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COMMUNICATION

Plasma-enhanced direct conversion of CO₂ to CO over oxygen-deficient Mo-doped CeO₂†Li Wang,^{*a} Xiaomin Du^a, Yanhui Yi^b, Hongyang Wang^a, Masaud Gul^a, Yimin Zhu^a and Xin Tu^{*c}Received 00th January 20xx,
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Plasma CO₂ splitting to CO over oxygen-deficient Mo-doped CeO₂ under mild conditions was investigated for the first time, showing ~20 times higher CO₂ conversion compared to pure CeO₂, which can be attributed to the increased oxygen vacancies (V_O) and the formation of Ce³⁺-V_O-Mo on the catalyst surface. Importantly, V_O sites showed excellent catalytic stability.

Converting CO₂ to value-added fuels and chemicals has been considered as a promising route in CO₂ utilization. Significant efforts have been devoted to the chemical transformation of CO₂, including thermal catalysis,¹ photocatalysis,^{2,3} electrocatalysis,^{4,5} and plasma catalysis.^{6,7} Direct splitting of CO₂ to CO without using any reductant is attractive for CO₂ conversion, as CO is an important chemical feedstock for the synthesis of a range of chemicals and fuels. However, this reaction has to overcome a strong thermodynamic barrier (CO₂ → CO + 1/2O₂, ΔH_{298 K} = 280 kJ/mol = 2.9 eV molecule⁻¹) to break the C=O bond, since CO₂ is very stable. Ultrahigh temperatures (2000 K) are often required to activate CO₂ (Fig. S1, ESI†).

In recent years, using non-thermal plasmas (NTPs) for the activation of inert molecules with strong chemical bonds (e.g., CO₂, CH₄ and N₂) under mild conditions has attracted significant interest, including CO₂ reforming with CH₄ to oxygenates,^{8,9} CO₂ hydrogenation to methanol,¹⁰ and ammonia synthesis.¹¹ NTP is rich in energetic electrons with a typical energy of 1–10 eV, which is sufficient to activate reactants into chemically reactive species, enabling thermodynamically unfavorable reactions (e.g. CO₂ splitting) to proceed at ambient conditions.

Up until now, studies on plasma CO₂ splitting to CO mainly

focused on the optimization of operating parameters,^{12–16} and only a few catalysts (e.g., Ni/SiO₂, NiO/TiO₂ and Rh/TiO₂) have been evaluated (Table S1, ESI†).^{17–20} Recently, surface oxygen vacancies (V_O) have been suggested to be the active sites in plasma-catalytic CO₂ splitting to CO. Mei et al. reported that higher CO₂ conversion was achieved when coupling plasma with BaTiO₃, which can be explained by the formation of more V_O sites on the surfaces of BaTiO₃ compared with TiO₂.²⁰ Chen et al. found the V_O on Ni/TiO₂ contributed to the enhanced CO₂ dissociation.¹⁸ In fact, the coupling of catalysts and plasma is a promising strategy to improve CO₂ conversion and energy efficiency. However, the knowledge in selection of appropriate catalysts for highly efficient CO₂ splitting to CO using NTP was still very limited until now.

Herein, CO₂ splitting to CO over M-doped CeO₂ catalysts (M = Fe, Co, Ni, Cu, Cr, V, Mn or Mo) has been carried out in a dielectric barrier discharge (DBD) reactor (Fig. S2–S5, ESI†). CeO₂ not only serves as a support to anchor and disperse the metal oxide particles but also generates V_O active sites through the interaction with metal oxides. Significant differences were observed among the M-doped CeO₂ catalysts in terms of CO₂ conversion, and the Mo-doped CeO₂ exhibited the best activity in CO₂ conversion (Fig. S3, ESI†). Therefore, Mo-doped CeO₂ has been selected for further studies.

Comprehensive catalyst characterization was carried out to understand the physicochemical properties of Mo-doped CeO₂. As shown in Fig. 1, the X-ray diffraction (XRD) pattern of CeO₂ exhibits characteristic peaks of a cubic fluorite phase (JCPDS, 34-0394). For Mo-doped CeO₂, small peaks of α-MoO₃ (JCPDS, 05-0508) and Mo₄O₁₁ (JCPDS, 05-0337) are observed, revealing the coexistence of Mo (VI) and Mo (V) species. Notably, the characteristic peaks of CeO₂ downshift compared to pure CeO₂, which suggests that Mo doping leads to the expansion of the CeO₂ unit cell. Usually, inserting Mo ions into CeO₂ induces shrinkage of the CeO₂ unit cell since the radius of Mo ions is much smaller than that of Ce ions, resulting in upshifting of CeO₂ peaks, rather than downshifting. Thus, Mo ions do not insert into the CeO₂ unit cell, and there might be other reasons responsible for this downshift. X-ray photoelectron spectroscopy (XPS) was employed to analyze surface

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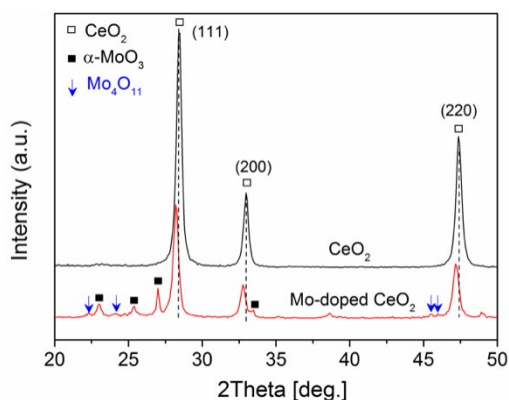


Fig. 1 XRD patterns of CeO₂ and as-prepared Mo-doped CeO₂.

properties of Mo-doped CeO₂. The deconvoluted Ce3d XPS spectra are presented in Fig. 2(a). The peaks labeled as v, v', v'', v''' and u, u', u'' are assigned to 3d_{5/2} and 3d_{3/2} electrons of Ce⁴⁺, respectively, while the peaks of v', u' and v_o, u_o correspond to 3d_{5/2} and 3d_{3/2} electrons of Ce³⁺, respectively.²¹ Clearly, Ce³⁺ exists in CeO₂ and Mo-doped CeO₂, suggesting the formation of V_o in both samples. More importantly, the proportion of Ce³⁺ in Mo-doped CeO₂ is 40.2%, higher than that in CeO₂ (30.0%) (Fig. S6 and S7, ESI[†]). This finding suggests that Mo doping induces partial transformation of Ce⁴⁺ to Ce³⁺ and creates more V_o on Mo-doped CeO₂. As reconfirmed by the O1s XPS spectra in Fig. 2(b) and Fig. S6, a higher surface V_o (30.4%) is achieved in the Mo-doped CeO₂ in comparison to pure CeO₂ (21.0%). Furthermore, the transformation of Ce⁴⁺ to Ce³⁺ leads to the expansion of the CeO₂ unit cell since the ion radius of Ce³⁺ (1.23 Å) is higher than that of Ce⁴⁺ (0.97 Å),²² which explains the reason for the downshifting of CeO₂ peaks in Fig. 1. More interestingly, the binding energies of Ce3d shift significantly towards higher values after Mo doping, revealing that the electron density of the surface CeO₂ species is lower in Mo-doped CeO₂ compared with pure CeO₂, which might be induced by the electron transfer from Ce to Mo, due to the higher electronegativity of Mo. These results suggest different properties of V_o sites in the form of Ce³⁺-V_o in CeO₂ and Ce³⁺-V_o-Mo in Mo-doped CeO₂, as well as the strong interaction between Mo and CeO₂, which agrees with the results of H₂-temperature programmed reduction (H₂-TPR), scanning electron microscopy (SEM) and transmission electron microscopy (TEM) (Fig. S8-S11, ESI[†]). Fig. 2(c) shows the deconvoluted Mo3d spectra, in which the Mo-doped CeO₂ sample exhibits typical doublet peaks of Mo⁶⁺ with an energy gap of c.a. 3.1 eV, indicating the formation of MoO₃ in Mo-doped CeO₂.²³ The two smaller peaks observed, however, are identified to be 3d_{3/2} and 3d_{5/2} electrons of Mo (V), demonstrating the formation of the non-stoichiometric MoO_{3-x},²³ which is consistent with the Mo₄O₁₁ species confirmed by the XRD analysis (Fig. 1). Fig. 2(d) shows the Raman spectra of CeO₂ and Mo-doped CeO₂. For pure CeO₂, the intense band at 465 cm⁻¹ is well-indexed to the typical F2g modes of a cubic CeO₂ fluorite structure, and the weak bands at 262, 597 and 1171 cm⁻¹ are assigned to V_o, reconfirming the XPS results in Fig. 2(a) and (b).²³ For Mo-doped CeO₂, the emerging Raman

bands at 673, 824 and 997 cm⁻¹ are assigned to MoO₃ crystallites.²⁴ However, the band at 955 cm⁻¹ is associated with Mo suboxides (MoO_{3-x}).^{24,25} These results indicate that the valance state of Mo in suboxides is Mo⁵⁺. Moreover, the presence of Mo⁵⁺ and Ce³⁺ indicates that more V_o sites are created through the strong interaction between Mo and CeO₂, as well as the calcining atmosphere with deficient oxygen and rich, energetic Ar species, which agrees with the results reported by Chen et al.¹⁸

Fig. 3 shows the effect of different operating conditions on CO₂ conversion. Clearly, no reaction occurred without plasma (Catalyst only, 400 °C). The conversion of CO₂ was 3.8% in the plasma reaction without a catalyst (Plasma only). In the plasma reaction coupled with pure CeO₂, the CO₂ conversion dropped to 1.2%, which suggests that pure CeO₂ is unfavorable for CO₂ splitting to CO despite CeO₂ being O-deficient. Using Mo-doped CeO₂ instead of CeO₂, however, results in a significant increase of CO₂ conversion by a factor of 9 at 400 °C. In addition, the Mo-doped CeO₂ showed stable CO₂ conversion for at least 10 h (Fig. S12, ESI[†]). Interestingly, the reaction performance can be further improved by using a lower reaction temperature (30 °C) and an additive gas (Ar or N₂). This promotional effect was more pronounced when adding N₂. The highest CO₂ conversion of 23.2% and energy efficiency of 14.3% were achieved in the plasma splitting of CO₂ with N₂ addition over Mo-doped CeO₂ at 30 °C (Table S1, ESI[†]), while the corresponding formation rate of CO and O₂ was 24.9 mmol/h and 12.4 mmol/h, respectively (Table S2, ESI[†]). The optimal energy efficiency achieved in this study is comparable to that reported in previous works (Table S1, ESI[†]).

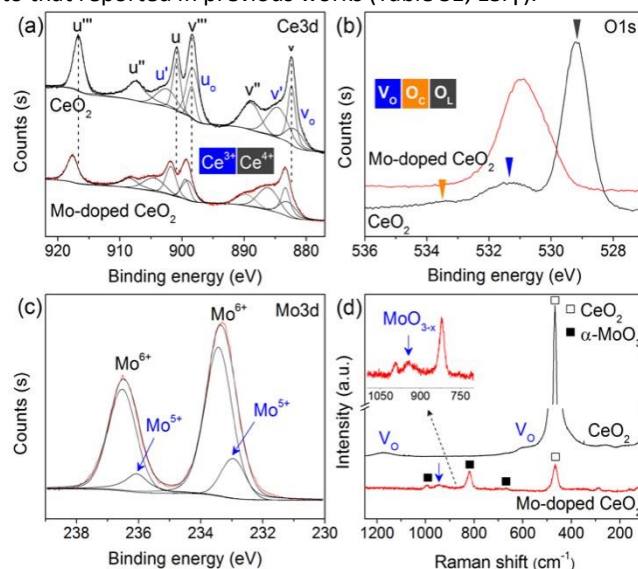


Fig. 2 XPS and Raman spectra of CeO₂ and as-prepared Mo-doped CeO₂ (a) Ce3d, (b) O1s, (c) Mo3d and (d) Raman spectra (V_o, O_c and O_l represent oxygen vacancy, chemisorbed oxygen species and oxygen lattice, respectively).



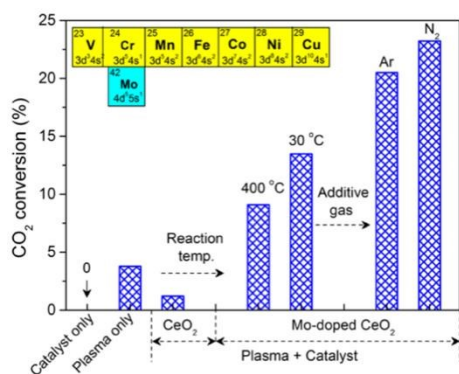


Fig. 3 Effect of reaction temperature and additive gas on CO₂ conversion (CO₂ flow rate 40 ml/min, SEI 20 kJ/L, molar ratio 5:1 and 30 °C for CO₂/Ar and CO₂/N₂; Catalyst only 400 °C).

Regarding surface reactions, the improved activity over Mo-doped CeO₂, on one hand, is mainly attributed to the increased formation of V_o (Fig. 2 and Fig. S6), since V_o serve as adsorption centers for CO₂ dissociative adsorption,^{17,26} i.e., CO₂ + V_o → O_i/O_c + CO. On the other hand, the promoted performance originates from the different properties of V_o in the forms of Ce³⁺-V_o and Ce³⁺-V_o-Mo due to strong interaction between Mo and CeO₂ and the higher electronegativity of Mo compared with Ce (Fig. 1, 2 and Fig. S8), which leads to a stronger binding strength of CO₂ with the V_o of Ce³⁺-V_o-Mo. As discussed above, V_o is the active site for CO₂ activation; thus, the stability of V_o greatly influences the subsequent catalytic cycle. It is well recognized that oxygen can be produced in plasma CO₂ splitting, and the produced O species could poison the catalyst through filling V_o sites to form stable lattice oxygen species, resulting in termination of the catalytic cycle.

Therefore, the spent Mo-doped CeO₂ catalysts were further characterized by XPS, Raman, XRD and H₂-TPR (Fig. 4). Interestingly, compared with the fresh catalyst, the spent Mo-doped CeO₂ catalysts show an increased amount of Ce³⁺ and MoO_{3-x}, which can be confirmed by the higher intensities of Ce³⁺ peaks and the Raman band at ~ 950 cm⁻¹ in Fig. 4(a) and (b), respectively. The enhancement effect is more pronounced for the catalyst used at 400 °C. Correspondingly, more V_o sites were created in the high-temperature reaction (Table S3, ESI†). In addition, the color of the catalyst changed from gray/blue (MoO_{3-x}) to yellow (MoO_{3-y}) with x > y after the reaction at 30 °C, while no visible changes were observed on the phase structure of Mo-doped CeO₂ before and after the reaction (30 °C), as shown in Fig. 4(c). These results indicate that some O atoms from CO₂ splitting are adsorbed onto the catalyst, as seen by the slightly increased H₂ consumption in Fig. 4(d). Even so, the V_o concentration of Mo-doped CeO₂ used at 30 °C remained at a similar level with that of the fresh sample (Table S3, ESI†). These findings suggest that V_o-rich Mo-doped CeO₂ is stable after the plasma reaction, and high-temperature reactions facilitate the formation and recovery of V_o sites, resulting from accelerating recombinative desorption of adsorbed O atoms.²⁷

In addition to surface reactions, gas-phase reactions also play a crucial role in the plasma-catalytic process. In a pure CO₂

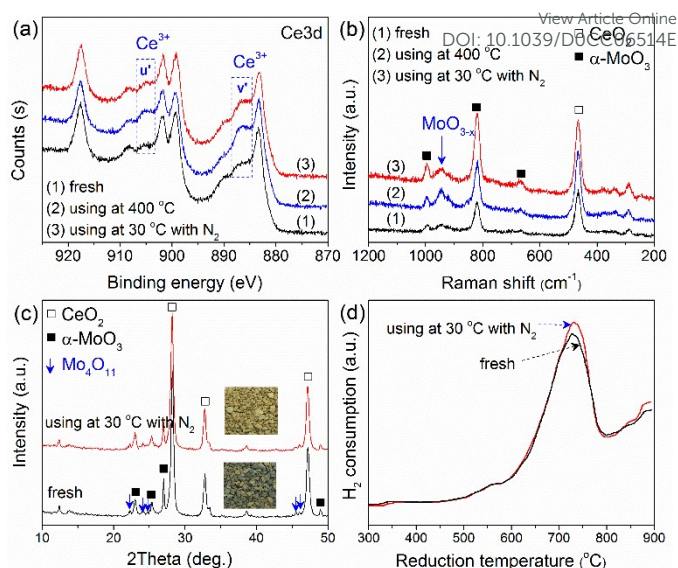


Fig. 4 (a) XPS spectra, (b) Raman spectra, (c) XRD patterns, (d) H₂-TPR profiles of Mo-doped CeO₂ before and after reaction.

DBD, CO₂ splitting to CO mainly proceeds through the electron impact dissociation of CO₂ (CO₂ + e → CO + O + e), which can be confirmed by plasma chemical kinetic modeling,²⁸ as well as the formation of CO bands and O atomic lines detected by optical emission spectra of CO₂ DBD (Fig. 5a). As shown in Fig. 5(a), the presence of strong N₂ (C³Π_u → B³Π_g, B³Π_g → A³Σ_u⁺) molecular bands and Ar atomic lines suggests the formation of excited nitrogen species (N₂^{*}) and metastable Ar species (Ar^{*}).^{29,30} These species create an additional reaction route for CO₂ dissociation (N₂^{*} (or Ar^{*}) + CO₂ → CO + O + N₂ (or Ar)), supported by the increased intensity of O atomic lines and CO bands when adding N₂ or Ar, which contributes to the enhanced CO₂ conversion. Furthermore, 150 ppm NO_x was detected by Fourier transform infrared (FTIR) in the case of N₂ addition (Fig. S13, ESI†), revealing that N₂ can be regarded as an alternative scavenger of O species.¹² The elimination of partial O species can effectively limit the reverse reaction, i.e., O + CO + M → CO₂ + M, and thus enhance the CO₂ conversion. This could explain why adding N₂ has a stronger promotion on the CO₂ conversion compared with Ar.

Interaction between reactive species in the gas phase and catalyst is also crucial in plasma-catalytic reactions.³¹ Compared to plasma only, packing Mo-doped CeO₂ into the discharge zone decreased the current (Fig. S14, ESI†), lowering the contribution of the gas-phase reactions. In this case, the CO₂ conversion, however, was still improved, which might be attributed to the interaction between active species and V_o-rich Mo-doped CeO₂, accelerating V_o recovery. Therefore, a possible reaction mechanism is proposed in Fig. 5(b). Firstly, CO₂ is activated to species of CO₂⁺, CO₂(v), CO and O radicals as shown in Fig. 5 (a) (step 1). Then, the energetic CO₂-species are adsorbed on the V_o sites to decrease their internal energy (step 2). After that, the V_o sites have the potential to grasp the O atom of the adsorbed CO₂ molecule, which weakens the C=O bond, producing adsorbed CO and O (step 3). Subsequently, the adsorbed CO desorbs as the final CO product. While the



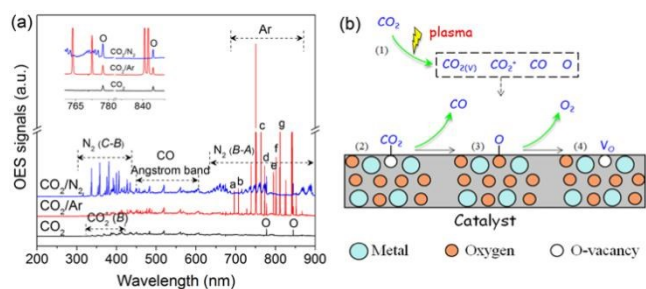


Fig. 5 (a) Emission spectra of CO₂ plasma, (b) Possible pathways of plasma-catalytic CO₂ splitting over V₀-rich catalyst.

adsorbed O mainly desorbs from V₀ sites in the form of O₂ through reacting with the active O radicals produced in the gas phase ($O_g + O_{ad}\text{-}V_0 \rightarrow O_{2,g} + V_0$), i.e., Eley-Rideal (E-R) mechanism. Meanwhile, V₀ sites recover completing the catalytic cycle (step 4). Using isotope trace analysis, we demonstrated the desorption of N_{ad} through an ER reaction in plasma-catalytic NH₃ decomposition.³¹ Therefore, the desorption of O_{ad} through ER reaction is also expected. Note that, too strong of a CO₂-V₀ bond makes it easy to split the CO₂ molecule, but the corresponding desorption of adsorbed O is difficult. By contrast, too weak of a CO₂-V₀ bond means it could be hard to split CO₂, although the adsorbed O can easily desorb from the catalyst surface. Therefore, a catalyst with a proper binding strength between V₀ sites and CO₂ benefits the conversion of CO₂ and favors the catalytic cycle.

In conclusion, plasma-catalytic CO₂ splitting over M-doped CeO₂ catalysts (M = Fe, Co, Ni, Cu, Cr, V, Mn or Mo) has been investigated. Mo-doped CeO₂ exhibited the best activity; this is attributed to the increased oxygen vacancies created by strong interaction between Mo and CeO₂, as well as the calcining atmosphere being oxygen-deficient and rich in Ar metastable species. Furthermore, oxygen vacancies were stable during the reaction, which is ascribed to the interaction between active O produced in the gas phase and the adsorbed O on the oxygen vacancy site, resulting in desorbing as O₂ molecules and recovering oxygen vacancy sites. These findings suggest that introducing proper doping on CeO₂ offers a potential route to tune properties of oxygen vacancy in CeO₂. Additionally, adding N₂ and Ar into the plasma process enhanced the CO₂ conversion, especially when adding N₂. This promotional effect is mainly attributed to the new reaction routes induced by the presence of metastable species. We found that N₂ can be used as an O scavenger to forward the chemical equilibrium and inhibit the reverse reaction to form CO₂.

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Conflicts of interest

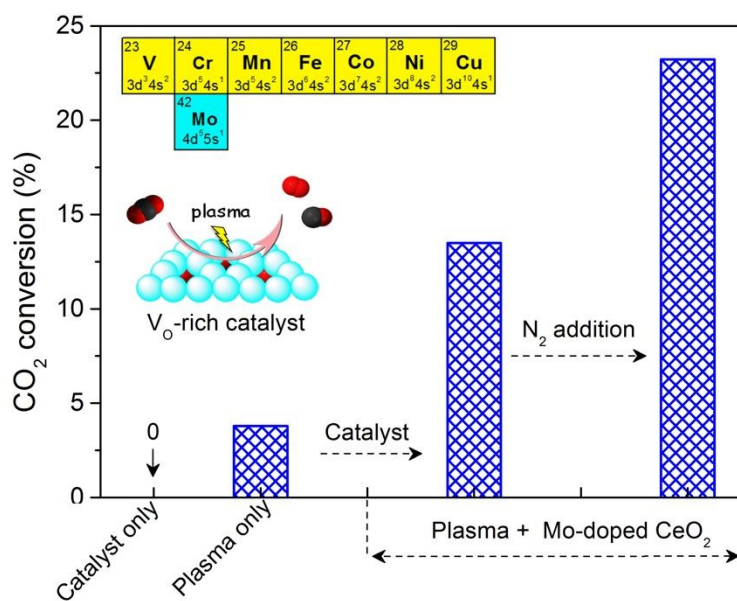
There are no conflicts to declare.

Notes and references

- J. Zhong, X. Yang, Z. Wu, B. Liang, Y. Huang and T. Zhang, *Chem. Soc. Rev.*, 2020, 49, 1385.
- S. Xie, Q. Zhang, G. Liu and Y. Wang, *Chem. Commun.*, 2016, 52, 35.
- Y. Lan, Y. Xie, J. Chen, Z. Hu and D. Cui, *Chem. Commun.*, 2019, 55, 8068.
- D. U. Nielsen, X. Hu, K. Daasbjerg and T. Skrydstrup, *Nat. Catal.*, 2018, 1, 244.
- X. Yuan, Y. Luo, B. Zhang, C. Dong, J. Lei, F. Yi, T. Duan, W. Zhu and R. He, *Chem. Commun.*, 2020, 56, 4212.
- A. George, B. Shen, M. Craven, Y. Wang, D. Kang, C. Wu and X. Tu, *Renew. Sust. Energ. Rev.*, 2021, 135, 109702.
- A. Bogaerts, X. Tu, J. C. Whitehead, G. Centi, L. Lefferts, O. Guaitella, F. A. Jury, H. H. Kim, A. B. Murphy, W. F. Schneider, T. Nozaki, J. C. Hicks, A. Rousseau, F. Thevenet, A. Khacef and M. Carreon, *J. Phys. D: Appl. Phys.*, 2020, 53, 443001.
- D. Li, V. Rohani, F. Fabry, A. P. Ramaswamy, M. Sennour and L. Fulcheri, *Appl. Catal. B*, 2020, 261, 118228.
- L. Wang, Y. Yi, C. Wu, H. Guo and X. Tu, *Angew. Chem. Int. Ed.*, 2017, 56, 13679.
- L. Wang, Y. Yi, H. Guo and X. Tu, *ACS Catal.*, 2018, 8, 90.
- Y. Wang, M. Craven, X. Yu, J. Ding, P. Bryant, J. Huang and X. Tu, *ACS Catal.*, 2019, 9, 10780.
- R. Snoeckx, S. Heijckers, K. V. Wesenbeeck, S. Lenaerts and A. Bogaerts, *Energy Environ. Sci.*, 2016, 9, 999.
- D. Mei and X. Tu, *J. CO₂ Util.*, 2017, 19, 68.
- D. Mei, X. Zhu, Y. He, J. D. Yan and X. Tu, *Plasma Sources Sci. Technol.*, 2015, 24, 015011.
- K. V. Laer and A. Bogaerts, *Plasma Process. Polym.*, 2017, 14, 1600129.
- D. Ray and C. Subrahmanyam, *RSC Adv.*, 2016, 6, 39492.
- K. Zhang, G. Zhang, X. Liu, A. N. Phan and K. Luo, *Ind. Eng. Chem. Res.*, 2017, 56, 3204.
- G. Chen, V. Georgieva, T. Godfroid, R. Snyders and M. Delplancke-Ogletree, *Appl. Catal. B*, 2016, 190, 115.
- L. F. Spencer and A. D. Gallimore, *Plasma Sources Sci. Technol.*, 2013, 22, 015019.
- D. Mei, X. Zhu, C. Wu, B. Ashford, P. T. William, X. Tu, *Appl. Catal. B*, 2016, 182, 525.
- C. Anandan and P. Bera, *Appl. Surf. Sci.*, 2013, 283, 297.
- W. Wang, Q. Zhu, F. Qin, Q. Dai and X. Wang, *Chem. Eng. J.*, 2018, 333, 226.
- K. Murugappan, E. M. Anderson, D. Teschner, T. E. Jones, K. Skorupska and Y. Román-Leshkov, *Nat. Catal.*, 2018, 1, 960.
- B. Liu, L. France, C. Wu, Z. Jiang, V. L. Kuznetsov, H. A. Al-Megren, M. Al-Kinany, S. A. Aldrees, T. Xiao and P. P. Edwards, *Chem. Sci.*, 2015, 6, 5152.
- K. Chen, S. Xie, A. T. Bell and E. Iglesia, *J. Catal.*, 2001, 198, 232.
- L. Liang, X. Li, Y. Sun, Y. Tan, X. Jiao, H. Ju, Z. Qi, J. Zhu and Y. Xie, *Joule*, 2018, 2, 1004.
- P. G. Dickens and M. B. Sutcliffe, *Trans. Faraday Soc.*, 1964, 60, 1272.
- R. Aerts, T. Martens and A. Bogaerts, *J. Phys. Chem. C*, 2012, 116, 23257.
- Y. Horikawa, T. Hayashi and K. Sasaki, *Jpn. J. Appl. Phys.*, 2012, 51, 126301.
- J. B. Boffard, G. A. Piech, M. F. Gehrke, L. W. Anderson and C. C. Lin, *Phys. Rev. A*, 1999, 59, 2749.
- L. Wang, Y. Zhao, C. Y. Liu, W. M. Gong and H. C. Guo, *Chem. Commun.*, 2013, 49, 3787.



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Oxygen-deficient Mo-doped CeO₂ showed significantly higher CO₂ conversion compared to pure CeO₂ in the plasma splitting of CO₂.

