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Atomically isolated and unsaturated Sb sites created on Sb₂S₃ for highly selective NO electroreduction to NH₃†

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Sb₂S₃ comprising an atomically isolated and unsaturated Sb (Sb_{AIU}) site is demonstrated as a fascinating catalyst for highly selective electrochemical NO-to-NH₃ conversion (NORR). Theoretical calculations reveal the crucial function of SbAIU sites to favor the adsorption and activation of NO, accelerate the protonation energetics of the NO-to-NH₃ pathway and impede the coverage of H₂O/H species, thereby boosting both NORR activity and selectivity. Consequently, the developed SbAILI-rich Sb2S3 catalyst exhibits an excellent NO-to-NH $_3$ faradaic efficiency of 93.7% and a high NH $_3$ yield rate of 168.6 μ mol h⁻¹ cm⁻², representing the highest NORR selectivity among all reported NORR catalysts.

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Introduction

Ammonia is a pivotal chemical that is widely applied in many aspects of social and economic development. 1-3 Recently, N2 electrofixation emerged as a promising technology for green NH₃ synthesis, whereas its efficiency is greatly limited by intractable issues of ultrastable N≡N bonds. 4-10 Alternatively, NO possesses a relatively low N=O bond energy and thus electrochemical NO-to-NH3 conversion (NORR) represents a more prospective approach than N2 electrofixation for NH3 electrosynthesis. 11-14 Nevertheless, the NORR effectiveness is greatly retarded by the sophisticated five-electron reaction process and severe competition from the hydrogen evolution reaction (HER), and it is imperative to explore efficient NORR electrocatalysts capable of boosting the NO-to-NH3 pathway with high selectivity. 15-20

Transition metal-based catalysts commonly exhibit high NORR activity owing to their partially occupied d-orbitals boosting NO adsorption.21-27 Nevertheless, d-orbitals also favor the formation of metal-H bonds to trigger the competitive HER, giving rise to low NORR selectivity.²⁸ Promisingly, main group p-block metals (Sb, In, Bi, etc.) are catalytically inert in the HER because of their closed d-band shells.²⁹ Meanwhile, the partially occupied p-orbitals in p-block metals are confirmed to be active for N=O bond dissociation, making p-block metal-based materials promising as a new class of NORR catalysts. 30-34 P-block Sb-based catalysts are appealing

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NORR candidates owing to the great capability of Sb sites to impede the HER and activate the nitrogen-containing molecules.35 On the other hand, catalysts with atomically isolated sites are known to present outstanding catalytic performance because of their high atom utilization and optimal binding with intermediates and reactants.36-38 Besides, defect engineering by creating vacancies or unsaturated sites is considered an effective strategy to tailor the electronic structure of catalysts with enhanced catalytic activities.39-41 In view of the above, creating atomically isolated and unsaturated Sb sites is therefore an attractive strategy for designing high-efficiency NORR catalysts.

In this study, p-block Sb₂S₃ is designed as a fascinating catalyst for highly selective NORR, which exhibits an excellent NO-to-NH₃ faradaic efficiency (FE_{NH₂}) of 93.7% and a high NH_3 yield rate of 168.6 μ mol h⁻¹ cm⁻², representing the highest NORR selectivity among all reported NORR catalysts. Detailed structural characterization and theoretical computations reveal that atomically isolated and unsaturated Sb sites created on Sb₂S₃ play a crucial role in greatly enhancing the NORR activity and selectivity.

Results and discussion 2.

A solvothermal method was utilized to synthesize Sb₂S₃. The XRD pattern of the as-synthesized Sb₂S₃ (Fig. 1a) shows distinct peaks that are assigned to the pure orthorhombic Sb₂S₃ phase with a good crystallinity. The SEM image of Sb₂S₃ (Fig. 1b) shows a typical nanoflower morphology consisting of numerous vertically aligned nanosheets. The nanosheet feature can be further confirmed by the TEM image (Fig. 1c).

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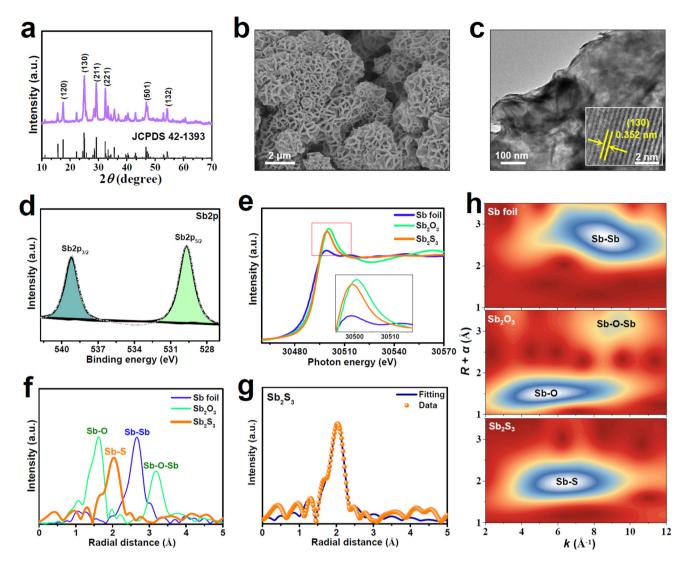


Fig. 1 Characterization of Sb₂S₃: (a) XRD pattern, (b) SEM image, (c) TEM image and HRTEM image (inset), (d) XPS Sb2p spectrum, (e) Sb K-edge XANES spectra, (f) EXAFS spectra and (h) WT profiles of Sb₂S₃ and reference samples. (g) EXAFS fitting curve of Sb₂S₃.

As shown in the HRTEM image (Fig. 1c, inset), the lattice spacing of Sb₂S₃ nanosheets is determined to be 0.352 nm, corresponding to the (130) facet of orthorhombic Sb₂S₃, in line with the XRD result (Fig. 1a). The XPS Sb spectrum of Sb₂S₃ (Fig. 1d) can be split into $Sb^{3+}2p_{3/2}$ (539.3 eV) and $Sb^{3+}2p_{5/2}$ (529.8 eV), while the deconvolution of the S2p spectrum (Fig. S1†) shows two peaks of $S2p_{1/2}$ (163.6 eV) and $S2p_{3/2}$ (161.8 eV), in good accordance with those reported for Sb₂S₃.42-44

We employ X-ray absorption near-edge structure (XANES) and extended X-ray absorption fine structure (EXAFS) characterizations to further examine the valence states and coordination structures of Sb₂S₃. The Sb K-edge XANES spectra (Fig. 1e) show that the white line of Sb₂S₃ is slightly lower than that of Sb₂O₃, suggesting the valence state of Sb to be smaller than the intrinsic Sb valence of Sb₂S₃ (+3), which is caused by the presence of coordinatively unsaturated Sb sites in Sb₂S₃.

The Sb K-edge EXAFS spectra (Fig. 1f) show that Sb₂S₃ exhibits a dominant peak at 2.03 Å assignable to the Sb-S bond, which largely differs from those of Sb foil (Sb-Sb: 2.66 Å) and Sb₂O₃ (Sb-O: 1.62 Å, Sb-O-Sb: 3.18 Å), indicating that Sb_2S_3 comprises the isolated state of Sb and no oxidized Sb species are present on Sb₂S₃. Likewise, the corresponding wavelet transform (WT) contour plots (Fig. 1h) show only one intensity maximum at 6.3 Å^{-1} corresponding to the Sb-S coordination, suggesting the existence of atomically dispersed Sb atoms. The EXAFS fitting data (Fig. 1g and Table S1†) reveal the average coordination number (CN) of Sb₂S₃ to be 4.2, much smaller than the crystallographic value of Sb₂S₃ (CN = 5), ⁴⁵ corroborating the existence of plentiful unsaturated Sb sites in Sb₂S₃. These XAS results reveal that the prepared Sb₂S₃ naturally contains abundant atomically isolated and unsaturated Sb (Sb_{AIII}) sites, which are considered to be catalytically active towards NORR.

Electrocatalytic NORR measurements were carried out using a gas-tight H-type electrolytic cell containing 0.5 M Na₂SO₄ solution. 46 Several colorimetric approaches (Fig. S2 and S3†) were performed to detect the liquid products, while the gaseous products were detected by gas chromatography. We conducted linear sweep voltammetry (LSV) measurement to initially assess the NORR activity of Sb₂S₃. It is displayed in

Fig. 2a that Sb_2S_3 presents a noticeable current density (j) enhancement in the NO-saturated electrolyte relative to the Arsaturated one, proving that Sb₂S₃ has a high NORR activity. We then quantitatively determined the NORR performance of Sb₂S₃ with the integration of chronoamperometry (Fig. 2b) and colorimetric tests at various potentials. As shown in Fig. 2c, with increasing the potential, both the NH3 yield rate and

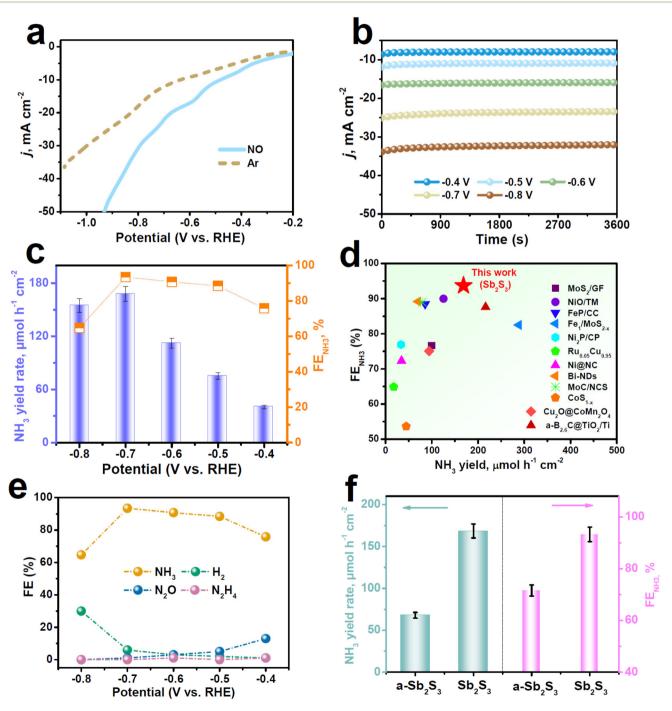


Fig. 2 (a) LSV curves of Sb₂S₃ in Ar/NO-saturated 0.5 M Na₂SO₄. (b) Chronoamperometry test of Sb₂S₃ at various potentials, and the resulting (c) NH_3 yield rates and FE_{NH_4} . (d) Comparison of NH_3 yield rates and FE_{NH_3} between Sb_2S_3 and the recently reported NORR catalysts. (e) FEs of different products on Sb_2S_3 after NORR electrolysis at various potentials. (f) NH_3 yield rates and FE_{NH_3} of Sb_2S_3 and $a-Sb_2S_3$ at -0.7 V.

FE_{NH}, of Sb₂S₃ exhibit a volcanic shape and reach their highest values of 168.6 μ mol h⁻¹ cm⁻² and 93.7% at -0.7 V, respectively. Strikingly, as shown in Fig. 2d (see Table S2 for details†), the FE_{NH}, of Sb₂S₃ shows the highest NORR selectivity among all the reported NORR catalysts, while its NH3 yield rate is also superior to those of most reported NORR catalysts. Meanwhile, Fig. 2e shows that the FEs of N-containing side products (N₂O and N₂H₄) are rather low at all considered potentials, in good accordance with the partial current density data (Fig. S4†), signifying the outstanding NO-to-NH3 selectivity of Sb2S3. Regarding the NORR stability, the chronopotentiometric test presents a stable current density for at least 20 h of electrolysis

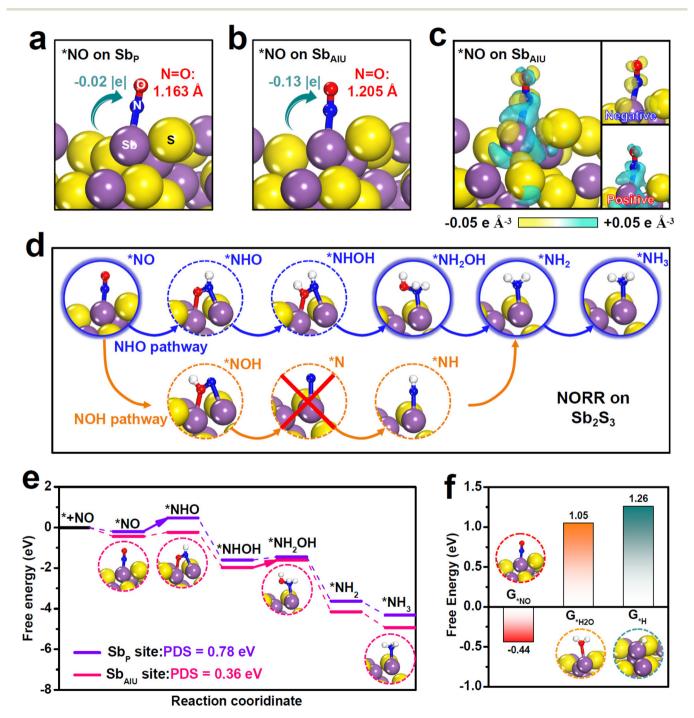


Fig. 3 (a and b) Atomic structures of absorbed NO on (a) the Sb_P site and (b) the Sb_{AIU} site of Sb_2S_3 . (c) Charge density difference of *NO on the Sb_{AIU} site (yellow: accumulation; cyan: depletion). (d) Schematic of two NORR pathways (NHO and NOH) on Sb₂S₃. (e) Free energy profiles of the NORR process (NHO pathway) on Sb_P and Sb_{AIU}. (f) Binding free energies of *H₂O, *H and *NO on Sb_{AIU}.

(Fig. S5†), and the resulting FE_{NH_3} shows very small attenuations, indicating the good long-term stability of Sb_2S_3 . Besides, no remarkable fluctuations in the NH_3 yield rate and FE_{NH_3} occur during the seven electrolysis cycles (Fig. S6†), proving the favorable cycling stability of Sb_2S_3 .

We conducted several experiments to verify the NH₃ origin. First, NH₃ is almost undetectable in the control colorimetric tests (Fig. S7†).³² In addition, upon feeding ¹⁵NO gas, the resulting ¹H nuclear magnetic resonance (NMR, Fig. S8†) spectra reveal the characteristic ¹⁵NH₄⁺ doublets, whereas feeding Ar gas leads to the absence of ¹⁵NH₄⁺ doublets.^{51–53} Furthermore, the switching NO–Ar test (Fig. S9†) reveals significant NH₃ production in NO cycles, whereas NH₃ is nearly undetectable in Ar cycles. All these results validate that the produced NH₃ stems from the electrochemical NORR process catalyzed by Sb₂S₃.

For comparison, we evaluated the NORR property of annealed Sb_2S_3 (a- Sb_2S_3) with much reduced Sb_{AIU} (Fig. S10 and Table S1†) under identical measurement conditions at -0.7 V. Impressively, Fig. 2f shows that the NORR performance of a- Sb_2S_3 is significantly poorer than that of the original Sb_2S_3 , revealing that the Sb_{AIU} sites play a vital role in dramatically boosting the NORR property of Sb_2S_3 . Electrochemical surface area (ECSA, Fig. S11 and S12†) measurements show that the ECSA-normalized NORR performances of the two catalysts (Fig. S13†) present the same trend as that shown in

Fig. 2f. Besides, both catalysts have comparable charge transport kinetics (Fig. S14 \dagger). These findings demonstrate the intrinsic superior NORR property of Sb₂S₃.

Theoretical computations were carried out to shed light on the boosted NORR property of Sb₂S₃. To start, we evaluated the adsorption behaviors of the NO molecule on two sites of Sb₂S₃, namely the pristine Sb (Sb_P) site and the Sb_{AIU} site, as the NO adsorption is the initial critical step to trigger the NORR.46 Upon absorbing NO on the Sb_P site (Fig. 3a), *NO exhibits a rather small N=O elongation (1.163 Å, 1.159 Å for original NO) with negligible Sb_p -to-*NO electron transfer (-0.02 |e|), which means poor NO adsorption on the Sb_P site. As a sharp comparison, *NO on the Sb_{AIU} site (Fig. 3b) presents dramatic N=O bond elongation (1.205 Å) and Sb_{AIU}-to-*NO electron transfer (-0.13 |e|), indicating largely improved NO adsorption on Sb_{AIU}. Additionally, the charge density difference (Fig. 3c) clearly shows strong *NO/Sb_{AIU} electronic interactions, where both remarkable positive and negative charge aggregations can be seen on *NO, proving that SbAIU enables powerful NO activation via a "donation-backdonation" mechanism.

To investigate the entire NORR process, we initially conducted online differential electrochemical mass spectrometry (DEMS) measurements to experimentally probe the reaction intermediates formed on $\mathrm{Sb}_2\mathrm{S}_3$ during the NORR electrolysis. The online DEMS spectra (Fig. S15†) reveal the generation of distinct NH₃ (m/z=17) and NH₂OH (m/z=33) signals.

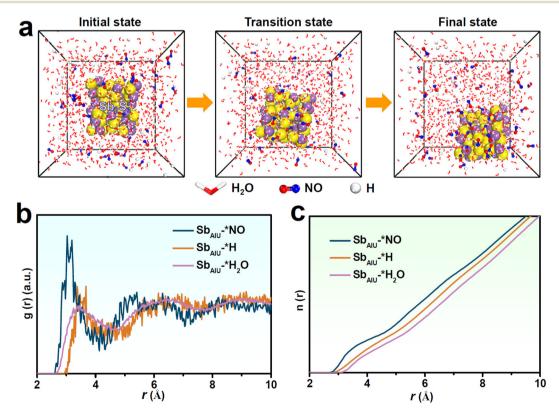


Fig. 4 (a) Initial, transition and final simulated states of the dynamic adsorption process of $*H_2O$, *H and *NO on Sb_{AIU}, and the corresponding (b) RDF and (c) integrated RDF curves of the interactions between Sb_{AIU} and *NO, *H and $*H_2O$.

Specifically, N (m/z = 14), which is the key intermediate involved in the NOH pathway, is absent in the NORR electrolysis, demonstrating that Sb₂S₃ preferentially undergoes the NHO pathway to drive the NORR process,⁵⁸ as illustrated in Fig. 3d. As displayed in the free energy profiles of the energetic-preferred NHO pathway (Fig. 3e and Fig. S16†), the Sb_p site exhibits a large energy barrier of 0.78 eV to drive the first protonation step of *NO → *NOH as the potential-determining step (PDS). In stark contrast, by virtue of powerful NO activation, the Sb_{AIU} site presents a largely reduced barrier of 0.21 eV for the same *NO → *NOH, suggesting that the initial protonation step can be greatly boosted on the Sb_{AIU} site. The PDS of Sb_{AIU} is changed to *NHOH \rightarrow *NH₂OH with only 0.36 eV uphill, corroborating the significantly enhanced NORR energetics over the SbAIU site that renders a high NORR activity of Sb₂S₃. We then investigated the catalytic behavior of the Sb_{AIU} site towards the HER, which is the main competitive reaction for NORR.24 The calculated binding free energies (G) of various species (Fig. 3f) show that G_{*NO} (-0.44 eV) is much more negative than $G_{*H,O}$ (1.05 eV) and G_{*H} (1.26 eV), demonstrating that the SbAIU site preferentially absorbs NO over H₂O/H species to impede the competing HER.

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Molecular dynamics (MD) simulations were conducted to further examine the competitive adsorption of NO and H₂O/H on Sb_{AIU}. After simulation, the snapshots (Fig. 4a) show prominent NO aggregation on Sb_{AIU} together with an enhanced Sb_{AIU}-*NO interaction over Sb_{AIU}-*H₂O and Sb_{AIU}-*H interactions, as displayed in the radial distribution function (RDF, Fig. 4b) curves and the corresponding integrated RDF curves (Fig. 4c), ⁵⁸⁻⁶² proving a high tendency of Sb_{AIU} for the adsorption and coverage of NO over H₂O/H, which is greatly favorable for HER suppression to obtain a high NORR selectivity.

3. Conclusion

In summary, Sb_{AIU} -rich Sb_2S_3 has been corroborated as a high-performing p-block metal catalyst for NORR. Theoretical computations reveal the critical role of Sb_{AIU} sites in promoting the activation and protonation of NO, while concurrently prohibiting the coverage of H_2O/H species. This work not only highlights the critical design of atomically isolated and unsaturated sites to dramatically enhance the catalytic NORR activity and selectivity, but also demonstrates the promising prospects of p-block metal elements in the design of high-efficiency NORR electrocatalysts.

Conflicts of interest

There are no conflicts of interest to declare.

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