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Key intermediates and Cu active sites for CO₂ electroreduction to ethylene and ethanol

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Electrochemical reduction of CO₂ (CO₂RR) to multi-carbon products is a promising technology to store intermittent renewable electricity into high-added-value chemicals and close the carbon cycle. Its industrial scalability requires electrocatalysts to be highly selective to certain products, such as ethylene or ethanol. However, a substantial knowledge gap prevents the design of tailor-made materials, as the properties ruling the catalyst selectivity remain elusive. Here we combined in situ surface-enhanced Raman spectroscopy and density functional theory on Cu electrocatalysts to unveil the reaction scheme for CO₂RR to C₂₊ products. Ethylene generation occurs when *OC–CO(H) dimers form via CO coupling on undercoordinated Cu sites. The ethanol route opens up only in the presence of highly compressed and distorted Cu domains with deep *s*-band states via the crucial intermediate *OCHCH₂. By identifying and tracking the critical intermediates and specific active sites, our work provides guidelines to selectively decouple ethylene and ethanol production on rationally designed catalysts.

Electrochemical reduction of CO₂ (CO₂RR) to chemicals is a promising approach to store intermittent renewable energy as valuable fuels and feedstocks^{1,2}. In particular, the synthesis of multi-carbon (C₂₊) products, such as ethylene and ethanol, is highly attractive because of their versatility in the chemical and energy industries³, and processes involving C–C bond formation are of great relevance from the point of view of fundamental research^{2,4}.

Copper-based materials are the most selective catalysts for electrochemically reducing CO₂ to C₂₊ products². A myriad of studies have focused on understanding the C–C coupling mechanism, and although some consensus has been reached, the dependence of these paths on the particular material history is yet to be confirmed^{5,6}. Several coupling pathways have been proposed^{7,8}, suggesting adsorbed CO (*CO) as the building block of multi-carbon products^{5,9,10} via dimerization (OC–CO)⁷ or coupling (OC–CHO or OC–COH)⁸ steps. Experimentally, *CO has been detected on Cu surfaces using in situ Raman and infrared spectroscopy during CO₂RR^{6,11,12}, and a direct correlation between CO

coverage and selectivity towards C₂₊ products exists¹³. Recently, possible C–C coupling intermediates *OCCO or *OCCOH were detected by infrared spectroscopy during the electrochemical reduction of CO (COR)^{14,15}. However, while CO coupling has been repeatedly confirmed, observing and tracking potential-dependent CO dimerization and intermediates during the subsequent gradual reduction process towards final products has not yet been achieved.

Among the CO₂RR reaction intermediates^{7,8}, *OCHCH₂ is considered the last common precursor in the ethylene and ethanol routes, although experimental confirmation is still missing^{2,7}. In fact, glyoxal and glycolaldehyde reduce to acetaldehyde, ethanol and ethylene glycol only on polycrystalline copper^{16–18}, suggesting an exclusive ethanol-selective route via *OCHCH₂. Recently, a methyl carbonyl intermediate, *OCCH₃, has been proposed as an alternative intermediate for ethanol and propanol^{19,20}. In general, the reaction pathways for ethylene and ethanol formation are defined by logical intuition based on experimental and computational results^{7,8,16,21}. However, the lack of

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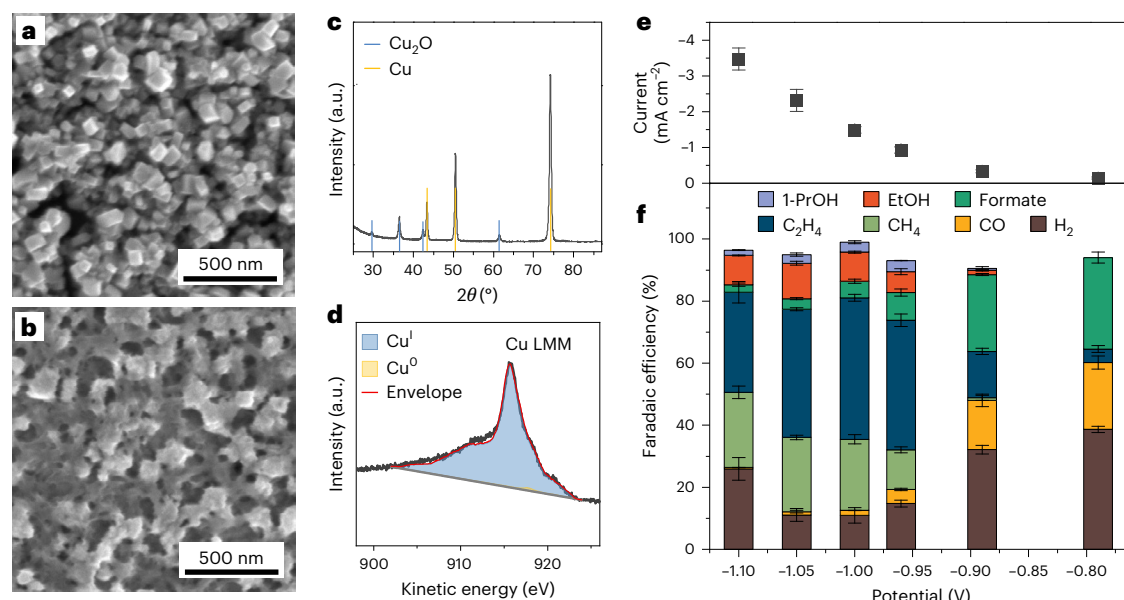


Fig. 1 | Characterization of the morphology of electrochemically treated Cu foil electrode and its CO₂RR performance. **a, b**, SEM images of an as-prepared (electrochemically treated) Cu foil electrode acquired before **(a)** and after **(b)** CO₂RR in CO₂-saturated 0.1 M KHCO₃ electrolyte at $-1.0 V_{\text{RHE}}$ for 1 h. **c**, XRD pattern of the as-prepared Cu foil electrode. **d**, Cu LMM XAES spectrum of the

as-prepared Cu foil electrode. **e**, Potential-dependent current density. **f**, Faradaic efficiency of the electrochemically treated Cu foil electrode in CO₂-saturated 0.1 M KHCO₃ electrolyte for 1 h. The error bars in **e** and **f** correspond to the s.d. of three independent measurements. Data are given as average \pm s.d.

robust experimental evidence hinders the rational design of CO₂RR electrocatalysts, limiting the overall energy efficiency of the process.

The dynamics of electrocatalysts following charge accumulation, redox chemistry and the presence of adsorbates which can structurally deteriorate the catalyst surface lead to a very complex behaviour⁴. Thus, the generalization of insights gathered through model interfaces in an ultrahigh vacuum (UHV) system needs to be compared with the in situ electrocatalytic solid–liquid interface²². So far, a direct link between the local atomic surface structure and the Cu coordination environment on the catalytic process and, in particular, its influence on distinct reaction pathways remains unclear. CO strongly deteriorates the Cu surface and leads to undercoordinated sites²³, which has a significant influence on CO₂RR. For example, by comparing various single-crystal surfaces with different surface roughness, we previously showed that undercoordinated Cu sites are required for C₂ formation²⁴. However, it is important to further close this knowledge gap by unravelling how Cu coordination and local stress under reaction conditions affect the catalytic behaviour and thus the full mechanistic picture. To this end, it is required to overcome the challenging low surface coverages of intermediates due to their short lifetimes as well as disentangle the similarities in the vibrational properties of different C–C coupling intermediates¹⁴.

Here we provide direct spectroscopic evidence of potential-dependent CO dimerization and subsequent reduction intermediates during CO₂RR on a Cu surface by combining insights from in situ surface-enhanced Raman spectroscopy (SERS) and density functional theory (DFT)-based vibrational analysis. This allows us to identify crucial Cu sites and surface intermediates for either ethylene or ethanol, leading to the definition of an updated reaction scheme for CO₂RR to C₂ products.

Electrode preparation and CO₂RR test

The Cu electrodes were prepared by an electrochemical oxidation–reduction process (see Methods for details). Scanning electron microscopy (SEM) images show the formation of cubic structures with high density (Fig. 1a,b and Supplementary Fig. 1). The X-ray diffraction

(XRD) pattern confirms the presence of Cu₂O (Fig. 1c). Cu LMM X-ray Auger electron spectroscopy (XAES) data indicate a surface composition of about 94% Cu^I and 6% Cu⁰ species (Fig. 1d and Supplementary Fig. 2), while further elemental analysis confirmed the absence of other elements, such as Na, Cl and S (Supplementary Fig. 3). After 1 h of CO₂RR at $-1.0 V_{\text{RHE}}$ (where RHE is reversible hydrogen electrode) in 0.1 M KHCO₃, the XRD pattern of Cu₂O almost completely disappeared (Supplementary Fig. 4), and the cubic morphology partially changed (Fig. 1b), consistent with previous reports¹³. In spite of these morphological changes, no unexpected elements (for example, K) were present in post-catalysis X-ray photoelectron spectroscopy (XPS) analysis (Supplementary Fig. 5). Thus, we opted to use this treatment to obtain sufficient enhancement of the Raman signals.

Similar to the oxide-derived Cu (OD-Cu) materials, which are selective for C–C coupling^{24–27}, the as-prepared Cu electrode with a high electrochemical surface roughness factor (14.6; Supplementary Fig. 6, electropolished Cu foil as a reference) shows high performance towards C₂₊ products and provides the opportunity to detect C–C coupling intermediates²⁵. The specific current densities increase up to at least $-1.1 V$ (Fig. 1e), while the Faradaic efficiencies of CO₂RR products and H₂ vary strongly with the applied potential (Fig. 1f). The Faradaic efficiencies of C₂₊ products show a typical volcano dependence on the applied potential, with a maximum of 65% at about $-1.0 V_{\text{RHE}}$. The onset potentials for ethylene and ethanol are about $-0.8 V_{\text{RHE}}$ and $-0.9 V_{\text{RHE}}$, with these products reaching a maximum value at $-1.0 V_{\text{RHE}}$ and $-1.05 V_{\text{RHE}}$, respectively.

Potential-dependent intermediate evolution

To reveal molecular insights into C–C coupling intermediates and their potential dependence, we carried out in situ SERS measurements (Supplementary Fig. 7). Figure 2a shows the in situ Raman spectra acquired at the same position on the electrochemically treated Cu foil electrode as a function of the applied potential in a CO₂-saturated 0.1 M NaClO₄ electrolyte. A NaClO₄ solution leading to a Raman band at $\sim 935 \text{ cm}^{-1}$ (Supplementary Figs. 8 and 9) was used to decrease the influence of highly concentrated bicarbonate in the wavenumber

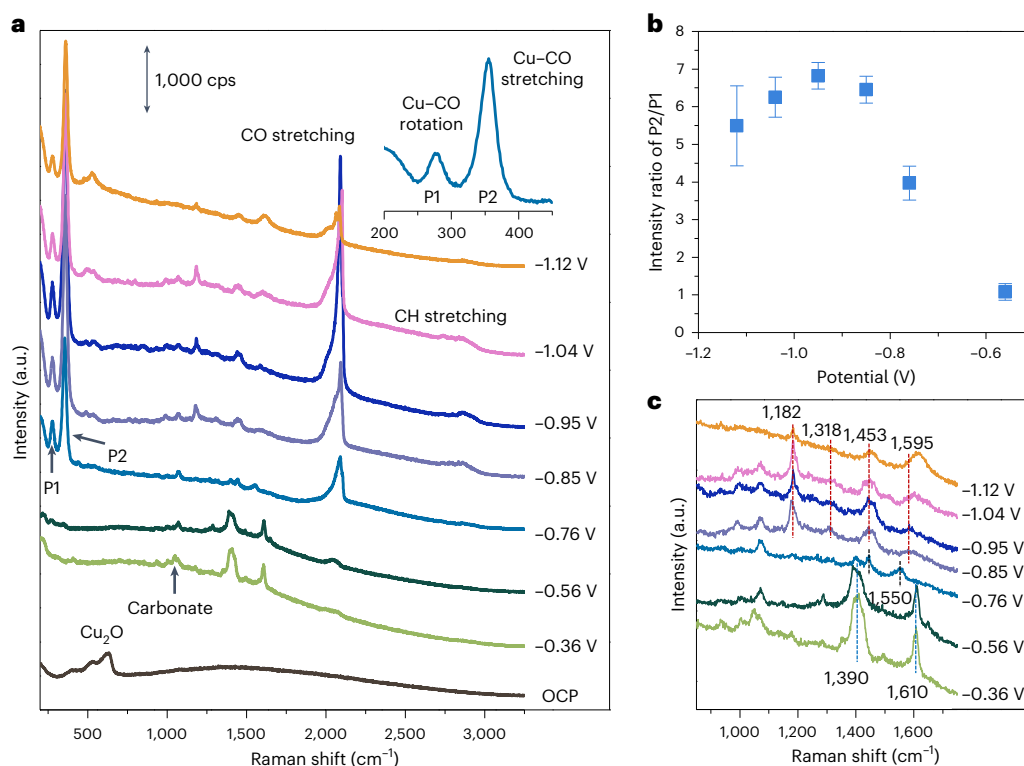


Fig. 2 | In situ SERS measurement during CO₂RR. a, Raman spectra of an electrochemically treated Cu foil acquired during CO₂RR for potentials ranging from the open-circuit potential (OCP) to about -1.1 V_{RHE} in a CO₂-saturated 0.1 M NaClO₄ electrolyte. cps, counts per second. **b**, Potential-dependent intensity ratio of P2 (Cu–CO stretching, ~ 360 cm⁻¹) to P1 (restricted rotation of adsorbed

CO, ~ 280 cm⁻¹). **c**, Zoom-in Raman spectra in the region of 900–1,700 cm⁻¹ from about -0.4 V_{RHE} to -1.1 V_{RHE}, with relevant peaks highlighted via dashed lines. The error bars in **b** correspond to the s.d. of three independent measurements. Data are given as average \pm s.d.

range of 1,000–2,000 cm⁻¹ (Supplementary Figs. 10 and 11). We note here that irrespective of the electrolyte anionic species, carbonate and bicarbonate ions will be present due to the CO₂/H₂O equilibrium. Although a lower Faradaic efficiency of C₂₊ products is obtained during CO₂RR in CO₂-saturated 0.1 M NaClO₄ (ref. 28), the onset potentials and potential-dependent trends for ethylene and ethanol formation are similar to those in 0.1 M KHCO₃ (Supplementary Fig. 12).

Initially, at open-circuit potential, Raman peaks at 400 cm⁻¹, 528 cm⁻¹ and 620 cm⁻¹ from a CuO_x phase are detected^{12,29}. At a potential of -0.36 V_{RHE}, the CuO_x is reduced to metallic Cu on the surface, and a small peak is detected at 1,070 cm⁻¹, typically assigned to carbonate¹³. Two new peaks at $\sim 1,390$ cm⁻¹ and $\sim 1,610$ cm⁻¹ appear, which are attributed to the symmetric and asymmetric stretching vibrations of carboxyl(ate) groups, respectively, based on control experiments in Ar-saturated NaClO₄ with 1 mM HCOOH solution (Supplementary Fig. 13) and in Ar-saturated KHCO₃ solution (Supplementary Fig. 11).

At -0.56 V_{RHE}, peaks of CO adsorbed on Cu are detected, with vibrational features at ~ 280 cm⁻¹, 355–360 cm⁻¹ and 1,970–2,110 cm⁻¹ corresponding to the restricted rotation of adsorbed CO (P1), Cu–CO stretching (P2) and C–O stretching, respectively. Consistent with our recent finding on the CO coverage-driven C–C coupling mechanism¹³, the P2/P1 ratio, a proxy for CO surface coverage on copper, follows a volcano trend with the applied potential (Fig. 2b). At -0.76 V_{RHE}, Raman bands at 490–530 cm⁻¹ appear, which can be attributed to Cu–O stretching of oxygen or hydroxide species on Cu, or Cu–C stretching^{12,29,30}. There are no indications of Cl⁻ related adsorbates, as the Raman band should appear at ~ 300 cm⁻¹ (refs. 31, 32).

More interestingly, the peaks at 1,390 cm⁻¹ and 1,610 cm⁻¹ disappear with increasing CO surface coverage from -0.56 V_{RHE} to -0.76 V_{RHE}, and two new peaks evolve at 1,450 cm⁻¹ and 1,550 cm⁻¹ (Fig. 2c), which were previously attributed to the *OCCO intermediate¹⁵.

The observation of these peaks agrees well with a CO-coverage-determined C–C coupling during CO₂RR¹³ and indicates a similar intermediate for C–C coupling during CORR and CO₂RR. Concurrently, the Raman peaks of *HCOO⁻/^{*}HCOOH disappear, which suggests that CO or C–C coupling intermediates may affect the production of formic acid due to competition for surface sites.

At more cathodic potentials, CO coverage further increases, and four new peaks can be detected at 1,182 cm⁻¹, 1,318 cm⁻¹, 1,453 cm⁻¹ and 1,595 cm⁻¹ from -0.85 V_{RHE}, which show a regular shift with the potential, indicating the existence of new adsorbates. These peaks appeared simultaneously during the time-resolved in situ SERS experiment after a potential switch from -0.36 V_{RHE} to -0.96 V_{RHE} (Supplementary Fig. 14). Concurrently, a broad band in the range of 2,830–2,990 cm⁻¹ appeared, which can be attributed to the stretching band of C–H (ref. 12).

Intermediates responsible for CO₂RR to ethylene and ethanol

To confirm the assignment of the vibrational modes detected experimentally, we reverted to DFT (PBE-D2³³) through the Vienna Ab initio Simulation Package^{34,35}. To mimic OD-Cu catalysts, we used two different models. Our first simulation cell consisted of a pristine OD-Cu structure, taken from a Cu(111)/Cu₂O(111) epitaxy precursor optimized through ab initio molecular dynamics³⁶. Due to the original oxygen-induced reconstruction, Cu surface sites with Cu–Cu coordination numbers varying from 4 to 10 were obtained (Supplementary Figs. 15 and 16). As a reference, a four-layer-thick (100) crystalline supercell (Supplementary Fig. 15) was used, as this facet is often deemed responsible for CO–CO dimerization¹⁰. Surface atoms in this system were characterized by a Cu–Cu coordination number of 8. To obtain the DFT vibrational frequencies of CO₂RR reaction intermediates, we first optimized them on different active sites on the OD-Cu distorted surface and the crystalline

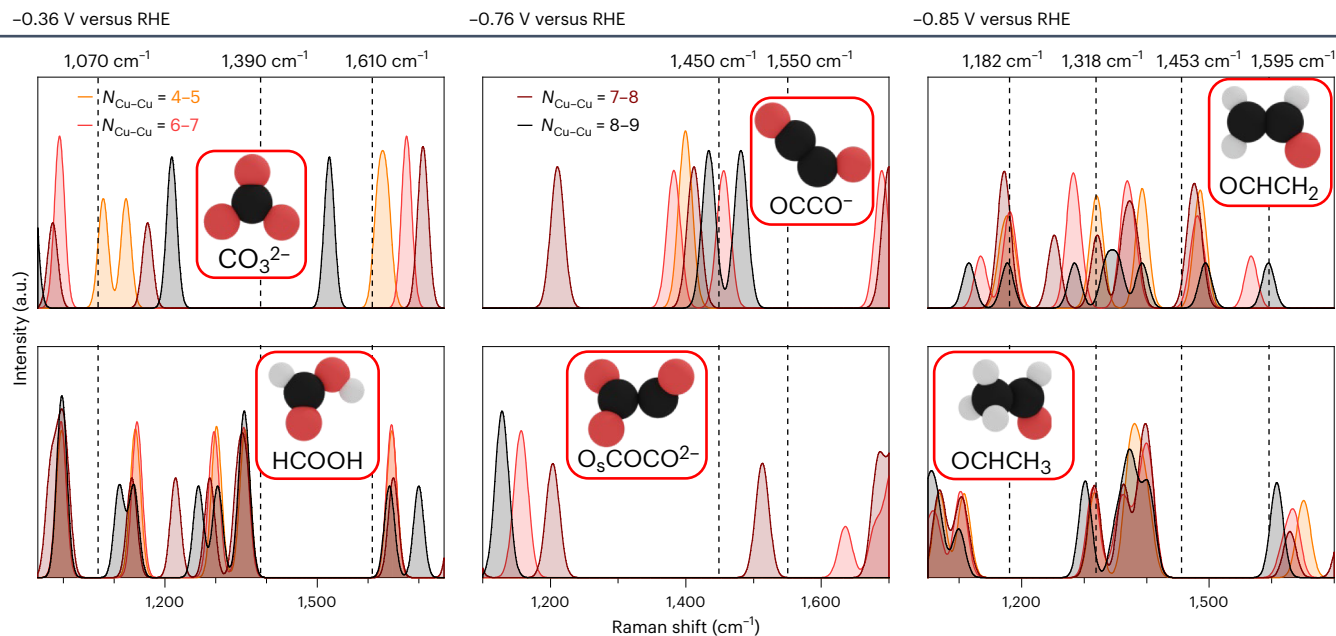


Fig. 3 | DFT-optimized CO₂RR reaction intermediates and their vibrational fingerprints. DFT vibrational frequencies for *CO₃²⁻, *COCO⁻, OCHCH₂ (top, left to right), *HCOOH, *O_sCOCO²⁻ and *OCHCH₃ (bottom, left to right) on adsorption sites with different coordination numbers, increasing from orange to black. Experimental signals at different applied potentials are indicated on top and

highlighted in the panels by vertical dashed lines. Raman spectra were achieved by applying a smearing of 10 cm⁻¹ on each DFT frequency and overlapping the resulting peaks. Inset: different CO₂RR reaction intermediates, with H atoms given in white, O atoms in red and C atoms in black.

Cu(100) and then carried out vibrational analysis on the final configurations. Simulated vibrational frequencies can be visualized through the ioChem-BD database³⁷ (see the explanatory tutorial in Methods and Supplementary Fig. 17).

In Fig. 3, we show the main reaction intermediates responsible for the vibrational frequencies detected experimentally (Fig. 2a). After the reduction of the Cu oxidic phases, *CO₃²⁻ and *HCOO⁻/^{*}HCOOH species form (see 1,070 cm⁻¹, 1,390 cm⁻¹ and 1,610 cm⁻¹ signals in Fig. 3; Supplementary Tables 1–3). Consistent with previous reports^{14,15}, the signals appearing at 1,450 cm⁻¹ and 1,550 cm⁻¹ from -0.76 V_{RHE} can be attributed to *OCCO(H), with the C=O vibration mode (Fig. 3 and Supplementary Tables 4 and 5). Alternatively, such frequencies can be assigned to an OCCO⁻ dimer adsorbed on surface oxygen (O_s), known as deprotonated glyoxylate O_sCOCO²⁻ (ref. 36), which also shows the 1,070 cm⁻¹ band detected at -0.76 V_{RHE} (Supplementary Table 6).

Among other additional possible intermediates (*OCCHO, *OHC-COH, *OCCHOH, *CHO and *CH; Supplementary Tables 7–11), we attribute the 1,182 cm⁻¹, 1,318 cm⁻¹, 1,453 cm⁻¹ and 1,595 cm⁻¹ signals detected at -0.85 V_{RHE} and below to the CCO symmetric stretching, CCO antisymmetric stretching, C–C stretching and C–O (or C=C) stretching of OCHCH₂ (or OCHCH₃) species, respectively (Supplementary Table 7). Although this assignment is based on different independent experiments, we cannot fully rule out that the Raman bands observed might also result from (a set of) very similar adsorbates.

In addition, we carried out ¹³C- or D-labelling SERS experiments at -0.95 V_{RHE} (Fig. 4a). ¹³C/¹²C exchange led to obvious redshifts of the 1,455 cm⁻¹ and 1,602 cm⁻¹ peaks, in addition to the CO stretching (2,100 cm⁻¹), Cu–CO stretching (358 cm⁻¹) and CO rotation (275 cm⁻¹) bands, proving that these peaks are related to the CO₂RR process. Such redshifts were also confirmed by DFT vibrational analysis of O¹²CH¹²CH₂ and O¹³CH¹³CH₂ (Fig. 4b and Supplementary Table 12). Water shows a broad O–H bending band at about 1,600 cm⁻¹ (refs. 14,15) (Supplementary Table 13), limiting the identification of vibrations from other species in this regime. In agreement with our assignment, the peak at about 1,602 cm⁻¹ still appears after the D₂O/H₂O isotope exchange. Besides, the D₂O/H₂O exchange negligibly affected the peaks at about

1,320 cm⁻¹ and 1,455 cm⁻¹. For the peak at 1,182 cm⁻¹, no obvious shift was observed in the D-labelling experiment, while the low intensity in the ¹³C/¹²C exchange experiment did not allow for a robust determination of the isotope-induced shift.

Since similar C–C coupling intermediates were proposed for CORR^{3,38}, to validate our observations, we performed in situ SERS during CORR. Our data show similar bands (Supplementary Fig. 18). We further prove the appearance of C–C coupling intermediates by observing analogous signals on a different Cu foil with distinct surface morphology, yet with still good performance towards C₂₊ products (Supplementary Fig. 19).

As ethanol and acetaldehyde are the main C₂ products for glyoxal reduction on polycrystalline copper and are proposed to share the same *OCHCH₂ intermediate^{16–18}, we performed in situ Raman experiments of glyoxal and ethanol reduction (Supplementary Figs. 20 and 21). As shown in Fig. 4c, similar bands at about 1,290 cm⁻¹, 1,420 cm⁻¹ and 1,605 cm⁻¹ are observed during glyoxal reduction. We attribute the variations in relative intensities and positions to the substantially different chemical environment in the absence of predominantly co-adsorbed CO, as is the case in CO₂RR. The increasing relative intensity of the band at ~1,550 cm⁻¹ is probably caused by key intermediates for ethylene glycol formation, which is the dominant product of glyoxal reduction at lower potentials²⁰. Instead, these signals were not observed for ethanol reduction (Supplementary Fig. 21). Thus, we reasonably confirmed the detection of a common intermediate along the CO, CO₂ and glyoxal reduction route to ethanol, which is *OCHCH₂. Overall, the presence of CO molecules on the Cu surface during CO₂RR is linked to and probably causes the formation of *CO–CO or *CO–COH at about -0.76 V_{RHE}, and then these species further reduce to, for example, *OCHCH₂ at -0.85 V_{RHE} and -0.95 V_{RHE}.

Cu active sites selective for CO₂RR to ethylene and ethanol

The potential-dependent formation of C–C coupling intermediates explains the selectivity trend towards C₂₊ products observed during CO₂RR. In correspondence with an increase in the CO coverage from

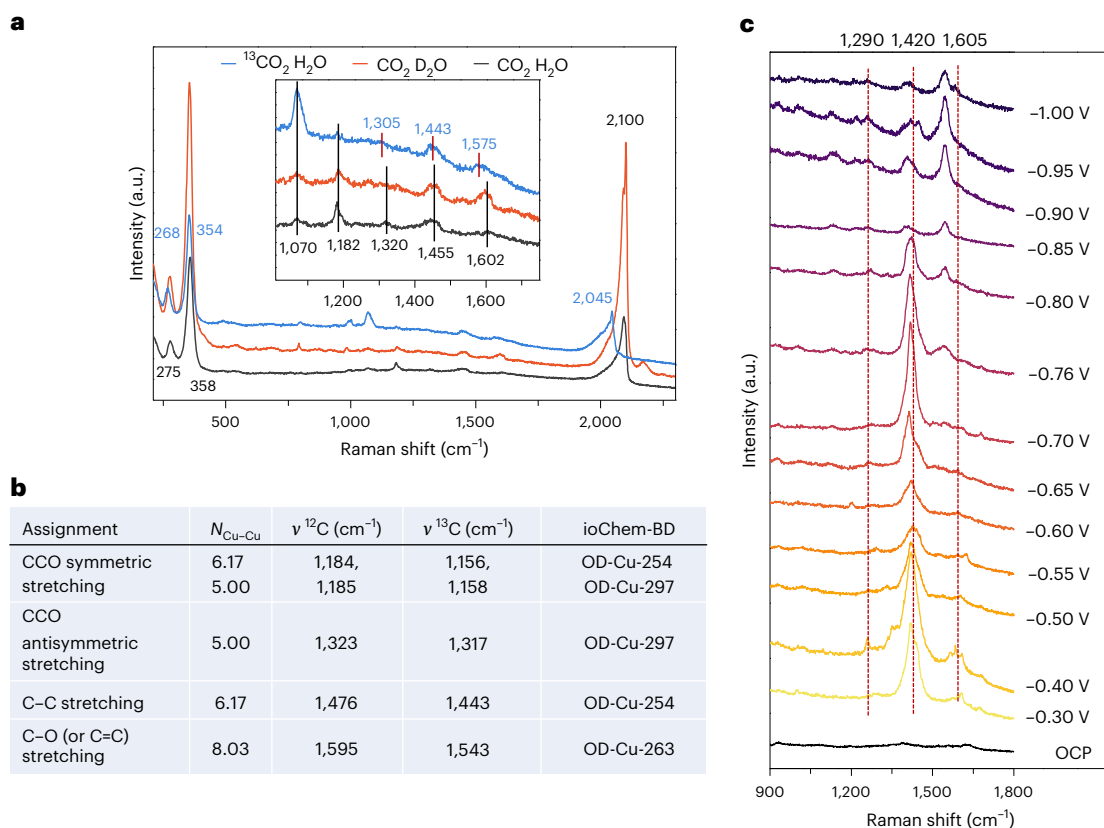


Fig. 4 | In situ SERS measurement and DFT vibrational analysis with the isotope exchange. a, Raman spectra of species adsorbed on the electrochemically treated Cu electrode at $-0.95 V_{\text{RHE}}$ in $^{13}\text{CO}_2$ -saturated 0.1 M NaClO_4 electrolyte and CO_2 -saturated 0.1 M $\text{NaClO}_4/\text{D}_2\text{O}$ electrolytes. **b**, OCHCH₂

vibrational fingerprints on selected active sites determined by DFT simulations for ^{12}C and ^{13}C (see Methods, ref. 62). **c**, Raman spectra of an electrochemically treated Cu foil acquired in 0.05 M glyoxal for potentials ranging from $-0.3 V_{\text{RHE}}$ to about $-1.0 V_{\text{RHE}}$ in an Ar-saturated 0.1 M NaClO_4 electrolyte.

$-0.56 V_{\text{RHE}}$ to $-0.76 V_{\text{RHE}}$, the *OCCO intermediate forms on the surface and evolves to ethylene at $-0.76 V_{\text{RHE}}$. Instead, the *OCHCH_x key intermediate is detected from $-0.85 V_{\text{RHE}}$, the observed onset potential for CO_2RR to alcohols. Besides, the ratio of Faradaic efficiencies towards ethanol and ethylene continuously increases with increasingly negative applied potential (Fig. 5a).

To further correlate the catalyst structure, surface intermediates and reaction products, we carried out quasi in situ Cu LMM XAES, in situ SERS, cyclic voltammetry and simulations. The surface of the electrochemically treated Cu foil was fully reduced to metallic Cu after CO_2RR at $-0.8 V_{\text{RHE}}$ (Fig. 5b). Figure 5c shows the potential-dependent variations of the C–O stretching band of adsorbed CO during CO_2RR . The C–O stretching frequency of atop CO on Cu depends on the coordination of the underlying metal atom^{39,40}; thus, it can be used as a probe to track the potential-dependent density of different active sites. In principle, the peak shifts to higher wavenumbers for adsorption sites with lower coordination number (although other effects, such as dipole coupling, can interfere)⁴⁰, consistent with DFT simulations (Fig. 5d and Supplementary Table 14). Four Gaussian peak functions centred at about $2,035 \text{ cm}^{-1}$, $2,075 \text{ cm}^{-1}$, $2,090 \text{ cm}^{-1}$ and $2,100 \text{ cm}^{-1}$ were used to fit the recorded potential-dependent Raman spectra. C–O stretching bands with intermediate frequencies ($2,075 \text{ cm}^{-1}$ and $2,090 \text{ cm}^{-1}$) become the main contribution at $-0.76 V_{\text{RHE}}$, from which the *OCCO intermediate is identified and ethylene is produced, in line with the observation of a $2,060 \text{ cm}^{-1}$ CO precursor reacting towards C–C coupling as reported in a previous SERS study⁶. At $-0.95 V_{\text{RHE}}$, the C–O stretching bands at $2,090 \text{ cm}^{-1}$ and $2,100 \text{ cm}^{-1}$, assigned to atop CO adsorbed on defect Cu sites, further increase and reach a maximum at $-1.04 V_{\text{RHE}}$, coinciding with the detection of the *OCHCH_x key intermediate and ethanol.

The formation of defects on the Cu surface during CO_2RR , for instance, adatoms or small Cu clusters with low-coordinated Cu atoms, has been experimentally observed via electrochemical scanning tunnelling microscopy⁴¹. Moreover, the subsurface incorporation of atomic impurities such as C or O during CO_2RR cannot be ruled out, as this could also lead to a defective Cu surface with the modified Raman shifts obtained here. Cyclic voltammetry has been used to compare the defect density on the Cu surface after CO_2RR using the charge transferred above $+0.3 V_{\text{RHE}}$ (ref. 25). Clearly, CO_2RR at $-1.0 V_{\text{RHE}}$ induced a higher defect density compared with $-0.8 V_{\text{RHE}}$ (Fig. 5e), and the cyclic voltammogram agrees well with that of a restructured/roughened Cu foil upon pulsed electrolysis into the Cu^{2+} regime²⁵. These findings are further supported by Pb underpotential deposition experiments^{42,43}, during which an increased defect site density of CO_2RR at $-1.0 V_{\text{RHE}}$ was observed (Supplementary Fig. 22). Finally, adsorbed CO linked to a lower C–O stretching band Raman shift becomes preeminent beyond $-1.1 V_{\text{RHE}}$, where CH_4 production again significantly increases, in line with a previous report⁴⁴. Thus, both in situ SERS and cyclic voltammetry hint at the key role of structural defects in tuning the ethylene/ethanol ratio. These defects are probably formed under reaction conditions and generate distinct surface sites with strong CO binding.

On the basis of these mechanistic insights, we aimed to correlate specific active sites and reaction intermediates with ethylene and ethanol production during CO_2RR . Recent experimental studies have highlighted the relevance of defects and polarized Cu sites in enabling CO_2RR ^{25,26,45,46}, while flat atomically ordered surfaces mainly yield H_2 (ref. 24). Moreover, defective structures and highly disordered Cu(0)/Cu(I,II) interfaces created through pulsed electrolysis conditions were found to significantly enhance ethanol selectivity^{25,45,46}. Thus, we initially assessed the role of two structural descriptors to identify defects

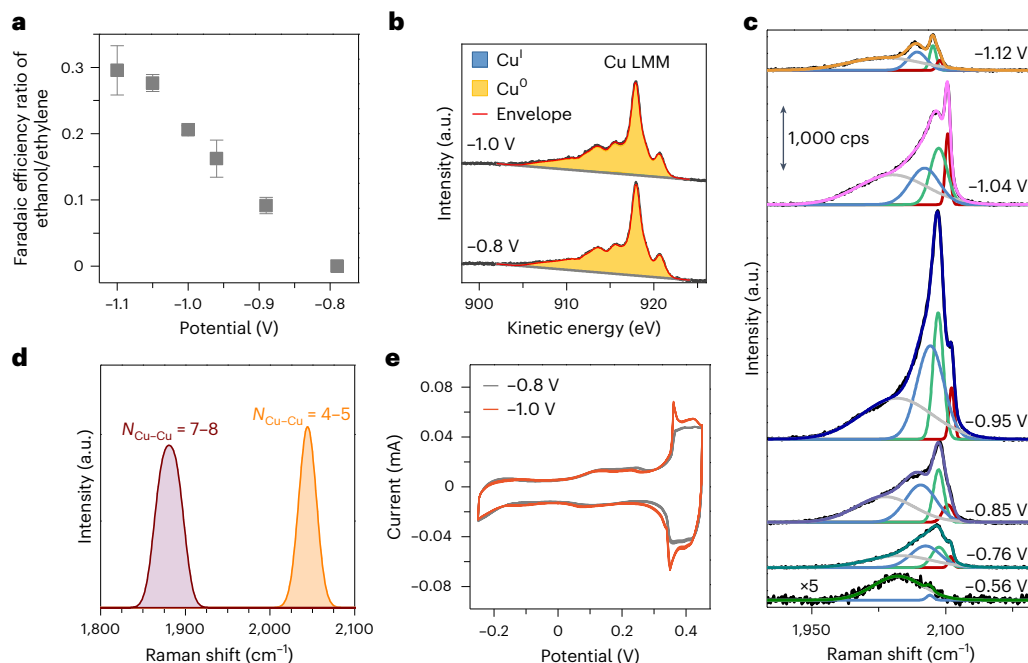


Fig. 5 | Defect-driven mechanisms for CO₂RR to ethylene and ethanol. a, Ratio of the Faradaic efficiencies of ethanol and ethylene as a function of the applied potential. **b**, Quasi in situ Cu LMM XAES spectra of electrochemically pre-treated Cu foils after 1 h of CO₂RR at $-0.8 V_{\text{RHE}}$ and $-1.0 V_{\text{RHE}}$ without air exposure. **c**, Dependence of the C–O stretching band on the applied potential. The Raman spectra are fitted with the sum of 4 Gaussian functions with peaks at about $2,035 \text{ cm}^{-1}$ (grey), $2,075 \text{ cm}^{-1}$ (blue), $2,090 \text{ cm}^{-1}$ (green) and $2,100 \text{ cm}^{-1}$ (red).

The Raman data in **c** are from the same dataset as those in Fig. 2. **d**, DFT C–O stretching wavenumber as a function of the Cu–Cu coordination number, decreasing from orange ($N_{\text{Cu-Cu}} = 4-5$) to dark brown ($N_{\text{Cu-Cu}} = 7-8$). **e**, Cyclic voltammograms of the electrochemically treated Cu foil after 1 h of CO₂RR at $-0.8 V_{\text{RHE}}$ and $-1.0 V_{\text{RHE}}$. Cyclic voltammetry was performed in an Ar-saturated 0.1 M NaOH with a scan rate of 50 mV s^{-1} . The error bars in **a** correspond to the s.d. of three independent measurements. Data are given as average \pm s.d.

among the considered active sites: their coordination number ($N_{\text{Cu-Cu}}$; Supplementary Fig. 23) and the relative compressive three-dimensional strain, calculated by dividing the distances between the active site and neighbouring atoms by the Cu–Cu bulk distance ($\Sigma_i(\Delta d_i/d)N_{i,\text{Cu-Cu}}^{-1}$ with i ranging from 1 to the number of neighboring atoms, see Supplementary Table 15 and Methods for additional details). Remarkably, the strain does not scale with the coordination number for the distorted sites from the OD-Cu model. Instead, on crystalline domains such as Cu facets and adatoms, both parameters correlate (Supplementary Fig. 23), suggesting a mutual dependence of coordination- and strain-based linear scaling relationships for crystalline sites^{47,48}.

To sample the reactivity of such surface defects, we estimated the binding energy of atop *CO and *OCHCH₂ versus $N_{\text{Cu-Cu}}$ and $\Sigma(\Delta d/d)N_{i,\text{Cu-Cu}}^{-1}$. *CO was taken as a C_{2+} selectivity descriptor¹⁰, whereas *OCHCH₂ binding strength was used as a descriptor of OCHCH₂ stability on the surface. On crystalline domains, *CO binding depends weakly on the strain, in line with results on crystalline surfaces⁴⁷, while differences of more than 0.4 eV are observed on highly strained low-coordinated OD-Cu sites (Supplementary Fig. 24 and Supplementary Table 16). Besides, both crystalline and distorted morphologies with coordination number below 8 show strong CO binding ($< -0.2 \text{ eV}$).

Localized compressive strain plays a crucial role in stabilizing *OCHCH₂ species on distorted sites (red empty data points in Fig. 6a). In fact, *OCHCH₂ formation energies increase following the increment of compressive strain, and stronger binding is observed on undercoordinated distorted sites rather than crystalline sites. Such difference between crystalline and distorted sites can be ascribed to their s -band states (Supplementary Table 16). Distorted domains present deeper s -band states, whereas crystalline sites are characterized by positive s -band centres (versus the Fermi energy). The s -band equally affects a previously employed descriptor for ethylene/ethanol competition, the *O binding strength⁴⁹. Crystalline sites with

a positive s -band centre show weak *O binding (black data points in Fig. 6b), whereas distorted sites with a negative s -band centre enable strong *O binding, thus promoting the adsorption of intermediates with terminal oxygen along the ethanol route⁴⁹. The s -band centre shows a strong correlation with the d -band centre (Supplementary Fig. 25 and Supplementary Table 17). Finally, we observe that scaling relationships between the binding energy of adsorbed molecules and strain are heavily affected by the nature of active sites (Supplementary Note 2).

Overall, these insights highlight a clear correlation between active sites and product distribution. Undercoordinated Cu sites enable strong *CO binding, thus sustaining a high CO coverage on the surface, which opens the ethylene pathway via an OCCO(H) intermediate, explaining the evidence of C₂H₄ as the only C₂₊ product observed at $-0.76 V_{\text{RHE}}$ (Fig. 1f). This scheme explains the typically high CO₂RR selectivity towards C₂ of OD-Cu²⁵, which is due to the abundant undercoordinated sites on these materials³⁶ (about 74% for $N_{\text{Cu-Cu}} < 8$ on our OD-Cu model; Supplementary Fig. 16). Furthermore, from $-0.85 V_{\text{RHE}}$ onwards, undercoordinated distorted sites with high surface strain and deep s -band states originate (Fig. 5c,e) and enable the formation of OCHCH₂ at the surface (Fig. 6b), detected experimentally through Raman spectroscopy (Figs. 2c and 3) together with the production of ethanol (Fig. 1f).

A careful comparison of ethylene, ethanol and methane Faradaic efficiency versus CO selectivity (taken from Fig. 1f) confirms the existence of key differences between the ethylene and ethanol routes (Fig. 6c). Instead, the similar dependence of ethanol and methane Faradaic efficiency on CO selectivity supports the hypothesis of CH_x as common precursors for the two products, providing additional parallel pathways from CO–CH_x coupling, in line with the recent CH₃/CO reduction study²⁰. These undercoordinated distorted sites open the OCHCH₂-mediated ethanol route (Fig. 6d).

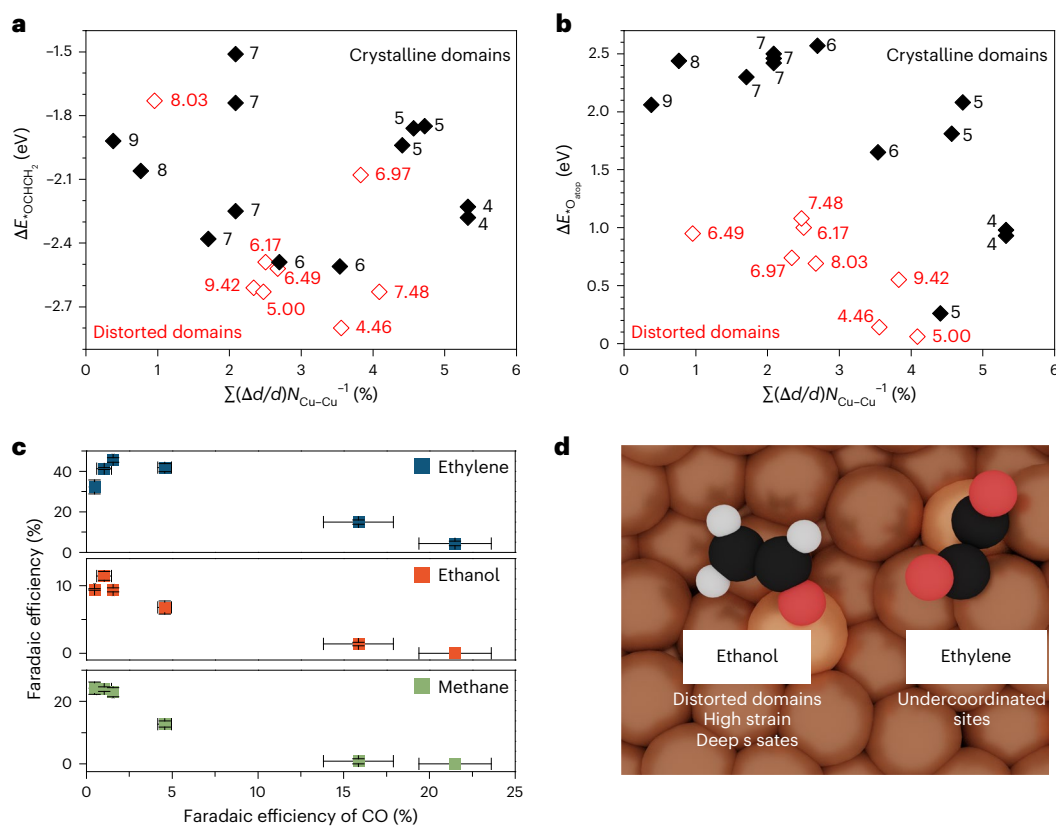


Fig. 6 | Morphological descriptors for CO₂R to C₂₊ products. **a, b**, Correlation of $^*\text{OCHCH}_2$ ($\Delta E_{\text{OCHCH}_2}$) (**a**) and $^*\text{O}_{\text{atop}}$ ($\Delta E_{\text{O}_{\text{atop}}}$) binding energies (**b**) versus $\Sigma(\Delta d/d)N_{\text{Cu-Cu}}^{-1}$. Cu-Cu coordination numbers are reported as labels. Red data points indicate Cu sites on distorted domains, and black data points represent crystalline domains. **c**, Comparison between ethylene, ethanol and methane

Faradaic efficiency versus CO Faradaic efficiency. Data retrieved from Fig. 1f. **d**, Key reaction intermediates and properties of the active sites selective towards ethanol and ethylene, with H atoms given in white, O atoms in red and C atoms in black. The error bars in **c** correspond to the s.d. of three independent measurements. Data are given as average \pm s.d.

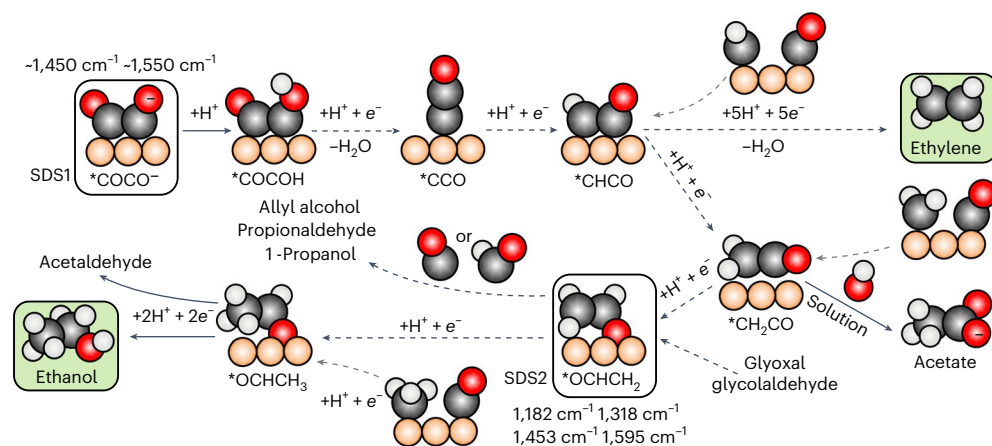


Fig. 7 | Proposed reaction scheme for CO₂ reduction to C₂₊ products. Proposed reaction scheme, including ethylene and ethanol, was extracted from the present experimental Raman data, our DFT data and additional mechanistic insights reflected in refs. 16,21,51,63. The main C₂₊ products are highlighted in green.

Reaction steps confirmed by experimental studies are reported as solid lines, and proposed steps are labelled as dashed lines. Grey arrows indicate potential CO-CH_x coupling routes. H atoms are given in white, O atoms in red and C atoms in black.

Proposed reaction scheme for CO₂RR to C₂₊ products

The proposed OCHCH₂-mediated ethanol pathway suggests an updated reaction scheme for CO₂RR towards C₂₊ products (Fig. 7). Ethylene and ethanol formations are pH-independent on the RHE scale⁵. Thus, according to the state of the art^{2,7}, CO-CO dimerization, which involves a single electron transfer, is assumed to be the

rate-determining step (RDS) towards multi-carbon molecules during CO₂ reduction. Such hypothesis has been recently challenged by mechanistic studies of CO reduction⁵⁰; thus, competing RDSs may exist depending on the catalyst morphology. If formed, the CO-CO(H) species is characterized by either a single or double C-C bond⁷ (Supplementary Table 18) and acts as a selectivity switch between C₁ and C₂₊ products (C₂₊ selectivity-determining step 1, SDS1).

The hypothesis of OCCO(H) as a common C_{2+} precursor for CO_2 reduction is reinforced by the strong correlation between ethanol and ethylene Faradaic efficiency on copper ($R^2 = 0.90$, values taken from ref. 51; see Supplementary Fig. 26 and Supplementary Table 19). In line with recent advances²⁰, additional parallel pathways, such as CO–CH_x coupling (grey arrows, Fig. 7), may also open, yet our DFT simulations disprove any major role of these on distorted sites. In fact, the protonation of CH_x to CH_{x+1} species (and eventually to methane) is always more favourable than the CO–CH_x coupling, apart from the CO–CH case (Supplementary Fig. 27).

Once formed, CO–CO(H) dimers quickly protonate and evolve into an adsorbed ketene *CCO upon the loss of one H₂O molecule, as previously suggested^{21,27}. Such ketene then reduces to *CHCO upon proton-coupled electron transfer^{7,21}, the last common precursor between ethylene and ethanol⁴⁹. *CHCO can then either reduce to *OCCH₂ along the acetate/ethanol pathway or undergo reduction to ethylene via five proton-coupled electron transfers and the release of one H₂O molecule²¹. Along the acetate/ethanol route, OCCH₂ can desorb and react in solution with OH[−] to form acetate²¹. Following the C₂ route, when highly strained distorted sites are present, an alternative reaction pathway opens, that is, enabling the reduction of *OCCH₂ to *OCHCH₂ by strongly binding the terminal oxygen in a monodentate configuration. *OCHCH₂ (ref. 7; characterized by a double C–C bond, see Supplementary Table 18) can either reduce to acetaldehyde and ethanol or couple with a CO/COH species to form allyl alcohol and, at later reduction stages, 1-propanol⁵¹ (see the correlation between Faradaic efficiency for both products in Supplementary Fig. 26 and Supplementary Table 19).

Thus, although a methyl carbonyl intermediate (OCCH₃) was recently suggested as the ethanol precursor during CH₃I and acetaldehyde/CO reduction²⁰, we here identify *CHCO reduction to *OCHCH₂ as the selectivity switch (selectivity-determining step 2, SDS2) to ethanol, acetaldehyde, 1-propanol and allyl alcohol (Supplementary Note 1 and Supplementary Figs. 28 and 29), as confirmed by the strong correlation between acetaldehyde and ethanol selectivities ($R^2 = 0.82$ (ref. 51); Supplementary Fig. 26 and Supplementary Table 19). Besides, in situ Raman spectroscopy during CO₂, CO and glyoxal reduction to ethanol confirms the existence of a shared reaction intermediate, which is reasonably OCHCH₂ (Supplementary Fig. 28). The reduction of OCHCH₂ to OCHCH₃ is thermodynamically sluggish (Supplementary Fig. 30), which might explain the experimental observation of OCHCH₂ species, reflecting a significant population on the Cu surface to be detected via SERS on a very rough Cu surface. In fact, a strong *OCH₂CH₃ signal was also observed on other ethanol-selective catalysts⁵².

Conclusion

On the basis of in situ SERS and DFT simulations, we identified the crucial active sites and reaction intermediates responsible for ethylene and ethanol formation in CO₂RR over a Cu surface. We unveiled that defects in Cu with a low coordination number (<8) enable strong *CO binding, thus sustaining high surface CO coverages and subsequent CO–CO dimerization. These undercoordinated sites are mainly selective to ethylene via the traditional route, *CO–CO or *CO–COH couplings, which are C₂₊ product precursors. However, defects characterized by a highly compressed and distorted coordination environment and deep s-band states are instead generated at higher overpotentials and stabilize the adsorption of OCHCH₂ via the terminal oxygen, opening an alternative selective route towards ethanol on copper. By combining the potential-dependent evolution of CO adsorption and C–C coupling intermediates, we here describe an updated CO₂RR-to-C₂₊ reaction scheme that correlates between active sites, surface intermediates and products. Insights from the identified active sites provide key guidelines to rationally design electrocatalysts to maximize the selectivity of each of these products independently.

Methods

Electrode preparations

A commercial polycrystalline copper foil (Advent Research Materials, 99.995%) was used in all experiments. Before each experiment, the copper foil was electropolished at 3 V versus a titanium foil for 3 min in a H₃PO₄/H₂SO₄ solution consisting of 130 ml H₃PO₄ (VWR, 85 wt%), 20 ml H₂SO₄ (VWR, 95%) and 60 ml ultrapure water. After that, all working electrodes were rinsed with ultrapure water and placed in the electrochemical cell for the electrochemical oxidation–reduction process. The three-electrode system consisted of the copper foil as the working electrode, a platinum wire as the counter electrode and a leak-free Ag/AgCl reference electrode (LF-1, Alvatek). The copper electrodes were treated at room temperature by cyclic voltammetry in gas-saturated 0.1 M NaClO₄ (Aldrich, 99.99%) without the use of halide, at a sweep rate of 10 mV s^{−1} from −1.3 V_{RHE} to +0.9 V_{RHE} for two cycles.

Characterization of samples

The crystal structure of the catalysts was studied using XRD with a Bruker-AXS D8 Advance in parallel beam configuration equipped with a Cu X-ray tube, a Goebel mirror and equatorial Soller slit (0.3°) as well as an energy-dispersive LynxEye detector. The diffraction pattern was recorded through the grazing incidence mode with an incidence angle of 1° to decrease the bulk contribution of the Cu foil.

The size and morphology of the samples were determined by SEM with a ThermoFisher Apreo microscope and a Hitachi S-4800 system, including a cold field emission gun.

XPS measurements were performed with a commercial hemispherical analyser (Phoibos 150, MCD-9 Detector, SPECS, $E_{\text{pass}} = 15$ eV) and a monochromatic X-ray source (SPECS) with an Al anode ($E_{\text{K}\alpha} = 1,486.7$ eV as X-ray energy) at a power of $P = 300$ W. All spectra were aligned by fixing the Cu $2p_{3/2}$ of Cu⁰ and Cu⁺ to 932.67 eV as a reference.

In situ Raman experiments

The in situ Raman spectra were obtained using a Renishaw (InVia Reflex) confocal Raman microscope with a 785 nm laser. A water immersion objective with a long working distance (Leica Microsystems, ×63, numerical aperture of 0.9) was chosen to perform the in situ experiments in an electrolyte. The objective with a long working distance was needed to avoid diffusion hindrance during the Raman measurements¹³. During the measurements, the objective was protected from the electrolyte by a Teflon film (DuPont, film thickness of 0.013 mm). The laser power was about 0.36 mW. The acquisition time was 10 s for the steady-state experiments at different potentials. The spot size of the focused laser beam was about 2 μm in diameter. The electrochemical measurements were performed in a home-built spectro-electrochemical cell made of Teflon and controlled by a Biologic SP-240 potentiostat. The cell was equipped with a reference electrode (leak-free Ag/AgCl, Alvatek), a counter electrode (Pt ring) and a Cu foil working electrode. Typically, a 15 ml CO₂-saturated 0.1 M NaClO₄ solution was used as the electrolyte, and CO₂ was continuously injected into the solution during the experiment. Ar-saturated 0.1 M KHCO₃ and Ar-saturated 0.1 M NaClO₄ were used in the experiments as well. For the steady-state experiment, each potential was applied for at least 10 min before collecting the spectra to ensure steady-state conditions at the surface of the catalyst.

CO₂RR testing

Electrocatalytic measurements were performed with a Biologic SP-240 potentiostat in an H-type cell equipped with an anion exchange membrane (Selmion AMV, AGC). The three-electrode system consisted of the Cu foil as the working electrode, a platinum gauze (MaTeck, 3,600 mesh cm^{−2}) as the counter electrode and a leak-free Ag/AgCl reference electrode (LF-1, Alvatek). A CO₂-saturated 0.1 M KHCO₃ aqueous solution, purified from trace metal ion impurities by a cation-exchange resin (Chelex 100 Resin, Bio-Rad), was used as the electrolyte. The

CO₂ (99.995%) flow rate was 20 ml min⁻¹. For each cathodic potential, the chronoamperometry lasted 3,600 s. All potentials are given versus the RHE scale and were corrected for the *iR* drop. Each presented data point corresponds to an identical freshly prepared sample following this protocol at different potentials. The electrochemical surface roughness factor, estimated from double-layer capacitance measurements, is 14.6, which was measured by cyclic voltammetry in a non-Faradaic potential range from 0.10 V_{RHE} to 0.25 V_{RHE} at scan rates of 20 mV s⁻¹, 40 mV s⁻¹, 60 mV s⁻¹, 80 mV s⁻¹ and 100 mV s⁻¹ in a CO₂-saturated 0.1 M KHCO₃ solution after 1 h of electrochemical reaction.

Gas products were detected and quantified every 15 min by online gas chromatography (Agilent 7890B), equipped with a thermal conductivity detector and a flame ionization detector. Liquid products were analysed after each measurement with a high-performance liquid chromatograph (Shimadzu Prominence), equipped with a NUCLEOGEL SUGAR 810 column and a refractive index detector, and a liquid gas chromatograph (Shimadzu 2010 Plus), equipped with a fused silica capillary column and a flame ionization detector¹³.

All catalytic results in this study are shown in terms of Faradaic efficiency. The Faradaic efficiency of the gas product *x* was calculated using equation (1):

$$FE = \frac{\dot{V} \times C_x \times z_x \times F}{A \times V_M \times j_{\text{total}}} \times 100\%, \quad (1)$$

and for the liquid product *x* was calculated using equation (2):

$$FE = \frac{V \times \Delta C_x \times z_x \times F}{\Delta Q} \times 100\%. \quad (2)$$

Here FE is the Faradaic efficiency of product *x*, \dot{V} is the CO₂ gas flow rate (l s⁻¹), *C_x* is the volume fraction of the product *x* detected by gas chromatography, *z_x* is the number of electrons transferred for reduction to product *x*, *F* is the Faradaic constant (C mol⁻¹), *A* is the geometric area of the electrode (cm²), *V_M* is the molar volume (22.4 l mol⁻¹), *j_{total}* is the total current density during CO₂ bulk electrolysis (A cm⁻²), ΔC_x is the final concentration of product detected by high-performance liquid chromatography and liquid gas chromatography (mol l⁻¹), ΔQ is the total charge transferred during electrolysis at constant potential or current (C), and *V* is the volume of the electrolyte (l).

Quasi in situ XPS

Quasi in situ XPS experiments were performed to avoid exposure of the sample to air after the electrochemical treatment. In this set-up, an electrochemical cell is directly attached to the UHV system where the XPS chamber is located to allow the sample transfer without air exposure. The electrochemical measurements were carried out using a potentiostat (Autolab PGSTAT 302N) and a CO₂-saturated 0.1 M KHCO₃ electrolyte. After the electrochemical treatment, the samples were rinsed with Ar-saturated H₂O and subsequently transferred under an Ar atmosphere into the load-lock of the UHV system.

DFT details

The DFT calculations were performed using the Vienna Ab initio Simulation Package^{34,35}, with the Perdew-Burke-Ernzerhof (PBE) density functional³³. We included dispersion according to the DFT-D2 method^{53,54}, with the re-parametrization of *C₆* coefficients for metals performed by our group⁵⁵. To account for solvent stabilization of intermediate formation energy, we employed the VASPsol code^{56,57}. Inner electrons were represented by projector augmented wave (PAW) pseudopotentials^{58,59}, whereas the mono-electronic states for the valence electrons were expanded as plane waves with a kinetic energy cut-off of 450 eV.

We modelled the OD-Cu catalyst investigated experimentally by considering a Cu(111)/Cu₂O(111) epitaxy with surface reconstruction

induced through ab initio molecular dynamics for 1 + 10 ps (3 fs time step)³⁶, and a 4-layer thick crystalline Cu(100). For the Cu(100), the two uppermost layers were fully relaxed and the rest fixed to the bulk distances. The Brillouin zone was sampled by a Γ -centred *k*-points mesh from the Monkhorst-Pack method⁶⁰, with a reciprocal grid size smaller than 0.03 Å⁻¹. The vacuum between the slabs was larger than 12 Å. The adsorbates were placed only on one side of the slab, thus requiring a dipole correction to remove spurious contributions arising from the asymmetric configuration⁶¹. Formation energies for the selected intermediates were obtained assuming CO₂(g), H₂(g), H₂O(g) and clean surfaces as energy references.

Cu–Cu coordination number

Two Cu atoms are coordinated if their distance falls below a certain threshold. Since bulk Cu (face-centred cubic) and Cu₂O show Cu–Cu bond distances of 2.57 Å and 3.05 Å, respectively, we assigned a coordination number *N_{Cu–Cu}* for metallic Cu between 0.0 (*d_{Cu–Cu}* = 3.05 Å) and 1.0 (*d_{Cu–Cu}* = 2.57 Å) following a decay controlled by the error function (erf)³⁶, as shown in equations (3) and (4). In equation (3), *N_{Cu–Cu}* is the Cu–Cu coordination number (dimensionless), and *d_{Cu–Cu}* is the Cu–Cu distance (Å). In equation (4), *t* (dimensionless) is the variable of integration, and 0 and *z* represent the integration limits:

$$N_{\text{Cu–Cu}} = \frac{1}{2} - \frac{1}{2} \operatorname{erf} \left(\frac{d_{\text{Cu–Cu}} - 2.57 \text{ \AA}}{0.1 \text{ \AA}} \right) \quad (3)$$

$$\operatorname{erf}(z) = \frac{2}{\sqrt{\pi}} \int_0^z \exp(-t^2) dt \quad (4)$$

Three-dimensional localized strain

Localized three-dimensional strain for a given Cu active site *j* was estimated by assessing the local deformation of Cu–Cu distances versus the bulk value (*d_{Cu–Cu}*(bulk) = 2.57 Å; Supplementary Table 15) for a given atom *i* within the coordination shell of species *j*, as shown in equation (5). Then, such deformations were summed among all the neighbouring Cu atoms and normalized by the Cu–Cu coordination number (*N_{Cu–Cu}*) of the active site *j*, as shown in equation (6). Distances are given in Å, coordination numbers are dimensionless, and three-dimensional strain is reported as a percentage of deformation. Negative values of strain indicate expansion, whereas positive values characterize contraction:

$$3\text{D strain}(j, i) = \frac{d_{\text{Cu–Cu}}(\text{bulk}) - d_{\text{Cu–Cu}}(j, i)}{d_{\text{Cu–Cu}}(\text{bulk})} \times 100 \quad (5)$$

$$\Sigma(\Delta d/d) N_{\text{Cu–Cu}}^{-1}(j) = \sum_{i=1}^{N_{\text{Cu–Cu}}} \frac{3\text{D strain}(j, i)}{N_{\text{Cu–Cu}}^{-1}(j)} \quad (6)$$

Visualization of vibrational fingerprints

To visualize vibrational frequencies of a given reaction intermediate in ioChem-BD³⁷, it is necessary to follow the next steps, summarized in Supplementary Fig. 17.

- (1) Access ref. 62 and click on the ‘frequencies’ collection (top left)
- (2) Select the desired item to visualize by clicking on the title ‘frq-X’
- (3) Once a new tab opens, click on ‘Actions → View data’ (top right)
- (4) Once a new tab opens, scroll down to ‘vibrational frequencies’ and click on it
- (5) Click on ‘Load vibrations’
- (6) Rotate the point of view by pressing the left button of the mouse and select the desired frequency

Data availability

Regarding the experimental datasets, the data are available in the main text, in the Supplementary Information file or as Source Data files for Figs. 1e,f, 2b, 5a, 6c and Supplementary Fig. 12. Additional data are available from the corresponding authors upon reasonable request. The DFT datasets generated during the current study are available in the ioChem-BD database³⁷ at <https://doi.org/10.19061/iochem-bd-1-251> (ref. 62).

References

1. Nitopi, S. et al. Progress and perspectives of electrochemical CO₂ reduction on copper in aqueous electrolyte. *Chem. Rev.* **119**, 7610–7672 (2019).
2. Birdja, Y. Y. et al. Advances and challenges in understanding the electrocatalytic conversion of carbon dioxide to fuels. *Nat. Energy* **4**, 732–745 (2019).
3. De Luna, P. et al. What would it take for renewably powered electrosynthesis to displace petrochemical processes? *Science* **364**, eaav3506 (2019).
4. Gao, D., Arán-Ais, R. M., Jeon, H. S. & Roldan Cuenya, B. Rational catalyst and electrolyte design for CO₂ electroreduction towards multicarbon products. *Nat. Catal.* **2**, 198–210 (2019).
5. Hori, Y., Takahashi, R., Yoshinami, Y. & Murata, A. Electrochemical reduction of CO at a copper electrode. *J. Phys. Chem. B* **101**, 7075–7081 (1997).
6. An, H. et al. Sub-second time-resolved surface enhanced Raman spectroscopy reveals dynamic CO intermediates during electrochemical CO₂ reduction on copper. *Angew. Chem. Int. Ed.* **60**, 16576–16584 (2021).
7. Kortlever, R., Shen, J., Schouten, K. J. P., Calle-Vallejo, F. & Koper, M. T. M. Catalysts and reaction pathways for the electrochemical reduction of carbon dioxide. *J. Phys. Chem. Lett.* **6**, 4073–4082 (2015).
8. Garza, A. J., Bell, A. T. & Head-Gordon, M. Mechanism of CO₂ reduction at copper surfaces: pathways to C₂ products. *ACS Catal.* **8**, 1490–1499 (2018).
9. Hori, Y., Murata, A. & Yoshinami, Y. Adsorption of CO, intermediately formed in electrochemical reduction of CO₂, at a copper electrode. *J. Chem. Soc. Faraday Trans.* **87**, 125–128 (1991).
10. Bagger, A., Ju, W., Varela, A. S., Strasser, P. & Rossmeisl, J. Electrochemical CO₂ reduction: a classification problem. *Chem. Phys. Chem.* **18**, 3266–3273 (2017).
11. Hori, Y., Koga, O., Yamazaki, H. & Matsuo, T. Infrared spectroscopy of adsorbed CO and intermediate species in electrochemical reduction of CO₂ to hydrocarbons on a Cu electrode. *Electrochim. Acta* **40**, 2617–2622 (1995).
12. Moradzaman, M. & Mul, G. In situ Raman study of potential-dependent surface adsorbed carbonate, CO, OH, and C species on Cu electrodes during electrochemical reduction of CO₂. *ChemElectroChem* **8**, 1478–1485 (2021).
13. Zhan, C. et al. Revealing the CO coverage-driven C–C coupling mechanism for electrochemical CO₂ reduction on Cu₂O nanocubes via operando Raman spectroscopy. *ACS Catal.* **11**, 7694–7701 (2021).
14. Pérez-Gallent, E., Figueiredo, M. C., Calle-Vallejo, F. & Koper, M. T. M. Spectroscopic observation of a hydrogenated CO dimer intermediate during CO reduction on Cu(100) electrodes. *Angew. Chem. Int. Ed.* **56**, 3621–3624 (2017).
15. Kim, Y. et al. Time-resolved observation of C–C coupling intermediates on Cu electrodes for selective electrochemical CO₂ reduction. *Energy Environ. Sci.* **13**, 4301 (2020).
16. Schouten, K. J. P., van der Ham, C. J. M., Qin, Z. & Koper, M. T. M. A new mechanism for the selectivity to C₁ and C₂ species in the electrochemical reduction of carbon dioxide on copper electrodes. *Chem. Sci.* **2**, 1902 (2011).
17. Reichert, A. M., Piqué, O., Parada, W. A., Katsounaros, I. & Calle-Vallejo, F. Mechanistic insight into electrocatalytic glyoxal reduction on copper and its relation to CO₂ reduction. *Chem. Sci.* **13**, 11205–11214 (2022).
18. Delmo, E. P. et al. The role of glyoxal as an intermediate in the electrochemical CO₂ reduction reaction on copper. *J. Phys. Chem. C* **127**, 4496–4510 (2023).
19. da Silva, A. H. M., Lenne, Q., Vos, R. E. & Koper, M. T. M. Competition of CO and acetaldehyde adsorption and reduction on copper electrodes and its impact on n-propanol formation. *ACS Catal.* **13**, 4339–4347 (2023).
20. Li, J. et al. Intercepting elusive intermediates in Cu-mediated CO electrochemical reduction with alkyl species. *J. Am. Chem. Soc.* **144**, 20495–20506 (2022).
21. Heenen, H. H. et al. Mechanism for acetate formation in electrochemical CO₂ reduction on Cu: selectivity with potential, pH, and nanostructuring Hendrik. *Energy Environ. Sci.* **15**, 3978–3990 (2022).
22. Handoko, A. D., Wei, F., Jenndy, Yeo, B. S. & Seh, Z. W. Understanding heterogeneous electrocatalytic carbon dioxide reduction through operando techniques. *Nat. Catal.* **1**, 922–934 (2018).
23. Auer, A. et al. Self-activation of copper electrodes during CO electro-oxidation in alkaline electrolyte. *Nat. Catal.* **3**, 797–803 (2020).
24. Scholten, F., Nguyen, K.-L. C., Bruce, J. P., Heyde, M. & Roldan Cuenya, B. Identifying structure-selectivity correlations in the electrochemical reduction of CO₂: comparison of well-ordered atomically-clean and chemically-etched Cu single crystal surfaces. *Angew. Chem. Int. Ed.* **60**, 19169–19175 (2021).
25. Arán-Ais, R. M., Scholten, F., Kunze, S., Rizo, R. & Roldan Cuenya, B. The role of in situ generated morphological motifs and Cu(I) species in C₂₊ product selectivity during CO₂ pulsed electroreduction. *Nat. Energy* **5**, 317–325 (2020).
26. Liu, G. et al. CO₂ reduction on pure Cu produces only H₂ after subsurface O is depleted: theory and experiment. *Proc. Natl Acad. Sci. USA* **118**, e2012649118 (2021).
27. Li, C. W., Ciston, J. & Kanan, M. W. Electroreduction of carbon monoxide to liquid fuel on oxide-derived nanocrystalline copper. *Nature* **508**, 504–507 (2014).
28. Gao, D. et al. Activity and selectivity control in CO₂ electroreduction to multicarbon products over CuO_x catalysts via electrolyte design. *ACS Catal.* **8**, 10012–10020 (2018).
29. Ruiter De, J. et al. Probing the dynamics of low-overpotential CO₂-to-CO activation on copper electrodes with time-resolved Raman spectroscopy. *J. Am. Chem. Soc.* **144**, 15047–15058 (2022).
30. Zhao, Y. et al. Speciation of Cu surfaces during the electrochemical CO reduction reaction. *J. Am. Chem. Soc.* **142**, 9735–9743 (2020).
31. Brown, G. M. & Hope, G. A. A SERS study of SO₂-4Cl⁻ ion adsorption at a copper electrode in situ. *J. Electroanal. Chem.* **405**, 211–216 (1996).
32. Niaura, G. & Malinauskas, A. Surface-enhanced Raman scattering from chloride on copper electrodes. *Chem. Phys. Lett.* **207**, 455–460 (1993).
33. Perdew, J. P., Burke, K. & Ernzerhof, M. Generalized gradient approximation made simple. *Phys. Rev. Lett.* **77**, 3865–3868 (1996).
34. Kresse, G. & Furthmüller, J. Efficiency of ab-initio total energy calculations for metals and semiconductors using a plane-wave basis set. *Comput. Mater. Sci.* **6**, 15–50 (1996).
35. Kresse, G. & Furthmüller, J. Efficient iterative schemes for ab initio total-energy calculations using a plane-wave basis set. *Phys. Rev. B* **54**, 11169–11186 (1996).

36. Dattila, F., García-Muelas, R. & López, N. Active and selective ensembles in oxide-derived copper catalysts for CO₂ reduction. *ACS Energy Lett.* **5**, 3176–3184 (2020).
37. Álvarez-Moreno, M. et al. Managing the computational chemistry big data problem: the ioChem-BD platform. *J. Chem. Inf. Model.* **55**, 95–103 (2015).
38. Ma, W. et al. Electrocatalytic reduction of CO₂ and CO to multi-carbon compounds over Cu-based catalysts. *Chem. Soc. Rev.* **50**, 12897–12914 (2021).
39. Hollins, P., Davies, K. J. & Pritchard, J. Infrared spectra of CO chemisorbed on a surface vicinal to Cu(110): the influence of defect sites. *Surf. Sci.* **138**, 75–83 (1984).
40. Gunathunge, C. M. et al. Spectroscopic observation of reversible surface reconstruction of copper electrodes under CO₂ reduction. *J. Phys. Chem. C* **121**, 12337–12344 (2017).
41. Amirbeigiarab, R. et al. Atomic-scale surface restructuring of copper electrodes under CO₂ electroreduction conditions. *Nat. Catal.* **6**, 837–846 (2023).
42. Yang, Y. et al. Operando studies reveal active Cu nanograins for CO₂ electroreduction. *Nature* **614**, 262–269 (2023).
43. Sebastián-Pascual, P. & Escudero-Escribano, M. Surface characterization of copper electrocatalysts by lead under-potential deposition. *J. Electroanal. Chem.* **896**, 115446 (2021).
44. Bai, H. et al. Controllable CO adsorption determines ethylene and methane productions from CO₂ electroreduction. *Sci. Bull.* **66**, 62–68 (2021).
45. Jeon, H. S. et al. Selectivity control of Cu nanocrystals in a gas-fed flow cell through CO₂ pulsed electroreduction. *J. Am. Chem. Soc.* **143**, 7578–7587 (2021).
46. Timoshenko, J. et al. Steering the structure and selectivity of CO₂ electroreduction catalysts by potential pulses. *Nat. Catal.* **5**, 259–267 (2022).
47. Mavrikakis, M., Hammer, B. & Nørskov, J. K. Effect of strain on the reactivity of metal surfaces. *Phys. Rev. Lett.* **81**, 2819–2822 (1998).
48. Calle-Vallejo, F., Martínez, J. I., García-Lastra, J. M., Sautet, P. & Loffreda, D. Fast prediction of adsorption properties for platinum nanocatalysts with generalized coordination numbers. *Angew. Chem. Int. Ed.* **53**, 8316–8319 (2014).
49. Peng, H.-J., Tang, M. T., Halldin Stenlid, J., Liu, X. & Abild-Pedersen, F. Trends in oxygenate/hydrocarbon selectivity for electrochemical CO₂ reduction to C₂ products. *Nat. Commun.* **13**, 1399 (2022).
50. Hou, J., Chang, X., Li, J., Xu, B. & Lu, Q. Correlating CO coverage and CO electroreduction on Cu via high-pressure in situ spectroscopic and reactivity investigations. *J. Am. Chem. Soc.* **144**, 22202–22211 (2022).
51. Kuhl, K. P., Cave, E. R., Abram, D. N. & Jaramillo, T. F. New insights into the electrochemical reduction of carbon dioxide on metallic copper surfaces. *Energy Environ. Sci.* **5**, 7050–7059 (2012).
52. Ding, L. et al. Over 70% Faradaic efficiency for CO₂ electroreduction to ethanol enabled by potassium dopant-tuned interaction between copper sites and intermediates. *Angew. Chem. Int. Ed.* **61**, e202209268 (2022).
53. Grimme, S. Semiempirical GGA-type density functional constructed with a long-range dispersion correction. *J. Comput. Chem.* **27**, 1787–1799 (2006).
54. Bucko, T. et al. Improved description of the structure of molecular and layered crystals: ab initio DFT calculations with van der Waals corrections. *J. Phys. Chem. A* **114**, 11814–11824 (2010).
55. López, N. et al. State-of-the-art and challenges in theoretical simulations of heterogeneous catalysis at the microscopic level. *Catal. Sci. Technol.* **2**, 2405–2417 (2012).
56. Fishman, M., Zhuang, H. L., Mathew, K., Dirschka, W. & Hennig, R. G. Accuracy of exchange-correlation functionals and effect of solvation on the surface energy of copper. *Phys. Rev. B* **87**, 245402 (2013).
57. Mathew, K., Sundararaman, R., Letchworth-Weaver, K., Arias, T. A. & Hennig, R. G. Implicit solvation model for density-functional study of nanocrystal surfaces and reaction pathways. *J. Chem. Phys.* **140**, 084106 (2014).
58. Blöchl, P. E. Projector augmented-wave method. *Phys. Rev. B* **50**, 17953–17979 (1994).
59. Kresse, G. & Joubert, D. From ultrasoft pseudopotentials to the projector augmented-wave method. *Phys. Rev. B* **59**, 1758–1775 (1999).
60. Monkhorst, H. J. & Pack, J. D. Special points for Brillouin-zone integrations. *Phys. Rev. B* **13**, 5188–5192 (1976).
61. Makov, G. & Payne, M. C. Periodic boundary conditions in ab initio calculations. *Phys. Rev. B* **51**, 4014–4022 (1995).
62. Dattila, F. Raman-C2. *ioChem-BD* <https://doi.org/10.19061/iochem-bd-1-251> (2024).
63. Pablo-García, S. et al. Mechanistic routes toward C₃ products in copper-catalysed CO₂ electroreduction. *Catal. Sci. Technol.* **12**, 409–417 (2022).

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Author contributions

C.Z., F.D., A.B., N.L. and B.R.C. co-wrote the paper. B.R.C. and N.L. supervised the study. C.Z. designed the study and performed sample synthesis, characterization, catalytic measurements and the in situ SERS measurements. A.B. performed the XRD experiments. C.R., M.H., T.W. and F.S. performed the XPS experiments. C.R. performed the Pb UPD experiments. A.H. performed the time-dependent in situ SERS measurements. M.H. performed the in situ SERS measurements of glyoxal and ethanol reduction. F.D. carried out the density functional theory simulations. All authors contributed to the discussion and editing of the paper.

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Competing interests

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