. The electronic density of states (DOS) (Fig. 1c) suggests that Fe atom has a finite density of states at the Fermi energy level, implying the metallic character for Fe-N₃-Gra. The partial density of states (PDOS) shows that there is a strong hybridization between the 2p orbital of N atom and the 3d orbital of Fe atom near the Fermi energy level (-1.5 to 0 eV, Fig. 1d). At the lower energy level (<-1.5 eV), the DOS is mainly contributed by the strong hybridization between the 2p orbital of N atom and the 2p orbital of C atom. These results suggest that the electronic interaction leads to the bond formation of N-Fe and N-C, resulting in lower formation energy for Fe-N₃-Gra, similar to the previous study.³⁷ Bader charge analysis reveals that Fe atom has positive charge $0.96 |e|$ for clean Fe-N₃-Gra (Table 1). The three nitrogen atoms are negatively charged by $-3.59 |e|$. The total charges of the six carbon atoms bonding to the nitrogen atoms are positively charged by $2.45 |e|$. These results reveal that due to the different electronegativity of doping atoms and carbon, the local electroneutrality is broken and charge transfer occurs. The small net charge $-0.18 |e|$ between Fe-N₃ moiety and its adjacent six carbon atoms suggests that the small region around Fe-N₃ moiety and its adjacent six carbon atoms can be served as the catalytic active center for ORR on the Fe-N₃-Gra surface. This is in

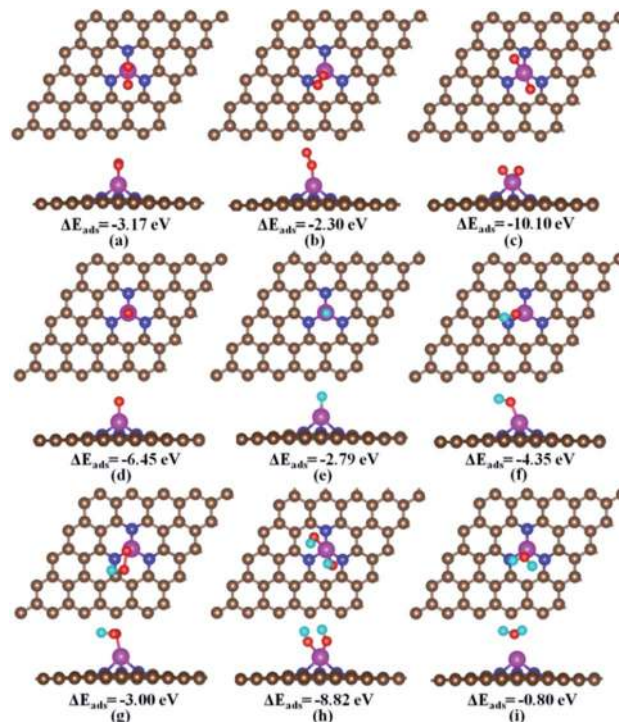


Fig. 2 The most stable adsorption configurations of the ORR intermediates on the Fe-N₃-Gra. ΔE_{ads} is the adsorption energy (eV). (a) Side-on O₂, (b) end-on O₂, (c) two separated O atoms, (d) atomic O, (e) atomic H, (f) OH, (g) OOH, (h) two OH co-adsorption, and (i) H₂O. In the figure, the brown, pink, blue, red, and cyan balls represent C, Fe, N, O and H atoms, respectively.

agreement with the charge density difference (Fig. 1b). Hence, the possible adsorption sites for the ORR intermediates are the top sites of the Fe, N and C atoms, namely T_{Fe}, T_N and T_C, as shown in Fig. 1a.

3.2 Adsorption of the ORR intermediates on the Fe-N₃-Gra

For each ORR intermediate *i.e.*, O₂, O + O, H, O, OH, OOH, HOOH, and H₂O, we optimized its various possible adsorption configurations at different adsorption sites on the Fe-N₃-Gra. The obtained stable adsorption structures and adsorption

Table 1 The Fe-O and O-O bond distance (Å) in FeN₃-Gra and Bader charge (Q [e]). Q(Fe), Q(N₃), Q(C-total) and Q(ads) refer to the total charge on Fe, N₃, the six adjacent C atoms connecting to the three N atoms, and each adsorbate, respectively. NC refers to the net change and is the sum of Q(Fe) + Q(N₃) + Q(C-total) + Q(ads). The values in the brackets are from the solvent environment

	$d_{\text{Fe-O}}$	$d_{\text{O-O}}$	Q(Fe)	Q(N ₃)	Q(C-total)	Q(ads)	NC
FeN ₃	—	—	0.96	-3.59	2.45	0.00	-0.18
Side-on O ₂	1.82(1.83)	1.42(1.44)	1.22	-3.44	2.58	-0.80	-0.44
End-on O ₂	1.69(1.70)	1.30(1.34)	1.14	-3.53	2.88	-0.62	-0.13
2O	1.63(1.66)	2.65(2.60)	1.40	-3.43	2.92	-1.23	-0.34
O	1.60(1.62)	—	1.15	-3.42	2.78	-0.65	-0.14
H	—	—	1.07	-3.62	2.97	-0.42	0.00
OH	1.76(1.79)	—	1.15	-3.41	2.39	-0.51	-0.38
OOH	1.84(1.86)	1.49(1.50)	1.25	-3.63	2.61	-0.59	-0.36
2OH	1.82(1.86)	2.67(2.64)	1.38	-3.50	2.72	-1.00	-0.40
H ₂ O	2.11(2.03)	—	1.06	-3.65	2.89	0.06	0.36



Table 2 Adsorption energies (eV) of the ORR intermediates on Fe-N₃-Gra. The values in the brackets are from the solvent environment. The comparison with other electrocatalysts is also listed

	O ₂	O	OH	OOH	H ₂ O
Fe-N ₃	-3.17 ^g / -2.30^h	-6.45	-4.35	-3.00	-0.80
Fe-N ₃ -sol	(-3.11 ^g / -2.32^h)	(-6.35)	(-4.05)	(-2.68)	(-0.83)
Fe-N ₃ ^a	-2.45	—	—	—	—
Fe-N ₂ ^b	-1.78	-5.12	-3.25	-2.08	-0.33
Fe-N ₄ ^c	-0.95	-4.37	-2.94	-1.87	-0.48
Fe-N ₄ ^d	-0.98	-4.35	-2.80	-1.76	-0.18
Fe-phthalocyanine ^e	-1.16	—	-3.41	—	-1.05
Pt(111) ^f	-0.62	-4.30	-2.21	-0.94	-0.20
Pt(100) ^f	-1.10	-4.38	-2.77	-1.30	-0.25

^a Ref. 50, doped in carbon nanotube. ^b Ref. 32. ^c Ref. 19. ^d Ref. 20. ^e Ref. 51. ^f Ref. 52. ^g Side-on configuration, this work. ^h End-on configuration, this work.

energies are shown in Fig. S1, ESI†. The most stable adsorption structures and energies are summarized in Fig. 2 and Table 2, respectively.

The favorable adsorption of the O₂ molecule on the Fe-N₃-Gra is the prerequisite for ORR to proceed. For O₂ adsorption, we obtained two adsorption configurations, that is, side-on and end-on. In the side-on configuration (Fig. 2a), the adsorbed O₂ molecule is parallel to the catalyst surface and forms two equal bond distances with Fe atom (Fe-O: 1.82 Å). The adsorption energy of -3.17 eV is stronger than that of -2.45 eV in Fe-N₃ doped carbon nanotube.⁵⁰ Upon adsorption, the O-O bond length is elongated to 1.42 Å compared with 1.22 Å in the free gas phase O₂, and the charge transfer from Fe-N₃-Gra to O₂ is -0.80 |e|, which indicates that a chemisorption exists between O₂ and Fe-N₃-Gra. This would facilitate the O₂ dissociation. For the end-on configuration (Fig. 2b), only one O atom bonds to the Fe atom with Fe-O bond distance 1.69 Å, while the other O atom is pointing away from the catalyst surface. Its adsorption energy is -2.30 eV, smaller than -3.17 eV for side-on configuration. The O-O bond length and charge transfer of end-on O₂ are 1.30 Å and -0.62 |e|, respectively. As the final state for O₂ dissociation, the two separated O atoms are co-adsorbed at top Fe site (Fig. 2c) with an energy of -10.10 eV. The charge transfer -1.23 |e| is nearly two times of the single O atom of -0.65 |e|. The adsorption energy of single O atom is -6.45 eV, which is the strongest among the studied single ORR intermediates, similar to the previous studies.^{19,20,32}

For hydrogen-containing intermediates (Fig. 2e-g), the most favorable adsorption site of H, OH, and OOH is the top Fe site with the adsorption energies of -2.79 eV, -4.35 eV, and -3.00 eV, respectively. For H atom, the second most favorable adsorption site is on the C atoms adjacent to N atoms with an adsorption energy of -1.50 eV (Fig. S1†). Since the top Fe site is always occupied by O-containing species during the reaction, the C atoms adjacent to N atoms are the primary active site for the adsorption of hydrogen in the hydrogenation reaction. For H₂O, the adsorption energy is -0.80 eV. The charge transfer from Fe-N₃-Gra to H₂O is 0.06 |e| with relatively long Fe-O distance of 2.11 Å (Fig. 2i), indicating that it might be desorbed easily from the Fe-N₃-Gra surface once it is formed.

For the HOOH species, the DFT study shows that it does not exist and is decomposed into either O + H₂O or OH + OH configurations. Quantum Chemical Molecular dynamics study confirmed this point (details concerning the computational method and corresponding results are presented in ESI†). The cleavage of O-O bond is observed at very short time (Fig. 3). Both O + H₂O and OH + OH configurations are observed depending on the different initial parameters. Therefore, the direct four-electron process occurs on the Fe-N₃-Gra surface.

3.3 ORR mechanism on the Fe-N₃-Gra

As mentioned above, the adsorption of O₂ molecule is the first step to initialize the ORR on the catalyst. Upon the O₂ adsorption, the ORR would proceed through two possible reaction pathways, *i.e.*, O₂ dissociation and O₂ hydrogenation, as shown in Fig. 4. We will introduce these reaction pathways in the following.

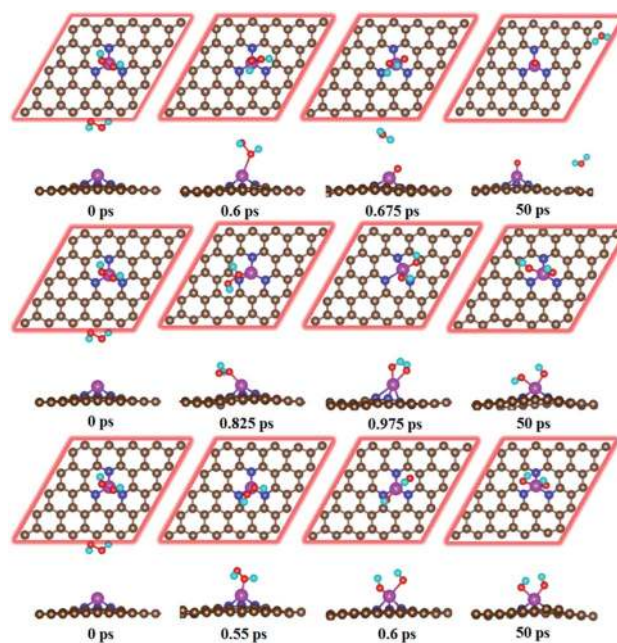


Fig. 3 Evolution of molecular dynamic simulations of the HOOH species without adsorbing ($d_{\text{Fe-O}} = 5 \text{ \AA}$) on the Fe-N₃-Gra surface at 300 K.



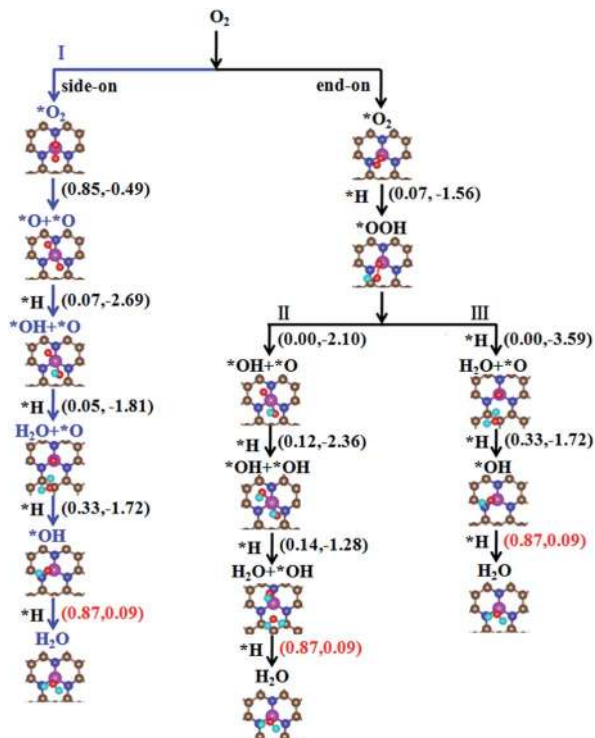


Fig. 4 Possible reaction pathways for ORR on the Fe-N₃-Gra. The numbers in parenthesis are the energy barriers and reaction energies in units of eV. * denotes that the ORR species is adsorbed on the catalyst surface.

O₂ dissociation – pathway I. For end-on configuration with smaller adsorption energy (−2.30 eV), our calculation indicates that it first converges to side-on configuration in searching the transition state of O₂ dissociation. This means that the side-on configuration is the first step in O₂ dissociation. During the reaction, the chemisorbed O₂ molecule undergoes the O–O bond cleavage to form two separated O atoms (Fig. 5a₁). At transition state, the O–O bond is enlarged to 1.80 Å compared with 1.42 Å in the initial state. For final state, the two separated O atoms are co-adsorbed at Fe atom with O–O distance of 2.65 Å. The O₂ → O + O reaction is exothermic with an energy of −0.49 eV and costs an energy of 0.85 eV, smaller than 1.19 eV (ref. 20) and 2.53 eV (ref. 19) for the O₂ dissociation in FeN₄ doped graphene. This implies that the O₂ dissociation would be relatively easy on the Fe-N₃-Gra surface. Following the O₂ dissociation, one of the O atoms is first hydrogenated to form O + OH with an energy barrier of 0.07 eV and a large of reaction energy of −2.69 eV as shown in Fig. 5b₁. After the O + OH species is generated, both the single O atom and OH will be hydrogenated. We will first discuss the hydrogenation of OH, while the hydrogenation of single O atom will be discussed in O₂ hydrogenation reaction in the following section. The hydrogenation of OH forms the first H₂O (Fig. 5c₁) with a small energy barrier of 0.05 eV. The O + OH + H → O + H₂O reaction is exothermic by −1.81 eV. After the first H₂O molecule is desorbed from the Fe-N₃-Gra surface, the remaining O atom will proceed with two sequential hydrogenation processes to form

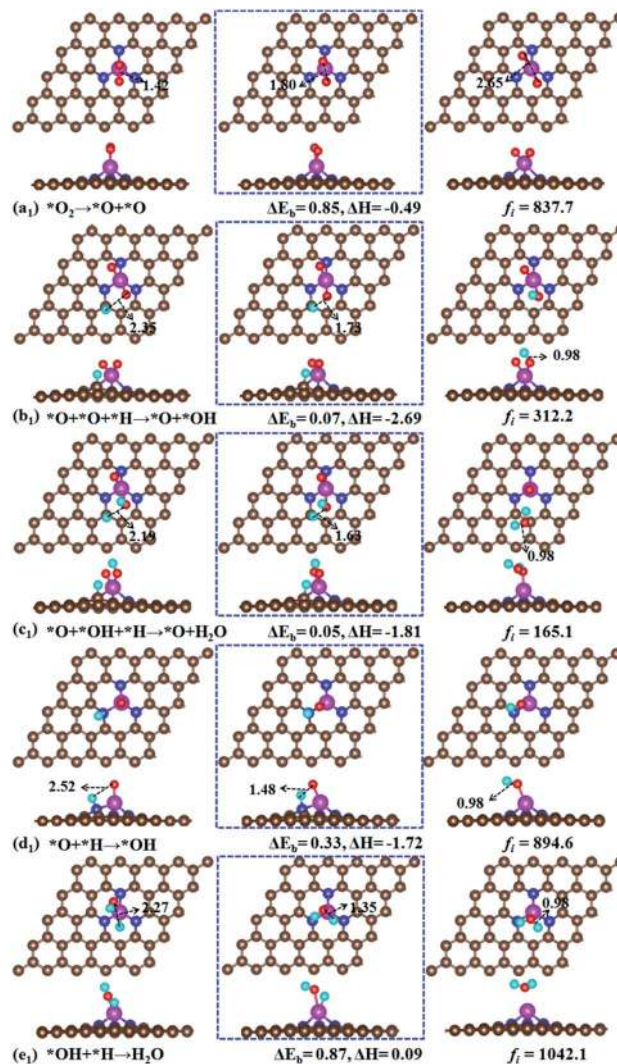


Fig. 5 Atomic structures of the initial state (left panel: IS), transition state (middle panel: TS), and final state (right panel: FS) for O₂ dissociation (a₁), atomic O hydrogenation (b₁), first H₂O formation (c₁), OH formation (d₁) and second H₂O formation (e₁). ΔE_b is the energy barrier (eV) and ΔH is the reaction energy (eV). f_i is the imaginary frequency for the transition state [cm^{-1}].

the second H₂O (Fig. 5). For the O + H → OH reaction, H atom would adsorb on either top C site or top N site, because the total energy of the two adsorbed system is nearly the same. For H atom adsorbed at top C site, the reaction needs to overcome an energy barrier of 1.09 eV (Fig. S2†), while the energy barrier is only 0.33 eV for H atom adsorbed on the top N site. This means that the hydrogenation of O atom with H adsorbed at top N site is kinetically favorable. This result also suggests that the reaction process depends strongly on the location of the introduced H atom. For the last hydrogenation step of OH, the OH and H co-adsorbed at top Fe site is energetically more favorable than H adsorbed at top C or top N site. The formation of second H₂O has an energy barrier of 0.87 eV with a slight endothermic reaction energy of 0.09 eV. If H atom first adsorbs at top C or N site, our calculation indicates H atom will first bond with Fe atom, then start the reaction with OH to form the second H₂O.



O₂ hydrogenation. For side-on O₂ configuration, our calculations show that the hydrogenation of O₂ molecule gives O + OH. That is, O–O bond is broken and OOH species is not formed. For end-on O₂ configuration, OOH species can be formed (Fig. 6f₁). For the O₂ + H → OOH reaction, it has a small energy barrier of 0.07 eV and a large exothermic reaction energy of –1.56 eV. The results suggest that O₂ hydrogenation to form OOH species is very easy. Following the OOH formation, there are two possible pathways, that is, OOH direct dissociation into O + OH and OOH hydrogenation into O + H₂O or OH + OH.

OOH dissociation – pathway II. For OOH → O + OH reaction, the OOH is spontaneously dissociated into O + OH without any barrier and large reaction energy of –2.10 eV. This is different from Fe–N₄ doped graphene, in which OOH dissociation needs to overcome an energy barriers of 0.56 eV (ref. 20) and 1.18 eV.¹⁹ Following the formation of co-adsorbed O + OH, the further hydrogenation would give either O + H₂O or OH + OH. The former reaction has been already discussed in O₂ dissociation section (pathway I in Fig. 4). Therefore, we only discuss the later reaction in the following. For O + OH + H → OH + OH reaction, this process needs an energy barrier of 0.12 eV and is exothermic by –2.36 eV (Fig. 6g₁). The following hydrogenation reaction OH + OH + H → OH + H₂O has an energy barrier of 0.14 eV and a reaction energy of –1.28 eV (Fig. 5h₁). After the generated H₂O is desorbed from the Fe–N₃-Gra surface, the remaining OH at top Fe site would be hydrogenated to give the second H₂O (OH + H → H₂O in Fig. 5e₁), as also shown in pathway I, Fig. 4. After the release of the second H₂O molecule, the catalyst will be refreshed and a new cycle begins.

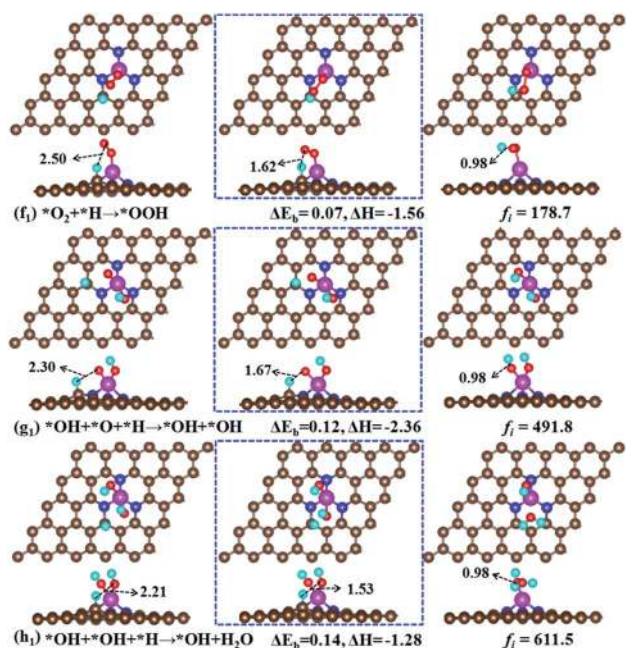


Fig. 6 Atomic structures of the initial state (left panel: IS), transition state (middle panel: TS), and final state (right panel: FS) for O₂ hydrogenation to OOH (f₁), the second OH formation (g₁), OH hydrogenation to H₂O (h₁). ΔE_b is the energy barrier (eV) and ΔH is the reaction energy (eV). f_i is the imaginary frequency for the transition state [cm⁻¹].

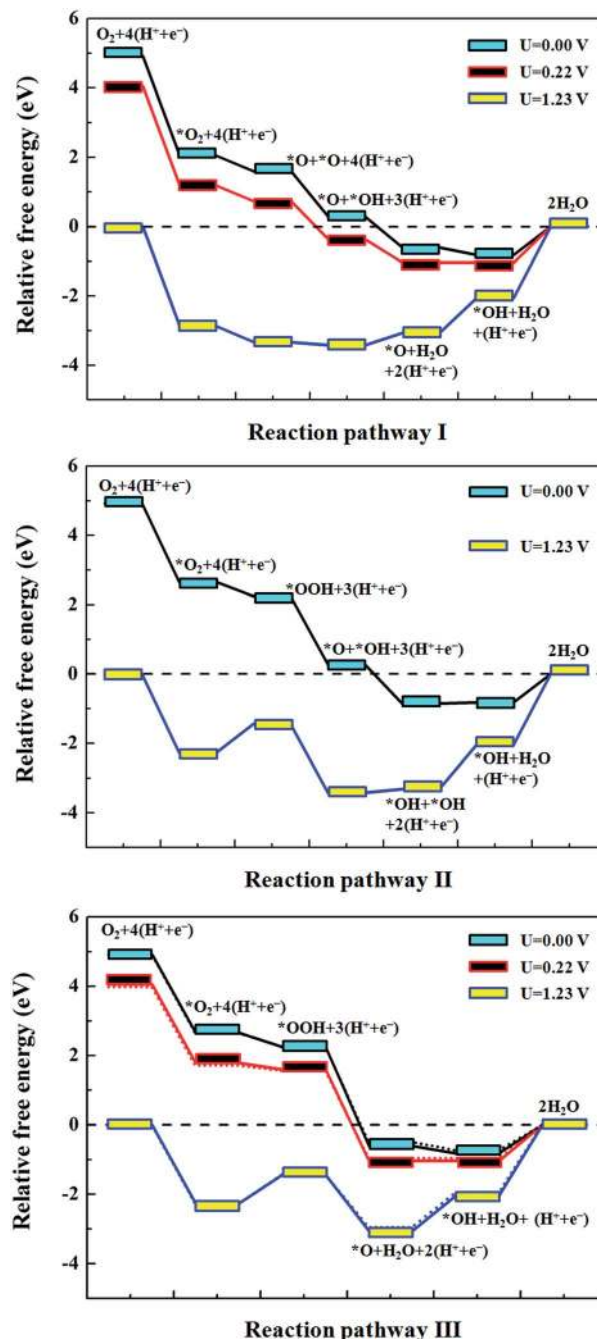


Fig. 7 The free energy diagrams for the reduction of O₂ to H₂O at different electrode potentials *U*. pathway I, O₂ dissociation; pathway II, OOH dissociation and pathway III, OOH hydrogenation; see also Fig. 4 for the detailed reaction pathways. The dotted lines in the bottom panel denote the results from the solvent environment.

OOH hydrogenation – pathway III. The hydrogenation of OOH would give HOOH, OH + OH and O + H₂O. As mentioned above, HOOH is very unstable and it dissociates into either OH + OH or O + H₂O. Meanwhile, our efforts to locate OH + OH from the direct hydrogenation of OOH also failed during the geometry optimizations. Therefore, only O + H₂O is observed. This is a spontaneous process and has more exothermic energy of



−3.59 eV. The remaining O at top Fe site will proceed directly with the two sequential hydrogenation processes to form the second H₂O (O + H → OH and OH + H → H₂O in pathway I, Fig. 4).

In a word, the four-electron ORR on the Fe–N₃–Gra surface could proceed through three possible reaction pathways (Fig. 4). The rate-determining step in the three possible pathways is the formation of the second H₂O, *i.e.*, OH + H → H₂O. The energy barrier of 0.87 eV, smaller than 0.56 eV (ref. 20) and 0.62 eV (ref. 19) for Fe–N₄ doped graphene, but close to 0.80 eV for pure Pt(111).⁵³ For Fe–N₄–Gra, the two-electron ORR is observed because HOOH species could be stably adsorbed on catalyst surface.¹⁹ However, the HOOH species will be decomposed immediately on Fe–N₃–Gra surface, suggesting a four-electron pathway. This suggests that the Fe–N₃–Gra could be a high performance catalyst for ORR. The obtained three pathways are competitive for the most favorable pathway, with the pathway of O₂ hydrogenation being slightly favored.

3.4 Effect of electrode potentials on the ORR

Since all of the above results are obtained under zero electrode potential, while in reality, electrochemical ORR at the electrode occurs under positive potentials, we studied the effect of the electrode potentials on the free energy of ORR on Fe–N₃–Gra. The free energy diagrams for three possible pathways are given in Fig. 7 based on the method of Nørskov *et al.*⁴⁸ For the three pathways, all of the reduction steps except the OH reduction to H₂O are downhill at zero potential. The endothermic process for the second H₂O formation is due to the strong adsorption of OH (−4.35 eV, Table 2) on the catalyst surface. For pathways I and III, the another step, *i.e.*, O + H₂O + H → OH + H₂O becomes uphill at potential larger than 0.22 V. A similar trend is observed after the solvent effect is considered (Fig. 7, dotted lines in the bottom panel).

4. Conclusions

Fe–N₃ doped graphene (Fe–N₃–Gra) is energetically stable. Fe–N₃ moiety and its six adjacent C atoms are the catalytic active sites for the oxygen reduction reaction on the catalyst surface. Both DFT and molecular dynamics studies indicate that HOOH does not exist on the catalyst surface, implying the direct four-electron process for Fe–N₃–Gra. O₂ dissociation and O₂ hydrogenation are competitive for the most favorable pathway, in which the pathway of O₂ hydrogenation is slightly favored. For these pathways, the rate-determining step is the formation of the second H₂O, *i.e.*, OH + H → H₂O, with an energy barrier of 0.87 eV. Due to the strong adsorption of OH on the catalyst surface, the endothermic process is observed for the second H₂O formation at zero potential.

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References

- 1 B. C. H. Steele and A. Heinzl, *Nature*, 2001, **414**, 345–352.
- 2 X. Xu, T. Yuan, Y. K. Zhou, Y. W. Li, J. M. Lu, X. H. Tian, D. L. Wang and J. Wang, *Int. J. Hydrogen Energy*, 2014, **39**, 16043–16052.
- 3 J. Snyder, T. Fujita, M. W. Chen and J. Erlebacher, *Nat. Mater.*, 2010, **9**, 904–907.
- 4 Y. J. Wang, N. N. Zhao, B. Z. Fang, H. Li, X. T. T. Bi and H. J. Wang, *Chem. Rev.*, 2015, **115**, 3433–3467.
- 5 B. Fang, J. H. Kim, M. S. Kim and J. S. Yu, *Acc. Chem. Res.*, 2013, **46**, 1397–1406.
- 6 B. Fang, N. K. Chaudhari, M. S. Kim, J. H. Kim and J. S. Yu, *J. Am. Chem. Soc.*, 2009, **131**, 15330–15338.
- 7 M. K. Debe, *Nature*, 2012, **486**, 43–51.
- 8 R. Jasinski, *Nature*, 1964, **201**, 1212–1213.
- 9 G. Wu, K. L. More, C. M. Johnston and P. Zelenay, *Science*, 2011, **332**, 443–447.
- 10 M. Lefevre, E. Proietti, F. Jaouen and J. P. Dodelet, *Science*, 2009, **324**, 71–74.
- 11 A. Serov, K. Artyushkova and P. Atanassov, *Adv. Energy Mater.*, 2014, **4**, 919–926.
- 12 K. Artyushkova, A. Serov, S. Rojas-Carbonell and P. Atanassov, *J. Phys. Chem. C*, 2015, **119**, 25917–25928.
- 13 S. Jiang, C. Z. Zhu and S. J. Dong, *J. Mater. Chem. A*, 2013, **1**, 3593–3599.
- 14 Q. Liu and J. Y. Zhang, *Langmuir*, 2013, **29**, 3821–3828.
- 15 S. H. Liu, Y. F. Dong, Z. Y. Wang, H. W. Huang, Z. B. Zhao and J. S. Qiu, *J. Mater. Chem. A*, 2015, **3**, 19657–19661.
- 16 L. L. Zhang, A. Q. Wang, W. T. Wang, Y. Q. Huang, X. Y. Liu, S. Miao, J. Y. Liu and T. Zhang, *ACS Catal.*, 2015, **5**, 6563–6572.
- 17 J. Kang, H. Wang, S. Ji, J. Key and R. F. Wang, *J. Power Sources*, 2014, **251**, 363–369.
- 18 J. Liang, R. F. Zhou, X. M. Chen, Y. H. Tang and S. Z. Qiao, *Adv. Mater.*, 2014, **26**, 6074–6079.
- 19 J. Zhang, Z. J. Wang and Z. P. Zhu, *J. Power Sources*, 2014, **255**, 65–69.
- 20 S. Kattel and G. F. Wang, *J. Phys. Chem. Lett.*, 2014, **5**, 452–456.
- 21 X. L. Zhang, Z. S. Lu and Z. X. Yang, *Int. J. Hydrogen Energy*, 2016, **41**, 21212–21220.
- 22 S. Kattel, P. Atanassov and B. Kiefer, *Phys. Chem. Chem. Phys.*, 2013, **15**, 148–153.
- 23 Z. Lu, G. Xu, C. He, T. Wang, L. Yang, Z. Yang and D. Ma, *Carbon*, 2015, **84**, 500–508.



- 24 J. B. Yang, D. J. Liu, N. N. Kariuki and L. X. Chen, *Chem. Commun.*, 2008, **3**, 329–331.
- 25 A. G. Kong, X. F. Zhu, Z. Han, Y. Y. Yu, Y. B. Zhang, B. Dong and Y. K. Shan, *ACS Catal.*, 2014, **4**, 1793–1800.
- 26 Y. S. Zhu, B. S. Zhang, X. Liu, D. W. Wang and D. S. Su, *Angew. Chem., Int. Ed.*, 2014, **53**, 10673–10677.
- 27 F. P. Pan, Q. P. Zhao, J. Wang and J. Y. Zhang, *ChemElectroChem*, 2015, **2**, 2032–2040.
- 28 H. He, Y. K. Lei, C. Xiao, D. R. Chu, R. R. Chen and G. F. Wang, *J. Phys. Chem. C*, 2012, **116**, 16038–16046.
- 29 E. F. Holby, G. Wu, P. Zelenay and C. D. Taylor, *J. Phys. Chem. C*, 2014, **118**, 14388–14393.
- 30 S. Kabir, K. Artyushkova, B. Kiefer and P. Atanassov, *Phys. Chem. Chem. Phys.*, 2015, **17**, 17785–17789.
- 31 J. Sun, Y. H. Fang and Z. P. Liu, *Phys. Chem. Chem. Phys.*, 2014, **16**, 13733–13740.
- 32 S. Kattel, P. Atanassov and B. Kiefer, *Phys. Chem. Chem. Phys.*, 2014, **16**, 13800–13806.
- 33 U. I. Koslowski, I. Abs-Wurmbach, S. Fiechter and P. Bogdanoff, *J. Phys. Chem. C*, 2008, **112**, 15356–15366.
- 34 D. H. Lee, W. J. Lee, W. J. Lee, S. O. Kim and Y. H. Kim, *Phys. Rev. Lett.*, 2011, **106**, 175502.
- 35 D. Deng, X. Chen, L. Yu, X. Wu, Q. Liu, Y. Liu, H. Yang, H. Tian, Y. Hu, P. Du, R. Si, J. Wang, X. Cui, H. Li, J. Xiao, T. Xu, J. Deng, F. Yang, P. N. Duchesne, P. Zhang, J. Zhou, L. Sun, J. Li, X. Pan and X. Bao, *Sci. Adv.*, 2015, **1**, 1500462.
- 36 H. R. Byon, J. Suntivich and Y. Shao-Horn, *Chem. Mater.*, 2011, **23**, 3421–3428.
- 37 S. Kattel, P. Atanassov and B. Kiefer, *J. Phys. Chem. C*, 2012, **116**, 8161–8166.
- 38 P. Hohenberg and W. Kohn, *Phys. Rev. [Sect.] A*, 1964, **136**, 864–871.
- 39 W. Kohn and L. J. Sham, *Phys. Rev. [Sect.] A*, 1965, **140**, 1133–1138.
- 40 G. Kresse and J. Furthmuller, *Phys. Rev. B: Condens. Matter Mater. Phys.*, 1996, **54**, 11169–11186.
- 41 G. Kresse and J. Furthmuller, *Phys. Rev. B: Condens. Matter Mater. Phys.*, 1996, **6**, 15–50.
- 42 P. E. Blochl, *Phys. Rev. B: Condens. Matter Mater. Phys.*, 1994, **50**, 17953–17979.
- 43 J. P. Perdew, K. Burke and M. Ernzerhof, *Phys. Rev. Lett.*, 1996, **77**, 3865–3868.
- 44 H. J. Monkhorst and J. D. Pack, *Phys. Rev. B: Solid State*, 1976, **13**, 5188–5192.
- 45 G. Henkelman, B. P. Uberuaga and H. Jonsson, *J. Chem. Phys.*, 2000, **113**, 9901–9904.
- 46 S. Grimme, *J. Comput. Chem.*, 2006, **27**, 1787–1799.
- 47 S. Grimme, J. Antony, S. Ehrlich and H. Krieg, *J. Chem. Phys.*, 2010, **132**, 154104.
- 48 J. K. Nørskov, J. Rossmeisl, A. Logadottir, L. Lindqvist, J. R. Kitchin, T. Bligaard and H. Jonsson, *J. Phys. Chem. B*, 2004, **108**, 17886–17892.
- 49 K. T. Chan, J. B. Neaton and M. L. Cohen, *Phys. Rev. B: Solid State*, 2008, **77**, 235430.
- 50 P. Zhang, X. F. Chen, J. S. Lian and Q. Jiang, *J. Phys. Chem. C*, 2012, **116**, 17572–17579.
- 51 R. R. Chen, H. X. Li, D. Chu and G. F. Wang, *J. Phys. Chem. C*, 2009, **113**, 20689–20697.
- 52 K. Li, Y. Li, Y. Wang, F. He, M. G. Jiao, H. Tang and Z. J. Wu, *J. Mater. Chem. A*, 2015, **3**, 11444–11452.
- 53 Z. Y. Duan and G. F. Wang, *Phys. Chem. Chem. Phys.*, 2011, **13**, 20178–20187.

