Hydrogen (H) atom adsorption and migration over heterocation doped CeO$_2$-based materials surface are investigated using density functional theory (DFT) calculations. Heterocations with smaller valence and smaller ionic radius induced the electron-deficient lattice oxygen, and the surface protonics is dominated by the H atom adsorption energy. H atom adsorption and migration over CeO$_2$-based materials are important for catalytic reactions involving hydrogen subtraction and migration (hydrogen spillover and surface protonics) and also for electrochemical devices.
Theoretical prediction by DFT and experimental observation of heterocation-doping effects on hydrogen adsorption and migration over the CeO$_2$(111) surface†

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1. Introduction

Hydrogen (H) atom adsorption and migration over a metal oxide surface are fundamentally important for various catalytic reactions, as summarized in an earlier review. Many researchers have investigated passive migration of H atoms (i.e. hydrogen spillover) that are useful for hydrogenation and dehydrogenation of hydrocarbons, CO$_2$ reduction and NH$_3$ synthesis. Furthermore, most recently, we demonstrated novel low-temperature catalysis involving H atom migration activated by an electric field, i.e. surface protonics. The electric field provokes the reaction through collision between H$^+$ over support and molecules (i.e. N$_2$, methylcyclohexane, and CH$_4$) over loading metals at the three-phase boundary (TPB). The H atom adsorption energy over metal oxides plays a fundamentally important role in catalytic reactions related to passive and electrochemically activated migration of H$^+$. Therefore, control of H atom adsorption over metal oxides is a central subject in the field of catalysts.

Doping of heterocations is a leading method among the methods that control metal oxide functions. Actually, H atom adsorption enhancement by doping has been reported for the cleavage of H–H, C–H, and O–H bonds. Therefore, elucidation of the correlation between dopant features and H atoms adsorption is highly demanded for tuning catalytic reactions involving H atoms adsorption and migration.

As described herein, we examined the doping effects on H$_2$ dissociative adsorption over the CeO$_2$ surface using irreducible divalent, trivalent, and quadrivalent heterocation-doping effects on H atom adsorption and migration over the CeO$_2$(111) surface using density functional theory (DFT) calculations. Results revealed that the electron-deficient lattice oxygen (O$_{lat}$) and the flexible CeO$_2$ matrix played key roles in strong adsorption of H atoms. Heterocations with smaller valence and smaller ionic radius induced the electron-deficient O$_{lat}$. In addition, smaller cation doping enhanced the CeO$_2$ matrix flexibility. Moreover, we confirmed the influence of H atom adsorption controlled by doping on surface proton migration (i.e. surface protonics) and catalytic reaction involving surface protonics (NH$_3$ synthesis in an electric field). Results confirmed clear correlation between H atom adsorption energy and surface protonics.

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heterocations. Additionally, the performance of doped CeO₂ was investigated experimentally using NH₃ synthesis in the electric field as a model reaction. Results confirmed close agreement with those obtained from DFT studies.

2. Method

2.1 Electronic structure calculations

We conducted DFT calculations for CeO₂(111) surfaces with dopants, as described in our earlier report. We have already confirmed the validity of the calculation conditions and models. We used the Vienna ab initio simulation program (VASP 5.4.4) for all DFT calculations. The core–valence interaction was described using the projector augmented wave (PAW) method. The valence electrons were expanded with the cutoff energy of 400 eV. We summarized the configurations of valence electrons in Table S1 (ESI†). The generalized gradient approximation (GGA) of Perdew–Burke–Ernzerhof (PBE) was applied to express the exchange correlation. Spin was polarized for all simulations. We used k-point mesh with Gaussian smearing for CeO₂ bulk (5 × 5 × 5) and slab (1 × 1 × 1) models. The energy convergence was checked with 10⁻⁵ eV criteria. The van der Waals (vdW) dispersion forces were applied using the DFT-D3 method described by Grimme. The DFT+U method was used for considering the on-site Coulomb repulsion of Ce 4f orbitals. The U value was set to 5.0 eV. We applied using the DFT-D3 method described by Grimme. The DFT+U method was used for considering the on-site Coulomb repulsion of Ce 4f orbitals. The U value was set to 5.0 eV.

2.2 Computational models

We used the CeO₂(111) surface as a repeated (4 × 4) supercell containing O–Ce–O tri-layers. The lattice constant of the DFT-optimized CeO₂ bulk structure (5.43 Å) was applied to that of slab models. Each slab was separated in the z direction with 20 Å vacuum gap. Only the bottom O–Ce–O layer was fixed during geometry optimizations without other notations. Two Ce at the uppermost surface were replaced by divalent (Ca, Sr, Ba), trivalent (Al, Ga, Sc, Y, La) and quadrivalent (Hf, Zr) cations for expressing the doped surfaces. Gaseous H₂ was placed in a 10 × 10 × 10 Å cubic box. Calculations were performed at Γ point. All calculation models were depicted as the X-ray source. The obtained powder was calcined at 773 K for 5 h with a ramping rate of 5 K min⁻¹.

5 wt% of Fe was loaded over synthesized CeO₂-based materials using a liquid-phase reduction method as reported elsewhere. First, Fe(NO₃)₃·9H₂O (Kanto Chemical Co. Inc.) was poured into distilled water. The support was dispersed in the obtained Fe aqueous solution by stirring for 1 h. Subsequently, the solution was heated at 393 K for 1 h under Ar flow. Then, 10% N₂₃H₄ solution (Fujiﬁlm Wako Pure Chemical Corp.) was added dropwise. The slurry was stirred at 393 K for 1 h under Ar flow. The slurry was filtered. The obtained cake was dried at 393 K overnight.

2.4 Activity tests

NH₃ synthesis rates were examined using a fixed bed flow type reactor equipped with a quartz tube under 0.1 MPa. 5 wt%Fe/Co. Inc.) were added. The precursors are presented in Table S2 (ESI†). A schematic image of the reactor is portrayed in Fig. S2 (ESI†). The activities were measured under N₂:H₂ = 1:3 (total flow 240 SCCM) at room temperature. Before the activity tests, pre-reduction was conducted at 773 K for 1 h under reaction conditions. The produced NH₃ was dissolved into distilled water and was quantified using an ion chromatograph (IC-2001; Tosoh Corp.).

2.5 X-ray photoelectron spectroscopy (XPS)

XPS measurements were performed using a Versa Probe II (ULvac-Phü). Al Kz as the X-ray source. The obtained binding energies were calibrated using C 1s assigned to C–H or C–C (284.8 eV). Samples (CeO₂ and Ce₀.₉M₀.₁O₂₋₄) were pre-reduced in the same manner as activity tests before XPS measurements. The pre-treated samples were transported to the measurement system without exposure to air using a transfer vessel. The peak fittings were conducted using the Proctor–Sherwood–Shirley method.

3. Results and discussion

3.1 Optimization of calculation models

Governing factors of the adsorption energies over the doped surface were investigated using the calculation flows presented in Fig. 1. Here, surfaces of two types and hydrogen adsorption energies of three types were considered. First, structures of the CeO₂(111) slab were optimized. Then, a ‘Fix surface’ and ‘Relax surface’ with heterocations were constructed. All possible arrangements of heterocations were considered similarly to our earlier study. The arrangements which exhibited the
The smallest total energies were applied to the next step. Fig. 2 portrays the obtained dopant distribution. Quadrivalent cations (Hf: 0.83 Å, Zr: 0.84 Å) and large cations with other valences (La: 1.16 Å, Sr: 1.26 Å, Ba: 1.42 Å) tend to separate from one another. Additionally, small divalent (Ca: 1.12 Å) or trivalent cations (Al: 0.54 Å, Ga: 0.62 Å, Sc: 0.87 Å, Y: 1.02 Å) favourably adjoin. The smaller the ionic radius of a heterocation, the more likely it is to cause lattice shrinkage on the CeO₂ surface. To mitigate this shrinkage, small cations need to be placed next to each other. In contrast, heterocations with large ionic radii push away surrounding atoms. To relax this distortion, the cations with larger ionic radii must exist apart from each other. It was also empirically known that the solubility of heterocations depends on ionic radii. The heterocations with lower valences also cause lattice distortion because of the change in the number of bonds allowed by the cations. Hence, the valence also affects the distribution of heterocations. In the CeO₂ matrix, Ce ions exist as quadrivalent cations. Therefore, as the next step, divalent or trivalent cation doping can be expected to induce voluntary oxygen vacancy formation. It is known that localized electron holes are formed on the lattice oxygen when metal oxides are doped with lower valence cations. The formation of electron holes by doping with lower valent cations and the compensation of the holes by the formation of oxygen vacancies were elucidated in our previous works. We examined all arrangements of oxygen vacancy at the surface and sub-surface. The sites which show the smallest oxygen vacancy formation energies were taken over for the following calculations. The obtained oxygen vacancy formation energies are presented in Table S3 (ESI†). Aside from Al-doping, the oxygen formation for charge compensation was an exothermic reaction. Peroxide (O₂⁻²⁻) was specifically formed; it compensated the charge difference as for Al-doped CeO₂(111). The obtained surfaces are depicted in Fig. 2. Those surfaces are the structure of the ‘Relax surface’ presented in Fig. 1. As the next step, the ‘Fix surface’ was constructed. Here, two of Ce were replaced by heterocations and oxygen vacancies for charge compensation were arranged (peroxide was placed over CeO₂ with Al). Then, the dopant position was optimized solely, although the other atoms were fixed. Dopants and oxygen vacancy were arranged along with the ‘Relax surface’ presented in Fig. 1. The obtained models of the ‘Fix surface’ are shown in Fig. S3 (ESI†). After that, H atom adsorptions of three types...
Fix 1 adsorption, Fix 2 adsorption and Relax adsorption were investigated using the Fix surface and Relax surface. Fix surface was applied to the calculations of Fix 1 adsorption. Only the adsorbed H atoms were relaxed in this calculation. In addition, the calculations of Fix 2 adsorption and Relax adsorption were conducted over the Relax surface. Regarding Fix 2 adsorption, only H atom was relaxed. The surfaces were optimized for the calculation of Relax adsorption. Comparison between Fix 1 adsorption and Fix 2 adsorption shed light on the effects of lattice constraint caused by heterocation-doping. Furthermore, the difference between Fix 2 adsorption and Relax adsorption shows us doping effects on surface distortion along with H atom adsorption.

3.2 Doping effects on H atom adsorption

H atoms preferably adsorb at the surface oxygen of CeO₂, where they exist as H⁺. Adsorption at all surface oxygens was considered for all doping models. Fig. 3 presents box plots of adsorption energies. The expression of $E(\text{Had})$ denotes adsorption energies of Relax adsorption, whereas $E(\text{Had}_{\text{fix1}})$ and $E(\text{Had}_{\text{fix2}})$, respectively, represent adsorption energies for Fix 1 adsorption and Fix 2 adsorption. Adsorption energies ($E_{\text{ad}}$) are calculated as eqn (1).

$$E_{\text{ad}} = \frac{E(\text{slab with H}) - E(\text{slab without H})}{1/2E(H_2)}$$

Hereinafter, $E(\text{slab with H})$ and $E(\text{slab without H})$, respectively, denote energy values of the slab with and without adsorbed H atoms. $E(H_2)$ represents the energy of gaseous H₂. Hence, the energy of H–H bond cleavage is included into the calculated $E_{\text{ad}}$. However, it is constant among all surfaces. Hence, the energy of H–H bond cleavage does not affect the trends of adsorption energies. Boxes in Fig. 3 are colored along with dopant valences. Black plots show average adsorption values. The box arrangement is determined by the ionic radius of dopants. The DFT calculations elucidated the importance of ionic radius and valence. First, results in Fix 1 adsorption (Fig. 3(a)) showed strong binding of H atoms over the divalent-cation-doped surfaces. The second was trivalent-cation-doped surfaces. The third was quadrivalent. The electron donation from cations to adjacent O_{lat} decreases as the dopant valence becomes smaller when the dopants are placed forcibly into the metal oxide matrix suitable for higher valence cations. Accordingly, doping of lower valence cations results in the formation of Lewis acid sites. Then, the H atom was anchored strongly over the divalent-cation-doped surfaces. Lattice relaxation of two types evidently changed this trend. The former is the change from Fix 1 adsorption to Fix 2 adsorption, and the latter is from Fix 2 adsorption to Relax adsorption. Smaller cation doping positively influences the H₂ dissociative adsorption as for both Fix 2 adsorption and Relax adsorption. The first reason is the change of O_{lat} charge induced by lattice distortion after doping. The Ce valence after oxygen vacancy formation depends on the Ce–O bond length. Therefore, we can assume that Ce–O bond expansion makes O_{lat} electron-deficient. In contrast, the Ce–O bond shrinkage makes the O_{lat} electron-rich. Large cations pushed the surrounding oxygen away, signaling shrinkage of the Ce–O bond as summarized in Fig. S4 (ESI†). As a result, the Lewis acidity derived from the difference of valence was moderated by the shrinkage. This moderation became smaller with the decrement in the dopant ionic radius. The change in the charge of O_{lat} by heterocation-doping and lattice distortion is summarized in Fig. S5–S10 (ESI†). In terms of Relax adsorption, the smaller cation-doped surface became more favourable sites for H atom adsorption. The difference between Fix 2 adsorption and Relax adsorption exhibited effects of lattice distortion during H₂ dissociative adsorption. A smaller cation-doped surface can take various relaxation patterns that are suitable for the acceptance of H atoms because of the spatial margin. In contrast, larger cations hinder the reconstruction of the surface along with...
adsorption. It means that the flexibility of the CeO$_2$ matrix related to H atom adsorption is an important factor for controlling adsorption energies. For this reason, H$_2$ dissociative adsorption over CeO$_2$ is facilitated by doping with small ionic radii. The salient results of DFT calculations are presented below.

1. Lower-valency dopant addition without lattice relaxation produces Lewis acid sites.
2. The Lewis acidity above is alleviated by lattice relaxation when the ionic radius of dopants is large.
3. The flexibility of the CeO$_2$ matrix was enhanced by dopants with smaller ionic radius, leading to the strong adsorption of H atoms.

### 3.3 Evaluation of OH amount using XPS

The effect of doping on H$_2$ dissociative adsorption was experimentally confirmed using XPS measurements. Fig. S14 and S15 (ESI†) represent the C 1s and O 1s spectrum of pre-reduced CeO$_2$ and Ce$_{0.9}$M$_{0.1}$O$_2$ (M: Sr, Al, Y, and Zr). Following the shape of differentiated spectra, the C 1s and O 1s spectra were decomposed into three and two components. The peaks around 285, 286 and 289 eV in C 1s spectra can be, respectively, assigned to C–C or C–H, C–O and O–C. Also, the peaks around 528 and 530 eV in O 1s spectra can be assigned to O$_{\text{lat}}$ and O–H or C–O or O–C–O, respectively. Then, the OH ratio over each sample was calculated as follows:

$$\text{OH ratio} = \frac{(\text{Area of } \text{OH} + \text{C} - \text{O} + \text{O} - \text{C} = \text{O in O 1s spectra}) - \text{RSF}_{\text{O 1s}}/\text{RSF}_{\text{C 1s}}(\text{Area of } \text{C} - \text{O} + \text{O} - \text{C} = \text{O in C 1s spectra})}{(\text{Area of } \text{O}_{\text{lat}} \text{in O 1s spectra})}$$

Here, RSF$_x$ (x = O 1s, C 1s) denotes a relative sensitivity factor reported by Ulvac-Phi Inc. Fig. 4 shows the correlation between OH ratios from XPS measurements and averages of $E(\text{H}_{\text{ad}})$ from DFT calculations using the ‘Relax adsorption’ model. Consequently, a clear correlation between experimental values and

Next, we evaluated the heterocation-doping effect on catalytic reactions involving surface protonics. NH$_3$ synthesis in the electric field was used as a model reaction. Enhancement of the NH$_3$ synthesis rate in a low-temperature region using the electric field has been reported. We obtained knowledge
that NH₃ synthesis in the electric field proceeds via the ‘associative mechanism’. The H⁺ over the support reacts with N₂ over the loading metal. Therefore, the reaction rate depends strongly on the amount of metal atoms at the periphery. Moreover, H atom stability over supports is an important factor for controlling activity. The NH₃ synthesis rate in the electric field can be a good indicator of heterocation-doping effects on H⁺ stability. Fig. 6 presents the apparent NH₃ synthesis rate and turnover frequency at the periphery (intrinsic activity at each active site, TOF-p) per unit of applied power. The TOF-p per unit of applied power was calculated as presented below.

\[
\text{TOF} = \frac{\text{Number of mols of converted N}_2 \text{ per unit time} [\text{mols}^{-1}] * \text{Imposed current [mA]} * \text{Response voltage [kV]}}{\text{Number of metal atoms at perimeter [mol]}}
\]

Metal atoms at the perimeter were counted from the metal loading weight and mean particle sizes using the hemisphere approximation of the loading Fe particle structure. Volcano plots are presented for both apparent activity and intrinsic activity at each site (Fig. 6). This dependence is also explainable by H⁺ stability over the support, as considered in H⁺ conductivity (Fig. 5). When the H⁺ binds too strongly over supports, the reactivity is limited, but excessively loose binding of H⁺ engenders a decrement of reactants (H⁺ coverage over supports). This trade-off led to the volcano type relation between DFT calculated E([H⁺]) and NH₃ synthesis rate in the electric field. In this manner, key roles of H⁺ stability over CeO₂-based materials on surface protonics and NH₃ synthesis in the electric field were elucidated by virtue of guidance given by DFT calculations, as presented in Fig. 7. Based on our findings, the optimal dopant for NH₃ synthesis in the electric field is expected to depend on temperature and H₂ partial pressure as shown below. The effect of the decrease in H⁺ coverage is more pronounced under low H₂ partial pressure, and high temperature. Hence, the doping of heterocations with a small ionic radius (e.g. Al) is optimal under such conditions. Conversely, the effect of the increase in H⁺ coverage becomes important when the H₂ partial pressure is high, and the temperature is low. Therefore, heterocations with a large ionic radius (e.g. Ba) are the best dopants.

4. Conclusions

In summary, we clarified heterocation-doping effects on H₂ dissociative adsorption over CeO₂(111) using DFT calculations. DFT-calculated adsorption energy of three types (‘Fix 1 adsorption’, ‘Fix 2 adsorption’ and ‘Relax adsorption’) shed light on the influence of dopant valence and ionic radius distinguishably. A Lewis acid site was formed with lower valence heterocation-doping (‘Fix 1 adsorption’). However, CeO₂ with lower valence dopants lost its acidity along with the lattice distortion caused by doping (‘Fix 2 adsorption’). This tendency was evident for dopants with larger ionic radii. Eventually, the addition of dopants with a small ionic radius led to strong binding of H atoms (‘Relax adsorption’). This strong adsorption resulted from the favourable lattice distortion during H₂ dissociative adsorption. Furthermore, the important role of H atom stability on surface protonics and NH₃ synthesis in the electric field was confirmed experimentally. The balance of H⁺ reactivity (mobility) and H⁺ coverage was fundamentally important for high H⁺ conductivity and catalysis involving surface protonics. Those insights for H atom adsorption over CeO₂-based materials are important not only for catalytic reactions involving hydrogen subtraction and migration.
Fig. 7  Schematic image of the correlation among H⁺ adsorption energy, and (a) H⁺ conductivity or (b) NH₃ synthesis rate in the electric field.

(hydrogen spillover and surface protonics), but also for electrochemical devices such as fuel cells and sensors.

Conflicts of interest

There are no conflicts to declare.

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References